The Sensitivity of a Global Ocean Model to Wind Forcing: A Test Using Sea Level and Wind Observations From Satellites and Operational Analysis

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Abstract

Investigated in this study is the response of a global ocean general circulation model to forcing provided by two wind products: operational analysis from the National Center for Environmental Prediction (NCEP); observations made by the ERS-1 radar scatterometer. The sea level simulated by the model using the two wind fields is compared to the observations made by the TOPEX/POSEIDON radar altimeter for a period of two years, The focus of the analysis is placed on the large-scale ocean variabilities at mid arid high latitudes. The sea level simulations resulting from the ERS-wind are found to be closer to the TOPEX/POSEIDON observations over most of the global oceans. The improvement due to the ERS-1 wind is most pronounced in the Southern Ocean, where the sea level variabilities are primarily caused by large-scale barotropic motions driven by wind and the improvement can be as large as 10 cm. This is also the place where conventional wind observations are scarcest, leading to poor operational analysis. Other areas of appreciable improvement include the western and central North Pacific, the western subtropical South Pacific and the South Indian Ocean. The result of the study has demonstrated the sensitivity of a widely-used ocean model to the quality of wind forcing, as well as the synergistic use of two satellite sensors in the study of ocean dynamics.

Introduction

There is a long history of the investigation of the variability of ocean currents in response to wind forcing. Analytical models have provided a framework for understanding the basic mechanisms of the ocean's response (e.g., Veronis and Stommel, 1956), whereas numerical models have been used to simulate the real ocean for comparison to observation in details (e.g., Willebrand et al. 1980). It has been shown that the tropical oceans are very sensitive to wind forcing and ocean models are indeed capable of producing better results when forced by better winds (Harrison et al., 1989; Liu et al. 1996). In the present study, we use the global sea level observation from the TOPEX/POSEIDON (abbreviated as T/P hereafter) Mission (Fu et al., 1994) to test the sensitivity of a global ocean general circulation model to the quality of wind forcing from two sources: operational analysis from meteorological centers versus observation from the ERS- 1 radar scatterometer (e.g., Offiler, 1994). The emphasis is placed on the large-scale (larger than the 100 km eddy scale) response of the ocean at mid and high latitudes, where the effects of wind on model performance is less well known.

Satellite altimetric observation of sea level is an effective tool for studying global ocean dynamics. After removing the steric effects on sea level from the T/P data, Stammer (1997) investigated the residual sea level variations and found that a time-dependent Sverdrup balance (see Pedlosky, 1979 for definition) was able to account for the zonally integrated mass transport inferred from the data north of 40° N in the Pacific Ocean. Fu and Davidson (1995) reported evidence for local time-dependent Sverdrup balance in certain high-latitude regions. Comparisons of T/P data to numerical models have revealed intra-seasonal, barotropic (or depth-independent) response of the ocean to wind forcing at mid and high latitudes (Chao and Fu, 1995; Fu and Smith, 1996), where significant coherence exists between observation and model simulation at periods of 20-100 days and scales larger than 1000 km. In this study we drive an ocean model using two different wind products and compare the results to T/P data. Can the model distinguish between the two wind fields in simulating the sea level observations?

The Model and Wind

The ocean model is the same as the one used by Chao and Fu (1995). It is the widely used Modular Ocean Model (MOM) developed by NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) (Pacanowski et al., 1991). The configuration we adopted has a horizontal resolution of 2 degrees in longitude and 1 degree in latitude, and 22 vertical levels. Such resolution is adequate for resolving the large-scale features of interests to the study. The model was first run for 10 years forced by the climatological monthly wind of Hellerman andRosenstein(1983). The initial condition was the January temperature and salinity from Levitus (1982) with zero currents. The surface temperature and salinity were restored to the climatological monthly values of Levitus (1982) with a relaxation timescale of 30 days.

After the spin-up the model was forced by two real-time wind products for the investigation. The first wind product is the 1000 mb wind analysis from NOAA's National Center for Environmental Prediction (NCEP, used to be called the National Meteorological Center). This is the same wind used by Chao and Fu (1995). The second wind product is based on the observations made by the ERS-1 radar scatterometer. The data were processed and objectively interpolated to a regular space-time grid by the French CERSAT Group of IFREMER (CERSAT, 1996). The gridded ERS- 1 wind has a resolution of 1 degree in both longitude and latitude, and is available every 7 days. The NCEP wind has a resolution of 2.5 degree in both longitude and latitude, and is available every 12 hours. To make the frequency content of the two wind products comparable, the 12-hour NCEP wind was low-pass filtered by averaging over 7-day intervals. A wind-speed-dependent drag coefficient formula (Large and Pond, 198 1) was used to convert wind speed from both products to wind stress. The resulting wind stress was then linearly interpolated onto the model space and time grids.

Displayed in Figure 1 is a scatter plot comparing the mean zonal wind stress computed from the two products over the global oceans for the period of October, 1992- October, 1994. It clearly shows that the NCEP 1000 mb wind stress is about 40-50% higher than the ERS- 1 wind stress. Similar results were obtained for the meridional component. This finding is consistent with that of Mestas-Nuñez et al (1994), who compared the ECMWF 1000 mb wind to the Seasat scatterometer observations. The discrepancy between the 1000 mb isobaric surface from the real ocean surface renders the 1000 mb wind generally too strong for being used as surface wind. The 1000 mb wind could be scaled down by a fudge factor to emulate the surface wind better, but this was not done for the study because our objective is the model's sensitivity to the quality of wind forcing instead of optimizing the simulation forced by operational analysis.

The ocean model was driven by the two wind products and the resultant simulation of sea level was compared to the observation of T/f' for the period of October 1992-October 1994. The switch to real-time wind forcing was made on April 1, 1992 when the ERS- 1 wind became available. The ocean's adjustment to such an abrupt shift of wind forcing from climatology to real-time observation would take years to settle down. For the present study, the long-term trends in the sea level simulations, which were affected by the adjustment processes, were removed before comparison to the observations. The focus of the study is therefore limited to seasonal timescales and shorter.

The root-mean-squares (rms) sea level difference between the two model runs is shown in the upper panel of Figure 2. The geographic patterns of the sea level difference are very different from those of the difference in wind (lower panel of Figure 2). The latter are primarily dependent on latitude: largest at high latitudes and smallest in the tropics. The former are more complicated, reflecting the regions where the sea level is sensitive to wind forcing. There are significant differences in sea level in the tropics as expected, despite the minimum difference in wind. The wind differences are large and pervasive at high latitudes, whereas the sea level differences have rather localized patterns. These sea level patterns, especially in the Southern Ocean, are similar to those of the barotropic intra-seasonal response of the ocean discussed in Chao and Fu (1995). The difference between the two model runs reveals the sensitivity of the model to wind forcing, but it does not indicate which run is better. The question is addressed by comparing the simulations to observations.

Comparison to Observations

The sea level observations made by the T/P radar altimeter have been used in a wide range of oceanographic and geophysical applications (see the two special issues of the Journal of Geophysical Research, Vol. 99, No. C12, 1994 and Vol. 100, No. C12, 1995). The data used in the study were processed in a standard manner: After the application of the project-supplied corrections (Callahan, 1994), the sea level data were interpolated to a set of fixed ground locations 6.2 km apart along the satellite track for collinear analysis. Also applied were the corrections for the ocean tides (Ma et al., 1994) and the loading of the atmospheric pressure (Fu and Pihos, 1994). After the time mean was removed from each data point, the time-varying residual sea levels were used for the study.

To extract the large-scale signals for comparison to the model, the T/P data were spatially smoothed within 50 boxes by a Gaussian weighting scheme with an e-folding scale of 500 km. The data were sampled on 10x 10x 10 day grids. A 10-day running mean filter was applied to both model runs for comparison to the T/P data, Figure 3 shows the differences between the simulations and the T/P observations. It clearly demonstrates the impact of using a better wind in simulating the global sea level variations. Except for small, scattered regions, the simulation forced by the ERS- 1 wind is generally better as expected, The globally averaged rms difference between simulation and observation has been reduced from 4.2 cm (forced by the NCEP wind) to 3.3 cm (forced by the ERS-1 wind).

In the tropics, the improvement is more pronounced in the Atlantic Ocean and the Indian Ocean than the Pacific Ocean, The prominent improvements to the east of Madagascar as well as off the northeast Australia are due to improved simulation of the annual cycle that is primarily wind-driven in these regions (Stammer, 1997). The improvements in the western and central subtropical North Pacific primarily reflect improved simulation of Rossby waves that are prevalent at these latitudes (Chelton and Schlax, 1996). The improvements at latitudes higher than 40 degrees are primarily related to the intra-seasonal barotropic fluctuations discussed previously. Chao and Fu (1995) demonstrated the barotropic nature of these variabilities by showing the coherence between sea level and the barotropic streamfunction of the model. This study confirms that these variabilities are essentially driven by wind.

Figure 4 shows the comparison of sea level time series averaged over a 1000 km by 1000 km box centered at 55°S and 100°W in the southeast region of the South Pacific Ocean, where the intra-seasonal variability has a local maximum. The correlation between observation and simulation increases from 0.3 to 0.5 while therms difference decreases from 5.9 cm to 3.1 cm when the model is forced by the ERS- 1 wind instead of the NCEP wind. Occasionally the improvement due to the ERS-1 wind amounts to 10 cm. Note the excessive fluctuations resulting from the NCEP wind forcing which is known to be too strong. As shown by Mestas-Nuñez et al, (1994), the 1000 mb wind can be scaled down by a fudge factor to emulate the 10-m wind. It is expected that using such 10-m wind would improve the simulation forced by operational analysis to some extent.

Conclusion

It is demonstrated in the study that the use of the ERS-1 scatterometer wind instead of the NCEP 1000 mb wind in driving an ocean general circulation model has improved the model's ability to simulate sea level variations over most of the global oceans. The global rms difference between the model simulation and the T/P observation is improved from 4.2 cm to 3.3 cm . The improvement is most pronounced in the Southern Ocean, where the sea level variabilities are primarily caused by large-scale barotropic motions driven by wind and the improvement can be as large as 10 cm. The Southern Ocean is also a place where direct wind observations are scarce and consequently the quality of the operational analysis is probably the poorest. Other areas of appreciable improvement include the western and central North Pacific, the western subtropical South Pacific and the South Indian Ocean. The result of the study has demonstrated the sensitivity of a widely-used ocean model to the quality of wind forcing, as well as the synergistic use of two satellite sensors in the study of ocean dynamics.

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Figure Captions

Figure 1. Mean zonal wind stress from the ERS-1 scatterometer versus the NCEP 1000 mb analysis.

Figure 2. Upper panel: rms sea level difference (in cm) between the two model simulations (denoted by OGCM) forced by the NCEP wind and the ERS-1 wind. Lower panel: rms of the vector difference between the ERS-1 and NCEP wind stress (in dynes/cm^2).

Figure 3. Upper panel: rms difference in sea level between the T/P observation and the model simulation (denoted by OGCM) forced by the NCEP wind. Middle panel: as in the upper panel except that the simulation is forced by the ERS-1 wind. Lower panel: the difference between the two (upper panel minus lower panel). A positive value means improvement in sea level simulation resulting from the ERS-1 wind forcing.

Figure 4. Sea level time series averaged over a 1000 km by 1000 km box centered at 55°S and 100°W: solid line - TOPEX/POSEIDON observation; dashed line - model simulation forced by the ERS-1 wind; dotted line - model simulation forced by the NCEP wind.

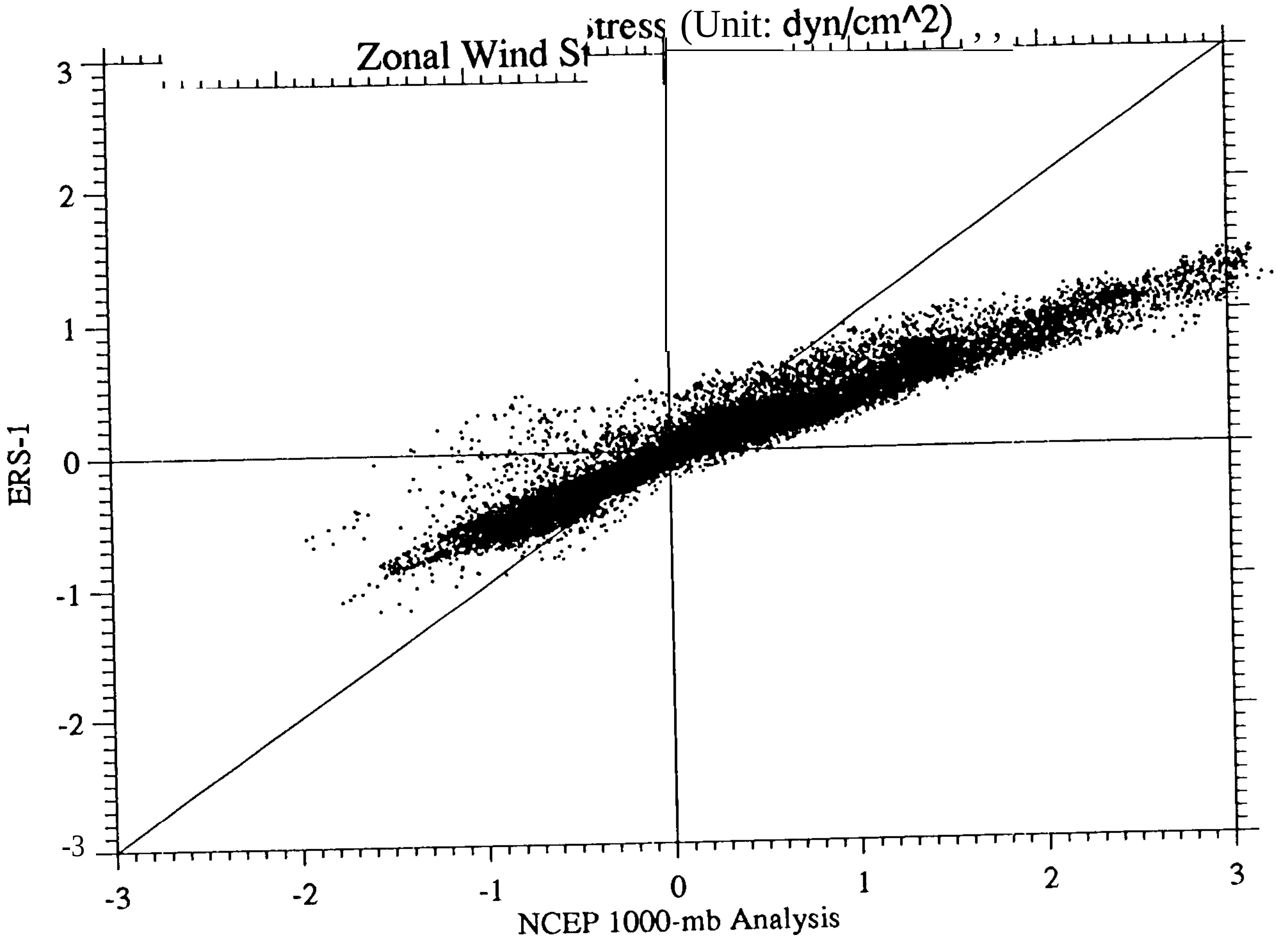
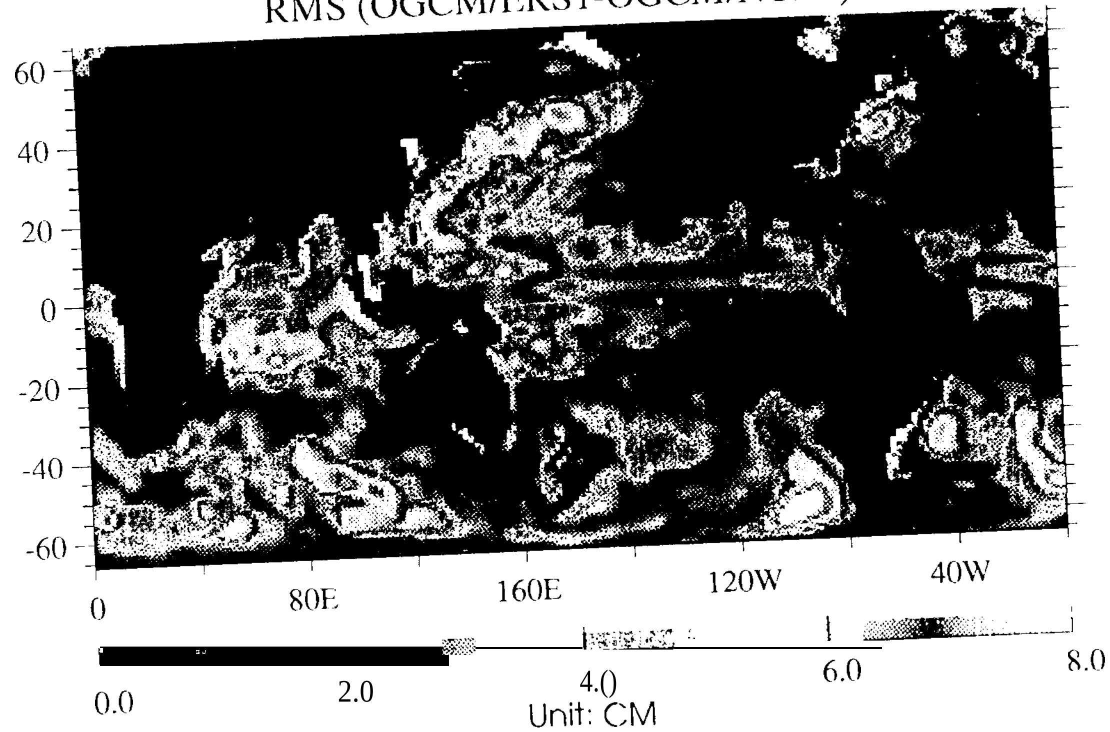

Zonal Wind Stress (Unit: dyn/cm^2)
ERS-1
NCEP 1000-mb Analysis
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3

Fig. 1


RMS (OGCM/ERS1-OGCM/NCEP)

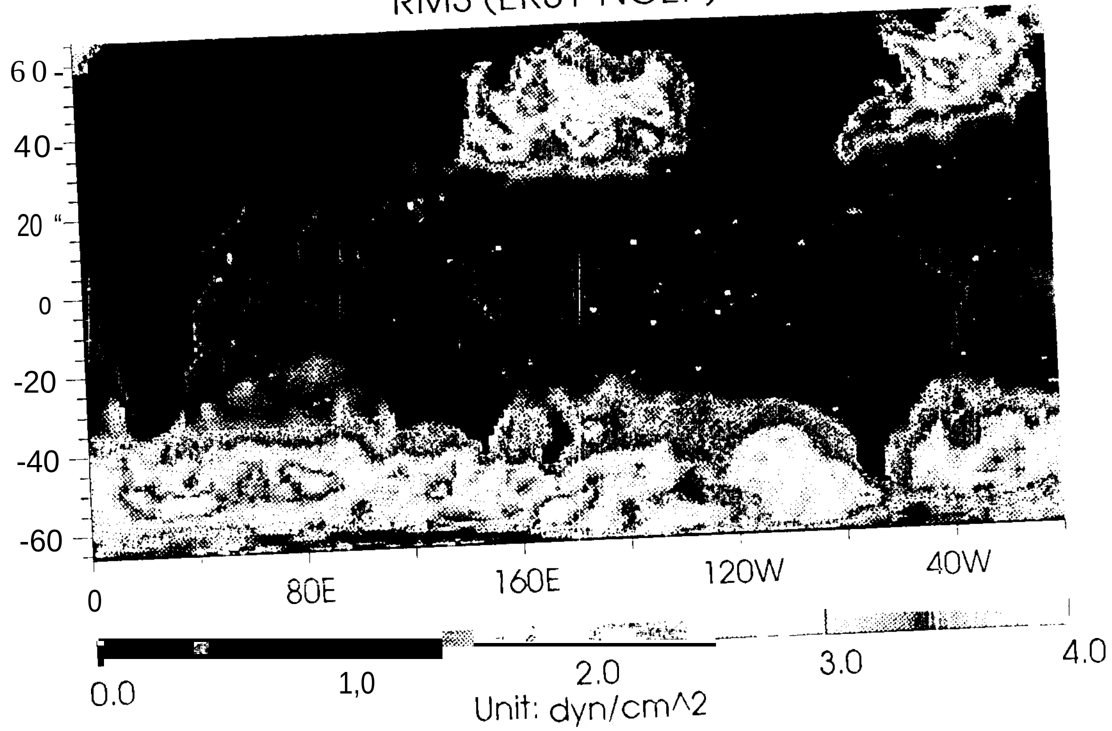

RMS (ERS1-NCEP)

Fig. 2

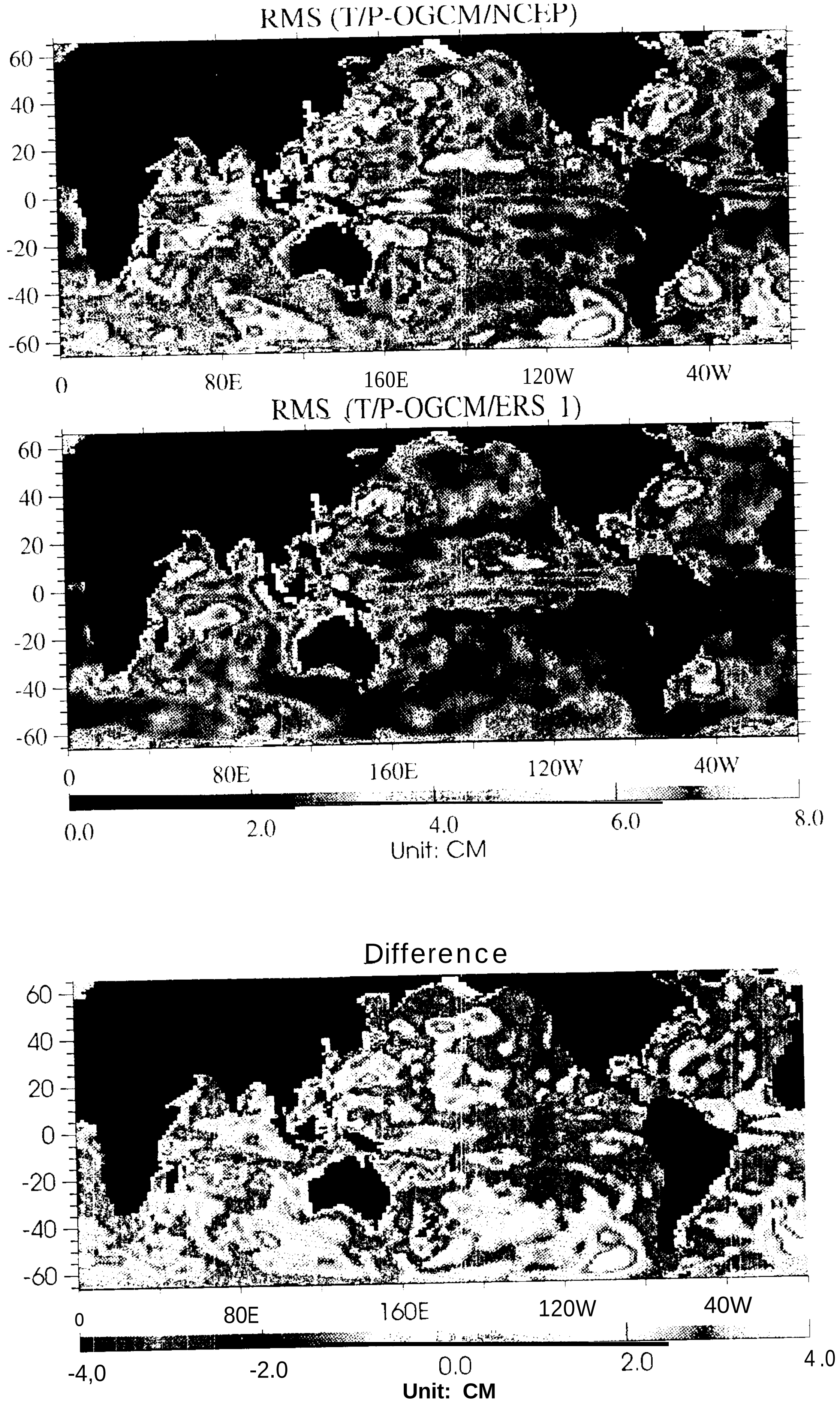
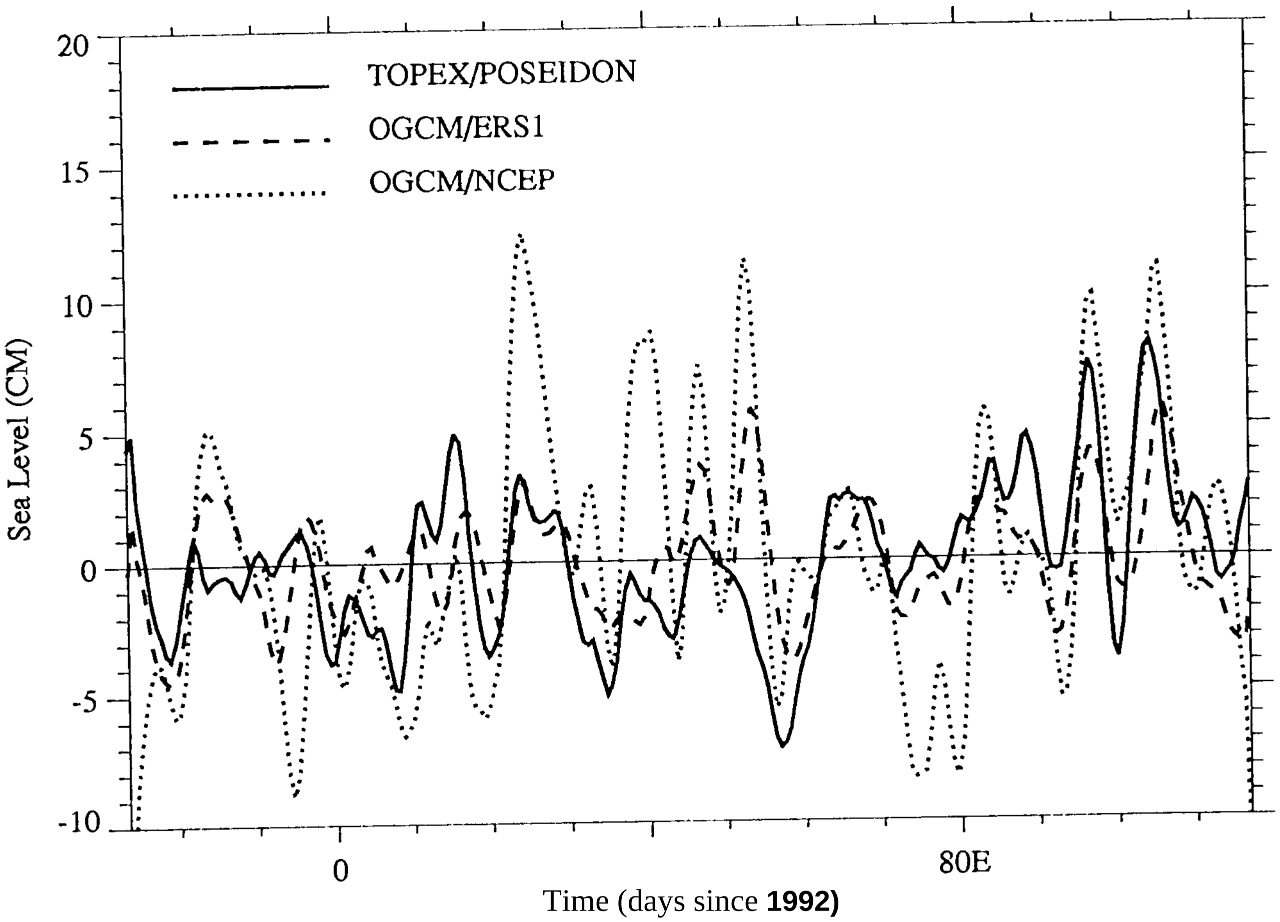

RMS (T/P-OGCM/NCEP)
60
40
20
0
-20
-40
-60
0
80E
160E
120W
40W
RMS (T/P-OGCM/ERS 1)
60
40
20
0
-20
-40
-60
0
80E
160E
120W
40W
0.0
2.0
4.0
6.0
8.0
Unit: CM
Difference
60
40
20
0
-20
-40
-60
0
80E
160E
120W
40W
-4,0
-2.0
0.0
2.0
4.0
Unit: CM

Fig. 3



20
15
10
5
0
-5
-10
Sea Level (CM)
TOPEX/POSEIDON
OGCM/ERS1
OGCM/NCEP
0
80E
Time (days since 1992)

Fig. 4