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Evolution and collapse of Arabian Sea warm pool during two contrasting monsoons 2002 and 2003

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सार – अप्रैल से मई के महीनों के दौरान दक्षिणी पूर्वी अरबसागर (एस. ई. ए. एस.) के समुद्र की सतह का तापमान अधिकतम 30° सें. अथवा उससे भी अधिक (दुनिया के महासागरों में सबसे उष्ण) तक पहुँचता है जो अरबसागर का उष्ण कुँड कहलाता है। सागर की यह उष्णता की स्थिति मानसून से पूर्व की ऋतु की पूरी अवधि के दौरान बनी रहती है और दक्षिणी पश्चिमी मानसून ऋतु के आरंभ के साथ इसका ह्रास हो जाता है। उष्णकुँड का स्थान इस दृष्टि से अत्यंत महत्वपूर्ण है क्योकि सामान्यतः मानसून के आरंभ की भ्रमिलता अरबसागर के इसी भाग में बनती है। उष्णकँड के विकास और ह्रास के लिए उत्तरदायी तंत्र को समझना अरबसागर मानसून प्रयोग (आरमेक्स) के मुख्य उद्देश्यों में से एक है। विरोधात्मक मानसून वर्ष (2002 और 2003) तथा इन वर्षों के दौरान समकालिक आरमेक्स प्रेक्षण यह समझने का सुनहरा अवसर देते है कि इस अवधि के दौरान महासागर स्थानीय और दूरस्थ प्रेरकों से किस प्रकार प्रभावित होता है। अरबसागर के उष्णकुँड क्षेत्र में तापमान को अनुकरित करने के लिए उत्तरी हिंदमहासागर (एन. आई. ओ.) के त्रिविमीय महासागर निदर्श का उपयोग किया गया है तथा उष्णकुँड के विकास और ह्रास के दौरान विस्तृत विश्लेषण विशेष रूप से किया गया है। क्विक स्कैट पवन क्षेत्रों का उपयोग करते हुए यह निदर्श प्रेक्षित अंतःवार्षिक अंतरो को सफलतापूर्वक अनुकरित कर सकता है।

ABSTRACT. During the month of April - May, the Sea Surface Temperature (SST) over the South East Arabian Sea (SEAS) attains a maximum over 30° C or more (warmest in the world ocean), called the Arabian Sea warm pool. The warming continues throughout the pre-monsoon period and collapses with the onset of southwest monsoon. The warm pool location is very important in the sense that over this part of the Arabian Sea, the monsoon onset vortex normally forms. One of the objectives of the Arabian Sea Monsoon Experiment (ARMEX) is to understand the mechanism responsible for the evolution and collapse of warm pool. The contrasting monsoon years (2002 and 2003) and the coincidental ARMEX observations during these years give a unique opportunity to understand how the ocean during this period responded to the local and remote forcing. A three-dimensional ocean model of the North Indian Ocean (NIO) is used to simulate temperature over the Arabian Sea warm pool region and detailed analysis is performed especially during the evolution and collapse of the warm pool. The model could successfully simulate the observed inter-annual differences using Quikscat wind fields.

Key words – ARMEX, Warm pool, Ocean model, TMI SST, Quikscat wind, Heat content.

1. Introduction

The role played by the tropical Indian Ocean in affecting regional climate appears to be very important although not well understood. There is evidence to strongly suggest that the east equatorial Indian Ocean cooling enhances the drought condition over Indonesia (Webster *et al*. 1999). Indian Ocean warm pool, a zonal band of high SSTs and its variability are well studied. Also the relation between the onset of southwest monsoon and the Arabian Sea SST has been established by several researchers. Kershaw (1985) observed that the strengthening of low level jet and the northward movement of the monsoon rain along the west coast of India and onset of monsoon are predictable once the accurate SST over Arabian Sea is known. All these studies emphasis the role of SST over the adjacent sea in influencing the Indian summer monsoon.

The onset of the southwest monsoon along the Kerala coast and its advancement is often associated with the formation of a low-pressure system off the west coast of India or in the east central Arabian Sea. A low pressure system, or onset vortex which forms over the east central

Arabian Sea, on the leading edge of the monsoon current and brings monsoon flow and sets the monsoon over the south peninsular India. The onset vortex generally forms in the latitudinal belt 10° N - 15° N and moves in the north northwestward direction or in the northwestward direction. Formation of the onset vortex has been attributed to the instability arising from the increase of horizontal shear of the monsoon current.

Based on observations during the monsoon experiment MONEX-79, Seetaramayya and Master (1984) have first noticed a zone of anomalous warm water (30.8^{o}C) in the upper layers of the SEAS prior to the onset of southwest monsoon coinciding with the onset vortex. This anomalous warm water is named as the Arabian Sea mini warm pool (Rao and Sivakumar, 1999). The warm pool emerges as a tongue of warm surface water of more than 30° C, in the SEAS during the pre-monsoon period. It is observed that the surface water in the warm pool area is less saline, and so favors the accumulation of heat in the upper mixed layer. The warmer and less saline water acts as a thin stable stratified surface layer that inhibits the mixing with deeper, cooler and high saline water. The evolving stage of this warm pool is believed to start with the formation of Laccadive High resulting from the incoming Rossby waves from south during November/December (Shenoi *et al*., 1999). Its intensity, extent and location vary from year to year. In general, during the pre-monsoon season, under clear skies and light winds, the radiative heat input overwhelms turbulent heat losses at the air-sea interface and net surplus heat energy accumulates in the upper layers of the Arabian Sea. This heating subsequently leads to the formation of the mini warm pool.

This mini warm pool, which is long lasting warmest water mass ($\geq$ 30 ° C) among the world oceanic regions, is conducive for the formation of onset vortices during the south west summer monsoons. Moreover, the higher rate of transfer of heat and water vapour due to the higher surface temperature, and its geographical extent affect the monsoon onset and rainfall over India. The mini warm pool in the northern Indian Ocean dissipates following the onset and advance of the southwest monsoon. This mini warm pool is found to be coincided with the regions of low salinity layer.

During the pre-summer monsoon season, the near-surface waters in the Arabian Sea progressively warm up, manifesting an evolution of mini-warm pool (>30° C), which started to form in early February itself in the southeastern region just before the onset of the summer monsoon. In the SEAS, during winter, low saline waters brought by the East India Coastal Current (EICC) and the North Equatorial Current (NEC) produce haline stratification within the near-surface isothermal layer. The underlying pycnocline shoals by about 20m from January-May, as a result of Ekman divergence caused by the surface wind stress curl and southwestward propagating mode-2 Rossby wave from off southwest India (Shenoi *et al*., 1999).

Rao and Sivakumar (1999) studied about the evolution of a mini-warm pool during the pre-summer monsoon season and the genesis of onset vortex in the southeastern Arabian Sea. They examined the possible mechanisms for the observed seasonal build up of this mini warm pool utilizing all the available monthly mean climatologies of surface wind field, surface heat fluxes, near-surface thermohaline fields, near-surface circulation, and mean sea level as monitored by satellites and by some of the recent model solutions on the Arabian Sea circulation. The heat budget analysis of the salinity dependent mixed layer from January-May showed maxima in the accumulated thermal energy in the south eastern Arabian Sea. The insulating near surface stratification and shoaling of pycnocline constrain the vertical re-distribution of the net surplus air-sea heat flux over a thin surface layer, resulting in the formation of a mini-warm pool in the SEAS.

Sanilkumar *et al*. (2004) found that the low saline waters and the resulting vertical density stratification in the upper layers of the south eastern Arabian Sea were conducive for the generation of the Arabian Sea mini warm pool during the pre-monsoon period. Horizontal extent of the low salinity layer controlled the area of the warm pool, while the depth of the highly stratified layer controlled its intensity and thickness. The warmest waters occur wherever the thinner, low salinity pockets (stratified layers) appear near the surface. The study also provided the existence of a clockwise gyre during May and the possibility of recirculation of the low salinity waters in the study region. The studies on Arabian Sea warm pool underlined the discovery of a 'high' in sea level in the Lakshadweep Sea during December to March by Bruce *et al.* (1994).

2. The ocean model

The model used in this study is a three dimensional sigma co-ordinate, free surface, primitive equation, Princeton Ocean Model (POM), of the NIO [20° S to 25° N, 35° E to 115° E], which is a general circulation ocean model as well as a coastal ocean model and provides a dynamic connection between the general circulation of the deep ocean and variation of the coastal sea level. The NIO model has a moderate horizontal resolution of 1° × 1° but a high vertical resolution consisting of 21 sigma levels. The majority of these levels are located in the upper layers to better depict the mixed layer processes and the equatorial, near equatorial surface current system. The model solves the following equations for the ocean velocity $U_i = (U, V, W)$, temperature T and salinity S :

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(U,V) + \frac{\partial}{\partial x_i}\left[U_i (U,V)\right] + f(-V,U)$$

$$= -\frac{1}{\rho_0}\left[\frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_M \frac{\partial}{\partial z}(U,V)\right] + (F_U, F_V) \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_i}(U_i T) = \frac{\partial}{\partial z}\left[K_H \frac{\partial T}{\partial z}\right] + F_T \tag{3}$$

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x_i}(U_i S) = \frac{\partial}{\partial z}\left[K_H \frac{\partial S}{\partial z}\right] + F_S \tag{4}$$

The hydrostatic approximation yields

$$\frac{P}{\rho_0} = g(\eta - z) + \int_z^{\eta} \frac{\rho - \rho_0}{\rho_0} g dz \tag{5}$$

Where $\rho=\rho\ (T, S, P)$, η is the free surface elevation, and ρ_0 is a reference density. The primitive equations are transformation to a sigma co-ordinate system

$$\sigma = (Z-\eta) / (H+\eta) \tag{6}$$

Where $H(x,y)$ is the bottom topography, details can be seen in Blumberg and Mellor (1987).

3. Methodology

The model was initialized by the annual temperature and salinity climatology of Levitus and Boyer (1994). The model bottom topography is derived from the 5' resolution ETOPO5 database. During model spin up, the model was forced by 1° × 1° resolution Hellerman and Rosenstein monthly climatological wind stress and surface heat flux from Southampton Oceanographic Center (SOC) climatology. Starting from rest, the model was spun up for a period of twenty years using climatological forcing. The model was then integrated from January 2002 to December 2003 using daily surface forcing derived from Quickscat winds, daily NOAA/NCEP Climate Prediction Center outgoing long wave radiation (OLR) and daily NCEP-NCAR Reanalysis air temperature. The fresh water flux is derived from SOC climatology. The wind stress was estimated using the bulk aerodynamic formula as follows. For wind speed less than 6 m/s drag coefficient (C_d) of 1.1×10^{-3} was used. For higher winds, $C_d = (0.61 + 0.063U) \times 10^{-3}$ was used.

In the tropics the weather is not as predictable as in the mid latitudes. Unlike the dominant instability or periodic wave motions like upper tropospheric Rossby waves occurring in mid latitudes, the weather in the tropics is mostly controlled by the convective activity taking place over the region. The variations in surface short wave flux in tropics especially over the warm pool regions are produced by variation in the cloud amount, in fact which is produced by the strong convective activities. The satellite measured OLR has been used for quantitative measurement of net shortwave flux. The daily short wave flux for the year 2002 and 2003 were computed based on the formula described by Sengupta *et al.* (2001)

$$Q_{sw} = Q_{ERBE} + OLR_a \times (Q_{ERBE} / OLR_c)$$

where Q_{ERBE} is the climatological net insolation

OLR_a is the $OLR_{(monthly\ climatology)} - OLR_{(daily)}$

OLR_c is the OLR daily climatology

4. Surface fluxes

Fig. 1 shows Quikscat surface winds over western equatorial Indian Ocean and Arabian Sea in the pre-monsoon and monsoon months, April to July for the consecutive years 2002 and 2003. During June to August the largest surface wind speed in the northern hemisphere are found in the Arabian Sea. For the months of April and May the wind speed over the region in 2002 shows higher in magnitude as compared to that in 2003. The early onset of Somali Jet and strong winds of May 2002 resulted an early cooling near the Somalia region. The cold upwelled water is further advected towards the Indian subcontinent by the monsoon currents and caused a decrease in SST over this region in the following monsoon season. The decrease in SST made its impact by reducing the evaporation rate over the region. In the months of June and July the winds over Arabian Sea and west equatorial Indian Ocean were stronger in 2003 as compared to 2002. This strong winds and SST over the region enhances the evaporation or the moisture content in the atmosphere, which is essentially critical in determining the rainfall over the Indian subcontinent. Another remarkable feature observed during June – July was the stronger cross –

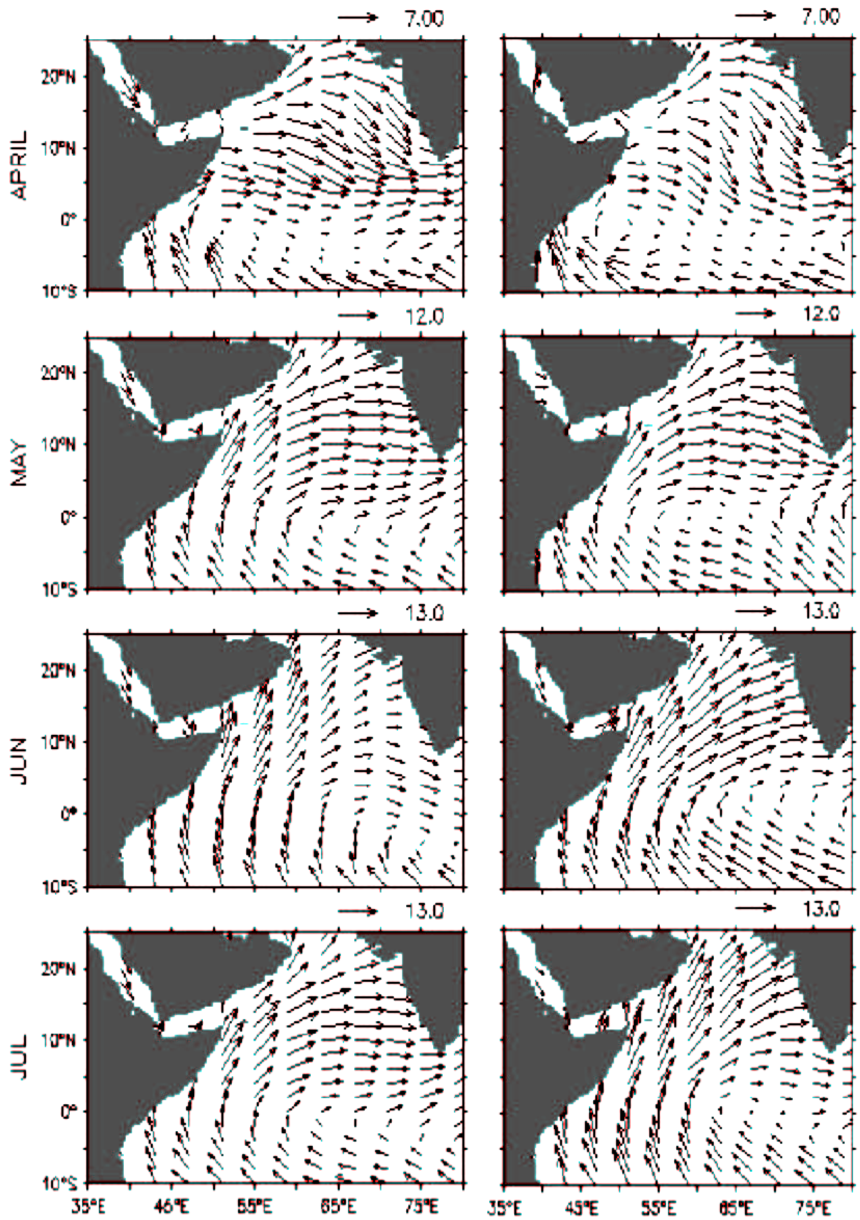


Fig. 1. Quikscat monthly averaged surface wind speed for 2002 (left) and 2003 (right) in m/s

equatorial flow existing in 2003. In July 2002 south of 10° N (south of Indian peninsula) relatively strong zonal flow of wind was observed. In contrast, in 2003 strong meridional component of wind drives the moisture rich air over ocean to the heart of the subcontinent and it enhanced the rainfall activity over the country.

In Fig. 2 left panel shows the difference in OLR between 2003 and 2002 and right panel shows the corresponding SST difference. In the month of April, a positive anomaly in SST is observed in the central and eastern Arabian Sea. However the OLR anomaly over the region doesn't show any remarkable indications of forthcoming unusual phenomena. But in May, the negative SST anomaly has been shifted towards the eastern coast of Arabian Sea and the OLR anomaly shows positive value over entire Arabian Sea. This feature confirms the presence of clouds in May 2002. In June

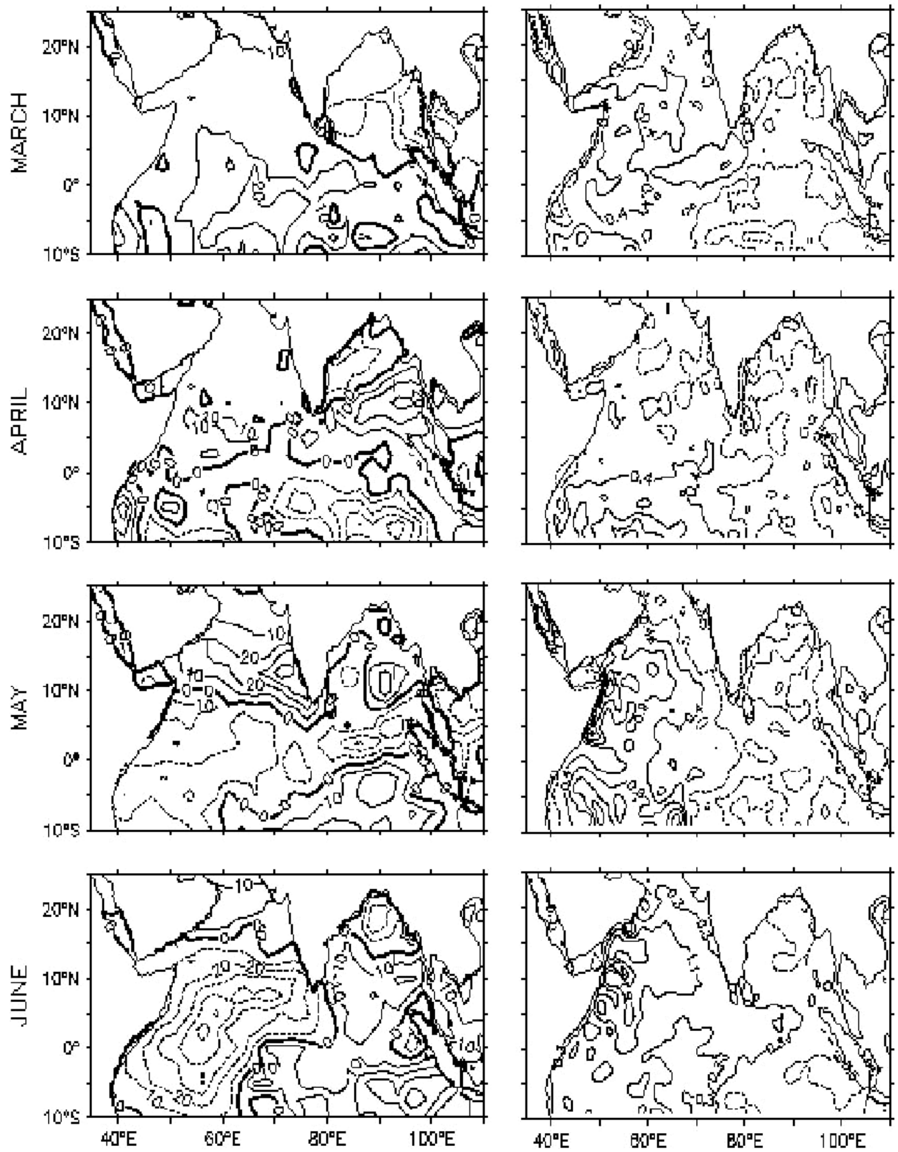
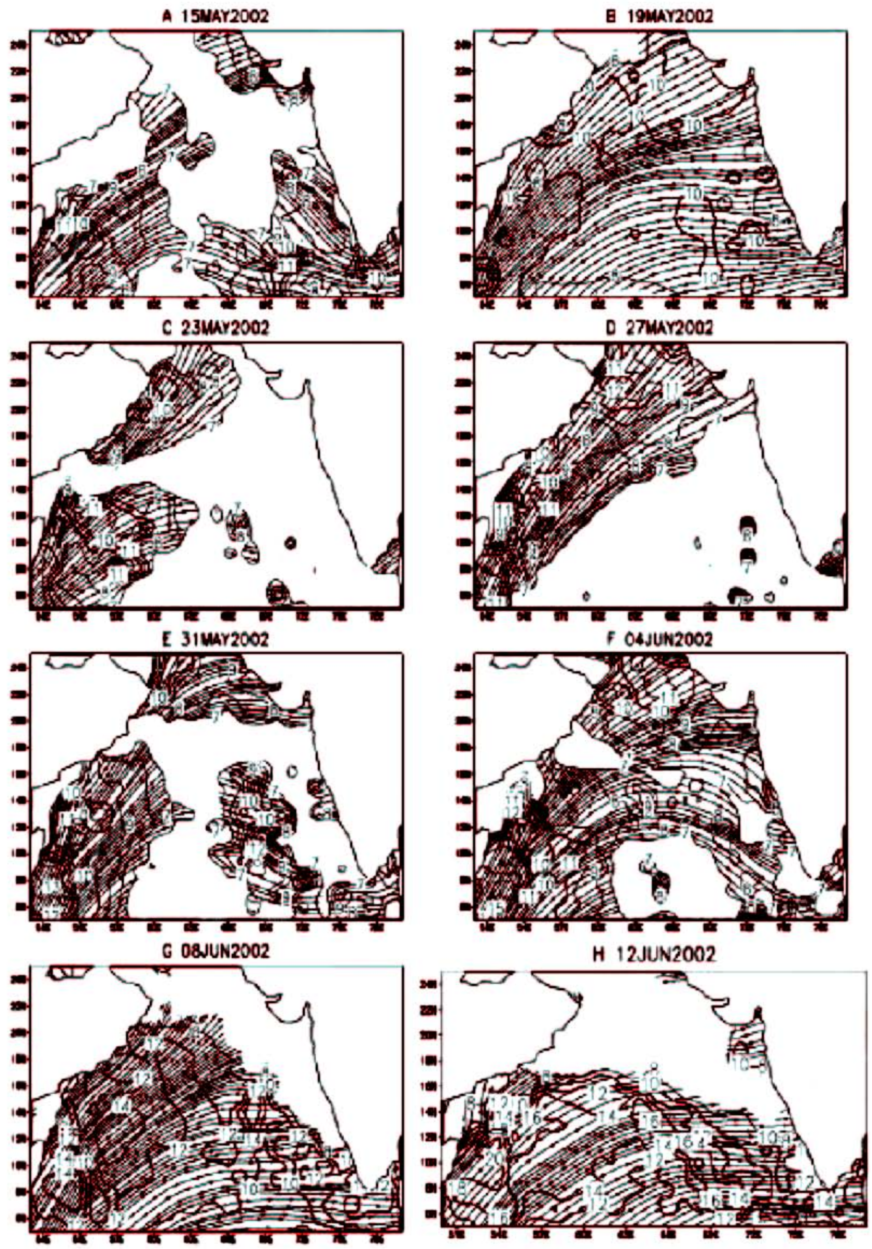


Fig. 2. Monthly NOAA/NCEP CPC OLR difference in W/m^2 (2003-2002) left and TMI SST difference in °C (2003-2002) right

warmer SST is observed in 2003 and OLR shows high negative anomaly, which indicates the abundance of rain bearing clouds. These features are consistent with our earlier discussions and it supports the idea that the anomalous warming in 2003 pre-monsoon season was mostly contributed by short wave radiation. However in June 2002, the cooling anomaly is found to be mainly due to the advection of cold water from the Somali coast.

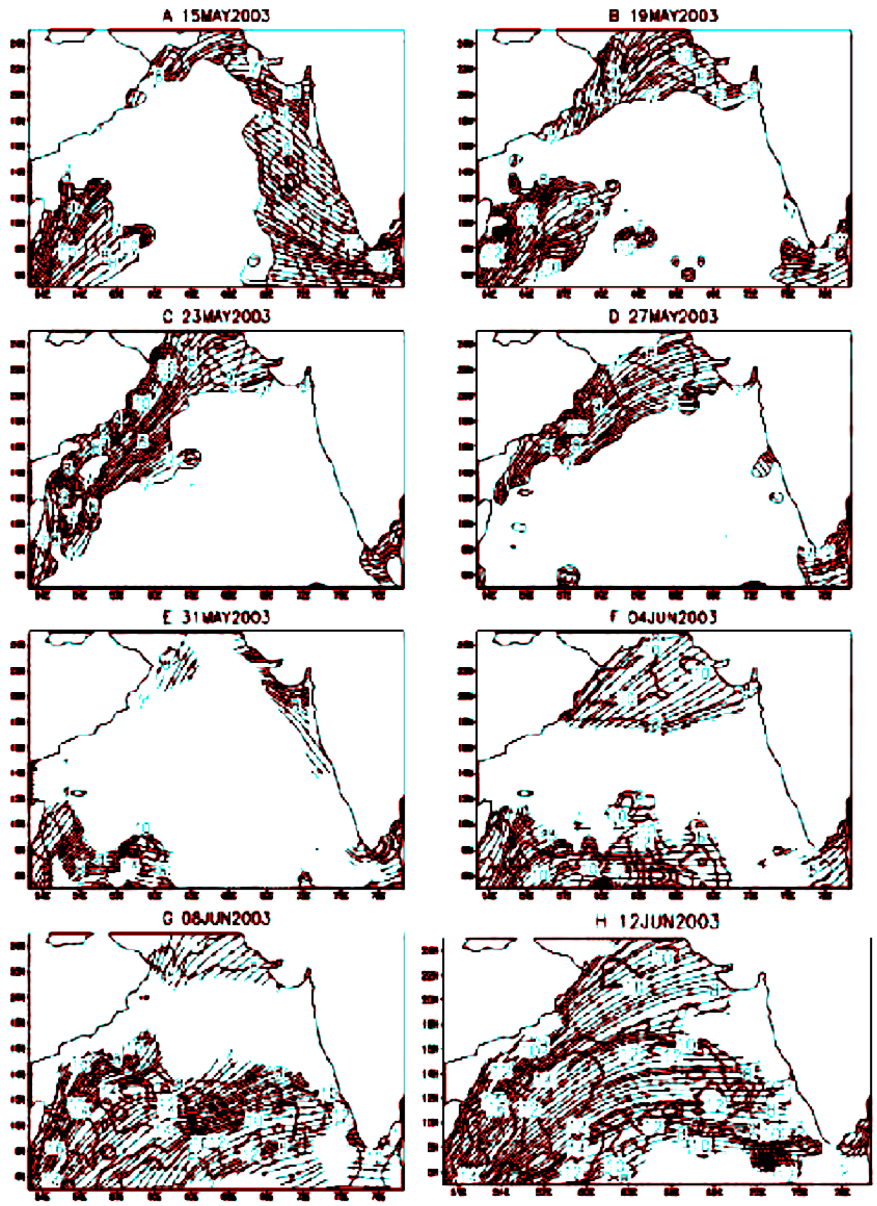
5. Onset phase in 2002 and 2003

Appropriate characteristics for the onset of Somali Jet are wind direction towards India, sustained wind speed above 7.5 m/s, May or June, time of occurrence, and increase in wind speed existing over one week (Halpern *et al.* 1998). The 7.5 m/s threshold, which corresponds to the approximate average wind speed over the global ocean is chosen because of Somali Jet speed would be greater than the global average wind speed. Figs. 3 & 4 show the Quikscat surface wind magnitude and stream lines (contour shows the wind speed above 7 m/s) over the Arabian Sea during onset phase of southwest monsoon for 2002 and 2003 respectively. We have chosen the onset phase dates from 15 May to 12 June, because both onset dates of 2002 and 2003 are lying in this period. It is observed that in 15 May, 2002 winds over Somali coast



Figs. 3(a-h). Quikscat daily winds over Arabian Sea during onset phase of monsoon 2002 in m/s

and SEAS are strong, more than threshold (7.5 m/s) value. The entire Arabian Sea [Fig. 3(b)] covered with strong winds of speed more than 7.5 m/s by 19 May. This indicates that in 2002 the onset of Somali jet was occurred early (19 May) over the SEAS, but this did not persist long time. By 23 May winds over SEAS weakened and this continued up to 27 May. On 28 May again wind speed increased (not shown) in the SEAS and continued further. This persistent stronger wind over SEAS might have helped for onset of monsoon over Kerala on 29 May 2002. But high winds over the Arabian Sea were observed from 4 June 2002 onwards, which was very strong over Somali coast. The high wind speeds defined to be above 12 m/s, which produce rough seas (Halpern *et al*. 1998). They also revealed that at the time of Somali jet, high wind speeds did not occur simultaneously throughout Arabian Sea, the coastal upwelling lowered SST, which reduced the air temperature over the coastal ocean to produce the south



Figs. 4(a-h). Quikscat daily winds over Arabian Sea during onset phase of monsoon 2003 in m/s

westerly geostrophic wind of Somali coast. This locally enhanced the Somali jet. However in 2002 it was not a situation during the month of July, the Somali jet over Arabian Sea was weak (not shown) even though the wind speed was strong enough to produce upwelling in the month of June [Figs. 3(g & h)]. By 12 June 2002 almost high wind speeds was observed over 60% of Arabian Sea.

It is interesting to note that even though monthly mean wind of May 2003 (Fig. 1) was weaker than 2002, on 15 May (Figs. 3 & 4) the pattern of wind is similar in both the years (Fig. 4), *i.e.*, high wind speeds were observed over Somali coast and SEAS region. But as we moves from 15 to 19 May 2003 the wind pattern was different from the corresponding dates of 2002. From 4 June 2003 onwards the wind speed increased towards the west coast of India and by 8 June stronger wind completely covered the southern Arabian Sea (south of 14° N) with wind speed more than 7 m/s of high wind speeds over Somali coast, which was the onset date of

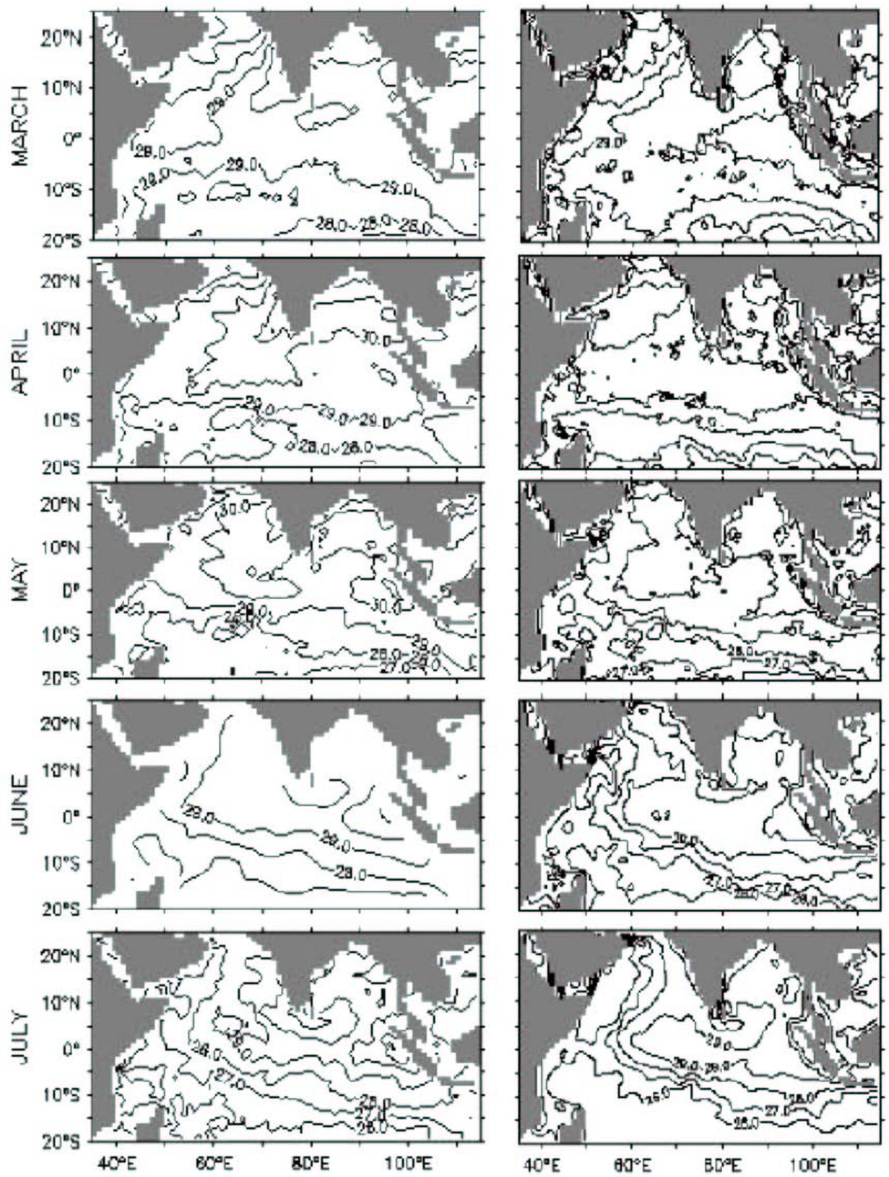


Fig. 5. Monthly SST model simulated (left) and TMI observed (right) in 2002 in °C

southwest monsoon in 2003. Further the strength of winds went on increasing and reached a maximum speed of 24 m/s in July. High wind speeds associated with the stronger cross equatorial flow in mid May 2002 might have played the role for early onset of monsoon as compared to 2003. Also the failure of monsoon in July is attributed to the weak winds, which are not strong enough to bring moisture from Arabian Sea to Indian subcontinent in 2002. It is well known that the circulation of Arabian Sea is more sensitive to wind forcing. So the strong winds in May 2002 may be responsible in advecting the upwelled water from Somali coast to the SEAS and resulting early collapse of warm pool as compared to 2003.

6. Model validation

Figs. 5 & 6 compare the model simulated SST (the temperature of the first level) with the TMI SST for 2002 and 2003 respectively. The model SST's are well comparable with the TMI SST's over the entire Arabian

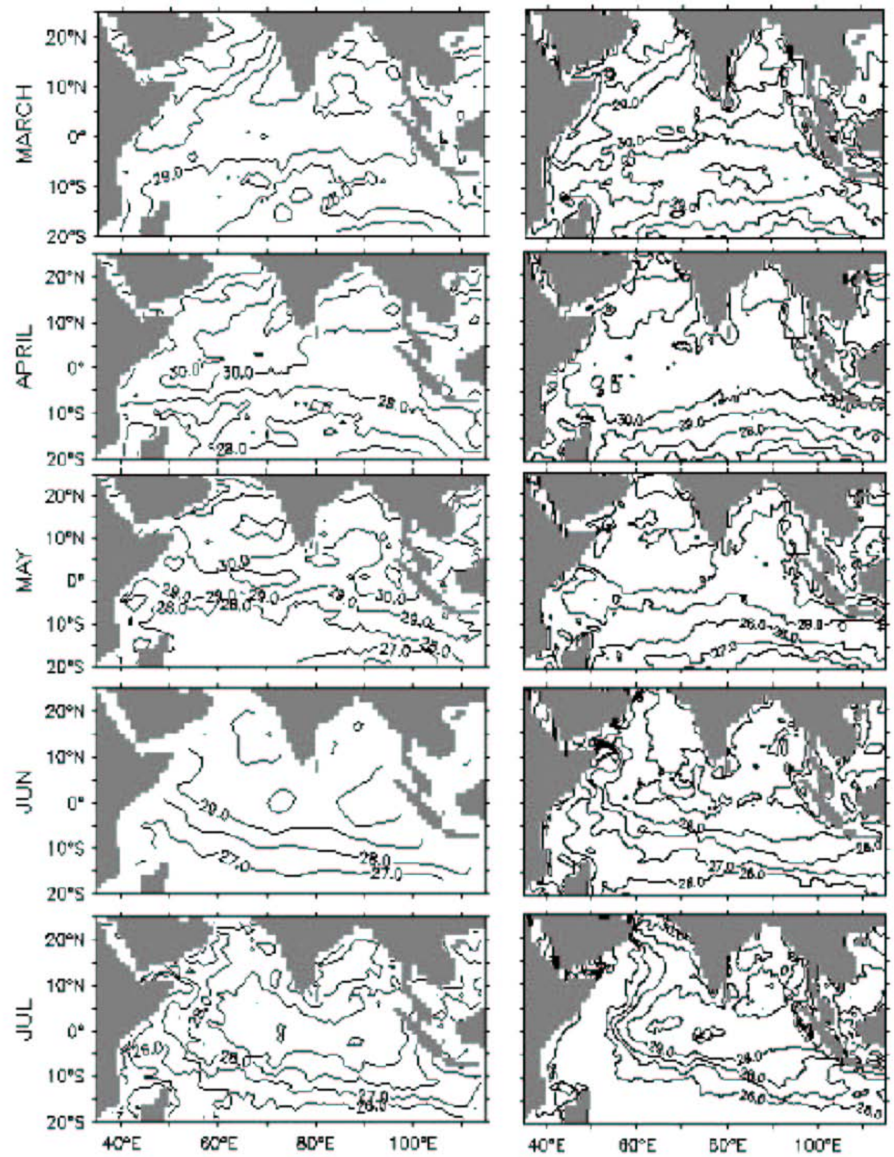


Fig. 6. Monthly SST model simulated (left) and TMI observed (right) in 2003 in °C

Sea especially over the warm pool region. The model is able to reproduce the cooling of SST in July 2002 (Fig. 5) over Arabian Sea. Also in 2003 (Fig. 6) the model simulated SST shows a good agreement with TMI observed SST. The pre-monsoon warming and gradual decrease of SST over Arabian Sea with the advection of cold water from the Somalia coast were well represented in the model results. Fig. 7 shows the time series of SST obtained from the model as well as TMI. It is seen from both TMI observation and model study that at time series location (TSL, 74.5° E, 9.213° N) the warm pool collapse in 2002 was observed on 15 June, but the collapse in 2003 was on 25 June, showing a lag of about 10 days. The lag was well correlated with the delay in the onset of monsoon, which further strengthen that the warm pool collapse is due to the onset of monsoon. In 2002, model SST started decreasing from 30.6° C on 15 May to 30.2° C on 21 May and thereafter increased up to 30.4° C on 24 May and then started decreasing. The TMI SST was 30.5° C on 20 May and then started increasing up to 31.1° C on 24 May and then decreased up to 30.5° C on 27 May and increased then up to 31.4° C on 30 May.

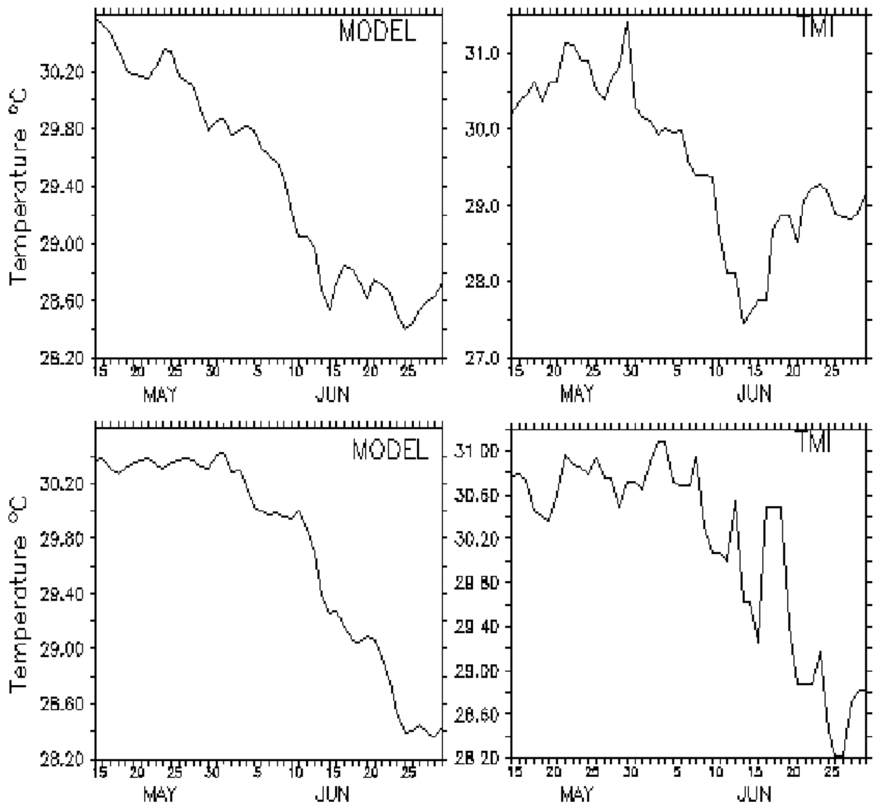


Fig. 7. SST at TSL (74.5° E and 9.213° N) for 2002 (upper panels) and 2003 (lower panels) in °C

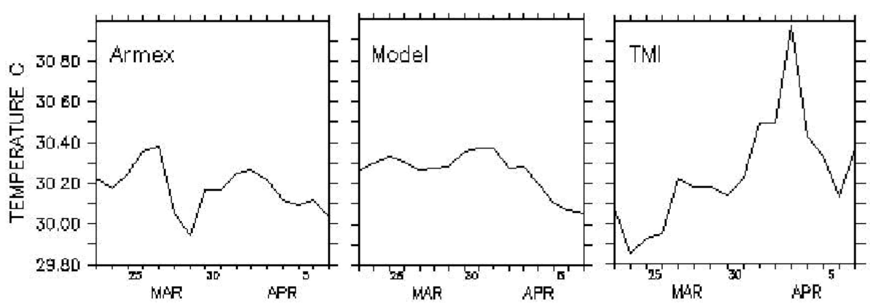


Fig. 8. ARMEX observed, model simulated and TMI observed SST at TSL in °C

Thereafter the SST was found to fall sharply and minimum was attained on 15 June. The SST peak observed in TMI on 30 May was not seen in the model, which may be due to coarse resolution forcing. In 2003, model SST was found oscillating around 30.4° C in the last weak of May. It peaked on 3 June and then started falling. Steep fall in SST started from 10 June onwards and the collapse (28.3° C) was observed on 24 June. The TMI SST was also found oscillating around 30.6° C in the last week of May and the collapse (28.2° C) was observed on 25 June. The strong winds were observed on 19 May in 2002 followed by the warm pool collapse on 15 June, however, in 2003, the corresponding dates were 8 and 25 June respectively. Even though there is a slight difference in magnitude of SST (0.2° C to 0.4° C) between model and TMI, both of them showed same pattern of evolution with time. The observed fluctuations in TMI SST may be due to large day to day variation of TMI skin SST

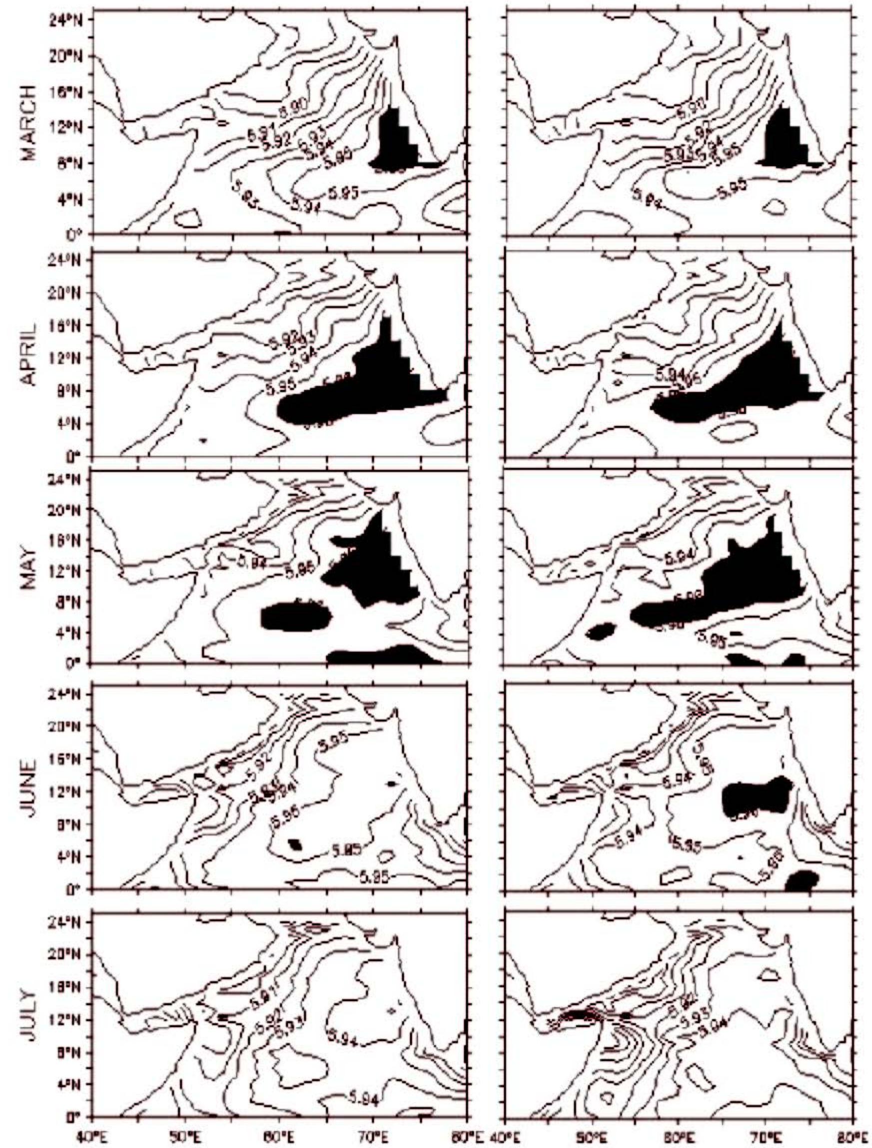


Fig. 9. Model derived 50 m heat content (in 10^{10} J/m^2) in the Arabian Sea for 2002 (left) and 2003 (right)

(Sengupta *et al*. 2001). There is inter-annual variability in the time (days) taken for the collapse of the SST high in 2002 (27 days) and in 2003 (17 days). This needs to be studied further.

Fig. 8 shows the SST at TSL during the ARMEX observation period 23 March to 7 April 2003. ARMEX observations showed that SST was around 30.2° C on 23 March and reached unto 30.4° C on 26 March and dropped to 29.9° C on 28 March then increased to 30.2° C on 3 April and then decreased to around 30° C on 6 April. The model showed similar picture but could not catch the cooling observed on 28 March. The TMI also could not catch the 28 March cooling but warming on 3 April was over estimated and this clearly indicates that the cooling observed on 28 March was locally forced. Strong thick cloud and drizzle were observed from Sagar Kanya SK-190 on 28 March 2003. On 7 April morning heavy rain (2 cm) was observed, that lead to the observed cooling, which was evident in the model also but TMI did not show the cooling.

7. Model heat content

Thermal energy of Upper Ocean is associated with the solar radiation, this energy is generally observed with near surface mixed layer. The heat from this mixed layer

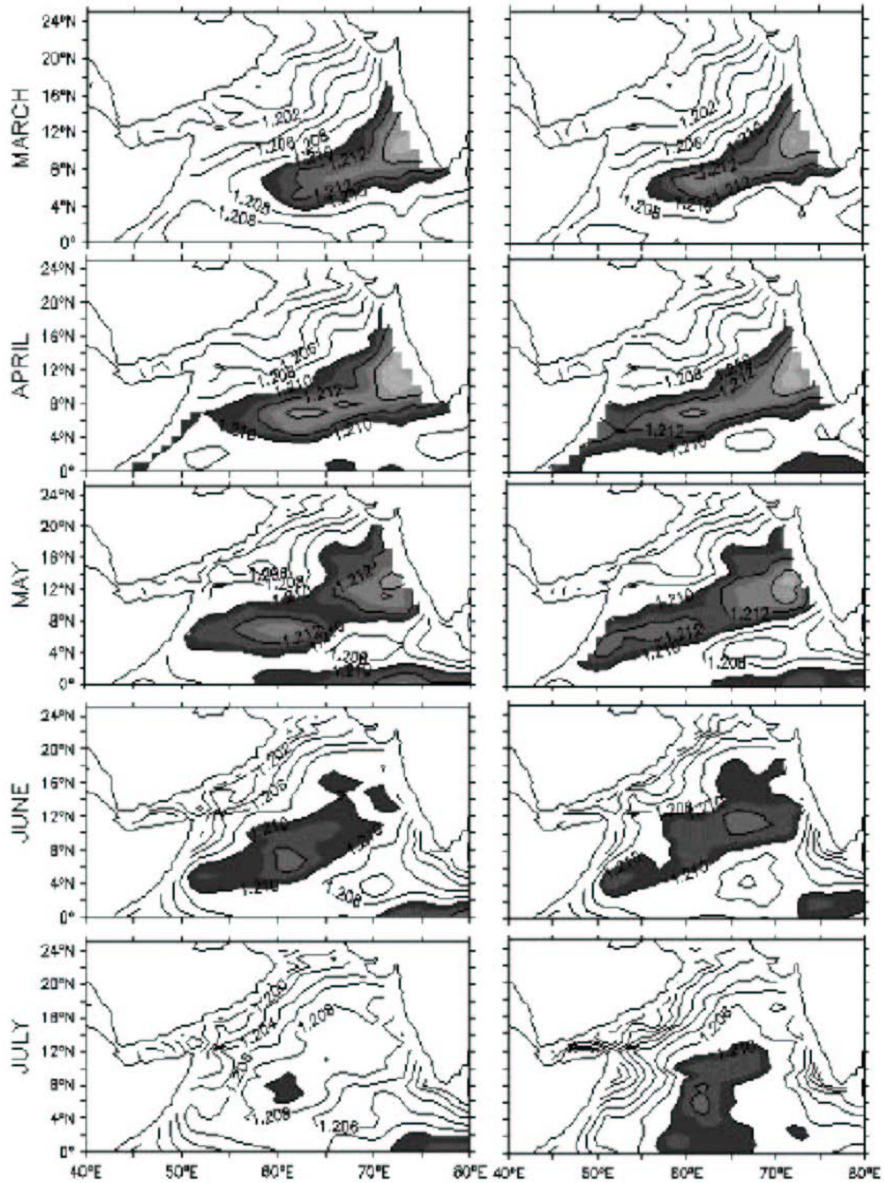


Fig. 10. Model derived 100 m heat content (in 10^{11} J/m^2) in the Arabian Sea for 2002 (left) and 2003 (right)

is immediately available for exchange with the counterpart, the atmosphere. It is mainly due to ocean's large thermal inertia, which appears to play a major role in driving the weather and climate variation. The heat content of upper Indian Ocean and its variability depends mainly on the surface wind forcing in monsoon rather than internal dynamics. During March – April the Arabian Sea is mostly cloud-free with weak surface wind speeds 2-3 m/s, large input of insolation and large positive heat fluxes enhancing the heat storage rate (heat content) in mixed layer. The monthly mean model heat content of upper 50 m over Arabian Sea is shown in Fig. 9 for 2002 and 2003. The evolution of warm pool in 2002 and 2003 can be clearly seen in Fig. 9. It is observed that maximum heat content was in the month of April during both 2002 and 2003 over the SEAS region. During 2003 high values of heat content persisted up to June in the SEAS, which is absent in 2002. The heat content (50 m) in July 2003 was higher as compared to 2002, in mainly west of 60° E. It is interesting to note that heat content during March and April in both years is almost similar in pattern and magnitude. In May 2002 higher values of heat content shifted towards west coast of India. More over the onset of monsoon in 2002 was in the month of May only. However the comparison of heat content of upper 50 m in 2002 and 2003 shows significant difference mainly from May to July (Fig. 9).

We also showed the evolution of heat content of upper 100 m over Arabian Sea (Fig. 10) during March to July. In both 2002 and 2003, maximum heat content was observed over SEAS during pre monsoon period. The heat content of 100 m has also shown the shift of maximum values towards the west coast of India in the month of May 2002 as compared to 2003. Where as in June the maximum heat content was observed in central Arabian Sea in 2002 and over SEAS in 2003. This was mainly attributed to the delay in onset of monsoon in 2003. The major difference in 100 m heat content was observed in the month of July, with high values in 2003 present over central Arabian Sea as compared to 2002. It is important to note that 100 m heat content shows the significant difference in the month of July, which may be because of the strong observed winds in 2003, causing more mixing.

8. Conclusions

The main focus of this study is to find the dynamical response of ocean to the atmospheric forcing and the scale to which these two massively coupled systems control the monsoon phenomena over the Indian subcontinent. An OGCM for the North Indian Ocean is used to examine the ocean's role in affecting this phenomenon. In this paper the authors tried to take advantage of modern satellite observations (Quikscat and TMI) for analysis and model integrations. The early onset of Somali Jet in May, its disintegration in June and near disappearance in July have played major role in the drought-like situation over the subcontinent in 2002 monsoon. In contrast, stronger cross-equatorial flow during June-July 2003, has contributed substantially to the normal rainfall over the Indian subcontinent. OGCM forced by daily Quikscat wind and short wave radiation flux (NOAA OLR derived) could simulate SST in intraseasonal time scale. The ARMEX observations at the point 74.5° E, 9.216° N provided an excellent opportunity for the calibration of the model. Even with a coarse resolution the model simulations are well comparable with ARMEX observations at the TSL. The breaking down of the Arabian Sea mini warm pool was well simulated in the model. The SST observation from TMI also showed good agreement with the model simulations. In consistent with the discussions, the 50m heat content (model) clearly shows the evolution (in March), peak (in May) and collapse (in June) of mini warm pool over the south east Arabian Sea. During 2003 high values of heat content persisted up to June in SEAS, but in 2002 it almost disappeared in May itself. But from May to July the heat content values showed significant difference between 2002 and 2003. The 100 m heat content also showed that in both 2002 and 2003 maximum heat content was observed over the SEAS during pre-monsoon season. The maximum heat content in June 2002 was observed over the central Arabian Sea and in 2003 over the SEAS. The major difference in 100 m heat content was observed in July with high values persisting in the central Arabian Sea in 2003 over a large area as compared to 2002. The mixing due to stronger winds has caused the deepening of thermocline in 2003. The study highlights the importance of accurate wind forcing which helped the model to produce observed inter-annual difference.

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