The Large Scale Response of the Upper Ocean to Atmospheric Forcing During TOGA–COARE

K.J. Richards and M.E. Inall, Department of Oceanography,
University of Southampton, England

G. Eldin and C. Henin, ORSTOM, Noumea, New Caledonia

During the Intensive Observational Period of TOGA–COARE, from 1 December 1992 to 1 March 1993, high resolution temperature, salinity and current data were collected along 156°E from 5°S–5°N (Delcroix *et al*, 1993). Eighteen north/south sections were made with each section taking approximately 3 days to complete. For 12 of the sections measurements of the upper ocean temperature and salinity were made using a SeaSoar giving approximately 3km resolution in the horizontal down to a depth of 300m. The remaining 6 sections consisted of CTD stations taken at half degree intervals. The hydrographic measurements were supplemented by continuous surface measurements made by a SeaBird thermosalinograph. Throughout the whole period velocity measurements were taken using a hull mounted ADCP.

The large–scale characteristics of the upper ocean along 156° E have been described in Eldin *et al* (1994). Here we will give a brief description of the response of the upper most 100m of the ocean to the changing atmosphere followed by a more detailed study of the changes in the ocean heat content.

The meteorological conditions changed dramatically during the period of the survey, giving a range of forcing conditions for the upper ocean. The survey period includes the December westerly wind event, followed by a strong easterly wind event in mid–February and a second westerly event in February, (see fig. 3, Eldin *el al*, 1994). The intervals between the wind events were periods of light winds. There was considerable latitudinal variation in the distribution of the wind, with the westerly events strongest south of the equator whilst the easterly event was predominantly to the north of the equator. The westerly events produced an homogenisation of the upper ocean with the mixed layer deepening to 100m at the equator. The easterly event caused the thermocline to rise with the mixed layer restricted to 40m depth, despite the strong winds. There was a marked asymmetry about the equator in the changes to both the mixed layer depth and SST. In contrast the change in the depth of the 20°C isotherm is very symmetric with the greatest variation occurring in a band within 1 degree of the equator.

Averaging the measurements with respect to the time of day over the survey period shows a strong diurnal signal. The mixed layer varied from a daytime minimum of around 20m to a nighttime maximum of 50m, with a corresponding diurnal change in near sea surface temperature (taken at 1m) of 0.4°C. (Individual days showed a significantly larger diurnal signal.) Fresh water pools were observed, with a predominance of pools having a reduced surface temperature. However, the times when the difference between the near SST and the temperature at 10m depth was less than -0.1°C accounted for only 5% of the survey period. During 25% of the time the difference between the near SST and 10m temperature was greater than 0.1°C, showing the high frequency of daytime warming events.

Other features of the SeaSoar dataset include, a change in the stratification of the main thermocline with time, a shift in the northward extent of the high salinity core, strong and persistent surface fronts, particularly at 2° S and 4° S, and interleaving of high and low salinity waters across the equator.

Heat Content on 156°E

A principal objective of TOGA COARE is to establish the major factors controlling the temperature of the warm pool. Using the our hydrographic sections we can calculate the change in heat content on 156°E over most of the IOP. The net surface heat flux at 2°S is known from measurements made by the WHOI IMET buoy. Meteorological data at other latitudes is rather limited.

There is some reason to anticipate that the surface layer heat balance be predominantly local and the advective terms small on the long term in this region. Niiler and Stevenson (1982) in considering the annual mean heat budget of the region defined by the 28°C isotherm found that fluxes of heat across lateral boundaries to be negligible. However on shorter time scales advective terms are likely to be important, as was found in a 7 day experiment at 165°E (Richards *et al* 1995), where the advective terms dominated the local rate of change of temperature with values in excess of 200 Wm^{-2}.

To compare the ocean response with the surface heat flux at 2°S, the heat content of the upper ocean was averaged between 0.5°S and 3.5°S (approximately equivalent to a one day mean) and differenced between consecutive sections. To account for some of the effect of vertical advection the temperature profiles were "squashed" or "stretched" according to the vertical displacement of a density surface below the direct influence of surface forcing. The highest correlation with the net surface heat flux was found by considering the top 40m of the ocean.

Figure 1a shows the heat content change of the upper 40m of the ocean compared with the IMET surface heat flux. The time axis is in days with day 0 being 0:00 UT 1 January 1993. The correspondence between the two curves is very good (remember the ocean data are being averaged over 3 degrees of latitude). The ocean heat content change reflects the heating and cooling phases of the surface flux in both amplitude and phase. The correlation coefficient between the two is 0.67. The average over the whole period of the survey for the net surface flux was -13 Wm^{-2} and for the heat content change was -4 Wm^{-2}. The small difference between the two is well within sampling error, supporting the hypothesis of a local heat balance. There is a period around 20 December of positive surface heat flux which is absent in the ocean heat content change. We shall come back to this point later.

Figure 1b shows the heat content change averaged over 2°N–5°N and 5°S–2°S, the northern and southern parts of the section, respectively. The shape of both curves is very similar to that centred on 2°S, although the amplitude of the 15 day oscillation from mid–January to late February is somewhat larger. The phase difference in the positive heat content change around 10 January has important consequences for the latitudinal distribution of the average temperature of the ocean.

Figures 2a and b show the change in the mean temperature of the upper 40m of the ocean averaged over the 3 latitudinal ranges as a function of time (essentially the integral of Figure 1). The change in temperature during the sampling period (two and a half months) is remarkedly uniform over the latitudinal extent of the section. The difference in the net change between the northern and southern parts of the section is around 0.1° C. The exception is the period around 10 January when a difference of 0.8° C develops. This difference can be attributed to

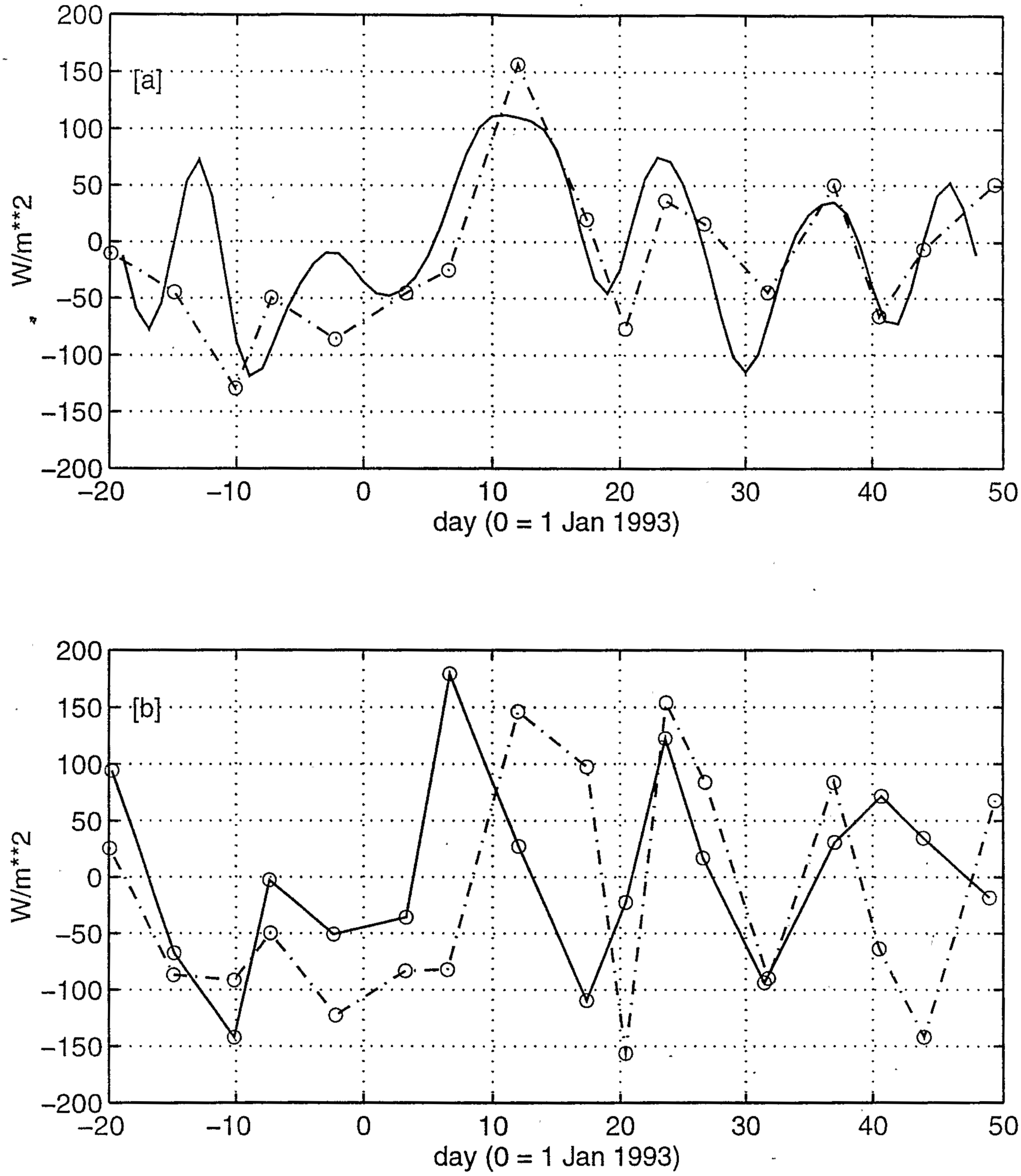

Figure 1: [a](upper panel): Heat content change averaged from 0.4°S to 3.6°S (dash-dot line) for the 0–40 m layer. Net surface heat flux from IMET Buoy with six day low pass filter applied (solid curve). [b](lower panel): Heat content change 1.7°N to 5°N (solid line). Heat content change 1.7°S to 5°S (dash-dot line).

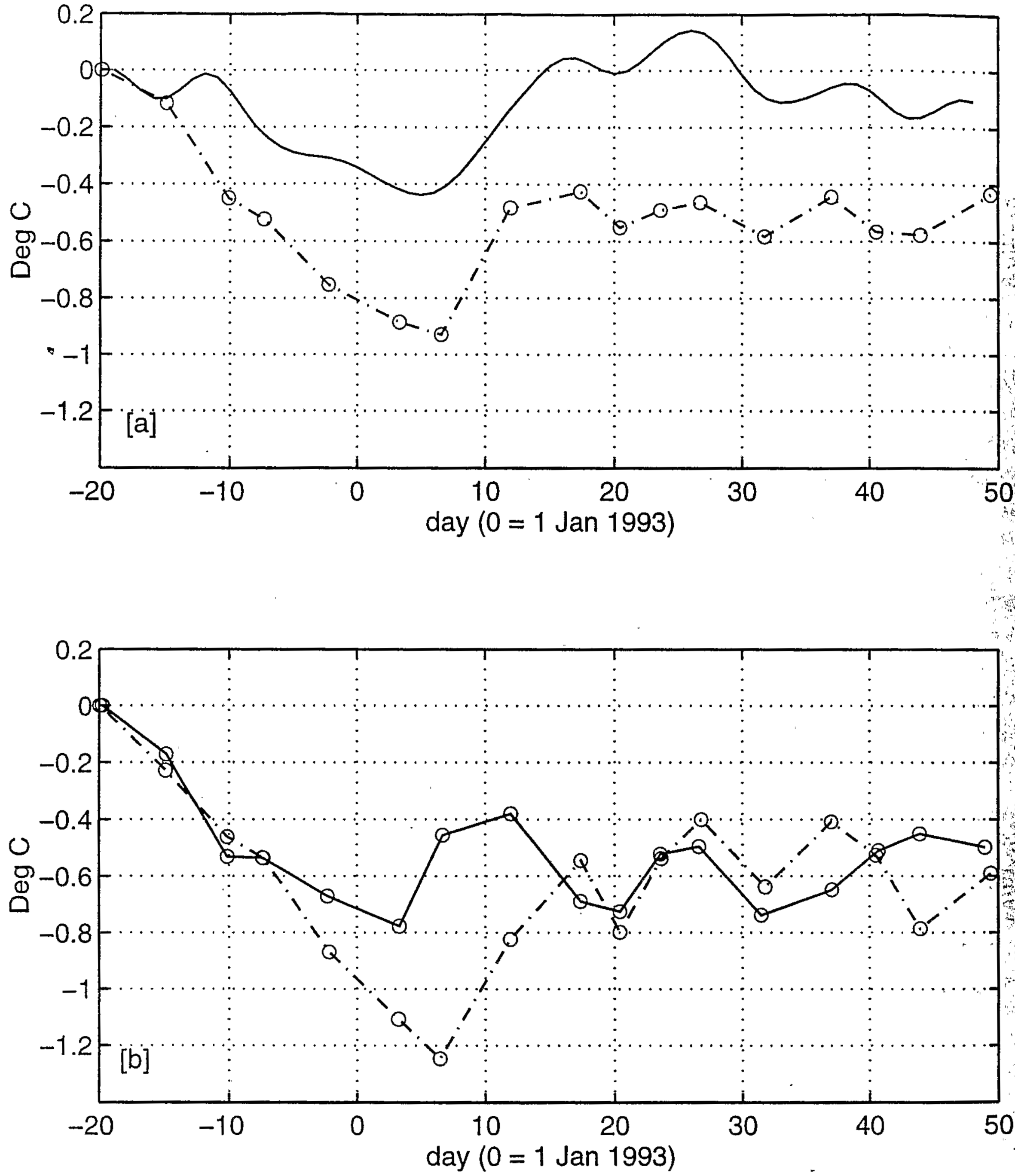

Figure 2: [a](upper panel): Average temperature change 0–40 m averaged from 0.4°S to 3.6°S (dash-dot line). Time integral (divided by $(C_p \times \rho \times 40\,\mathrm{m})$) of IMET net heat flux at 2°S. [b](lower panel): Average temperature change 1.7°N to 5°N (solid line) and 1.7°S to 5°S (dash-dot line).

the difference in timing with latitude of the warming event caused by the lull in wind speed between the westerly and easterly wind events.

Also shown in Figure 2a is the implied change in temperature from the surface heat flux measurements. Over the sampling period the net decrease in temperature is some 0.4°C less than that observed. This difference in temperature is brought about partially by the positive surface heat flux around 18 December but also by the more rapid cooling of the ocean than that implied by the surface flux from 20 December through to 7 January . The extra cooling during this time is commensurate with estimates of the zonal advection of heat from buoy data (Niiler, personal communication).

Although we not have surface heat flux measurements from other latitudes the TAO winds allow us to estimate the wind stress along the section as a function of time. The TAO winds have been objectively analysed and averaged over the 3 degree latitude bands. The correlation between the TAO and IMET wind stress estimates is very strong (coefficient 0.94) and there is a strong correlation between the wind stress and surface heat flux (−0.65) principally through the latent heat flux. Assuming that this correlation holds over all latitudes we can compare the ocean heat content change with the wind stress. Centred on 2°S the correlation coefficient between TAO wind stress and ocean heat content change is −0.62. The correlation coefficient drops to -0.4 for both the northerly and southerly latitude bands. This is not surprising since the wind stress has a large latitudinal variation.

These results pose an interesting question. Why is the ocean response, in terms of the heat content, so coherent across 10 degrees of latitude when the wind stress, and presumably the surface heat flux, show large variations? It could be that our reliance on wind stress as an indicator of surface heat flux changes is inappropriate. It could be that away from the equator zonal and meridional advection is playing a role on these time scales. Examination of the spatial and temporal structure of those events that cause the largest ocean heat content change may provide the answer.

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