The Coupled Ocean–Atmosphere Modeling Problem in the Tropical Pacific and Asian Monsoon Regions

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ABSTRACT

Two ocean formulations, one a simple, 50-m slab ocean and another a coarse-resolution global ocean general circulation model (GCM), are coupled to a global atmospheric GCM. To determine what part of the simulation error is introduced by the atmospheric model and what part arises from limitations of the ocean formulation, results are compared to observations as well as to integrations involving the ocean GCM run with observed atmospheric forcing and the atmospheric GCM run with specified observed sea surface temperatures (SSTs). The tropical Indian and Pacific regions are studied because of the associations involving the dynamically coupled ocean–atmosphere system in those regions related to large-scale tropical and global interannual variability. Analysis of the net surface heat flux leads to the conclusion that limitations in the ocean formulations contribute more to errors in the coupled climate simulations than inherent deficiencies in the atmospheric model. In spite of the limitations of the ocean formulations in simulating SST, the atmospheric model simulates most major features associated with the low-level wind fields in the tropical Indian and Pacific regions with differences consistent with the SSTs supplied by the ocean models. The implication is that increased quality of the ocean simulation will result in substantial improvements of the coupled climate model simulations even without upgrades to the atmospheric model. The point is raised that a coupled model with surface fluxes computed interactively produces a more internally consistent climate simulation than could be expected from the same atmospheric model forced with observed SSTs, even if the SSTs computed by the coupled model do not exactly match the observed values. Surface fluxes, then, are not "absolute" values and must be interpreted as compensatory products of the limitations (and strengths) of the respective media in simulating SST patterns. Thus, even the present generation of imperfect coupled models can provide insight into some of the processes, mechanisms, and sensitivities of the coupled climate system that no other research tool can.

1. Introduction

Atmospheric general circulation models (GCMs) coupled to interactive ocean formulations have emerged as potentially powerful tools to study climate variations and climatic change. The already difficult problem of simulating climate with prescribed ocean temperatures and sea ice (the conventional method of climate simulation using only an atmospheric GCM) becomes even more complicated when a mutually interactive ocean model of some type is included, in that limitations or errors in one medium can affect the other. For example, Meehl and Washington (1985) note that inherent limitations of a simple, 50-m slab ocean coupled to a global, spectral atmospheric GCM produced higher-than-observed sea surface temperature (SSTs) across the global tropics and warm anomalies of up to 6°C in the tropical eastern Pacific. They attributed the anomalies in the Pacific, in part, to lack of upwelling in the simple slab-ocean model, and they documented resulting adjustments in the surface-energy balance in the coupled atmosphere and slab-ocean model.

An analysis of a coupled model must take into account what part of the simulation error is produced by the atmospheric model and what part arises from limitations in the ocean formulation. One purpose of this paper is to report on such analyses of climate simulations produced by a global atmospheric GCM, first run with specified observed SSTs and sea ice, then coupled to a simple 50-m slab, mixed-layer ocean, and finally coupled to a coarse-grid ocean GCM. A second purpose is to determine which components of the coupled models most need improvement. Is the ocean model or the atmospheric model responsible for most of the coupled climate simulation errors? Such an assessment will indicate where model improvement is needed and where the greatest benefits can be realized most quickly.

The tropical Indian and Pacific regions, the geographical areas studied in this paper, play a critical role in the interannual variability of the dynamically coupled ocean–atmosphere system associated with the

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Southern Oscillation (e.g., Trenberth 1981; van Loon and Shea 1985, 1987; Meehl 1987). These regions could also be important in climate-change scenarios (e.g., Meehl and Washington 1986). Accurate simulation of the coupled climate system is of interest in the study of interannual variability of the Asian monsoon systems, since large-scale teleconnections have links to ocean and atmospheric features there (e.g., van Loon and Madden 1981; Blackmon et al. 1983; Meehl 1988; Meehl and Albrecht 1988 and many more). Recently, even more attention has been focused on this region through coupled ocean–atmosphere models involving the tropical Pacific (e.g., Philander et al. 1984; Zebiak and Cane 1987; Battisti 1988, etc.). It is essential to understand the workings of the simulated coupled climate system in this region in order to interpret results from regional and global models.

Section 2 provides details of the models, the simulations, and the observed data sources. Section 3 documents features of the ocean model simulations. Section 4 explores the consequences of the limitations of the ocean formulations on the atmospheric circulation in the Indian and Pacific regions. In section 5, the annual cycle of low-level winds in the various model simulations is examined in terms of the limitations of the respective atmosphere and ocean models. A summary and conclusions follow in section 6.

2. Models, simulations, and observed data

The atmospheric model used in all the simulations is a variant of the National Center for Atmospheric Research (NCAR) community climate model (CCM) with an annual cycle of solar forcing, computed soil moisture, snow cover, cloudiness, and radiation. The CCM is a global spectral GCM with realistic geography, nine layers in the vertical, and rhomboidal 15 truncation which yields a resolution of approximately 4.5° latitude by 7.5° longitude.

The atmospheric model is run with three ocean formulations. The first is the specified annual cycle of global SSTs and sea ice from Alexander and Mobley (1976). This model configuration is called SPEC SST. Results are shown for averages of the last three years of a five-year integration. The second type of ocean surface is a 50-m deep slab ocean with a computed thermodynamic sea-ice model. The model run in this configuration is called MIX1 (for single mixed layer). Averages are computed for the last three years of the 11 years of model integration with a 365-day solar cycle. This period was preceded by model spinup intervals of accelerated solar cycles described more fully by Washington and Meehl (1984). The main limitation of this ocean formulation is that ocean dynamics (including upwelling) are not included. Basic features of this coupled model are shown by Washington and Meehl (1984) and Meehl and Washington (1985). The third type of ocean is a coarse-grid (5° latitude by 5° longitude, four layers in the vertical) global ocean GCM with a thermodynamic sea-ice formulation. This model configuration is referred to as COUPLED. The ocean was first run with observed atmospheric forcing for 50 years [here called DOC for decoupled ocean and generally described by Meehl et al. (1982)]. Then the atmosphere from the slab-ocean case was coupled to the ocean model and run in a series of shakedown tests for 16 model years. Finally, the coupled model was integrated for 30 years and averages were taken from the last five years of the experiment. General characteristics and sensitivities of this coupled model are shown by Washington and Meehl (1989). The ocean GCM includes ocean dynamics and thermohaline processes. One of the main limitations of this ocean model is that the coarse grid requires relatively high horizontal heat diffusion which contributes to tropical SSTs that are too low and high latitude SSTs that are too high (Meehl et al. 1982). In addition, equatorial upwelling is active in the model, and the coarse vertical resolution in the upper ocean (50-m top layer, 450-m second layer) contributes to the tropical SSTs being too low. That is, when Ekman divergence in the upper ocean layer occurs in conjunction with easterly wind stress, the cold water from the 450-m thick second layer is brought to the surface. This coarse vertical resolution necessarily neglects more subtle mixed-layer dynamics taking place in the real ocean which would act to confine upwelling to a more restricted vertical extent with relatively warmer water.

Washington and Meehl (1989) document the general features of the coupled model and note a climate drift of about 0.01°C yr⁻¹ in tropical SST. This drift, as well as a secular drift in the MIX1 case noted by Washington and Meehl (1984), is considered of sufficiently small amplitude so as not to greatly affect the year-to-year patterns of simulated climate considered here.

Statistical significance of differences between the model runs is not calculated because of the small sample size of model data. For low-level winds, standard deviations for winds are about 2–4 m s⁻¹. Standard deviations of SSTs from the slab ocean model are shown by Meehl and Washington (1985). The variability of the CCM run with observed SSTs has been described by Malone et al. (1984) for a number of time and space scales. Standard deviations of low-pass-filtered-model data from a version of the CCM run with observed SSTs (Meehl and Albrecht 1988) are comparable to those from the present model version. Differences between model and observed winds are not computed because the model levels are not exactly the same as the observed data levels. Observed surface winds (1,000 hPa) are compared qualitatively to winds from the lowest model level (σ = 0.99)1. Although the levels are not exactly the same, the winds from the lowest σ-level are used by the model as surface winds for the surface flux and surface wind stress calculations.
and, in effect, should be compared to the observed surface winds.

The observed atmospheric wind data in this study are derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses and have been interpolated to the CCM grid by Trenberth and Olson (1988). Coverage runs from 1979–1986, and long-term monthly and seasonal means are computed for that period. Long-term monthly mean precipitation is from Jaeger (1976). Surface heat-flux data are from Esbensen and Kushnir (1981).

3. Ocean simulation features

References mentioned previously suggest that many simulation errors of SSTs can be ascribed to limitations of the ocean formulations. Figure 1 shows SSTs for the Indian and Pacific sectors for the two coupled models (MIX1 and COUPLED) compared to observed values. As noted in previous studies, the MIX1 case simulates SSTs in the tropics that are higher than observed, while the COUPLED case produces SSTs that are lower than observed. The earlier studies postulated that the lack of ocean upwelling in MIX1 contributes greatly to the high SSTs and that the strong upwelling and coarse horizontal and vertical resolution in the COUPLED case bring about the lower-than-observed SSTs. Because the SSTs produced by the coupled models greatly influence the associated atmospheric circulation, however, it is of interest to ascertain in more detail what part of the SST errors can be ascribed to flaws in the ocean formulations. One method is to look at the net surface heat flux over the ocean. The net surface heat flux equation can be written

\[ S_A + F_1 + F^+ - \eta - L\beta = F_{net}, \]

where the net surface heat flux \((F_{net})\) is determined by absorbed solar flux at the surface \((S_A)\), \(F_1\) is downward
infrared flux, $F^4$ is upward infrared flux, and $\eta$ and $L\beta$ are sensible and latent heat fluxes, respectively. Meehl and Washington (1985) showed zonal mean surface energy balance components and net surface heat flux for the MIX1 case. The altered flux components partially compensated for the lack of poleward ocean heat transport in the slab ocean, but lack of upwelling in the tropics maintained warmer-than-observed SSTs there and altered the heat flux at the surface accordingly. In particular, their modeled net heat flux in the tropics evolved from positive to negative with the seasonal cycle and did not remain positive (net heat flux into the ocean) year-round as in the observations (see their Fig. 9). The analysis showed that inherent limitations of the simple slab ocean could not be totally compensated for by the atmospheric model, and the result was an SST distribution that reflected those limitations (Fig. 1).

To assess errors from the ocean GCM coupled to the atmospheric GCM, net surface heat-flux values for the COUPLED case are compared with those generated by the ocean run by itself with observed atmospheric forcing (DOC) and the atmosphere run by itself with observed SSTs (SPEC SST) (Figs. 2 and 3). Even though net surface heat flux in these regions is poorly observed and there are problems with interpreting heat flux values from models with either atmospheric or ocean forcing specified (discussed below), such a comparison should provide qualitative insight into the relative errors being introduced to the coupled model simulation from the respective component parts.

In Fig. 2, observed values from January are shown with January net heat flux from the DOC case (see Meehl et al. 1982, for details), January values from SPEC SST, and December–January–February (DJF) values from COUPLED. It is likely that the observed estimates over this region are accurate only to within about 10% to 20% (Esbensen and Kushnir 1981). Because surface air temperature with a Haney-type forcing constant was used in the DOC case to drive the ocean
Fig. 2. Net heat flux at the surface (W m⁻²; heat flux into the ocean is positive, negative values are dashed) for January: (a) observed (Esbensen and Kushnir 1981), (b) DOC (ocean model run with observed wind stress and surface air temperature forcing), (c) SPEC SST; (d) DJF values for COUPLED.

(Meehl et al. 1982), the quantity called heat flux here is actually a measure of where corrections are made to the ocean to force it to the observed temperature distribution. In Fig. 2b, the heat-flux correction term is large and positive (corrections applied to raise the SST) over the tropical oceans in this region, indicative of the ocean model's inherent tendency to produce SSTs that are too low there. Elsewhere, the heat flux is negative in the winter hemisphere and positive in the summer hemisphere following the annual cycle.

The surface heat flux produced by the SPEC SST (Fig. 2c) is indicative of areas of probable errors in the atmospheric model. This quantity also includes the corrections provided to the atmosphere from the
oceans' specified SSTs to drive it toward the observed state. Errors in the atmospheric model are indicated in the equatorial eastern Pacific, where the relative maximum in downward heat flux from the observed values is about 50% less in the SPEC SST case. A poorly simulated South Pacific Convergence Zone (SPCZ, as shown for SPEC SST below in Figs. 4 and 5) is associated with fewer clouds, greater incoming solar radiation, and greater downward heat-flux values in the southwest Pacific. Relatively smaller positive and larger negative net heat-flux values in the northern Indian Ocean in SPEC SST do not compare well with the observed values in that area. Elsewhere, the general pattern and magnitude are reproduced with negative values (upward heat flux from the surface) in the winter hemisphere.

Heat-flux values for DJF from the COUPLED case are shown in Fig. 2d. From the heat-flux correction errors in the DOC case in Fig. 2b, the coupled model should show greater-than-observed values of net downward (positive) surface heat flux in the tropics to go along with the lower-than-observed SSTs. This is indeed the case in Fig. 2d. Similarly, the negative heat-flux values in the SPEC SST case in the northern Indian Ocean are present in the COUPLED case, as are the lower-than-observed positive values in the eastern equatorial Pacific. Note that the heat-flux correction terms for the DOC case are much larger than the COUPLED case because the DOC was forced to the observed temperatures, while the COUPLED has arrived at lower SSTs and, appropriately, smaller compensatory surface heat fluxes.

A similar comparison is made for the northern summer season in Fig. 3. The DOC case shows large positive heat-flux corrections in the equatorial tropics similar to the January values in Fig. 2, indicating that the colder-than-observed SSTs occur year-round in the ocean model. Heat-flux errors from the SPEC SST case in Fig. 3c include a northward excursion of the zero line in the central tropical Pacific and large negative values northwest of Australia. The heat flux maximum in the equatorial eastern Pacific, however, is better simulated at this time of year. The COUPLED net surface heat-flux values in Fig. 3d again reflect the errors in the respective model components, with large positive heat-flux values across the equatorial tropics indicative of the ocean model’s tendency to produce SSTs that are too low there.

As mentioned above, because of the uncertainties in the observed data and the interpretation of fluxes computed from specified forcing, this comparison can give only qualitative information. Yet, the ocean model clearly is introducing the largest errors in the equatorial tropics. The low SSTs require compensating downward net surface heat flux from the atmosphere. The atmospheric model also produces net heat-flux errors, but these are generally much smaller than those introduced from the ocean model. For example, in Fig. 2, during northern winter in the central equatorial Indian Ocean, observed and SPEC SST are near 40 W m⁻² while COUPLED is around 80 W m⁻². In that same season in the equatorial Pacific west of the date line, SPEC SST and observed are near zero and COUPLED is greater than 40 W m⁻². Similar large discrepancies exist in those regions and elsewhere during northern summer in Fig. 3. It follows from this analysis that a better ocean model simulation would contribute greatly to an improved coupled model climate simulation even if no upgrades were made to the present atmospheric model.

4. Atmospheric simulation features

As a consequence of the inherent limitations of the atmosphere and ocean formulations that produce the SST patterns shown in Fig. 1, climatic features simulated by the atmospheric model are affected in various ways. Because the SST errors produced by the ocean part of the simulations were greater than those associated with errors in the atmospheric part of the coupled models, the climates simulated in the coupled models resemble SST anomaly experiments. This can be seen in the simulated precipitation fields for the northern winter season (Fig. 4). The SPEC SST somewhat overestimates the centers of monsoon precipitation over Indonesia and New Guinea. Other versions of the CCM (e.g., Pitcher et al. 1983) also simulate tropical precipitation amounts that are greater than observed. Precipitation associated with the Australian monsoon in the Cape York and Gulf of Carpentaria areas is underestimated in the SPEC SST. The SPCZ in the southwest Pacific in the SPEC SST is also not well defined in its southeastern extension (as reflected in the net heat-flux values in Fig. 2c).

The tendency for precipitation in these regions to be confined more closely to the equator than observed is accentuated in the MIX1 case in Fig. 4c. The high SSTs from the slab ocean are associated with an almost zonal band of precipitation across the Indian and Pacific oceans. The associations between high SSTs and larger amounts of precipitation have been documented in a version of this atmospheric model in SST anomaly experiments (Blackmon et al. 1983).

When tropical SSTs are substantially reduced by the ocean GCM simulation in the COUPLED case, precipitation amounts are also much less (Fig. 4d). Monsoon precipitation over Indonesia is markedly reduced and precipitation in the ITCZ in the Pacific is suppressed. This is also seen in lowered SST experiments with a version of this model (Blackmon et al. 1983).

Similar precipitation characteristics as a result of the SSTs produced by the ocean formulations are evident in the northern summer season as well. Precipitation in the Indian monsoon in SPEC SST is greater than observed (Fig. 5a). In the MIX1 case, precipitation increases over the warm water in the tropical central
and eastern Pacific and decreases over the Indian monsoon region and western Pacific, especially north of New Guinea. This is associated with the decrease of east–west SST gradient (Fig. 1) and an alteration of the large-scale, east–west atmospheric circulation between the Indian and Pacific sectors of this model such that an increase of precipitation over the tropical central and eastern Pacific in MIX1 is associated with a suppression of precipitation over the Indian monsoon and western Pacific regions. These types of linkages associated with the Walker Circulation between the eastern and western Pacific and Indian monsoon regions occur in the observed system (e.g., Rasmusson and Carpenter 1983), in this model coupled to the 50-m slab ocean (Meehl and Washington 1986), and in another version of this model with prescribed SST changes in the Pacific (Blackmon et al. 1983).

In the COUPLED case where the tropical SSTs are
Fig. 4. DJF precipitation (mm day$^{-1}$); light stippling indicates areas greater than 8 mm day$^{-1}$, dark stippling for areas greater than 10 mm day$^{-1}$: (a) observed (Jaege 1976), (b) SPEC SST, (c) MIX1, (d) COUPLED.

lower, precipitation is much less (Fig. 5d). The Indian monsoon precipitation retreats from the cool ocean and occurs almost entirely over land areas compared to the SPEC SST. Precipitation in the Pacific is also much less than in the other model cases and the observed.

To further illustrate the precipitation changes in these regions, area averages are computed for the "In-
dian sector” and “Pacific sector.” These include precipitation regimes west and east, respectively, of regions affected by the east–west atmospheric circulation between the Indian/western Pacific and eastern Pacific associated with the Southern Oscillation (e.g., Meehl 1987). The Indian area average is calculated over 30°N to 30°S and 45°E to 155°E. The Pacific area covers 30°N to 30°S and 155°E to 90°W. Figure 6 shows area-averaged precipitation differences for MIX1 minus SPEC SST (Fig. 3a) and COUPLED minus SPEC SST. For both seasons, increases of area-averaged precipitation are present in the Pacific and decreases are ev-
ident in the Indian sector in MIX1 minus SPEC SST. In particular, a large decrease in the Indian sector in Fig. 6a can be traced in Figs. 5b and 5c to a withdrawal to the southeast and reduction in magnitude of the Indian monsoon and a reduction of rainfall north of New Guinea. In the Pacific, the southward shift and intensification of ITCZ rainfall in the MIX1 case compared to the SPEC SST case are associated with an increase (on the order of 10%) of area-averaged precipitation in both seasons.

In the COUPLED minus SPEC SST, precipitation decreases with the cooler ocean surface in both seasons for both sectors. The decreases in the Indian sector are relatively larger year-round as a result of the greater percentage decreases of the precipitation maxima there compared to precipitation in the Pacific (Figs. 4 and 5).

Examination of the surface wind fields further indicates how the coupled models are affected by the SST simulations from the respective ocean formulations. Figures 7 and 8 compare surface winds from the SPEC SST, MIX1, and COUPLED cases with the ECMWF winds for northern winter and summer. For northern winter (Fig. 7), the SPEC SST simulates a well-developed northeast monsoon over the Arabian Sea, Bay of Bengal, and South China Sea. Strong northeast trades are present north of the equator across the tropical Pacific. The model also captures the weak westerly component winds in the far eastern equatorial Pacific. The most obvious model deficiency is in the region of the SPCZ in the southwestern Pacific. The observed surface winds show weak winds and strong convergence in that region, while the SPEC SST simulates strong southeast trades right across the South Pacific. This model error is reflected in deficient rainfall there, as discussed earlier.

The MIX1 and COUPLED cases in Figs. 7c and 7d should mirror the inherent model errors of SPEC SST as well as those errors introduced by the limitations of the ocean formulations. Indeed, neither the MIX1 nor COUPLED cases simulate the SPCZ with any success, although both coupled models reproduce the northeast monsoon winds over southern Asia, the northeast trade winds over the Pacific north of the equator, and the southeast trades south of the equator in the Indian and Pacific Oceans.

For the northern summer season in Fig. 8, the SPEC SST model reproduces the strong cross-equatorial flow in the western Indian Ocean associated with the Indian monsoon, the southeast trades south of the equator in the Indian and Pacific oceans, and the northeast trades north of the equator in the Pacific. The northeast trades are too strong in the western Pacific in the model, and this deficiency appears in both coupled model cases in Figs. 8c and 8d. For the COUPLED case where active equatorial upwelling is already an inherent problem, partially as a result of the coarse vertical resolution discussed earlier, these stronger-than-observed easterlies drive even more vigorous upwelling resulting in still lower SSTs there than in the northern winter season (Fig. 1). The cool water in the central and eastern equatorial Pacific in the COUPLED case inhibits surface convergence and results in weak easterlies and re-
Fig. 7. Surface vector winds (scaling vector at lower right is 6 m s\(^{-1}\)) for DJF: (a) observed (ECMWF analysis at 1000 hPa), (b) SPEC SST (model level \(\sigma = 0.991\)), (c) MIX1 (model level \(\sigma = 0.991\)), (d) COUPLED (model level \(\sigma = 0.991\)).
Fig. 8. Same as Fig. 7, except for JJA.
FIG. 9. Surface vector wind differences (scaling vector at lower right is a difference of 3 m s⁻¹): (a) MIX1 minus SPEC SST for DJF, (b) COUPLED minus SPEC SST for DJF; (c) MIX1 minus SPEC SST for JJA, (d) COUPLED minus SPEC SST for JJA.
duced precipitation (Fig. 5d). The weakened Indian monsoon in the COUPLED case is also associated with decreased southwesterly flow over the Arabian Sea.

To highlight the discrepancies between the model cases, vector differences are computed for the two seasons (Fig. 9). The MIX1 minus SPEC SST vector differences for both seasons (Figs. 9a and 9c) show the increased convergence in the tropical Pacific associated with the decreased east–west SST gradient, the generally warmer SSTs, and the increased precipitation there in the MIX1 case compared to the SPEC SST case. The weakening of the trade winds north and south of the equator and decrease in surface convergence associated with the lower SSTs in the Pacific (and decreased east–west SST gradient) are indicated by the westerly anomaly winds in Figs. 9b and 9d for the COUPLED case minus SPEC SST. The weakened southwesterly inflow into the Indian monsoon during June–July–August (JJA) for both MIX1 and COUPLED cases is indicated by northeasterly vector wind anomalies over the western Indian Ocean in Figs. 9c and 9d.

5. Annual cycle of low-level winds

To indicate how the seasonal timing of the surface wind fields is affected in the model simulations, the annual cycle of zonal mean $u$-component surface winds is shown for the Indian and Pacific sectors (as defined previously) in Figs. 10 and 11. For the Indian sector in Fig. 10, the SPEC SST shows seasonal easterly maxima (near 10°N during northern winter) that are stronger than the observed by about 3 m s$^{-1}$, and northern summer westerly maxima that are weaker than the observed, mainly due to the easterlies north of Indonesia in the SPEC SST (Fig. 8). Similarly, south of the equator the SPEC SST easterlies are somewhat stronger than the observed. Seasonal timings and latitudes of $u$-wind maxima from the SPEC SST compare favorably to the observed.

The addition of the computed ocean formulations alters the annual cycle of $u$-component surface winds. Thus, the weakening of the Indian monsoon in the MIX1 case is associated with a substantial reduction of the westerly wind maximum during northern summer north of the equator even though the easterly maxima north and south of the equator during the rest of the year are similar in timing and magnitude to SPEC SST. For the COUPLED case, the Indian monsoon westerlies are shifted north as the southwesterlies in the Arabian Sea weaken and more precipitation falls over land during JJA (Figs. 5 and 8). As in the MIX1 case, however, the timing and magnitude of the easterly maxima north and south of the equator the rest of the year closely resemble the SPEC SST case.

In the Pacific sector (Fig. 11), the problems in the atmospheric model in the western Pacific and SPCZ are evident in the SPEC SST case, as indicated by a lack of seasonal latitudinal excursion of the easterly wind maxima that is evident in the observed $u$-wind plot (Fig. 11a). The observed minimum of the easterlies lies to the south of the equator during northern winter and north of the equator during northern summer. In SPEC SST, the easterly $u$-wind minimum lies on the equator year-round. This model tendency is reflected in the MIX1 case in Fig. 11c. The COUPLED case displays an improved simulation over the SPEC SST in the pattern of the seasonal latitudinal excursion of the easterly $u$-wind minimum through the course of the annual cycle. This is manifested by the minimum of the $u$-wind easterlies occurring north of the equator late in northern summer (mostly in the eastern Pacific in Fig. 8d) and another minimum of the $u$-wind easterlies south of the equator during northern winter (mainly in the western Pacific in Fig. 7d). In addition, the secondary easterly maximum seen near 15°N during June in SPEC SST and during September in MIX1 is not present in either the observations or the COUPLED case. The implication is that, in spite of the inherent limitations of both atmospheric and oceanic models, interactions in the coupled ocean–atmosphere system appear to produce a better simulation than could be expected from either of the components. However, the improved net surface heat fluxes in these regions in the COUPLED case compared to the SPEC SST case noted in Figs. 2 and 3 were the product of compensations occurring at the surface due to inherent problems, mainly in the ocean simulation. The decreased surface wind convergence in the eastern Pacific region in the COUPLED case (Figs. 8d and 9d) occurs fortuitously as a consequence of the lower equatorial SSTs and reduced convective activity in the ITCZ. Therefore, apparent improvements in certain climate features in the COUPLED case must be taken in the context of the more realistic surface heat flux compensations taking place in the models. Yet, the imposition of observed SSTs in the SPEC SST may not always provide the atmosphere with the "best" fluxes (or the most internally consistent fluxes or fluxes that take into account day-to-day SST variability) to drive the atmospheric circulation. This raises the point that a coupled model using computed SSTs could produce a more internally consistent climate simulation even though the computed SSTs would not exactly correspond to the observed values.

6. Summary and conclusions

Integrations with a global spectral R15 (4.5° × 7.5°, nine $\sigma$-levels) atmospheric GCM run with the prescribed annual cycle of observed SSTs (SPEC SST) and coupled to a 50-m slab ocean mixed layer (MIX1) and a coarse-grid (5° × 5°, four-layer) global ocean GCM (COUPLED) are analyzed to determine the relative contribution of coupled climate simulation errors
FIG. 10. Mean annual cycle of zonal mean $u$-component surface wind (m s$^{-1}$) for the Indian sector (including the western Pacific, see text for longitudinal limits of the Indian sector; positive (westerly) contours are solid, negative (easterly) contours are dashed): (a) observed (ECMWF analysis at 1000 mb), (b) SPEC SST (model level $\sigma = 0.991$), (c) MIX1 (model level $\sigma = 0.991$), (d) COUPLED (model level $\sigma = 0.991$).
FIG. 11. Same as Fig. 10 except for the Pacific sector (see text for longitudinal limits of the Pacific sector).
from each of the separate components. The tropical Indian and Pacific oceans are selected for study because of the central role of dynamically coupled processes in those regions and the importance of those areas to regional and global interannual climate variability.

Comparisons of net surface heat flux from the SPEC SST case and the COUPLED case indicate that the largest errors of simulated SSTs in the COUPLED case arise from deficiencies in the ocean GCM. The consequences of the computed SSTs from the ocean GCM [and from the slab-ocean mixed layer analyzed by Meehl and Washington (1985)] include alterations of the simulated precipitation and low-level wind fields such that relatively higher SSTs are generally associated with greater precipitation, stronger easterly trade winds, and increased near-equatorial surface wind convergence (e.g., in the Pacific for MIX1) and vice versa for relatively lower simulated SSTs (e.g., for the COUPLED case).

The annual cycles of zonal u-component surface winds from the model simulations generally reflect the characteristics noted for the geographical vector wind plots, in that inherent atmospheric model errors in the SPEC SST case are present in the MIX1 and COUPLED cases with appropriate alterations due to the particular characteristics of the SSTs simulated by the respective ocean formulations. Some aspects of the annual cycle of u-component wind simulation show apparent improvement in the COUPLED case in the Pacific sector, but the errors of the simulated SST due to limitations of the ocean GCM and resulting compensations in surface energy balance are mainly responsible for these improvements. Such constraints must provide the context for interpretation of coupled model results. Two main conclusions, therefore, are:

1) Regarding the NCAR coupled model simulations, model errors introduced by the ocean formulations are contributing more to deficiencies in these coupled models than those from the atmospheric component. Therefore, substantial improvement of the ocean component's ability to simulate the observed SST distribution will greatly improve the climate simulated by these coupled models, even with no upgrades to the present atmospheric model.

2) Coupled ocean–atmosphere models provide internally self-consistent coupled climate simulations compared to atmospheric models run with observed SSTs. This is due to the coupled model's ability to generate and maintain compensatory surface fluxes in time and space as a function of the individual characteristics of the ocean and atmospheric model. Therefore, surface fluxes are not necessarily "absolute" quantities in coupled models and must be interpreted in the context of the limitations (and strengths) of the respective media in producing the simulated SST patterns.

It follows that SSTs simulated by coupled ocean–atmosphere GCMs may not be exactly as observed, but justification can be made for the use of such models for realistic insights into some processes and mechanisms of the dynamically coupled ocean–atmosphere system. Present coupled GCMs with imperfect climate simulations provide, perhaps, the best research tools now available to study such processes in the context of the limitations of the respective components.

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