COARE98: Proceedings, Conference on TOGA-COARE, Boulder, CO, 7-14 July, WCRP-107, WMP/TD 940, 1-15.

TOGA-COARE: HOW WELL HAVE WE PROGRESSED TOWARDS UNDERSTANDING AIR-SEA COUPLING IN THE WARM POOL?

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1. Introduction

This review — based on a talk given at the COARE98 Workshop, and updated to include new information presented at the meeting — considers how well we have met the first of the objectives that the organizers of COARE set themselves, some years before the field phase began (Webster and Lukas, 1992). The first of these COARE objectives was:

"To describe and understand the processes responsible for the coupling of the ocean and atmosphere in the western Pacific warm-pool system."

Bjerknes (1966) suggested that the El Nino-Southern Oscillation phenomenon is the result of positive feedbacks inherent in ocean-atmosphere coupling. Models developed during the TOGA Decade 1985-1994 — e.g. Stockdale et al. 1998 — have fleshed out Bjerknes' idea, and turned it into a set of tools with some skill for predicting ENSO events. However, despite the success of such models, there was a concern that some of the physics deliberately omitted from these prediction tools in the interests of simplicity might in fact be quite important for understanding and predicting interannual climate variability. Prominent among these omitted items of physics were those associated with the Madden-Julian Oscillation (Madden and Julian, 1971); the MJO generates westerly wind bursts along the equator over the Warm Pool. These WWBs are a major part of the forcing for the Kelvin waves which warm the eastern Pacific in an El Nino event (e.g. McPhaden et al., 1998). MJO events are strong enough to regularly spawn tropical cyclones as by-products (e.g. Keen, 1982). The effort to organize the TOGA-COARE experiment was to a large extent motivated by a concern that air-sea interactions in the Warm Pool, omitted from earlier models, might be an important contributor to the mechanism of ENSO events.

Briefly, the answer to the question posed in our title is: We have made considerable progress towards understanding air-sea coupling in the Warm Pool; there is now strong reason to believe that this coupling is a major part of the ENSO mechanism; and we are well positioned to make substantial further progress, thanks in large part to the COARE data set. To illustrate this, in Section 2 we will outline some new ideas on how air-sea coupling may operate in the Warm Pool region. In each case we will outline how recent data sets (including COARE) have been used to test the new hypotheses.

If these new ideas are correct, they strongly imply that atmospheric models must deliver much more accurate air-sea fluxes than they presently do, when given accurate SST, if we are to be able to realistically forecast climate variability. A 10 W/m^2 target for averages over several months may be appropriate. Conversely, ocean models must deliver more accurate SST's, when given accurate surface fluxes. A stumbling block to achieving such goals is that — while presently available SST products are probably accurate to a marginally acceptable level of 0.5°C, outside regions of heavy cloud and/or humidity and in the absence of volcanic aerosols — observationally-based flux products are well below the level of accuracy needed. However, work during COARE, plus external developments, offer the possibility of major improvements in obtaining accurate, observationally-based flux products. These issues are discussed in Section 3.

The task of building AGCMs that generate accurate surface fluxes on a day-by-day basis is certainly a very hard one, because it is not enough to generate accurate deep convection (challenging enough in itself). In addition, cloud cover, atmospheric optical depth and air-sea humidity differences must be realistically simulated for given large-scale environmental conditions, implying also that the largescale effects of downdraughts must be simulated. In suppressed conditions also, the subgridscale convection and its effects on shortwave radiation and on surface humidity must be well simulated.

Luckily, results reported at COARE98 from extremely high (3 km) resolution cloud-resolving models suggest that these apparently very daunting problems can be solved — in a research context. However, translation of these results into forms that can be used in coarse-resolution climate models for real-time ensembles of prediction runs will require several years of work, in which many different kinds of COARE data will play an essential calibration role. Some more data will also be essential, in climate regimes that have so far not been sampled. Corresponding uncertainties in ocean models relate primarily to the parameterisation of mixing, especially in regions affected by strong internal tides. These issues will be discussed in Section 4.

Finally, the results are summarised in Section 5, and several other results from COARE98 are discussed in the context of the ideas developed in earlier sections.

2. Recent ideas on air-sea interaction mechanisms in the Warm Pool

2.1. Barrier-Layer Switchoff of Entrainment

At the meeting at which COARE was first seriously discussed, Lukas (1988) noted that daily wind records from islands near 170°E in the equatorial Pacific usually show gentle (3 m/s) easterlies. However, these are interspersed with sharp "spikes" of a few days' duration, known as Westerly Wind Bursts, associated with the MJO. The very anomalous winds associated with the 1982-1983 El Nino started and ended with spikes very like other Westerly Wind Bursts — it was just that between these spikes, the westerlies never stopped blowing. This occurred at a time of unusually high SSTs in the central equatorial Pacific. Lukas suggested that these higher SSTs might encourage the formation of stronger MJO episodes (though he was not specific about the mechanism by which this might occur).

However, Lukas was quite specific about a mechanism by which Barrier Layer physics might warm the SST of the Warm Pool slightly. He suggested that warm (~28.5°C), relatively salty water flowing westward along the equator as part of South Equatorial Current might subduct beneath fresher, slightly warmer surface water, and that this might maintain a long-lived barrier layer to the west of the subduction zone.

A Barrier Layer (Godfrey and Lindstrom 1989, Lukas and Lindstrom 1991) is a layer of water directly underlying the Surface Mixed Layer, which has a closely similar temperature but higher salinity. When wind mixing does work against buoyancy under these conditions, it entrains salty water into the mixed layer, but no significant entrainment cooling results. The thermocline begins at the base of the barrier layer, but the vertical eddy diffusivity is (in most parts of the ocean) much reduced there compared to that at the base of the surface mixed layer; so entrainment cooling — a major factor in maintaining low SST's in the eastern equatorial Pacific — would be suppressed if a permanent barrier layer were to form by subduction of salty water. Shinoda and Lukas (1995) showed that away from the equator, a barrier layer could be formed by subduction, in a Lagrangian model of a mixed layer advected by the South Equatorial Current; but their model contained no shear between the mixed and barrier layers.

Picaut and Delcroix (1995) and Picaut et al. (1996) found evidence indirectly supporting the idea of subduction, on the equator — with shear between the barrier and mixed layers. They examined zonal currents averaged over 5°N-5°S, deduced from altimeter data, and found that progressive vector diagrams generated from these currents converged near the 28°C isotherm, from any longitude on either side; i.e. they converged onto the eastern edge of the Warm Pool. As is well-known, the 28°C isotherm moves east and west in close correlation with the Southern Oscillation Index, so the Picaut et al. "drifters" followed this movement. From sparse surface salinity data, Picaut et al also found that a region of strong zonal salinity gradient seemed to occur near the 28°C isotherm; and two direct observations showed a definite, sharply-defined salinity front near this location, with small temperature differences across it. All these phenomena were consistent with surface water subducting at a salinity front.

Vialard and Delecluse 1998a,b (referred to below as V&D) undertook a modeling study of the oceanography of these phenomena. They drove an OGCM covering the equatorial Pacific with interannually-varying wind stresses. They relaxed their model SST towards observed SSTs. They also forced their model with various interannually-varying products for the net Precipitation - Evaporation, (P-E). Model results varied considerably depending on their choice of (P-E) product, but general principles emerged. First, a semipermanent salinity front formed in the model, near the 28°C isotherm; it moved east and west in synchrony with the Southern Oscillation Index, consistent with available salinity observations (Figure 1). Secondly, in the model, salty water subducted at this front and continued westward at a depth of 50-100m, thereby maintaining a semipermanent barrier layer; in the model, this occurred in a region about 2000 km wide to the west of the front, except for a few months during La Nina events. Sparse observations of barrier layer variations (Ando and McPhaden, 1997) broadly supported the model results, though they suggested that the time for reestablishment of a barrier layer might be longer than found by V&D, and that its zonal extent might be greater when established.

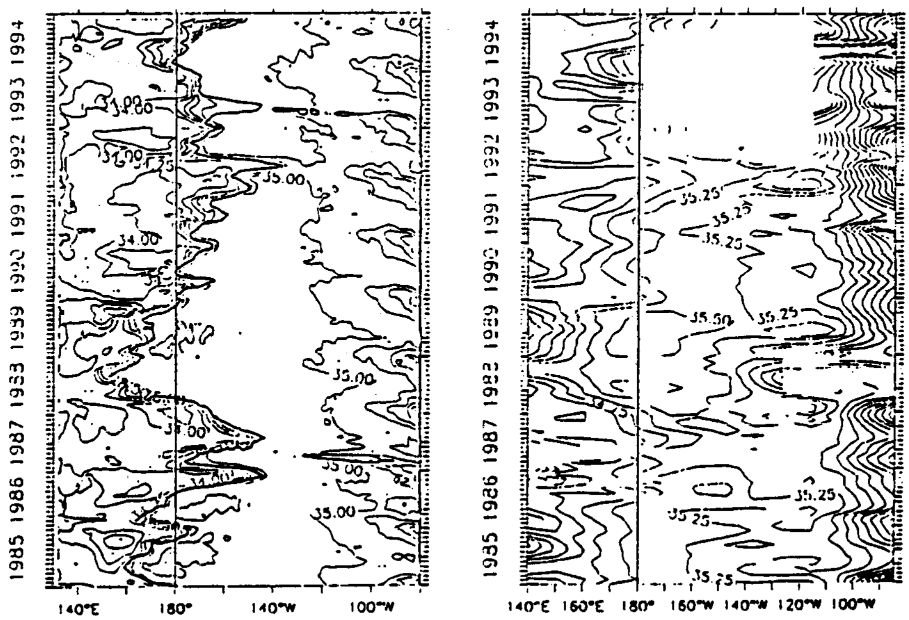

Figure 1: Time-longitude evolution of Sea Surface Salinity in the 2°N-2°S band. (a) from control experiment. (b) from data along four navigation tracks. Contour interval is 0.25 psu. From Vialard and Delecluse, 1998b.

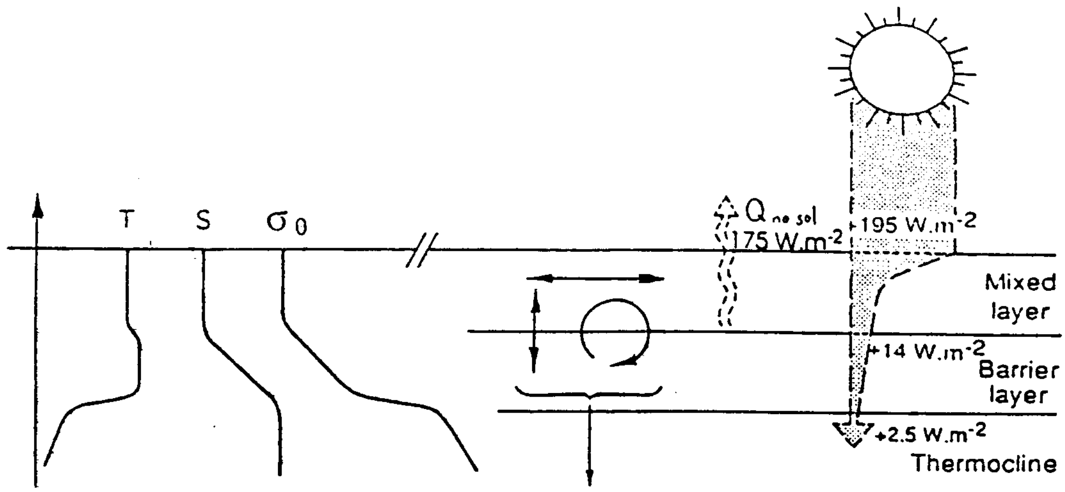

Figure 2. Simplified vertical heat budget in the presence of a barrier layer in the Warm Pool region. Adapted from Vialard and Delecluse, 1998a.

The thermodynamics of a barrier layer are rather exotic. Figure 2 (adapted from V&D) illustrates this for a typical situation of a 30m deep barrier layer lying below a 40m deep mixed layer. For a typical influx of shortwave radiation of 195 W/m^2, and for typical ocean transparency profiles, 14 W/m^2 will penetrate into the barrier layer and 2.5 W/m^2 will leave it, so 11.5 W/m^2 are available to warm the barrier layer. Anderson et al. (1996) provide more detailed discussion of barrier layer thermodynamics. However, it is now known from COARE data (Weller and Anderson, 1996) that the net heat flux into the COARE region is probably close to 20 W/m^2, i.e. 175 W/m^2 must leave the mixed layer by latent, sensible and longwave heat losses — all of which extract heat directly from the ocean surface. Therefore only (20-14 = 6) W/m^2 is available to warm the mixed layer. This situation will eventually cause the barrier layer to be slightly warmer than the mixed layer, i.e. a temperature inversion is to be expected. V&D find that such inversions occurred in 41% of cases where a significant barrier layer was found. Under these circumstances, turbulent entrainment at the base of the mixed layer will warm rather than cool it; this may be why such inversions seldom exceed 0.1°C. However, V&D find that the entrainment flux is a strong function of barrier layer thickness — for thicknesses of 30m or more, entrainment warms the mixed layer by 5 W/m^2, while for thicknesses of less than 10m, entrainment cools the mixed layer by 5-20 W/m^2 (depending on location).

Intuitively, the sudden introduction of a barrier layer can be expected to cause the mixed layer (and hence the SST) to warm up, if all other things are equal: but how great will this warming be? In the Warm Pool, air temperature T_a generally follows SST, so that (SST - T_a) is rather constant at about 1°C; and Relative Humidity (RH) is generally close to 80%. Hence if wind speed W is constant at a typical speed of 4 m/s, the effect of increasing SST will be a slow increase in latent heat loss Q_l. For the above numbers, the gradient $\partial Q_l/\partial(SST)$ is readily calculated to be about 10-15 W/m^2/°C (e.g. Seager et al., 1988). If shortwave radiation is constant, and neglecting smaller changes in longwave radiation, SST should increase after a barrier layer is suddenly introduced until the reduced heat loss this causes (about 10-25 W/m^2, according to the previous paragraph) is compensated by increased heat loss due to latent heat. Thus SST should rise by somewhat more than 1°C.

This will be a quite slow process. Observed temperature inversions of 0.1°C are small compared to the expected temperature rise of 1°C, so the combined depth H = 70m of mixed layer and barrier layer will warm together. Thus the e-folding time for the SST rise is about $\rho C_p H/ [\partial Q_l/\partial(SST)]$, or about 200 days ($\rho$ and C_p are the density and heat capacity of water, respectively). This SST rise will not begin until a deep barrier layer has reestabished, after a La Nina; since this takes several months according to the model and limited observations, the time for the Warm Pool to warm up by this mechanism following establishment of La Nina conditions is of order a year. If — as suggested by Lukas (1988) — such SST changes are enough to strengthen the Westerly Wind Bursts associated with MJO episodes, it is plausible that this may be an important criterion for making the Western Pacific susceptible to onset of the next El Nino event. The question of how MJO events respond to such steady SST changes within the Warm Pool has not yet been investigated; but their response to SST changes on MJO timescales is under active study at present, as discussed in 2.2 below.

2.2. Modification of Madden-Julian Oscillations by Sea Surface Temperature fluctuations

It was noticed during the COARE IOP that SST varied as much as 1°C during passage of the two MJO events that occurred at that time. The cause of those variations were obvious enough to scientists on ships during the events: for ten or more days before MJO convection started atmospheric conditions were calm, sunny and hot, and afterwards they were cloudy, windy and rather cold, so the SST naturally reached a maximum a few days before the maximum of MJO convection. These MJO events appeared to generate a small subsequent east Pacific warming (Lukas et al. 1995). RMS variations deduced from satellite measurements are somewhat smaller (e.g. Shinoda and Hendon (this volume), C. Zhang (this volume)). Krishnamurty (1986) had noted such variations in data from the International Geophysical Year, but their phasing relative to deep convection was not known. Trapping of solar radiation in the barrier layer during the suppressed phase of MJO contributes significantly to these SST changes (Anderson et al. 1996).

These observed SST variations raised the important question: do they feed back significantly on the MJO itself, to alter its strength or other characteristics? Some early theories considered such possibilities (see Waliser et al. 1998 for a review) but the question had not seriously been addressed, with adequate data to test theories. Flatau et al. (1997) ran two experiments with their 5-level AGCM, which they ran over an "aquaplanet" — a globe with only a water surface. In the first, SST was zonally uniform, with a maximum of 29°C at the equator. In the second, SST was allowed to rise in easterly winds and fall in westerlies, according to an empirical rule derived from observations obtained on drifting buoys during COARE and CEPEX (CEPEX was a second experiment conducted just after COARE). Flatau et al found that Kelvin-like waves developed along the equator in the first experiment; but the variations in SST, of typical peak-to-trough amplitude 1°C in their model, played a strikingly large role in strengthening and organizing the Kelvin-like waves in their second experiment, and slowing them slightly.

Several observational papers presented at COARE98 addressed the relation of SST and surface flux variations to MJO behavior; but only one paper (Waliser et al., 1998), further examined the response of an AGCM to such SST changes. Like Flatau et al. (1997), Waliser et al. found fairly marked MJO response to small SST changes, which in nearly every case improved the realism of the model's MJO behavior (Figure 3). They used the Goddard Laboratory for Atmospheres (GLA) model, which had previously been found to show superior performance in an intercomparison of MJO behavior in several AGCMs run over specified SSTs (Slingo et al. 1996, Sperber and Slingo 1997). Waliser et al. considered the choice of such a model to be crucial to the success of the experiment, since unlike many others it delivered fluctuations in surface heat fluxes on MJO timescale that were in qualitative accord with the observations. They ran their model over a global domain, first with prescribed, mean seasonal SST (control run, CTL); then with a perturbation T' in SST, that obeyed:

$$H\partial T'/\partial t = Q' - HT'/\tau,$$

Finally it may be noted that McPhaden (this volume) reported an analysis of the forcing for the downwelling Kelvin waves, associated with the very energetic 1997-1998 El Nino event. Near the start of the event, downwelling Rossby waves approached the western boundary, and they reflected at the western boundary into Kelvin waves in the familiar way; however, these reflected Kelvin waves were very small compared to those generated in the western equatorial Pacific, by the action of WWBs associated with three MJO events. This argues that direct action of the WWBs, rather than a "delayed action oscillator" mechanism, seemed the most likely immediate cause of this event. McPhaden also noted that SSTs were unusually warm at the time in the western Pacific; he suggested that the downwelling Rossby waves might have induced the warm SSTs, but without specifying a mechanism. Barrier Layer Switchoff of Entrainment is a possible candidate, but lack of salinity data may preclude adequate test of this hypothesis, for the 1996-97 El Nino event.

2.3. Fetch Enhancement of MJO winds

A third mechanism by which air-sea coupling over the Warm Pool might cause successive MJO episodes to extend over a greater fetch than their predecessor, and hence deliver greater momentum flux into ocean Kelvin waves, was suggested by Kessler et al. (1995). They proposed a simple analytic model, in which climatological mean winds are disturbed by sinusoidally-varying zonal winds that are uniform in strength from the far western Pacific to the 29°C isotherm. However, the longitude of the latter is allowed to vary, in response to zonal surface currents associated with the Kelvin waves that are generated by the sinusoidal winds. (Kessler et al. show from TAO mooring data that during active MJO convection, such zonal advection is often a major cause of central Pacific SST change). In their model, the winds — which are assumed to establish themselves instantaneously — lead the resulting currents by some tens of days in the central Pacific. As a result, the zonal advection is not in quadrature with the wind forcing, and there is a net eastward movement of the 29°C isotherm with each MJO event, leading to greater fetch of the next event. This can lead to an exponential increase in the rate of eastward movement of the 29°C isotherm, i.e. to the development of an El Nino event.

2.4. Warm Pool air-sea interactions on shorter timescale

Air-sea interactions on short timescales are potentially important contributors to air-sea interactions on all timescales. For example, it was learned after COARE that convection and cloudiness have complex diurnal cycles, with deep convection and cloudiness reaching a maximum around 2 am local time (e.g. Chen and Houze 1997). Because of this phasing, cloudiness is relatively light during the day. If (say) an AGCM generated the correct mean rainfall and cloudiness but averaged them over the diurnal cycle, the shortwave radiation would decrease considerably, with large consequent reductions on SST — on long timescales, as well as on diurnal timescales. This could have serious consequences for the performance of such an AGCM, when it was coupled to an OGCM for climate predictions.

Such nonlinear behavior seems widespread at these short periods. It is well-known that east Asian "pressure surges" lead deep west Pacific convection (e.g. Lau et al. 1996); Compo et al. (this volume) report that MJO activity appears in turn to modulate the pressure surges. Wheeler and Kiladis (1998), and Wheeler et al. (1998) report the existence of waves with the dispersion relations and spatial characteristics of Kelvin, equatorial Rossby, mixed Rossby-gravity and inertio-gravity waves over the warm pool; they all had deep convection associated with them, and a slow phase speed suggestive of coupling between the convection and the large-scale fields.

It is at this stage too early to consider whether direct ocean-atmosphere coupling is important for these phenomena; but horizontal SST variability on short timescales may be important in some applications. For example, Redelsperger (this volume) ran a 1-km with Q' a (model-generated) heat flux departure from the control run's annual cycle (coupled run, CPL). H, τ were constants of 50m, 50 days respectively. These constants were deliberately chosen to keep T' rather small and the SST climatologies of the two simulations rather similar. The model developed stronger, better-organized

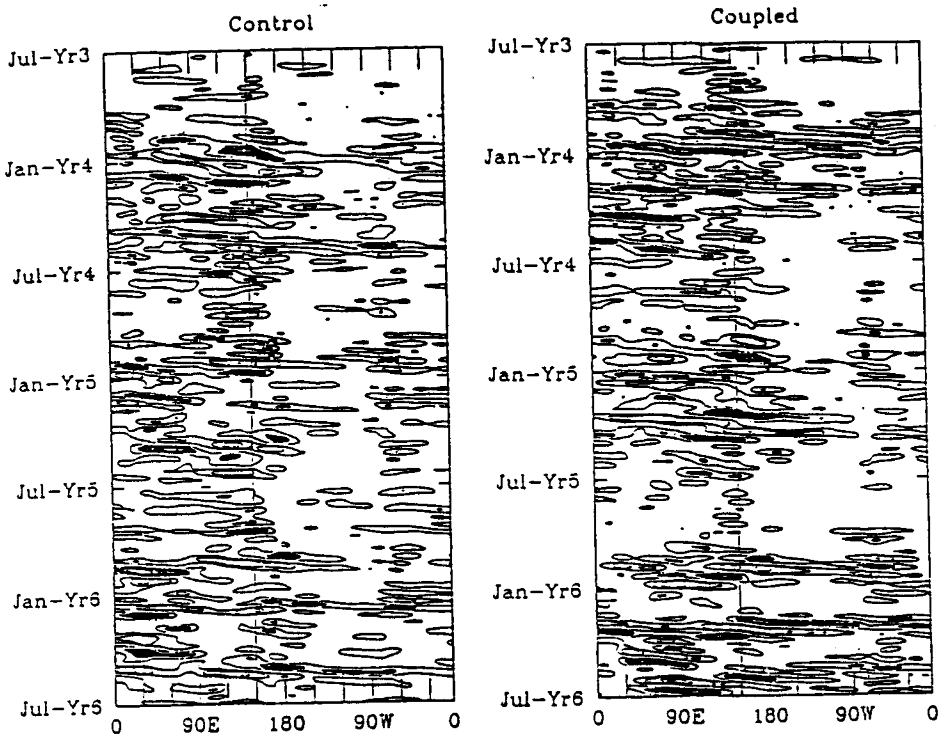

Figure 3: Time-longitude diagrams of the equatorial (4°N to 4°S) 20-100day band passed 200 mb velocity potential for a selected three year period of the CTL (left) and CPL (right) simulations. The $-8 * 10^6$ m^2s^{-1} contour is filled. The contour interval is $4 * 10^6$ m^2s^{-1}. The vertical line denotes the 150°E longitude line.

MJOs in the CPL run, whose propagation speed slowed by nearly a factor of 2 over the Warm Pool compared to the control run. The seasonality of MJO events was also improved in their model. The pattern of MJO-related surface heat fluxes was not very different in the two runs; yet moisture content of the Marine Atmospheric Boundary Layer (MABL) increased considerably relative to the control run, in the warm, calm conditions preceding MJO convection. The cause of this increase was traced back to increased meridional convergence of moisture, towards the region of maximum SST. Waliser et al. suggested that this convergence might in turn be due to the Lindzen-Nigam (1987) mechanism whereby the development of an SST maximum might lead to a local Sea Level Pressure minimum and convergence towards this minimum; though they did not substantiate this possibility.

In summary, these recent modeling results provide strong evidence that MJO intensity is remarkably sensitive to small (O(0.5°C rms)) changes in SST, that are phased appropriately relative to the MJO convection center. However, so far no test has been reported of the idea that longer duration SST variations in the west Pacific, such as those between El Nino and La Nina conditions, might also affect the likelihood of occurrence of MJOs and/or the strength of the Westerly Wind Bursts delivered by them. Such studies would provide valuable tests of the idea outlined in 2.1, that SST changes such as those generated by Barrier Layer Switchoff of Entrainment might modify MJO behavior, in a way that tends to generate El Nino events.

resolution, nonhydrostatic model on a day of near-zero wind and very suppressed conditions, obtaining realistic, small cloud towers. When Lebedev (pers comm) applied the fluxes from Redelsperger's model to an ocean model of similar resolution, he obtained rms variability of 0.3°C in SST at local midday over a 50 km domain, with some differences exceeding 1.0°C. It is at least plausible that — as has been found for the MJO, see 2.2 above — such SST variations may in turn affect the mean properties of the cloud towers; coupled experiments are in preparation to test this idea. In general, exploration of the possibility that convection over the ocean is a coupled ocean-atmosphere process at *all* relevant length and timescales will be an exciting topic for research in coming years.

3. Development of accurate flux maps.

If further model experiments and data analysis confirm the sensitivity of the atmosphere over the Warm Pool to small SST variations, not merely on ENSO timescales but also on MJO and probably shorter timescales as well, it follows that much more attention must be paid to the air-sea fluxes delivered by these models than has been done in the past. It is definitely inadequate to "flux-correct" mean seasonal errors away; it seems probable that on coupling ocean and atmosphere models, flux errors on any timescale can translate into errors at any other timescale, as suggested by the examples of 2.2 and 2.4 above.

There is a duality between air-sea fluxes and SST. It may useful to consider an OGCM as a device for taking 7 surface flux components — 2 of momentum, 4 of heat, and the (precipitation - evaporation), or (P -E) — and using them (with the present state of the ocean) to predict SST at the next timestep. Conversely, an AGCM may be regarded as a device for taking SST, and using it (with the present state of the atmosphere) to predict the 7 components of fluxes at the next timestep. Climate prediction months in advance may not be a safe activity until ocean and atmosphere models are developed which perform these tasks much better than at present.

A first task in improving AGCMs and OGCMs is to develop more accurate, observationally-based flux data sets. However, as noted in the Introduction, present errors in observationally-based estimates of the 7 fluxes are much worse than those in SST. A major achievement of COARE has been to radically improve this situation — at for the IFA, hopefully fairly representative of much of the Warm Pool. Before COARE, climatologies of net heat flux into the western equatorial Pacific differed by up to 80 W/m^2. Pilot studies for COARE narrowed this down considerably (e.g. Godfrey et al., 1991, Bradley et al., 1991), and rigorous ocean budget-closure tests undertaken in COARE (Feng et al., 1998 and this volume; Antonissen et al., this volume) showed that the final, calibrated flux estimates obtained at the IMET mooring (Weller and Anderson, 1996) were accurate to better than 10 W/m^2, in both suppressed and active MJO conditions. Freshwater budgets closed to about 2 mm/day. An account of the COARE community effort to achieve these results, including the development of new and intensively-validated algorithms for latent and sensible heat loss (Fairall et al., 1996), is given in the "COARE Interim Report" (Godfrey et al., 1998).

Various initiatives to develop accurate flux maps were reported at COARE98, using measured fluxes from the COARE IFA as the primary calibration. Schulz et al. (this volume) used remotely-sensed data to estimate all components of fluxes; unfortunately an algorithm for estimating surface air humidity that works well at higher latitudes turns out to have problems in the Warm Pool, when relative humidity is high in the upper troposphere, so there are problems with their estimates of latent heat loss. Shinoda and Hendon (this volume) found that, while wind stresses and latent heat fluxes were fairly well represented by the NCEP reanalysis, shortwave radiation and precipitation both showed a variation with the MJO that was a factor of two too small. When these NCEP fluxes were used to estimate SST variations by driving a mixed-layer model, the resulting SST amplitude was 30-40% too small. Taylor (this volume) reported that his group's efforts to improve flux estimates based on merchant ship data, by careful quality control of the data from each ship, was less successful near the IMET site than at other locations due to difficulties in estimating bulk transfer coefficients at low wind speeds.

S. Zhang et al. (this volume) developed maps of heat fluxes, whose four components agreed quite well with IMET fluxes on a day-by-day basis. Shortwave radiation was from an ISCCP remotely-sensed product. Turbulent fluxes were estimated using the data from a special, high-resolution reanalysis of COARE data, undertaken by ECMWF in 1994. Examples of these fluxes (Figure 4) illustrate the very large differences in net surface heat fluxes between suppressed and active MJO conditions — and the very wide spatial region affected by these changes. However, once several techniques come available that estimate net heat fluxes over the Warm Pool by different techniques, it will be important as a self-consistency check to see how their agreement degrades with distance from the IMET mooring, and also at the IMET site at times outside the IOP.

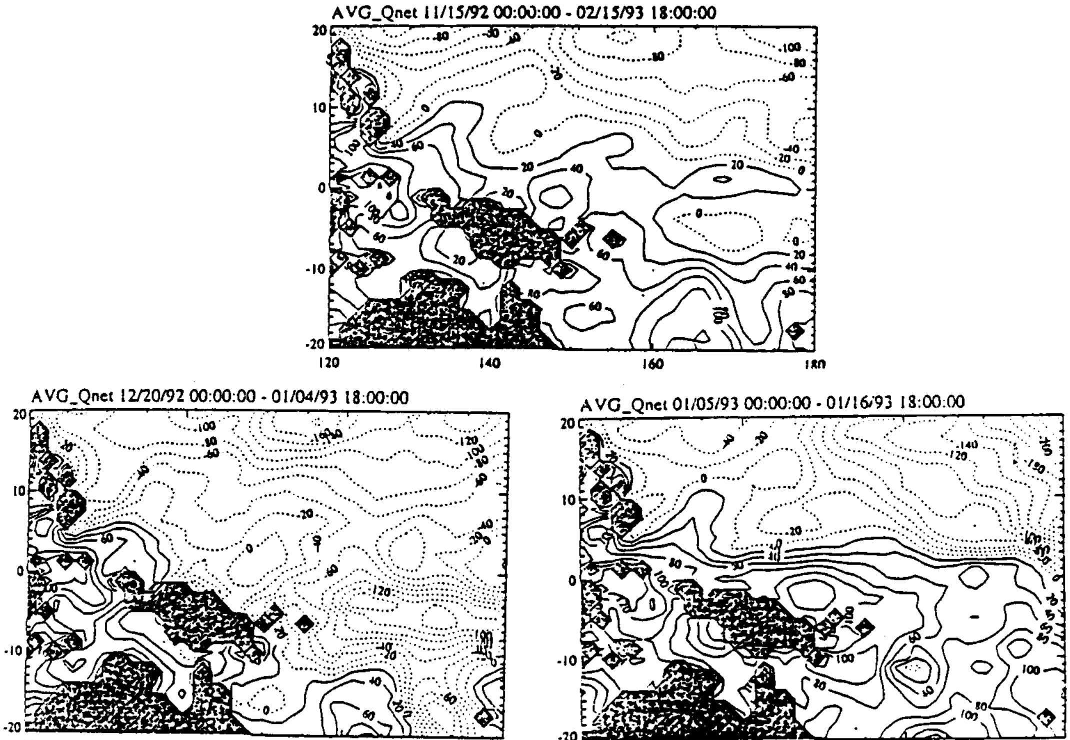

Figure 4: Net heat flux in the COARE region, from the product of Zhang et al. (see text). (a): 3-month average over the IOP. (b): Average over an active MJO period (20 Dec 1992 to 4 Jan 1993). (c) Average over a suppressed period (5 Jan - 16 Jan 1993).

4. On relating fluxes to SST, in AGCMs and OGCMs

4.1. Obtaining accurate surface fluxes from AGCMs

The problem of getting AGCMs to generate fluxes in "reanalysis" mode that match these accurate flux products is particularly difficult, since (at least in convective conditions) all fluxes are tied into the representation of deep convection. Different AGCMs use parameterizations containing closures with very different underlying physics (e.g. moisture convergence versus buoyancy), suggesting that consensus has not yet been reached on what the "correct" physical basis for the convection algorithm should be. Slingo and Sperber (1996) intercompared the performance of AGCMs in delivering realistic MJO activity, in the absence of SST feedback; they concluded that AGCMs with a buoyancy closure were more successful in this respect, and also in reproducing details of the seasonal cycle of convection in the tropics. Sperber et al. (1997) made a more detailed intercomparison among those models that performed relatively well.

The uncertainty in the "correct" choice of convection algorithm strongly complicates the problem of obtaining accurate surface fluxes, since all of them are linked in a coupled situation. Changing the convection parameterisation will affect the surface fluxes in several ways. By affecting cloudiness, it will change the shortwave radiation reaching the surface. It also affects things like the depth of the MABL, and the strength and composition of the downdraughts, thereby changing latent and sensible heat fluxes. Longwave radiation will be affected by both the changes to cloudiness and to the MABL. These changes will feed back immediately on the convection, and also on longer term through the effects of the fluxes on SST. Even within this complex of closely-related problems there are many other issues of concern. For example, Donner and Seman (this volume) showed that changing the representation of suspended ice content in deep stratiform clouds could drastically alter the surface shortwave radiation.

On a positive note, Wu and Moncrieff (this volume) describe simulations with a nonhydrostatic, two-dimensional cloud-resolving model with a grid spacing of 3km over a 900 km-domain representing the COARE IFA, for a 39-day period that began and ended in suppressed conditions but spanned a period of active deep convection and a westerly wind burst. Large-scale forcing was obtained from the objectively analysed sounding array (Lin and Johnson 1996) and 6-hourly SST was prescribed using the mean value from four buoys (including diurnal fluctuations). The net surface energy budget delivered by this model agreed to better than 10 W/m^2 with the IMET averages over the same period. Furthermore, when the model fluxes were used to drive a one-dimensional ocean model, the resulting modeled SST time series agreed with IMET observations remarkably well. This suggests that the problems described above should in principle be soluble - though an intensive, interdisciplinary effort will be needed to develop parameterizations of all the processes that permit much coarser climate models to faithfully reproduce the large-scale aspects of such cloud-resolving simulations. The COARE data set is likely to prove invaluable in such efforts.

Also, Wu and Moncrieff reported the successful completion of a one-week long, three-dimensional cloud-resolving simulations but these have not yet been analysed (the same procedure as used in the two-dimensional work will be adopted). The COARE data set is likely to prove invaluable in such efforts.

4.2. Obtaining accurate SSTs from OGCMs

Away from steep topography and especially from western boundaries, it is — in principle — considerably simpler to solve the corresponding problem of obtaining accurate predictions of SST once accurate fluxes are given. In the atmosphere, one must parameterize deeply convecting towers, which grow into existence through subgridcale processes; two phase changes must be accounted for, and therefore details of organization of the growing subgridscale towers contribute to their ultimate strength. By contrast, it is believed that inclusion of four parameters into an ocean model is sufficient to describe subgridscale mixing. These are the diapycnal and epipycnal (roughly, vertical and horizontal) eddy diffusivity and viscosity. Water transparency is also an important parameter within the top few tens of meters. There are now a number of mixed layer models which can reproduce the observed development of the mixed layer temperature, salinity and depth of the COARE data set (e.g. Anderson et al., 1996; Weller and Anderson, 1996; Webster et al., 1996; Godfrey and Schiller, 1997). The limitation is probably the O(10 W/m^2) accuracy of the heat fluxes used, rather than the physics of the mixed layer. Diapycnal eddy diffusivity and viscosity have been inferred from direct observations of turbulence (e.g. Peters et al. 1988), and ocean models with these parameterizations perform quite well in generating observed SSTs over the bulk of the Pacific (e.g. Chen et al., 1994) — again, within the limitations of our knowledge of fluxes. Thus, in many parts of the ocean it will be useful to use data assimilating OGCMs as a tool to help infer accurate net surface fluxes of heat and momentum (e.g. Rothstein et al., this volume). The same would be true of freshwater, if adequate salinity data became available.

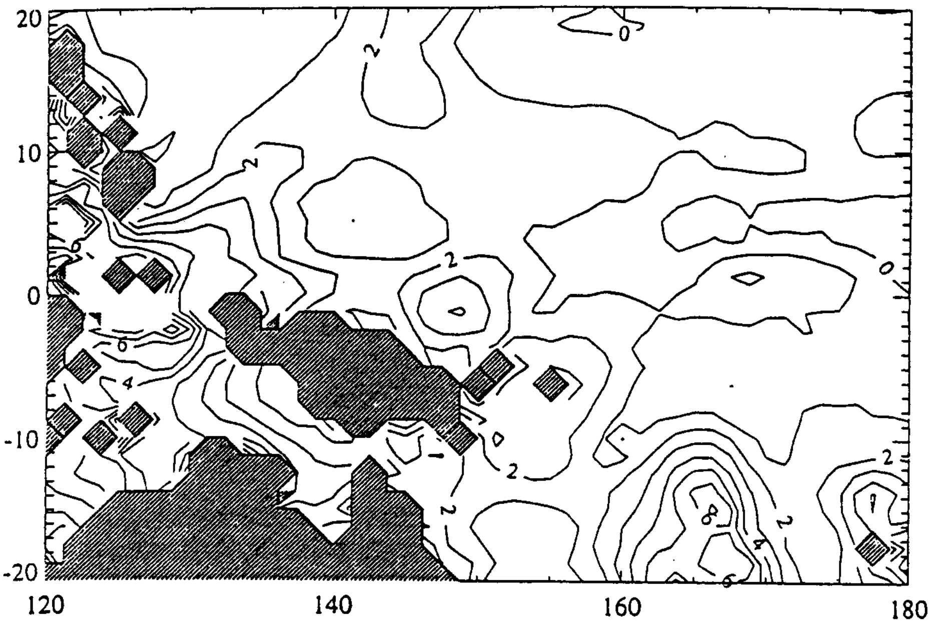

Figure 5: Map of the difference between the SST change across the 3 months for which fluxes are given in Figure 4, as inferred by running a 1-D mixed layer model at each point, compared to the observed SST difference. Conour interval 1°C.

Nevertheless, there are serious local deficiencies in ocean modeling, that will require field experiments to correct. The problem is illustrated in Figure 5. It shows the difference between the SST change across the 4 months of the IOP, as inferred by running a 1-D mixed layer model with the fluxes of Figure 4 compared to the observed SST difference. In most locations, the 1-D model gives an SST change that is about 2°C too high; the deficit must be taken up by ocean mixing and advection. However, in some locations the difference between the 1-D model simulation and observations is as much as 10°C, in 4 months! These all tend to occur in places where large internal tides are known to be generated (e.g. Sjoberg and Stigebrandt, 1992, Figure 6), such as the Indonesian region, Australia's Northwest Shelf, the shelf edge south of Papua New Guinea and the New Hebrides. One possible interpretation is that internal tides dissipate below the surface mixed layer, causing thermocline water to mix into the surface mixed layer and cooling them. Pinkel et al. (this volume) observed strong solitons associated with internal tides, which they suggested might contribute 10-15 Wm^{-2} to the heat flux through the mixed layer base, in the COARE region. Such phenomena suggest that the vertical eddy diffusivity in an ocean model should be a strong function of position (and perhaps also of the phase of the spring-neap cycle, though this is probably less important for climate applications). However, much work remains to be done to work out the details of this function. The horizontal eddy diffusivity may also be a function of position — for example, see Richards, (this volume).

5. Summary and further applications

In conclusion, the new results on (a) the sensitivity of the MJO to small SST variations, and (b) slower ocean mechanisms such as Barrier Layer Switchoff and Fetch Enhancement, support the suggestions of Webster and Lukas (1992) and Anderson et al. (1996) that ENSO events may come about through the charging and discharging of a "capacitor". The annual net freshwater flux in the western Pacific acts to increase stratification and support the accumulation of heat, especially near the dateline, thereby charging the "capacitor". This allows SST to rise by perhaps 1°C — a small amount, but enough (it is hypothesised) to result in an eastward displacement of the westerly Asian monsoon winds, which in turn expel the excess of fresh, warm water eastward and then poleward, much as suggested by Wyrtki (1985); this discharges the "capacitor". This is qualitatively different ENSO mechanism from those proposed earlier. However, model tests have not yet been carried out to examine whether MJO behavior is also sensitive to SST variations on timescales longer than the MJO. If they are, it implies a need for AGCMs to deliver fluxes which are accurate to perhaps 10 W/m^2, on average over several months, because the SST changes come about through the action of such small fluxes over several months, as illustrated in Section 2.2 ("Barrier Layer Switchoff of Entrainment"). Experiments with cloud-resolving models suggest that such flux accuracy is in principle possible, but much work is needed on developing appropriate algorithms, and validating them against COARE (and other) data. On the ocean side, Figure 4 shows that neglect of ocean processes in the Warm Pool, below the mixed layer, would lead to unacceptable SST errors in a few months; the spatial inhomogeneity in Figure 4 suggests inhomogeneity in the mixing that occurs in the ocean, possibly largely associated with tidal mixing.

Two results presented or discussed in COARE98 are of particular interest in this context. First, Webster et al. (1998) described an El Nino-like event in the Indian Ocean, in 1997/98. Zonal winds in the central Indian Ocean had typical timescales of 30-60 days, i.e. there appeared to be an MJO character to them. A second result (Slingo et al., this volume) was that MJO intensity has shown a clear increase over the last 40 years, particularly in the mid-1970's when SST increased particularly rapidly in the Indian Ocean.

Both of these results, and the results of Section 2.2, point to an urgent need to investigate the sensitivity of MJO strength to long-term changes in SST — either due to ENSO in the Pacific, or to ENSO-like disturbances in the Indian Ocean, or to any continuance of the present long-term rising trend in SST.

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