ERS-2 ALTIMETRY IN OPERATIONAL NOAA FORECAST MODELS

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ABSTRACT

NOAA's Laboratory for Satellite Altimetry has been producing real-time altimetry products from ERS-1 and ERS-2 since 1995. Significant enhancements are made to ESA's fast-delivery data sets, most notably the addition of orbit information provided by the Delft University of Technology. In late 1998, several enhancements were made to the NOAA/Delft altimetry products: ESA's fast-delivery data now include measured wet troposphere corrections from the on-board radiometer; the Delft DGM-E04 gravity model (specifically tuned for ERS) is used in the orbit determination system; and an iterative feedback scheme is now performed to refine the real-time orbits by incorporating altimetric heights and crossovers. Within NOAA, several collaborative efforts are utilizing real-time ERS-2 data in their operational forecast models. At the largest scales, the Climate Modeling Branch at the National Centers for Environmental Prediction (NCEP) is assimilating TOPEX/Poseidon and ERS-2 altimetry into a coupled model for El Niño / Southern Oscillation prediction. Timeliness is not as critical as absolute accuracy in this modeling effort. Thus, we are combining the ERS-2 data with the more accurate TOPEX/Poseidon altimetry to further reduce orbit and environmental correction errors before assimilation in the ENSO model. At finer resolution, the NCEP Ocean Modeling Branch is assimilating TOPEX/Poseidon and ERS-2 altimetry into the Coastal Ocean Forecast System, which produces nowcast and 24-hour forecast fields for the Gulf Stream/western North Atlantic region. Evaluations carried out during a recent demonstration project established that addition of sea surface height anomalies derived from TOPEX/Poseidon added significant detail to the real-time products: sea surface heights, 1-meter currents, and subsurface temperatures. Parallel forecast experiments are now in progress to determine the impact of the addition of ERS-2 altimetry. The increased spatial resolution provided by ERS-2 is expected to further improve the model's skill at determining mesoscale features. Recently, a unique use of altimetry data was begun with NOAA's National Hurricane Center. Products containing surface height anomalies, upper ocean heat content, and upper layer thickness will be available operationally to the forecasters this hurricane season for the Western Atlantic Ocean. The upper ocean heat content and upper layer thickness are inferred from sea surface heights, which augment sea surface temperature and in-situ subsurface measurements. Again, the increased spatial resolution provided by ERS-2's sampling will greatly benefit the determination of these oceanic parameters, thereby improving the prediction of tropical cyclone intensity.

REAL-TIME ALTIMETRY FROM ERS-2

One of the unique aspects of the European Space Agency's (ESA) Earth Remote Sensing satellite (ERS) missions is the rapid delivery of its data products to end users. For "low bit-rate" data sets, which include measurements from the on-board altimeter and radiometer systems, the latency between down-link telemetry and reception by the user is no greater than six hours, Fig. 1. The primary receiving stations at Kiruna, Sweden and Maspalomas, Spain typically show latencies of 2-3 hours, while the remote stations at Gatineau and Prince Albert, Canada exhibit somewhat longer delays. The data acquired by the Prince Albert station became a part of the fast-delivery data stream in July, 1999, after a leased line was installed between the two Canadian ground stations.

When fast-delivery altimeter data arrives at NOAA's Laboratory for Satellite Altimetry (LSA) it does not contain an accurate orbit, but rather only crude satellite state vectors. Through a long-standing and highly successful collaboration with the Delft University of Technology's Institute for Earth-Oriented Space Research (DEOS) we obtain precise orbit information for the ERS satellites on a daily basis. The Delft/NOAA system has been continually improved, with orbit errors now estimated at 7-10 cm radially, as described further below. Once the altimetric range is combined with the satellite's orbital elevation it is possible to generate sea surface height measurements. However, atmospheric path delay corrections must also be obtained. The operational weather forecasting system at NOAA's National Centers for Environmental Prediction (NCEP, formerly NMC) provides estimates of sea level pressure and total precipitable water, which can be converted to wet and dry troposphere corrections. These fields are routinely available within nine hours past the end of a day, Fig. 1. Once the satellite orbits and atmospheric correction fields have been received, the final NOAA Real-time Geophysical Data Record (RGDR) is generated within an hour, so that the net latency for creation of the daily files is ten hours past midnight of the previous day.

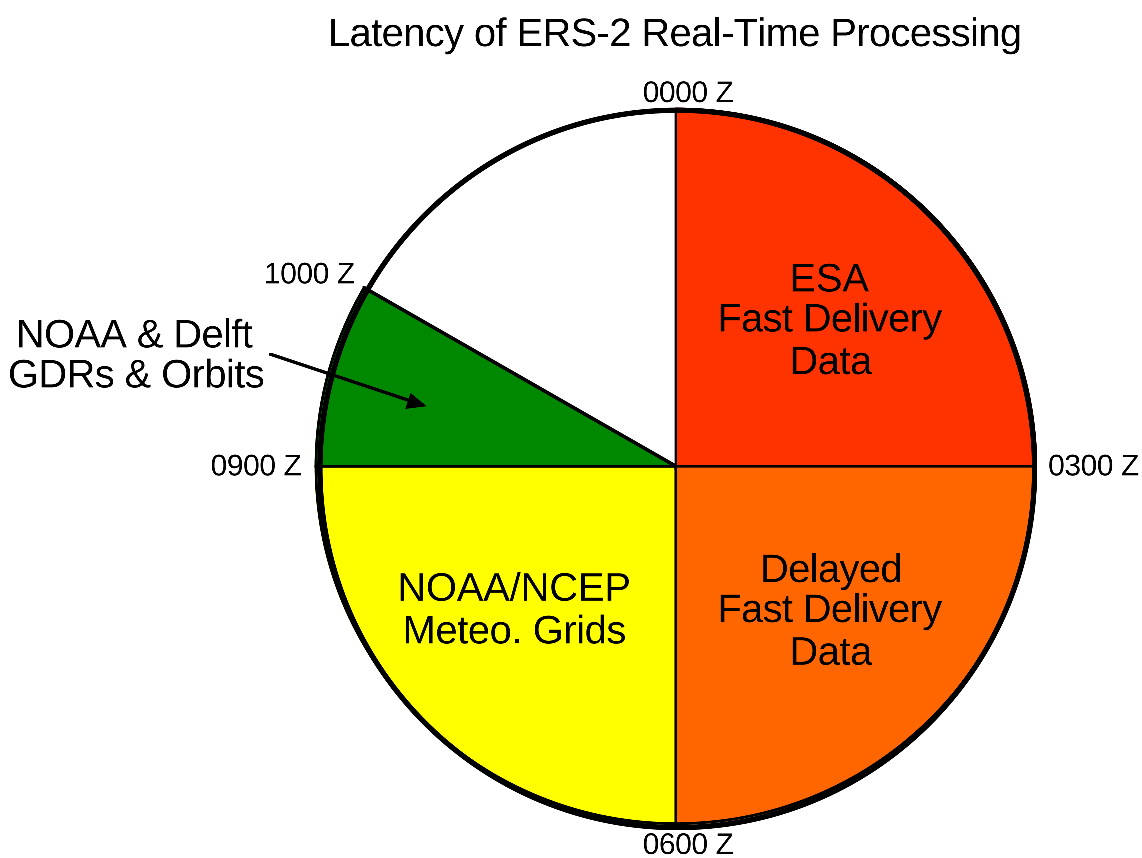


Fig. 1. Approximate latency between acquisition of ERS-2 altimetry data and generation of the final NOAA RGDR. Roughly 90% of ESA's fast-delivery altimeter data is available within 3 hours, with the remainder acquired within 6 hours. The operational weather model running at NOAA's National Centers for Environmental Prediction provides meteorological grids for computation of the wet and dry troposphere corrections, which delays the processing an additional three hours. The generation of the final RGDR and Delft orbit files takes less than an hour, yielding a total latency for the daily products of about 10 hours.

Recent Improvements

In late 1998 several improvements were made to the real-time altimetry system described above. First, ESA modified its ground processing system so that the measured wet troposphere correction from the on board microwave radiometer was provided in the fast-delivery data. This was the first time in the seven years since the launch of ERS-1 that a measured, rather than modeled, value of wet troposphere correction was available in near real-time.

A major improvement in the real-time orbits at DEOS was accomplished through gravity field tuning, which tailored the gravity model specifically for ERS-1 and ERS-2 [1]. Orbits based on this tuned gravity model, DGM-E04, show a reduction of several cm in radial orbit error, compared to the previous orbits based on the JGM-3 gravity model [2].

Finally, a unique "feedback loop" was put into place, linking the altimetry processing system at LSA with the orbit determination system at DEOS. This scheme, illustrated in Fig. 2, utilizes altimetric range and crossover data to improve on the real-time orbits. A preliminary RGDR is generated by combining the fast-delivery altimetry with a predicted Delft orbit, created a day earlier. The environmental corrections are added at this time, and a preliminary RGDR is then sent to Delft. Range measurements as well as crossovers are then combined with the direct laser tracking data to yield a better orbit determination than laser tracking data alone would provide. This improved orbit is then fed back to NOAA, along with a predicted orbit for the next day. The final RGDR is created by replacing the predicted orbital information with the improved orbit's values, and adjusting the sea surface height by the difference between the predicted and final orbit heights.

The reduction in radial orbit error (the largest residual error in the sea surface heights) can be seen by comparing the preliminary and final versions of the RGDRs. Fig. 3 shows the rms height variability for each daily RGDR based on predicted (red) and final (blue) versions of the Delft orbits. These statistics include the true oceanic variability, roughly 10 cm rms, as well as errors from both environmental corrections and orbit error. The level of orbit error in this automated daily processing scheme is on the order of 7-10 cm. Differences between these real-time orbits and precise orbits generated a few months later are generally around 5 cm rms.

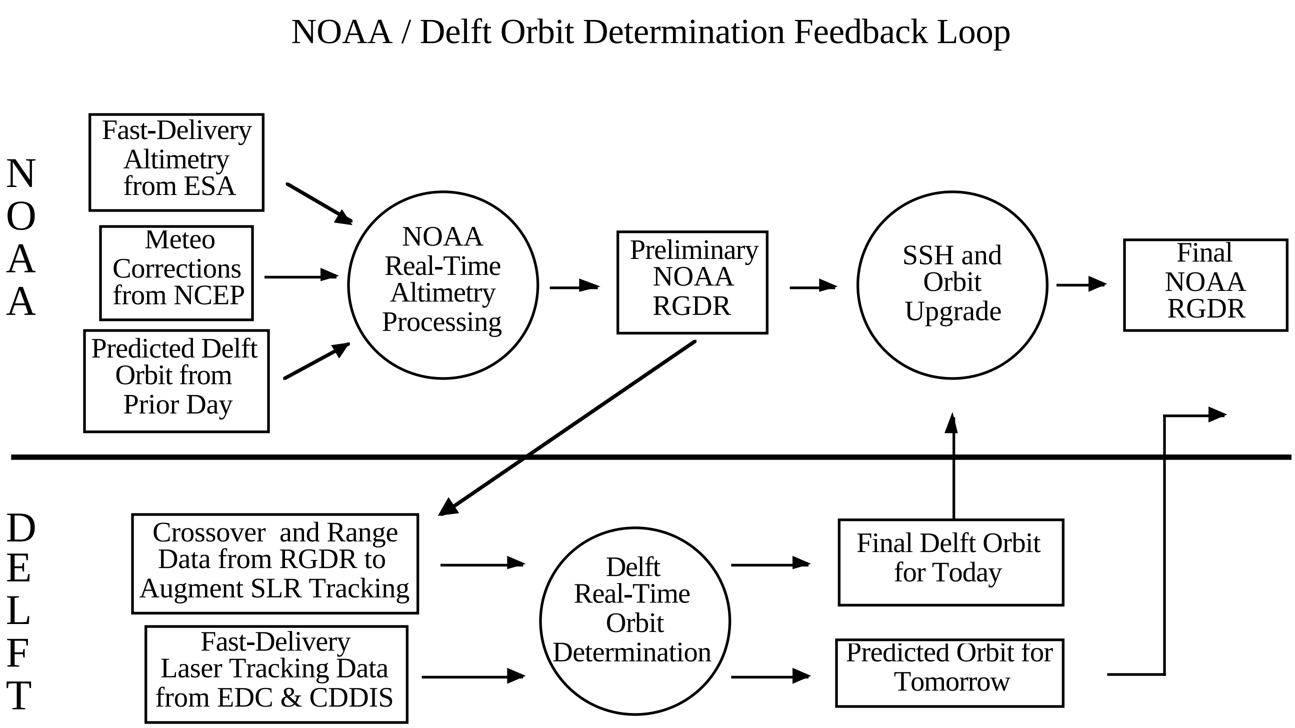


Fig. 2. Schematic representation of the feedback loop between NOAA and Delft, which upgrades the initial predicted orbit using a preliminary version of the altimetry data. Both altimetric range and crossover information are combined with the laser tracking data to improve the final real-time orbit for the current day. The sea surface height, geographic location, and orbital heights are then updated using the improved orbit.

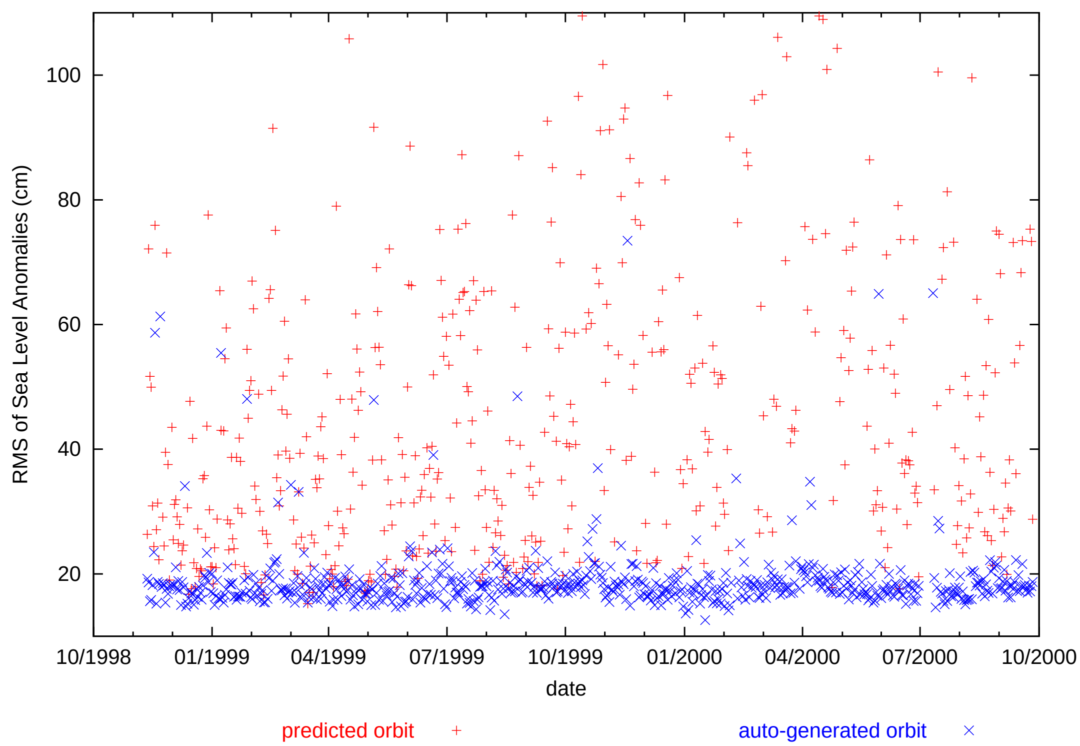


Fig. 3. Global RMS variability of daily ERS-2 sea level anomalies. The red crosses are computing from RGDRs with the predicted Delft orbit from the prior day. The blue crosses are computed from RGDRs using the real-time orbit, after it is recomputed using the current day's altimetry data in the orbit determination. The daily values of global RMS sea level are reduced from tens of cm (primarily orbit error) down to 10-20 cm. The remaining outliers (blue crosses) are primarily due to poorly modeled satellite orbit maneuvers.

Within NOAA there are a variety of ocean forecasting models being run, from global scale to mesoscale. The following sections of this paper describe three such activities which are utilizing LSA's real-time altimetry data in their modeling efforts: El Niño forecasting by the Climate Modeling branch at NCEP; coastal ocean forecasting in the NW Atlantic by the Ocean Modeling branch at NCEP; and tropical cyclone predictions performed by NOAA's National Hurricane Center.

EL NIÑO / SOUTHERN OSCILLATION FORECASTING

At the largest spatial scales (ocean-basin to global) and long time scales (seasonal to interannual and decadal) the most important combined ocean-atmosphere phenomenon is the El Niño Southern Oscillation (ENSO) in the tropical Pacific. The Climate Modeling group at NCEP is running a coupled ocean-atmosphere model to make ENSO predictions with several months of lead time. Their standard model is initialized through assimilation of subsurface temperature data from in situ observation programs [3], [4]. In late 1996 LSA began providing fast-delivery TOPEX altimetry data to NCEP, in the form of global sea level deviations relative to a 3-year mean time period (1993-1995), with a latency of two days [5]. The NCEP assimilation scheme was modified to include this sea level data as an added constraint, forcing adjustments in the internal temperature structure of the model to best fit the sea level observations [6]. The assimilation system does not ingest salinity observations, primarily because of the paucity of direct measurements. However, in the strong 1997-1998 El Niño, a substantial change in sea level in the western tropical Pacific was observed which is believed to be partially driven by changes in the near-surface salinity [7]. The inclusion of sea level deviations in the model, which reflect changes in both temperature and salinity throughout the water column, allows the model to respond to changes in salinity in the western Pacific. Fig. 4 illustrates these differences by comparing the sea level deviations from the model without altimetry vs. model runs with assimilation of altimetry. These parallel model runs were performed as a hindcast experiment, using TOPEX data provided by LSA for the time period 1993-1998. The largest differences in equatorial sea level between the models are seen in the western Pacific, exceeding 10 cm in late 1996, just prior to the '97-'98 El Niño. The model run which included altimetry shows better correspondence with in situ sea level data from tide gauges in this region, Fig. 5.

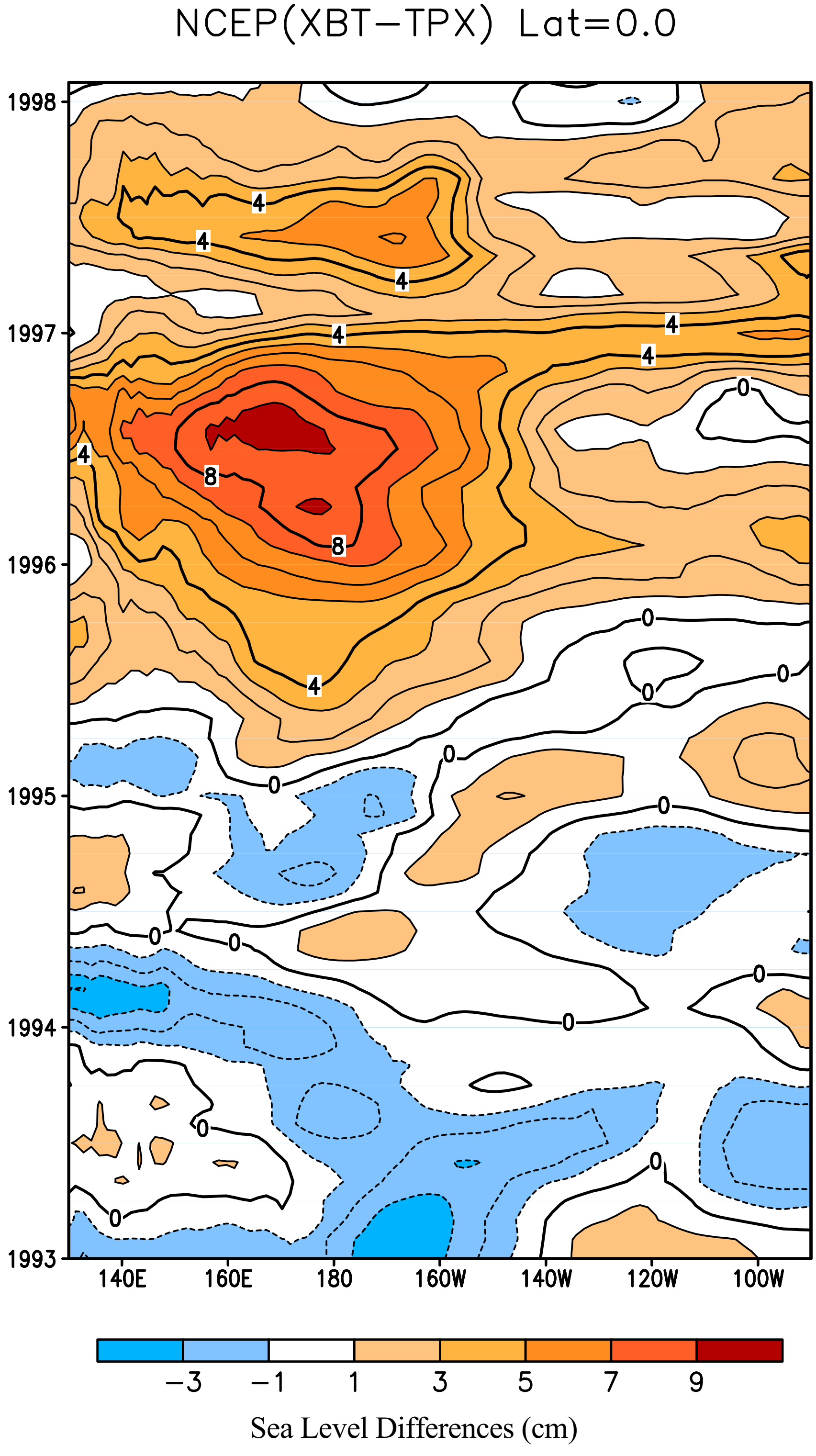


Fig. 4. Time-Longitude plot along the equator in the tropical Pacific, showing the differences in sea level deviations between the NCEP ENSO model with no altimetry (XBT) vs. the model with assimilation of TOPEX altimetry (TPX). Differences exceeding 10 cm in the western Pacific are seen in mid-1996, prior to the strong 1997-1998 El Niño event. These large sea level differences are primarily due to salinity changes which aren't properly accounted for in the model without altimetry. The altimetric data reflect both internal temperature and salinity variations, thus improving the model when the TOPEX data are assimilated.

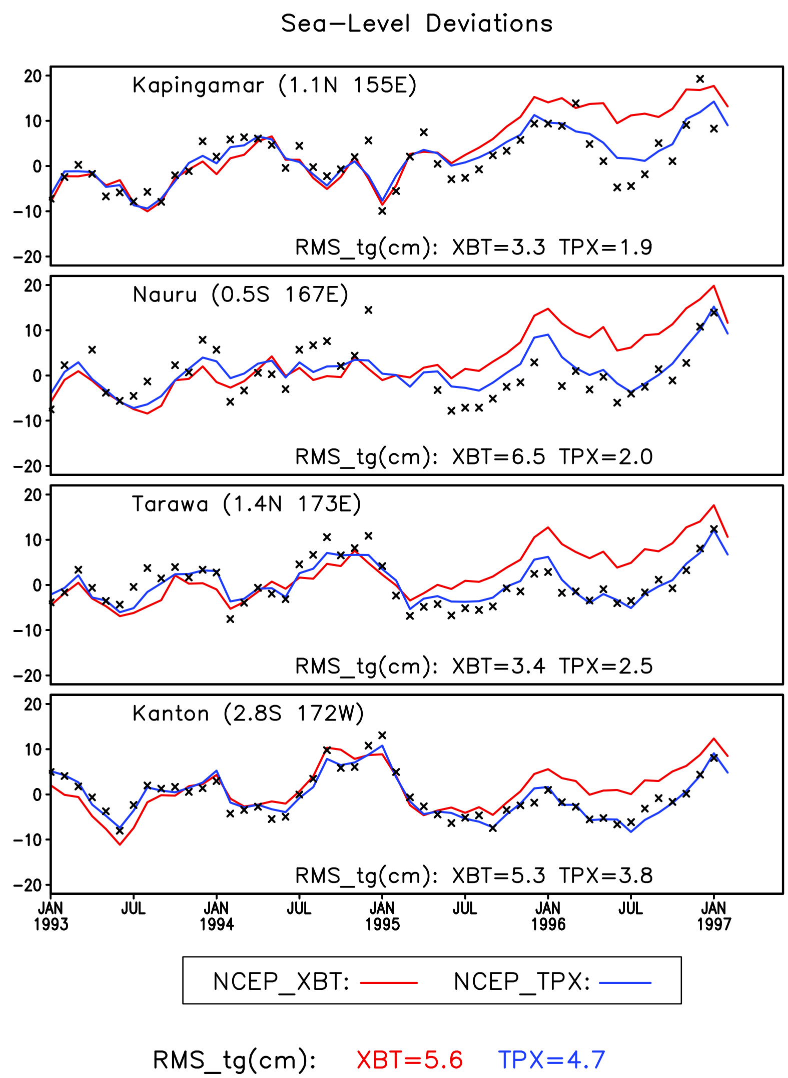


Fig. 5. Time series of sea level at four tide gauge locations in the western tropical Pacific. The red curves are from the ENSO model without altimetry (XBT), the blue curves are from the model including altimetry (TPX) and the black crosses are the tide gauge values. The model without altimetry diverges from the tide gauge values in mid-1996, while the model including altimetry continues to track the observed sea level. The rms agreement between the curves and the tide gauges is significantly lower when altimetry is assimilated.

In order to assimilate ERS-2 sea level deviations into the ENSO prediction model, it is necessary to further reduce the residual orbit error in the real-time altimetry products. Traditional collinear methods of orbit error removal retain short-wavelength mesoscale features, but remove large-scale north-south tilts in sea level. These hemispheric tilts are associated with seasonal heating and cooling, and must be retained if the data are to be useful for ENSO prediction. We have developed a methodology similar to that of Le Traon [8], which uses dual-satellite crossovers between TOPEX and ERS-2 to remove orbit error without significantly damping large-scale oceanographic signals. Crossover height differences between the two satellites, with a separation time between ascending and descending tracks of ± 5 days, are fitted by an along track spline function. Since the predominate orbit error signal has a once and twice per revolution character, the spline knots are adjusted to respond to signals with those length scales. This procedure primarily corrects for ERS-2 orbit error, but also removes any systematic biases between the orbit determination systems of the two missions, including offsets between the "geocenters" of their reference frames. The adjustment homogenizes the two sea level data sets so they can be easily blended into the NCEP assimilation scheme. Fig. 6 shows an example of the improvement in the ERS-2 data using this technique. The top panel represents the sea level deviations from ERS-2 with no adjustment to remove orbit error; the middle panel shows the effect of applying the corrections from spline-fitting to the TOPEX/ERS-2 crossovers; and the bottom panel shows the corresponding sea level deviations from TOPEX alone. The agreement between TOPEX and the crossover adjusted ERS-2 data is clearly much better, and the adjusted ERS-2 data retain the hemispheric differences expected from seasonal heating.

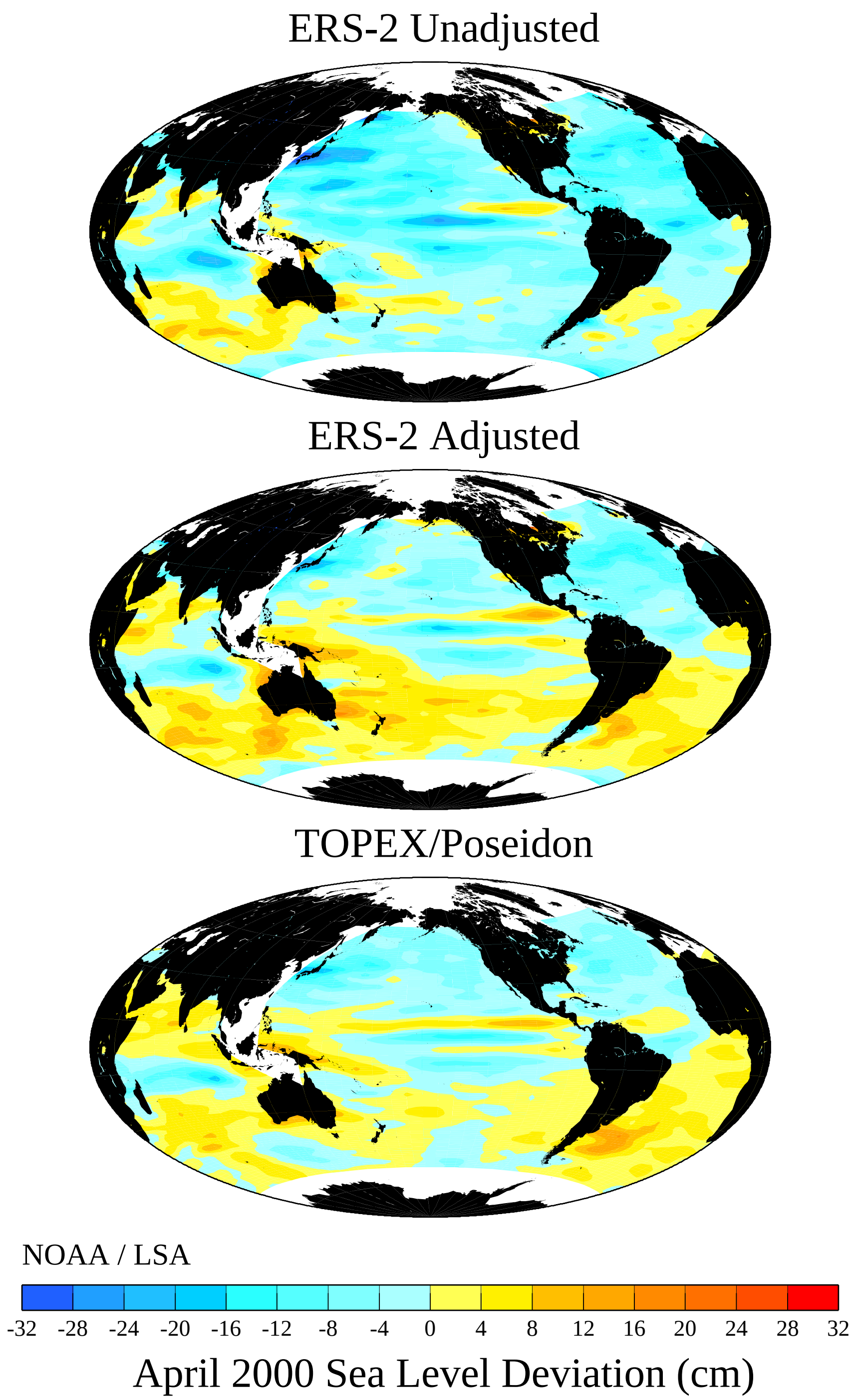


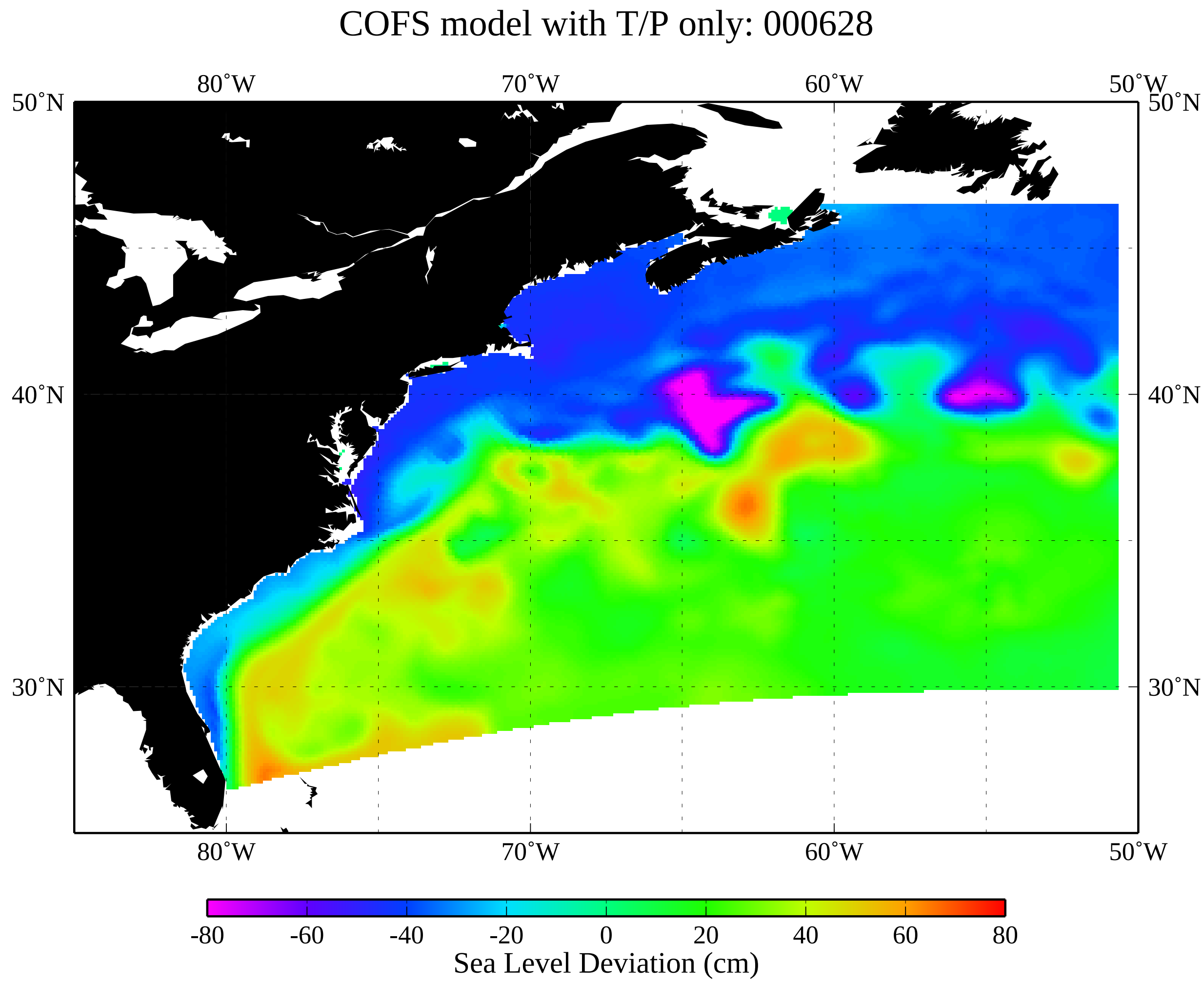
Fig. 6. Sea level deviations in April, 2000 from unadjusted ERS-2 data (top), ERS-2 adjusted from spline-fitting the crossovers with TOPEX (middle), and the original TOPEX/Poseidon data (bottom). The unadjusted ERS-2 map doesn't exhibit the north-south tilt seen in the TOPEX/Poseidon map, with a maximum in sea level in the southern hemisphere (austral fall) and a minimum in sea level in the northern hemisphere (boreal spring). After the crossover adjustment the ERS-2 data show this seasonal tilt in sea level, and agree better with the TOPEX/Poseidon data in the equatorial Pacific as well.

We are presently working with the Climate Modeling Branch at NCEP to incorporate the adjusted real-time ERS-2 data into their assimilation system. We will then proceed to evaluate the improvement in the ENSO model's prediction skill after addition of this higher spatial resolution data.

COASTAL OCEAN FORECAST SYSTEM

The Ocean Modeling Branch at NCEP runs the Coastal Ocean Forecast System (COFS) for near-shore regions of the U.S. East Coast and western north Atlantic. This coupled ocean-atmosphere model is based on the Princeton Ocean Model [9], and assimilates sea surface temperature (SST) measurements, Gulf Stream "North Wall" positions, and sea level deviations from altimetry [10]. The timeliness of the ERS-2 data is ideal for this application. It is not as critical that the large scale seasonal signal be retained, but rather that energetic mesoscale features are properly located in the observations driving the model. ERS-2 has a distinct advantage for mesoscale monitoring such as this, due to the closer spacing of its 35-day repeat ground tracks compared to TOPEX/Poseidon. The combination of sea level data from multiple altimetric missions increases the spatial coverage available for the model assimilation. Unlike the ENSO model described above, COFS does not currently assimilate in situ subsurface temperature observations. However, the sea level data is a vehicle for correcting the internal temperature structure of the model, through the strong vertical correlation between subsurface temperatures and sea level deviations.

The COFS model delivers daily nowcast and 24-hour forecast maps of SST, surface height, surface salinity, near-surface (1-m level) currents, and selected subsurface fields. To assess the contribution of ERS-2 data assimilation, parallel model runs were conducted. The model was first run assimilating only SST and TOPEX data and then run assimilating SST, TOPEX, and ERS-2 data. Fig. 7 compares these two model runs via the nowcast surface height fields. The location of the main axis of the Gulf Stream is visible in the sea surface height field where the large gradient occurs, going from green to dark blue. If we compare these maps to the nearest observed SST analysis from NOAA's Satellite Active Archive, Fig. 8, there is better agreement in the path of the Gulf Stream and location of eddy features in the model run that includes ERS-2. For example, the more northward extension of the Gulf Stream just off Cape Hatteras is not shown in the TOPEX-only model run, and the structure of the current and eddy field due south of Nova Scotia is more similar between the SST field and the model run with ERS-2 data included.



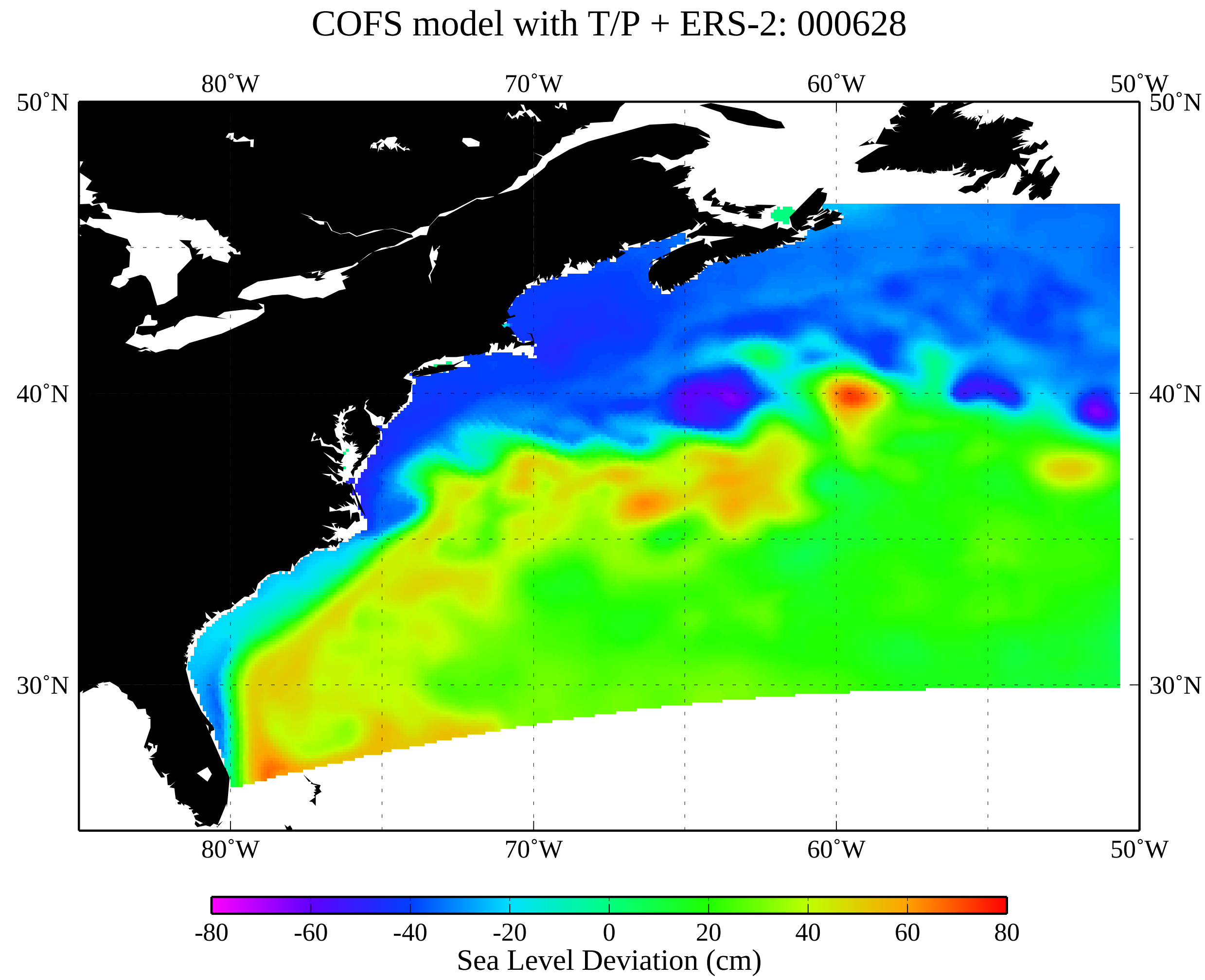


Fig. 7. Sea level deviations from the Coastal Ocean Forecast model nowcast for June 28, 2000. The top panel is from a model run with altimetry from TOPEX only, while the bottom panel is from a run with TOPEX and ERS-2 data assimilation. The run that includes ERS-2 data exhibits more realistic Gulf Stream current structure and eddy locations due to the enhanced spatial resolution of the combined data sets.

At present the COFS model uses a two-step assimilation which first ingests altimetry data and then the SST observations. This procedure tends to weaken the impact of the altimetry data on the model dynamics. One of the planned improvements to the COFS system is to replace this with a multi-variate scheme, allowing both temperature and sea level data to be assimilated simultaneously. The gains from adding ERS-2 data to this system are expected to be even more pronounced than with the current scheme. Plans are being made by LSA to also include altimetry from the Navy's Geosat Follow-On (GFO) mission, further improving the spatial and temporal coverage of the data ingested by the COFS model.

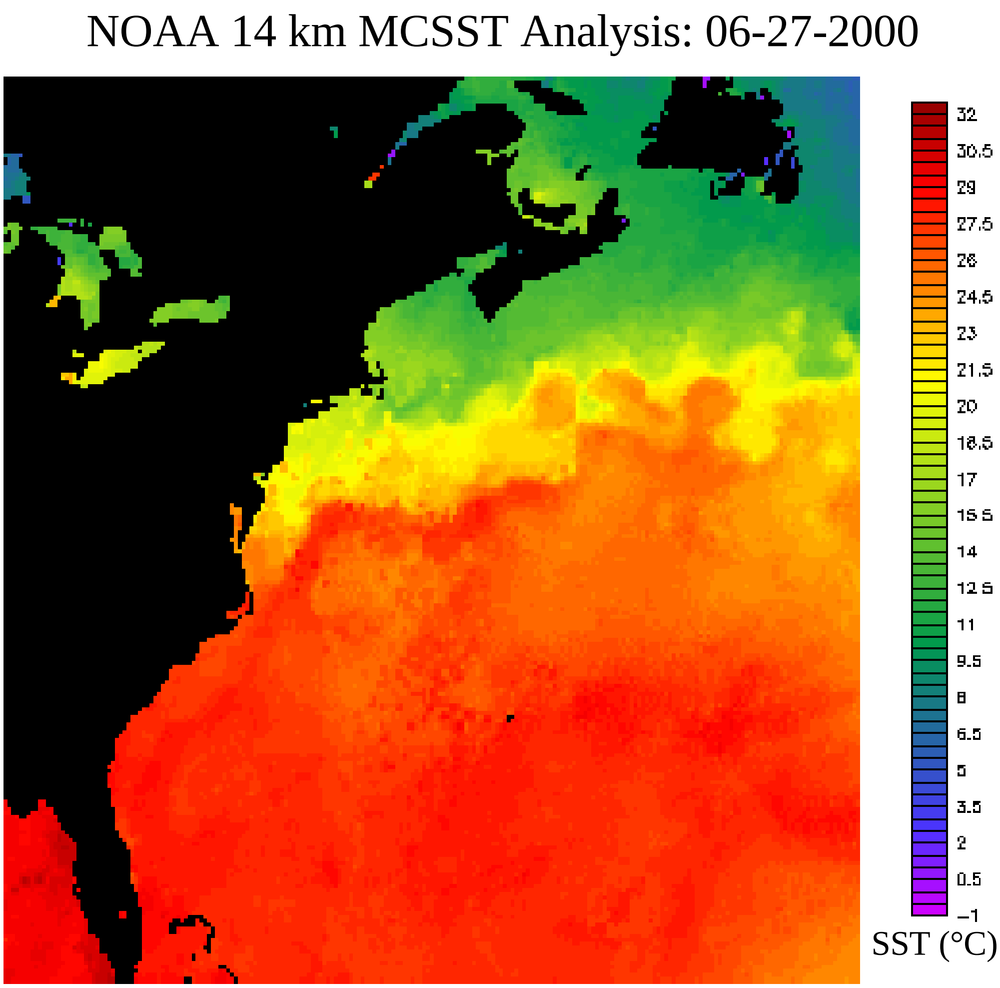


Fig. 8. Sea surface temperature analysis from the NOAA Satellite Active Archive for June 27, 2000. Each pixel is 14 km square, and has had cloud removal algorithms applied by compositing several days worth of SST observations. The spatial resolution is sufficient to delineate the North Wall of the Gulf Stream (red to yellow transition) and the locations of warm core rings to the north of the current.

TROPICAL CYCLONE FORECASTING

Certainly the most destructive atmospheric phenomena known to mankind are tropical cyclones: hurricanes and typhoons. NOAA's National Hurricane Center (NHC) is responsible for timely as well as accurate forecasts of hurricane paths, intensities, and landfall locations. Although predictions of hurricane paths have improved greatly in recent years, changes in storm intensity are still forecast poorly. Both observational data and hurricane models indicate that rapid intensification of a hurricane can occur when the underlying ocean is "feeding" heat to the storm [11]. A measure of the surface oceanic conditions which are favorable for storm intensification is the integrated heat content from the surface to the depth of the 26° C isotherm. This quantity, dubbed "heat potential" by hurricane forecasters, is better correlated with hurricane intensification than high sea surface temperatures alone. The thermal structure within warm-core eddies, spun off the Gulf Stream and Gulf of Mexico Loop Current, have high heat potential which can cause hurricanes passing over them to intensify.

In order to generate maps of heat potential it is necessary to know the depth of the main thermocline (nominally the depth of the 20° C isotherm in this region) as well as the sea surface temperature. Sea level deviations from altimetry can be used to infer changes in the depth of the main thermocline by means of a simple two-layer model [12]. Using real-time altimetry and SST information, plus a climatological relationship between the depths of the 20° and 26° isotherms, it is possible to generate daily maps of heat potential for hurricane forecasting. At present, the real-time fields of heat potential are not directly assimilated into the NHC hurricane model, but they are being used by hurricane forecasters as a tool in their analyses.

The data being providing to the NHC consists of sea level deviations from TOPEX and, beginning in the summer of 2000, ERS-2 data as well. The combination of data from these two sources gives better spatial coverage of mesoscale features within the Gulf of Mexico and tropical northwest Atlantic. Mesoscale features in the ocean, such as the warm-core eddies which trigger hurricane intensification, are not optimally sampled with the large ground-track separation of TOPEX. The addition of ERS-2 data makes it much more likely that an eddy's location and strength will be correctly observed by the altimetry. An example of the daily sea level deviation maps being provided by LSA is shown in Fig. 9. Both the TOPEX and ERS-2 data have had a short-arc orbit error removal procedure applied, which assures consistency in the merged sea level field.

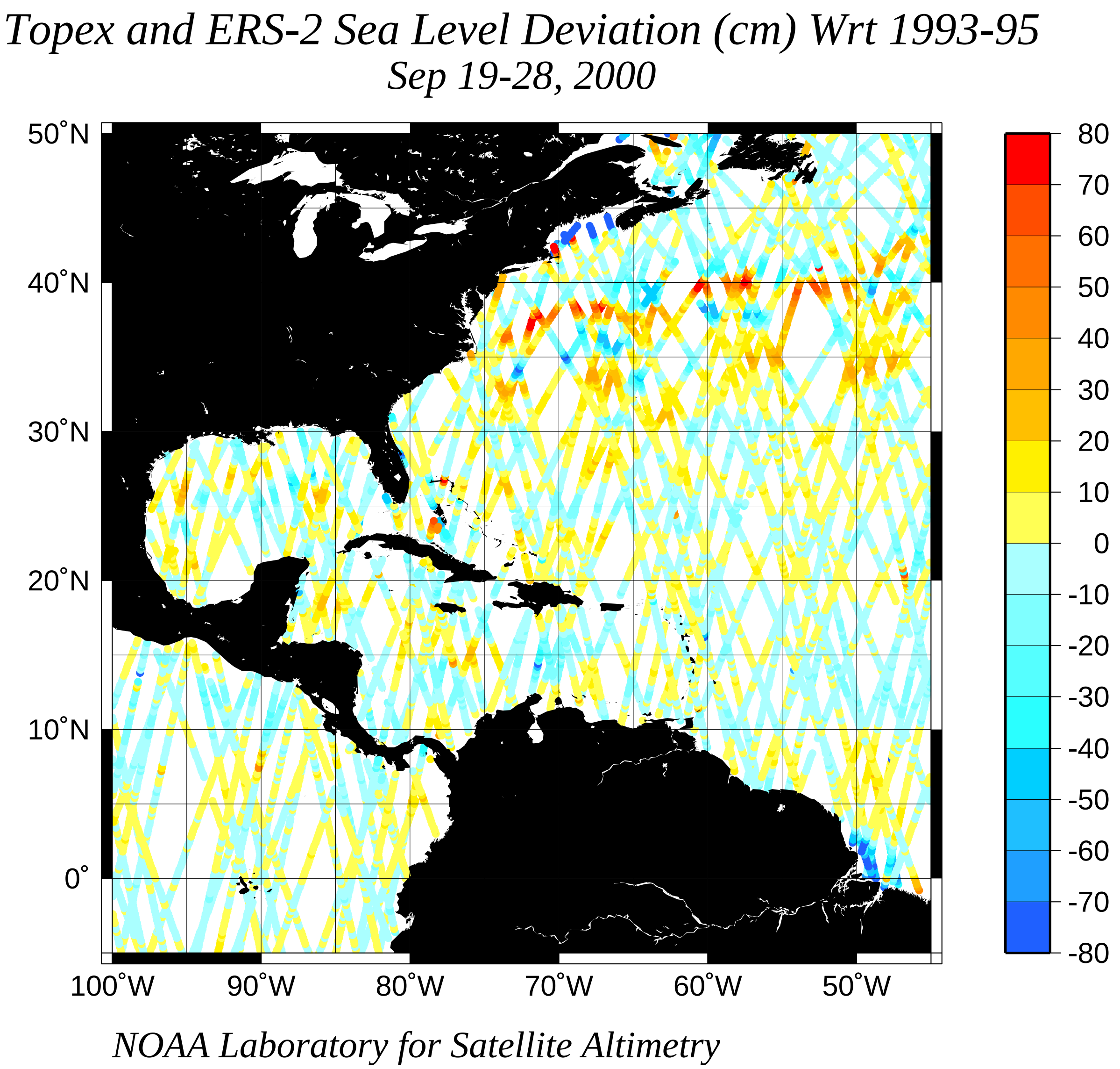


Fig. 9. Real-time sea level deviation map for the western north Atlantic, utilizing both TOPEX and ERS-2 altimetry. The enhanced spatial coverage provided by ERS-2 helps to better delineate the strength and location of the Gulf Stream system and mesoscale features within the region. Data from the two missions are referenced to a common three year mean (1993-1995) and both have had orbit error removal applied via short-arc collinear methods.

The NHC began utilizing the combined TOPEX/ERS-2 sea level maps during the 2000 hurricane season. The utility of the heat potential maps can be shown by examining one of the hurricanes from this season: in mid-September hurricane Gordon spawned off the Yucatan peninsula and intensified to a Category-1 storm (winds in excess of 74 mph) as it crossed a warm meander in the Gulf of Mexico Loop current. The storm made landfall on the Gulf coast of Florida four days later after it had weakened to a tropical storm, Fig. 10.

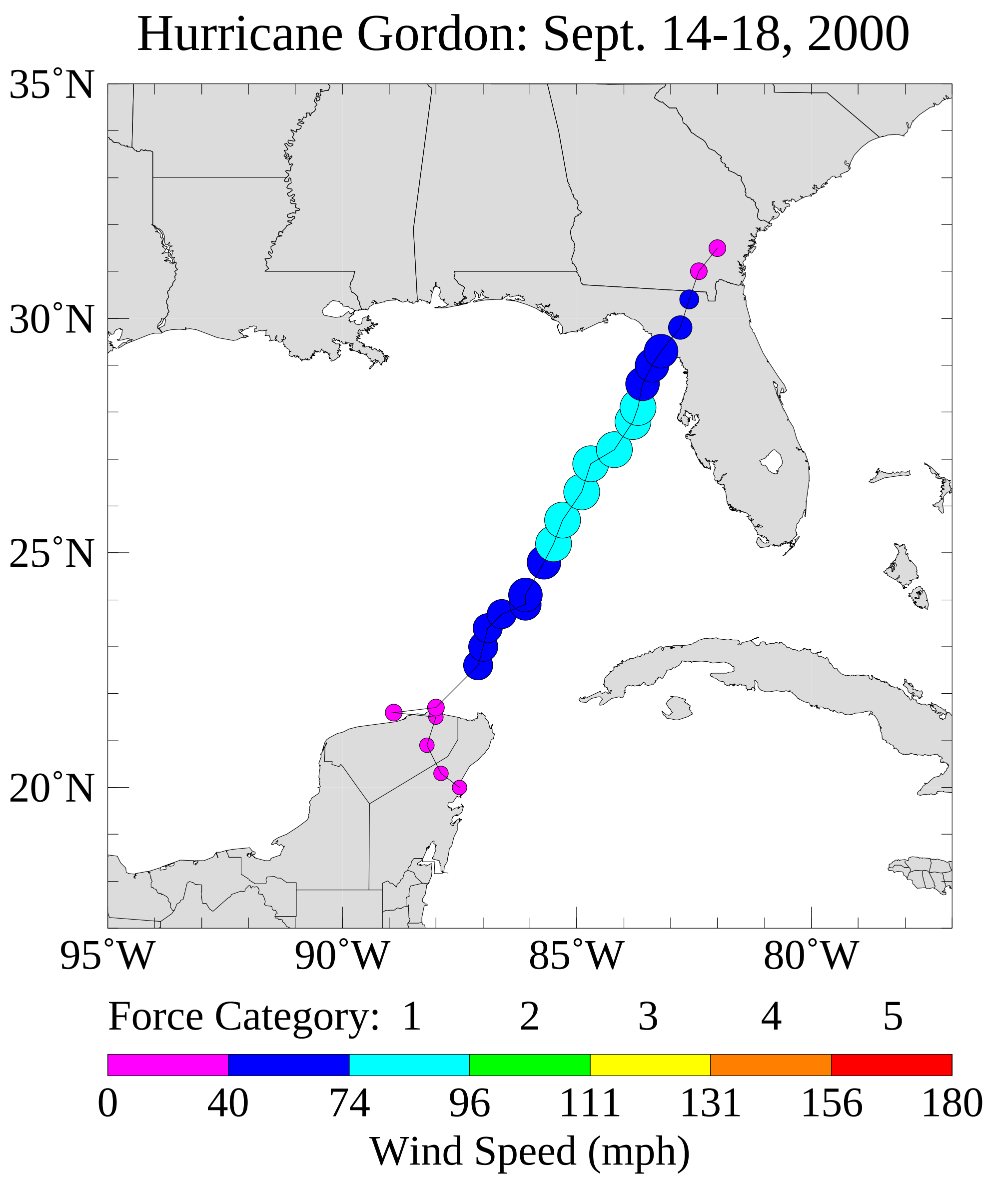
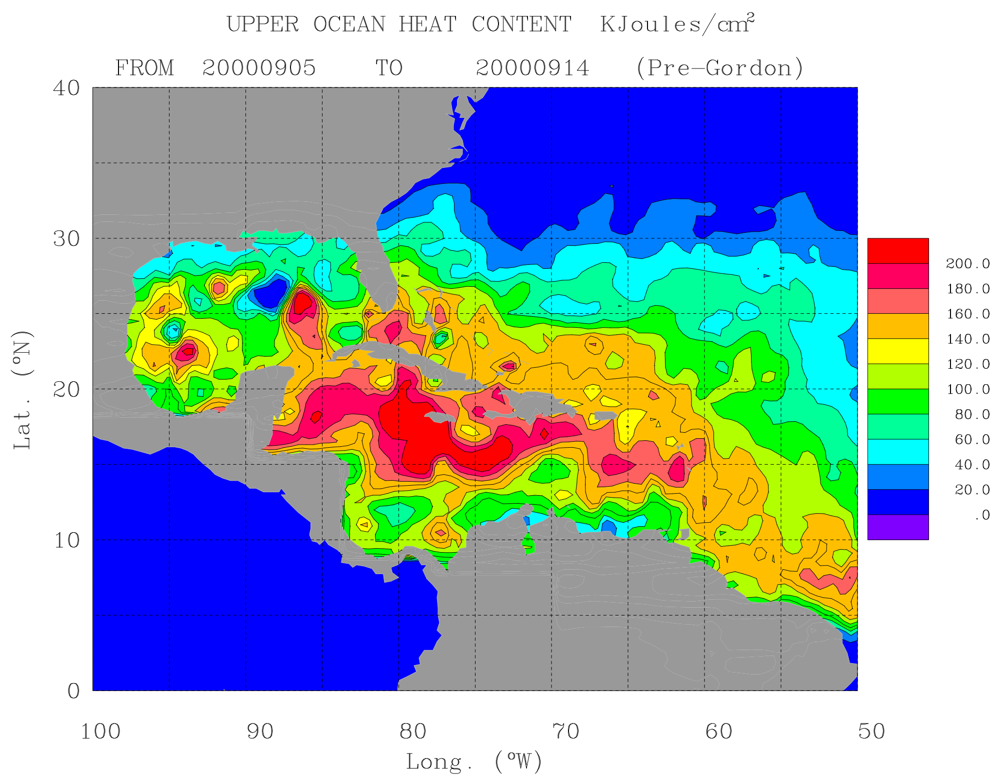


Fig. 10. Track of Hurricane Gordon from its early stages on the Yucatan peninsula through landfall on the Gulf coast of Florida, September 14-18, 2000. Symbol sizes along the storm track are scaled by the maximum observed wind speed, and are color coded according to storm force category. This hurricane attained a category-1 status, with wind speeds in excess of 74 mph, and then weakened to tropical storm force prior to landfall. The intensification phase of the storm occurs over the Gulf of Mexico Loop Current, which extends into the Gulf of Mexico between Cuba and the Yucatan.

Heat potential maps from before and after hurricane Gordon were generated by the NHC, using a blended analysis based on both TOPEX and ERS-2 data, Fig. 11. There is a region of high heat potential shown in the pre-Gordon map (top panel), where the Loop current extends northward between the Yucatan and Cuba, near 26° N, 86° W. This feature was crossed by Hurricane Gordon as it tracked NE towards Florida, and may well have contributed to the storm's intensification. The post-Gordon map (bottom panel) shows a weaker signal in the heat potential of this feature, as well as a region of anomalously low heat potential (dark blue) extending from 25-30° N along 86° W. It is possible that this feature was caused by the passage of the hurricane, due to the large amount of heat removed from the ocean.

Detailed comparisons with in situ observations taken during hurricane Gordon will be used to confirm the changes seen in these maps. Ultimately the real-time maps of heat potential will be assimilated directly into the hurricane forecasting model to better predict hurricane intensification.



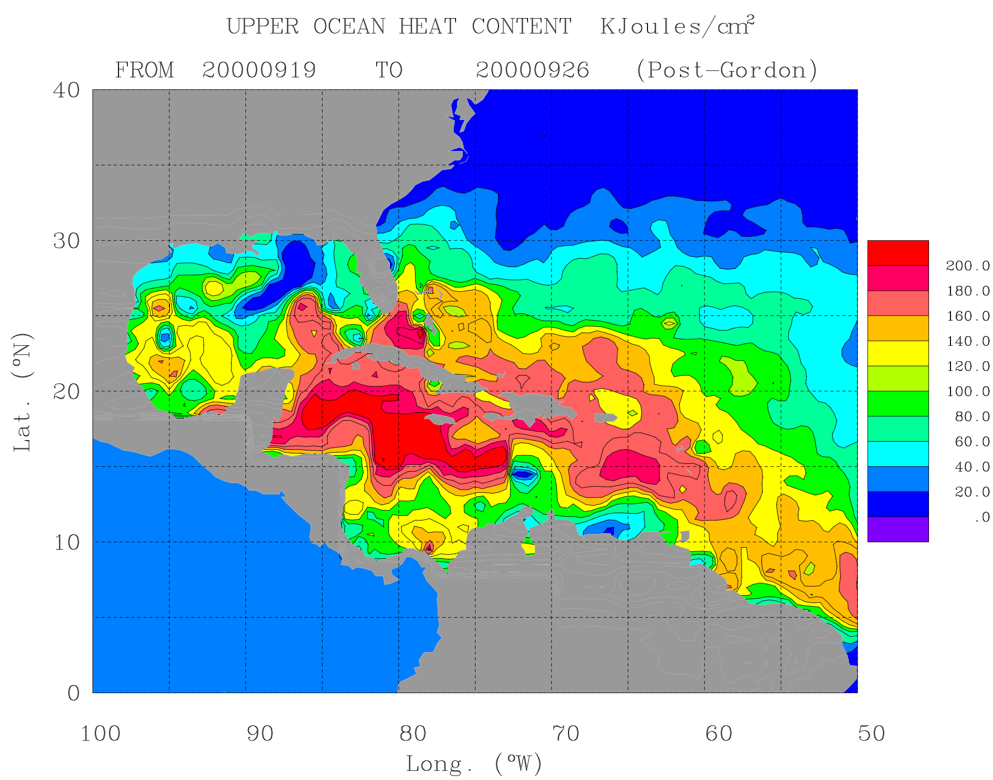


Fig. 11. Maps of upper ocean heat potential before (top) and after (bottom) the passage of hurricane Gordon. The storm traversed the Gulf of Mexico between the Yucatan Peninsula and the Gulf coast of Florida. The region of high heat potential extending into the Gulf between Cuba and the Yucatan is associated with the Loop current. Intensification of the hurricane occurred during its passage over this feature. The post-Gordon heat potential map shows a region of unusually low heat potential along 86° W, presumably due to the heat loss from the ocean during the storm's passage.

CONCLUSION

Three diverse examples of the use of real-time altimetry in NOAA forecasting have been shown. The availability of sea level deviations from multiple satellite missions, with a latency of hours to days can benefit a variety of modeling efforts. Large-scale models such as ENSO prediction require the highest accuracy with some relaxation in timeliness; regional and coastal models such as COFS are best suited to daily real-time products without a strong need to retain large-scale seasonal signals; while tropical cyclone forecasting is aided by knowledge of the underlying upper ocean structure and heat content. All benefit greatly from the addition of sea level information from altimetry. In the future, NOAA's Laboratory for Satellite Altimetry will continue to refine their real-time data sets and augment them with data from new altimetry missions such as GFO, JASON, and ENVISAT.

ACKNOWLEDGEMENTS

We would like to thank several members of the LSA for their help in developing the real-time altimetry system, and for generating the data sets used in the analyses above: Bob Cheney, John Kuhn, Laury Miller, and Walter Smith. We would also like to acknowledge the efforts of Bert Katz and Ilya Rivin at NCEP's Ocean Modeling Branch, who performed the parallel COFS model runs and provided the model grid files used to generate Fig. 7. The storm track data for hurricane Gordon was kindly provided by Steve Babin at the Johns Hopkins University Applied Physics Laboratory, and the concept for Fig. 10 was taken from a figure on his web site: http://fermi.jhuapl.edu/hurr/00/gordon.

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