Ocean Model Response to Temperature Data Assimilation and Varying Surface Wind Stress: Intercomparisons and Implications for Climate Forecast

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(Manuscript received 16 May 1994, in final form 5 December 1994)

ABSTRACT

Two 11-yr Pacific Ocean simulations using an ocean general circulation model are compared with corresponding ocean analyses and with in situ observations from moorings and island tide gauges. The ocean simulations were forced by combining the climatological wind stress of Hellerman and Rosenstein with wind stress anomalies obtained from (a) the Florida State University surface wind analysis and (b) a two-member ensemble from an atmospheric model simulation. The ocean analyses were obtained by assimilating observed surface and subsurface temperatures into an ocean GCM, forced with the same wind stress anomaly fields used in the simulations.

The difference in thermocline depth between simulation and analysis using the same wind stress forcing is large in the off-equatorial regions near the North Equatorial Counter Current trough and in the South Pacific, suggesting that the mean climatological stress fields may be in error. The simulation results using the atmospheric GCM stress anomalies failed to show anomalous interannual sea level responses in the eastern equatorial Pacific, indicating that there are significant errors in the AGCM stress anomalies due to errors in the atmospheric model. The analyses show significant improvement over the comparable simulations when compared with the tide gauge data, indicating that assimilation of subsurface oceanic thermal data can compensate for stress-forcing errors and model errors on interannual timescales. However, the more accurate stress-forcing field leads to a better ocean analysis, indicating that the present density of temperature data is not sufficient to determine the ocean state.

1. Introduction

The ocean plays a major role in determining climatic variations. Bjerknes (1969) was the first to point out that large-scale interannual climate variability associated with the El Niño–Southern Oscillation (ENSO) phenomenon is a result of coupled interaction between the tropical ocean and the global atmosphere. Wyrtki (1975, 1979a) pointed out that the oceanic response to the ENSO is dynamical and basin wide. Since the oceanic response to the change of surface wind is much slower (months to years) than the atmospheric response to the change of sea surface temperature (SST), the ocean plays a dominant role in determining the timing and strength of climate variability on seasonal to interannual timescales. Accurate knowledge of oceanic conditions is important not only for understanding the physical mechanisms of ENSO and its development and demise, but also for facilitating reliable prediction of the SST and related atmospheric responses in extratropical regions (Miyakoda and Rosati 1993; Ji et al. 1994).

Oceanic circulations depend on the past history of the surface wind stress. Accurate estimates of oceanic circulation and subsurface thermal structure rely on accurate estimates of the surface wind stress. The largest source of error in model estimates of oceanic conditions may come from the surface wind stress forcing error (Ji et al. 1995). However, surface wind errors over the ocean are difficult to estimate due to lack of data coverage. Until recently, direct comparison of surface wind fields to observations could be made only at a limited number of moored buoy sites where time series of wind data were available (Reynolds et al. 1989). One very useful, although indirect, way of evaluating wind stress fields is through examination of ocean model response when forced with these stress fields.

Assimilation of observed surface and subsurface data into an ocean model is an effective way to compensate for the impact of wind stress errors in ocean model simulations. An ocean data assimilation system has been developed at the National Meteorological Center (NMC) by Ji et al. (1995). This system is based on a variational objective analysis method (Derber and Rosati 1989) in which observed surface and subsurface temperature data are assimilated continuously into the ocean model. In this paper, two Pacific Ocean analyses denoted RA2 and RA3 covering the period of July 1982–June 1993 obtained using two different surface wind stress anomalies are described. In addition, two Pacific Ocean model simulations denoted HCMP and HFSU were performed using the same wind fields.

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Monthly mean sea level anomalies and subsurface oceanic thermal fields produced from the ocean simulations are compared to each other and compared to the two ocean analyses. Both the simulations and the analyses are compared to in situ observations from moorings and island tide gauges.

Because of the ocean's greater heat capacity compared to the atmosphere, low-frequency climate signals reside primarily in the ocean, and high-quality assessment of oceanic conditions is an essential component of climate prediction (Ji et al. 1994; Miyakoda and Rosati 1993). A number of coupled ocean–atmosphere prediction models have forecast SST variations associated with the ENSO in the tropical Pacific with varying degree of success. A common method of ocean model initialization is to spin up the ocean using an observed surface wind stress, such as The Florida State University (FSU) analysis (Goldenberg and O'Brien 1981) prior to starting the forecasts. Examples of coupled models using this initialization method are Zebiak and Cane (1987), Latif et al. (1993), Barnett et al. (1993), and Balmaseda et al. (1994). These models in general do not outperform persistence of SST anomalies during the first one to two seasons of the forecasts (Latif et al. 1993, 1994), suggesting that errors in the wind stress may limit accuracy of ocean initializations.

The climate forecast model of Ji et al. (1994) consists of a coupled atmospheric general circulation model (AGCM) and an ocean general circulation model (OGCM). This model uses an anomaly-coupling scheme for the surface stress field, which is produced from the AGCM to force the OGCM. In this scheme, surface stress anomalies produced from the AGCM are combined with the climatological stress field of Helleman and Rosenstei (1983, HR hereafter) to form a total stress forcing field for the OGCM. The advantage of using anomaly coupling is that it reduces the possible climate drift of the coupled model. The ocean initial conditions used for this coupled model is from the Pacific Ocean analyses. Hindcast results for the period 1984–1993 have shown that this model yields forecast skill comparable to, or higher than, persistence even during the first one to two seasons of the forecasts (Ji et al. 1994). This suggests that ocean data assimilation can improve ocean initialization, possibly by compensating for errors in the wind stress forcing and model physics.

The motivations for this study are threefold. First, we wish to compare the monthly mean ocean fields produced using ocean data assimilation (RA3) with a model simulation (HFSU) in which no data are assimilated. Both integrations used the FSU surface stress anomalies. Both the RA3 and the HFSU ocean fields have been used to provide ocean initial conditions for the NMC coupled climate forecast model. The FSU wind forcing has also been used to initialize many other coupled models without assimilating observed data. Such comparison reveals differences in ocean initial conditions that could have implications for coupled model forecasts. Knowledge gained from such a comparison could facilitate future studies on the impact of data assimilation to climate predictions. The second motivation is to evaluate ocean model response when forced with wind stress anomalies obtained from an AGCM simulation. The AGCM is the same model used by the NMC coupled model. By comparing ocean model responses to the AGCM stress anomaly forcing and a better-known stress anomaly forcing field from the FSU analysis, we hope to gain some insight on the error characteristics of the AGCM stress anomalies. This could potentially help us to improve both the AGCM and the coupled model. Third, by comparing two ocean analyses, that is, RA2 and RA3, which were produced with assimilation of observed data but used different wind stress forcing, we can examine the impact of wind stress quality on the ocean analysis when data assimilation is used.

In section 2 the data, analyses, and ocean simulations are described. In section 3, intercomparisons of simulations with analyses and in situ observations are presented. Discussions are given in section 4. Section 5 summarizes our findings.

2. Data, analyses, and simulations

The ocean model was developed at the Geophysical Fluid Dynamics Laboratory (GFDL) by Bryan (1969) and Cox (1984) and subsequently improved by Philander et al. (1987). It is a Pacific Basin model covering a domain from 45°S to 55°N and 120°E to 70°W. The model has 28 vertical levels and a zonal resolution of 1.5°. Its meridional resolution is 1/3° in the Tropics within 10° of the equator and reduces gradually outside of the equatorial region to 1° poleward of 20° latitude.

The wind field used in RA3 and HFSU is a hybrid field obtained by combining the wind field anomalies from the FSU analyses with the HR climatology reduced by a factor of 0.9 because our past experience with the GFDL OGCM indicates that this reduction of the HR climatology better simulates the annual cycle. A constant drag coefficient of 1.3 × 10^{-3} was used to convert a FSU pseudostress anomaly into a stress anomaly. The wind field used in HCMP is a similar hybrid forcing field, except that the wind stress anomalies are obtained from an ensemble average of two AGCM simulations forced with observed monthly SST for the period 1982–93. The wind field used in RA2 is similar to the hybrid forcing field used in the HCMP. It was obtained by combining the climatological wind stress of Harrison (1989) increased by a factor of 1.1, with the stress anomalies obtained from the two-member ensemble of the AGCM simulations. These AGCM simulations are similar to those carried out under the atmospheric model intercomparison project (AMIP) (Gates 1992) but for a different time period. The AGCM is a climate version of the NMC's Medium
### Table 1. List of ocean simulations and analyses, and their respective forcing and initial conditions.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Stress</th>
<th>Heat flux</th>
<th>Initial conditions</th>
<th>Data assimilation</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFSU</td>
<td>0.9HR + FSUA</td>
<td>OCL</td>
<td>11</td>
<td>No</td>
<td>Feb 82–Dec 93</td>
</tr>
<tr>
<td>RA3</td>
<td>0.9HR + FSUA</td>
<td>None</td>
<td>11</td>
<td>Yes</td>
<td>Feb 82–Dec 93</td>
</tr>
<tr>
<td>HCMP</td>
<td>0.9HR + AMIP</td>
<td>OCL + NC</td>
<td>11</td>
<td>No</td>
<td>Feb 82–Oct 93</td>
</tr>
<tr>
<td>RA2</td>
<td>1.1HCL + AMIP</td>
<td>OCL</td>
<td>12</td>
<td>Yes</td>
<td>Jul 82–Jun 93</td>
</tr>
<tr>
<td>WA2</td>
<td>NMC</td>
<td>None</td>
<td>13</td>
<td>Yes</td>
<td>Jan 91–Jun 93</td>
</tr>
</tbody>
</table>


11: The HFSU simulation started on 1 February 1961, but only the period February 1982–December 1993 is considered in this paper. The RA3 analysis and the HCMP simulation started from the 1 February 1982 initial condition obtained from the HFSU integration. The first five months from the HCMP simulation were discarded to avoid possible spinup effects due to change of stress anomaly forcing.

12: The initial condition for the RA2 analysis was obtained from an analyzed January ocean field, which was then spun up for one year using 1.1HCL wind stress and OCL + NC heat flux forcing. Therefore, the initial state does not really correspond to 1 February 1982, but the wind and the temperature data used at the start of the RA2 analysis do. The first five months from the RA2 analysis were discarded in order to account for a model spin up to 1982 conditions.

13: The WA2 analysis started in July 1989, but only the period January 1991–June 1993 are used for this paper.

**Range Forecast (MRF) Model (Kanamitsu 1989), with a spectral resolution of T40 and 18 vertical levels. Modifications to the MRF’s physical parameterizations such as convection, cloudiness, and vertical diffusion improved the model’s precipitation climatology and the robustness of the model’s midlatitude response to the tropical SST anomalies (Ji et al. 1994). In this paper, we will refer to this climate T40 MRF model as CMP model, and the stress anomalies obtained from the AMIP-type simulations using the CMP model are referred to as AMIP stress anomaly.**

The stress climatology from the AMIP-type simulations is poor and is not suitable for forcing ocean models (Ji et al. 1995). An additional reason for using hybrid wind stress forcing fields is that the NMC coupled model uses a combination of the HR climatological stress and stress anomalies from an almost identical version of the CMP model. Thus, assuming there is no climate drift for the coupled model, the HCMP simulation mimics conditions during the coupled model integration. This can help to show the impact of stress errors of the CMP model on coupled forecast results.

The surface heat flux used in both simulations is the climatological heat flux estimated by Oberhuber (1988). However, ocean simulations using the climatological heat flux alone without further constraint to the SST often leads to excessive heating or cooling of SST during extended integrations (Stockdale et al. 1993). We constrain the SST to its climatology using Newtonian cooling in the ocean model through a heat flux correction $Q$ based on the difference between the model SST and the observed climatological SST during the model integrations that takes the form

$$Q = -rac{d	heta}{dT} (T_c - T),$$

where $T$ is the model SST and $T_c$ is the climatological SST. The quantity $d	heta/dT$ is the Newtonian cooling coefficient estimate of Oberhuber (1988). In this paper, we focus attention on thermocline structure and upper-ocean heat content variabilities.

In addition, weekly mean real-time ocean analyses (denoted WA2) averaged for months from 1991 to 1993 are also used for some comparisons. The WA2 analyses are produced from the ocean data assimilation system at NMC using surface winds analyzed by the NMC’s operational MRF model. Since operational atmospheric models assimilate real-time observed surface winds from ships and some TOGA–TAO buoys (McPhaden 1993), surface winds from these analyses are potentially better wind products. Comparison of real-time ocean analyses with observations and analyses of RA2 and RA3 could also yield some insight on the quality of surface wind fields from the MRF model.

The simulations and analyses, initial conditions, forcing fields used, and use of data assimilation are summarized in Table 1.

**3. Intercomparison of simulations, analyses, and in situ observations**

The most straightforward estimation of model simulation errors is made by comparing the model results directly against in situ observations. Subsurface ocean temperature records lasting for longer than a few years are available at only three locations (165°E, 140°W, and 110°W) on the equator in the Pacific. Continuous sea level records from the mid-1970s are available at a
number of island tide gauge stations throughout the Pacific Basin.

Model simulation results are also compared against the ocean analyses, that is, RA2, RA3, and WA2, which give an optimal estimate of oceanic thermal conditions in consistent temporally and spatially continuous datasets. Although model and forcing errors inevitably affect the quality of the analyses, assimilation of observed data into model fields improves analyses when the same wind is used for both simulation and data assimilation. This will be demonstrated later in this section.

a. Thermocline depth

Shown in Fig. 1 are comparisons of the depth of the 20°C isotherm (\(H_{20}\) hereafter) in the Pacific at 165°E, 140°W, and 110°W on the equator for the HFSU simulation, the RA3 analysis, and the mooring records. As the 20°C isotherm lies in the middle of the thermocline, it is often used as a measure of the thermocline depth. The root-mean-square (rms) differences between the RA3 analysis and the moorings are 5.7 m at 165°E, 6.9 m at 140°W, and 5.2 m at 110°W, showing that the analysis and the mooring records are in good agreement. This is not surprising because these mooring data are assimilated into the analyses. The HFSU simulation captured variations similar to the observations at all three mooring sites. However, noticeable errors in amplitude and phase exist for the thermocline depth variations produced from the HFSU simulation (rms of 13.3, 16.0, and 20.0 m, respectively). On the other hand, errors for the mean \(H_{20}\) simulated by the model are relatively low; for example, the mean thermocline depth differences (bias) between the HFSU simulation and the above moorings are 6.4, 7.4, and 6.4 m, respectively.

Shown in Fig. 2 are comparisons of anomalous \(H_{20}\) at the same three equatorial sites for the HFSU simulation, the HCMP simulation, and the RA3 analysis. The mean and annual cycle of each simulation and of the RA3 analysis for the same 11-yr period are computed and removed individually. For both simulations, the variability of the \(H_{20}\) anomaly in the western Pacific (165°E) is noticeably weaker than for the RA3 analy-
sis. In the eastern Pacific (110°W), the HCMP simulation significantly underestimated the 1986/87 warm event and the 1988/89 cold event and basically missed the 1991/92 warm event. The rms differences in anomalous $H_{20}$ between the HFSU simulation and the RA3 analysis at the above mooring stations are 11.9, 13.8, and 17.8 m, respectively; for comparison, the rms differences between the HCMP simulation and the RA3 analysis are 12.0, 17.5, and 21.6 m, respectively. In the above comparison, the RA3 analysis is used as a qualitative reference to compare low-frequency interannual variability of the equatorial thermocline with the HFSU and the HCMP simulations. This is reasonable because mooring data are assimilated into the analysis at all three mooring sites, and the RA3 and the moorings are in very good agreement, as can be seen in Fig. 1.

Time evolution of the $H_{20}$ anomaly along the equator is shown in Fig. 3 in Hovmöller diagrams for the HCMP (left), the HFSU (middle), and the RA3 (right) for 1982 to 1993. In the eastern Pacific, both the RA3 analysis and the HFSU simulation produced comparable interannual anomalous thermocline depth variability, albeit with some differences in timing. On the other hand, the HCMP simulation produced weak amplitudes for the 1982/83 warm event and the 1988/89 cold event and almost no anomaly at all for the 1986/87 and the 1991/92 warm ENSO events. To the west of approximately 150°W, the thermocline anomalies for both the HCMP and the HFSU simulations are much smaller than those in the RA3 analysis.

These comparisons suggest that the FSU wind stress anomaly is a better product than the AMIP wind stress anomaly when used to force the ocean model to simulate interannual thermocline variability, a result that will be further supported by comparisons with sea level anomaly records later in this section.

To examine the differences in thermocline structures between the HFSU simulation and the RA3 analysis, we show in Fig. 4 the 11-yr mean $H_{20}$ fields for the HFSU simulation (upper), the RA3 analysis (middle), and the difference field (lower). Comparison of the 11-yr mean $H_{20}$ fields show that the thermocline ridge near 10°N simulated from the HFSU experiment is about 20 m deeper than that from the RA3 analysis; the gyre in the southern tropical Pacific near 15°S simulated from the HFSU experiment is almost 40 m shallower than that from the RA3 analysis. The lower panel of the Fig. 4 shows that the differences in the mean $H_{20}$ field are largest in the vicinity of the North Equatorial Counter Current (NECC) trough near 10°N and in the gyre in the southern tropical Pacific. In the equatorial region, the difference is relatively small, consistent with Fig.

![Fig. 3. Anomalous depth of 20°C isotherms along the equator for the HCMP simulation (left), the HFSU simulation (middle), and the RA3 ocean analysis (right). Contour interval is 10 m. Dark shading is for anomalies greater than 20 m, light shading is for anomalies below -20 m.](image-url)
b. Sea level variability

An alternative measurement of oceanic interannual variability is sea level variability, which is directly related to upper-ocean heat content variations and inversely related to the large-scale thermocline depth variations on interannual timescales. Island tide gauges are located in the western, central, and eastern Pacific. Relatively long-term sea level records are available both near the equator and at off-equatorial island stations, providing independent verification for the analyses and simulations.

Shown in Fig. 5 are comparisons of sea level anomalies for the RA3 analysis and the HFSU and HCMP simulations with the tide gauge sea level records at Santa Cruz (1°S, 90°W), Christmas (2°N, 157°W), Honolulu (21°N, 158°W), and Funafuti (8.5°S, 179°E). For the simulations and the analyses, sea level

Fig. 4. The 11-yr mean $H_{20}$ (m) field for the HFSU simulation (upper), the RA3 analysis (middle), and the difference field (lower). For the difference field, areas where the $H_{20}$ difference is greater than 20 m are in dark shading, areas where the $H_{20}$ difference is lower than -40 m are in light shading; for the mean fields, areas where $H_{20}$ is between 100 and 140 m are in light shading, areas where the $H_{20}$ is greater than 240 m are in dark shading.

1. Since the HFSU simulation and the RA3 analysis used the same stress-forcing field, the difference in the mean $H_{20}$ field represents the effect of data assimilation on the ocean analysis. If we believe the RA3 analysis is closer to reality because of the large amount of subsurface data assimilated into it, the above comparison suggests the curl of the climatological stress used in the HFSU simulation, that is, the HR climatology, is too weak.

A possible implication of this mean thermocline depth difference for climate forecasting is that it leads to errors in the ocean initial conditions used for the NMC coupled model since the HR climatology is used as the mean wind stress forcing in this model. Consequently, the model's mean thermocline climatology may be closer to the HFSU simulation than to the RA3 analysis. When RA3 analyses are used as ocean initial conditions for the NMC coupled model, potential imbalances between the model and the initial condition's thermal field may result. We will study the impact of such a potential imbalance to coupled model forecasts in a future paper.

Fig. 5. Sea level anomalies from the island tide gauges (heavy), the RA3 analysis (light), the HFSU simulation (light dash), and the HCMP simulation (heavy dash) for the 11-yr analysis period of July 1982–June 1993. The island stations are at Santa Cruz (1°S, 90°W), Christmas (2°N, 157°W), Honolulu (21°N, 158°W), and Funafuti (8.5°S, 179°E). The units are in 0.01 m. The rms errors indicated in the figure are computed against the island tide gauge records.
is derived from the surface pressure anomalies of the ocean model on its rigid lid. At Christmas Island in the central Pacific, both the HFSU and the HCMP simulations produced a reasonably good interannual sea level response, although the sea level response from the HCMP simulation appears to have somewhat lower amplitude. In the eastern equatorial Pacific (Santa Cruz), the sea level anomaly is well reproduced in the HFSU simulation in contrast to the HCMP simulation that shows almost no interannual variability. Off the equator, the low-frequency interannual sea level variations were reproduced by both the HFSU and HCMP simulations reasonably well at Honolulu, however, both failed to capture an anomalously low sea level signal observed in late 1983. At Funafuti in the tropical South Pacific, the HFSU reproduced much better anomalous sea level variability than HCMP, indicating problems of AMIP stress anomalies in this region. The quality of the HFSU simulated sea level anomalies is comparable to the RA3 analysis results at most locations throughout the basin as can be seen from the error statistics given on Fig. 5. These results are qualitatively consistent with comparisons of thermocline depth anomalies presented earlier.

In Fig. 6, sea level anomalies at the equatorial island stations of Kapingamarangi (1°N, 155°E) and Santa Cruz (1°S, 90°W) and at the off-equatorial island stations of Johnston (17°N, 169.5°W) and Funafuti (8.5°S, 179°E) are shown. The sea level anomalies are from the HFSU simulation (thin dash), the RA3 analysis (light), the tide gauge records (heavy), and the real-time ocean analysis WA2 (heavy dash) for the period of January 1991 to June 1993. The annual cycle for this 2.5-yr period was computed and removed from the model and the tide gauge data. Since real-time surface wind observations from ships and some of the TAO buoys are assimilated into the operational wind analysis, the real-time ocean analysis using the operational winds potentially could be better than the RA3 analysis. Indeed, the rms errors relative to the tide gauges for the real time analysis (WA2) at these island stations are generally lower than for either the RA3 analysis or the HFSU simulations, as indicated in the figure.

c. Impact of data assimilation

From the previous intercomparisons of thermocline depth and sea level anomalies, it is evident that the AMIP stress anomaly is poor, and the FSU stress anomaly is a better forcing field. An interesting question is how much impact ocean data assimilation could have in compensating for wind stress errors. Comparison of the RA2 analysis and the HCMP simulation against tide gauge sea level records gives some evidence on how much ocean data assimilation can do to improve ocean analysis given a poor wind-forcing (AMIP) field. Although the climatological stress-forcing fields used in RA2 and HCMP are not identical, by comparing sea level anomalies with the observations, we can still examine the impact of data assimilation because both RA2 and HCMP used the same stress anomalies. Comparisons are shown in Fig. 7 for the island stations of Santa Cruz, Christmas, Honolulu, and Funafuti. Improvements to the ocean analysis due to assimilation of thermal data are obvious. In the eastern Pacific (Santa Cruz), the missing anomalous sea level responses for the HCMP simulation for the 1982/83 and 1991/92 ENSO events are clearly shown by the RA2 analysis. The rms errors for RA2 at all these island stations are lower than for the HCMP simulation. However, when a better wind stress forcing (FSU) was used, data assimilation still improved the quality of the ocean analysis. This can be seen in Fig. 5 by comparing the HFSU simulation and the RA3 analysis. We found that rms
sea level anomaly errors for the RA3 analysis are in general lower than those for the HFSU simulation. These comparisons show the magnitude of the improvement due to data assimilation in an analysis on the interannual timescale.

Shown in Fig. 8 are sea level anomaly comparisons at the same four island stations for RA2, RA3, and tide gauge records. For these comparisons, the possible impact of different climatological stress forcing is minimized because the respective annual cycles for RA2 and RA3 are removed. In general, we found that RA3 anomalies exhibit lower errors than RA2 anomalies when compared to the tide gauge data. This shows that a better quality wind forcing can still improve the quality of the ocean analysis in the presence of the same data assimilation, implying that by themselves the data are insufficient to determine the ocean state.

4. Discussions

Comparing the FSU simulation and RA3 analysis, we found that the most significant difference between them is in the mean field. The largest amplitudes of the mean thermocline depth $H_{10}$ difference are found off the equator in the gyre in the southern tropical Pacific and in the NECC trough region near 10°N. The dominant off-equatorial feature of this mean thermocline depth difference suggests that the curl field of the mean climatological wind stress associated with the trade winds is too weak. Since the same forcing field is used for both the RA3 analysis and the HFSU simulation, but a large number of observed subsurface temperature data are assimilated into the analysis, we believe that the analysis is closer to reality than the model simulation results. If the source of error is wind induced, then the above result implies that the error is in the mean field, that is, in the HR climatology rather than in the anomaly fields. However, it is difficult at this point to separate model errors from wind stress errors.

On interannual timescales, sea level variations from the HFSU simulation show a surprisingly good agreement with the tide gauge measurements throughout the equatorial Pacific. Sea level anomaly variations are also captured well by the HCMP simulation in the western

FIG. 7. Same as in Fig. 5 except for the island tide gauges (heavy), the RA2 analysis (light), and the HCMP simulation (heavy dash).

FIG. 8. Same as in Fig. 5 except for the island tide gauges (heavy), the RA2 analysis (light), and the RA3 analysis (heavy dash).
Pacific and, to some extent, in the central Pacific near Christmas Island (157°W). Further east, however, the HCMP simulation failed to show the ENSO-related interannual variation in tropical Pacific sea level. The failure in the HCMP simulation to produce ENSO-related oceanic responses in the eastern equatorial Pacific indicates that significant errors in the AMIP stress anomalies may have prevented Kelvin wave–like ENSO signals from propagating all the way through the equatorial Pacific basin to the eastern boundary. Analysis of the FSU and the AMIP wind stress anomalies supports this hypothesis. Shown in Fig. 9 is the leading empirical orthogonal function obtained using singular-value decomposition (SVD) for the zonal stress anomaly of the FSU (top panel) and the AMIP (middle panel). Their corresponding time series are depicted in the lower panel. The spatial patterns of the zonal stress anomalies show great similarities throughout the basin, especially in the western and central Pacific. However, on the equator a stronger westerly zonal stress anomaly is found for the FSU wind in the western Pacific, and a much stronger easterly stress anomaly is found in the AMIP winds in the eastern Pacific.

Shown in Fig. 10 are difference fields (warm–cold) of 3-month mean (December–February) zonal stress anomaly for 1991/92 and 1988/89. This essentially represents a typical zonal stress anomaly pattern with double amplitude during the onset of an ENSO winter because the former is a warm event and the later is a cold event. Zonal stress differences for the FSU anomalies are shown in the upper panel and for the AMIP anomalies in the lower panel. On the equator the FSU winds show a strong westerly anomaly in the western to central Pacific with maximum strength of 0.09 N m\(^{-2}\), while in the eastern Pacific the zonal stress anomaly is easterly but considerably weaker (about 0.02 N m\(^{-2}\)). For the AMIP wind, the westerly zonal stress anomaly in the western to central Pacific is significantly weaker than the FSU wind on the equator (less than 0.06 N m\(^{-2}\)) and in the eastern Pacific, the easterly zonal stress anomaly is stronger than the FSU anomaly. Assuming a linear oceanic response, the sea level response to the anomalous wind stress forcing in the equatorial Pacific is proportional to the zonal integral of the zonal stress anomaly. From Figs. 9 and 10, it is clear that the zonal integral in the equatorial Pacific for the AMIP stress anomaly would be significantly weaker than for the FSU stress anomaly. The lack of anomalous sea level response from the HCMP simulation seems to be the result of this improper balance of the east–west zonal stress anomaly. The impact of this type of stress anomaly error may be significant for the NMC coupled model. Ji et al. (1994) found that the NMC coupled forecast model has lower forecast skill in the eastern equatorial Pacific than in the central Pacific. The zonally integrated zonal stress anomaly error demonstrated by the wind anomalies from the CMP model may be one reason for low skill in that region. This hypothesis will be considered carefully in a future study.
The HCMP simulation and the RA2 analysis used the same stress anomaly forcing, which was found to be a rather poor one in this study. The HFSU simulation and the RA3 analysis also used the same stress anomaly forcing, which was found to be of higher quality. Comparisons of sea level anomalies derived from these two pairs of ocean model integrations against tide gauge sea level records show that ocean model responses on the interannual timescales are improved significantly when observed subsurface thermal data are assimilated into the ocean model. This indicates the worthiness of ocean data assimilation to improve ocean analyses by compensating for wind stress and model errors. Additionally, intercomparisons of sea level anomalies obtained from RA2, RA3, and the tide gauge data show further improvement in analysis quality when a better stress forcing (FSU) is used. This is despite the fact that the same data assimilation system and the same subsurface data were used for both the RA2 and RA3. This indicates that the presently available data assimilation cannot completely overcome errors in the winds and the ocean model in this ocean analysis system, and therefore improvement of surface winds should be given a high priority.

Our study suggests that the surface wind analysis from the operational atmospheric model may be a better product, probably because surface wind observations available in real time are assimilated into the atmospheric analysis. Busalacchi (1993) combined observed surface winds from the TAO array with the same winds used for the HCMP simulation in this study and found that significant improvements are achieved in ocean model responses using the combined winds as opposed to using the AGCM winds alone.

5. Summary

In this study, we used two different surface wind anomalies, the FSU and the AMIP stress anomaly, to form hybrid wind stress forcing fields by combining them with the Hellerman and Rosenstein stress climatology. Two 11-yr ocean simulations were carried out by forcing an OGCM with these hybrid wind stress forcing. The two simulation results were compared with two 11-yr Pacific Ocean analyses, produced using similar hybrid stress forcing fields as well as in situ observations from moorings and island tide gauges.

The objectives were to compare ocean initial conditions obtained by ocean data assimilation and by OGCM simulations forced by winds only to evaluate errors in the AMIP stress anomaly and to study the impact of ocean data assimilation on the quality of ocean analyses. These comparisons have implications for coupled model forecasts at NMC. Our findings are the following.

1) The largest difference between model simulation results and ocean analyses is found in the mean off-equatorial thermocline structure, suggesting errors in the curl of the climatological stress field. This shows that the mean thermal structure of ocean initial conditions, produced with and without ocean data assimilation, are different. This may result in an imbalance between ocean initial conditions and the equilibrium state of the NMC coupled model.

2) The AMIP stress anomaly simulated using the CMP atmospheric model is unable to generate interannual timescale anomalous sea level responses from the OGCM in the eastern Pacific. This indicates errors in the CMP model that may have a significant impact on the NMC coupled model.

3) Assimilation of subsurface thermal data improves ocean analyses significantly by compensating for wind stress and model errors. However, better wind stress still gives a better analysis, suggesting that high quality of wind stress cannot be substituted for by ocean data assimilation.

Acknowledgments. We would like to thank Dr. Ants Leetmaa for numerous valuable discussions that greatly helped this research. Suggestions from Drs. David Behringer, John Derber, and Michael McPhaden and two anonymous reviewers helped to improve an earlier version of this paper greatly. Particular thanks to Dr. David Anderson for his invaluable suggestions that improved this manuscript greatly. Sea level records from island tide gauges were obtained from the TCGO sea level center at University of Hawaii; temperature data from the equatorial moorings were obtained from NOAA/PMEL; the FSU wind anomalies were obtained from the Florida State University. Support for this research is provided by NOAA's Office of Global Program through the Climate and Global Change Program.

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