

Do the cold and low salinity waters pass through the Indo-Sri Lanka Channel during winter?

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Abstract

During winter, along the east coast India, the near-surface flow is characterized by the southward flowing East India Coastal Current (EICC) which bends around Sri Lanka and enters into the southeastern Arabian Sea (AS). This current carries cooler and low salinity waters from the head Bay of Bengal (BoB) into the southeastern AS. But due to lack of any direct insitu measurements, it is not clear whether any part of this current that flows through the Indo-Sri Lanka Channel (ISLC) is significant. An attempt is made in this study to look for any observational evidence for the southward flow of cooler and low salinity waters through the ISLC during winter. In the absence of direct insitu measurements on the observed currents in the non-navigable shallow ISLC, the observed high resolution Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST), Sea-viewing Wide Field-of-View Sensor (SeaWiFS) chlorophyll-a and historic sea surface salinity (SSS) data are utilized as tracers to track any southward water flow through the Pamban Pass and the Adam's Bridge in the ISLC. The analysis suggests that both the non-navigable shallow Pamban Pass and the Adam's Bridge in the ISLC act as barriers and limit the southward flow of cooler and low salinity waters into the Gulf of Mannar in the south during winter.

1. Introduction

The confluence zone of the AS and the BoB between the southeast coast of India and the west coast of Sri Lanka known as the Indo-Sri Lanka Channel (ISLC) is an important region on two counts. It offers the shortest passage for the surface navigation for all the ships sailing between the ports of the Arabian Sea and the ports on the east coast of India and Bangladesh. Recently the government of India has taken up Sethusamudram Shipping Channel Project to dredge this channel to facilitate economic surface navigation of ships through the ISLC, thus saving a sailing distance of about 650 km. The ISLC is also a region of large productivity of fisheries with abundant occurrence of chlorophyll-a as seen by the satellites (*Yapa, 2000*). During winter, along the east coast India, the near-surface flow is characterized by the southward flowing EICC which bends around Sri Lanka and enters into the southeastern AS (*Shankar and Shetye, 1997*). This current carries cooler and low salinity waters from the head BoB into the southeastern AS (*Rao and Sivakumar, 1999, 2003, Shenoi et al., 1999, Han and McCreary, 2001, Prasanna Kumar et al., 2004, Durand et al., 2007, Thadathil et al., 2008, Rao et al., 2008*). During winter, the ISLC with its complex coastal geometry acts as a duct to the northeasterly surface winds to converge and intensify in the south resulting in intense localized sea surface cooling which is primarily attributed to wind driven mixing and the associated turbulent heat losses (*Kawamura, 2000, Luis and Kawamura, 2001 and 2002, Rao et al., 2008*). However, no direct current measurements are available to assess the role of southward advection of the cooler waters that might flow through the Pamban Pass and the Adam's Bridge in the ISLC on the intense localized cooling that occurs in the south. *Han and McCreary (2001)* in their 4.5 layer model solution suggested that during the northeast monsoon, part of the river water flows out of the BoB in the shallow channel between India and Sri Lanka: Only when this channel is opened in the upper layer (of thickness greater than or equal to 10m) do solutions develop a strong, across-shelf salinity gradient along the west coast, consistent with the observations. In an ocean GCM solution, *Durand et al. (2007)* have also shown that the realistic river runoff distribution and the Indo-Sri Lanka passage have strong impact on the realism of the salinity simulated in the southeastern AS during winter. In the absence of data available on the directly observed currents in the non-navigable shallow region, the observed high resolution AVHRR SST, SeaWiFS chlorophyll-a and historic SSS observations are utilized as tracers to track any southward water flow through the Pamban Pass and the Adam's Bridge in the ISLC during winter.

2. Observations

All the available historic high resolution satellite derived SST and chlorophyll-a and insitu SSS and ship drift vector measurements are utilized to describe and understand the observed variability in and around the ISLC region. The QuikSCAT surface winds (*Wentz et al., 2001*) and the AVISO merged and blended sea surface height anomalies are utilized to characterize the observed near-surface circulation around south India and Sri Lanka (*Fu and Chelton, 2000*). The observed daily TMI SST data (*Wentz et al., 2000*) are utilized to characterize the cooler waters transported by the EICC from the head BoB into the southeastern AS. The observed daily high resolution AVHRR SST data (*Walton et al., 1998, Kilpatrick et al., 2001, Reynolds et al., 2007*) are utilized as a tracer to characterize any southward advection of cooler waters through the ISLC. As this study is carried out for winter, the atmosphere over this region being relatively cloud free with minimum moisture content is ideal for examining the variability of the SST measured with radiometers. The SeaWiFS chlorophyll-a data (*O'Riley et al., 1998*) are also utilized as a tracer to track the southward water flow through the ISLC. The mean monthly (July-August) climatologies of SSS from Simple Ocean Data Assimilation (SODA) analysis (*Carton et al., 2005*), TMI SST and SeaWiFS chlorophyll-a are utilized to characterize the intrusion of high salinity, cooler and high concentration chlorophyll-a AS waters into the BoB. The observed ship drift vectors (*Mariano et al., 1995*) are utilized to characterize the surface flow patterns. All the available historic SSS data are also pooled up from multiple sources for three representative regions to characterize the observed salinity variability caused by the EICC, the Winter Monsoon Current (WMC) and the southward flow through the ISLC if any. The SODA which assimilates all available temperature and salinity observations in the world oceans, satellite altimetry, and sea surface temperature (SST) observations to constrain a numerical model of the primitive equations of motion. SODA has been used for studying the heat budgets of the Atlantic and Pacific Oceans (*Wang and Carton 2002*) and coupled dynamics in the Indian Ocean (*Xie et al. 2002*). *Xie et al., 2002* further mentioned that SODA reproduces the seasonal cycle of variability in the Indian Ocean (*Xie et al. 2002*) The study of *Shenoi et al. 2005* has estimated the accuracy of SODA product for the calculation of Estimating Heat Budgets of the near-surface layers of the Arabian Sea and Bay of Bengal. *Carton and Giese (2006)* studied the reliability of the SODA reanalysis product by comparisons of several to independent data sets. The sources, periods, accuracies and the resolutions of the data sets utilized in this study are shown in Table–1.

3. Analysis

3.1 The Indo-Sri Lanka Channel and its bathymetry

The bathymetry chart of the ISLC shows very shallow depths ($< 12\text{m}$) in the Palk Bay and the Palk Strait in the north while the Gulf of Mannar in the south is relatively deeper. These are separated by an almost east-west running island reef embedded with the Pamban Pass in the west and the bottle neck shaped Adam's Bridge in the east (Figures 1a & 1b). The Pamban Pass is a narrow pass of about 3 km width with shallow depths of $< 6\text{m}$ while the Adam's Bridge spans approximately about 30 km with shallow depths of $< 5\text{m}$. The Adam's Bridge comprises of 103 small patch reefs lying in a linear pattern with reef crest, sand cays and intermittent deep channels. The sea water flow through the Pamban Pass and the Adam's Bridge is constrained by the shallow bathymetry and the prevailing tidal circulation. The tide induced mixing resulting in large suspended matter is quite pronounced in the Palk Bay, the Palk Strait, the Adam's Bridge region and along the northern rim of the Gulf of Mannar where the bathymetry is very shallow (Figure 1b). Large concentrations of suspended sediment are also reported in the Palk Bay, the Palk Strait regions almost throughout the year from the ocean colour data of the Ocean Colour Monitor onboard Oceansat-I (*Sridhar et al.*, 2008). As the area is non-navigable, no direct insitu oceanographic measurements could be made from research vessels in the past. The satellite measurements available with high spatial resolution offer excellent means to characterize the inferred surface flow patterns from the observed property distributions of the surface parameters of this region. The observed spatio-temporal variability of the satellite derived parameters such as SST, chlorophyll-a and insitu measurements of SSS are used as tracers to characterize any southward flow through the Pamban Pass and the Adam's Bridge in the ISLC.

3.2 Evolution of the near-surface circulation and SST around south India and Sri Lanka

The evolution of the estimated near-surface circulation and the observed SST during October-March around south India and Sri Lanka is shown in Figure 2. During winter, along the east coast of India, the near-surface flow is characterized by the southward flowing EICC which bends around Sri Lanka and enters into the southeastern AS. This current carries cooler and low salinity waters from the head BoB into the southeastern AS. South of Sri Lanka, the WMC flows from the east into the southern AS. During October, south of the ISLC, low SSTs appear as the relic of summer monsoon cooling due to local upwelling (*Rao et al.*, 2006a and 2006b) and the near-surface flow is mostly directed from the

southeastern AS into the BoB. As the winter sets in and progresses the cooling intensifies from November both in magnitude and spatial extent reaching its peak by January. The near-surface circulation also reverses from October to November and persists during the following winter months. These cooler waters flow primarily southwestward and on occasion branches northwestward by the Maldives Island Chain. A careful examination of SST and near-surface circulation fields during the winter clearly reveals that the cooler waters from this mini-cold pool flow into the Lakshadweep Sea and re-circulate around the Lakshadweep High (*Shankar and Shetye, 1997*). Although the TMI SST resolves the spatial features in the open ocean accurately and adequately, it is less reliable near the coastline and hence it is not possible to map its variability accurately within the ISLC.

3.3 Inferring near-surface circulation patterns from surface property distributions

In the oceans, if the property distributions are influenced by the prevailing horizontal circulation it would be possible to infer the flow patterns from the observed horizontal gradients of the properties. One such example is shown in Figure 3 where the Summer Monsoon Current (SMC) shows intrusion of cooler, high concentration chlorophyll-a and high salinity waters into the BoB during July-August. The flow patterns clearly show agreement with the observed ship drift vectors of *Mariano et al., (1995)* depicting the intrusion of the SMC into the BoB from the AS. From an array of current meter moorings deployed off the southern coast of Sri Lanka, *Schott et al. (1994)* have shown that the SMC transports 8 Sv into the BoB. In an OGCM simulation, *Vinayachandran et al. (1999)* have shown that the intrusion of the SMC into the BoB is controlled both by Ekman pumping and the westward propagating Rossby wave radiation. In another model simulation, *Jensen (2001)* has shown inflow of high salinity waters from the AS into the BoB is significant and occurs after the mature phase of the summer monsoon. Advantage of this concept is taken in this study to track any water flow through the Pamban Pass and the Adam's Bridge in the ISLC from satellite monitored surface property distributions and where no direct current measurements are available.

3.4 Evolution of the observed annual cycle of SST in the ISLC

In the absence of direct insitu measurements, and as the TMI SST data are not reliable near the coasts, all the AVHRR SST data available at higher spatial resolution (9 km) are utilized to map the observed variability in the ISLC region for all the twelve months (Figure 4). The observed high resolution satellite AVHRR SST measurements are utilized as tracers to track any flow of cooler waters through the

Pamban Pass and the Adam's Bridge in the ISLC during both the monsoon seasons. The observed annual cycle of the SST climatology based on multi-year averages shows strong seasonality with two heating regimes during pre-summer monsoon season and post-monsoon season and two cooling regimes during winter and summer monsoon season. During winter, the lowest SSTs occur in the Palk Strait under the influence of the southward flowing cooler EICC. However, during winter with the progress of the season, there is no sign of any southward flow of the cooler waters from this region through the Pamban Pass and the Adam's Bridge into the Gulf of Mannar. This suggests that the southward advection of cooler waters through ISLC is not an important process for the observed cooling further in the south. Due to shallow depths, waters in this region warm up very rapidly resulting in the highest SSTs during April-May. With the onset and the progress of the summer monsoon, the lowest SSTs occur in the Gulf of Mannar under the influence of the SMC which carries relatively cooler upwelled waters from the Somalia coast and from the nearby southwest coast of India. However, these cooler waters also do not show any northward intrusion into the Palk Bay through the Pamban Pass and the Adam's Bridge due to the barrier effect. Thus the spatial structure of SST suggests that the island reef comprising the Pamban Pass and the Adam's Bridge virtually constrains the water flow across it during the year.

The evolution of the multi-year daily averaged AVHRR SST ($^{\circ}\text{C}$) for the zonally averaged grid points in the ISLC region during winter is examined (Figure 5a). The SST shows a dramatic cooling from November to January, and this cooling is most pronounced off the southeast coast of India. This strong cooling is also limited to the region north of the Pamban Pass and the Adam's Bridge. The demarcation of the southern limit of the cold SSTs coinciding with 9°N latitude clearly suggests that not much cooler water flows southward through the Pamban Pass and the Adam's Bridge. As seen in Figure 4, there is also a suggestion of enhanced cooling in the Palk Bay and the Palk Strait regions approximately between 9°N - 10°N . This cooling may be attributed to intense tidal mixing in the shallow waters. Similar analysis of AVHRR SST for the individual years is shown in Figure 5b. The distribution of daily observed SST during winter of the individual years also shows similar features as seen in the Figure 5a. In addition, the observed daily evolution of SST during November-February for the years 1985-2007 also clearly shows that the cooling is episodic on intraseasonal time scale with predominant periodicity of about 12 days. Similar periodicities in the range of 8-15 days were also noticed in the intense localized mini-cold pool observed south of the ISLC primarily driven by the surface wind and net heat flux fields during winter (*Rao et al.*, 2008). These cooling episodes also show strong interannual

variability in their number, duration, intensity and the spatial extent. The differences in these attributes of the cooling episodes determine the observed year-to-year variability in this region.

The observed SST climatology during the peak phase of the winter monsoon clearly shows the southward progress of the EICC and the associated cooler waters off the southeast coast of India and off the coastline of Sri Lanka (Figure 6). With the progress of the season, the SST progressively drops and the cooler waters show their southward propagation. However, the arrest of the southward passage of cooler waters by the island reef embedded with the Pamban Pass and the Adam's Bridge is also distinctly seen. The observed cooling south of the Pamban Pass and the Adam's Bridge is attributed to strengthened surface wind field and the associated surface heat losses (*Kawamura, 2000, Luis and Kawamura, 2001 and 2002, Rao et al., 2008*).

3.5 Evolution of the observed chlorophyll-a in the ISLC

The analysis of Coastal Zone Colour Scanner data at 1-km resolution around Sri Lanka revealed that the waters in the Gulf of Mannar and the Palk Bay show large concentration of chlorophyll-a throughout the year (*Yapa, 2000*). However, these high values may represent other suspended particles and dissolved organic matter besides chlorophyll-a as this region is shallow (<100m). Occurrence of phytoplankton bloom in response to summer monsoon forced upwelling around Sri Lanka was reported by *Vinayachandran et al. (2004)*. In the southwestern BoB, intensification of phytoplankton bloom in the wake of the cyclones was also reported by *Vinayachandran and Mathew (2003)* and *Rao et al. (2006)*. The observed annual cycle of the SeaWiFS chlorophyll-a climatology based on multi-year averages shows strong seasonality in the Gulf of Mannar region with the highest (lowest) values occurring during summer monsoon (winter and pre-monsoon) season (Figure 7). However the coastal rim is an exception where relatively larger concentration of chlorophyll-a is seen throughout the year. During winter, the distribution of chlorophyll-a concentration along the southern edge of the Pamban Pass and the Adam's Bridge does not suggest any southward intrusion into the Gulf of Mannar. During the summer monsoon season intense blooming of chlorophyll-a is noticed with peak values during July-August off the southern tip of India under the influence of the monsoon driven coastal upwelling. Although both the Palk Bay and the Palk Strait regions show larger concentrations of chlorophyll-a throughout the year when compared to the Gulf of Mannar with the only notable exception off the southeast coast of India during July-August, the seasonal cycle of these regions shows a bimodal distribution. The primary

maxima (minima) occur during the summer monsoon (pre-monsoon) season and the secondary maxima (minima) occur during post-monsoon season (winter). A sharp fall in the chlorophyll-a concentration is noticed in the adjacent southwestern BoB throughout the year. Thus the observed annual cycle of the chlorophyll-a does not indicate any transport through the Pamban Pass and the Adam's Bridge.

3.6 Evolution of the observed SSS in the ISLC and its surroundings

To assess the passage of low salinity waters carried by the EICC through the Pamban Pass and the Adam's Bridge in the ISLC, all the available historic insitu observed SSS data in three representative boxes (Figure 8) are averaged after quality controlling for outliers. The box 'N' represents the SSS of the waters carried by the EICC off the southeast coast of India. The box 'C' represents the SSS of the waters just south of the Pamban Pass and the Adam's Bridge. The box 'S' represents the region where the SSS of the waters is influenced by both the EICC and the WMC. The multi-year averages of mean monthly SSS for these three boxes for the months October-March are shown in Figure 8. The temporal evolution of the SSS during October-March clearly depicts the seasonal minima during December at all the boxes. Among the three boxes, the spatial differences are also distinctly seen. The 'N' box shows lowest SSS followed by the 'S' box. The relatively larger values of SSS in the 'C' box clearly suggest that the waters in the Gulf of Mannar do not appear to be diluted by any southward flow of low salinity waters carried by the EICC through the Pamban Pass and the Adam's Bridge in the ISLC during winter.

4. Summary

An attempt is made to find any observational evidence on the southward transport of cooler and low salinity waters through ISLC by the EICC during winter. Due to non-navigable shallow depths of this region, no direct insitu measurements were made in the past. In view of this, all the available high resolution satellite measurements of AVHRR SST and SeaWiFS chlorophyll-a are utilized as tracers to track any southward flow through the Pamban Pass and the Adam's Bridge in the ISLC. The spatio-temporal variability of these two parameters does not suggest any significant southward flow through the Pamban Pass and the Adam's Bridge in the ISLC. The largest winter (November - January) cooling in SST is confined only to the Palk Bay and the Palk Strait north of the Pamban Pass and the Adam's Bridge. In addition, the observed daily evolution of SST during November-February for the years 1985-2007 also clearly shows that the cooling in the region north of the Pamban Pass and the Adam's Bridge is highly episodic on intraseasonal time scale with a predominant periodicity of about 12 days. The

chlorophyll-a also occurs in greater abundance again only in the Palk Bay and the Palk Strait regions north of the Pamban Pass and the Adam's Bridge throughout the winter. However, just south of the Pamban Pass and the Adam's Bridge, the observed variability in the chlorophyll-a concentration during November-February is not significant suggesting the absence of any southward flow through the Pamban Pass and the Adam's Bridge. The mean monthly climatologies of the SSS in three representative boxes off the southeast coast of India, south of the Pamban Pass and the Adam's Bridge, and south of the ISLC during October-March also do not suggest any significant southward flow of low salinity waters through the Pamban Pass and the Adam's Bridge. The spatio-temporal evolution of the three independent oceanographic parameters unambiguously suggests that the non-navigable shallow Pamban Pass and the Adam's Bridge in the ISLC act as barriers and limit the southward flow of cooler and low salinity waters into the Gulf of Mannar during winter. The completion of the Sethusamudram Shipping Channel Project will provide an opportunity to the oceanographic community to make the direct in-situ measurements in the ISLC to address this issue in greater detail.

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Table -1: Data sources, periods, accuracies and resolutions

Parameter	Source	Period	Accuracy	Spatio-temporal Resolution
QuikSCAT winds	www.ssmi.com	2000-2007	2 m/s	0.25°, daily
AVISO Blended Sea Surface Height Anomaly	www.aviso.oceanobs.com	1993-2007	2-3 cm	0.33°, 7-day
TRMM TMI Sea Surface Temperature	www.ssmi.com	1998-2007	~ 0.5°C	0.25°, daily
AVHRR SST	las.pfeg.noaa.gov/oceanwatch.php	1998-2005	~ 0.5°C	9 km, 8-day
AVHRR SST	www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php	1985-2006	~ 0.5°C	0.25°, daily
SeaWiFS Chlorophyll-a	oceans.gsfc.nasa.gov/SeaWiFS/Binned/8Day/	1998-2007	---	9 km, 8-day
Sea Surface Salinity	WOA2005 and INODC	1900-2004	0.01 PSU	random point measurements
Sea Surface Salinity	SODA	1993-2005	0.01 PSU	1°, monthly

Legends of figures:

Figure 1a: Bathymetry chart (m) of the Indo-Sri Lanka Channel region showing the island reef comprising of the Pamban Pass and the Adam's Bridge

Figure 1b: Landsat-5 satellite imagery of the Indo-Sri Lanka Channel region showing the island reef comprising of the Pamban Pass and the Adam's Bridge

Figure 2: Estimated multi-year averages of near-surface current vectors (Ekman + geostrophic) (cm/s) and the observed SST ($^{\circ}\text{C}$) around south India and Sri Lanka during October - February

Figure 3: Observed multi-year averages of (a) TMI SST ($^{\circ}\text{C}$), (b) SeaWiFS chlorophyll-a concentration (mg/m^3) and (c) SODA SSS (PSU) during July-August with superposed ship drift vectors (black arrows) showing the intrusion of the Summer Monsoon Current into the Bay of Bengal

Figure 4: Annual cycle of multi-year (1985-2007) averaged high resolution mean monthly climatology of the AVHRR SST ($^{\circ}\text{C}$) in the Indo-Sri Lanka Channel region

Figure 5a: Selected grid points off the southeast coast of India and in the Indo-Sri Lanka Channel region for the assessment of southward advection of cooler waters (left panel) and observed daily multi-year (1985-2007) averaged Hovomuller field of AVHRR SST ($^{\circ}\text{C}$) for the zonally averaged grid points during winter (right panel)

Figure 5b: Hovomuller fields of daily AVHRR SST ($^{\circ}\text{C}$) for the zonally averaged grid points shown in Figure 5a off the southeast coast of India and in the Indo-Sri Lanka Channel region during the winters of 1985-2007

Figure 6: Southward advection of multi-year averaged cooler SST by the EICC off the southeast coast of India and around Sri Lanka from 2 December to 16 January at 8-day interval

Figure 7: Annual cycle of multi-year (1998-2007) averaged high resolution mean monthly climatology of the SeaWiFS chlorophyll-a (mg/m^3) in the Indo-Sri Lanka Channel region

Figure 8: Location of the three representative boxes and the schematic tracks of the EICC and the WMC (top) and the observed multi-year averages of mean monthly SSS (PSU) in these boxes during October-March (bottom) (colours of the lines represent the respective colour boxes)



Figure 1a: Bathymetry chart (m) of the Indo-Sri Lanka Channel region showing the island reef comprising of the Pamban Pass and the Adam's Bridge



Figure 1b: Landsat-5 satellite imagery of the Indo-Sri Lanka Channel region showing the island reef comprising of the Pamban Pass and the Adam's Bridge

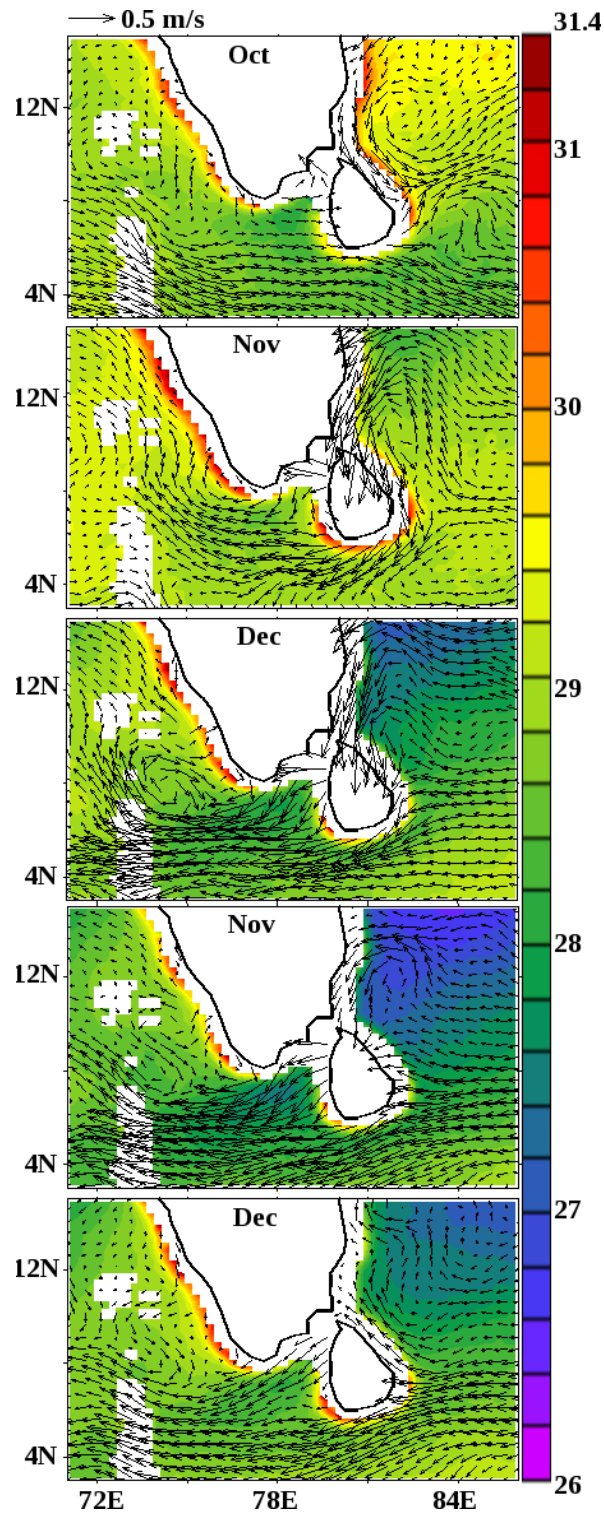


Figure 2: Estimated multi-year averages of near-surface current vectors (Ekman + geostrophic) (cm/s) and the observed SST ($^{\circ}\text{C}$) around south India and Sri Lanka during October - February

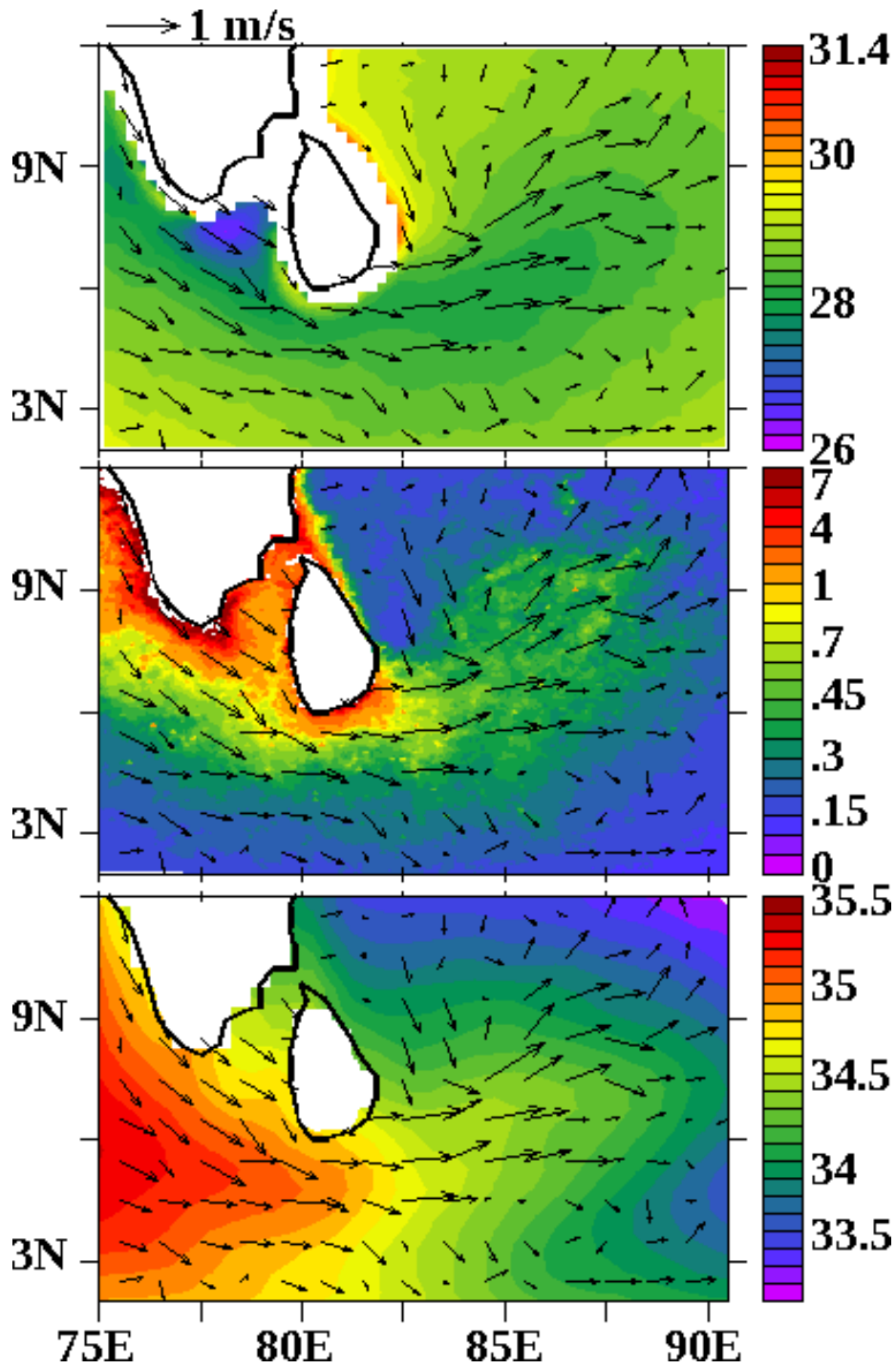


Figure 3: Observed multi-year averages of (a) TMI SST ($^{\circ}\text{C}$), (b) SeaWiFS chlorophyll-a concentration (mg/m^3) and (c) SODA SSS (PSU) during July-August with superposed ship drift vectors (black arrows) showing the intrusion of the Summer Monsoon Current into the Bay of Bengal

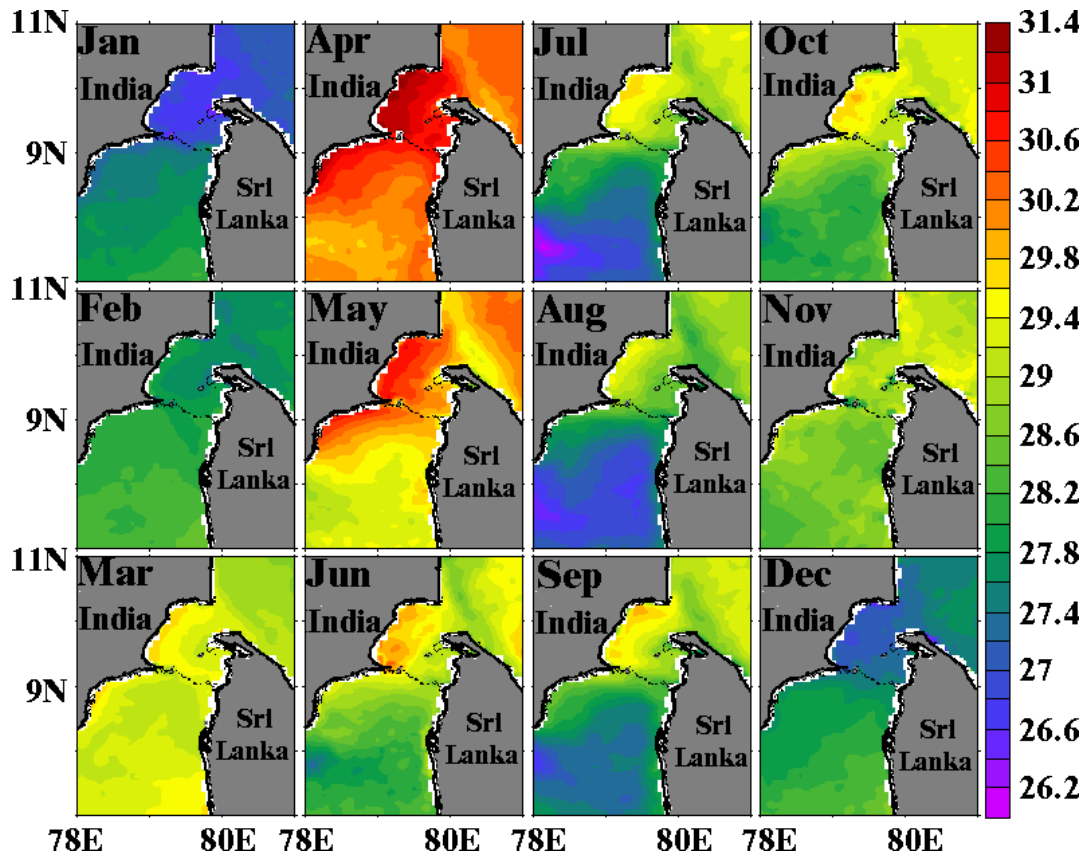


Figure 4: Multi-year (1985-2007) averaged high resolution mean monthly climatology of the AVHRR SST ($^{\circ}\text{C}$) in the Indo-Sri Lanka Channel region during January-December

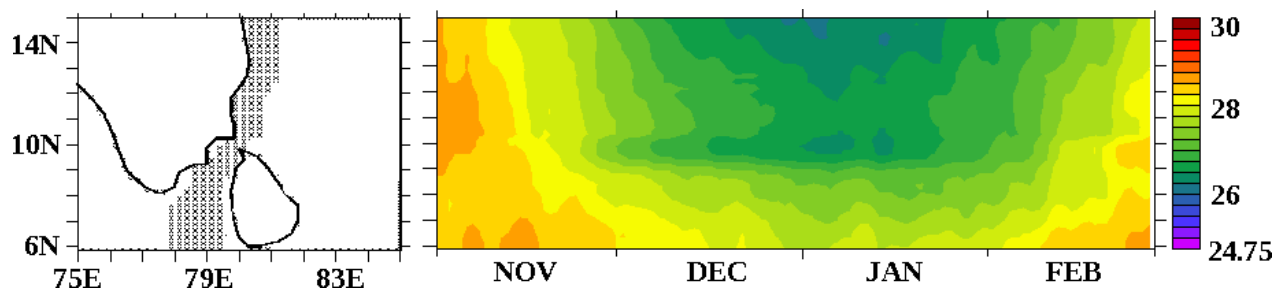


Figure 5a: Selected grid points off the southeast coast of India and in the Indo-Sri Lanka Channel region for the assessment of southward advection of cooler waters (left panel) and observed multi-year (1985-2007) daily averaged Hovomuller field of AVHRR SST ($^{\circ}\text{C}$) of the zonally averaged grid points during winter (right panel)

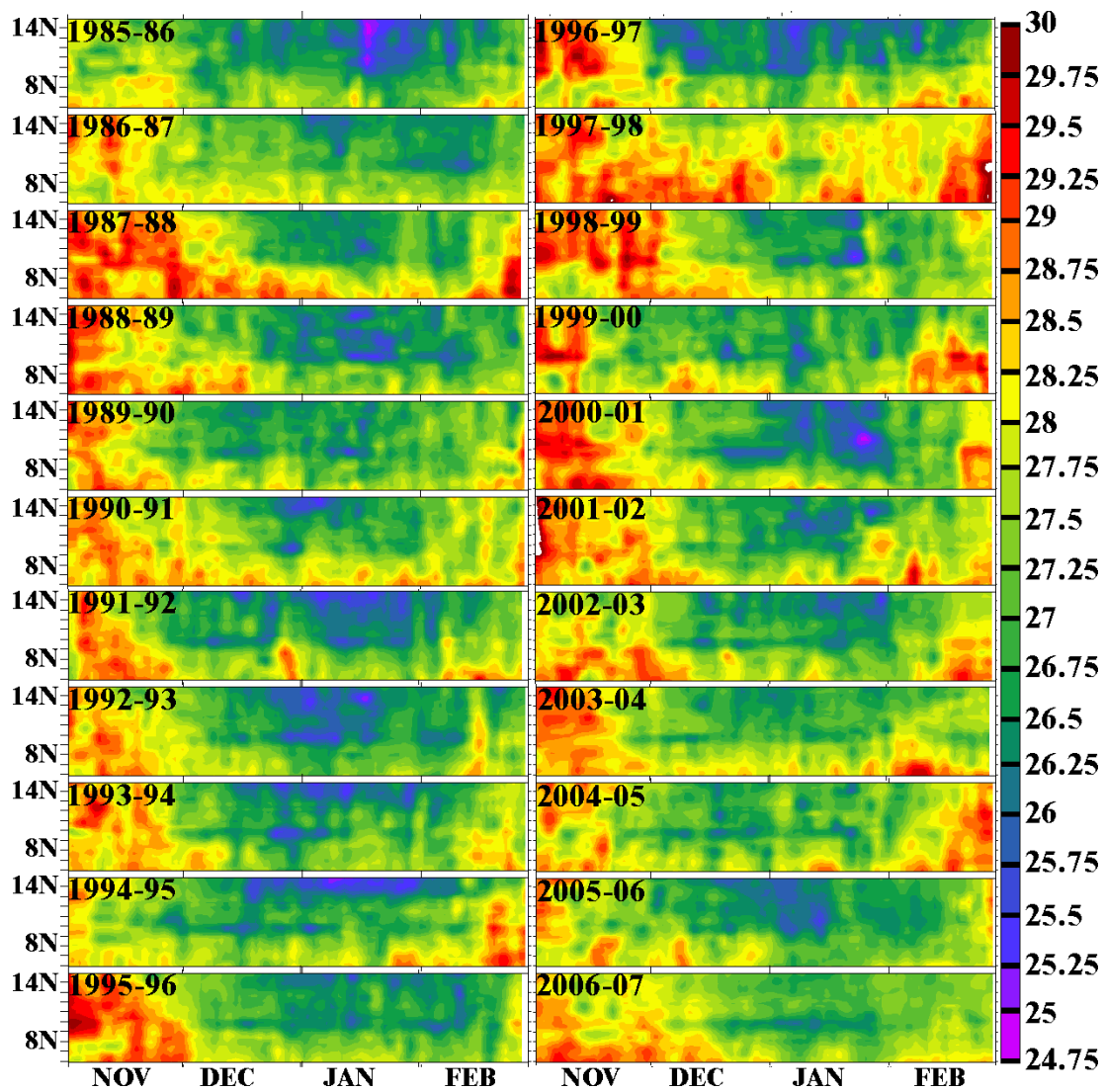


Figure 5b: Hovomuller fields of daily AVHRR SST (°C) for the zonally averaged grid points shown in Figure 5a off southeast coast of Indian and in the Indo-Sri Lanka Channel region during the winters of 1985-2007

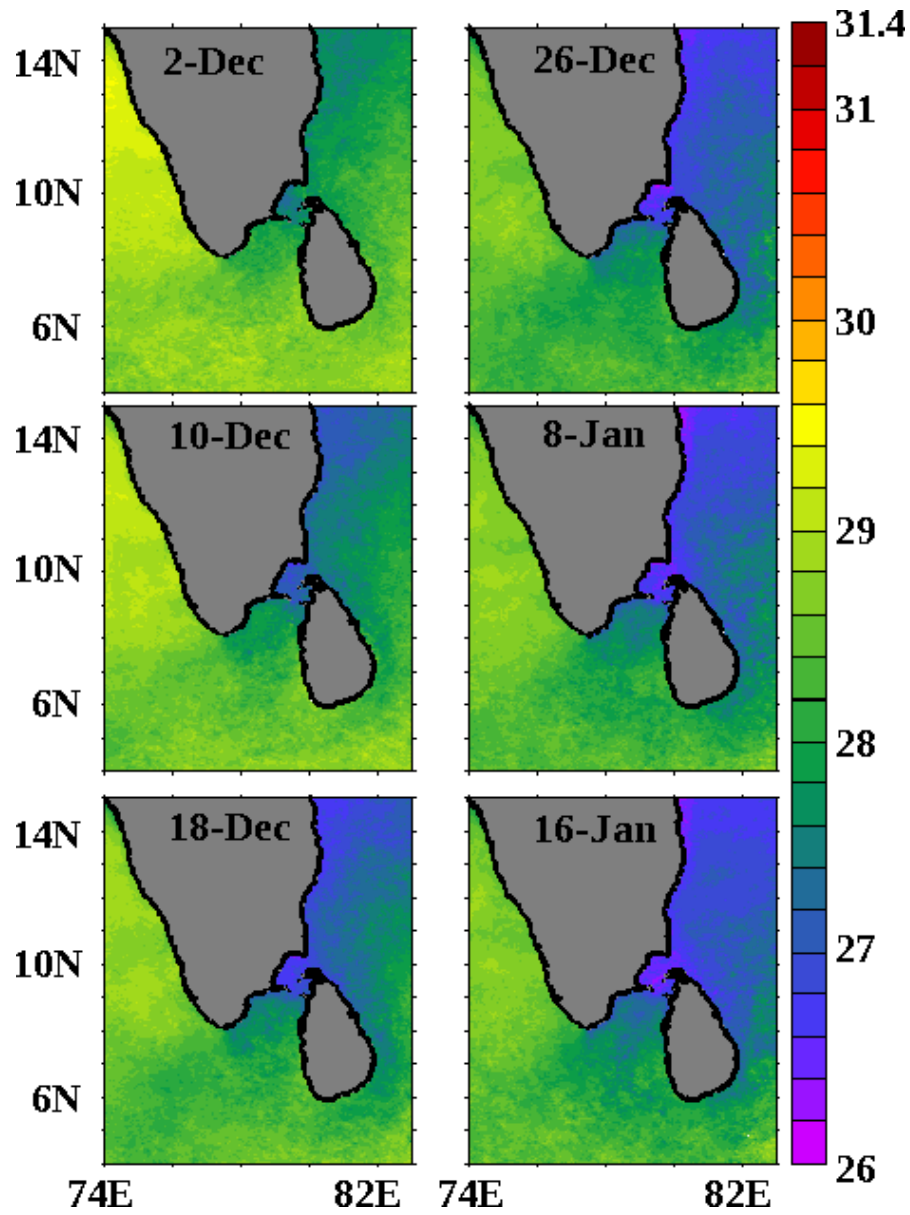


Figure 6: Southward advection of multi-year averaged cooler SST by the EICC off the southeast coast of India and around Sri Lanka from 2 December to 16 January at 8-day interval

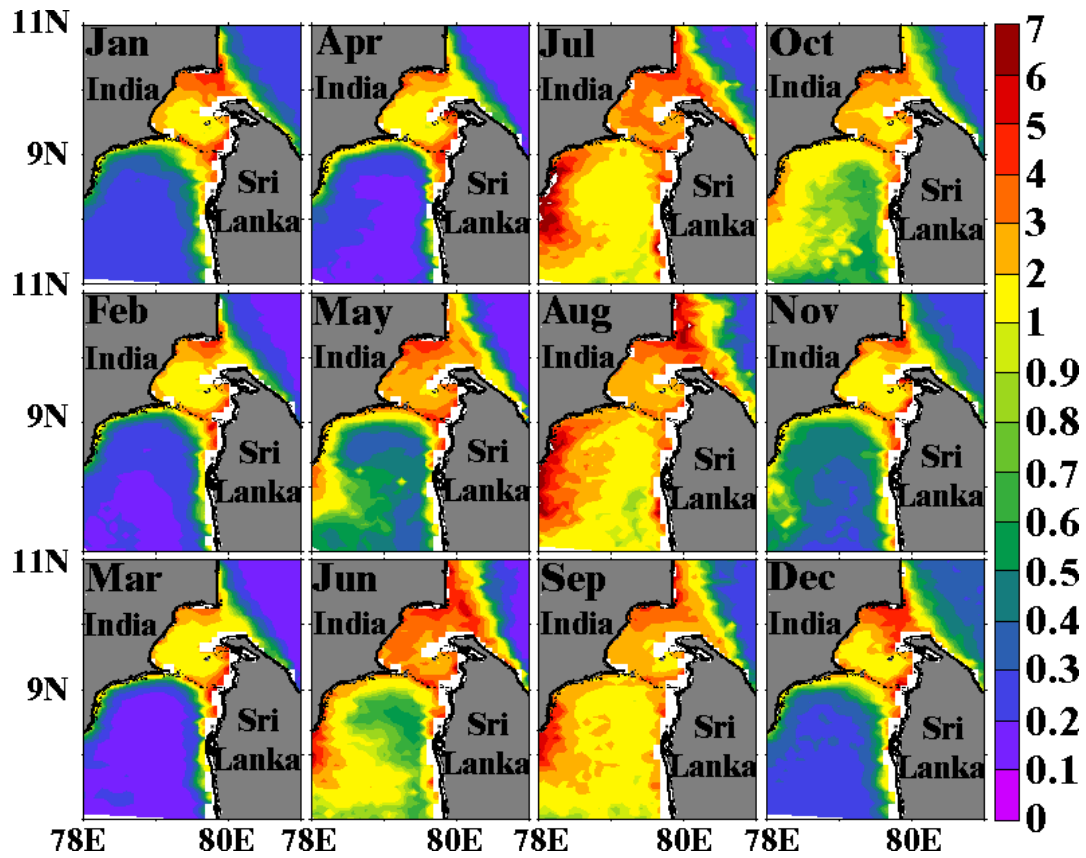


Figure 7: Multi-year (1998-2007) averaged high resolution mean monthly climatology of the SeaWiFS chlorophyll-a (mg/m^3) in the Indo-Sri Lanka Channel region during January-December

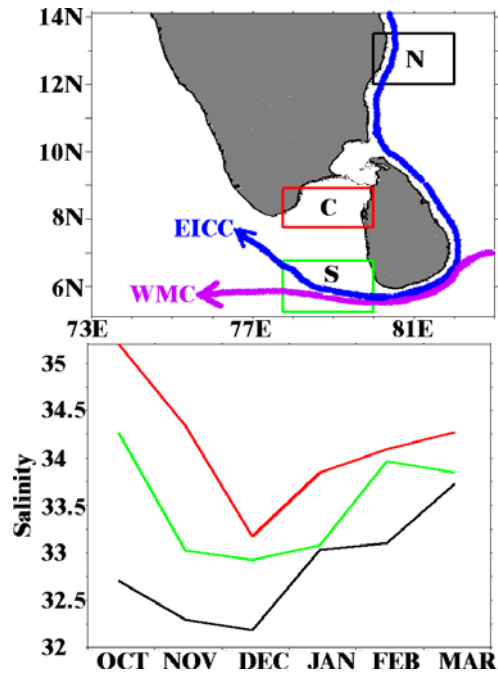


Figure 8: Location of the three representative boxes and the schematic tracks of the EICC and the WMC (top) and the observed multi-year averages of mean monthly SSS (PSU) in these boxes during October-March (bottom) (colours of the lines represent the respective colour boxes)