

Chapter 3 – Seasonal Variability of Mixed Layer and Barrier Layer

The seasonal variability of upper ocean parameters such as sea surface temperature (SST), sea surface salinity (SSS), mixed-layer depth (MLD) and barrier layer thickness in the Bay of Bengal is presented in this chapter.

3.1 Sea Surface Temperature

The spatial distribution of sea surface temperature (SST) in the Bay of Bengal during January showed a decrease from south to north (Fig. 3.1.1a). The lowest SST of 25°C was in the north, while the highest SST of 29°C was near the equator. The spatial distribution, thus, showed a 4°C cooling from equator to north. In February the SST distribution was similar to that of January except that the region of 29°C, which was located close to the equator had expanded (Fig.3.1.1b). The temperature in the northern Bay also showed an increase. The coldest temperature in the north was 26°C, which was 1°C warmer than that of January. The meridional difference in SST also reduced to 3°C from its January value of 4°C. During March the basin-wide SST showed a general warming of about 0.5°C compared to previous month (Fig.3.1.1c), though the variation from equator to head Bay remained the same as that of February (~3°C). The warming trend seen during March further intensified in April with northern Bay SST reaching up to 28.5°C (Fig.3.1.1d). Near the equatorial region SST was 30°C. The highest SST of 30.5°C occurred along the central part of the eastern boundary and a tongue of warm SST (~30°C) extended from this region offshore into the central Bay of Bengal. With the

basin-wide warming, a further reduction of the spatial contrast of SST from 3°C in March to 2.5°C in April was noticed.

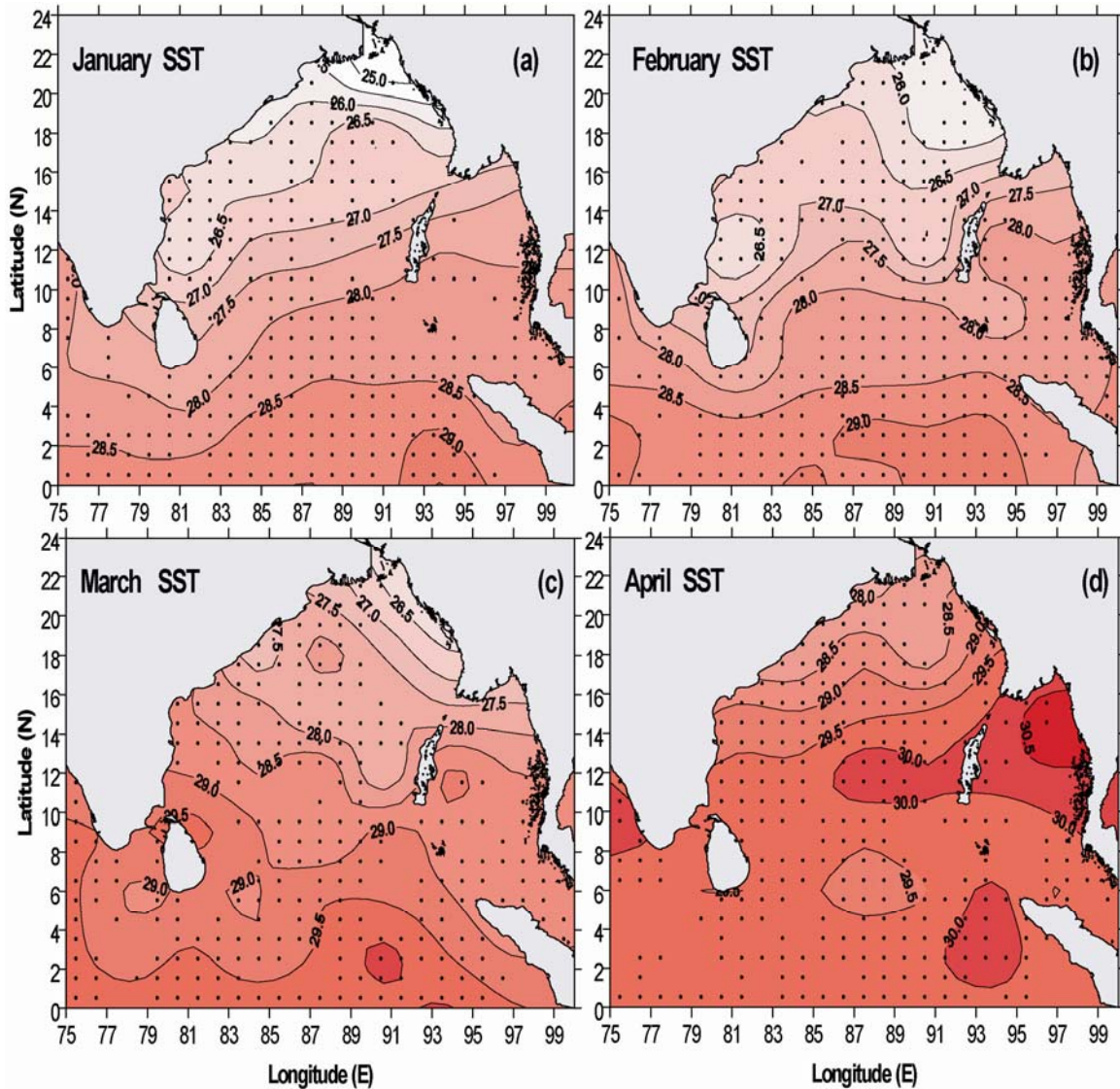


Fig.3.1.1 Monthly mean distribution of SST (°C) in the Bay of Bengal during January to April.

The basin-wide SST was the warmest in May with highest value of 31°C near the northeastern Bay (Fig.3.1.2a). The band of high SST (30°C) seen extending up to the central Bay in April, extends up to the western boundary in May. The SST, in general, was in excess of 29.5°C in the basin, except in the region surrounding southern part of Sri

Lanka where a distinct cold water patch (28.5°C) was seen. Another region of cold SST (29.0°C) was seen near southern part of central Bay. The meridional variation of basin-wide SST further reduced to 1.5°C indicating the continued warming in May.

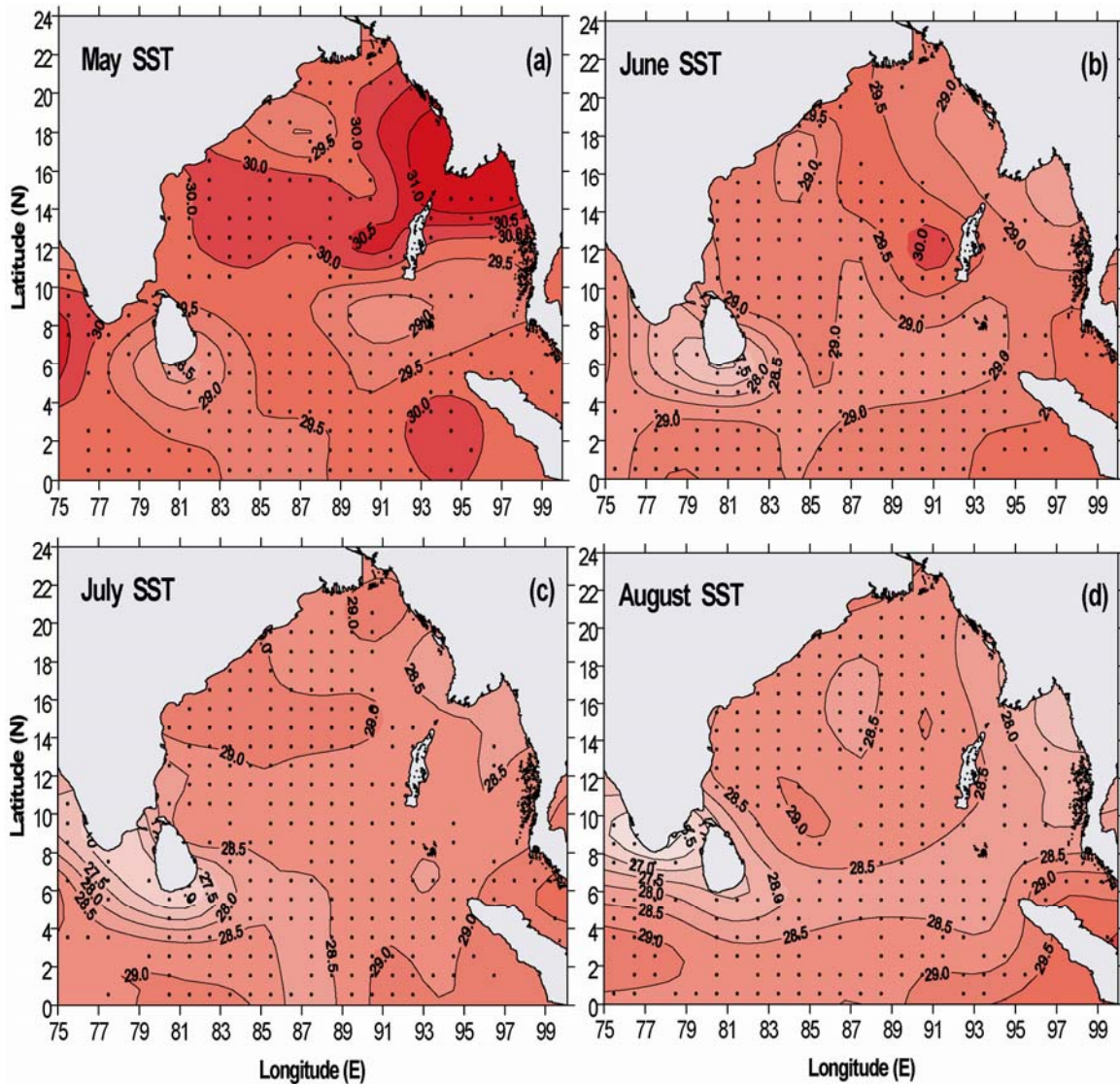


Fig.3.1.2 Monthly mean distribution of SST (°C) in the Bay of Bengal during May to August.

In June the basin-wide SST showed a cooling with values less than 29.5°C, except in a small patch extending from central to northwestern Bay (Fig.3.1.2b). The most prominent feature of the SST distribution was a region of cold water patch surrounding southern part

of Sri Lanka with a sharp thermal front. This patch ($\sim 27.5^{\circ}\text{C}$) was 1°C colder than the ambient temperature. The meridional difference of SST reduced further to 1°C . This reduction was brought about by the general cooling in the basin-wide SST. In July, the basin-wide SST varied between 28.5 to 29°C (Fig.3.1.2c), except in the region surrounding Sri Lanka, which showed further cooling of SST. The lowest SST was 27°C , which was 1.5°C colder than the ambient waters. The cold water region appeared to spread northward towards the peninsular India and southern part of the west coast of India. The basin-wide SST was about 28.5°C in the Bay during August, which increased towards equator with the highest value of 29.5°C (Fig.3.1.2d). The region of coldest SST moved from the southern part of Sri Lanka towards the tip of peninsular India in August. The lowest SST was about 26.5°C and it was 2.5°C colder than the ambient waters.

The basin-wide SST pattern remained the same in September as that of the previous month except for the warming near the head Bay (Fig.3.1.3a). The cold SST region, which encompassed the southern tip of the peninsular India and Sri Lanka diminished. The associated thermal front also weakened considerably. In October this cold water completely vanished and the basin-wide SST showed a warming once again (Fig.3.1.3b). The northwestern Bay showed cooling in November with SST of about 27.5°C (Fig.3.1.3c). This SST was about 1 to 1.5°C colder than the rest of the basin. This cooling intensified in December with lowest SST of 26.5°C in the northern Bay (Fig.3.1.3d). The meridional temperature difference was about 2.5°C with warmest waters (29°C) near the equator.

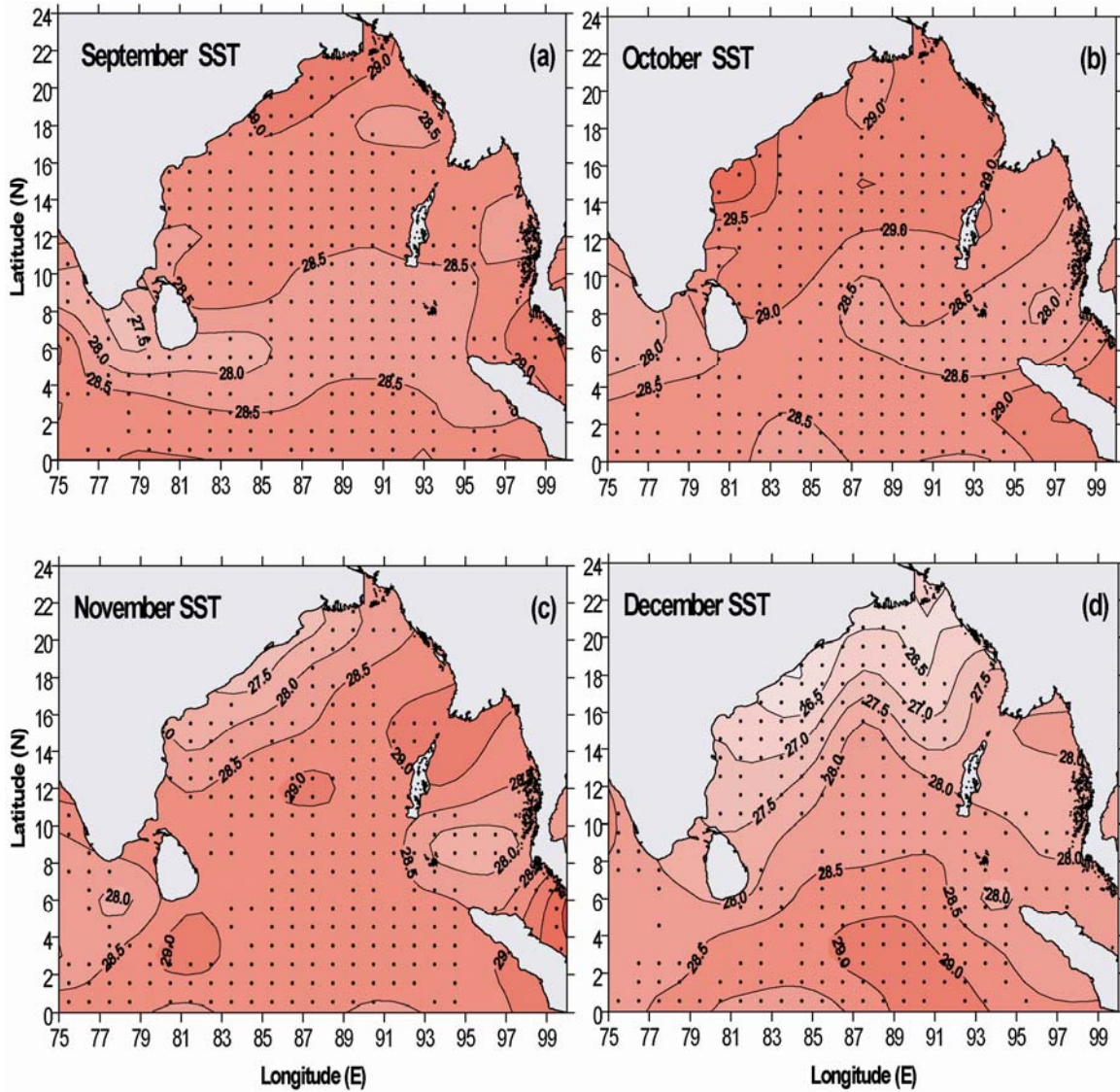


Fig.3.1.3 Monthly mean distribution of SST ($^{\circ}\text{C}$) in the Bay of Bengal during September to December.

In summary, the SST showed a strong seasonal (semi-annual) cycle. The amplitude of the seasonal cycle was about 6°C with coldest SST of about 25°C in the north during January and warmest SST of about 31°C in the central part of the eastern boundary during May. The seasonal cycle of SST showed two warming period with warm SST during April-May and October. The period of low SST was during January-February. The highest spatial variability occurred during January when SST varied 4°C from south to north. The

least spatial variability occurred during October, which was about 1.5°C. An interesting feature of the SST distribution in the southwestern Bay was the appearance of a thermal front with a region of cold water around Sri Lanka in May. This thermal front further developed in June-July and peaked in August. In July, the cold water region moved northward towards the peninsular India and along the southern part of the west coast of India. The coldest SST of 26.5°C was noticed in August with a thermal gradient of about 3°C from southern tip of peninsular India to south of Sri Lanka. By September this feature diminished. This feature must be associated with Indo-Sri Lankan upwelling system and the Sri Lankan dome.

3.2 Sea Surface Salinity

The distribution of sea surface salinity (SSS) in January showed the presence of low salinity waters close to the northeastern Bay with an increase towards south (Fig.3.2.1a). The lowest salinity was 31 psu while the highest value was about 35 psu. Along the eastern and western boundary also the salinity was low (~32.5-33.5 psu). The spatial variation of SSS from north to south was about 4 psu. In February the spatial distribution was similar to that of January with the lowest salinity of 30 psu in the north and highest salinity of 34.5 psu in the south (Fig.3.2.1b). However, the region of 31 psu salinity reduced in its spatial extent considerably, compared to January, and was confined very close to head Bay (Fig.3.2.1b). The meridional variation of SSS was about 4.5 psu in February. The SSS distribution in March showed an increase of 1 psu in the northern Bay with lowest salinity being 32 psu (Fig.3.2.1c). In the south, south of 10°N the spatial distribution of SSS was similar to that of February. The north-south variation of SSS was ~ 2.5 psu. During April the SSS distribution showed a 0.5 psu reduction in the salinity in

the head Bay (~31.5 psu) from that of March, while that along the western boundary was more than 33.5 psu (Fig.3.2.1d). The meridional variation in SSS was about 3 psu.

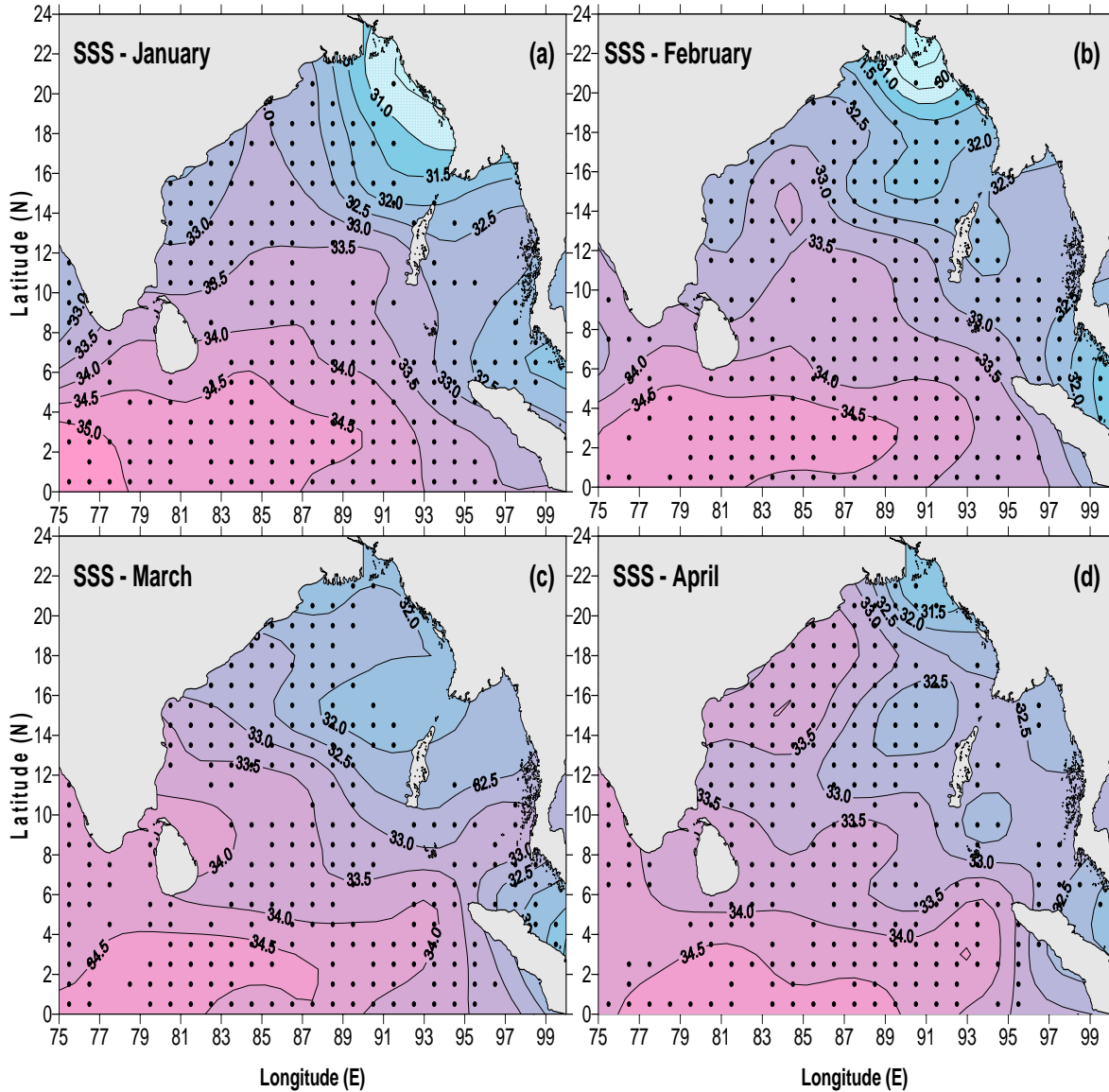


Fig.3.2.1 Monthly mean distribution of SSS (psu) in the Bay of Bengal during January to April.

The SSS distribution showed the least spatial variation of about 2 psu in May with low salinity waters confined to the eastern boundary of the Bay of Bengal (Fig.3.2.2a). Along the western boundary salinity was highest in May (33.5-34 psu). The lowest salinity was

32.5 psu while the highest was 34.5 psu. In June a low salinity patch appeared in the head Bay with a distinct salinity front north of 15°N showing the lowest salinity of 30.5 psu (Fig.3.2.2b). The salinity variation across the front was about 2.5 psu. In the south the distribution remained similar to that of previous month. The meridional variation of salinity was about 4 psu. A tongue of high salinity water (35 psu) was seen close to the

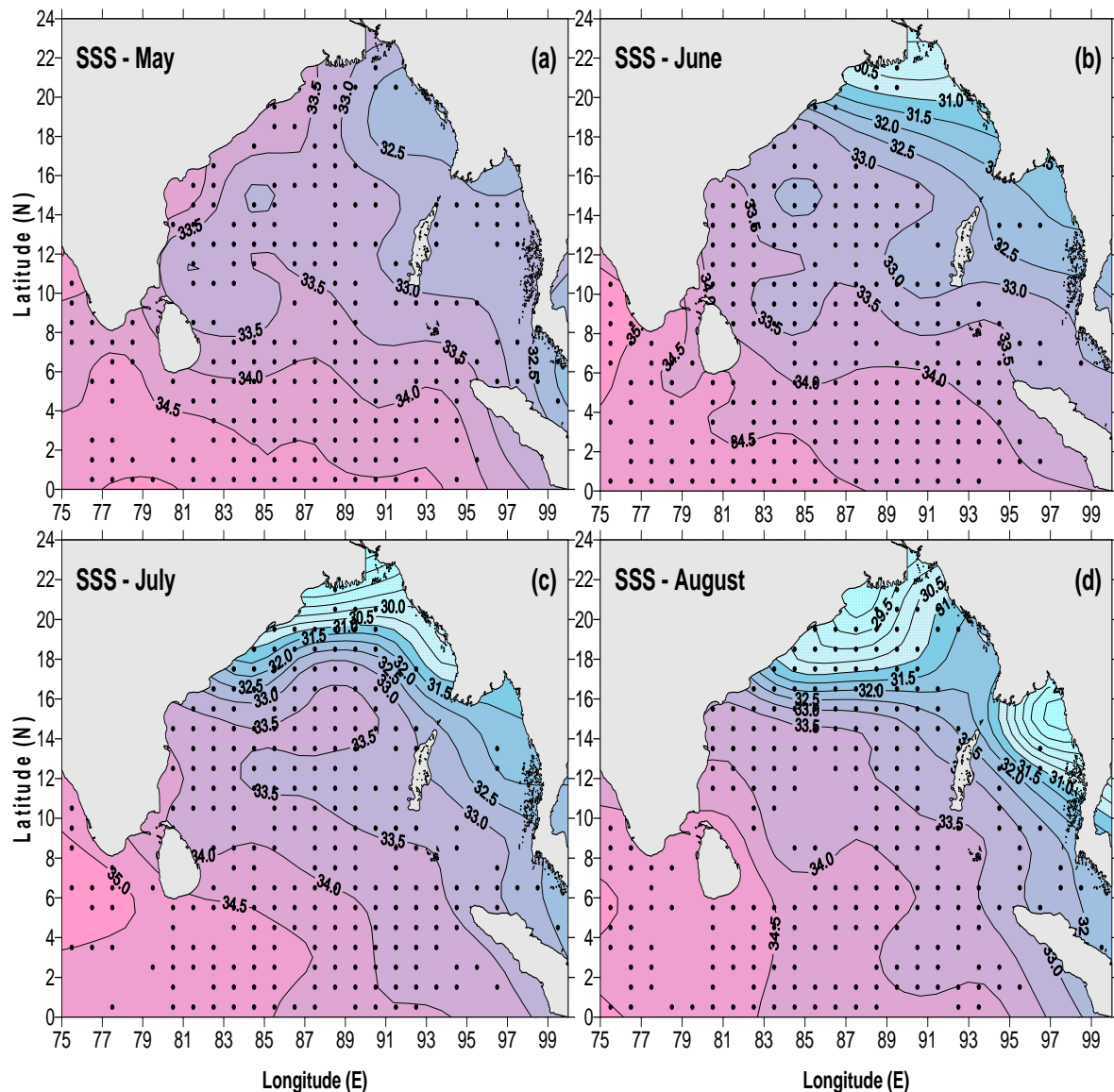


Fig.3.2.2 Monthly mean distribution of SSS (psu) in the Bay of Bengal during May to August.

southwestern part of peninsular India. The SSS during July showed fresher water near the head Bay with a minimum value of 29 psu. The region of low salinity expanded further away from the head Bay. The salinity front strengthened much more compared to June and the salinity variation across the front was about 4.5 psu, while the basin-wide north to south variation was 5.5 psu. The tongue of high salinity waters seen in June had spread

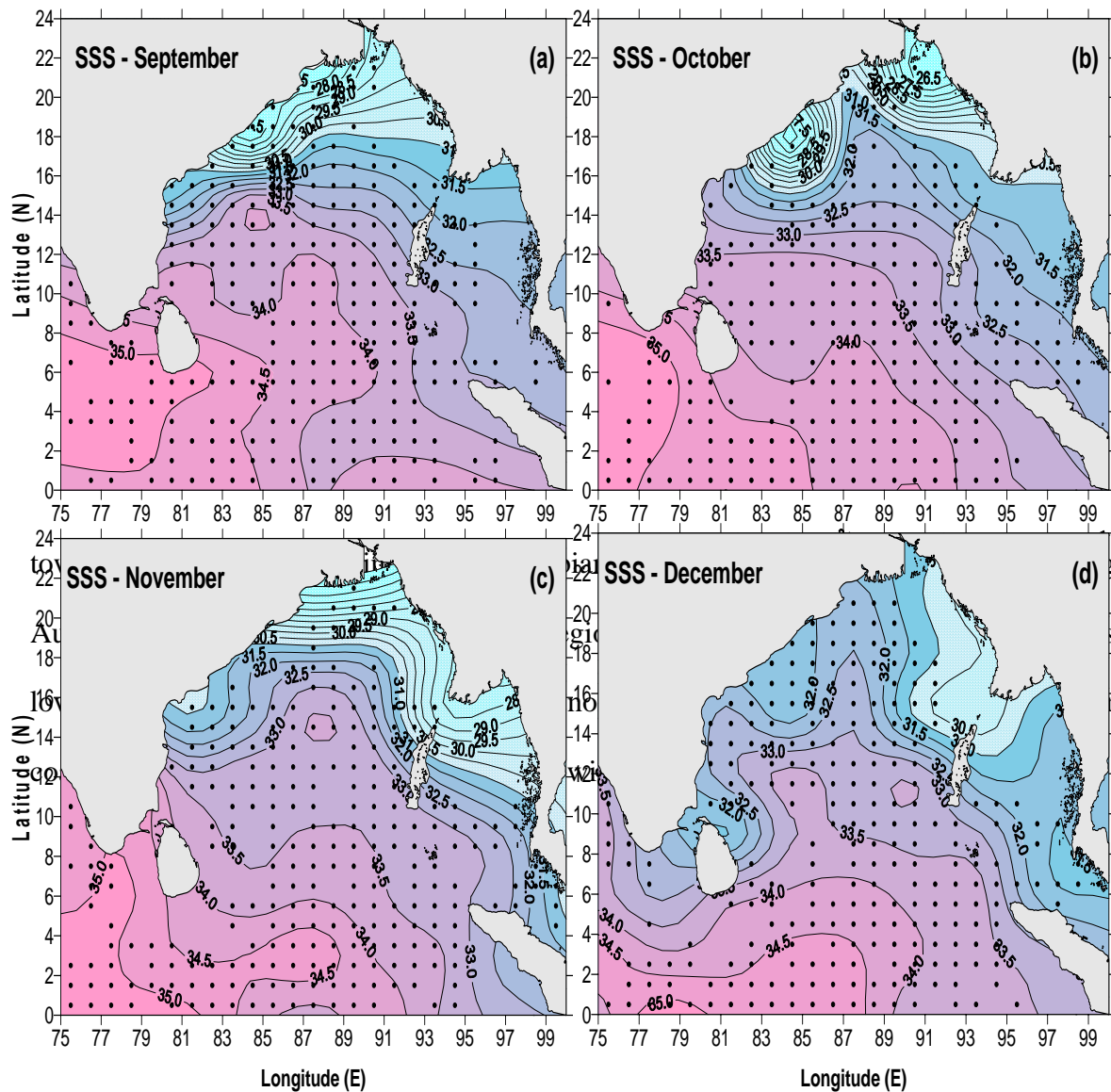


Fig.3.2.3 Monthly mean distribution of SSS in the Bay of Bengal during September to December.

The SSS during September showed further reduction in the salinity in the northern Bay with the lowest value of 27.5 psu (Fig.3.2.3a). The salinity front also showed much stronger gradient with variation of 6 psu salinity across the front. The tongue of a high salinity waters with salinity of 35 psu were seen intruding from the west further into the southern Bay south of Indian peninsula and Sri Lanka. Thus, SSS showed an increase of 7.5 psu from north to south. The lowest SSS in the Bay of Bengal was encountered during October with a salinity of 26.5 psu close to the head Bay (Fig.3.2.3b). In addition to the freshening near the head Bay, another region of freshening was seen located along the northern part of the western boundary with minimum salinity of 27 psu. Towards south, surface salinity showed an increasing trend reaching a maximum salinity of 35 psu near the equator. The spatial variation in salinity during this month was 8.5 psu, which was the highest compared with other months. The low salinity region close to the northern part of the western boundary seen in the previous month disappeared in November (Fig.3.2.3c). The band of low salinity was seen extending from northwestern Bay along the head Bay to the northeastern Bay. The lowest salinity was 26.5 psu close to head Bay. In the south the high salinity water was pushed further towards the equator. The variation in SSS from north to south was about 8 psu. In December the lowest salinity was 30.5 psu seen close to the Myanmar coast (Fig.3.2.3d). The low salinity waters, ~32 psu, were seen along the eastern as well as the western boundaries and also around Sri Lanka and into the southern part of the west coast of India. The waters with highest salinity were confined to the equator. The spatial variation in surface salinity was about 4 psu in December.

In summary, the SSS showed a strong annual cycle. The amplitude of the annual cycle was about 8.5 psu with lowest salinity of 26.5 psu in the north during October and highest SSS of about 35 psu in the southern Bay during September to November. The highest spatial variability occurred during October when SSS varied by 8.5 psu from north to south while the least spatial variability occurred during May, which was about 2 psu. The annual cycle of SSS was driven by the freshening that occurred in the northern Bay of Bengal during June to October and the seasonal circulation that redistributed the fresher water influencing the ambient salinity. In the southern Bay salinity remained almost same except during June to October when the high salinity waters (35 psu) of the Arabian Sea origin is advected into the Bay of Bengal. Since the freshwater input was from the peninsular rivers, which are located in the northern part of the Bay along the eastern and western boundaries, it is important to decipher the variability of the northern and southern Bay separately. In the northern Bay, north of 15°N, the amplitude of the annual cycle was about 6.5 psu with the highest salinity in May (~33 psu) and lowest (~26.5 psu) in October. In the southern Bay the amplitude of the annual signal is about 0.5 psu and this was associated with the intrusion of the high salinity waters from the Arabian Sea.

3.3 Mixed Layer Depth

The spatial distribution of mixed layer depth (MLD) during January showed deep MLD in excess of 30 m in a large area encompassing southwestern Bay including the western and central equatorial region, central Bay, and the northeastern region (Fig.3.3.1a). The deepest MLD of 40 m was noticed at two locations between 84° and 89°E centered at 15°N and 10°N respectively. The MLD close to the western boundary and the head Bay

was about 25 m. The southeastern Bay including the eastern equatorial region showed shallow MLD and the minimum value was 10 m. Thus, the spatial variation in MLD within the basin was about 30 m. In February, the region of deep MLD remained the same as that of January except that a low patch of shallow MLD (~20-25 m) appeared

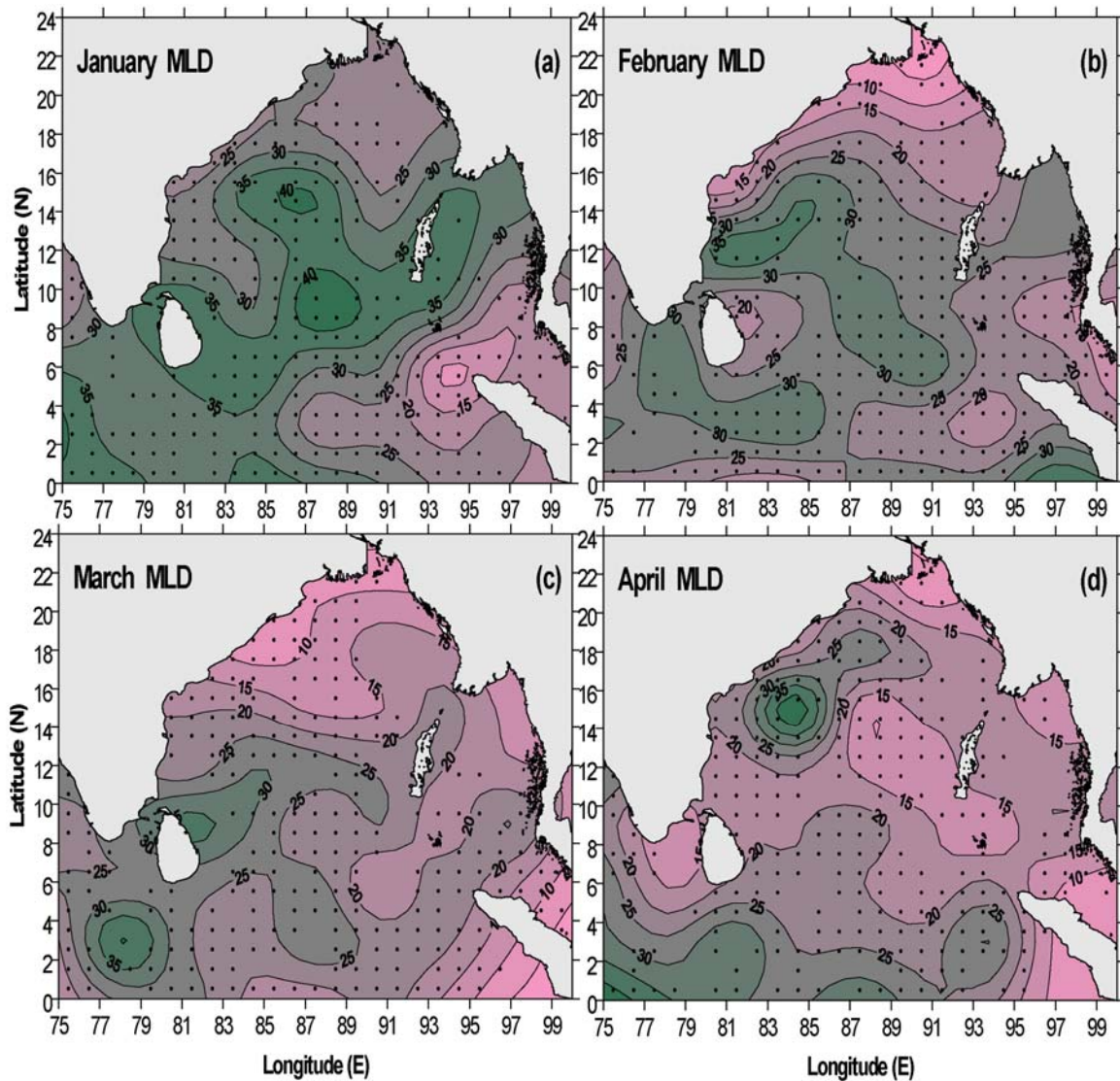


Fig.3.3.1 Monthly mean distribution of MLD (m) in the Bay of Bengal during January to April.

close to the Sri Lanka (Fig.3.3.1b). The region of the deepest MLD moved from the central Bay to the western boundary and was located between 12° and 14°N. Along the

western boundary north of 15°N and in the northern Bay the MLD shoaled to less than 15 m. The region of low MLD seen in the southeastern Bay in the previous month was also seen in February at the same location, but the depth showed a marginal deepening. During March most part of the Bay showed shallow MLD shallower than 25 m, except at two locations one around Sri Lanka and the other in the western equatorial region (Fig.3.3.1c). The shallowest MLD occurred close to the northwestern boundary including the head Bay and also in the southeastern part close to the equator. In April MLD in most part of the Bay was shallower than 20 m except two regions, one close to the equatorial region and the other region encompassing the western boundary between 12° and 18°N (Fig.3.3.1d).

During May two zonal bands of deep MLD (~ 30 m) was seen, one between 8°N and 16°N extending from western boundary towards the eastern boundary and the other between equator and 4°N (Fig.3.3.2a). However, east of 90°E the region of deep MLD tapered. These two zonal bands of high MLD were separated by a narrow band of comparatively shallow MLD of about less than 25 m. In the northern Bay, north of 16°N , MLD showed a rapid decrease with a minimum value of 15 m. Another patch of shallow MLD (~ 15 -20 m) was observed near the southeastern Bay. In June the region of deep MLD in the southwestern Bay joined the deep MLD region in the central and western Bay (Fig.3.3.2b). Thus, most part of the Bay had deep MLD, deeper than 30 m and the deepest was 45 m in the southern Bay. Along the western and eastern boundary the MLD was shallow (~ 15 -20 m). The MLD decreased rapidly north of 16°N and the shallowest MLD of 10 m was encountered close to the head Bay. Similarly, around Sri Lanka also the MLD decreased rapidly from 40 m to 20 m. The spatial distribution of MLD during

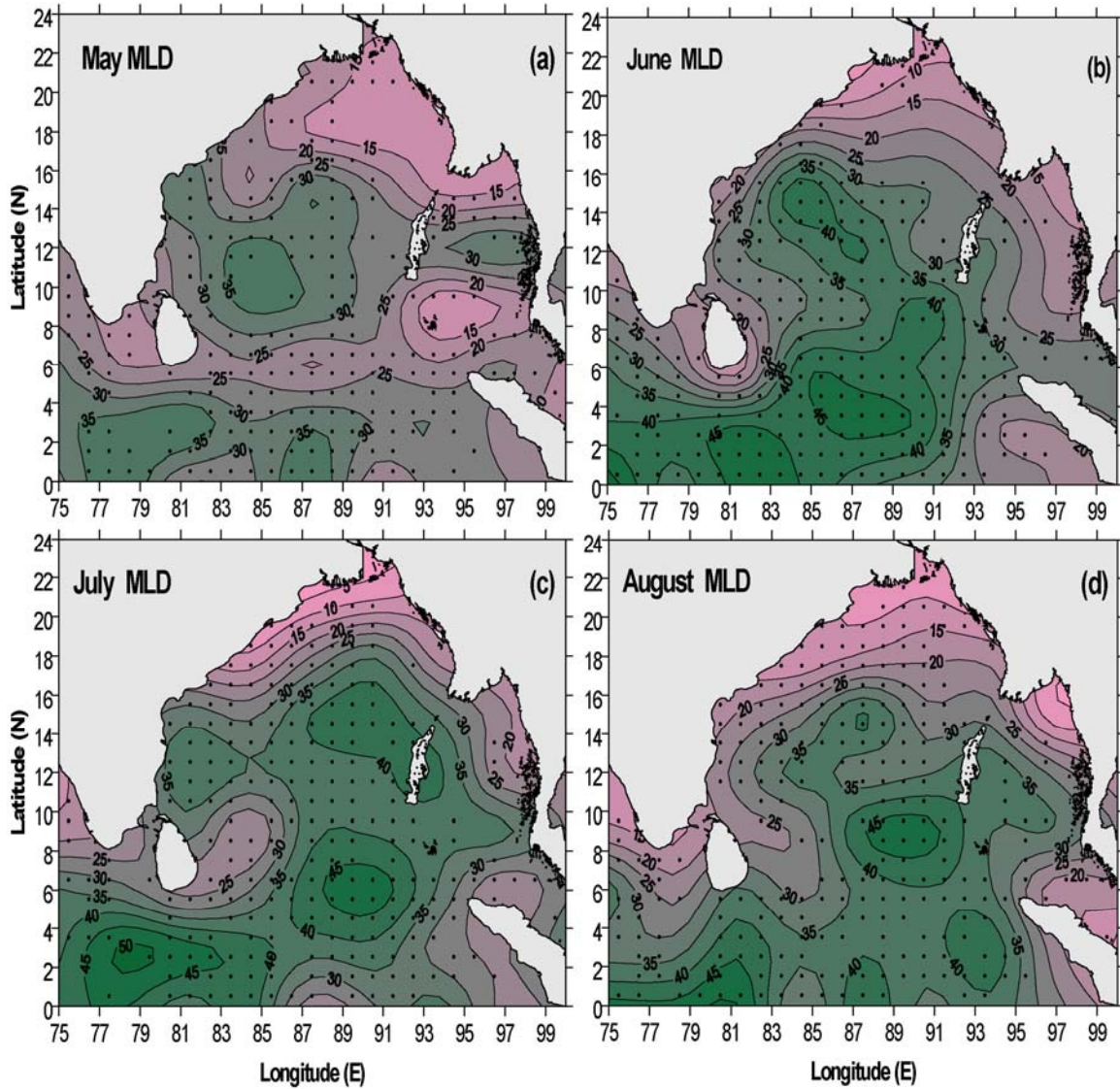


Fig.3.3.2 Monthly mean distribution of MLD (m) in the Bay of Bengal during May to August.

July was similar to that of June with most part of the Bay showing MLD deeper than 35 m (Fig.3.3.2c). The deepest MLD of 50 m was located close to the western equatorial region. The rapid shoaling of MLD seen in the north in June intensified further with shallowest MLD of 5 m close to the head Bay. Around Sri Lanka and southern tip of peninsular India MLD was shallow. In August also the spatial distribution of MLD was similar to that of July, except that shallower MLD was noticed in the central part of the

eastern boundary (Fig.3.3.2d). The MLD near the southern tip of India and Sri Lanka showed further shoaling of MLD compared to July.

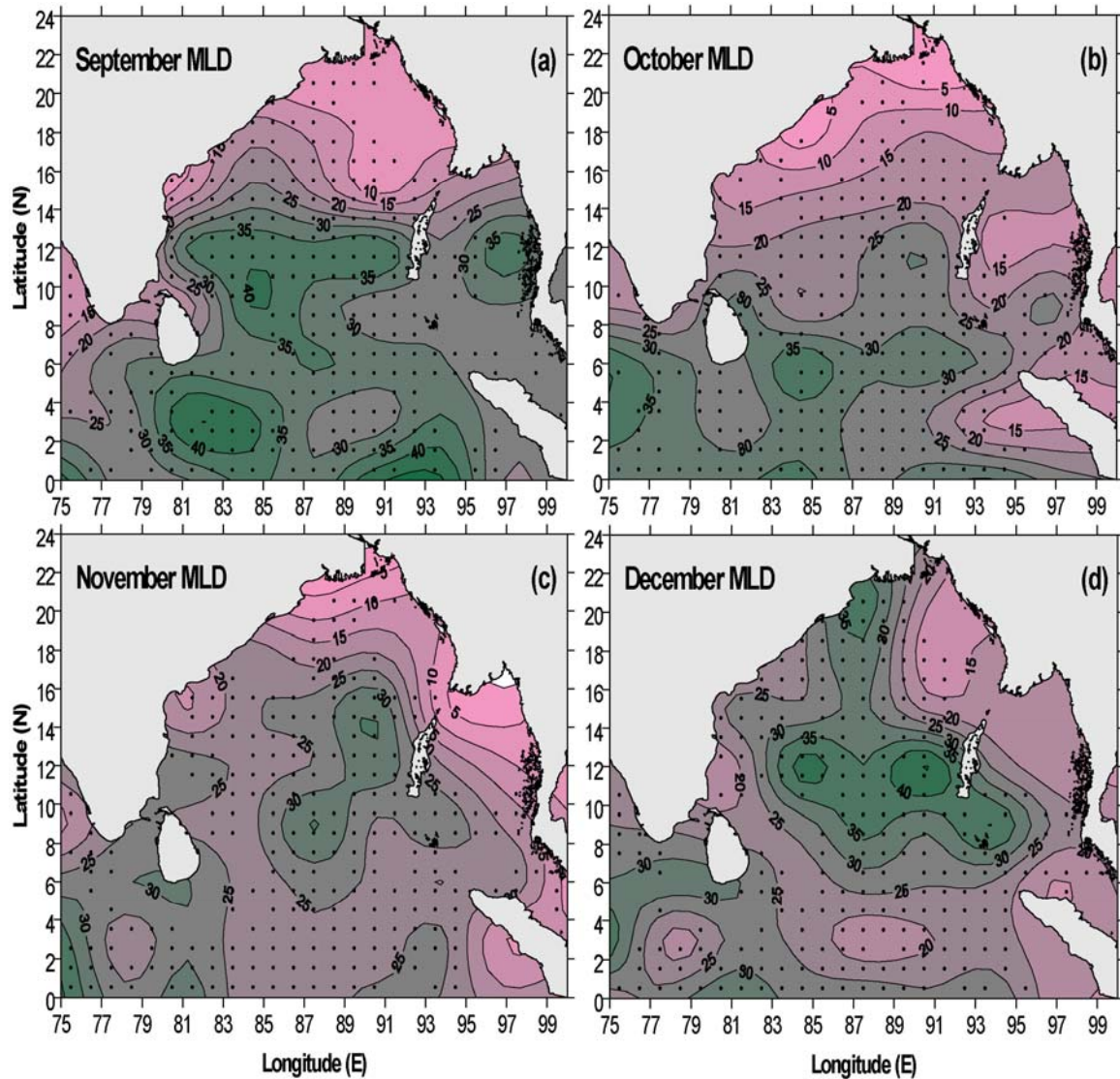


Fig.3.3.3 Monthly mean distribution of MLD (m) in the Bay of Bengal during September to December.

During September the region of low MLD (10-15 m) further expanded from head Bay towards south reaching up to 15°N (Fig.3.3.3a). Along the western boundary also the MLD decreased to 15 m. The deepest MLD (~40 m) occurred in the south central Bay

and equatorial region. In October the area of shallow MLD expanded further southward and reached up to 12°N (Fig.3.3.3b). Similarly, the shallow MLD region along the eastern boundary also expanded westward up to 92°E. Thus, the deep MLD region (~30 m) was mostly confined to south of 8°N and west of 92°E. The basin-wide MLD in November was shallower than 25 m except in two smaller regions – one in the central Bay and the other west of 83°E and south of 8°N (Fig.3.3.3c). The deepest MLD was 30 m in November. In December, the spatial pattern of MLD distribution was similar to that of November, except that a small patch of deep MLD appeared in the northwestern Bay, which was attached to the deep MLD of the central Bay (Fig.3.3.3d). The depth of MLD in the central and northwestern region increased to more than 35 m.

In summary, the deepest MLD was about 50 m in the southern Bay during July and shallowest MLD was about 5 m in the northern Bay during October and November and along southeastern Bay during March. The period of shallow MLD was during March-April. The highest spatial variability occurred during July when MLD varied 40 m from south to north. The least spatial variability occurred during April-May, which was about 20 m. The deepest MLD in the north occurred during December-January, which was about 25-30 m. The seasonal cycle of MLD in the north (north of 15°N) showed semiannual variability with deep MLD during December-January and June-July while shallowest MLD during March and October. The amplitude of seasonal cycle in the north was about 15 m. The seasonal cycle of MLD in the south (south of 15°N) showed deep MLD during June-August and shallowest during April. The amplitude of seasonal cycle of MLD in the south was about 17 m.

3.4 Barrier Layer Thickness

The barrier layer thickness (BLT) showed large spatial variability during January, varying from 70 m in the northern Bay and eastern equatorial region to less than 30 m in the central and southern Bay (Fig.3.4.1a). The region around Sri Lanka and peninsular

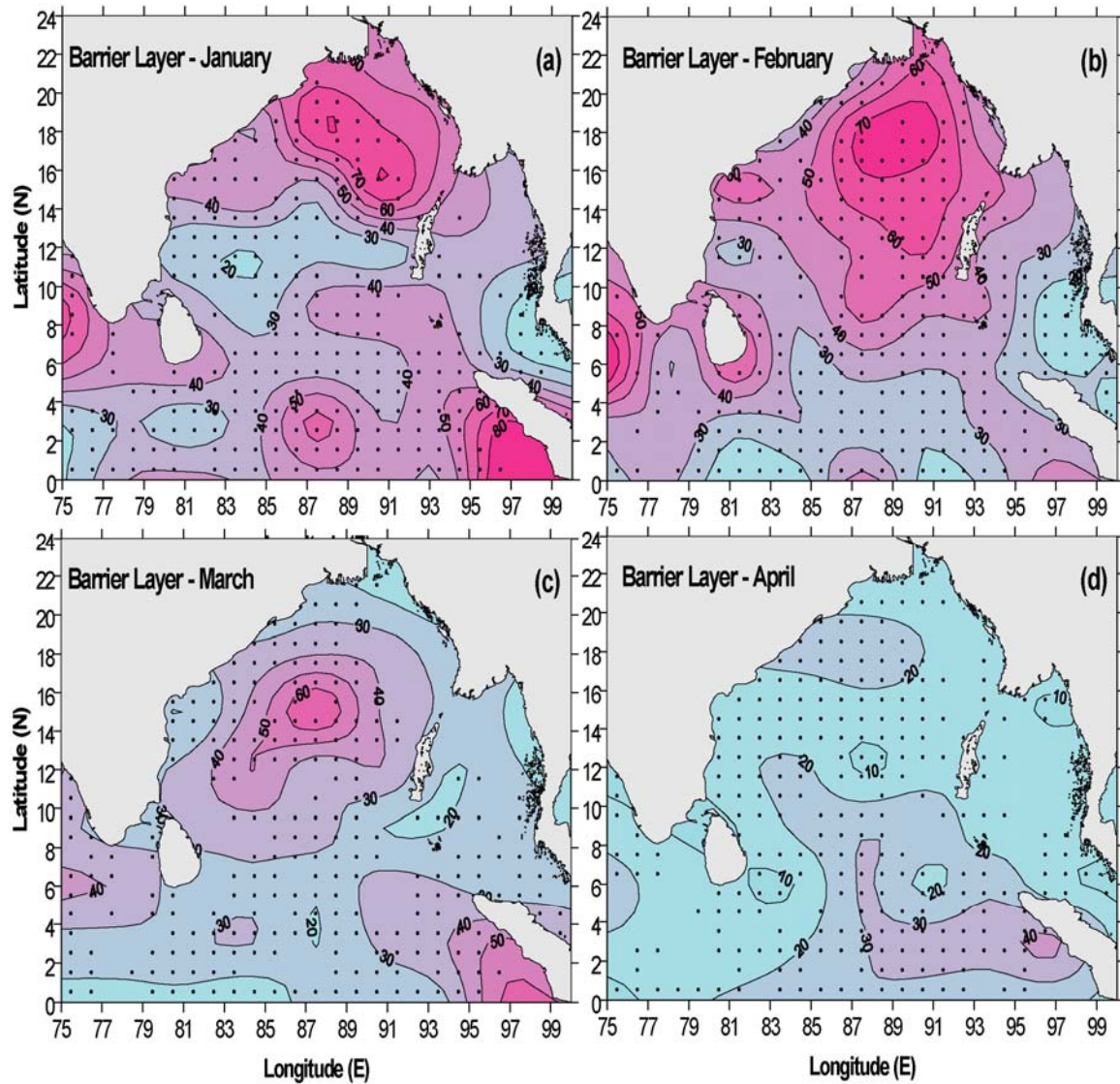


Fig.3.4.1 Monthly mean distribution of BLT (m) in the Bay of Bengal during January to April

India had a deep BLT. In February, the region of deep barrier layer expanded and occupied almost the entire basin (Fig.3.4.1b). Along the eastern and equatorial region

BLT was about 30 m. During March the basin was characterized by two regions of thick barrier layer, one in the central Bay of Bengal encompassing the western boundary and another region of high BLT near the Sumatra coast (Fig.3.4.1c). In the rest of the Bay BLT was low (20 m). The basin-wide BLT was the least in April, which was about 20 m, except close to the eastern part of the equator where it was about 30 m (Fig.3.4.1d). This

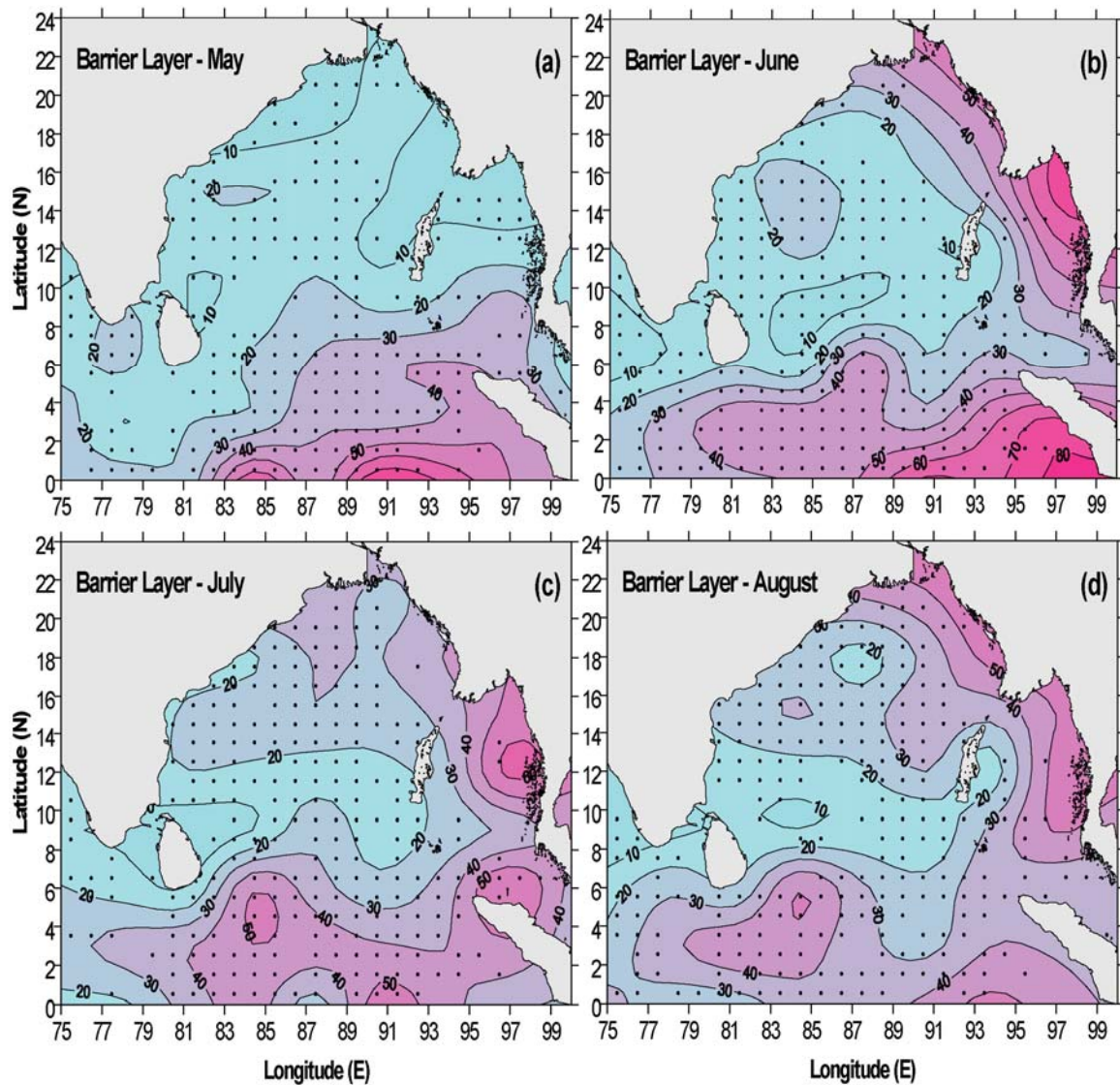


Fig.3.4.2 Monthly mean distribution of BLT in the Bay of Bengal during May to August.

patch of thick barrier layer near equator further increased its thickness in May, while in the rest of the Bay the BLT was between 10-20 m (Fig.3.4.2a). In June the region of high BLT expanded northward along the equator and along the eastern boundary (Fig.3.4.2b). The spatial distribution pattern of BLT remained similar in July (Fig.3.4.2c) and August (Fig.3.4.2d) with the exception that along the eastern boundary BLT increased westward.

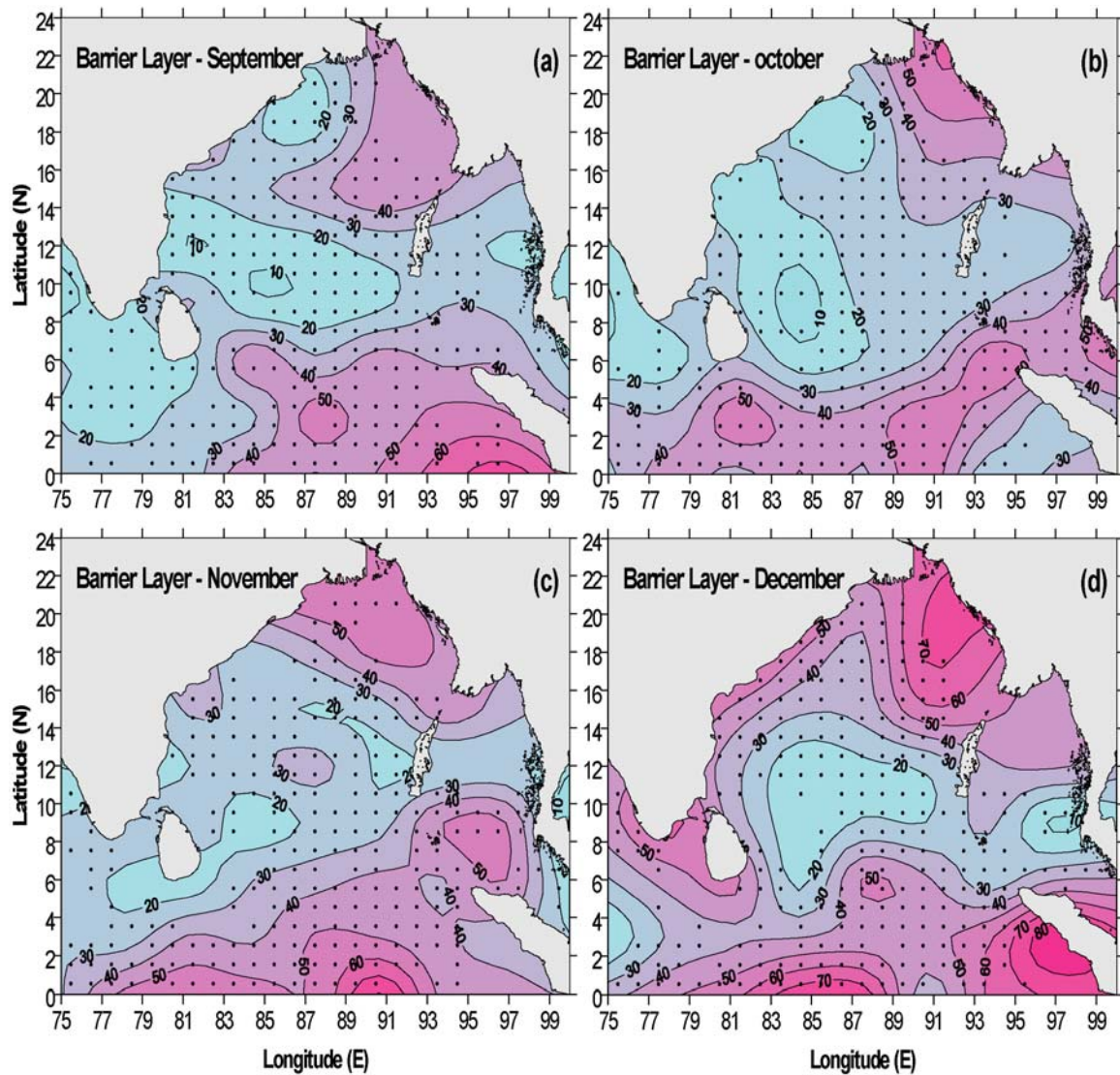


Fig.3.4.3 Monthly mean distribution of BLT (m) in the Bay of Bengal during September to December.

During September the barrier layer showed an increasing trend towards southeast Bay, south of 8°N with maximum barrier layer thickness of about 60 m very near to the equator (Fig.3.4.3a). In the central Bay of Bengal BLT varied between 20 and 30 m. The BLT in the northeastern Bay was 40 m. In October along the equatorial region, eastern boundary and the head Bay BLT deepened with maximum thickness of about 50 m (Fig.3.4.3b). Along central and western Bay BLT was thin and varied between 20 and 30 m. In November the BLT near the equator showed an increase with a maximum value of 60 m (Fig.3.4.3c). Similarly, in the northern Bay also BLT increased with maximum value of 50 m. During December BLT along the equator and the eastern and western boundary was high (Fig.3.4.3d). A zonal band of low BLT was seen between 6° to 14°N where the thickness was between 20-30 m.

In summary, the amplitude of the seasonal cycle of Barrier layer was about 70 m with thickest barrier layer of about 80 m in the south during December-January and thinnest barrier layer of 10 m in the central Bay during April-May and around Sri Lankan dome during June-July. The period of thick barrier layer was during January-February. The highest spatial variability occurred during June when Barrier layer varied 70 m within the basin. The least spatial variability occurred during April, which was about 20 m. The thickest barrier layer in the south occurred during June and December-January, which was 50 m deeper than the rest of the southern Bay. The deepest barrier layer in north occurred during December-January and February, which was about 70 m.