Air-sea interaction on intraseasonal timescales and its implications for the representation of the upper ocean for medium and extended range prediction

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ABSTRACT

The correct representation of the Madden-Julian Oscillation in GCMs used for extended range prediction is important for both medium range and seasonal forecasting. Atmospheric GCMs typically have a poor representation of the MJO and the well document impact of the MJO on SST has led to speculation that the MJO may be a coupled ocean-atmosphere phenomenon. However, coupled GCMs have shown only marginal improvement (if any) in their representation of the MJO. One possible source of errors in these coupled models may be the representation of the upper ocean. Using a 1D mixed layer model, it is shown that the modelled SST (and mixed layer) response to the MJO is sensitive to the representation of the upper ocean and the surface forcing.

1 Introduction

The Madden-Julian Oscillation (MJO) and other tropical variability on intraseasonal timescales provides a potentially important source of predictability on weekly and longer timescales. Within the Indian Ocean and west Pacific region the MJO has been shown to be associated with the variability and onset of the Australian summer monsoon (Hendon and Leibmann, 1990) and has been associated with the active/break cycles of the Indian Summer Moonson (e.g. Lawrence and Webster, 2002). These links imply that a model which is able to maintain and propagate a Madden-Julian Oscillation which exists within the initial conditions of a model will have some predictability locally on timescales of the order of a few weeks. In addition to this local (in time and space) predictability, the Madden-Julian Oscillation has been linked to intraseasonal variability in other regions of the tropics and extra-tropics, for example Matthews (2002) has proposed a mechanism by which the MJO may trigger intraseasonal variability in convection over west Africa, and Higgins and Mo (1997) show a link between the eastward extension of the Pacific jet and the passage of the MJO through the tropical west Pacific.

The Westerly Wind Bursts in the west Pacific associated with the passage of the Madden-Julian Oscillation have been shown to be important for simulating the evolution of at least some El Niño events (e.g. McPhadden and Yu, 1999; Lengaigne *et al.*, 2002). Through this rectification of intraseasonal variability onto the longer timescales, the presence of a realistic MJO in dynamical models for seasonal prediction may improve the prediction of El Niño in these models and hence lead to predictability on timescales much longer than those associated with the MJO. However it should be noted that Slingo *et al.* (1999) found that the interannual variability in MJO activity appears to be unpredictable in an atmosphere only GCM forced by prescribed SSTs and so whilst an accurate representation of the MJO may lead to a better representation of the development of El Niño in coupled models, it may increase the spread in an ensemble of forecasts.

The potential impact of the MJO on prediction for timescales from a few weeks to seasonal (and beyond) highlights the importance of an accurate representation of the MJO in dynamical models used for extended range prediction. Atmospheric General Circulation Models (GCMs) generally show little skill in simulating the MJO, indeed many of the models used for NWP in medium range weather forecasting are incapable of maintaining an MJO which is present in the initial conditions of the forecast (e.g. Jones *et al.* 2000)

The apparent lack of skill in simulating the MJO in both operational forecasts and atmospheric GCMs for climate simulations could be due to any of a number of potential sources of errors. The most likely source of error within in atmospheric GCMs is the convection scheme; studies such as Wang and Schlesinger (1999) have shown that the simulated MJO in an atmospheric GCM is sensitive to both the choice of convection scheme and the choice of parameter values within a convection scheme. Furthermore, Inness *et al.* (2001) have shown that the simulation of the MJO in the Met Office Unified Model version HadAM3 is sensitive to the vertical resolution, primarily through differences in the behaviour of the convection scheme at different resolutions.

As well as the potential weaknesses in atmosphere only GCMs a further potential source of error in the representation of the MJO may arise in the absence of an interactive ocean. Flatau *et al.* (1997) proposed a coupled atmosphere-ocean mechanism for the MJO based on a limited number of observations. Analysis of the intraseasonal variability of SST and surface fluxes in much larger datasets (e.g. Woolnough *et al.*, 2000) confirmed the relationship between surface fluxes, SST and convection associated with MJO for the coupled mechanism of Flatau *et al.* (1997).

Figure 1, taken from Woolnough *et al.* (2000), shows the relationship between 20-100day bandpassed anomalies of surface fluxes from the ECWMF Reanalysis and operational analyses, Reynolds SST and NOAA AVHRR OLR. A full description of the figure can be found in Woolnough *et al.* (2000). Each point in the figure shows the time of significant maximum and minimum lag correlations between each of the surface fields and OLR. Across the region there is a coherent relationship between the convection, surface fluxes and SST on intraseasonal timescales.

Before periods of enhanced convection there is a maximum in the surface heat flux due to enhanced shortwave fluxes and reduced evaporation (easterly anomalies on a westerly mean leads to a reduced wind stress and hence reduced evaporation), and the positive surface flux anomalies into the ocean lead to a maximum SST about 10 days before the maximum in convection. Associated with the enhanced convection there is a reduction in the surface shortwave flux, and lagging the convection by up to 5 days, there are enhanced surface westerlies and increased evaporation. These negative surface flux anomalies lead to a minimum in SST about 10 days after the enhanced convection.

Despite the strong evidence that the MJO impacts on the upper ocean, it has been difficult to determine through modelling studies whether such intraseasonal variability in SST can feedback on the convection associated with MJO. A number of simulations with coupled GCMs with oceans of varying complexity have shown limited improvements in the simulation of the MJO on coupling to an interactive ocean. (e.g. Waliser *et al.*, 1999; Inness and Slingo, 2002) and indeed some studies (e.g. Hendon, 2000) show almost no impact on the simulation of the MJO on coupling to an ocean model. However, the absence of a substantial improvement in the simulation of the MJO in these integrations is not sufficient to discount such a mechanism for the MJO. Inness *et al.* (2002) show that within a coupled framework the simulation of the MJO is sensitive to the basic climatology of the model, for example the proposed coupled mechanism relies on basic state surface westerlies in the Indian Ocean and west Pacific; if these westerlies are absent from the coupled model climate (as is often the case) then the response in the surface fluxes will be wrong and the possibility of simulating a coupled MJO is removed.

In addition to errors in the basic state leading to errors in the simulation of the MJO a further possible source of errors exists in the representation of the upper ocean processes in coupled GCMs. Inness *et al.* (2002) showed that the coupled model is able to produce intraseasonal surface flux anomalies comparable magnitude to those from observations, but that these flux anomalies produce SST anomalies which are too weak. Observations

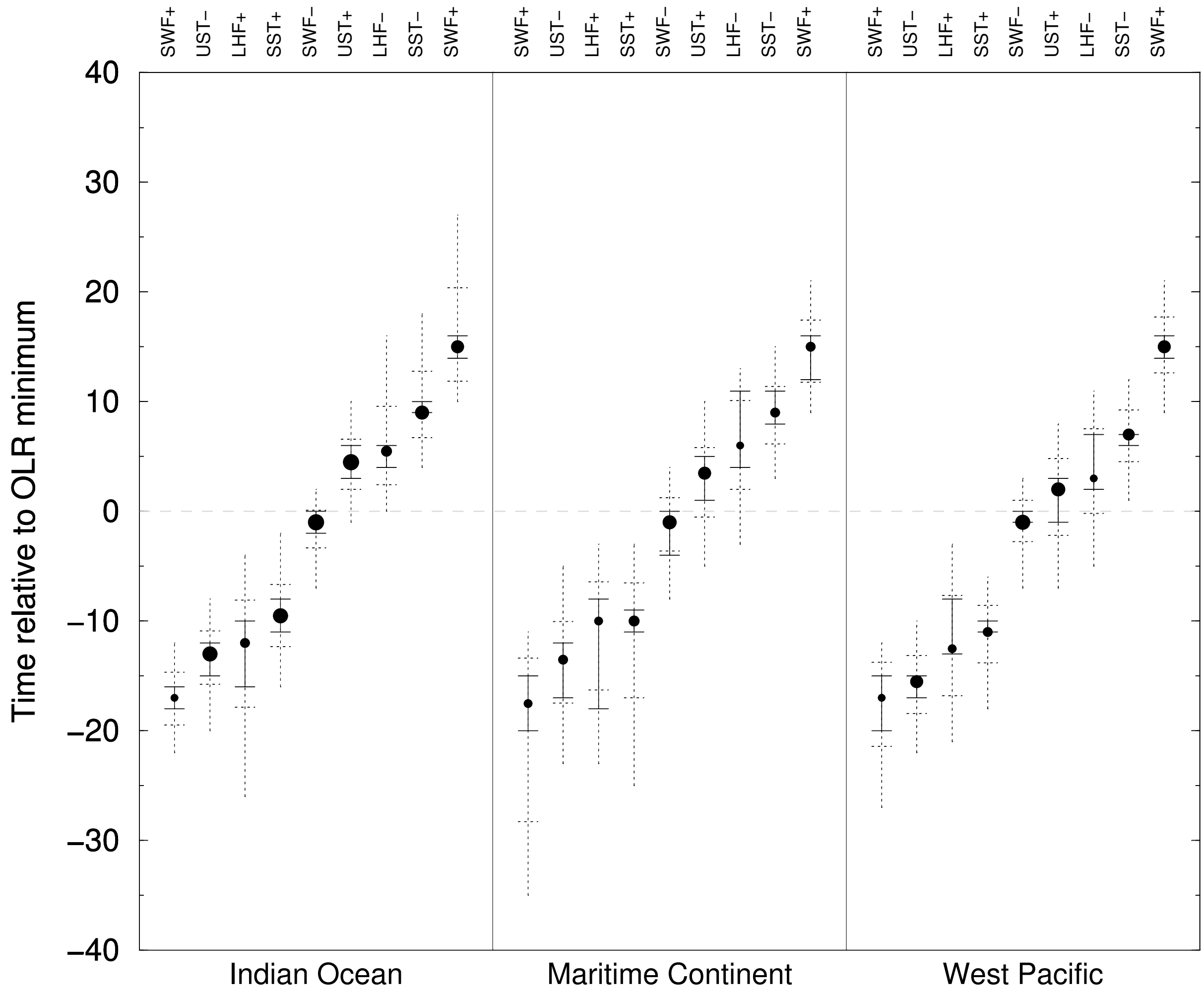

Figure 1: Summary of the temporal relationships between the convection and surface fields (shortwave flux, zonal wind stress, latent heat flux and SST). The dots indicate the lags at which extrema in correlation coefficients occur for 15 years of data. The labels along the top axis indicate the type and sign of the surface anomaly associated with a minimum in OLR (maximum in convection) at the given lag. Taken from Woolnough et al. (2000) (see the article for a full description of the figure)

from the TOGA-COARE Intensive Observing Period (IOP) (Anderson *et al.*, 1996) indicate that the mixed layer depth during light winds can become significantly shallower than 10m (the typical thickness of the top layer of ocean models in coupled GCMs), and show significant diurnal variability (coupled GCMs typically only pass daily mean fluxes from the atmosphere to the ocean). These weaknesses could contribute to a significant underestimation of the intraseasonal variability in SST in coupled GCMs, and hence, if these SST anomalies are important for the variability of the convection, to errors in the representation of the MJO in coupled models. This paper will describe the results from some simple sensitivity tests with a 1D mixed layer model to investigate the impact of some these errors in the representation of the mixed layer on intraseasonal SST variability. Section 2 will describe some observations from the TOGA-COARE IOP and section 3 will describe some sensitivity experiments with a 1D mixed layer model.

2 Observations of intraseasonal SST variability

Figure 2 shows the SST (actually at 0.46m below the surface) and 9.77m temperature from the IMET Mooring deployed at 1°45'S 156°E, during the TOGA-COARE IOP (see Weller and Anderson (1996) for a more complete description of the mooring and observations). Two features stand out in this timeseries. There is strong intraseasonal variability in the temperature at 10m with a peak to peak amplitude of the order of 1°C. These variations are closely linked to the variations in surface fluxes associated with the passage of the MJO as described above. In addition to this intraseasonal variability of the 10m temperature there are periods with a pronounced diurnal signal in SST with a peak elevation of the SST above the 10m temperature regularly exceeding 1°C and occasionally reaching in excess of 2°C. Note that the diurnal signal is not apparent in the 10m temperature trace. These periods of strong diurnal variability occur during the warming phase of the intraseasonal variability and will act to elevate the mean SST above that of the 10m temperature and enhance the intraseasonal variability of SST that would otherwise occur in the absence of this diurnal signal. Figures 3 and 4 show the net surface heat flux and total wind stress during the IOP. There is strong diurnal variability in the surface fluxes throughout the period, because of the large shortwave forcing, but the periods of strong diurnal signal in SST are most closely related to periods of very low wind stress, rather than an enhancement of the diurnal variability in surface fluxes.

Figure 5 shows a time-depth cross section of the temperature for the period 1-20 January 1993, which includes one of the periods of strong diurnal variability in SST, accompanied by an intraseasonal warming of the mixed layer. Initially during a period of strong windstress the upper ocean is well mixed down to 30m and below. During the period 8-17 January the windstresses are low and a very strong diurnal SST signal develops which is concentrated in the top 2-3m of the ocean with very little penetration below 5m. During this period there is a slow warming of the upper ocean with the depth to which the warm water extends increasing gradually throughout the period.

3 Modelling of intraseasonal SST variability

This section describes some sensitivity experiments with a 1D mixed layer model driven by the surface fluxes from the IMET mooring. The model uses the KPP vertical mixing scheme of Large *et al.* (1994) and includes a representation of the penetration of shortwave radiation following Paulson and Simpson (1977). The control integration uses 1 hourly fluxes at the IMET mooring (version 2.5b of the IMET BUOY FLUX DATA). The control integration has 100 points in the vertical over a 200m domain with a stretched vertical grid such that the resolution near the surface is 0.5m. Figure 6 shows the temperature from the top model level (0.25m) in the control integration, along with the SST (0.46m) from the observations for comparison. There is a small drift in SST (of about 1°C) compared to the observations over the duration of the integration but generally the model captures the variability in the observations well. In particular the intraseasonal variability and diurnal variability is well resolved. However, the model systematically underpredicts the large diurnal warming events but captures the amplitude well for smaller events. These errors may arise from a weakness in the model under such conditions, but it is possible that the model is particularly sensitive to errors in the flux dataset in such conditions. Figure 7 shows a temperature depth cross section for the same period as figure 5. The model captures the vertical structure of the diurnal and intraseasonal SST variability well.

3.1 Sensitivity to resolution

Figure 8 shows the SST timeseries from an integration with a vertical resolution of 10m and daily mean flux data, designed to replicate the typical resolution and coupling frequency of a coupled GCM. Clearly under such

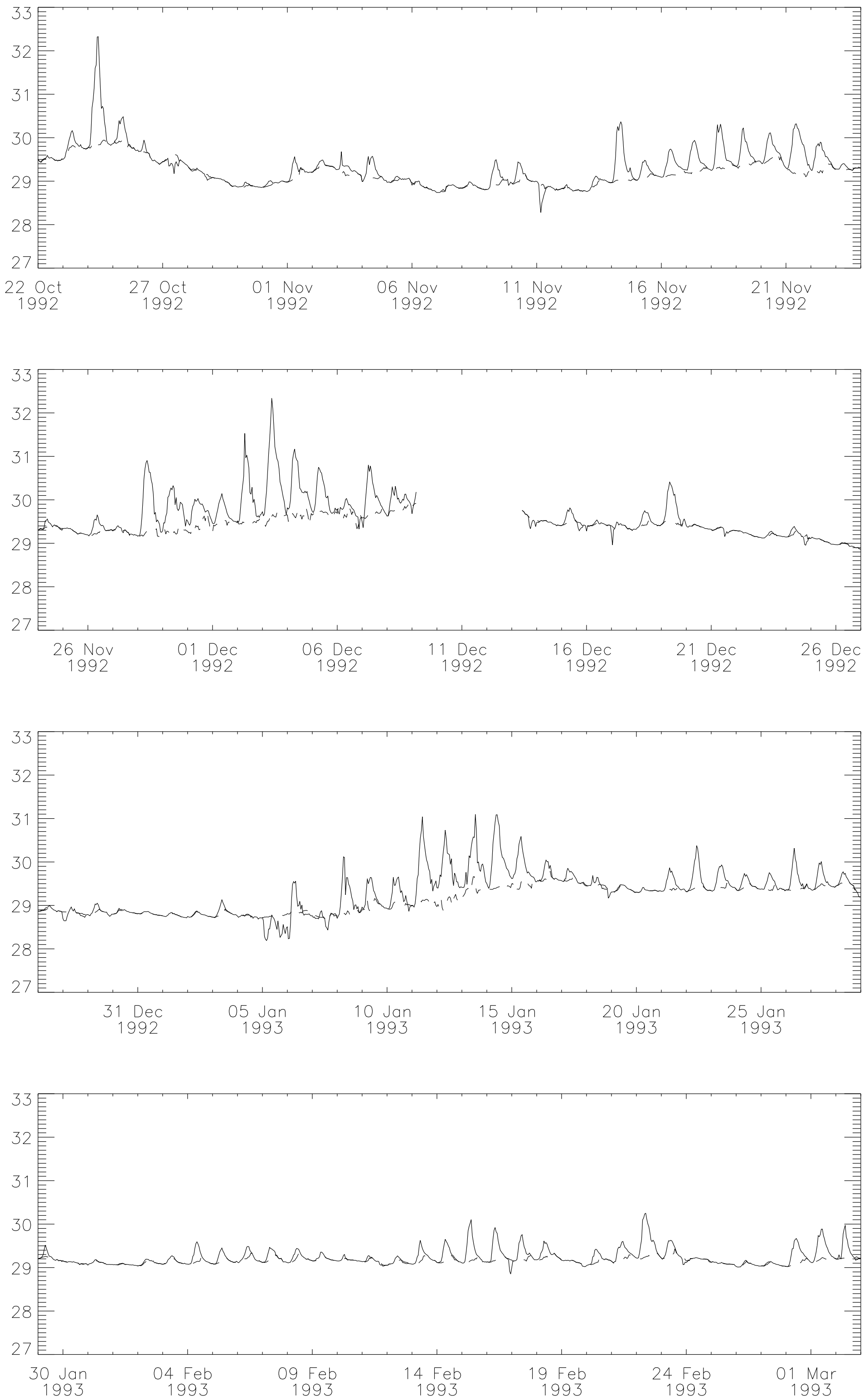

Figure 2: SST (0.46m depth, solid line) and 9.77m depth (dashed line) temperature from the IMET mooring during the TOGA COARE Intensive Observing Period

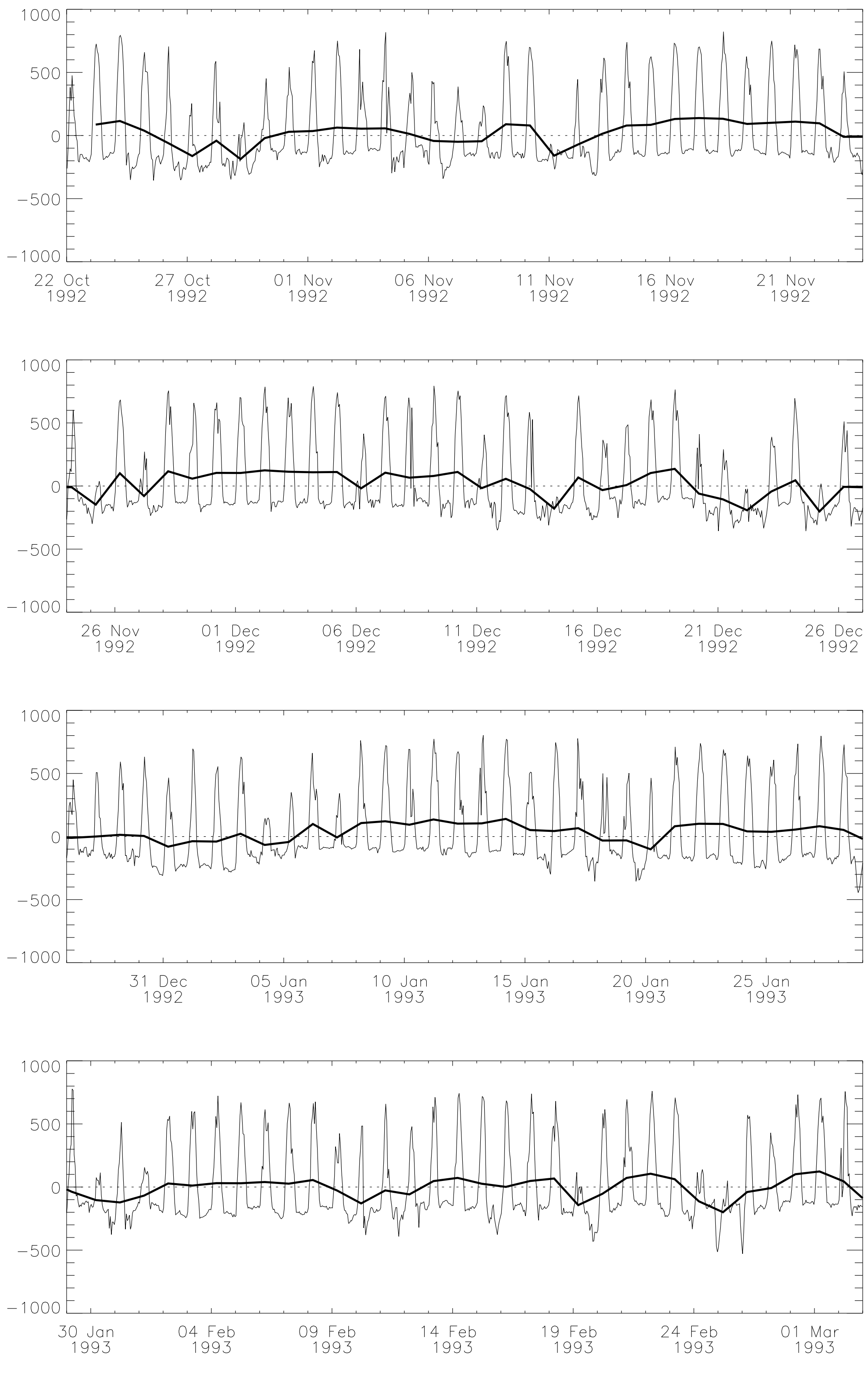

Figure 3: Net surface heat flux (W m^{-2}) from the IMET mooring site during the TOGA COARE IOP. The thin line shows that hourly mean fluxes, the thick line shows the daily mean fluxes.

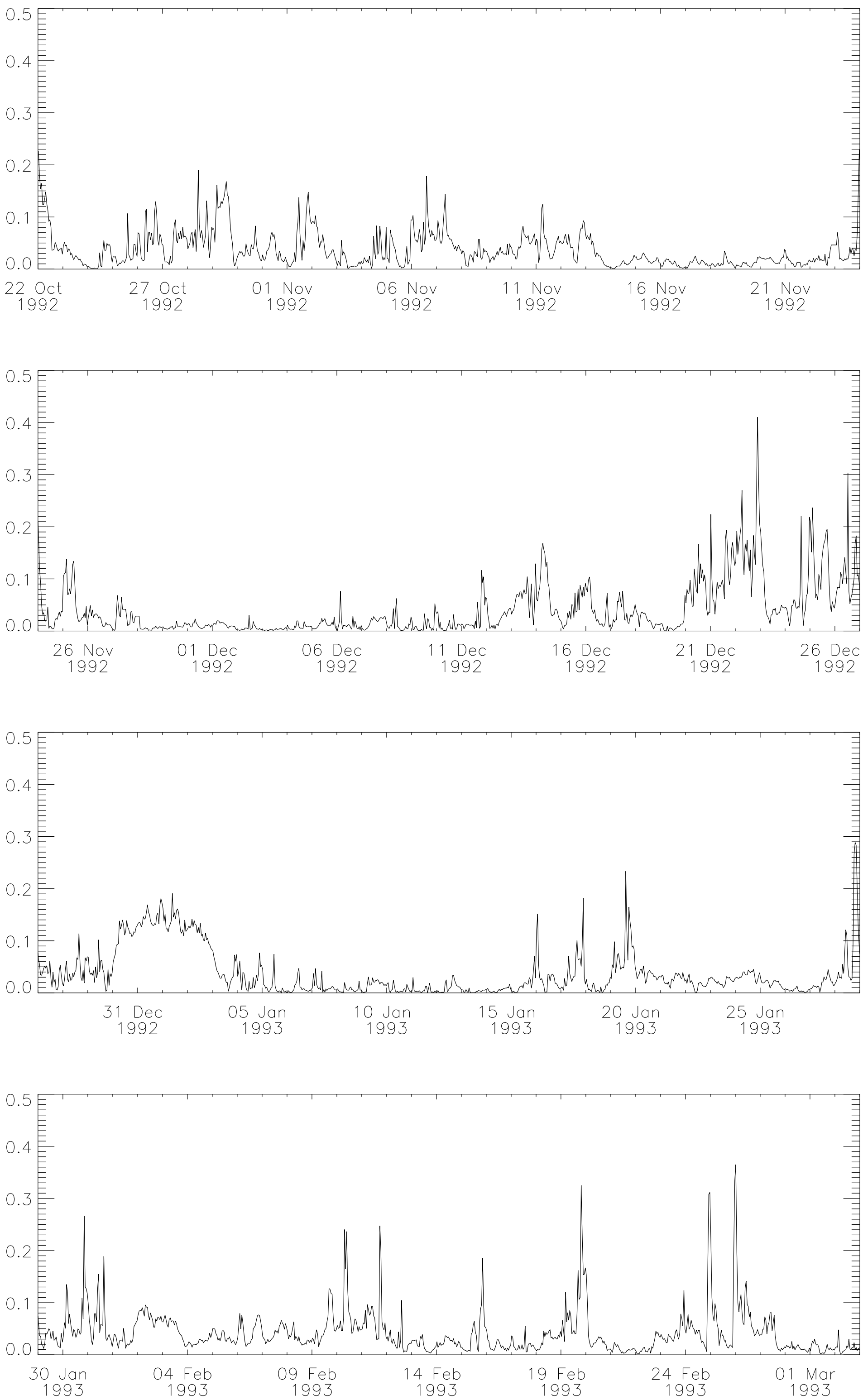

Figure 4: Total surface wind stress ($N\,m^{-2}$) from the IMET mooring site during the TOGA COARE IOP

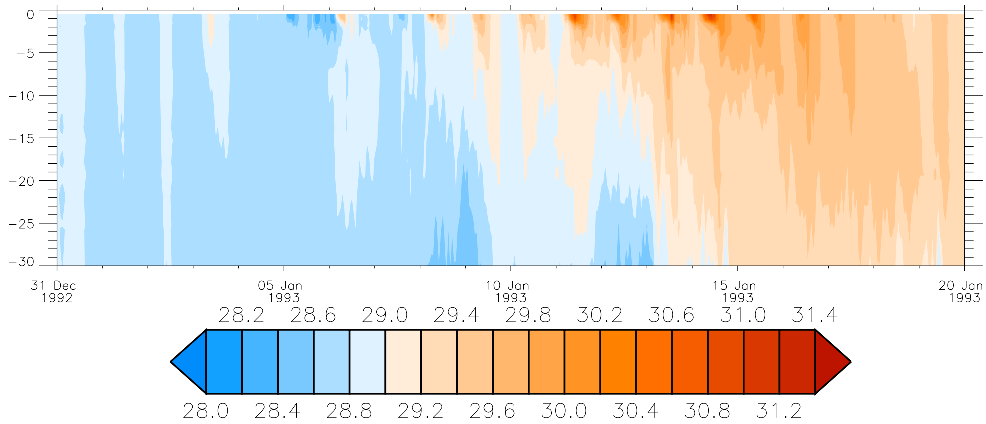

Figure 5: Time-depth cross section of temperature at the IMET mooring site during a 20 day period of the TOGA COARE IOP, during which a strong diurnal cycle in SST was observed.

conditions the model will not be able to capture the diurnal variability, because of the temporal resolution of the forcing. Despite the absence of the diurnal forcing in the fluxes, the evolution of the model 5m temperature in this integration is very close to the 5m temperature from the control integration (not shown). The model captures the bulk temperature well, but essentially misses the elevation of the daily mean SST due to the rectification of the diurnal cycle during light winds. Improving the temporal resolution of the surface fluxes to 1 hour, but using the same vertical resolution introduces a small diurnal signal in SST (about 0.2°C), but still much weaker than in the control integration.

3.2 Sensitivity to wind stress

Figure 9 shows the SST from an integration of the model in which the windstress is held fixed at the mean value for the period (0.039N m^{-2}). The intraseasonal variability in the magnitude of the diurnal cycle of SST is underestimated in this integration. There is a very small increase in the magnitude of the diurnal cycle compared to the control integration during strong wind stress conditions and a very large decrease in the magnitude of the diurnal cycle compared to the control integration during low wind stress conditions. In addition to these changes in the strength of the diurnal cycle there is a significant decrease in the intraseasonal variability of the SST. In fact during the low windstress periods the integration with fixed windstress can have SSTs as much as 0.5 °C below the 10m temperature of the control integration. Figure 10 shows the vertical cross section of temperature during the same period as figure 5. It is clear that the temporal evolution of the mixed layer during this period is very different from that of the control integration (figure 7), with no evidence of the shoaling of the mixed layer during this period, leading to the much weaker SST variability.

4 Conclusions

The observations from the TOGA COARE IOP described in section 2 show clear evidence of a strong diurnal signal in SST during light wind conditions. This strong diurnal signal will rectify onto the daily mean SST during these periods and, because these periods occuring during warmings associated with the break phase of the MJO, it will act to enhance intraseasonal variability in SST over that of the deeper 'mixed' layer.

1D processes, as modelled by a good vertical mixing scheme, are sufficient to capture most of the features

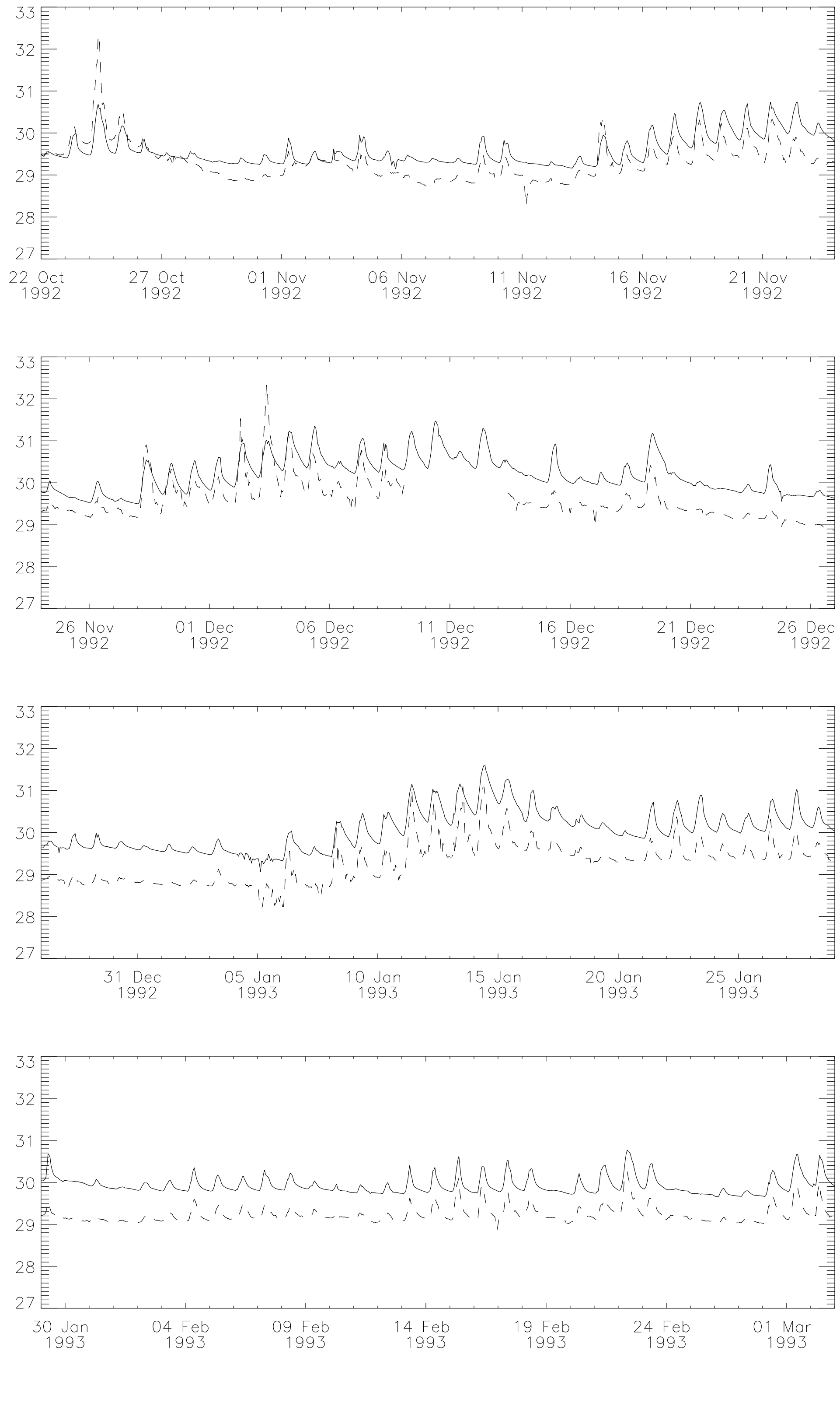

Figure 6: SST (0.25m,depth) for and integration of the 1D mixed layer model forced with surface fluxes from the IMET mooring. The dashed line shows the observed SST (0.46m depth) for the same period.

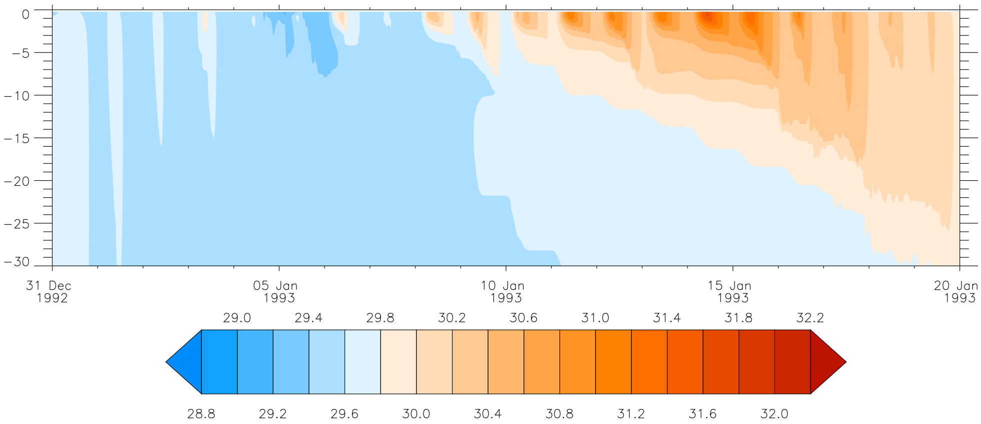

Figure 7: Time-depth cross section of the temperature from the 1D model forced by the surface fluxes from the IMET mooring. The time period is the same as that shown in figure 5. The colour scale has been shifted by 0.8°C compared to figure 5 to compensate for the difference between the SST from the model and observations at the start of this period.

of the intraseasonal and diurnal variability of the SST. The corollary of this is that, to properly represent the intraseasonal and diurnal variability of SST the 1D process in our models must be properly represented. In particular the vertical resolution of typical coupled GCMs is not sufficient to capture the diurnal variability in SST, even if forced at sufficiently high temporal resolution, leading to an underestimate of the intraseasonal variability of SST.

As well as ensuring that the upper ocean is well represented both in terms of the vertical resolution and a good parametrization of vertical mixing, the sensitivity of SST to wind stress, shown in section 3 indicates that it is important that GCMs are able to capture properly the variability in surface windstress. In particular the very low wind stress conditions, during which the diurnal cycle is large and the shoaling of the mixed layer contributes significantly to the intraseasonal warming of the SST, are important for capturing the full intraseasonal variability in SST.

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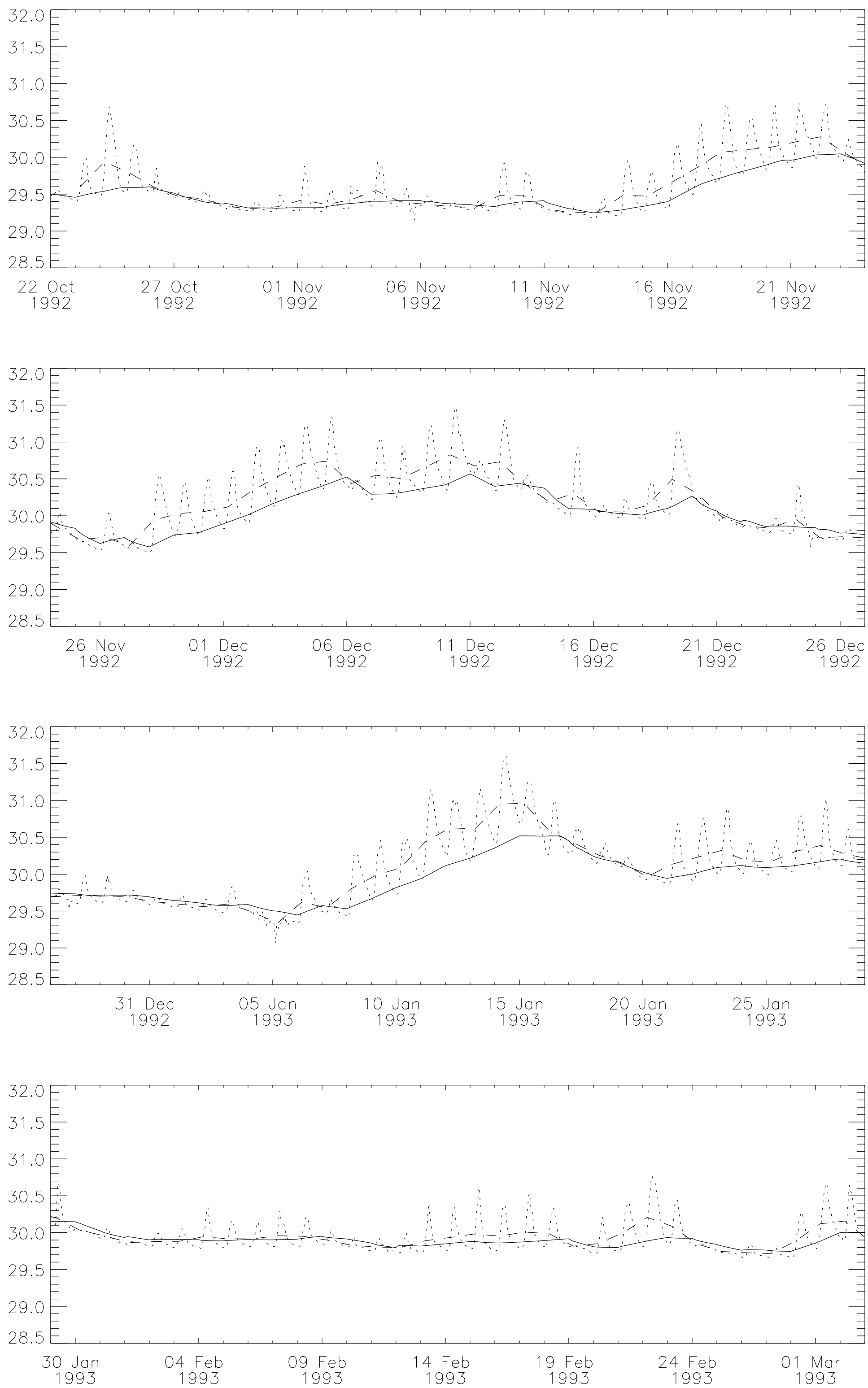

Figure 8: SST (5m depth) from an integration of the 1D model with a vertical resolution of 10m forced by daily mean fluxes. The dotted line shows the SST from the control integration of the 1D model. The dashed line shows the daily mean SST from the control integration, it highlights the difference between the daily mean SST in the two integrations during light wind conditions.

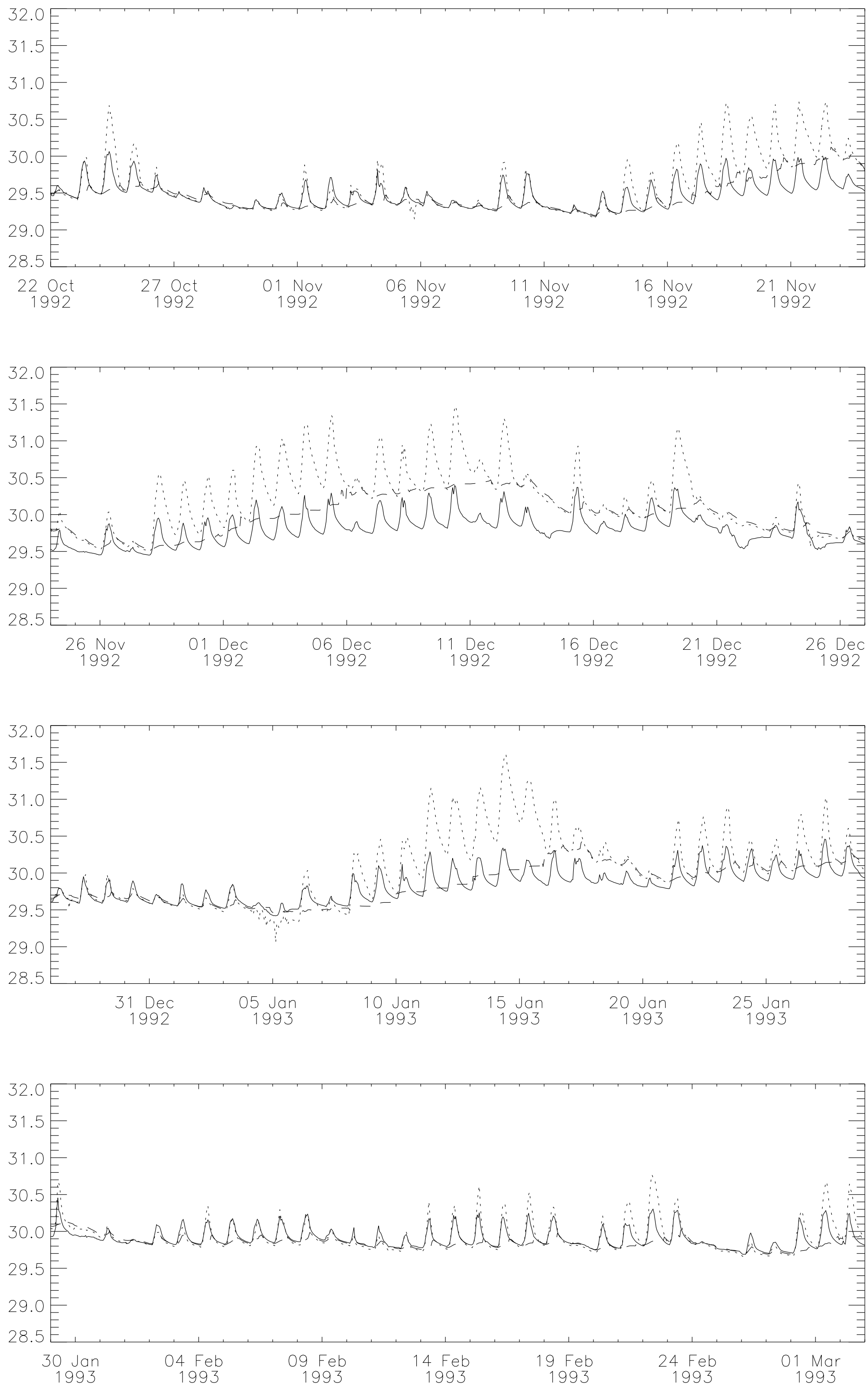

Figure 9: SST (0.25m depth) from and integration of the 1D model with the windstress fixed to the time mean value for the IOP ($0.039Nm^{-2}$). The dotted line shows the SST from the control integration and the dashed line shows the 9.77m temperature from the control integration.

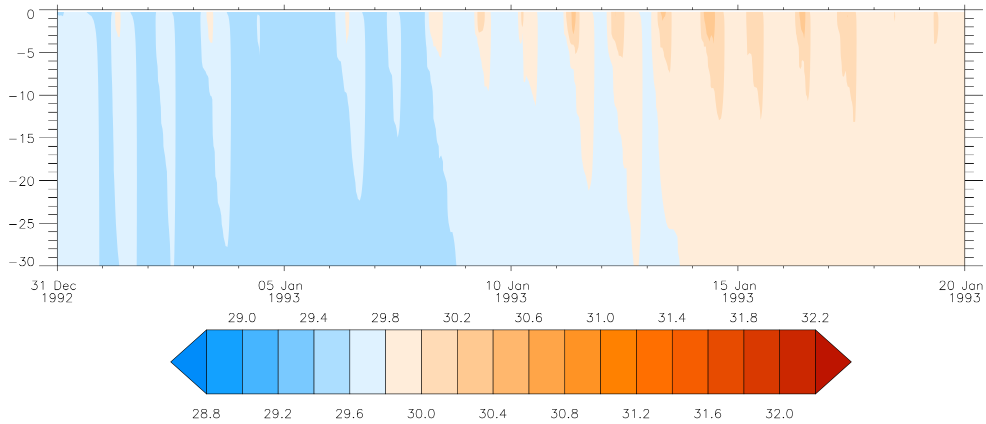

Figure 10: Time-depth cross section of the integration of the 1D model with fixed windstress of 0.039N m^{-2}. The time period and colour scale are the same as that for figure 7.

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