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MODELING INDIAN OCEAN CIRCULATION: BAY OF BENGAL FRESH PLUME AND ARABIAN SEA MINI WARM POOL

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ABSTRACT: The Indian subcontinent divides the north Indian Ocean into two tropical basins, namely the Arabian Sea and the Bay of Bengal. The Arabian Sea has high salinity whereas the salinity of the Bay of Bengal is much lower due to the contrast in freshwater forcing of the two basins. The freshwater received by the Bay in large amounts during the summer monsoon through river discharge is flushed out annually by ocean circulation. After the withdrawal of the summer monsoon, the Ganga – Brahmaputra river plume flows first along the Indian coast and then around Sri Lanka into the Arabian Sea creating a low salinity pool in the southeastern Arabian Sea (SEAS). In the same region, during the pre-monsoon months of February – April, a warm pool, known as the Arabian Sea Mini Warm Pool (ASMWP), which is distinctly warmer than the rest of the Indian Ocean, takes shape. In fact, this is the warmest region in the world oceans during this period. Simulation of the river plume and its movement as well as its implications to thermodynamics has been a challenging problem for models of Indian Ocean. Here we address these issues using an ocean general circulation model – first we show that the model is capable of reproducing fresh plumes in the Bay of Bengal as well as its movement and then we use the model to determine the processes that lead to formation of the ASMWP.

Hydrographic observations from the western Bay of Bengal have shown the presence of a fresh plume along the northern part of the Indian coast during summer monsoon. The Indian Ocean model when forced by realistic winds and climatological river discharge reproduces the fresh plume with reasonable accuracy. The fresh plume does not advect along the Indian coast until the end of summer monsoon. The North Bay Monsoon Current, which flows eastward in the northern Bay, separates the low salinity water from the more saline southern parts of the bay and thus plays an important role in the fresh water budget of the Bay of Bengal. The model also reproduces the surge of the fresh-plume along the Indian coast, into the Arabian Sea during northeast monsoon.

Mechanisms that lead to the formation of the Arabian Sea Mini Warm Pool are investigated using several numerical experiments. Contrary to the existing theories, we find that salinity effects are not necessary for the formation of the ASMWP. The orographic effects of the Sahyadris (Western Ghats) and resulting reduction in wind speed leads to the formation of the ASMWP. During November – April, the SEAS behave as a low-wind heat-dominated regime where the evolution of sea surface temperature is solely determined by atmospheric forcing. In such regions the evolution of surface layer temperature is not dependent on the characteristics of the subsurface ocean such as the barrier layer and temperature inversion.

1. INTRODUCTION

The two main basins of North Indian Ocean, namely the Arabian Sea and the Bay of Bengal, have contrasting salinity characteristics, in spite of both being located within the same latitude range and being under the direct influence of monsoons. The Arabian Sea has high salinity (usually in the range 35 to 37psu) due to excess of evaporation over rainfall. In contrast, the Bay of Bengal has much lower salinity due to the large influx of fresh water from river discharge and high amount of rainfall. Winds over the Indian Ocean, which is the main forcing function, reverse twice during the year. They blow from the southwest during May – September and from the northeast during November – January with the transition taking place during the months in between. Forced by these winds, circulation in the Indian Ocean has a general eastward direction during summer and westward during winter. These reversing currents carry high salinity Arabian Sea water into the Bay of Bengal and *vice versa* playing a crucial role in maintaining the freshwater and salt balance of the North Indian Ocean. Quantitatively accurate simulation of the resulting seasonal distribution of salinity as well as capturing the salinity effects on sea surface temperature (SST) is a major challenge for models of the Indian Ocean. This study presents a simulation of the Indian Ocean circulation, temperature and salinity that compares remarkably well with the observations, using an ocean general circulation model.

The most important oceanic parameter that affects ocean-atmosphere coupling directly is the SST. Consequently, the oceanic warm pool (i.e., regions with SST > 28°C) occupies a special place in studies of tropical air-sea interaction. A warm pool envelops the entire Indian Ocean during May with peak SST above 30°C. The southeastern Arabian Sea (SEAS) attains high (28°C or above) SST much before May and remains the warmest region in the North Indian Ocean during February – April. This warm region is known as Arabian Sea Mini Warm Pool (ASMWP) and this mini warm pool is believed to be important for the onset and advance of monsoon along the west coast of India (see [1] for a review).

What causes the south-eastern Arabian Sea to warm preferentially? The special feature of the SEAS is its lower salinity compared to its surroundings. This low salinity has its source in the northern Bay of Bengal. The coastal currents around India carry low salinity water from the Bay of Bengal into the SEAS during the winter. The circulation in the SEAS, characterised by a clockwise flow around the “Lakshadweep High” traps the low salinity water within the SEAS. Shenoi et al. (1999)[2] and Rao et al. (1999)[3] attributed salinity effects as the factor responsible for the mini warm pool formation. The mixed layer becomes thin in the presence of a low salinity cap which leads to absorption of solar radiation in a thinner layer resulting in higher SST. Here we test this hypothesis using an ocean general circulation model and find that salinity effects are not necessary for the generation of the Arabian Sea Mini Warm Pool but orographic effects are crucial for its formation[4].

2. MODEL DESCRIPTION

The Indian Ocean model used in this study is based on the Modular Ocean Model (MOM4p0) of the Geophysical Fluid Dynamics Laboratory. This model solves the hydrostatic primitive equations for a free-surface Boussinesq ocean with z-coordinates in the vertical and generalized orthogonal horizontal coordinates. The equations are discretized on an Arakawa B-grid. The model domain covers the tropical Indian Ocean between 30°S--30°N and 30°E--120°E. The horizontal grid spacing is approximately 28km and there are 40 vertical levels in the model. In order to resolve the upper layer well the vertical grid resolution is kept at 5m for the upper 60m. Further details of the model may be found in [4]. The model is started from a state of rest and climatological temperature and salinity. It is forced at the surface by winds and heat and freshwater fluxes. Additionally, river discharge is prescribed at the oceanic grid-point near the river mouths. The model is integrated for a period of seven years and results from the last year of the model run are used for this analysis.

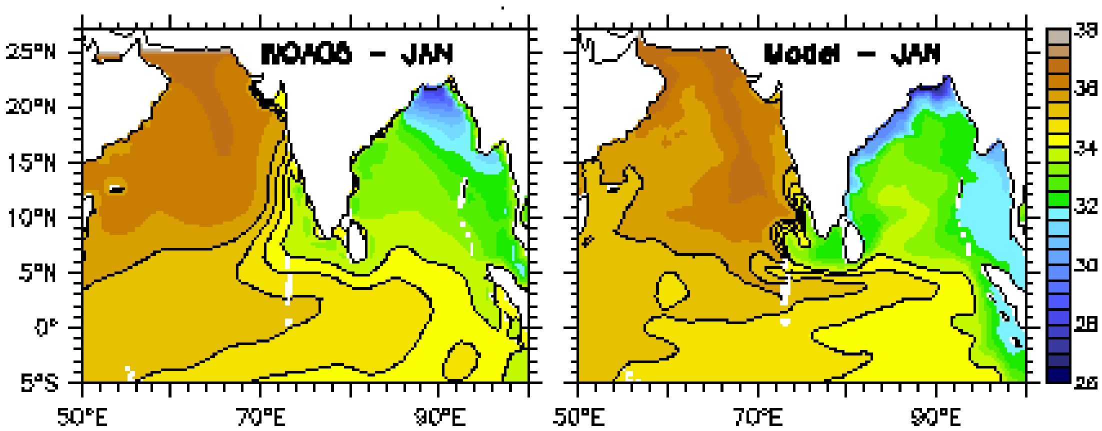

Figure 1. Intrusion of the low salinity plume from the Bay of Bengal into the Arabian Sea along the Indian coast. The figure shows salinity for the month of January from the model simulation (right panel) and from climatological data set (left panel).

3. BAY OF BENGAL FRESH WATER PLUME

The Bay of Bengal receives large quantity of fresh water in the form of river discharge and rainfall during the southwest monsoon. A major part of this freshwater is derived from the Ganga--Brahmaputra river system that debouches into the northern Bay of Bengal during the summer monsoon. The fresh water plume does not advect southward during this season due the monsoon winds that blow from the southwest till the end of September and the North Bay Monsoon Current that flows eastward across the Bay, restricting the low salinity water to its north[5]. After the withdrawal of summer monsoon, the fresh plume flows southward along the east coast of India, around Sri Lanka into the Arabian Sea. The model is able to capture this intrusion of low salinity water into the Arabian Sea (Figure 1). The low salinity water reaches in the SEAS during November and the supply continues till January.

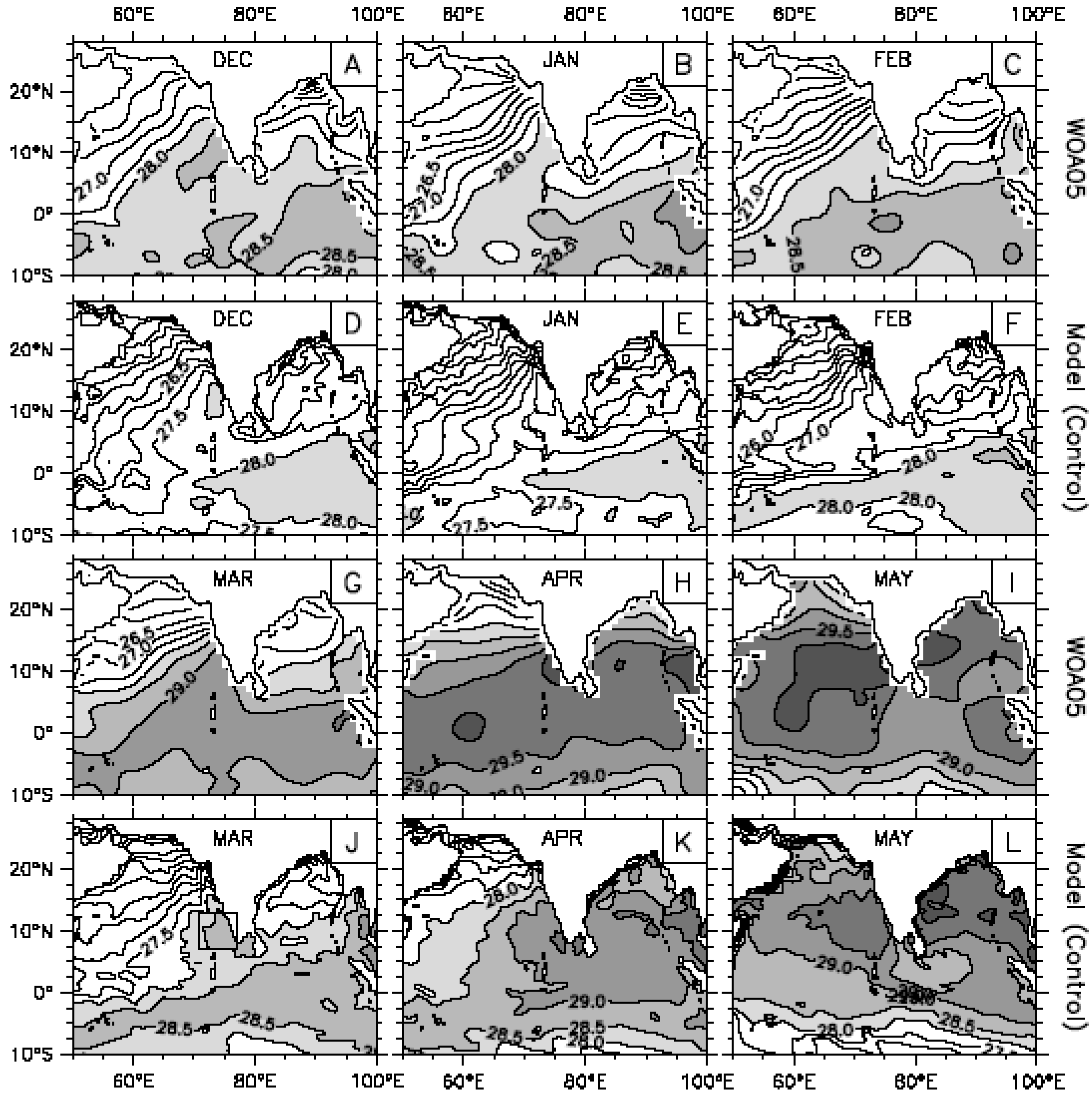

Figure 2. Comparison betweenWOA05 (observed) climatology (1st & 3rd rows) and model simulation of (2nd & 4th rows) SST (°C) during December – May. Isotherms have a spacing of 0.5°C and SSTs above 28°C are shaded. The box marked on (J) shows the Southeastern Arabian Sea (SEAS).

4. ARABIAN SEA MINI WARM POOL

The seasonal and interannual evolution of the Indian Ocean SST in the model occurs in a manner that closely matches with the observations[4,5,6]. The difference between the simulated and observed SST is within 0.5 – 1°C over major part of the model domain. The evolution of the ASMWP is also reproduced well by the model (Figure 2). The SEAS remains warmer than the surroundings during November-April and SST above 28°C is observed in the SEAS during December. A well-defined patch of warmer water appear in the SEAS during March which has been called as the Arabian Sea Mini Warm Pool. The ASMWP grows further during April and the peak SST of about 29°C is attained during April--May. The ASMWP loses its identity when the rest of the Arabian Sea and Bay of Bengal warms to similar temperature during May, leading to the formation of the much bigger Indian Ocean warm pool.

To determine the role of low salinity water arriving from the Bay of Bengal on the formation of ASMWP, an additional model experiment was carried out in which the model salinity was held at a constant value of 35 psu everywhere in the model domain. This was achieved by prescribing an initial condition of 35 psu everywhere and switching off evaporation, rainfall and river discharge. Surprisingly, in the fixed salinity run, a warm pool very similar to that in the control run was simulated. (Figure 3). The evolution of SST in the fixed salinity experiment is also very similar to that in the control run (Figure 4) suggesting that salinity effects are not necessary for the formation of ASMWP.

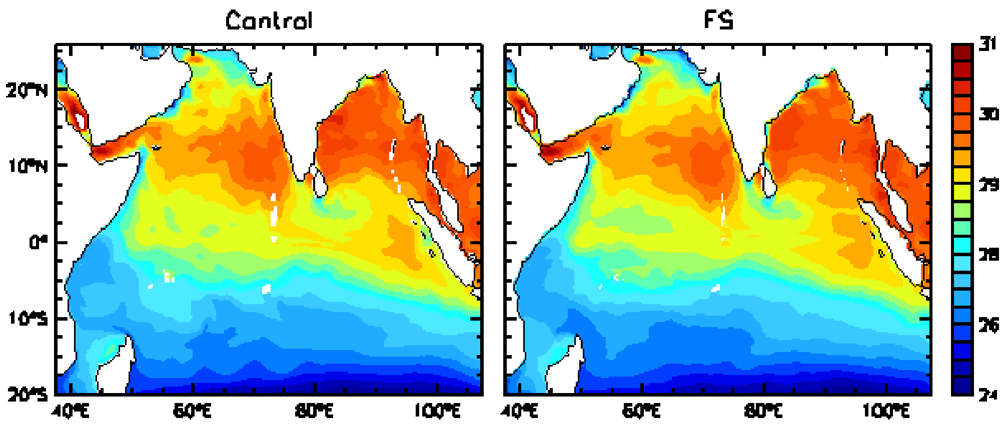

Figure 3. Sea surface temperature for the month of May from the control experiment (left panel) and from the experiment in which the salinity was held at a constant value of 35 psu (right panel).

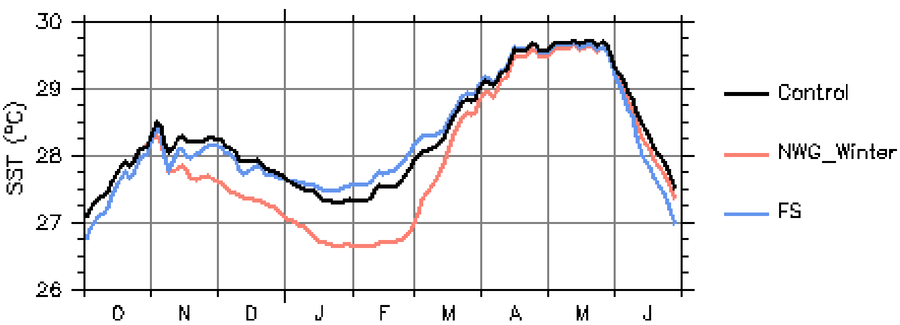

Figure 4. Evolution of sea surface temperature in the SEAS from the control run (black line), from the experiment in which salinity was held constant (blue line) and from the run in which the orographic effects of Sahyadri were removed (red line).

In order to understand the processes leading to the formation of the ASMWP, local air-sea interaction over the SEAS was examined in detail. During winter, the SEAS cools by a considerably lower amount than its surroundings. This is due to the low latent heat loss over the SEAS which results from a lower wind speed. The winds are weaker over the SEAS due to the orographic effect of Sahyadris. This low winter cooling, in fact, plays a decisive role in the formation of the ASMWP. This is illustrated by another numerical experiment.

In this experiment, the atmospheric variables used for forcing the model were modified such that the differential cooling of the SEAS is absent. This is achieved by replacing winds, air temperature and humidity over the SEAS from a region west of the SEAS that unaffected by the Sahyadris. In this experiment the SST in the SEAS during the winter months were lower than that in the control run (Figure 4) suggesting that the orographic effects of Sahyadris is crucial for the formation of the Arabian Sea Mini Warm Pool.

5. SUMMARY AND CONCLUSIONS

A high resolution model of the Indian Ocean is used for investigating two aspects of the Indian Ocean circulation. First is the simulation of the fresh water plume in the Bay of Bengal and the other is mechanisms leading to the formation of the Arabian Sea Mini Warm Pool. The model simulates the freshwater plume in the Bay of Bengal as well as the warm pool reasonably well. The process experiments carried out using the model suggest that salinity effects are not necessary for the formation of the Arabian Sea Mini Warm Pool. Its formation is due to the orographic effects of Sahyadri. The Sahyadris block the cold northeasterly winds from blowing over the SEAS. Consequently SEAS is region of net heat gain during winter compared to its surroundings. This lesser winter cooling of the SEAS helps it to maintain a warmer temperature and leads to the formation of the mini warm pool. This study suggests that stratification caused by low salinity effects does not play an active role in determining SST in regions where winds are weak. Evolution of SST is determined by atmospheric heat fluxes rather than sub-surface oceanic processes.

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