Naval Research Laboratory
Stennis Space Center, MS 39529-5004

NRL/MR/7323--96-7722

Warfighting Contributions of the Geosat Follow-On Altimeter

Gregg A. Jacobs
Michael R. Carnes
Daniel N. Fox
Harley E. Hurlburt
Robert C. Rhodes
William J. Teague

Ocean Dynamics and Prediction Branch
Oceanography Division

John P. Blaha

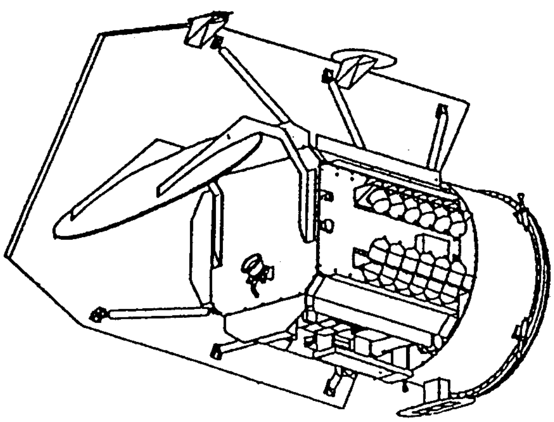
Naval Oceanographic Office
Stennis Space Center, MS

Richard Crout

Commander, Naval Meteorology and Oceanography Command
Stennis Space Center, MS

Ole Martin Smedstad

Planning Systems Incorporated
Slidell, LA



February 9, 1996

REPORT DOCUMENTATION PAGE	*Form Approved* *OBM No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** February 9, 1996	**3. REPORT TYPE AND DATES COVERED** Final

4. TITLE AND SUBTITLE

Warfighting Contributions of the Geosat Follow-On Altimeter

5. FUNDING NUMBERS

Job Order No.	573595706
Program Element No.	0601153N
Project No.	
Task No.	LR031034A, RR032083A, LR0310342
Accession No.	DN163509, DN153054

6. AUTHOR(S)

Gregg A. Jacobs, Michael R. Carnes, Daniel N. Fox, Harley Hurlburt, Robert C. Rhodes, William J. Teague, John P. Blaha*, Richard Crout†, and Ole Martin Smedstad††

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7323--96-7722

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Naval Oceanographic Office, Stennis Space Center, MS
†Commander, Naval Meteorology and Oceanography Command, Stennis Space Center, MS
††Planning Systems Incorporated, 115 Christian Lane, Slidell, LA 70458

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Geosat Follow-On altimeter will provide valuable information to the warfighter on scene. This real time knowledge of the ocean environment is critical to making intelligent decisions in the field. In particular, the acoustic environment depends on the synoptic mesoscale density distribution which is retrievable from the altimeter. Surface geostrophic currents are inferred from the altimeter data, and these allow calculation of mine drift paths. Altimeter data also provides key data for forecasting tidally generated heights and currents throughout the world. For numerical ocean models, it represents the most useful source of operational oceanic data for nowcasting and forecasting of ocean frontal locations, meandering currents and mesoscale eddies as well as larger scale oceanic analysis.

14. SUBJECT TERMS

altimetry, mesoscale oceanography, ocean forecasting, ocean models, satellite altimetry, data assimilation, remote sensing

15. NUMBER OF PAGES	13
16. PRICE CODE	

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Warfighting Contributions of the Geosat Follow-On Altimeter

The Geosat Follow-On altimeter will provide valuable information to the warfighter on scene. This real time knowledge of the ocean environment is critical to making intelligent decisions in the field. In particular, the acoustic environment depends on the synoptic mesoscale density distribution which is retrievable from the altimeter. Surface geostrophic currents are inferred from the altimeter data, and these allow calculation of mine drift paths. Altimeter data also provides key data for forecasting tidally generated heights and currents throughout the world. For numerical ocean models, it represents the most useful source of operational oceanic data for nowcasting and forecasting of ocean frontal locations, meandering currents and mesoscale eddies as well as larger scale oceanic analysis.

Acoustics

The altimeter currently represents the only satellite borne instrument which returns a measurement directly related to the dynamical state of the ocean. The observed sea surface height variations are directly related to the temperature, salinity, and sound speed structure and to geostrophically balanced currents in the upper ocean (down to the bottom of the main thermocline). Thus, the altimeter is the sole remote sensing instrument at hand capable of providing vital information on acoustic properties throughout the world. Through GFO these data will be acquired in real time by ships in the field for on-site determination of the ocean environmental state.

One way the altimeter derived SSH is utilized is to first infer temperature and salinity profiles at depth beneath the satellite ground track. These so-called “synthetic profiles” are then used in objective data assimilation systems such as MODAS. To obtain synthetic profiles, the SSH measured by the altimeter is related to subsurface temperature and salinity by climatological correlation analyses. Through a measurement of SSH and sea surface temperature, much of the subsurface variability in temperature and salinity may be estimated across most of the world's oceans. This provides the capability of real time delivery of synthetic profiles. That is, each SSH measurement along the altimeter ground track (spaced about every 7 km) may be transformed in real time into a synthetic profile. These synthetic temperature and salinity data are then directly assimilated into existing Navy operational systems such as TESS and MODAS in the same manner as conventional insitu data.

The GFO data is transmitted in real time, and every ship receiving the altimeter data is then be capable of adding the synthetic temperature and salinity profiles to a current nowcast of the ocean mesoscale state. In this manner, the local acoustic environment surrounding a ship is then continuously updated by the GFO data which it receives. This capability is provided regardless of weather conditions, particularly cloud cover.

The impact of these data on knowledge of the mesoscale field is enormous. Without continuous assimilation of measurements, the best estimate of the ocean acoustic state is derived from the history of prior sampling, or the climatological data. However, large deviations from the climatological state are the rule, not the exception. Thus the climatological state is a very crude estimate indeed, compared to environmental sensing capabilities provided by GFO.

An example of the difference between the climatological acoustic state and the sampled acoustic state is shown in Figure 1. This is the acoustic signal excess that would be seen by a ship in the southern region of the Sea of Japan just east of the Korean coast. The top panel indicates the signal excess based on climatological data, and the bottom panel is the signal excess based on a mesoscale model. The climatology completely misses a large blind spot in the signal excess return. Thus it is vital to continuously monitor the ever changing mesoscale field of the ocean.

The capabilities of altimeter data in the Sea of Japan have been demonstrated using TOPEX/POSEIDON. The synthetic profiles based on the TOPEX/POSEIDON observations over a 10 day period are used through MODAS to compute the ocean environment at the central time of the data. A comparison of the synthetic ocean temperature and a concurrent intensive AXBT survey is made in Figure 2. The temperatures of the altimeter derived field at 150 m is in good agreement with the AXBTs. Without the GFO data, our best estimate would be climatology which is shown in Figure 2c. The altimeter derived temperatures provide a measurement of the true field which is far better than the field derived from climatology.

Numerical Model Assimilation

Numerical ocean models and altimeter data represent a complementary pair, and the combination of their capabilities alleviates problems which are inherent in the individual systems. Numerical ocean models require data to update the chaotic mesoscale field which is not deterministic from wind forcing alone. Ocean models enhance altimeter data by dynamically interpolating in space and time what may be old data and by producing fields which otherwise are not directly observable from the altimeter. In particular, nongeostrophic currents, though related to the SSH measured by the altimeter, are not directly retrievable from the data without the addition of the model assimilation system.

Numerical ocean models are currently capable of representing the mesoscale characteristics of the true ocean. However, the actual eddy events which occur in the ocean are not directly determined by the wind forcing which is used in the models. Thus even though the models contain the dynamics which generate the mean current paths, reproduce the observed variability, and propagate mesoscale features, they do not contain the currently observed, or synoptic, mesoscale field. This situation is shown in Figure 3a which is a comparison of a the Kuroshio position calculated by a numerical model and observed by InfraRed analysis. The positions of the model and observed current meanders agree poorly. The mesoscale meanders of the Kuroshio Extension are chaotic and not determined from the winds which force the model. So the model must be updated by observations to reproduce the synoptic mesoscale field.

Data from both the TOPEX and ERS-1 altimeters are assimilated into the model through a nudging technique in which the SSH and subsurface pressures of the model are set according to the SSH observed from the altimeter. Synoptic mesoscale features are impressed into the model through this procedure. The model then maintains and propagates the features using its ocean dynamics. After assimilating the altimeter data, a comparison in figure 3b of the model nowcast to the same IR frontal position indicates that the altimeter data has indeed put the synoptic mesoscale features into the model and a good agreement is found between the model and observed frontal position. Thus, the altimeter data is vital for the model to reproduce the mesoscale field.

After assimilation, the model is capable of reproducing the temperature, salinity, and acoustic propagation over any region. An example of these properties along one transect through the Kuroshio Extension is shown in Figure 4. A great advantage to using the numerical model over using the altimeter data alone is that the model has forecast capabilities.

The model's assimilative capability is useful in nowcasting as well as predicting the future. It allows the model (a) to fill in temporal gaps in the data by using its predictive skill, (b) to dynamically and therefore more accurately convert observed surface fields into subsurface structure, and (c) to convert atmospheric forcing into oceanic information which is merged with the altimeter information. The model forecasting capability is particularly useful in the application of SSH from satellite altimetry where the most recent data can be up to a repeat cycle old. Thus, the model compensates for the space-time resolution of the data. Since each track is sampled every 17 days, the forecast skill of the model is important in nowcasting, i.e. bringing the old data up to date. The model can also provide unobserved fields from the data that are not easily inferred by other means, such as total velocity, rather than only the geostropic component with respect to some chosen reference level.

Currents

Currents are necessary for forecasting the paths of drifting bodies. There are two prime warfighting cases for which the altimeter makes a significant contribution. The first is free floating mines which are seeded in one area and then allowed to move with the ocean currents. Knowledge of the possible position of mines allows for efficient and quick disposal. The second use for drifting paths is for search and rescue of personnel and lost equipment.

For the mesoscale field, the altimeter provides a measure of currents through the geostrophic relation. An example comparing the observed paths of drifters to those geostrophically inferred from altimeter data is shown in Figure 5. A drifter was initially seeded in the northwestern Gulf of Mexico and was advected about a cyclonic eddy. The drifter track is broken into 10 day segments, and the altimeter-determined drifter trajectories are calculated for each 10 day segment for comparison to the actual trajectories. The paths generated by geostrophic currents from altimeter data generally match with the actual path.

The computation of nongeostrphic currents requires the joint use of the altimeter data with numerical ocean models. This is particularly true in shallow and littoral regions where processes are typically nongeostrophic. The altimeter data provides a synoptic measurement of events which the numerical model may assimilate. The SSH measures the pressures which drive both geostrophic and nongeostrophic surface currents alike. The ocean model is then capable of dividing the observed pressure into geostrophic and nongeostrophic components based on its own dynamics and wind forcings. Once assimilated, the model provides a nowcast of total currents.

Tides

Tides are one of the first order contributors to currents and sea surface height in shallow water and littoral regions. Each small coastal area of the world is unique in its tidal characteristics, and the present knowledge of tides along the world's shores is inadequate for accurate forecast of tidal heights and currents. The reasons are two-fold. First, bathymetry is not known accurately with sufficient spatial resolution. Second, the data to assimilate into tide models is sparse and generally not representative of the offshore tide. The GFO altimeter will help provide the required data to estimate tide variations within any region of the world. The assimilation of GFO data into tide models will aid in overcoming the problems inherent with use of inaccurate bathymetry.

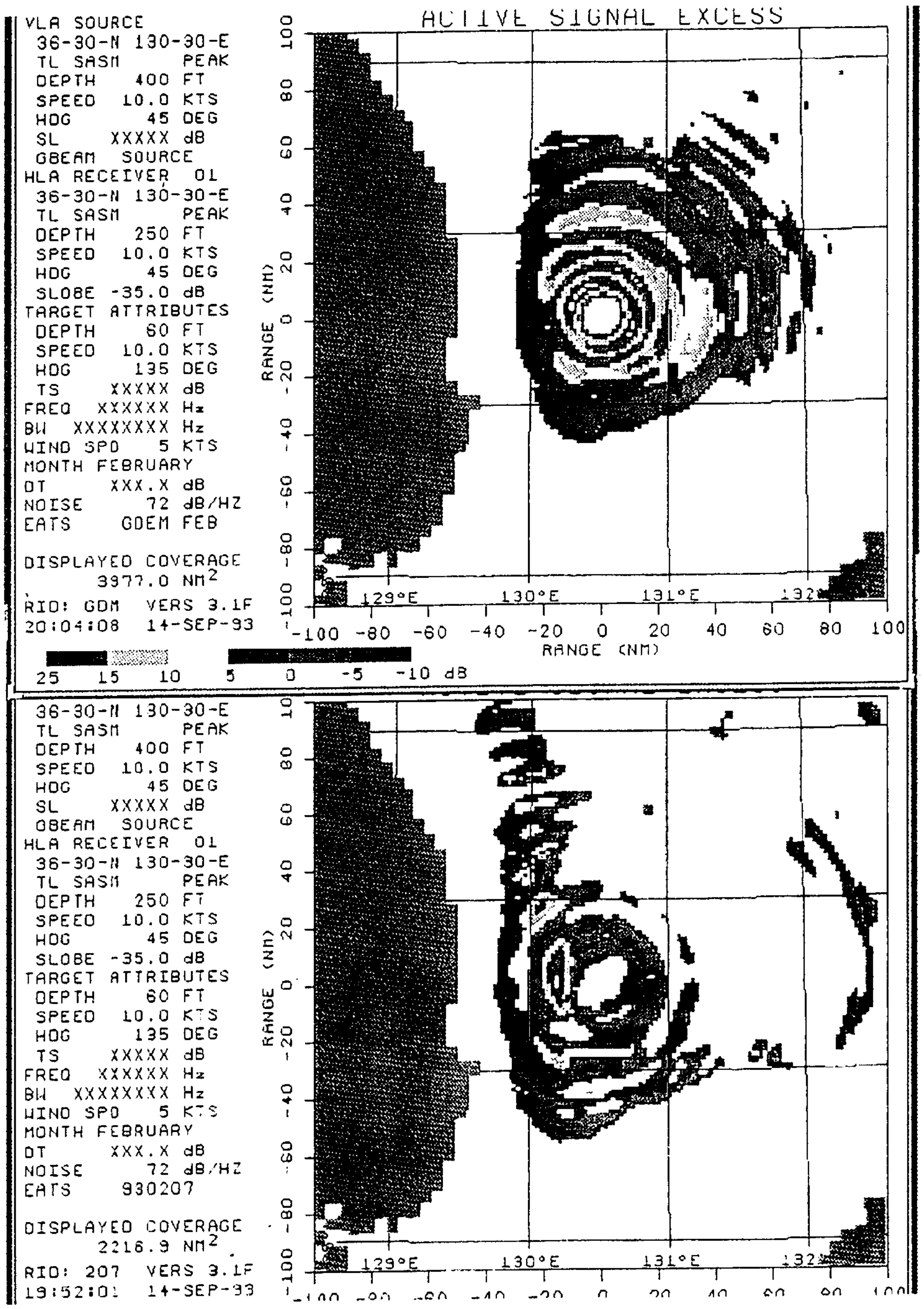
Even though the time between consecutive GFO samplings is much longer than most tidal periods and thus most tides are aliased, the alias characteristics are known a priori so that evaluation of tidal amplitudes and phases can be carried out. Each point along every ground track of the GFO satellite acts as a tide gauge. That is, the GFO data set can be viewed as a set of tide gauges spaced every .7 km along the ground tracks, and this data set is superior to conventional shore-based tide gauges in several respects. The altimeter tide data provide a substantially larger quantity of information on the tides. The tidal information is more uniformly distributed throughout space and is much denser than data from conventional tide stations.

To produce a tide solution at a particular shoreline in the world's oceans, a telescoping series of numerical models is used. The first model is global with a large grid scale. Each successive model covers a smaller region with higher resolution, assimilates data, and has boundary conditions provided by the solution of the previous larger scale model. The final model computes the tides at the shoreline and is of such small scale that generally no data is available for assimilation. Thus the final result is determined almost entirely by the boundary conditions of the final model. Regional tide solutions (such as tide solutions for the Yellow Sea) therefore must be as accurate as possible so that solutions within bays and estuaries on the edges of the region will be accurate.

Conventional tide gauge data is inadequate for producing tide solutions on global or even regional scales such as the Yellow Sea with sufficient accuracy. Usually tide gauges are placed in harbors or on coastlines where the tide is not a good indicator of the regional tide we wish to solve for. Altimeter data provides accurate tide measurements within semienclosed seas (Figure 6). Thus it will be the data from the GFO satellite which provides us with the capability to forecast the tides at any shoreline throughout the world on demand.

Global tide models developed entirely from TOPEX altimeter data are sufficiently accurate for problems of interest to the science community involving basin scale gyre circulation. However, the models are not accurate in coastal regions and are not accurate enough to produce regional solutions without further assimilation of altimeter data. The time period covered by the altimeter data on hand is not extensive enough to resolve the necessary tide constituents from significant oceanographic variability. Thus a lengthening of the altimeter data set through GFO is required to accurately solve for tides in regional and coastal areas.

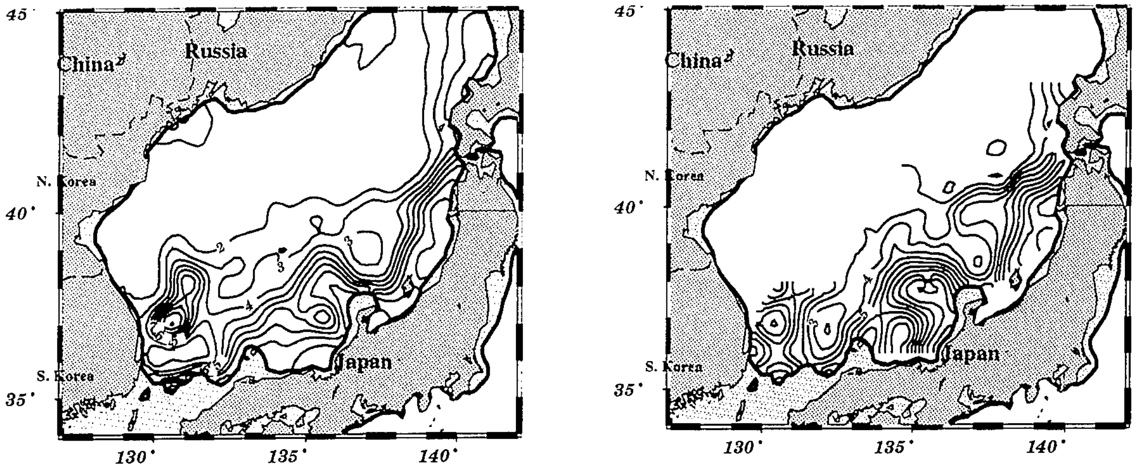
Figure 1: The acoustic signal excess seen by a ship in the south Sea of Japan based on only climatological data (top) and based on modeled mesoscale eddy field (bottom). A region of decreased acoustic return is observed to the northeast of the ship position when using realistic data. This region of decreased return is not present when using only climatological data. Thus a realistic view of the acoustic ocean state requires continuously updated data as available from GFO.



```
VLA SOURCE
 36-30-N 130-30-E
 TL SASM       PEAK
 DEPTH    400 FT
 SPEED  10.0 KTS
 HDG        45 DEG
 SL     XXXXX dB
 GBEAM  SOURCE
HLA RECEIVER  01
 36-30-N 130-30-E
 TL SASM       PEAK
 DEPTH    250 FT
 SPEED  10.0 KTS
 HDG        45 DEG
 SLOBE -35.0 dB
TARGET ATTRIBUTES
 DEPTH     60 FT
 SPEED  10.0 KTS
 HDG       135 DEG
 TS     XXXXX dB
FREQ  XXXXXX Hz
BW  XXXXXXXX Hz
WIND SPD    5 KTS
MONTH FEBRUARY
DT      XXX.X dB
NOISE       72 dB/HZ
EATS     GDEM FEB

DISPLAYED COVERAGE
       3977.0 NM^2
RIO: GDM   VERS 3.1F
20:04:08   14-SEP-93
```

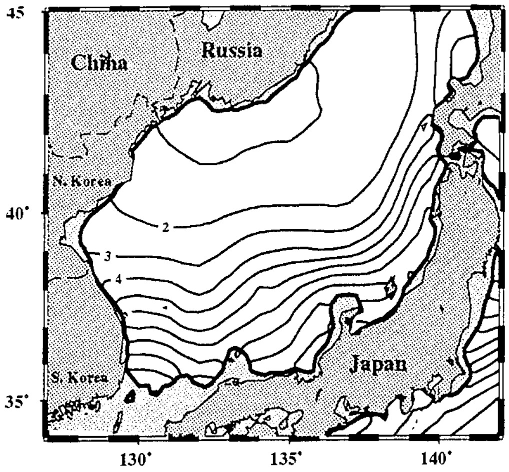
```
 36-30-N 130-30-E
 TL SASM       PEAK
 DEPTH    400 FT
 SPEED  10.0 KTS
 HDG        45 DEG
 SL     XXXXX dB
 OBEAM  SOURCE
HLA RECEIVER  01
 36-30-N 130-30-E
 TL SASM       PEAK
 DEPTH    250 FT
 SPEED  10.0 KTS
 HDG        45 DEG
 SLOBE -35.0 dB
TARGET ATTRIBUTES
 DEPTH     60 FT
 SPEED  10.0 KTS
 HDG       135 DEG
 TS     XXXXX dB
FREQ  XXXXXX Hz
BW  XXXXXXXX Hz
WIND SPD    5 KTS
MONTH FEBRUARY
DT      XXX.X dB
NOISE       72 dB/HZ
EATS     930207

DISPLAYED COVERAGE
       2216.9 NM^2
RIO: 207   VERS 3.1F
19:52:01   14-SEP-93
```

Figure 2: The temperature field at 150 m depth in the Sea of Japan based on the TOPEX altimeter (a), based on a single simultaneous intensive AXBT survey (b), and based on climatology (c). Subsurface temperature values are determined from altimeter data through statistical correlations. Without altimeter data, the first estimate of ocean state would be the climatology, and any correction to climatology would require an intensive BT survey. The GFO altimeter provides the mesoscale field continuously.



(a) Temperature at 150 m based on altimeter-derived synthetic BT input to MODAS

(b) Temperature at 150 m based on an intensive AXBT survey



(c) GDEM climatology

Figure 3: A comparison of the model position of the Kuroshio Extension (blue line) to the observed north and south wall positions based on IR analysis (red lines) without altimeter assimilation (a). The positions do not agree well because the mesoscale field is random and chaotic relative to the wind forcing. Thus we would not expect the model to exactly reproduce the observed mesoscale field. After assimilating TOPEX and ERS-1 altimeter data (b), the observed mesoscale field is impressed into the model and the frontal position is in good agreement. Thus, it is necessary to assimilate altimeter data into a mesoscale ocean model in order for the model to represent nondeterministic oceanic variability. Once assimilated, the model is capable of providing accurate fields of currents and other unobservable parameters.

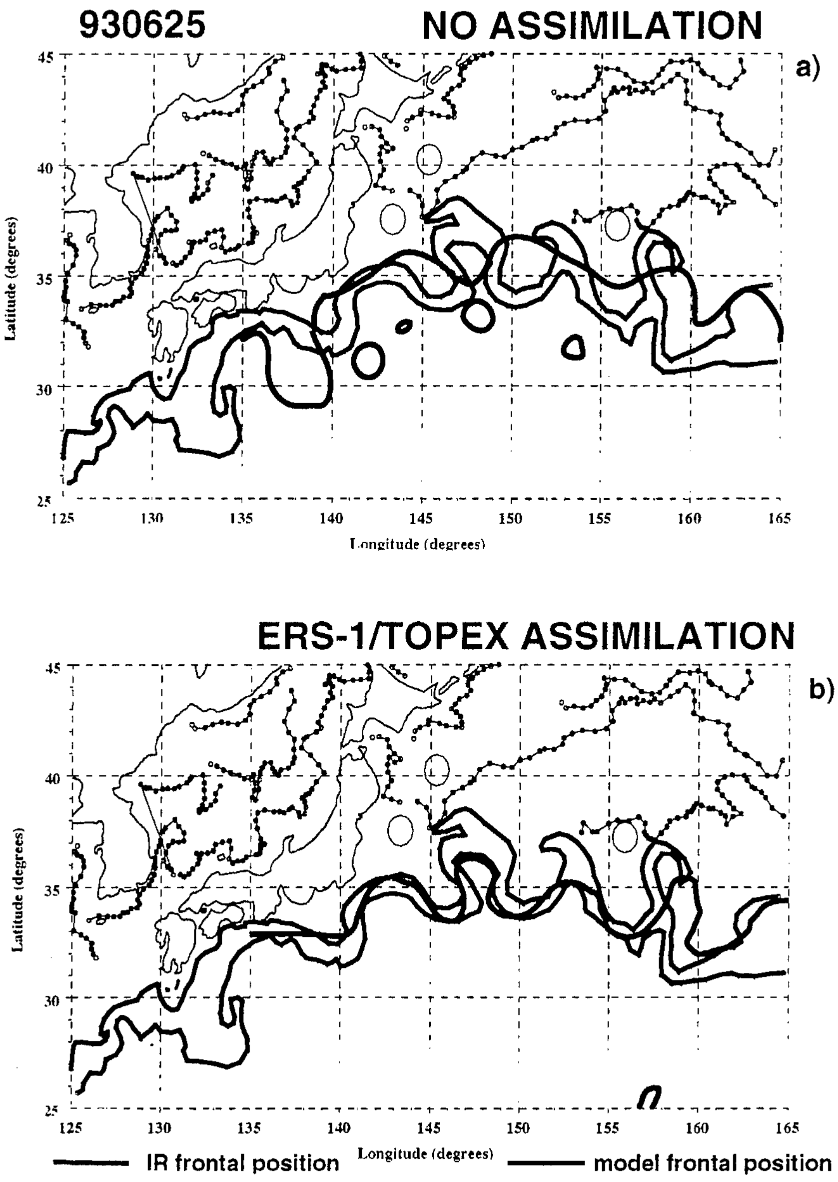
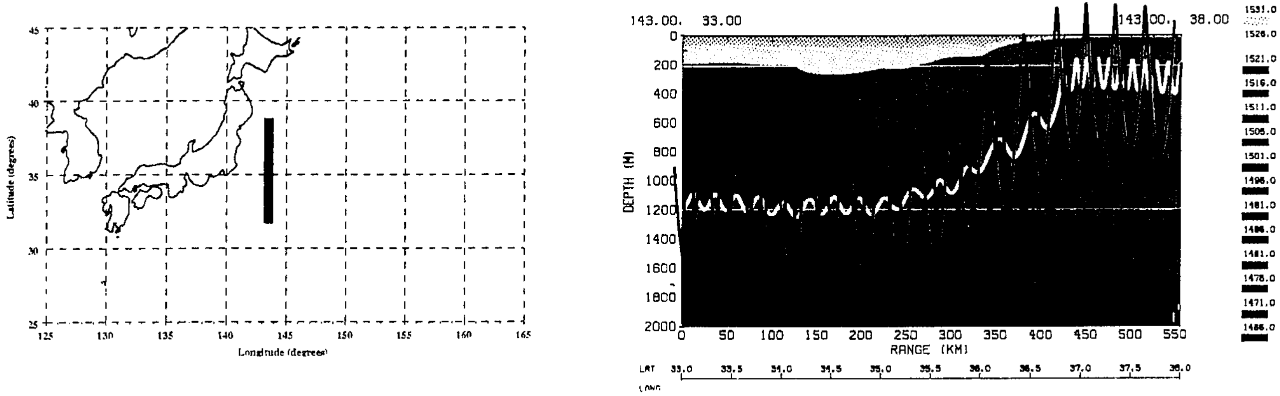


Figure 4: An example of the ocean environment calculated along one transect through the numerical ocean model. By assimilating the data into the model, not only is the accuracy improved, bu the model also provides the capability to forecast by running the model forward in time. Thus it is possible to forecast the mesoscale ocean environment up to a month or more.

DART/MODAS Output August 18, 1992



Model transect

Sound Speed (M/S)
Acoustic ray paths: Source at 1200 m
Receiver at 200 m

Temperature

Salinity

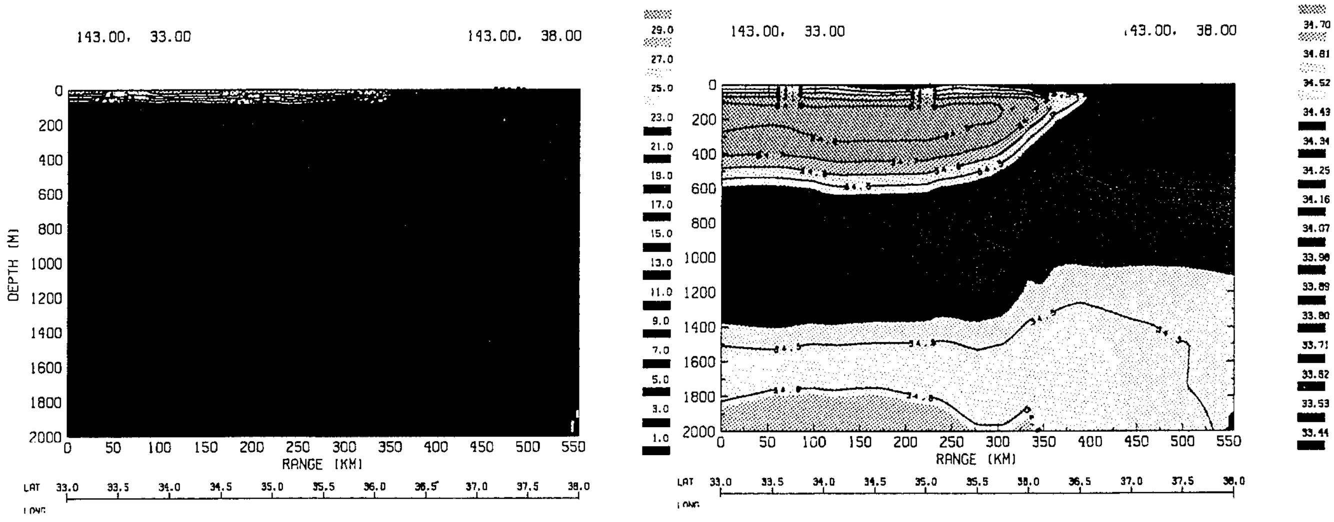


Figure 5: Comparison of an actual drifter path to the path computed from altimeter data. The actual drifter path is the black line. The drifter data is broken into segments each of which is 10 days long. Altimeter-derived drifters are initiated at the beginning of each 10 day segment, and these positions are indicated by the diamonds. The altimeter-derived drifters indicate general agreement with the path of the actual drifter. The coloring on which the paths are plotted is the SSH anomaly measured by TOPEX during the central time of the drifters. The low SSH anomaly about which the drifters rotate is a cyclonic eddy seen by the altimeter.

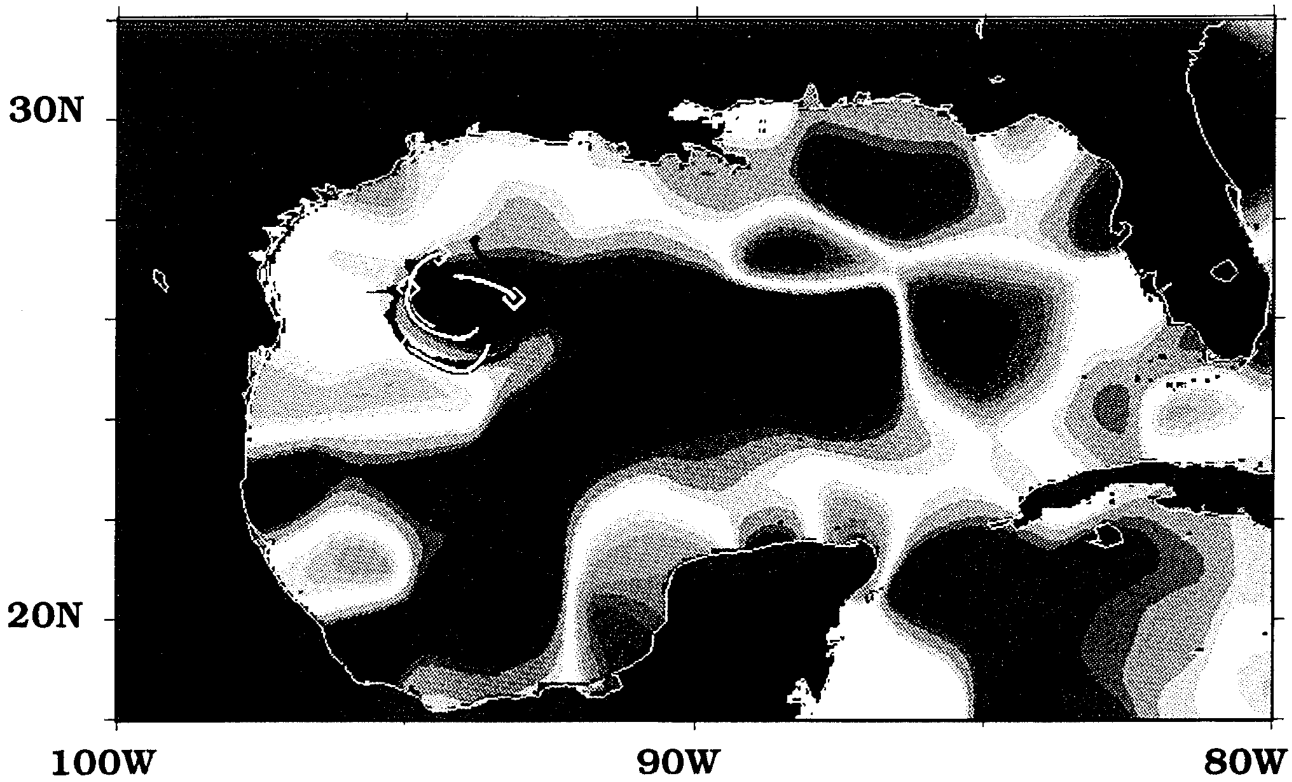
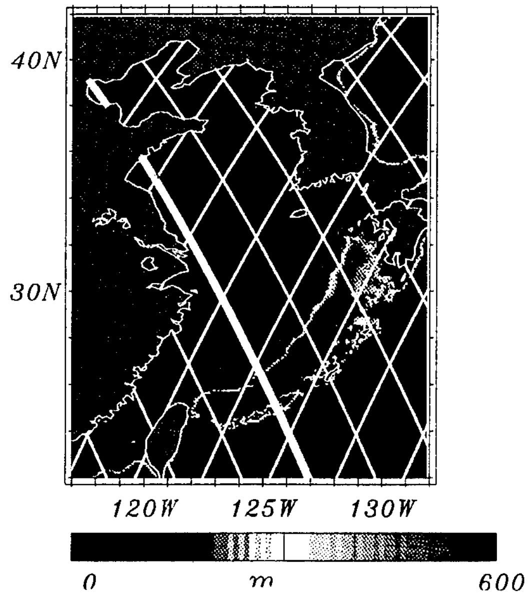
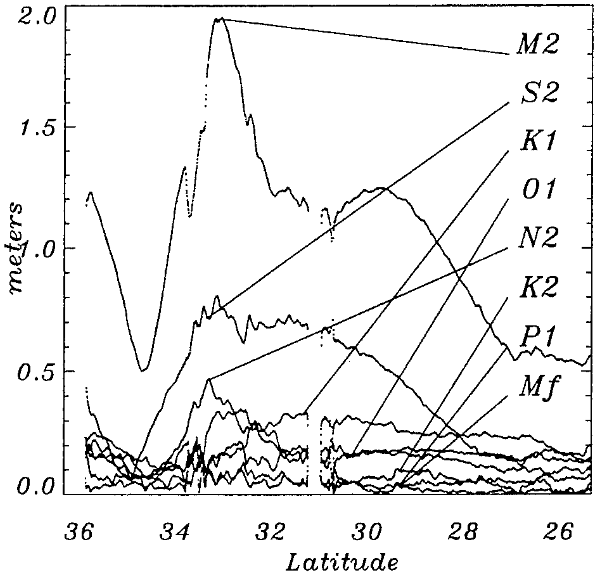


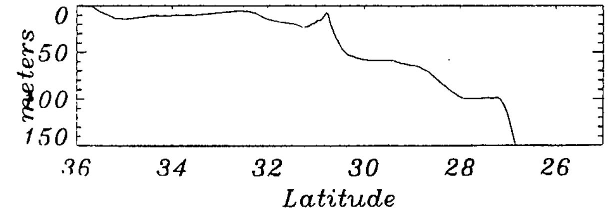
Figure 6: An example of tidal amplitudes measured by TOPEX along one ground track in the Yellow Sea. The data recovered in this one plot far outweighs all the conventional shore-based tide gauge data in the Yellow Sea region. Measurements of the tide constituents are calculated every .7 km along the ground track. This data indicates that the largest tide constituent (M2) has amplitudes near 2 meters in places and some very strong spatial strucutre which would not be seen with conventional tide gauge data. The ground tracks of GFO are spaced apart by about 120 km at this latitude. Thus, about 24 ground tracks of tide data such as this will be produced by GFO. This data will allow us to create accurate tide solutions over regions such as the Yellow Sea. These regional solutions will then be used to derive boundary conditions for shore, bay, and estuary tide models.

Ground tracks over the Yellow Sea





Tide constituent amplitudes beneath the highlighted ground track



Bathymetry beneath the ground track