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SAMPLING STRATEGIES AND FOUR-DIMENSIONAL ASSIMILATION OF ALTIMETRIC DATA FOR OCEAN MONITORING AND PREDICTION

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ABSTRACT

Numerical experiments using simulated altimeter data are conducted in order to examine the assimilation of altimeter-derived sea surface heights into numerical ocean circulation models. A reduced-gravity, primitive equation circulation model of the Gulf of Mexico is utilized; the Gulf of Mexico is chosen because of its amenability to modeling and the ability of low vertical-mode models to reproduce the observed dynamical features of the Gulf circulation. The simulated data are obtained by flying an imaginary altimeter over the model ocean and sampling the model sea surface just as a real altimeter would observe the true ocean. The data are used to initialize the numerical model and the subsequent forecast is compared to the true numerical solution. Results indicate that for a stationary, circular eddy, approximately 3-4 tracks (either ascending or descending) across the eddy are sufficient to ensure adequate spatial resolution.

1. INTRODUCTION

The satellite radar altimeter offers the most promising capability of routinely providing global, timely observations suitable for initializing an ocean circulation forecasting model. The inability, though, of a single nadir-beam altimeter to provide a truly synoptic measurement which adequately resolves the mesoscale eddy field, major current systems and fronts poses a serious obstacle to the development of a skillful forecasting ability. A balance between track spacing and period of the repeat tracks is necessitated. Hence, in addition to the observational accuracy requirements, a viable oceanic forecast will also depend on an innovative development of sampling strategies, four-dimensional data assimilation techniques and initialization methods. The thrust of this report is an examination of sampling strategies which optimize the usefulness of altimeter derived sea-surface heights in ocean monitoring and prediction. In particular, we will attempt to determine the minimum track spacing which adequately resolves the detectable meandering current systems and eddies and to investigate the ability of numerical circulation prediction models to fill in the resulting temporal gaps.

In addition to assimilating altimetric data, numerical ocean models are useful in simulation mode for generating "synthetic" sea surface heights to investigate optimum sampling and initialization strategies and for comparison with actual altimeter data (Thompson et al., 1983). A reduced-gravity, primitive equation circulation model of the Gulf of Mexico (Hurlburt and Thompson, 1980) is utilized in order to examine the methodology of incorporating satellite altimeter data into ocean forecasting models. Simulated altimeter measurements of sea surface height are obtained by: 1) integrating the model to statistical

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equilibrium, 2) flying an imaginary altimeter over the model ocean, 3) objectively mapping the perfect (i.e., uncontaminated by geoid, tide or noise) sampled data onto a numerical grid. The model is initialized and restarted using the "observed" field, and the subsequent forecast (up to several months) is compared to the true solution. This approach allows us to investigate the maximum ratio of track spacing to eddy diameter for adequate mesoscale mapping, the optimum sampling period/track spacing for repeat orbits, four-dimensional data assimilation methods , initializacion schemes and techniques for updating the forecast. This, admittedly, antiseptic approach to studying the assimilation problem is intended as a first step. Experiments with contaminated data are also being conducted in order to assess the accuracy requirements of altimeter data for use in ocean forecasting. The results of these experiments will be reported elsewhere.

2. THE GULF OF MEXICO MODEL

The Gulf of Mexico has been chosen for this study for several reasons. As a semi-enclosed sea with well defined inflow and outflow ports, it is highly amenable to modeling. The size of the basin is small enough to permit a relatively large number of experiments with fine resolution, and is sufficiently large so that the dynamical features possess many similarities to those found in larger ocean basins. The primary forcing in the Gulf is the intense Loop Current which enters through the Yucatan Straits and exits through the Florida Straits. Approximately once per year, the Loop Current sheds an anti-cycloaic eddy which propagates westward. Both the Loop Current and the associated eddies have large sea-surface signatures (~ 30-50 cm). Additionally, the eddies propagate slowly (~ 3 cm/sec) and have large horizontal scales (300-500 km in diameter). Also, during a portion of the GEOSAT (a U. S. Navy spacecraft whose primary altimetric purpose is geodetic) mission there is a proposed field experiment capable of providing verification data for the numerical forecast experiments.

The numerical simulations use the one-layer reduced-gravity version of the Hurlburt and Thompson (1980) model of the Gulf of Mexico circulation. This formulation represents the ocean as two incompressible, homogeneous layers. The lower layer is motionless because the pressure gradient generated by the slope of the interface exactly balances that due to the surface slope. Hence, the interface (model pycnocline) slope is an inverted representation of the surface height field. This is an advantageous formulation for altimeter applications because the internal pressure field is uniquely determined by the sea-surface height variations. In spite of its simplicity, the model has demonstrated a remarkable ability to reproduce such observed features as the shedding of eddies from the Loop Current with realistic diameters, amplitudes and westward propagation speeds (Hurlburt and Thompson, 1980). In addition, the two layer version of the model was used in the study by Thompson et al. (1983) as an aid in identifying the Loop Current system from collinear-track altimetry from SEASAT.

3. EXPERIMENT DESIGN AND RESULTS

The simulation experiments described herein are motivated by a NORDA research program to study ocean dynamics using the altimeter derived sea-surface heights acquired during the GEOSAT mission. The satellite track sequence during the first 18 months of GEOSAT is shown in Fig. 1. This pattern produces an equatorial track separation of 40 km with global coverage in approximately 70 days. The tracks, however, do not repeat and, hence, may be only marginally

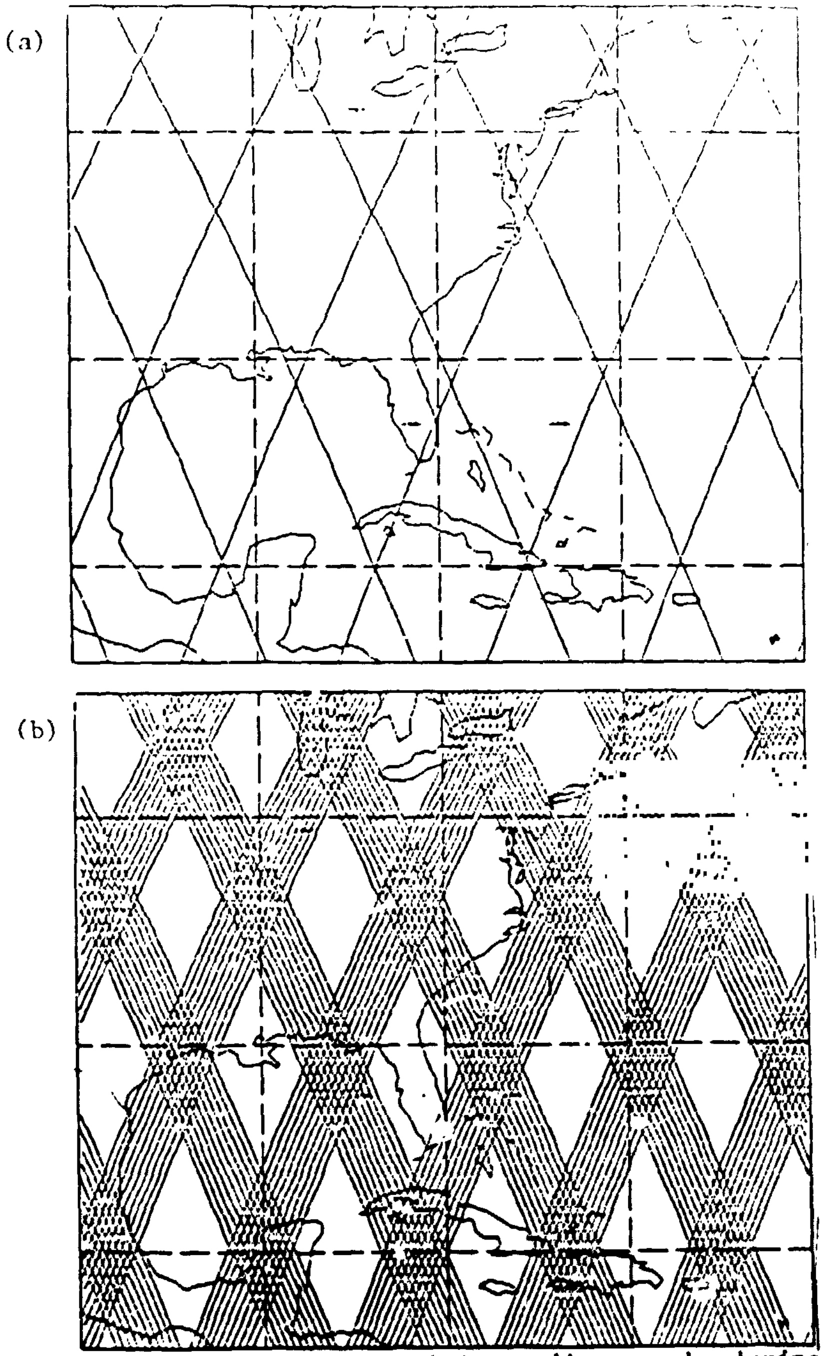

Figure 1. Ascending and descending tracks during the nominal geodetic mission of GEOSAT. (a) Coverage after 3 days. At this point, adjacent tracks in the Gulf of Mexico are 1 day apart and separated by approximately 900 km. (b) Track pattern after 30 days. The tracks fill the open regions from left to right. Adjacent tracks are 3 days apart and separated by approximately 36 km in the Gulf of Mexico. About 70 days are required for the entire pattern to fill in. (Courtesy of Dr. Z. Hallock, NORDA).

useful for mesoscale modeling. The geodetic portion of GEOSAT may be followed by an extended mission with exactly repeating tracks and a shorter repeat track period.

As a first step in designing an optimum sampling strategy for mesoscale modeling and forecasting, the track spacing required to resolve adequately a stationary eddy is examined. Figure 2(a) depicts the ascending and descending tracks with a separation of 100 km superimposed on the numerical solution at Day 1120. The values of the model pycnocline depth are sampled every 20 km along the tracks. Because, in general, the location of the observation points do not coincide with the model grid points, the observation is an interpolated value from the numerical solution. The 'observed' data are mapped back to the numerical grid in order to reconstruct the solution (Fig. 2(b)). The RMS error difference between the true solution and the observed values is determined; the error is calculated only within a square circumscribing the eddy and is normalized by the standard deviation of the true solution within the square. For each value of track separation, two values of the RMS error are calculated: a) only one set of tracks (i.e. ascending or descending are used in the analysis and b) both ascending and descending tracks are used to reconstruct the height field. The results (Fig. 3) reveal that if data from both tracks are used, track separation as large as an eddy radius adequately resolves the features. Additional tracks yield only a slightly improved representation. For cases in which the ascending and descending tracks sample the eddy at significantly different times, it may be advantageous to assimilate the observations from only one set of tracks. In such instances, Fig. 3 suggests that 3-4 tracks per eddy are required.

The non-stationarity of the ocean adds a frustrating complexity to the sampling problem. The inverse relationship between repeat track period and track separation for a single, nadir-beam altimeter demands a prudent sampling and four-dimensional assimilation strategy for optimum results. If the dynamical features of interest necessitate narrow track spacing, the temporal resolution may be inadequate unless a numerical model is able to fill in the temporal gaps. This problem is illustrated by Fig. 4 in which the interpolated Gulf of Mexico height field is shown for both a 72-day and a 39-day repeat track period. The model ocean is sampled during the repeat period just as a real altimeter would observe the true ocean. The 72-day sampling period grossly distorts the westward propagating eddy. The deformation is substantially reduced in the 39-day repeat period case; the 21-day repeat period sampling (not shown) exhibits very little distortion of the eddy.

The 'observed' data are used to initialize a forecast of the Gulf of Mexico circulation in order to measure the skill of a particular sampling strategy. The forecast begins on day 1200 of the numerical simulation and continues for 180 days. Initial conditions for the forecast are obtained by sampling the model ocean with an imaginary altimeter for a duration nearly equal to the repeat track period. This insures complete coverage of the basin. In each case, the last observation occurs on day 1200. Hence, the 21-day repeat period case samples the model ocean from day 1182 to day 1200 while the 72-day case 'observes' the ocean from day 1131 to day 1200. The height field is interpolated to the numerical grid and treated as a synoptic data set. The results described below are based on techniques which exclude both four-dimensional assimilation and updating of the forecast: future experiments will include these important aspects of the assimilation problem. The initial height fields are somewhat smoother than those shown in Fig. 4 due to the incorporation of data from both ascending and descending tracks. The initial velocity field is determined from the geostrophic approximation; the initial conditions are assumed to be valid at approximately the mid-

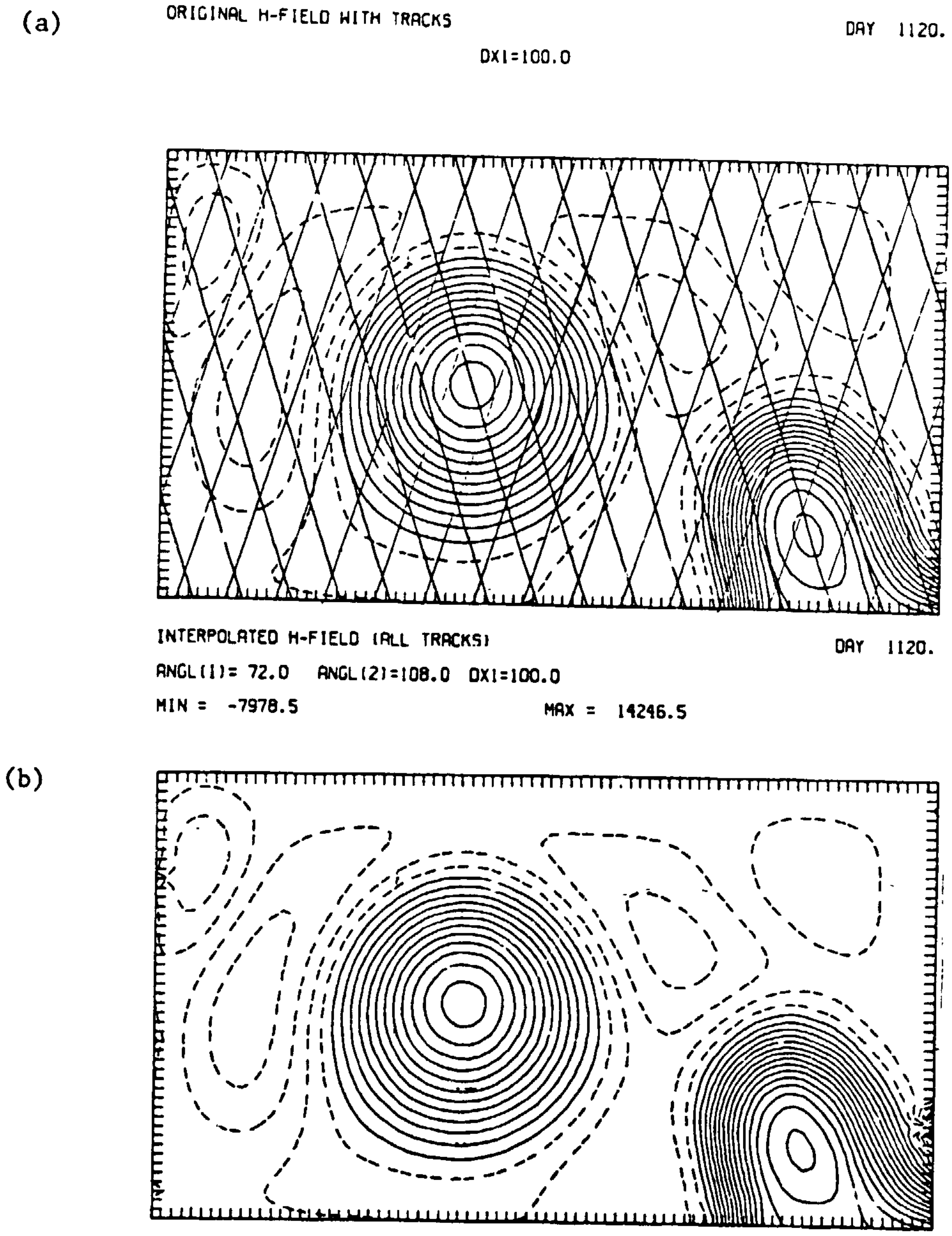

Figure 2. a) Ascending and descending tracks (separation equals 100 km) of an imaginary altimeter superimposed on the numerical solution of the Gulf of Mexico. The contours are the model interface deviation from its initial flat position. The contour interval is 10 m. Solid lines denote a deepening of the pycnocline while dashed lines represent shoaling. The model is sampled every 20 km along each track. The solution is stationary during the sampling process. b) A reconstruction of the numerical solution at Day 1120 from the values sampled along the tracks in (a). Experiment RG8 from Hurlburt and Thompson (1980) is the base experiment.

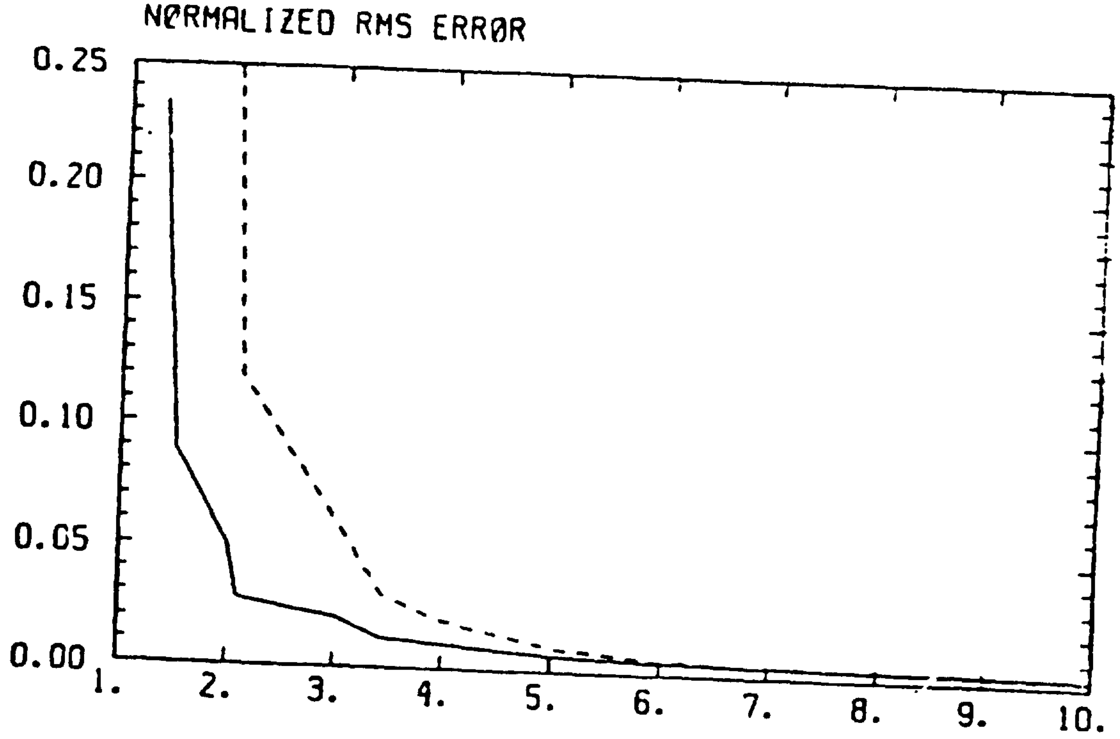

Figure 3. The RMS error difference between the interpolated field and the true numerical solution of an isolated, stationary eddy as a function of the ratio of eddy diameter to track separation. The solid line is the RMS error when both ascending and descending tracks are used whereas the dashed line is the same calculation utilizing only ascending <u>or</u> descending tracks. The RMS error is normalized by the standard deviation of the true solution.

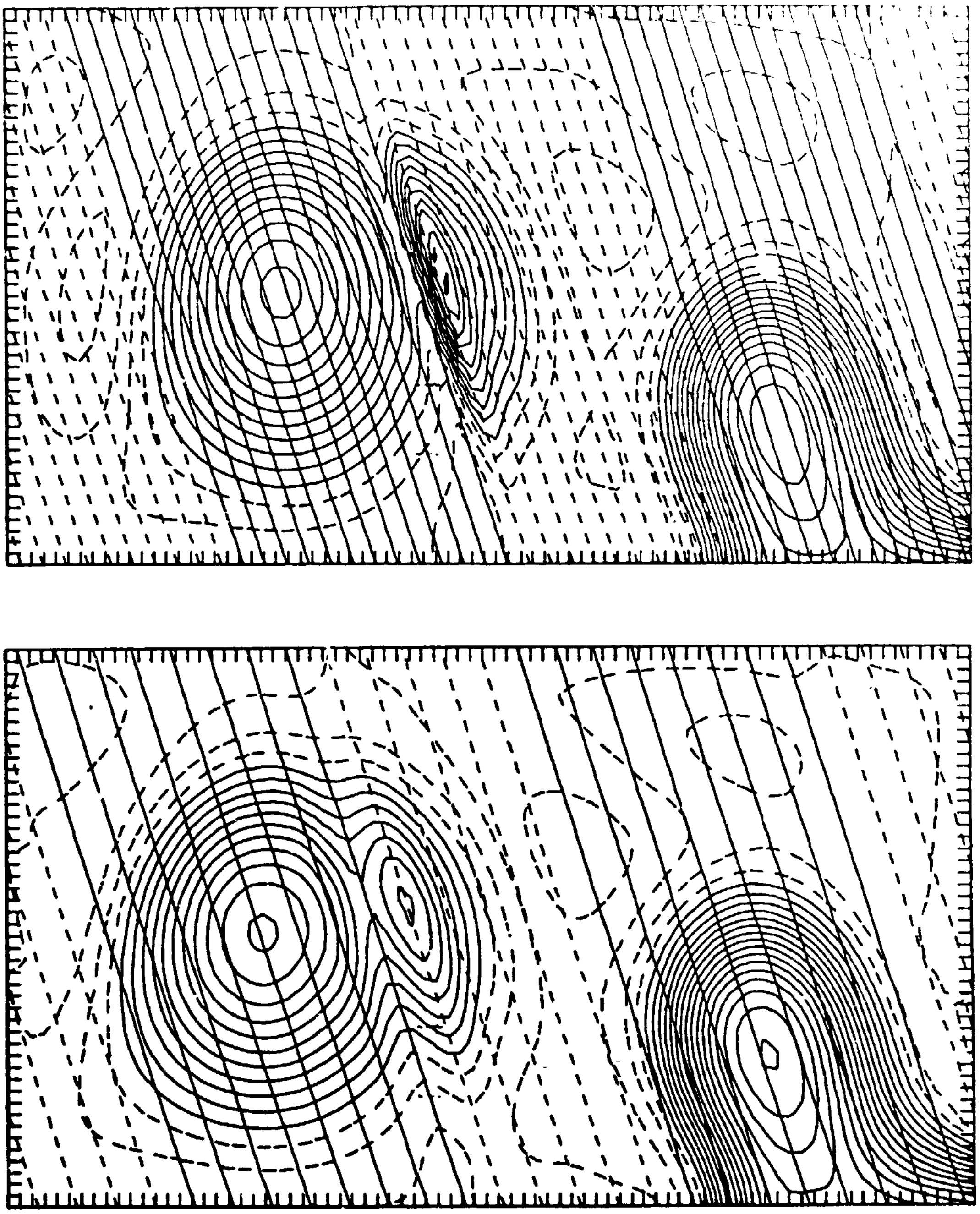

Figure 4. The ascending tracks of an imaginary altimeter superimposed on the interpolated height field. The values of the pycnocline height anomaly were determined by sampling the numerical model every 20 km along the tracks. The dashed track lines denote where the model was sampled during the first half of the repeat track period and the solid tracks depict where the model was sampled during the latter half. Adjacent tracks sampled the model three days apart. The most recent track (i.e. at Day 1200) is a solid track just to the left of an adjacent dashed track. a) 72-day repeat track period. The model was observed from Day 1131 to Day 1200. The distortion of the eddy is caused by westward propagation during the sampling period. The eddy is most distorted where two adjacent tracks differ by 69 days.
b) 39-day repeat track period. The model is sampled from Day 1164 to Day 1200. The distortion of the eddy is not as large as in (a) because the most recent and oldest tracks only differ by 36 days.

point of the sampling period. The skill of the forecast is determined by calculating the RMS error difference between the predicted pycnocline depth and the numerical solution throughout the basin. The results for three cases are shown in Fig. 5. For the Gulf of Mexico simulation, the 21-day repeat track case offers the best compromise between track separation and repeat period.

As a more stringent test of the optimum sampling strategy for the Gulf, the experiments are repeated with a very fine-resolution Gulf of Mexico simulation. The grid spacing and eddy viscosity are reduced from 20 km and 300 m^2/sec to 10 km and 100 m^2/sec, respectively. Although the essential elements of the Gulf circulation are still present, the fine scale solution is also characterized by a larger number of eddies exhibiting a wide range of shape, amplitude and horizontal scale. Moreover, the dynamical features behave in a much more irregular manner.

The methodology of the forecast is identical to the process described above except that the prediction begins on day 1530 instead of day 1200. This is due to the longer spin-up time of the fine-scale simulation. Forecasts are again performed for the 21, 39 and 72-day repeat periods. In addition, a 40-day repeat track case is conducted in which the adjacent tracks are laid down one day apart instead of three days. For a given track separation, this scheme has the advantage of sampling a given feature in the shortest time. A comparison of the true solution and the forecast initialized from the 40-day repeat period case is shown in Fig. 6. The RMS error plots of the forecasts are given in Fig. 7. Clearly, the 72-day repeat track period is inadequate. The relatively minor differences between the other cases is supported by Fig. 3. The track separation of the 21-day repeat period (~ 120 km) is sufficient to resolve the primary dynamical features. Hence, additional tracks do not significantly improve the spatial error of the measurement. The propagation speed of the eddies is slow enough that the 39 and 40 day repeat periods yield reasonably synoptic observations.

4. CONCLUSIONS

Simulated altimeter data have been incorporated into numerical ocean circulation models in order to examine optimum sampling strategies of a single nadir-beam altimeter. The numerical experiments suggest that approximately 3-4 tracks (either ascending or descending) across an eddy provide adequate resolution. For the Gulf of Mexico the track separation of the 20-day repeat period resolves the Loop Current and the westward propagating anti-cyclonic eddies. Sampling with a smaller track separation does not improve the forecast. In other oceanic regions, however, the 20-day repeat period yields a track separation unable to resolve the energetic mesoscale field. In western boundary systems, where eddies have smaller horizontal scales and propagate more rapidly, simultaneously obtaining adequate spatial and temporal resolution is more difficult. As part of this research program, numerical experiments using simulated altimeter data will also be conducted for the Gulf Stream region.

The experiments described in this report are merely a first step towards he development of a methodology for assimilating altimeter data into ocean forecast models. The utilization of contaminated data, optimal interpolation and initialization schemes, forecast updating methods and multi-layer models need to e examined. These studies may substantially alter any quantitative conclusions which might be derived from the results presented here.

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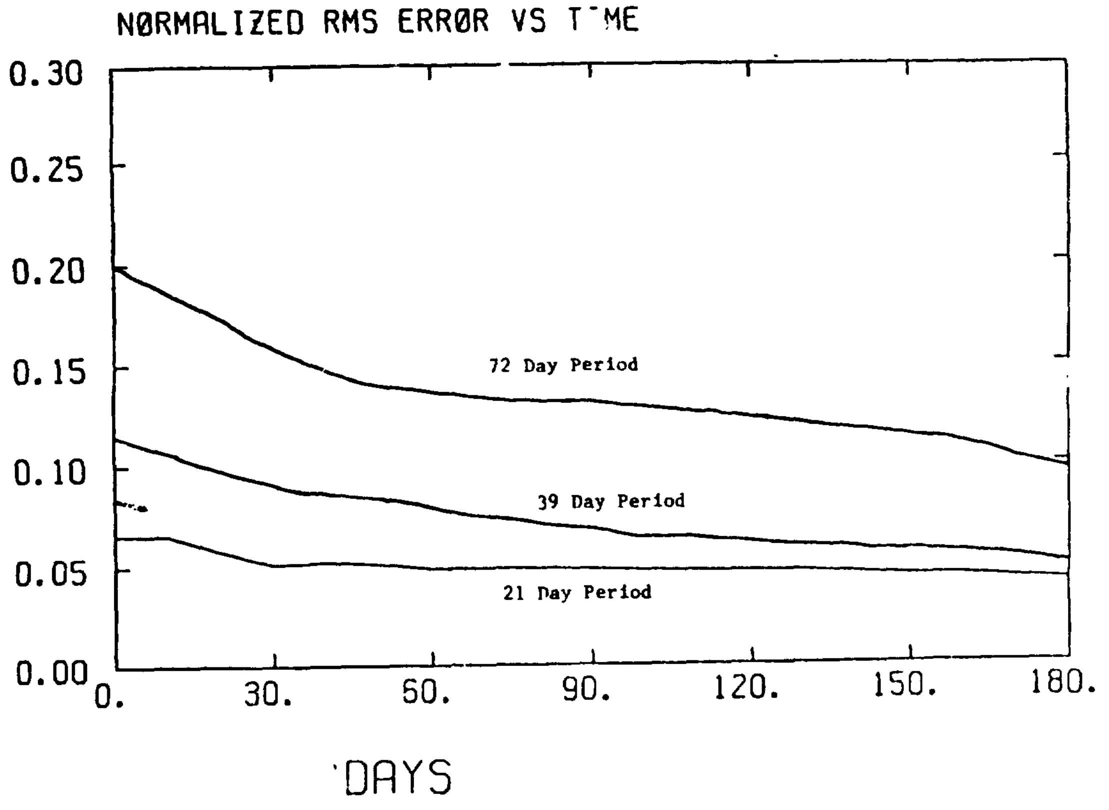

Figure 5. Normalized RMS error of forecast for the 21, 39, and 72-day repeat track periods. The error is the RMS difference between the forecast and the true solution normalized by the standard deviation of the true solution.

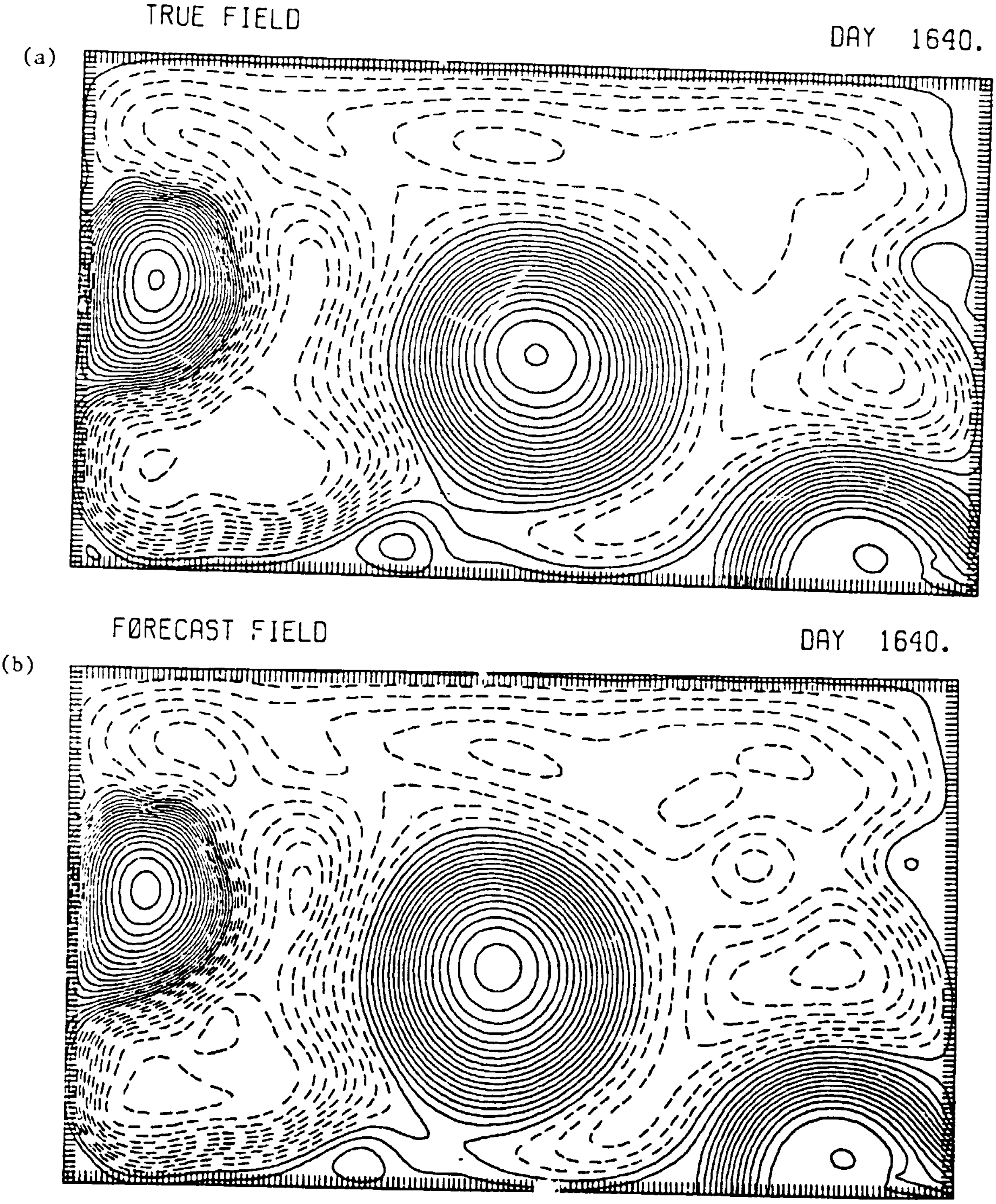

Figure 6. a) Contours of pycnocline height anomaly for the fine scale numerical simulation of the Gulf of Mexico circulation. b) Forecast of PHA in which simulated altimeter data are used to initialize the model. The forecast, which begins on Day 1530, is for the 40-day repeat track period case.

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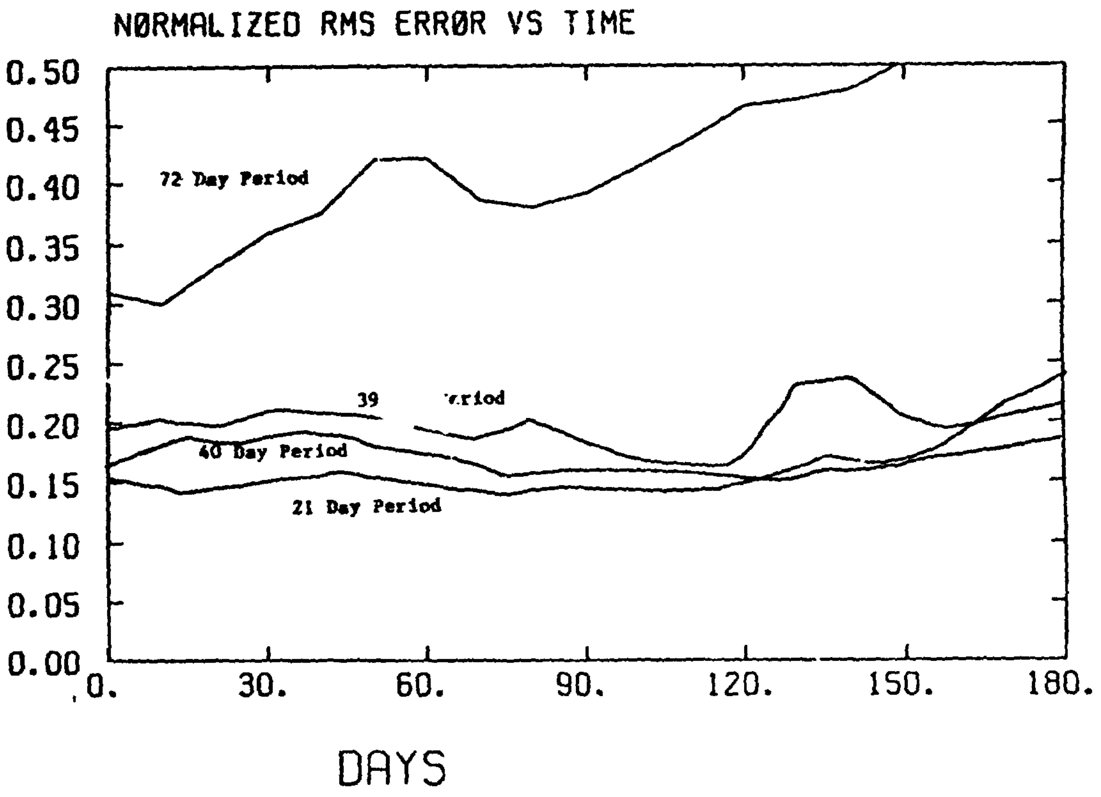

Figure 7. Normalized RMS error of the fine resolution forecast for the 21, 39, 40 and 72-day repeat track periods. Adjacent tracks for the 40-day period are one day apart instead of three.

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REFERENCES

Hurlburt, H. E. and J. D. Thompson, 1980: A numerical study of Loop Current intrusions and eddy shedding. J. Phys. Oceanogr., 10, 1611-1651.

Thompson, J. D., G. H. Born and G. A. Maul, 1983: Collinear-Track Altimetry in the Gulf of Mexico from SEASAT: measurements, models and surface truth. Geophys. Res., 88, 1625-1636.