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# A Feasibility Demonstration of Ocean Model Eddy-resolving Nowcast/Forecast Skill Using Satellite Altimeter Data

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**14. ABSTRACT**

A 1/16° Pacific Ocean model north of 20°S and a 1/4° global ocean model are used to assimilate satellite altimeter data and then to perform month-long forecasts initialized from the data assimilative states. The results constitute a feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill using altimeter data. In particular they demonstrate (1) that satellite altimetry is an effective observing system for mesoscale oceanic features, (2) that an ocean model with high enough resolution can be a skillful dynamical interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) that the high resolution ocean model can provide skillful forecasts of mesoscale variability for at least a month, when model assimilation of the altimeter data is used to define the initial state.

**15. SUBJECT TERMS**

Ocean data assimilation, Ocean nowcasting/forecasting, Satellite altimeter data, Eddy-resolving Pacific Ocean model, Kuroshio penetration

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# ABSTRACT

A 1/16° Pacific Ocean model north of 20°S and a 1/4° global ocean model are used to assimilate satellite altimeter data and then to perform month-long forecasts initialized from the data assimilative states. The results constitute a feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill using satellite altimeter data. In particular they demonstrate (1) that satellite altimetry is an effective observing system for mesoscale oceanic features, (2) that an ocean model with high enough resolution can be a skillful dynamical interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) that the high resolution ocean model can provide skillful forecasts of mesoscale variability for at least a month, when model assimilation of the altimeter data is used to define the initial state.

## 1. Research questions addressed by the demonstration

The figures in this report are designed to address the following questions:

1. Can satellite altimeter data be used to constrain an eddy-resolving ocean model so that it depicts the evolution of mesoscale features, such as individual current/frontal meanders and eddies?

2. Can an ocean model show skill as a dynamical interpolator for satellite altimeter data in depicting mesoscale features? Do we see a dependence on model resolution/simulation skill?

3. Can an ocean model show skill in forecasting the evolution of mesoscale features, when assimilation of altimeter data was used to define the initial state? For how long? And again what dependence do we see on model resolution/simulation skill?

## 2. Results of the demonstration

The remainder of this discussion is a commentary on the results in the figures used to address these questions. There are two groups of results; the first uses simulated altimeter data, the second real altimeter data. The simulated data are used to address the first question because the "truth" is precisely known, including the nonsteric mode and subsurface fields to the bottom of the model ocean. In addition, the simulated data are useful for observing system simulation experiments where the number and combination of satellite altimeters are varied. The real-data experiments are used to address questions 2 and 3.

### *2.1 Response to Question* 1

Altimeter data were simulated by a 1/16° six-layer Pacific Ocean model which covers the Pacific north of 20°S (Hurlburt et al., 1996b). The NRL Layered Ocean Model (NLOM) (Hurlburt and Thompson, 1980; Wallcraft, 1991; Wallcraft and Moore, 1997; Moore and Wallcraft, 1998) was used for this purpose. The 1/16° Pacific model realistically simulates a strongly meandering Kuroshio current system and numerous eddies. The model was spun up to statistical equilibrium, then run 1990 - present forced by 12 hrly Navy Operational Global Atmospheric Prediction System (NOGAPS) winds (Hogan and Rosmond, 1991) from the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The 8/90–7/97 temporal mean of these winds was replaced by the annual mean from the Hellerman and Rosenstein (1983) wind stress climatology. Then simulated altimeter data from 80 days in model year 1994 were assimilated into model year 1997, a time when the Kuroshio pathway was quite different. The corresponding 1994 winds were used during the assimilation.

Figures 1 and 2 show results 75 days into the assimilation experiment: (Fig. 1 top) the model truth field, (Fig. 1 bottom) the model with correct wind forcing for the last 75 days but no assimilation of altimeter data, (Fig. 2 top), the model with assimilation of simulated sea surface height (SSH) along Geosat 17-day repeat tracks, and (Fig. 2 bottom) with assimilation of simulated SSH along TOPEX/POSEIDON (10-day repeat), ERS-2 (35-day repeat) and Geosat ground tracks.

Figure 3 shows the rms SSH error over the whole domain and in the Kuroshio region as a function of the number of altimetric satellites available, 0 to 5 because 5 is a possibility for a period of time around the year 2001. Even one altimeter is quite effective, with the Geosat and ERS orbits giving lower error than TOPEX/POSEIDON (T/P). Reduced error is also found by having up to 3 satellites, but little further improvement is obtained by having 5 of them in this test.

Figures 4-7 show that the assimilation can constrain subsurface fields (model pressure fields for each of the six model layers), including the abyssal layer pressure field, which is only weakly correlated with the SSH field. However, the normalized rms error increases with depth.

The assimilation procedure consisted of calculating the deviations between the data along altimeter tracks that were sampled during the most recent 2 or 3 days, then performing an OI analysis once a day on this deviation data using covariance functions calculated from T/P, ERS-1/2 and GEOSAT data by Jacobs et al. (1999). For any given update much of the domain is outside the influence radius of any data and the resulting deviation analysis in those regions is zero. Next a statistical inference technique (Hurlburt et al., 1990) was used to project the deviation analysis downward (including to the abyssal layer) and geostrophy was used as a dynamical constraint away from the equator. The 1/16° Pacific grid is 2048 x 1344 x 6. Thus, it was necessary to use an efficient data assimilation technique (nudging). Related discussion can be found in Smedstad and Fox (1994), Carnes et al. (1996), Hurlburt et al. (1996a) and Smedstad et al. (1997, 1999).

### *2.2 Response to Question 2*

This question is addressed by assimilating real T/P and ERS-2 altimeter data into (1) the same 1/16° Pacific model and (2) a 1/4° global model (Metzger et al., 1998). The assimilation was initialized from the model forced by FNMOC winds up to that time, at least 2 mo before 1 Jan 99. The results of the assimilation experiments are compared to 1/8° SST analyses and purely statistical analyses of the altimeter data. The SST color scheme was chosen to highlight the Kuroshio pathway.

In two of the three experiments, the altimeter data are assimilated using the assimilative model state as the first guess for the updates with new altimeter data (which will be termed "direct assimilation" by the model). The statistical SSH analyses are independent analyses of the altimeter data which use a previous statistical analysis as the first guess. In the second 1/4° global experiment (run by FNMOC) the daily statistical analyses were assimilated into the model. Because the earth's geoid is not adequately known, only the altimetric deviations from their own mean are used in the assimilation. In the model assimilations a slightly modified 1993-1997 model mean is added to these deviations. The statistical analyses use a 1993-1997 mean surface dynamic height from the MODAS oceanic climatology developed at NRL. When appropriately compared, these means agree closely, but the 1/16° model mean gives a sharper depiction of mean currents.

Figures 8-12: Each figure shows panels for 1 Jan, 15 Jan and 1 Feb 1999. First compare the SSH from the data-assimilative 1/16° Pacific model (Fig. 8) with the statistical SSH analyses (Fig. 9) and the SST analyses (Fig. 10). If given each analysis by itself, one might doubt its accuracy in depicting the mesoscale features. One might doubt the SST analyses because of data gaps due to periods of cloudiness or false fronts due to compositing of IR data over a period of time, and one would expect differences in pattern from the SSH fields because some mesoscale features lack an SST signature and because there are differences in the dynamical processes that produce SST and SSH patterns. One might doubt the accuracy of the altimetric analyses because of concerns about the space-time resolution and accuracy of the altimeter data, the mean SSH added to the altimetric deviations from their mean, and the techniques used to analyze and assimilate the data. In this case the altimeter data were analyzed by very different techniques, direct assimilation by a numerical model vs a purely statistical technique, optimum interpolation (OI). If the different analyses show agreement for mesoscale features, then each enhances the credibility of the other because it is extremely unlikely that complex agreement would occur by chance.

There are a large number of features that can be compared. Particularly noteworthy are (1) the sharp meander between 155°E and 160°E on January 1 which pinches off an eddy on 15 January in a distinctive fashion, an eddy which begins to interact with the Kuroshio farther to the west by 1 Feb. This sequence is captured with striking agreement in all three sets of analyses. (2) A second noteworthy feature is the pinch off of a large eddy immediately east of Japan (centered near 36°N, 143°E) by Feb 1st, starting from a state (see 1 January) where there is a cold eddy south of the Kuroshio just east of Japan (centered near 33.5°N, 144°E). That event is not evident in the SST analysis, but it is a feature of the operational SST analyses performed independently by the Naval Oceanographic Office (Fig. 13).

Figures 11 and 12 show corresponding results from the 1/4° global model. In figure 11 altimeter data were assimilated directly in exactly the same manner (including the same covariance functions) as the 1/16° Pacific model. In figure 12 the "MODAS" OI SSH analyses were assimilated into the model. While figures 11 and 12 capture most of the main features seen in figures 8 and 9, the features are not as sharp. The broadening of the Kuroshio means the current speeds are lower and dynamically the current is not as inertial, which could have a substantial impact on model forecast skill and skill as a dynamical interpolator. Comparison of figures 8 and 11 clearly shows that the 1/4° model is not nearly as skillful a dynamical interpolator as the 1/16° model. This is consistent with the much greater simulation skill found in purely atmospherically-forced simulations for this region using a 1/16° vs a 1/4° model (Hurlburt et al., 1997; Hurlburt and Metzger, 1998).

### *2.3 Response to Question 3*

Figures 14-17 show the results of 14 and 31-day forecasts from 1 Jan 1999 which correspond to the analyses shown in figures 8-12. It should be noted that these are the very first forecasts performed using these models (not the best of many forecasts). Figure 14 shows the forecast from the 1/16° Pacific model, figure 15 from the 1/4° global model with direct assimilation of the altimeter data and figure 16 from the 1/4° model with "MODAS" OI analysis assimilation. Between 155°E and 160°E the 1/16° model is able to forecast the distinctive eddy pinch off (15

Jan) and subsequent interaction with the stream (1 Feb) in detail. It is also able to forecast the large eddy pinch off just east of Japan seen on 1 Feb. Neither of the 1/4° forecasts succeeds in forecasting these events. Figure 17 shows three 1/16° Pacific model forecast verifications against the model with assimilation. All show 1/16° model forecast skill better than climatology or persistence (a forecast of no change from the initial state) for at least a month.

In these forecasts the FNMOC winds were used for the duration of the forecast, when they would not be available for a real-time forecast. In the simulated data tests (response to question 1) the model evolution in the Kuroshio region shows low sensitivity to the details of the atmospheric forcing on this time scale (because the variability in this region is largely not a deterministic response to atmospheric forcing on the forecast time scale), but obviously the effects of atmospheric forcing on oceanic forecast skill must be a subject of future testing.

## 3. Summary

In this study we have addressed three issues: (1) the capability of satellite altimetry as an observing system for mesoscale oceanic variability, (2) ocean model skill as a dynamical interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) the potential for skillful forecasting of mesoscale variability using models with assimilation of satellite altimeter data as the initial state. In particular, we addressed three specific questions:

1. Can satellite altimeter data be used to constrain an eddy-resolving ocean model so that it depicts the evolution of mesoscale features such as individual current/frontal meanders and eddies?

Obviously the answer to question 1 is yes. Substantial skill at the mesoscale is obtained using even one altimeter with the Geosat and ERS orbits preferable to the T/P orbit, but errors can be reduced significantly by using up to three satellites.

2. Can an ocean model show skill as a dynamical interpolator for satellite altimeter data in mapping mesoscale features? Do we see a dependence on model resolution/simulation skill?

Clearly the answer to question 2 is yes for the 1/16° Pacific model which shows substantially greater skill for mesoscale features than the 1/4° model. In general, the 1/16° Pacific model shows much greater simulation skill for mesoscale variability and inertial currents like the Kuroshio, when the model is spun up for many years to statistical equilibrium with atmospheric forcing only.

3. Can an ocean model show skill in forecasting the evolution of mesoscale features when the model assimilates altimeter data to define the initial state for the forecast? What is the time scale for forecast skill? And again what dependence do we see on model resolution/simulation skill?

The answer to question 3 is yes for the 1/16° Pacific model with mesoscale forecast skill for at least a month, and much greater mesoscale forecast skill than the 1/4° model.

The results presented here should be regarded as preliminary. The forecasts shown here are the very first performed by these models (not the best of many) and there is ample opportunity to improve the data assimilation.

## Acknowledgements

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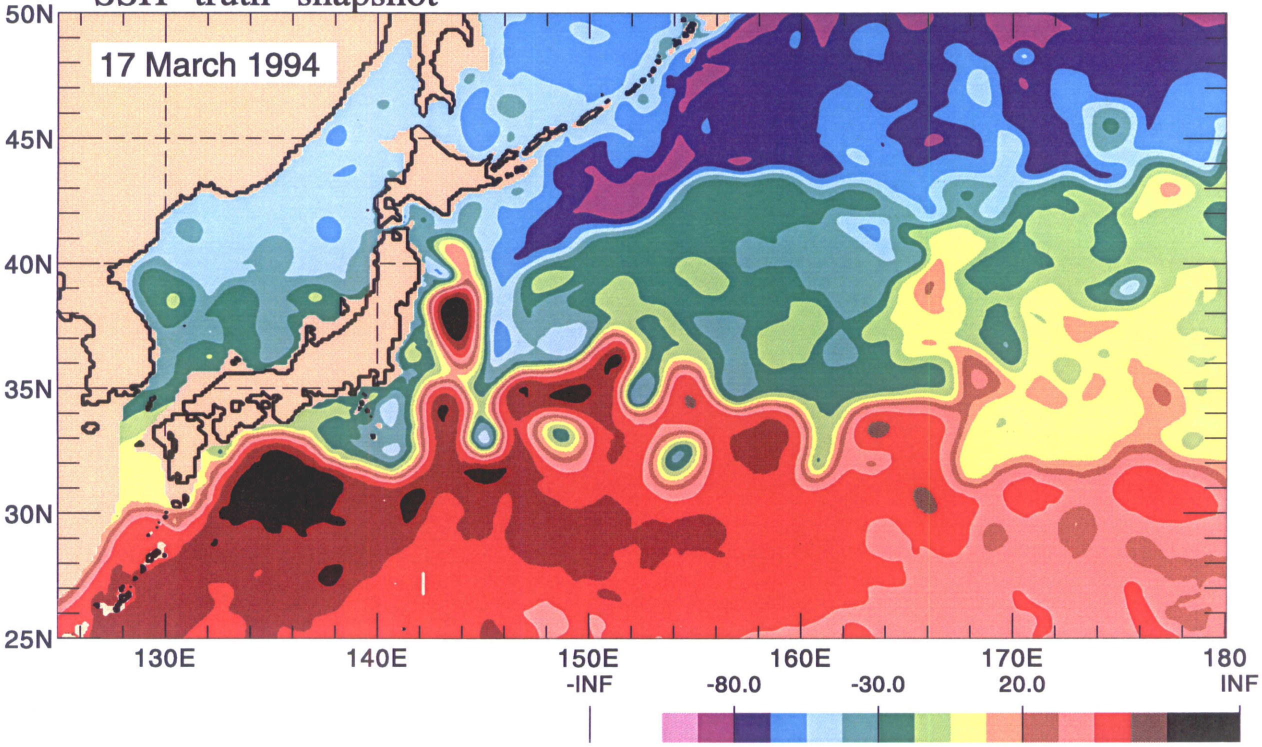
## Ability of Altimetry SSH to Constrain Highly Eddy-resolving Ocean Model

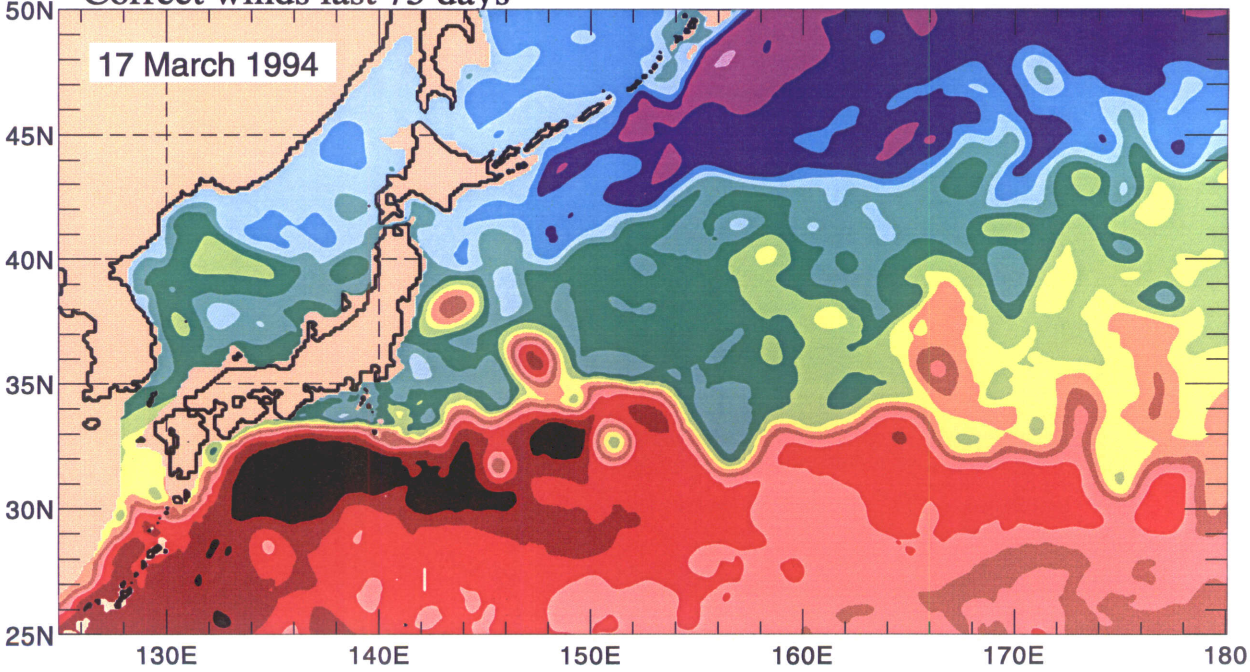
Tested by assimilation of error free SSH into the NRL 1/16° Pacific Ocean Model

SSH "truth" snapshot



CI = 12.5 cm

SSH snapshot, no assimilation
Correct winds last 75 days



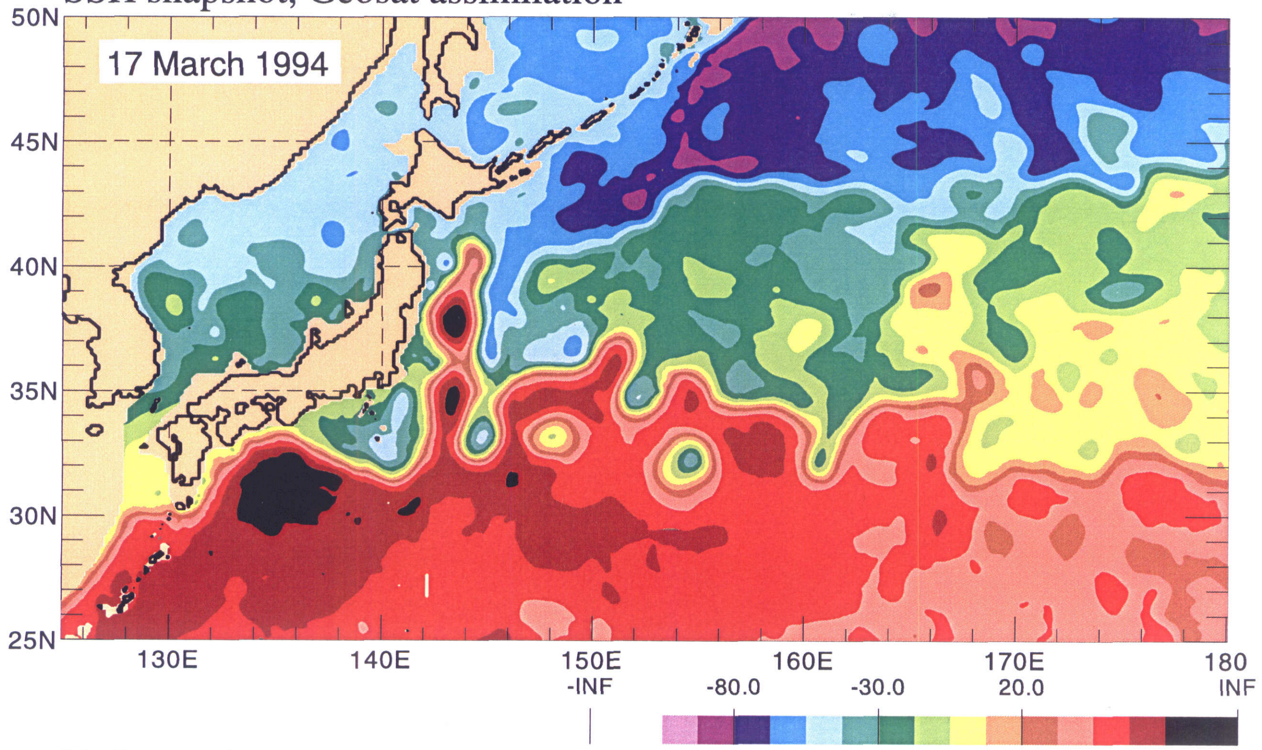
Control run (CR) was forced 1990-1998 using 12 hrly FNMOC winds. Many ocean features take > 75 days to respond to wind forcing or they are nondeterministic response to forcing.

**Figure 1**

## Ability of Altimetry SSH to Constrain Highly Eddy-resolving Ocean Models

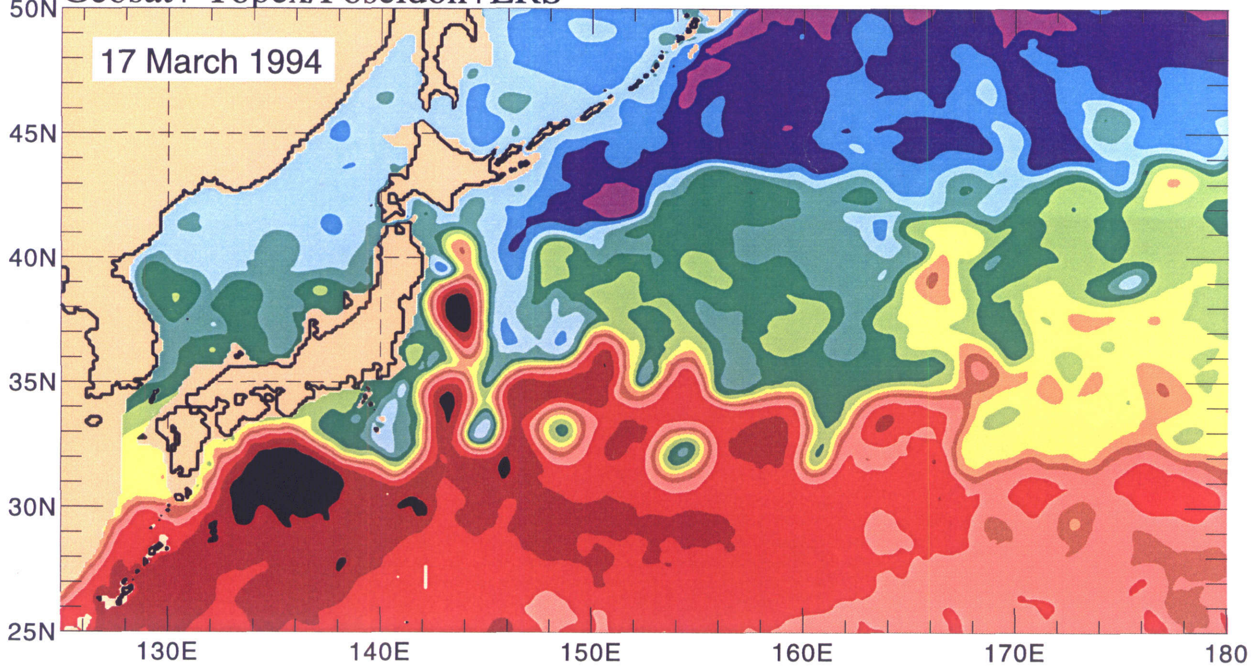
Tested by assimilation of error free SSH into the NRL 1/16° Pacific Ocean Model

SSH snapshot, Geosat assimilation



CI = 12.5 cm

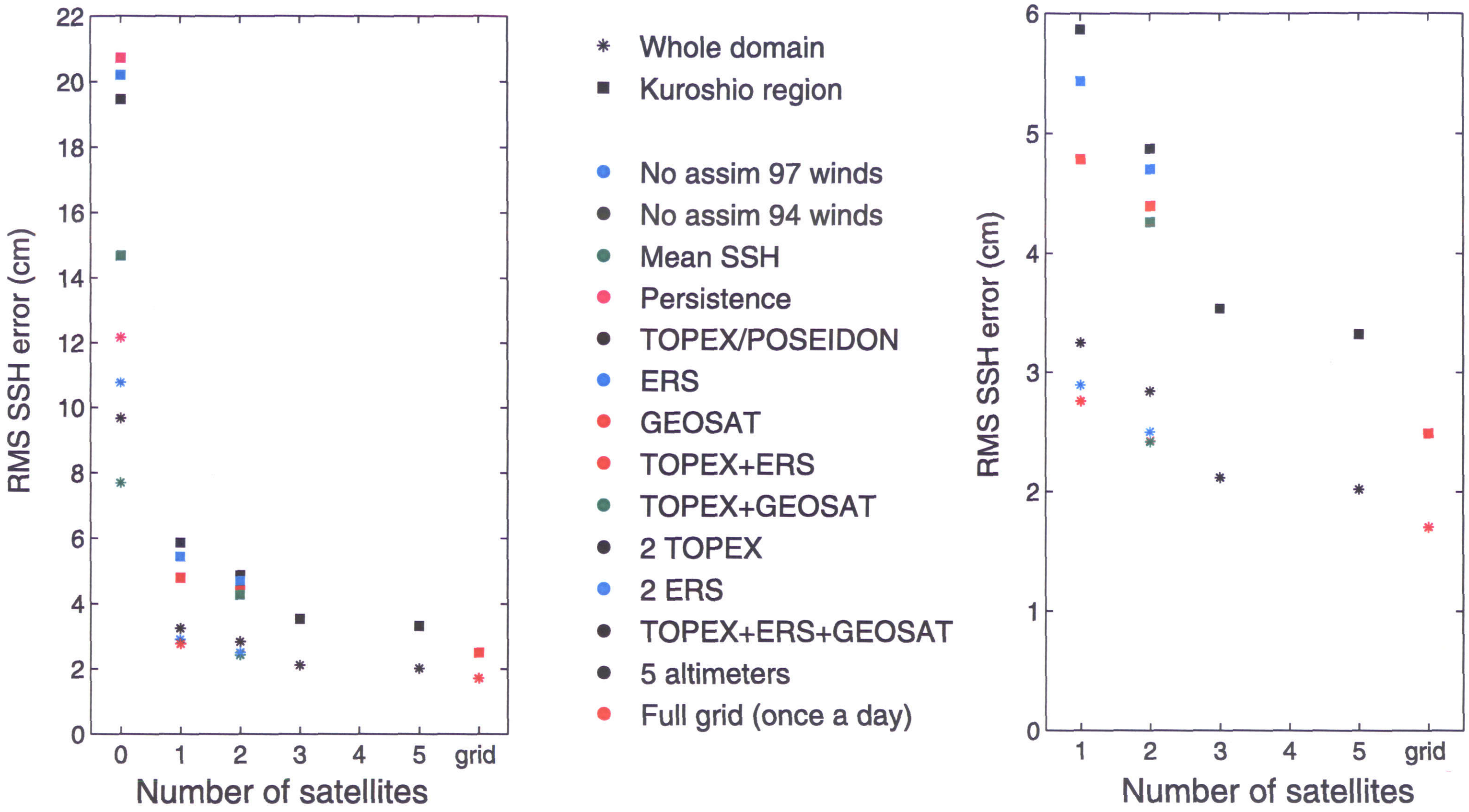
SSH snapshot, 3 altimeter assimilation
Geosat+ Topex/Poseidon+ERS



Control run (CR) was forced 1990-1998 using 12 hrly FNMOC winds. Starting from a 1997 CR initial state, 1994 wind forcing and simulated CR altimeter data from 1994 was assimilated for 80 days to make the model in 1997 look like the model CR in 1994.

**Figure 2**

**RMS Sea Surface Height (SSH) Error vs # of satellite altimeters used in Assimilation of Error Free SSH into the NRL 1/16° Pacific Ocean Model.**

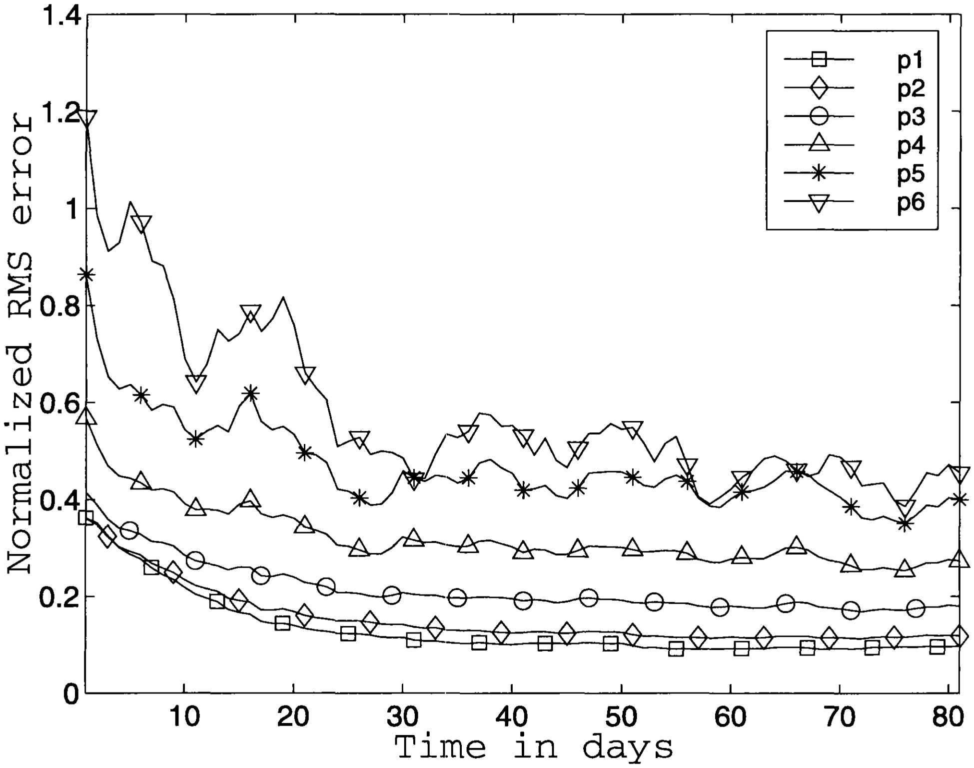


Test of altimeter data capability to constrain a realistic highly eddy-resolving ocean model. Control run (CR) was forced 1990-1998 using 12 hrly FNMOC winds. Starting from a 1997 CR initial state, 1994 wind forcing and simulated CR altimeter data from 1994 was assimilated for 80 days to make the model in 1997 look like the model CR in 1994. Many features take > 80 days to respond to wind forcing or are nondeterministic response to forcing SSH RMSE is the value over the last 30 days of assimilation. The right panel is the same as the left except that "0" satellites is omitted and the ordinate is expanded to better show the impact of increasing the number of satellites.

**Figure 3**

Normalized RMS pressure error as a function of time
Assimilation of simulated Geosat data into
the NRL 1/16° Pacific Ocean Model

Whole domain



Kuroshio region

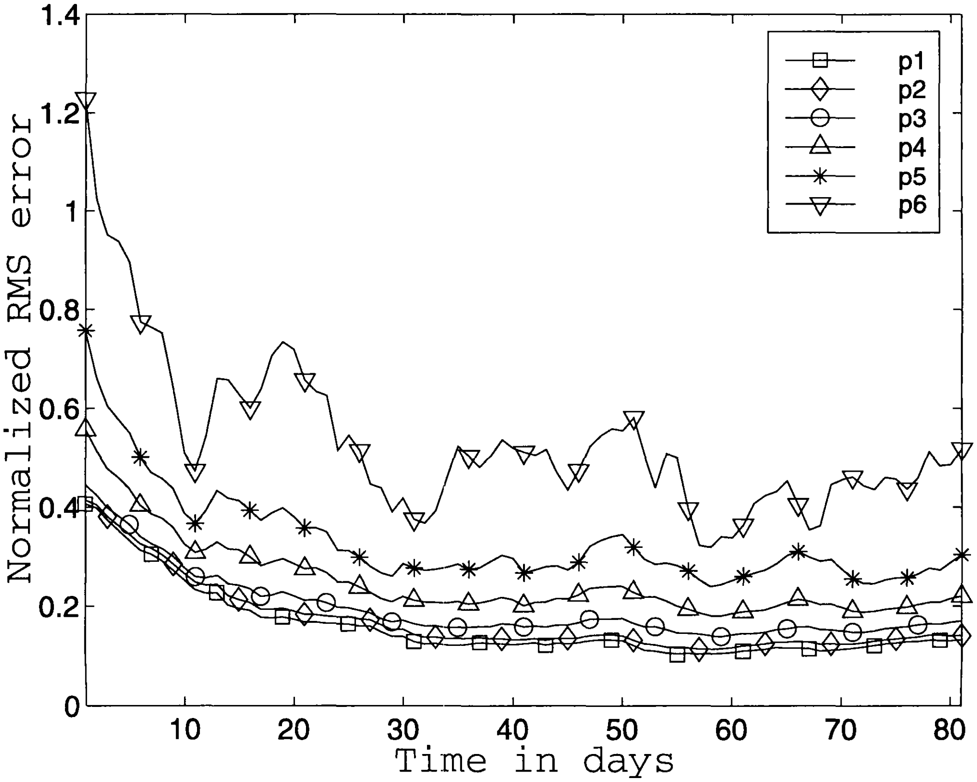
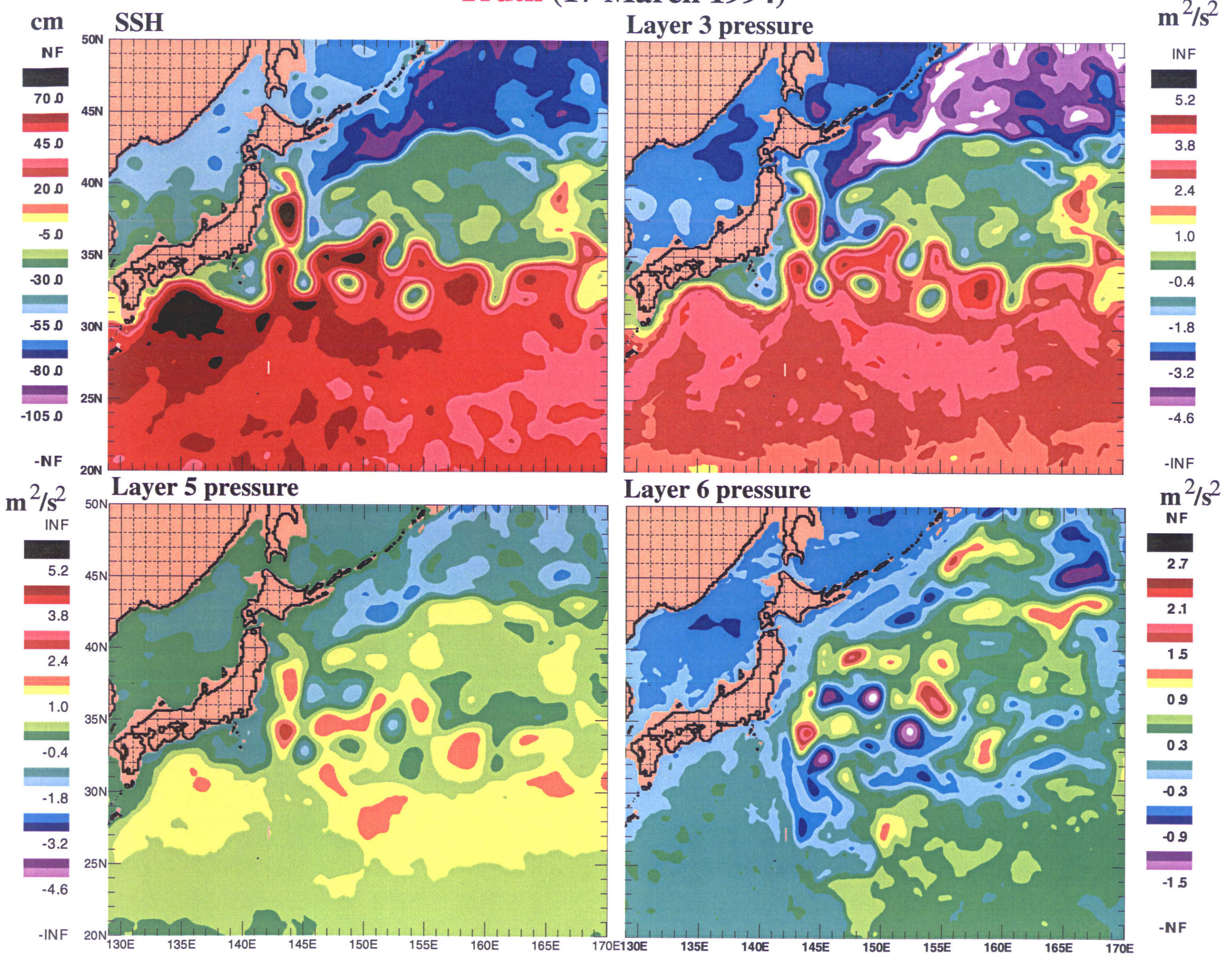


**Figure 4**

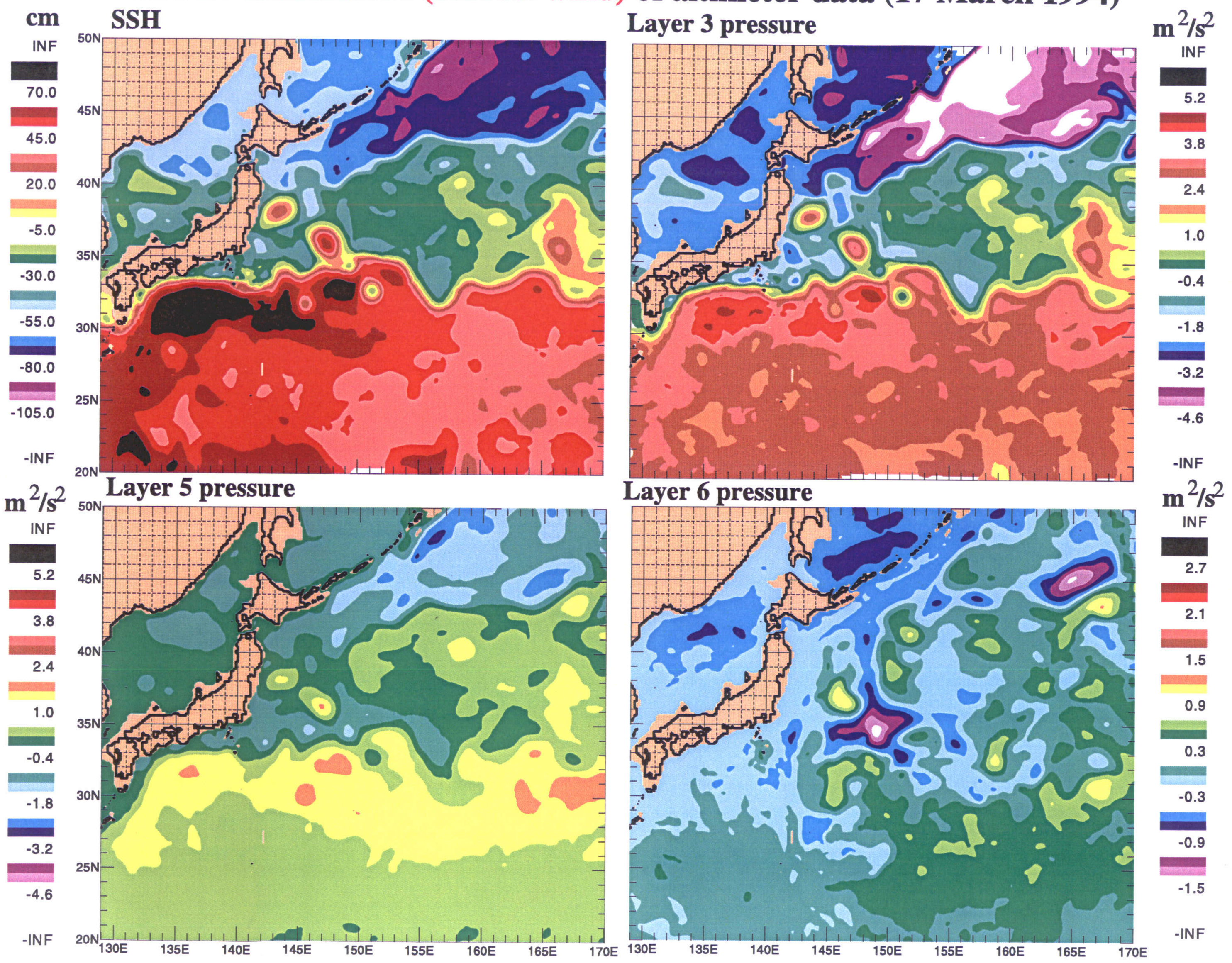
## SSH and pressure from the 1/16° Pacific NLOM
## Truth (17 March 1994)



Forced with the FNMOC/HR hybrid winds

Figure 5

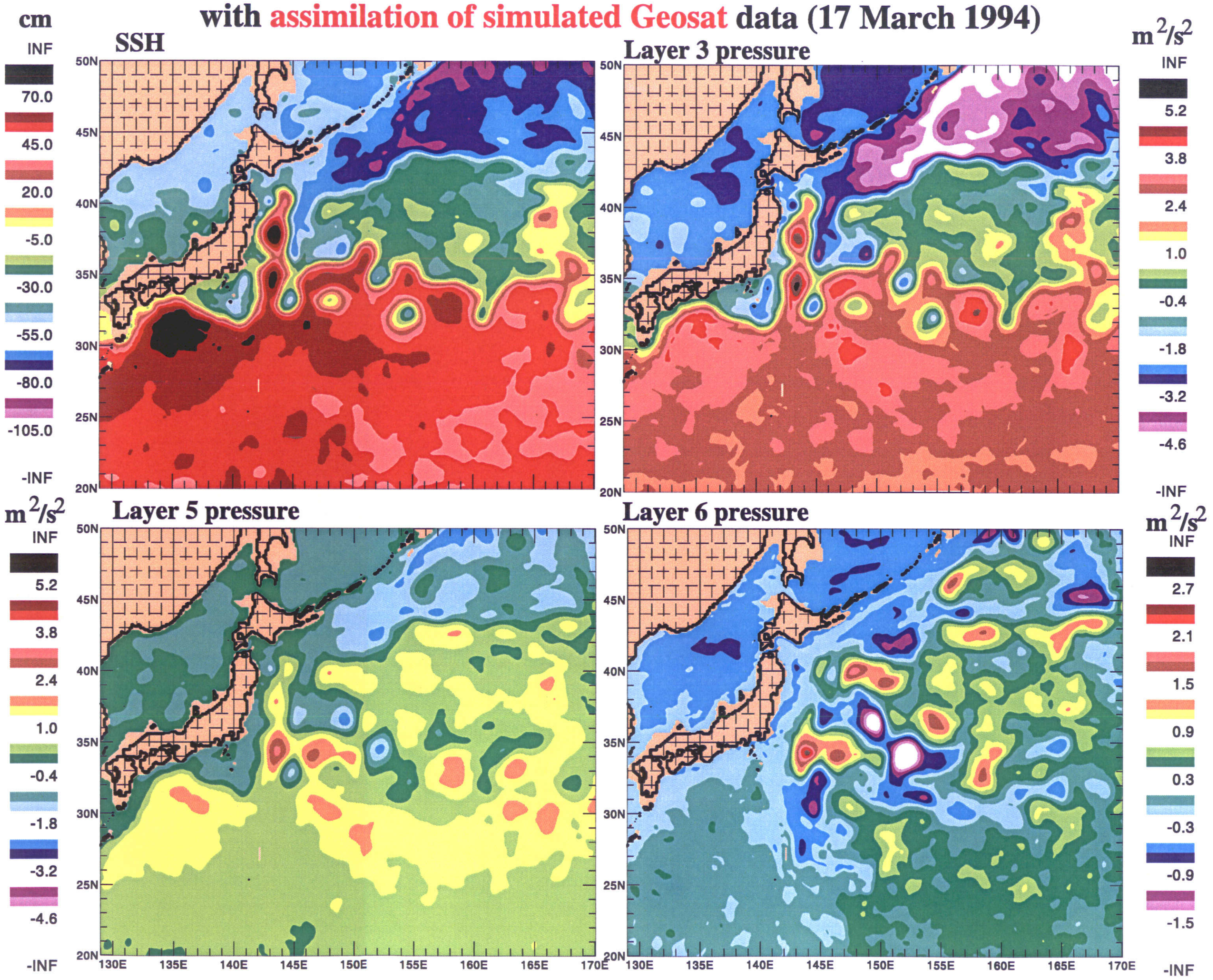
# SSH and pressure from the 1/16° Pacific NLOM with no assimilation (correct wind) of altimeter data (17 March 1994)



Forced with the FNMOC/HR hybrid winds

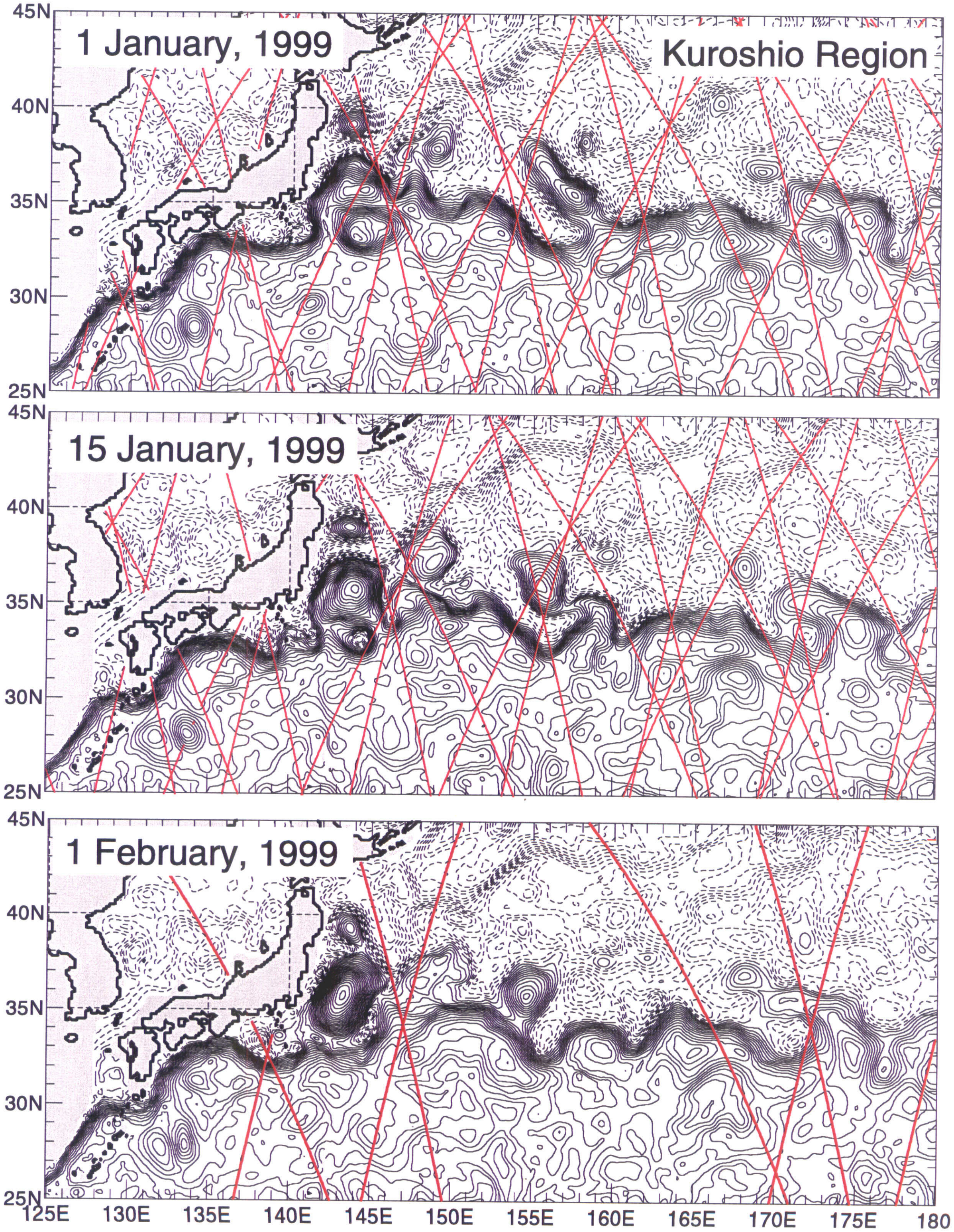
Figure 6

SSH and pressure from the 1/16° Pacific NLOM
with assimilation of simulated Geosat data (17 March 1994)



Forced with the FNMOC/HR hybrid winds

Figure 7



**1/16° Pacific NLOM SSH with Direct Assimilation of TOPEX + ERS-2 Altimeter Data**

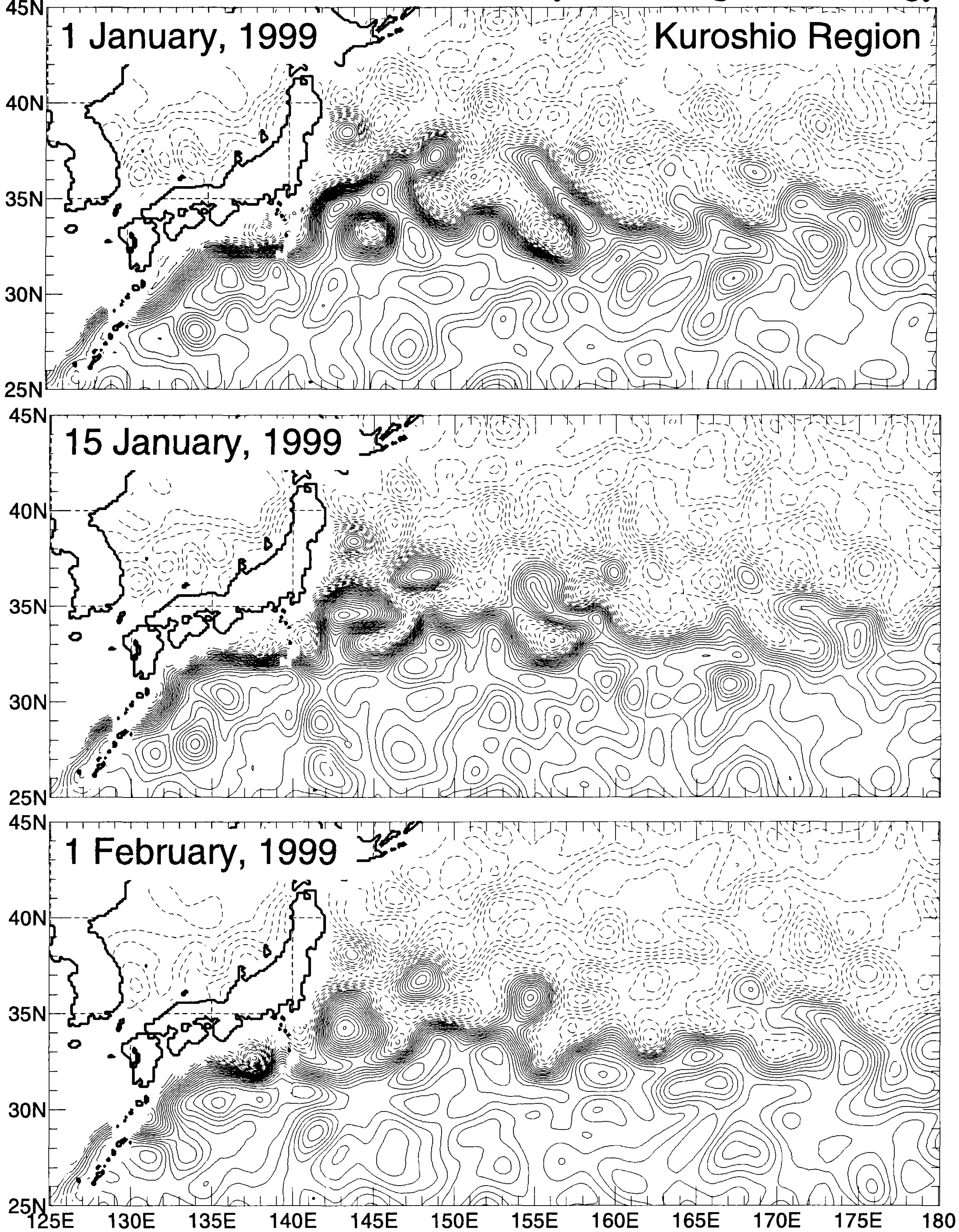
Contour interval = 5 cm

Altimeter tracks used in the most recent assimilation update are superimposed in red

Figure 8

# 1/8° MODAS SSH Analyses of TOPEX + ERS-2 Altimeter Data

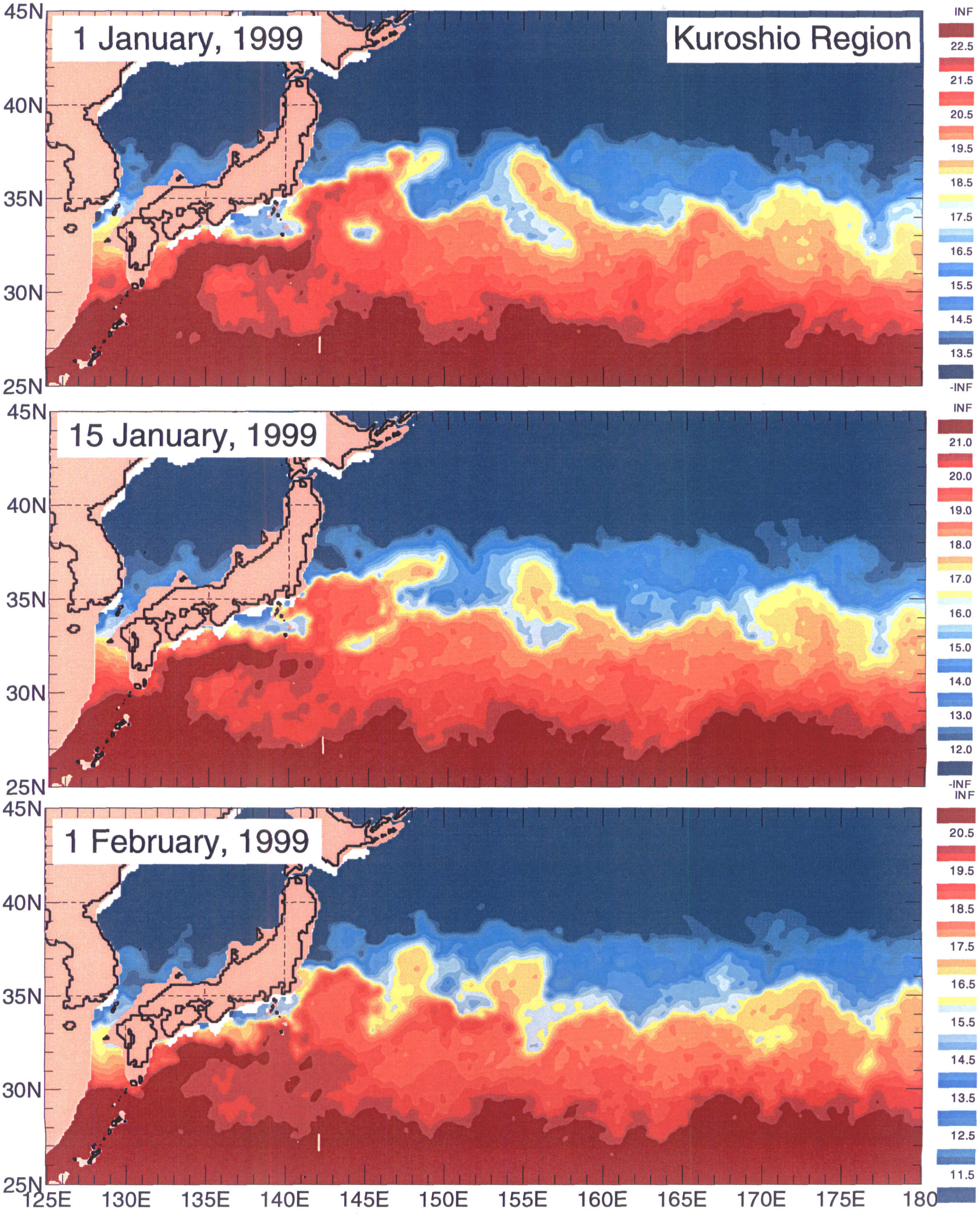
Mean SSH from MODAS surface dynamic height climatology



**Contour interval = 5 cm**

**Figure 9**

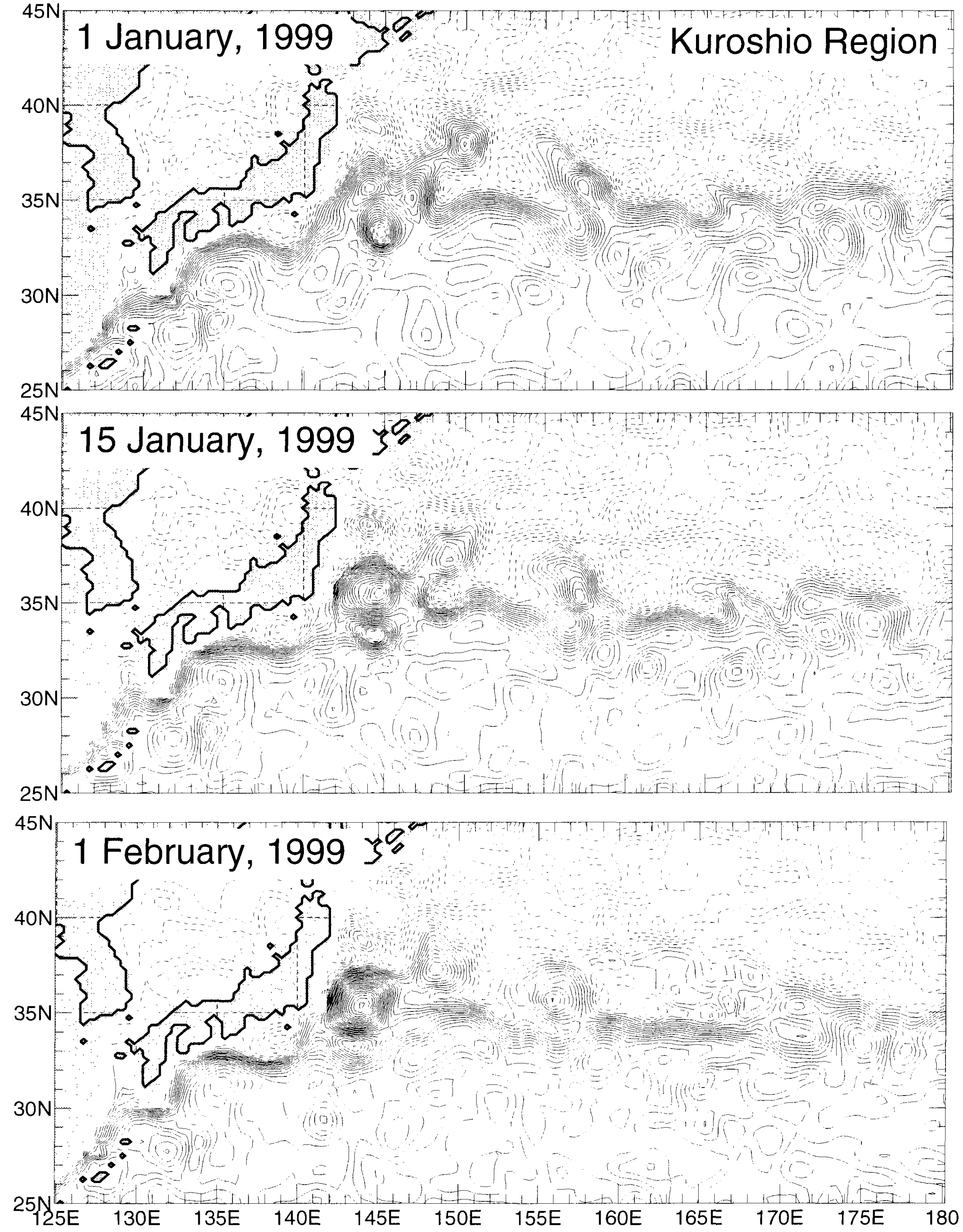
# 1/8° MODAS Sea Surface Temperature Analyses



Contour interval = 0.5° C

**Figure 10**

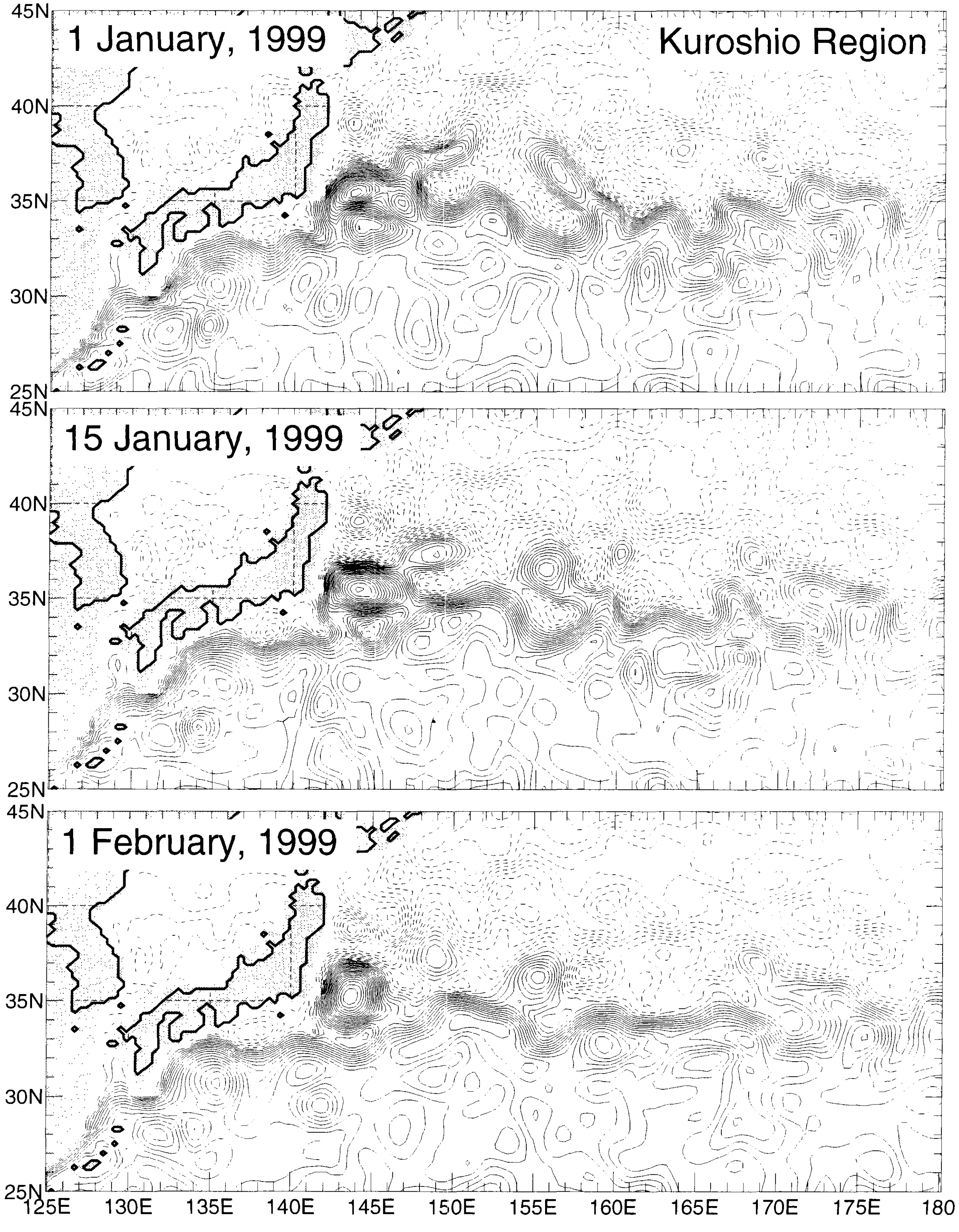
# 1/4° Global NLOM SSH with Direct Assimilation of TOPEX + ERS-2 Altimeter Data



**Contour interval = 5 cm**
**SSH = Sea Surface Height**

**Figure 11**

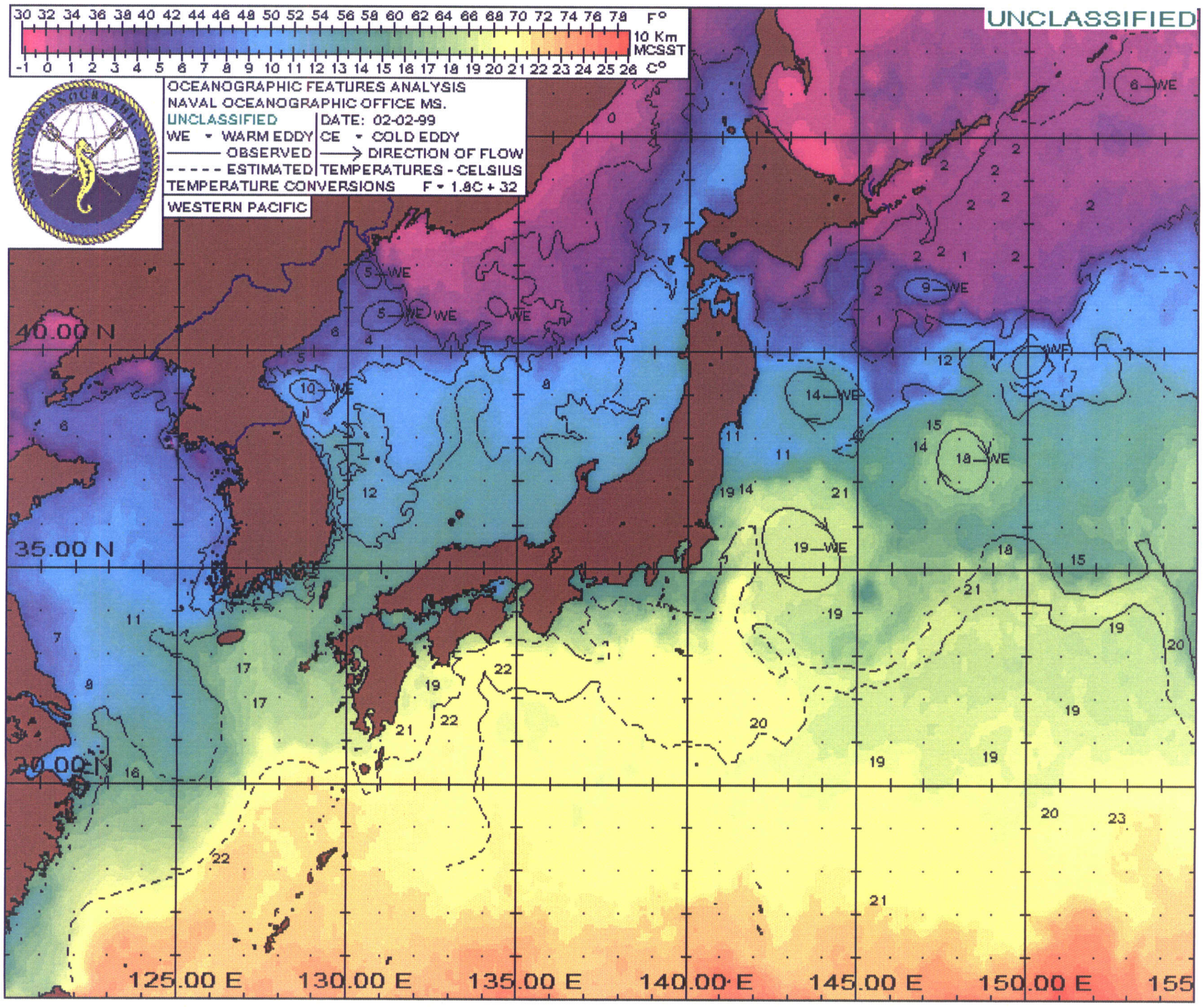
# 1/4° Global NLOM SSH with MODAS SSH Analyses Assimilation of TOPEX + ERS-2 Altimeter Data



**Contour interval = 5 cm**
**SSH = Sea Surface Height. Modified model mean used with MODAS anomalies.**

**Figure 12**

# NAVOCEANO WSC Frontal Analyses for Kuroshio

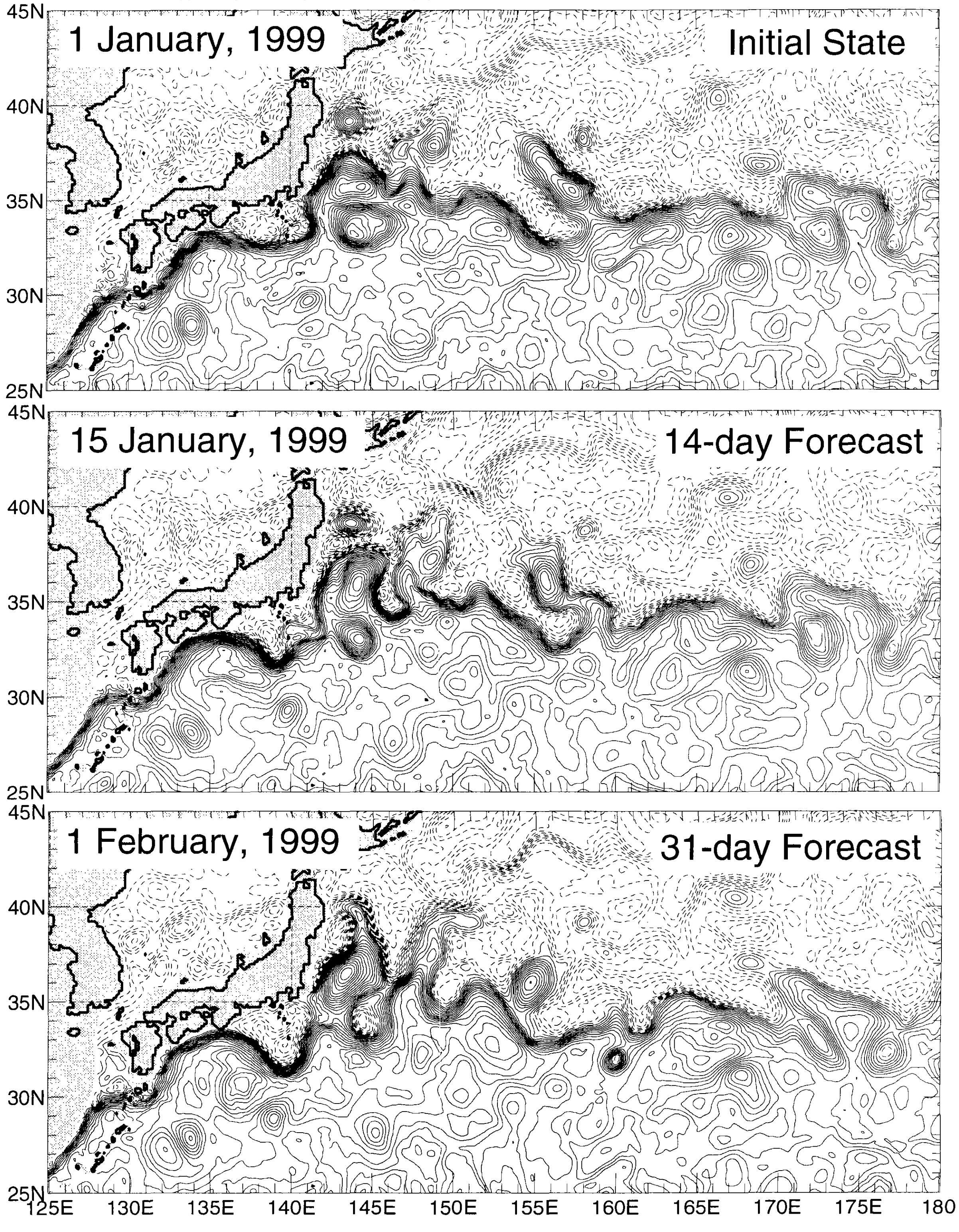


2 February, 1999

**Figure 13**

# 1/16° Pacific NLOM SSH 14 and 31 day Forecasts in the Kuroshio Region

Initialized from direct TOPEX + ERS-2 Assimilation

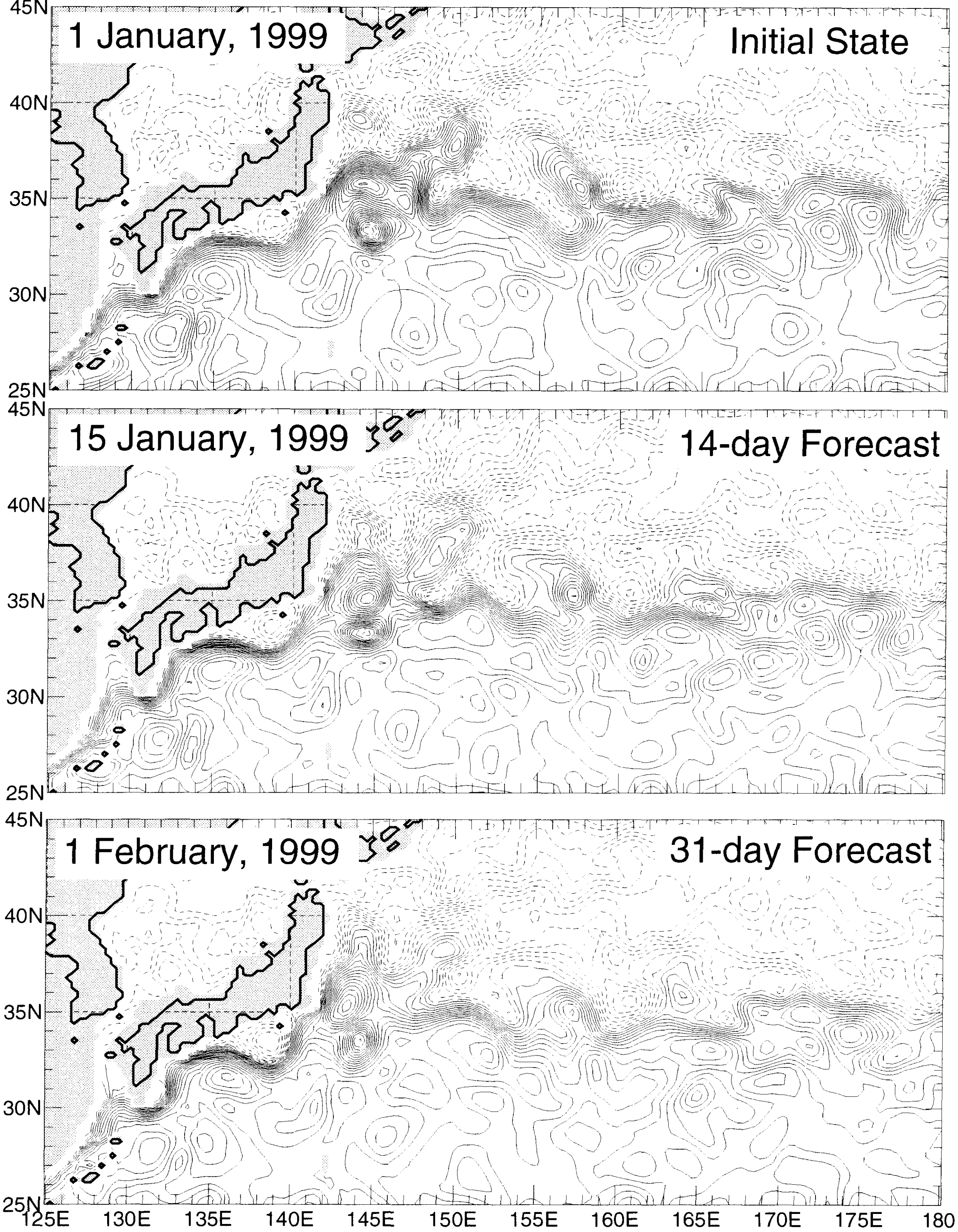


**Contour interval = 5 cm**
**SSH = Sea Surface Height**

Figure 14

# 1/4° Global NLOM SSH 14 and 31 day Forecasts in the Kuroshio Region

Initialized from direct TOPEX + ERS-2 Assimilation

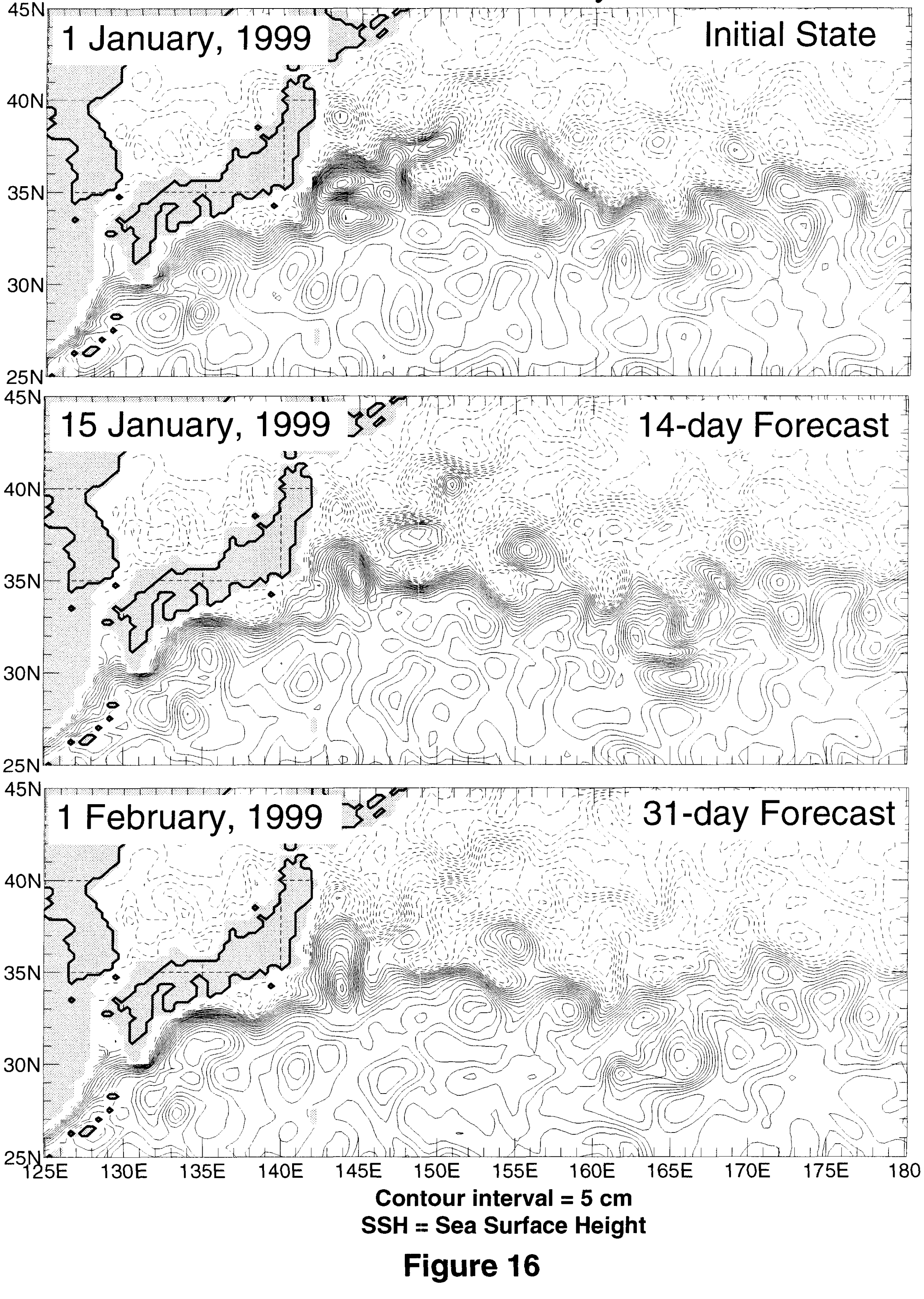


**Contour interval = 5 cm**
**SSH = Sea Surface Height**

**Figure 15**

# 1/4° Global NLOM SSH 14 and 31 day Forecasts in the Kuroshio Region

Initialized from MODAS SSH Analyses Assimilation



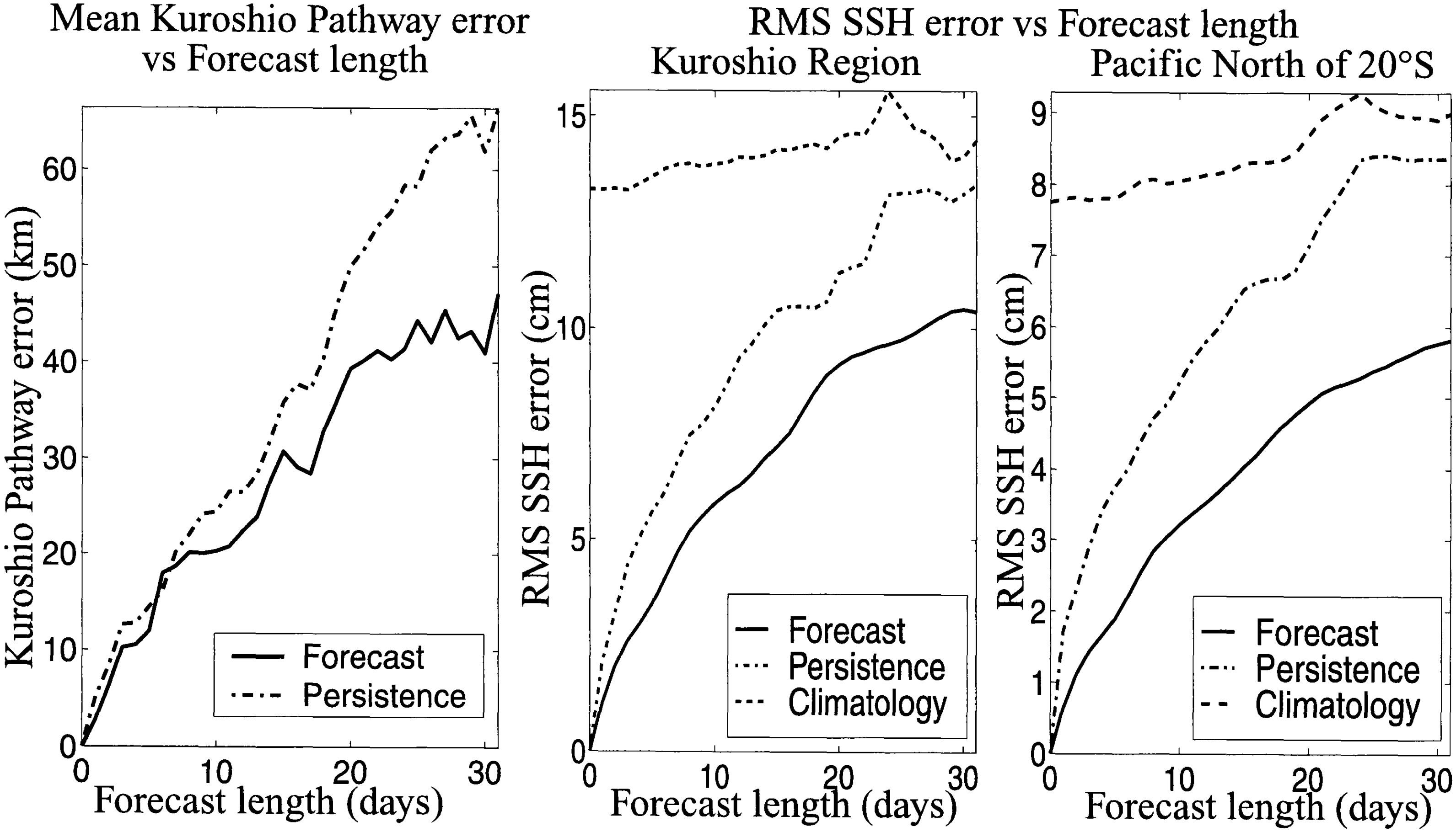
**Contour interval = 5 cm**

**SSH = Sea Surface Height**

**Figure 16**

1/16° Pacific SSH Forecast Verification against Model with TOPEX+ERS-2 Direct Altimeter Data Assimilation

Forecast Initialized from 1 Jan 1999



Persistence: Forecast of no Change from initial state
Mean Kuroshio Pathway Error: Area between observed and forecast contours divided by the length of the observed contour

**Figure 17**