The effect of seasonally varying optical properties of the Arabian Sea on SST biases and the Indian summer monsoon in a coupled GCM

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Introduction

Although coupled GCMs make a reasonable simulation of the seasonal cycle in the Arabian Sea, there are cold biases present, particularly in the north during boreal winter and spring in many of the CMIP3 models (Marathayil *et al.*, 2011). Anomalous precipitation over India during the summer months is linked with changes in the moisture supply from the Arabian Sea (see Fig. 1) and Levine & Turner (2011) have shown cold biases here to be detrimental to monsoon simulation.

- The strong seasonality in chlorophyll blooms in the region (Fig. 2) is predominantly related to mixed layer processes (Lévy *et al.*, 2007), themselves related to monsoon dynamics. Chlorophyll maxima increase the fraction of solar radiation absorbed in the top few metres of ocean.

- We study the effects of chlorophyll on Arabian Sea SST and the moisture supply to India first using a simple test of changing turbidity, and secondly a parameterization of prescribed chlorophyll concentrations in a fully coupled ocean-atmosphere GCM.

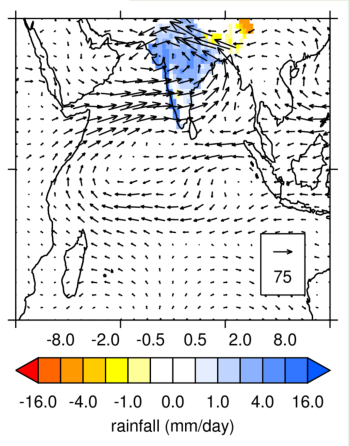


Fig 1: Composite difference of JJAS ERA-40 vertically integrated moisture flux and IMD rainfall between strong and weak monsoons.

Experiment design

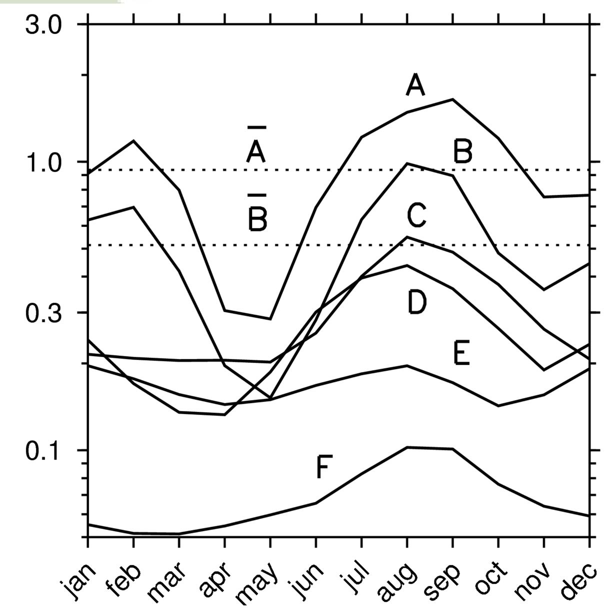
We use the HadCM3 coupled model (atmosphere: 3.75˚x2.5˚, L19, Pope *et al.*, 2000; ocean: 1.25˚x1.25˚, L20, Gordon *et al.*, 2000) which can reasonably simulate the South Asian summer monsoon (Turner *et al.*, 2005).

- Simple modifications are made to the Jerlov water type between type IB (clear water) and type III (turbid water, associated with chlorophyll blooms; see *e.g.* Paulson & Simpson 1979). In this *fixed* sensitivity test, the water type is set to type III in all seasons in the Arabian Sea only (north of ~9.5˚N).

- In more complex experiments, the two-band radiation scheme of the ocean model is modified such that the penetration of red and blue wavelengths is perturbed according to the concentration of chlorophyll present in the upper ocean, following Ohlmann (2003). We prescribe chlorophyll via the SeaWiFS-observed dataset presented in Lévy *et al.* (2007), who provide concentrations every 8 days over the Indian Ocean. We interpolated these data to monthly mean values on the 1.25° grid of the ocean model and perform experiments prescribing annual mean (*ann_mean*) and varying (*ann_cycle*) chlorophyll over the Arabian Sea only. Elsewhere low values of 0.05mg/m³ are used.

- Comparisons are made between 50 year experiments/controls.

Fig 2: Annual cycle of chlorophyll concentration at A: western Arabian Sea, B: central Arabian Sea, C: Lakshadweep Sea, D: SW Bay of Bengal, E: central Bay of Bengal, F: south-central Indian Ocean in the Lévy *et al.* (2007) dataset as interpolated to the 1.25° grid of the ocean model. Annual means are also shown for A & B regions.



Sensitivity test

Increasing the turbidity of the upper ocean in the *fixed* sensitivity test results in a shoaled mixed layer throughout the year (not shown) owing to stabilization of the vertical temperature profile.

- Throughout spring and early summer, the reduced MLD leads to surface warming. Following the monsoon onset (and also in boreal winter), the surface is cooled, enhancing the seasonal cycle and reducing the model bias (see Fig. 3).

- SST warming (cooling) in early (late) summer lead to enhanced (reduced) evaporation and atmospheric moisture, enhancing (reducing) monsoon precipitation as shown in Fig. 4.

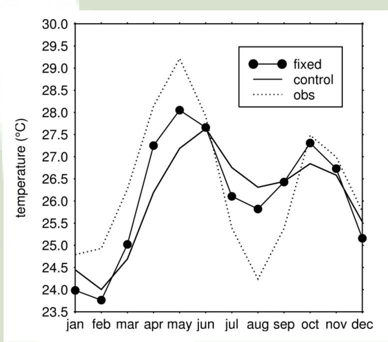
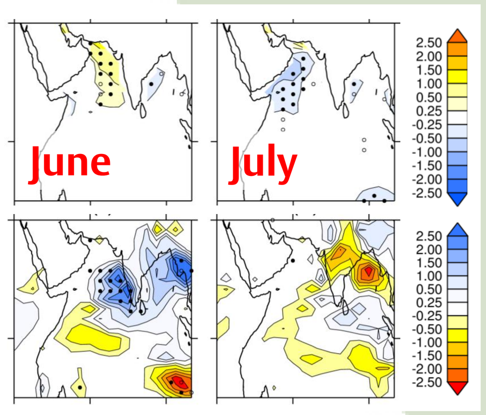


Fig 3: Seasonal cycle of SST averaged over 58-62°E, 15-18°N in HadISST observations, *control* and *fixed* experiments.

Fig 4: Differences between *fixed* and *control* experiments for SST (top) and precipitation (bottom) in June (left) and July (right).



Prescribed chlorophyll experiment

Impacts of the *ann_cycle* experiment on various field in boreal spring and summer are shown in Fig. 5.

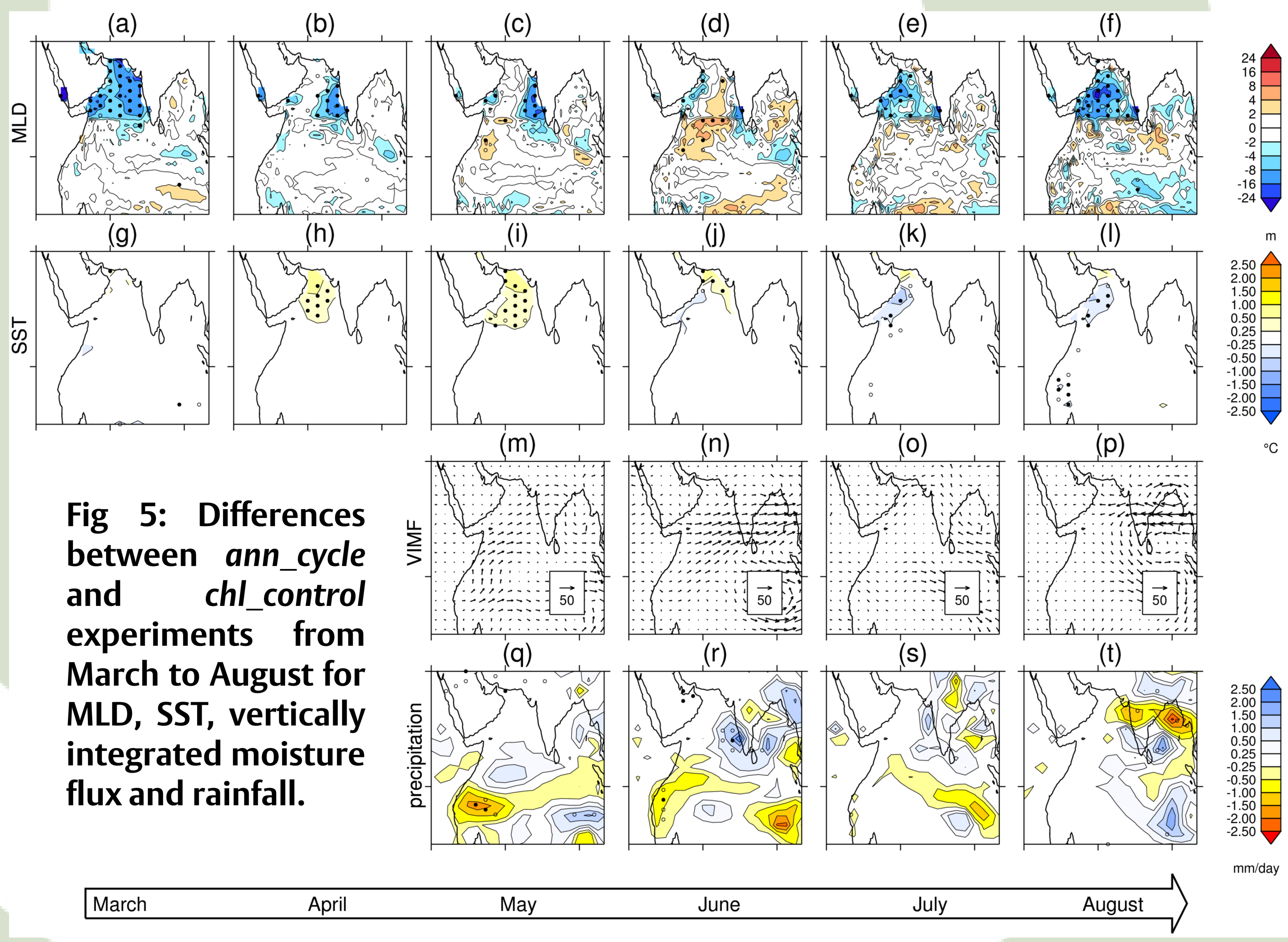


Fig 5: Differences between *ann_cycle* and *chl_control* experiments from March to August for MLD, SST, vertically integrated moisture flux and rainfall.

- Strongest mixed layer shoaling occurs during the equinoctial periods. Significant SST warming in late spring and early summer leads to increased evaporation (not shown) and stronger moisture fluxes incident on India. This leads to enhanced rainfall during the monsoon onset.

- Once the monsoon winds across the Arabian Sea have fully developed, the impact on SSTs is a net cooling, leading to reduced moisture fluxes and (insignificant) reductions in rainfall over India.

Discussion

To understand the alternate warming and cooling response in SST during late spring/summer we examine mixed layer depth (Fig. 6) and temperature tendencies in the upper ocean caused by various processes (Fig. 7).

- The mixed layer deepens in summer and winter owing to strengthening of the SW and NE monsoon winds. This rapid deepening is also associated with the influx of nutrients and supports chlorophyll blooms, especially in late spring (Fig. 2 and Lévy *et al.*, 2007).

- When the climatological mixed layer is shallow (*e.g.* in April) enhanced chlorophyll acts to warm the surface. The anomalous cooling region is found below the mixed layer and thus well separated from the surface.

- During deep mixed layer regimes, near surface warming and its shadow are encompassed entirely within the layer, resulting in no net surface warming. However, the mixed layer is shoaled by stabilization and so climatological net cooling tendencies act over a smaller heat capacity, enhancing the seasonal cycle of surface cooling.

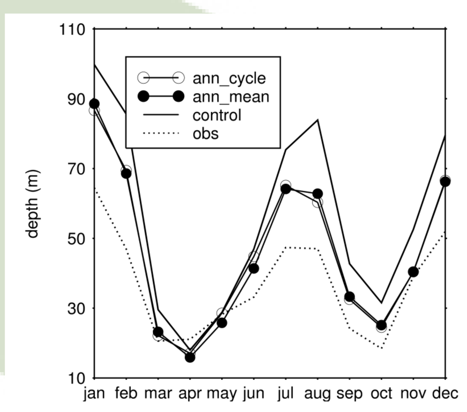
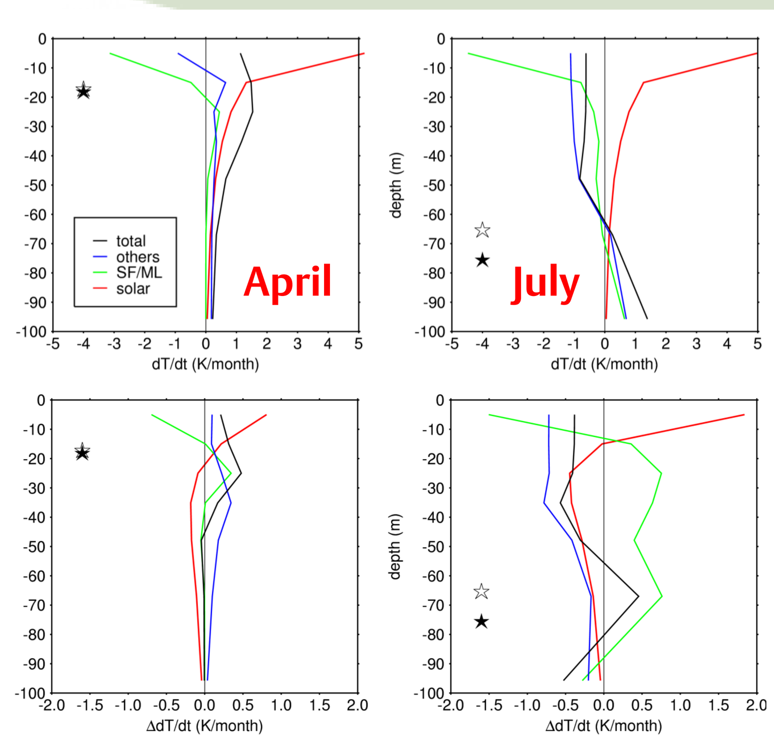


Fig 6: Seasonal cycle of mixed layer depth over 58-62°E, 15-18°N in L'OCEAN observations and control, *ann_mean* and *ann_cycle* experiments.

Fig 7: Contributions to ocean temperature tendencies over 58-62°E, 15-18°N from solar radiation, surface fluxes and mixing and other terms in the *control* experiment during April and July (top) and their change in *ann_cycle* (bottom). Solid (empty) star shows MLD in *control* (*ann_cycle*) experiments.



Conclusions and outlook

- **Given the importance of moisture fluxes across the Arabian Sea to realistic simulation of the monsoon and its variability, there is a need to reduce biases in the region.**
- **One potential missing process implicated in these biases is the biophysical effect of chlorophyll blooms.**
- **Simple sensitivity tests have shown that including the effect of chlorophyll blooms on the absorption of solar radiation can potentially reduce the cold bias during boreal spring, improving monsoon rainfall during the early summer by increasing the source of available moisture.**
- **Prescribing a spatially and temporally varying cycle of observed chlorophyll concentrations to the model gives results consistent with the sensitivity test: an enhanced seasonal cycle in Arabian Sea SST and mixed layer depth biases reduced by up to 50%.**
- **Extensions to the work could consider coupling with biophysical models in order to determine feedbacks from the monsoon onto chlorophyll development.**

References Gordon, C, C Cooper, CA Senior, H Banks, JM Gregory, TC Johns, JFB Mitchell & RA Wood (2000) *Clim Dyn* **16**: 147—168. // Levine, R & AG Turner (2011) *Clim. Dyn.* **in press**. // Lévy, M, D Shankar, J-M André, SSC Shenoi, F Durand & C de Boyer Montégut (2007) *JGR-A* **112**: C12014. // Marathayil, D, L Shaffrey & AG Turner (2011) *GRL* **in preparation**. // Ohlmann, JC (2003) *J. Clim.* **16**:1337—1351. // Paulson, CA & JJ Simpson (1977) *JPO* **7**: 952—956. // Pope, VD, ML Gallani, PR Rowntree & RA Stratton (2000) *Clim Dyn* **16**: 123—146. // Turner, AG, PM Inness & JM Slingo (2005) *QJRMS* **131**: 781—804. // Turner, AG, M Joshi, ES Robertson & SJ Woolnough (2011) *Clim. Dyn.* **submitted**.

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