A COLD POOL FORMATION IN THE LAKSHADWEEP SEA AND A POSSIBLE METHOD FOR THE SYNTHETIC ENHANCEMENT OF UPWELLING

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1. INTRODUCTION

Lakshadweep Sea (Fig.1), off the southwest coast of India exhibits strong air-sea interaction through seasonal variability in hydrography and circulation driven by seasonal reversal of winds, remote forcings and advection (Cutler and Swallow et al.,1984).

Present work addresses the formation of a cold pool (Fig.2) in the Lakshadweep Sea which we name as the Lakshadweep cold pool **(LCP)**, during the summer monsoon period.

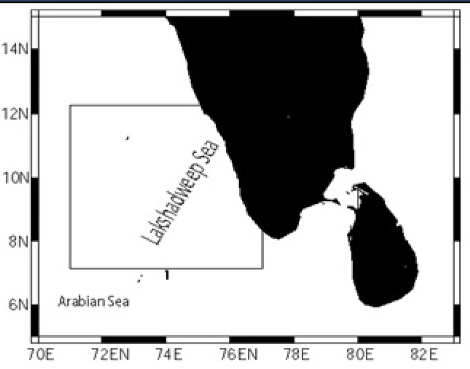
Fig.1 Lakshadweep Sea

LCP develops due to uplifting of a poleward under current over an elevated bathymetry (mount) in the region. It is further intensified by wind/eddy induced upwelling and strengthening of the poleward under current.

Chlorophyll-a concentration shows good correlation with the spatial spread and intensity of the cold pool.

A method to enhance the existing upwelling in the region is proposed.

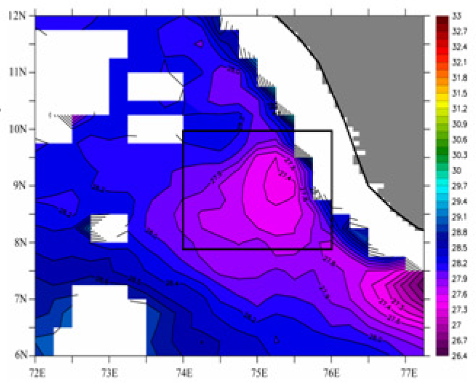
Fig.2 TMI SST (°C) (ave1998-2005) for July; LCP (within the box)

2. DATA SETS

3 day composite of TMI SST, 0.25° X 0.25° (1998-2005); GODAS pentad subsurface potential temperature and currents, 0.33° X 0.33° (1998-2005); SeaWifs Chlorophyll-a concentration (Chl-a), 9km x 9km (1998-2005); ETOPO1 Bathymetry (1km); QuikSCAT winds (10m), 0.25° X 0.25° (2000-2005); AVISO merged grided weekly sea surface height anomaly (SSH), 0.25° X 0.25° (1998-2005); Daily Netflux (OAFlux), 1° X 1° (1998-2005).

3. EVOLUTION OF LCP

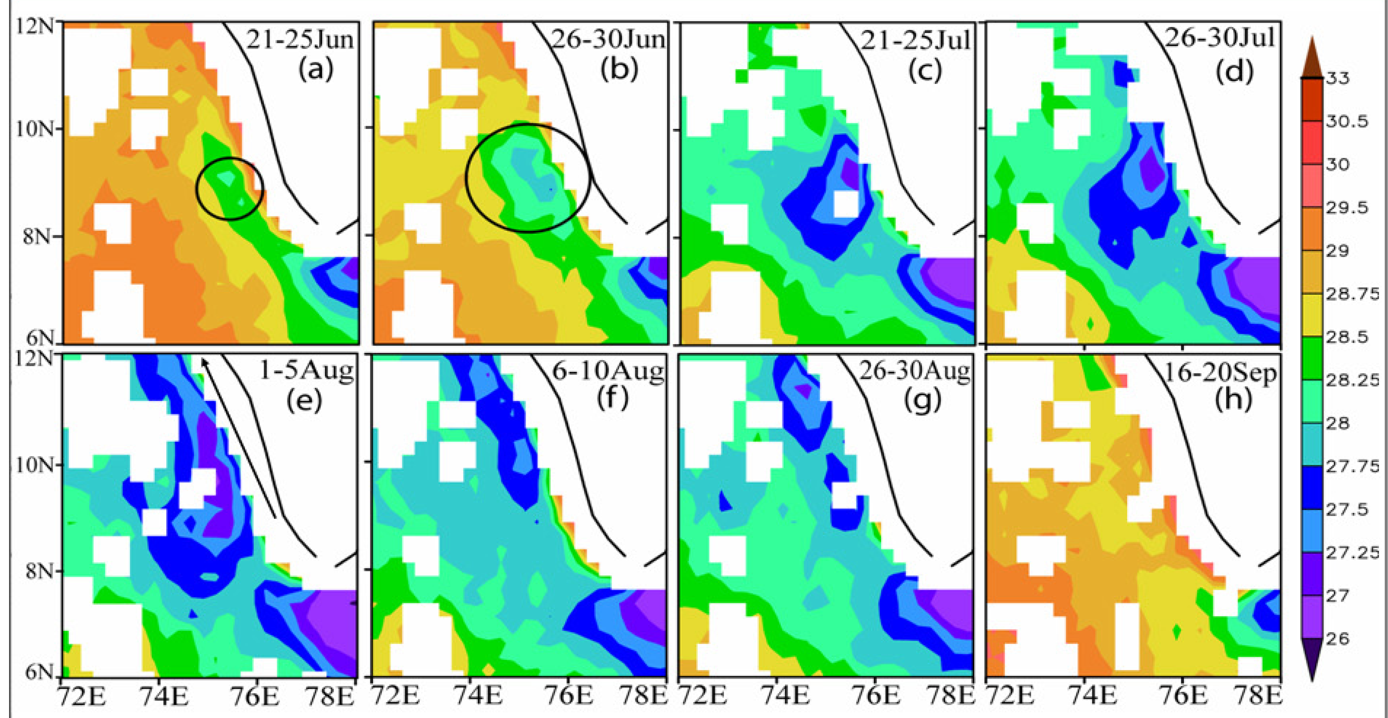
Fig.3(a-h) Multiyear average (1998-2005) of TMI SST(°C) in pentads

LCP forms during the fifth pentad of June as a small cooling in the gird 8-10°N/74-76°E (Fig.3a) within the northward advected cooler water from southern tip of India. Subsequently, it expands radially outwards and, by July, forms a circular pool with maximum spread and intensity (<27°C). During August, it extends northward (Fig.3e) along the coast as a patch of cooler waters intensifying with positive wind stress curl. By September, the pool gets completely dissipated.

4. SOUTHWESTWARD SPREADING OF LCP

During July, LCP advances southwestward (marked by black arrow) (Fig.4a). Lakshadweep Low is present since June. South of 10°N the surface flow is due north and it is due south north of 10°N (Fig.4b). These two currents meet near 9°N and propagate southwestward with the westward propagating LL dragging the LCP southwestwards (marked by black arrow)

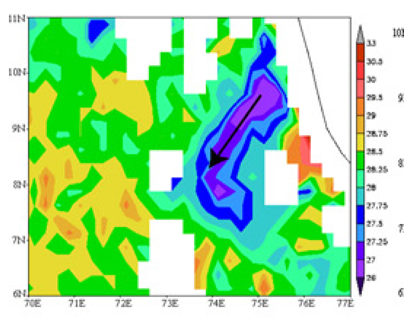
Fig.4a SST(°C) on 28th July 2000

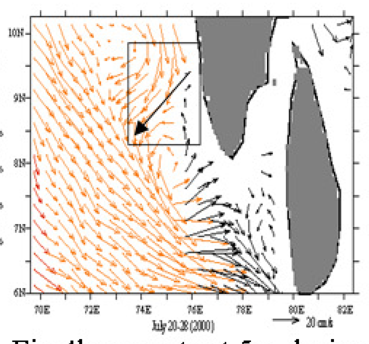
Fig.4b currents at 5m during 20-28 July 2000 (GODAS)

5. CHLOROPHYLL CONENTRATION

During June, Chlorophyll-a concentration (Chl-a) is high along the southwest coast of India due to coastal upwelling (Fig.5a). (White patches show data-void regions due to rainfall). With the formation of LCP in July, Chl-a shows rapid increase (marked in Fig.5b). Its concentration and distribution exhibit good correlation with intensity and spread of SST in LCP (Fig.5c,d).

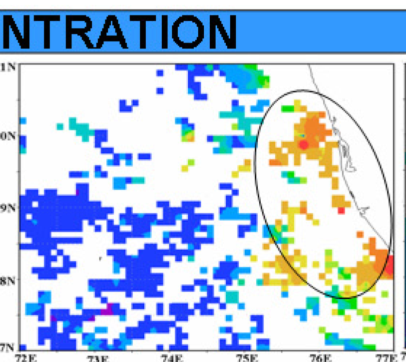
Fig.5a Spatial pattern of Chl-a for Jun 1998

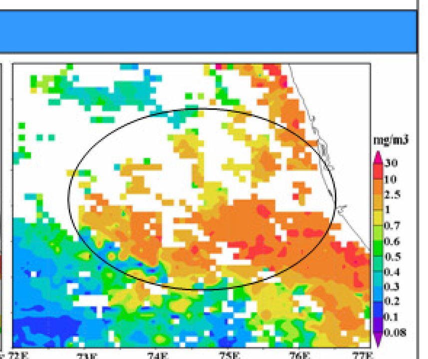
Fig.5b Spatial pattern of Chl-a for July 1998

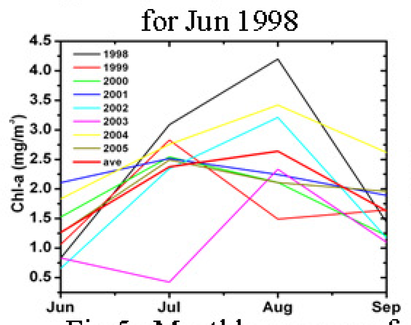
Fig.5c Monthly average of Chl-a for different years for the grid 8-10°N/74-76°E

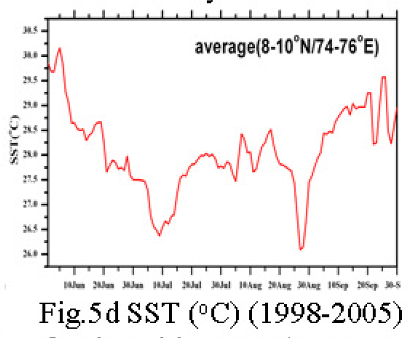
Fig.5d SST (°C) (1998-2005) for the grid 8-10°N/74-76°E

6. GOVERNING MECHANISMS

In order to the find the mechanism of formation of LCP, we have analysed 4 parameters namely windstress curl, net heat flux (Netflux), SSH, subsurface temperature profile and the bathymetry of the region in four Boxes 1-4 (Fig.6a).

24° isotherms show strong shoaling in Box 2 (where LCP forms) than adjacent regions (Fig.6b).

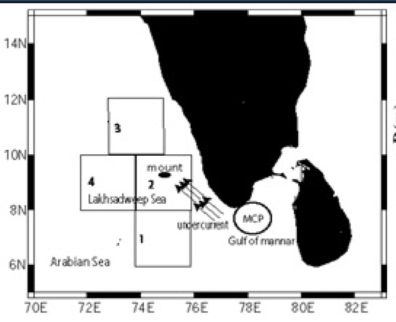
Fig.6a region divided into four 2° grids; b_1, b_2, b_3, b_4

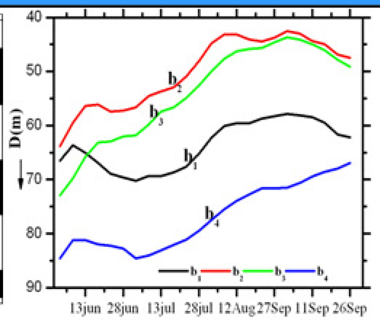
Fig.6b depth of 24° isotherms (°C) for the 4 Boxes (GODAS)

SST shows strong cooling in the Box 2 than the adjacent boxes (Fig.6c). This suggests that some unique mechanism exists in this grid causing enhanced shoaling of thermocline.

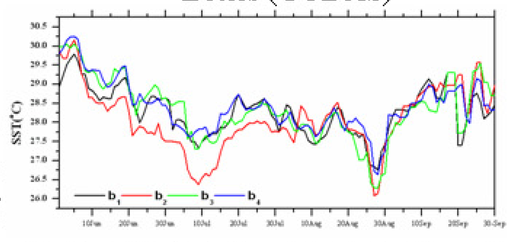
Fig.6c SST(°C) (ave,1998-2005) in the 4 boxes, b_1, b_2, b_3 and b_4

7. INFLUENCE OF SURFACE HEAT FLUX

SST tendency due to surface net heat flux is computed assuming that SST changes only due to surface heat flux. SST tendency (°Cday^{-1}) is positive beyond mid-June. Hence, surface flux does not act as a factor responsible for the genesis and intensification of LCP (Fig.7).

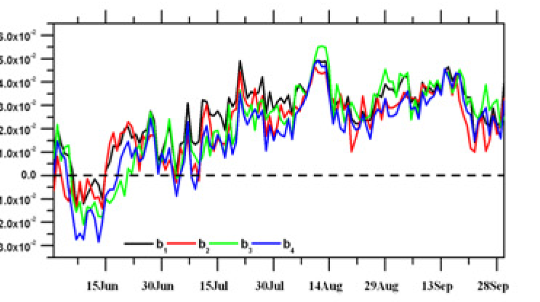
Fig.7 SST tendency (°Cday^{-1}) due to Netflux in the 4 boxes b_1, b_2, b_3 and b_4

8. INFLUENCE OF WIND FORCING

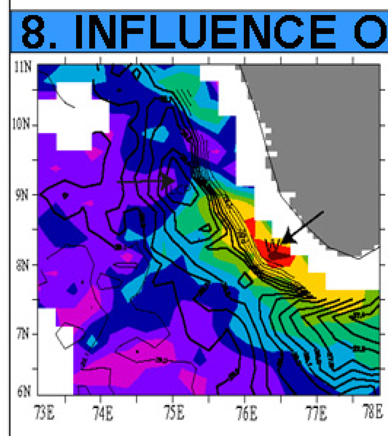
Fig.8a SST(°C) contours over laid on wind stress curl (Nm^{-3}s^{-1}) for June 16-30

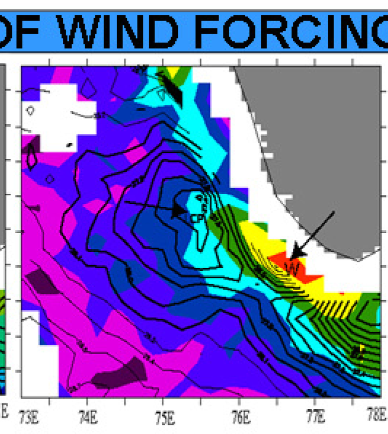
Fig.8b SST(°C) contours over laid on wind stress curl (Nm^{-3}s^{-1}) for July

It has been well established that +ve / -ve wind stress curl induces upwelling/ downwelling. During summer monsoon period, along the southwest coast of India, wind is northerly. Core of the Positive windstress curl lies near to the southern tip of India (Fig.8a,b,marked by "W") and extends northward along the coast from the southern tip of India. Towards the open ocean curl is weak or negative. In order to analyze the influence of windstress curl on the formation and intensification of LCP, two locations are selected (1), at the core of LCP during its genesis(9.2°N/75°E) (2), at the location of LCP during July (9°N/75.5°E) (Fig.8c).

During June, windstress curl is negative i.e. downwelling prevails at the location (Fig.8a). During July, LCP shifts southwards where positive windstress curl shows frequent gustiness (Fig.8b, Fig.8c(arrows shows gustiness). This triggers upwelling through Ekman pumping.

During August, LCP extends northward along the coast along with the northward stretch of positive wind stress curl (Fig. 8d).

Hence wind-driven upwelling does not contribute to the genesis of LCP but contributes towards its intensification.

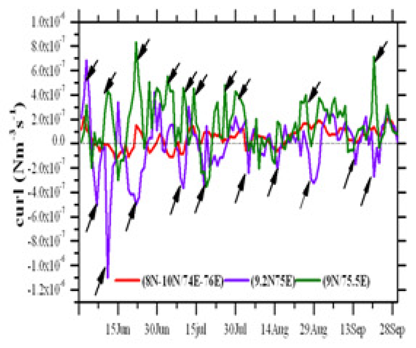
Fig.8c windstress curl at the two locations and for the Box2

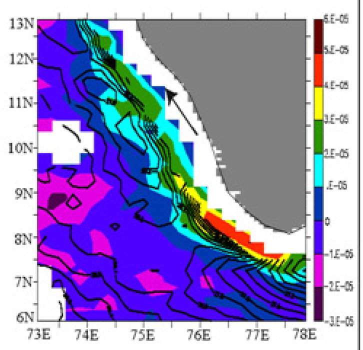
Fig.8d SST(°C) contours over laid on wind stress curl (Nm^{-3}s^{-1}) for August

9. INFLUENCE OF EDDY(LL) INDUCED UPWELLING

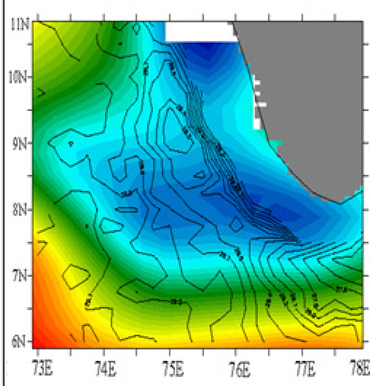
Fig.9a SST (°C) contours over laid over weekly SSH (cm) during 22-28 June

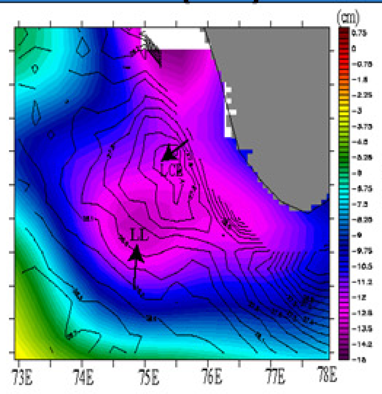
Fig.9b SST (°C) contours over laid over weekly SSH (cm) during July

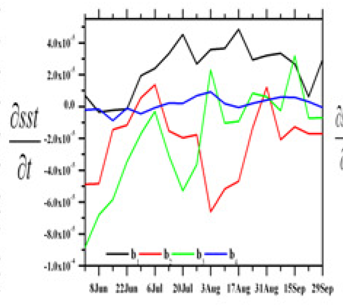
Fig.9c SST tendency (°Cweek^{-1}) due to geostrophic advection

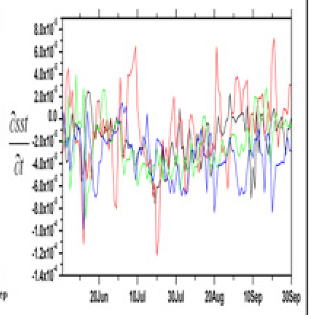
Fig.9d SST tendency (°Cday^{-1}) due to Ekman advection

During June, a cyclonic eddy (LL) forms at the southern tip of India and propagate westwards along with the westward propagating upwelling Rossby waves (Shankar et al., 1997). The influence of cyclonic eddies in SST cooling has been examined by many researchers (Prasanna Kumar et al., (2004).

During June, core of LL resides south of the location of genesis of LCP (Fig.9a shaded). In July, when LCP intensifies and spreads, the core of LL resides adjacent to the core of LCP (Fig.9b). This suggests that LL contributes to the intensification and spatial spread of LCP through eddy induced upwelling and westward propagation of LL but cannot be considered as a genesis mechanism for LCP.

Lowering of SST can also happen due to the geostrophic and Ekman current advections. Ekman/ geostropic advections computed from weekly SSH anomalies and daily Quickscat winds does not show contribution towards the genesis of LCP, but contributes towards the intensification of LCP after its formation (Fig.9 c,d).

10. INFLUENCE OF BOTTOM TOPOGRAPHY

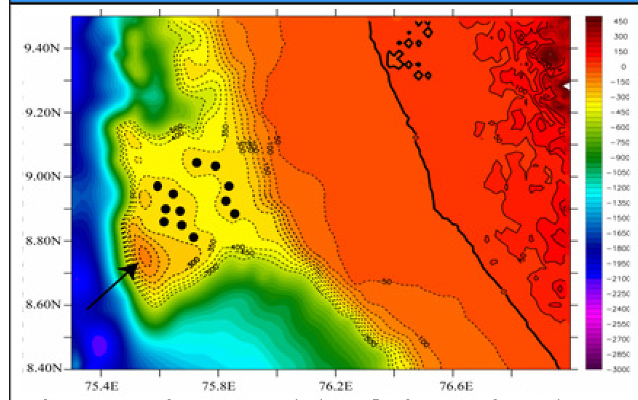
Fig.10 Bathymetry (m) of the region (mount marked by arrow); dark dots show positions where conical structures can be introduced

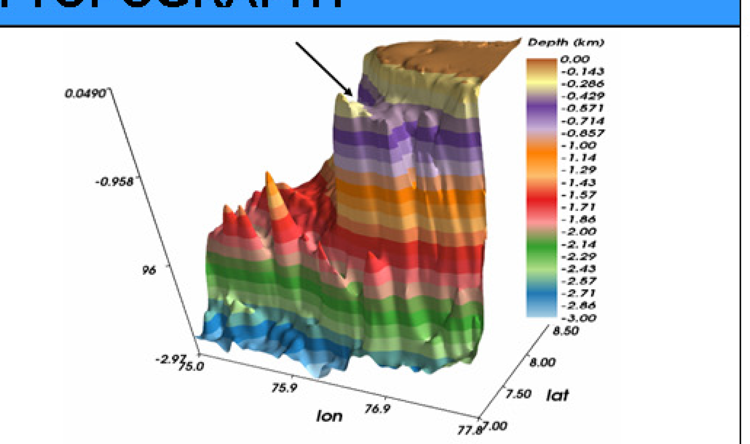
Fig.11 3D view of the bathymetry, mount marked by arrow

South of 10°N off the southwest coast of India, the shelf widens and forms into a wedge with an elevated bathymetry (mount) between 8.2-9°N / 75.5-76°E (Fig.10). The depth of the mount is 130m below the sea surface (Fig.11).

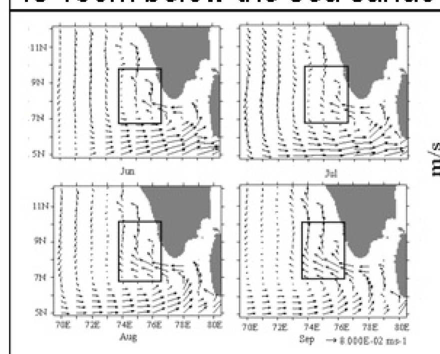
Fig.12a Poleward under current between (80-120m)

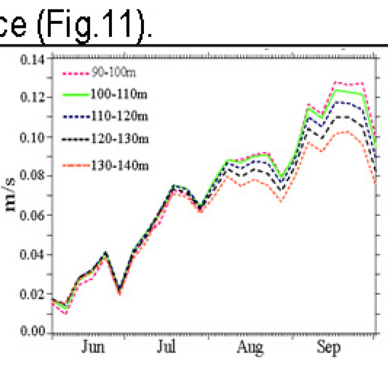
Fig.12b Poleward under current at different depths

During southwest monsoon season, a narrow (40km wide) poleward undercurrent flows on the continental shelf along the southwest coast with its core between ~(100 to 200m) depth (Shetye et al.,1990) (Fig.12a). The current intensifies steadily since June and declines during late September (Fig.12b).

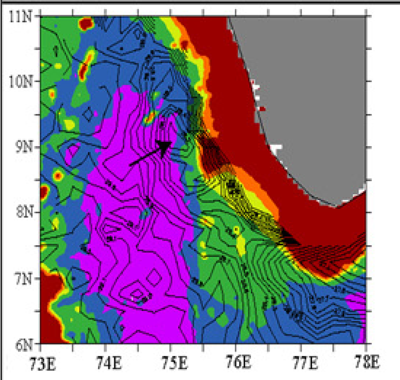
Fig.13a SST (°C) (contours) over laid over bathymetry (m) during June

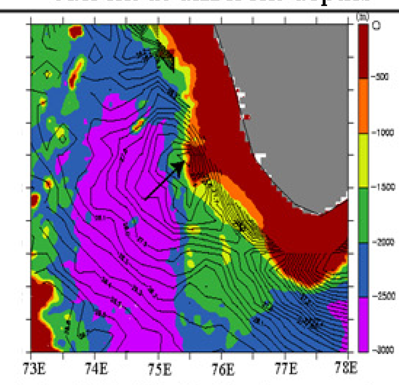
Fig.13b SST (°C) (contours) overlaid over bathymetry (m) during July

During all the years (1998-2005) LCP forms during the fifth pentad of June as a small circular surface cooling adjacent to the tip of the mount and radially expands with the progress of time(Fig.13a). During July, the contours are well centered above the mount (Fig.13b, marked by the arrow).

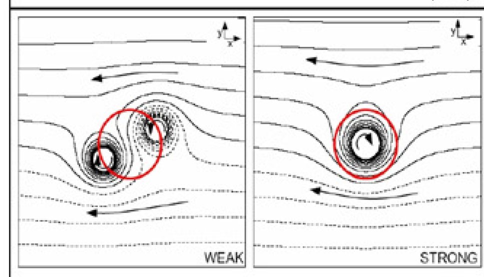

Fig.14 Taylor column, (courtesy, Beckmann & Mohn., 2002)

It has been well established that seamounts interacting with currents create flow complexities that depend on current speed, stratification, latitude and seamount morphology. Seamount effects include local upwelling and closed circulation patterns called Taylor columns. Under weak flow conditions, a dipole pattern will form and under strong flow conditions the dipole pattern evolve into a Taylor Column which rotate around the mount (Fig.14) (Beckmann & Mohn, 2002).

11. CONLUSIONS

The following multiple means of evidence suggest that interaction of undercurrent with the seamount accounts for the formation of LCP. (a) LCP originates as a circular surface cooling just above the submarine mount and expands radially outwards, (b) A seamount in a flow can trigger upwelling through Taylor columns, (c) The presence of a poleward undercurrent in the region, (d) The mount resides within the undercurrent, (e) Poleward undercurrent intensifies during the season, (f) During the genesis of LCP, the core region of positive wind stress curl and LL resides away from the location, (g) Net heat flux tendency is positive, (h) The contribution of lateral advection due to geostrophic and Ekman currents are negligible during the genesis of LCP.

12. LCP AND MONSOON ONSET

SST anomalies computed by subtracting the seasonal mean from the daily SSTs of LCP during June to September show alternate warming and cooling episodes during 25th June to 1st week of July (Fig.15). A cooler anomaly (shown with ellipses) indicates an earlier onset in the forthcoming year and a warmer anomaly indicates a later onset of the southwest monsoon (Fig.16).

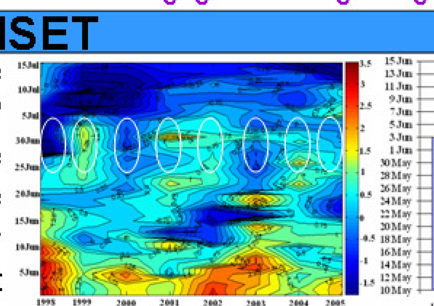
Fig.15 SST anomalies(°C) from 1998-2005

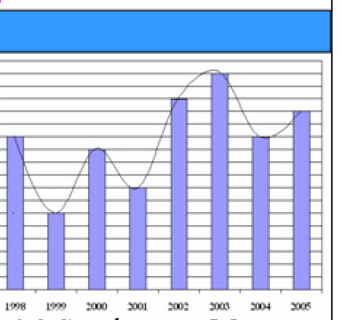
Fig.16 South west Monsoon onset dates 1998-2005 (Pai and Rajeevan., 2009)

13. METHOD TO ENHANCE UPWELLING

Upwelling and biological activity connected with seamounts has been well established in many studies. The region 8-10°N/74-76°N is one of the biggest fish spawning grounds of southwest coast of India Fig.17 shows the fish landings along the southwest coast of India. Among this, major amount of the fish catch is arriving from this location. Since all the factors are favorable for upwelling in this region, a small trigger through appropriate modification of the mount or inserting conical structures on the wedge within the undercurrent can results in enhancement of the existing upwelling. This can provide more nutrient-rich cooler waters in the surface layers. Consequently the spatial spread and intensity of the existing pool can be enhanced leading to increased productivity.

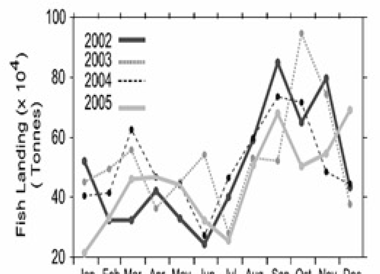
Fig.17 Monthly fish landings along the southwest coast of India (courtesy, Gopalakrishna et al., 2008)

14. FUTURE WORK

Further modeling studies have to carried out to quantify existing upwelling and to design modifications of the mount and dimensions of the conical structures to produce optimum upwelling volumes.

15. REFERENCES

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