

Suspended Sediment Concentration Profiles from Synoptic Satellite Observations

Ratheesh Ramakrishnan¹, A. S. Rajawat and O. S. Chauhan

Abstract— A method is developed to estimate vertical suspended sediment concentration (SSC) profiles in Gulf of Kachchh, from the sediment concentration values derived from synoptic observations of Ocean Colour Monitor (OCM). Under the influence of currents, vertical SSC profiles are defined by power law being based on the frictional velocities and sediment settling velocities. For each water pixels in OCM, the vertical variations in SSC are determined from the SSC profiles calculated from power law using corresponding simulated frictional velocities and sediment size parameters. OCM derived SSC is considered to be summation of sediment concentration values from surface to first attenuation depth (hereafter OCM-depth) with an exponential decay of values with depth. Vertical variation profiles from surface to OCM-depth are scaled with respect to the corresponding OCM SSC values and the projected concentrations at the bottom are derived. The bottom concentrations derived is observed to vary chiefly with the tidal conditions prevailing within the gulf, when during the slack hours increase in bottom SSC values get enhanced owing to the settling of sediments from suspension.

Index Terms— Sediment, Remote Sensing, Simulation, Tides.

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I. INTRODUCTION

To describe the natural sediment transport, the fundamental problem is to understand the processes that control the exchange of sediment particles between the bed load and the suspended load layer. A particle can enter the suspension layer when it is lifted to a level at which the turbulence induced forces are comparable or higher than the submerged particle weight [1]. If it is assumed that this turbulence is alone responsible for the maintenance of vertical profiles above the thin turbulent layer close to the bottom, conservation equation involving the settling velocity and the turbulent associated eddy diffusivity coefficient describes the vertical profiles of sediment concentration [2].

Estimation of bottom sediment concentrations finds its importance in sediment transport modeling, where the depositional and erosion strength is strongly influenced by the variations in bottom sediment concentrations [3]. For sediment transport models using satellite images, depth averaged models are taken as good representation of water column conditions [4], [5], while still, the possibility of using a 3-dimensional sediment transport model and approximating the bottom sediment concentrations are not achieved. The sediment concentration profiles are also widely used in the studies of biogeochemical processes and in prediction of zones of consumption and production [6]. One-dimensional vertical advection-diffusion equations govern the local sediment concentration profiles, where the lateral advections due to winds or sediment inputs from rivers are not considered. Solution of the equations are based on either analytical or numerical approach, in which analytical method assumes a constant settling velocity and eddy

diffusivity coefficient whereas in numerical methods concentration depended settling velocities as well as time and space varying eddy diffusivity is considered [7].

Many methods have been proposed and been used to collect in situ sediment profiles. Acoustic Backscattering System mounted on bottom tripod was used [8] to obtain the profiles of suspended sediment concentrations. From the ADCP (Acoustic Doppler Current Profile) measurements, suspended sediment concentration (SSC) profiles are estimated as the intensity of the return echo is proportional to the number of backscatter present in the water column [9]. In situ observations of SSC are mostly point observations and costly measurements, which make it formidable task to have denser spatial and temporal observations. Remote sensing the ocean colour and thus interpreting the sediment concentration is an alternative, cost-effective method to monitor the sediment dynamics in the coastal and shelf region. The present paper proposes a method to determine vertical sediment concentration profiles from satellite observations utilizing the Diffuse Attenuation coefficient (kd), simulated depth averaged velocity and sediment size distribution maps. The study converts a 2-dimensional sediment concentration map into a 3-dimensional map with sediment concentration profiles along each water pixels. The theory and method involved are detailed in section II.

Environmental Settings: Gulf of Kachchh (68° 20' to 70° 40' E; 22° 15' to 23° 40' N) is chosen as the study area, where the gulf is an east-west oriented; macro-tidal region in the west coast of India (Figure 1). The gulf is a high energetic system where the highest high tide reaches to about 6.6 m at Kandla and 7.2 m at Navalakhi.

In situ measurements were used to map the bottom and suspended sediment characteristics [10]-[13]. The complex system of the gulf is composed of fragile marine eco system where, amid the tidal channels, are small shoals and coral islands, controlling the tidal current patterns and sediment dynamics within the gulf. From the hydrodynamic simulation of tidal currents, the contrast in mixing and transport pattern between the outer and inner gulf was reported [14], which could be probably due to the existence of a dynamic barrier along Sikka–Mundra section, which divides the gulf into two distinct dynamic systems [15].

II. METHODOLOGY

A. OCM Observations

1) *Suspended Sediment Concentration*: Remote sensing of oceanic and coastal waters depend upon the interaction of light with optically active water constituent such as phytoplankton, total suspended matter and dissolved organic matter, also known as yellow substance. A large number of sensors are developed by Indian and other space agencies, which are dedicated to determine the ocean parameters optically. Oceansat satellite series was launched by ISRO intended for the benefit of research in the field of ocean studies. Ocean Colour Monitor (OCM) onboard Oceansat-1 collects data in eight spectral channels and has a temporal resolution of 2 days at a local time 12:00 hrs. Each OCM scene covers 1420 km by 1420 km ground area with a spatial resolution of 360 by 360 m on ground.

Geometric correction is applied separately on individual data sets to remove image distortion and the data are analyzed for aerosol and atmospheric corrections. Even though a large number of sediment algorithms have been proposed to quantify total suspended matter [16]-[18], universal

sediment algorithms are still unfeasible [19]. Using satellite image, the sediment dynamics within Gulf of Kachchh are studied by several authors [20]-[23] but a regional algorithm to derive suspended sediment concentrations from satellite imageries are still not being focused as thrust of the research works while Tassan algorithm [24] was used to derive SSC in their studies. The acceptability of the satellite derived SSC lays in its ability to preserve the general pattern of sediment distribution [23]. Pass synchronous measurements of SSC carried out in the Gulf of Kachchh during November -2004 is used to derive an empirical relationship between SSC and remote sensing reflectance at 555 nm and 670 nm of OCM channels.

Reflectance at 555 nm and 670 nm at 16 locations within the gulf (Figure 1) were used to establish an empirical relationship of the form

$$RSR = 0.048 \ln(SSC) - 0.0897 \quad (1)$$

where $RSR = L_{wn}(555) + L_{wn}(670)$ (water leaving radiance at 555nm and 670nm) and SSC measurements are in mg/l.

Figure 2 shows the plot of SSC values and RSR along with the fitted function. OCM images of 12th December-2004 and 16th December-2004 are used to derive SSC using equation (1) (Figure 3). The choice of 12th December and 16th December-2004 is to understand the effect of tidal currents in the vertical distribution of SSC, where OCM pass for the former corresponds to high tidal currents in the gulf and for the later, OCM pass is during slack hours.

2) *Diffuse Attenuation Coefficient*: The diffuse attenuation coefficient (kd) is associated with the penetration of natural light into the ocean, and the depth associated with the reciprocal of $K(490)$ is, in the present study, approximated as the depth up to which OCM observation are made.

kd is evaluated as given by [16]

$$kd = 0.07 + 0.7003[L_{wn}(443)/L_{wn}(670)]^{-0.87} \quad (2)$$

where $L_{wn}(\lambda)$ is the normalized water leaving radiance

Reciprocal of kd is called the first attenuation depth, i.e. the depth at which the surface light field reduces to $1/e$ or 37% of its surface value. In the study this depth is described as OCM-depth. The first attenuation depth or the OCM-depth obtained for 12th December-2004 and 16th December-2004 are shown in figure 4.

B. Hydrodynamic Simulation

ECOM-3D, the Estuarine and Coastal Ocean Model, is a three-dimensional hydrodynamic and sediment transport computer code developed by HydroQual for application to marine and freshwater systems. The model is designed to simulate time-dependent distribution of water levels, currents, temperature, salinity, tracers, cohesive and non-cohesive sediments and waves in marine and freshwater systems. The equations which form the basis of the circulation model

describe the velocity and surface elevation fields, and temperature and salinity fields under hydrostatic approximation and Boussinesq approximations [25].

Consider a system of orthogonal Cartesian coordinates with x increasing eastward, y increasing northward, and z increasing vertically upwards. The free surface is located at $z = \eta(x, y, t)$ and the bottom is at $z = -H(x, y)$. If \bar{V} is the horizontal velocity vector with components (U, V) and ∇ the horizontal gradient operator, the continuity equation is:

$$\nabla \cdot \bar{V} + \frac{\partial W}{\partial z} = 0 \quad (3)$$

Reynolds momentum equations are

$$\frac{\partial U}{\partial t} + \bar{V} \cdot \nabla U + W \frac{\partial U}{\partial z} - fV = -\frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z} \left(K_M \frac{\partial U}{\partial z} \right) + F_x \quad (4)$$

$$\frac{\partial V}{\partial t} + \bar{V} \cdot \nabla V + W \frac{\partial V}{\partial z} + fU = -\frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{\partial}{\partial z} \left(K_M \frac{\partial V}{\partial z} \right) + F_y \quad (5)$$

$$\rho g + \frac{\partial P}{\partial z} = 0 \quad (6)$$

where ρ_0 is the reference density

ρ is the insitu density

g is the acceleration due to gravity

K_M is the vertical eddy diffusivity of turbulent momentum mixing

f is the Coriolis parameter

W is the vertical velocity

P is the Pressure

The domain was selected to involve the entire Gulf of Kachchh region. Available NHO (National Hydrographic Office) hydrographic chart was used to create the bathymetry (fig 2). The resolution of bathymetry is chosen as that of the spatial resolution of OCM, which is 360 m. As the river input into the gulf can be neglected [13], the eastern part of the gulf is closed. The straight line separating the gulf from the open sea is considered as the open boundary so the water enters the gulf only through the western mouth. The model is forced using the tidal elevation at the open boundary, with Godia creek on the north and Okha on the south. Numerical simulations are initially done for November-2004 and the simulated results were calibrated/validated against *in situ* observations. The calibrated model is simulated for the month of December-2004 corresponding to the OCM observations.

C. Calculating Vertical Variation of SSC

The Gulf of Kachchh as detailed in section 1 is highly tide dominated region. As the gulf is a tidal regime, the suspended sediment concentration is critically characterized by concentration profiles under currents. The present study neglects the lateral advection of sediments in view of [5], which draws a relation between the tidal range and SSC within the gulf and the varying tidal current triggers the re-suspension and deposition of the sediments.

In a steady and uniform flow, the settling of grains towards the bed is counterbalanced by diffusion of sand upward due to the turbulent water motion near the bed [26]. The vertical distribution of the concentration is described by the equation governing this balance and is given as

$$w_s C = -K_s \frac{dC}{dz} \quad (7)$$

where w_s = settling velocity of the sediment grain

C = volume concentration of sediment at height z

K_s = eddy diffusivity of the sediment

The solution of eq (7) gives the vertical distribution of sediment concentration. The eddy diffusivity can be assumed to increase linearly or vary parabolically with height which leads to power-law concentration profiles or Rouse profiles respectively. Parabolic profiles leads to zero eddy diffusivity at the surface resulting in a prediction of zero sediment concentration at the surface [27]. In field observational studies, Rouse profile was observed to under predict surface SSC [28]. In the present study, eddy diffusivity is assumed to vary linearly and K_s is given as

$$K_s = \kappa u_* z \quad (8)$$

where κ = von Karman's constant = 0.40

z = height above the seabed

u_* = frictional velocity

the frictional velocity u_* depends on depth averaged velocity and the bed roughness length z_0 .

While relating z_0 to the grain size (d_{50}), for hydrodynamically rough flows $z_0 = d_{50}/12$ and the

frictional velocity is given by

$$u_* = \frac{\bar{V}}{7} \left(\frac{d_{50}}{h} \right)^{1/7} \quad (9)$$

where \bar{V} is the depth averaged current speed

d_{50} is the sediment size diameter

h is the depth

Solving eq (7) with K_s from eq (8) results in power-law concentration profile given as

$$C(z) = C_a \left(\frac{z}{z_a} \right)^{-b} \quad (10)$$

where z_a = a reference height near the seabed

C_a = sediment reference concentration at height z_a

$C(z)$ = sediment concentration at height z

b = Rouse number

$$b = \frac{w_s}{\kappa u_*} \quad (11)$$

The settling velocity w_s is given by

$$w_s = \frac{\nu}{d_{50}} \left[\left(10.36^2 + 1.049 D_*^3 \right)^{1/2} - 10.36 \right] \quad (12)$$

where ν is the kinematic viscosity of water = $1.36 \times 10^{-6} \text{ m}^2/\text{s}$

D_* is the dimensional sediment size parameter

$$D_* = \left[\frac{g(s-1)}{\nu^2} \right]^{1/3} d_{50} \quad (13)$$

where \mathcal{S} is the ratio of densities of sediment and water

The reference concentration is taken as unity at a reference height z_a which is calculated as

$$z_a = \frac{26.3\tau_{cr}T_s}{\rho g(s-1)} + \frac{d_{50}}{12} \quad (14)$$

where ρ is the water density = 1027 kg/m³

g is the acceleration due to gravity

τ_{cr} is the critical shear stress

$$\tau_{cr} = \theta_{cr} g d_{50} (\rho_s - \rho) \quad (15)$$

where ρ_s is the sediment density

θ_{cr} is the shield parameter

$$\theta_{cr} = \frac{0.30}{1 + 1.2D_*} + 0.055[1 - \exp(-0.020D_*)] \quad (16)$$

where T_s is the transport parameter

$$T_s = (\tau_{0s} - \tau_{cr}) / \tau_{cr} \quad (17)$$

where τ_{0s} is the skin-friction bed shear-stress

$$\tau_{0s} = \rho u_*^2 \quad (18)$$

Suspended sediment size (d_{50}) distribution map within the gulf compiled from the field observations [13] is used to evaluate the settling velocity w_s using equation (12). The depth averaged velocity \bar{V} obtained from numerical simulation of tidal currents, as explained in section II-B, is used along with the d_{50} values for calculating the frictional velocities u_* within the study region and thereby the Rouse number b is calculated using equation (11). Reference concentration C_a at the reference depth z_a is considered as unity, and the concentration profiles at each OCM pixels are evaluated using equation (10). By considering reference concentration as unity, the concentration profiles calculated can be assumed as the vertical variation of suspended sediments; therefore called as vertical variation profiles. The current paper proposes that, if sediment concentrations at any of the depths are known, from the vertical variation profiles the entire sediment concentration profiles can be evaluated.

D. Sediment Profiles from OCM SSC

SSC derived from OCM is presumed to be the summation of suspended sediment values from surface to the first attenuation depth, hereafter called as OCM-depth. Associated with scattering of light, the ability of OCM to observe SSC diminishes within the OCM-depth. An exponential decay with depth is assumed for SSC values derived by OCM. From the vertical variation profile, values within the OCM-depth is scaled up to the corresponding OCM derived SSC while considering the exponential decay.

For a pixel having OCM-depth = k , OCM SSC = C and total depth = D , the vertical variation profile is given as $\phi_1 + \phi_2 + \phi_3 + \dots + \phi_k + \dots + \phi_D$ and the scale factor σ is obtained from OCM SSC using the equation

$$\phi_1 e^{-\gamma(1)} + \phi_2 e^{-\gamma(2)} + \phi_3 e^{-\gamma(3)} + \dots + \phi_k e^{-\gamma(k)} = \sigma C \quad (19)$$

where $\gamma(1)$ increases from 0 to $\gamma(k) = 1$ to account for the exponential decrease of SSC derived from OCM

σ is the scale factor

The scale factor obtained from eq (19) is applied along the variation profile and the sediment concentration profile $\sum_{i=1}^D \alpha_i$ is derived.

$$\alpha_i = \sigma \sum_{i=1}^D \phi_i \quad (20)$$

III. RESULTS AND DISCUSSIONS

A. Tidal simulation

Calibration of ECOM-3D model in the Gulf of Kachchh is done against *in situ* current observations during November-2004. Bottom roughness coefficient is varied to calibrate the

model. Figure 5 shows the validation of calibrated model current speed with the observed speed. The calibrated model is then simulated to obtain the tidal current within the Gulf of Kachchh for December-2004. Figure 6(a) depicts the surface current distribution for 12th December-2004 during the OCM pass (12:00 PM) where as the current velocities at 12:00 PM for 16th December-2004 is shown in figure 6(b). OCM pass for 12th December-2004 corresponds to high tide time in the gulf where the current velocities are more than 1 m/s near the mid-gulf. During these periods, the upward turbulent induced forces are expected to be maximum causing the bottom sediments to enter as suspension layers. OCM pass on 16th December-2004 corresponds to slack hours and current velocities are small favouring the settling of suspended sediments.

B. Vertical concentration profiles

The depth averaged velocity \bar{V} obtained from hydrodynamic simulation corresponding to 12th and 16th December-2004 are used to calculate the vertical variation profiles as explained in section II-C. The vertical variation profiles were scaled according to the respective OCM derived SSC values (explained in section II-D) and the bottom and surface sediment concentrations are obtained. Figure 7 show the distribution of surface sediment concentration and figure 8 show the bottom sediment concentration distribution.

Pattern of the surface sediment distribution (figure 7) is almost preserved with respect to the OCM derived SSC (figure 3), while the sediment concentration values are decreased since the paper proposes that the OCM SSC are not purely the surface SSC but an integral of total suspended sediments within the OCM depth with an exponential decay of values with depth. Surface SSC are observed to have higher deviation of around 50% from OCM derived SSC near

the mid-gulf where OCM-depth (figure 4) in the mid-gulf is found to be in the range of 3-5 meters.

The sediment concentrations obtained from the above methodology showed an enhancement in the bottom concentration values with respect to their surface SSC values. Figure 8 shows that, in the mid-gulf, otherwise reported as SSC deficient region [13], [5], bottom SSC are high during the reversal of tide. The results suggests, the mid gulf to be a likely depositional area in the Gulf of Kachchh as the depositional rate of sediments directly depends on the sediment flux approaching the bed during settling.

Sediment concentration profiles for selected regions within the gulf are shown in figure 9. On 16th December-2004 (figure 9b), the bottom sediment concentrations near the tidal channels and head of the gulf are observed to increase rapidly than for 12th December-2004 (figure 9a), since the settling of sediments in suspension are enhanced during the slack hours for 12th December 2004. From the in situ observations [13] by Ramaswamy et al 2007, the increase in bottom SSC from its surface SSC were in the range of 10 % near the southern banks of mid-gulf to more than 200% in the tidal channels. The method proposed in the paper has also modeled an increase in bottom SSC of about 10 % to about 150% for the corresponding locations.

IV. CONCLUSIONS

In numerical simulation methods to describe the sediment transport processes, both re-suspension strength and depositional rates depends upon the bottom sediment concentrations. An

approximation of bottom sediment concentrations is made from the surface sediment concentration values, prevailing current conditions and sediment size parameters.

Gulf of Kachchh is a tide dominated region, where the sediment concentration profiles are presumed to be characterized by power-law. While taking reference concentration as unity in calculation of power-law profiles, the profiles are considered to be the vertical gradation of concentration values and for each OCM pixels, the profiles are calculated from the simulated current velocities and sediment size parameter. From the study, considering OCM derived SSCs aren't to be exactly the surface SSC but an integral of concentration values from surface to first attenuation depth, surface SSC especially in the mid-gulf had much variations from the OCM derived SSC values.

Bottom SSC from the methodology always showed an increase in concentration values corresponding to their surface values and when the currents in the gulf are weak the increase in bottom SSC values get enhanced due to settling of sediments in suspension. The dependency of the bottom SSC is attributed to the prevailing current velocity, bottom roughness length of the region and settling velocity of the sediments in suspension. During the slack hours of 16th December-2004 a higher value of bottom sediment concentration values were observed near the mid-gulf which is considered to be a region of less sediment concentrations from satellite observation studies.

The method provides good approximations of the bottom sediment concentrations which are indeed necessary to establish an accurate numerical simulation method to understand the

sediment transport processes. The bottom sediment concentrations also provide an insight of regions likely to get deposited when the tidal currents are low.

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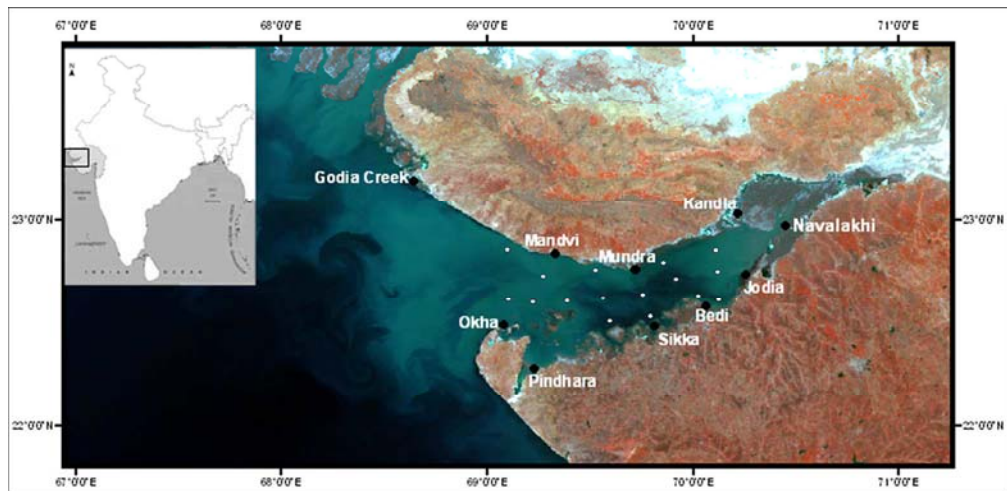


Figure 1 Location map of Gulf of Kachchh (white spot shows the in situ sediment observation sites)
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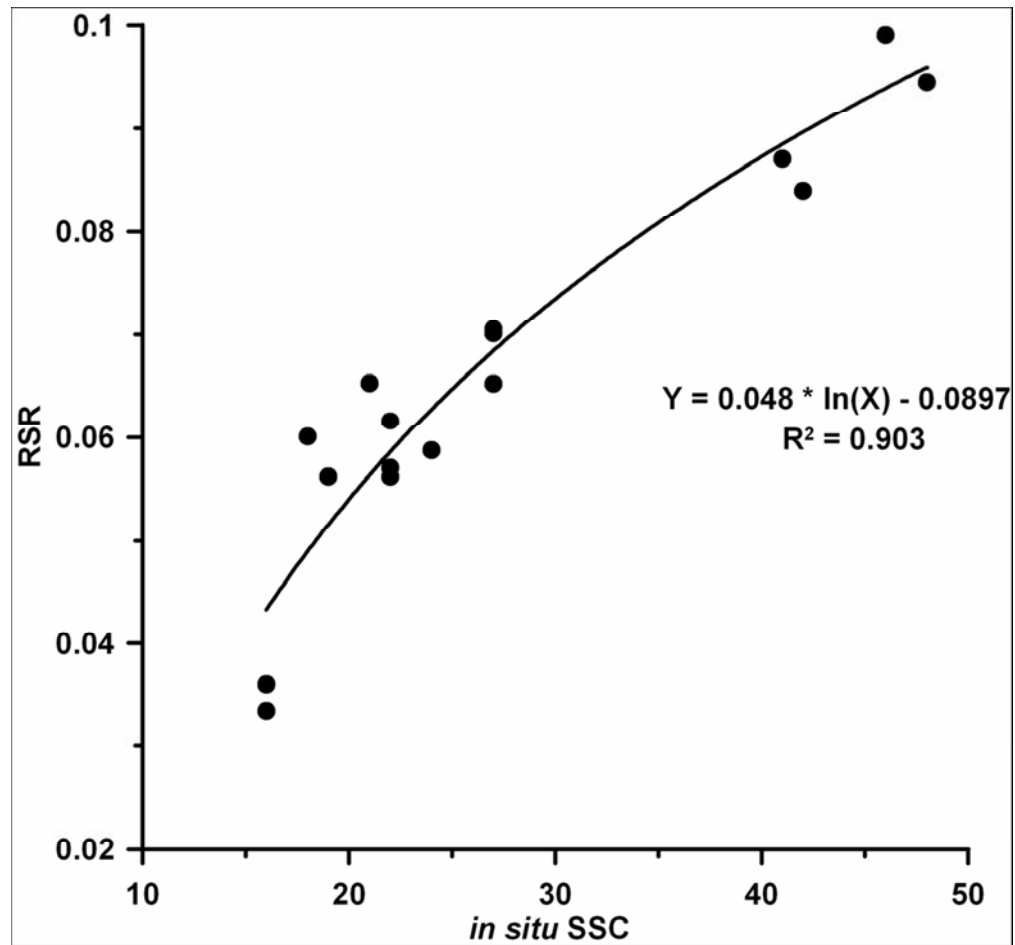


Figure 2 In situ SSC and RSR values along with the fitted function
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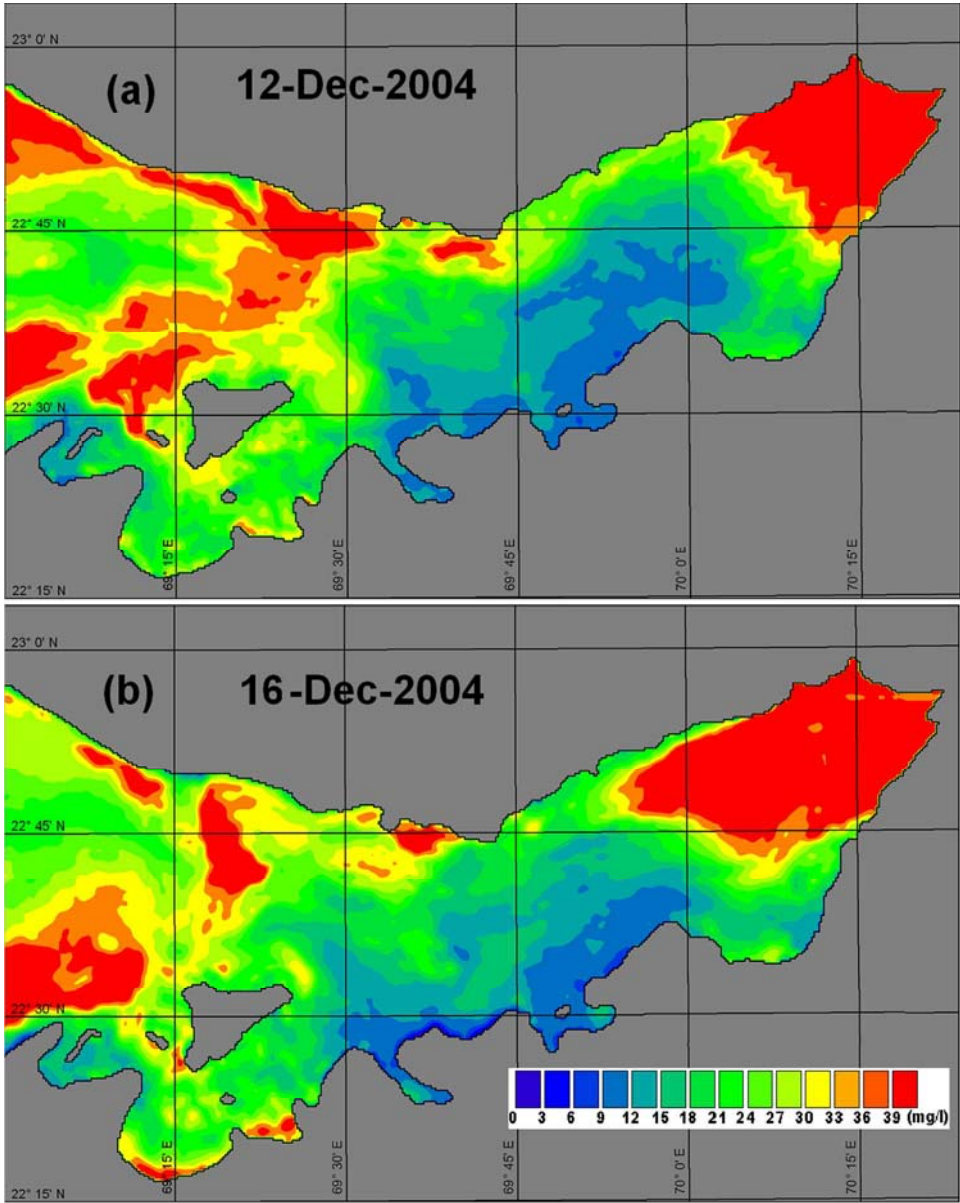


Figure 3 OCM derived SSC
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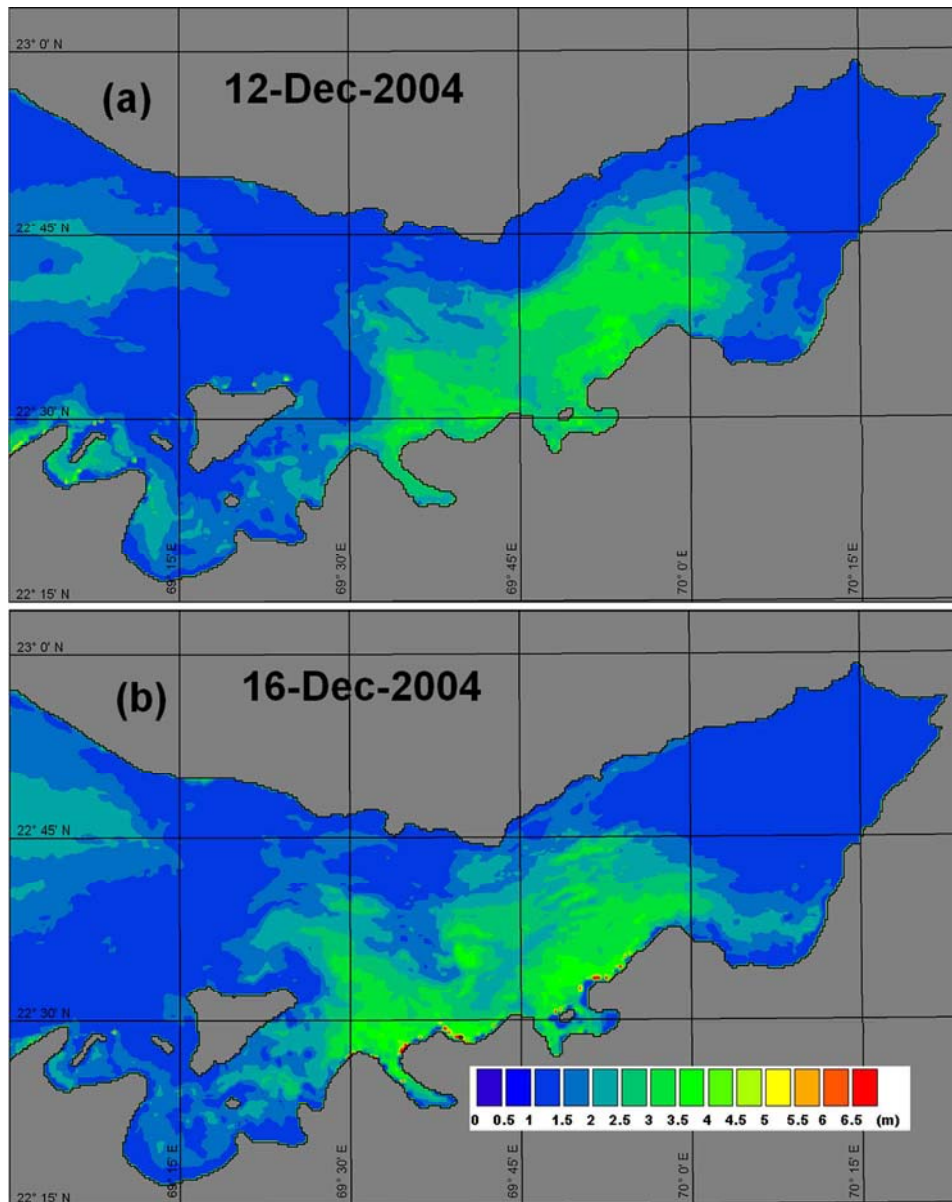


Figure 4 OCM-depth for 12th and 16th December-04
296x372mm (96 x 96 DPI)

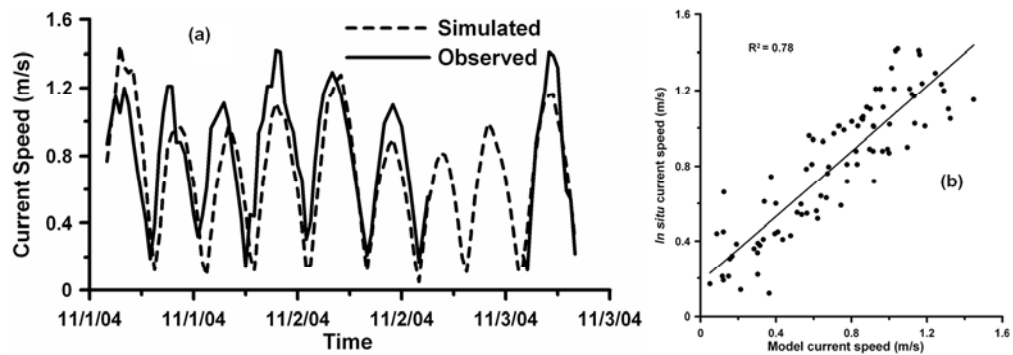


Figure 5 (a) Comparison of simulated and observed current speed, (b) scatter diagram
458x158mm (96 x 96 DPI)

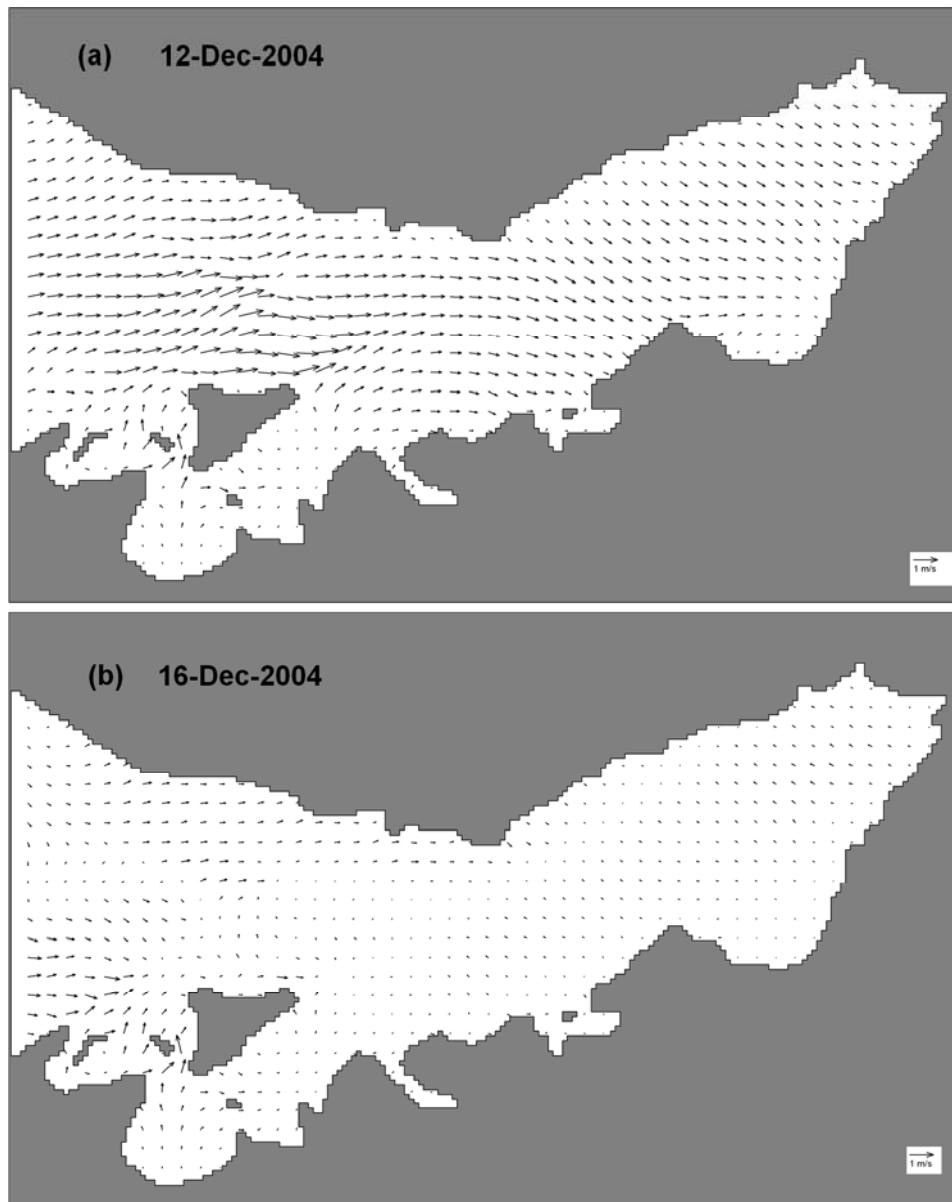


Figure 6 Current conditions in the gulf
434x545mm (96 x 96 DPI)

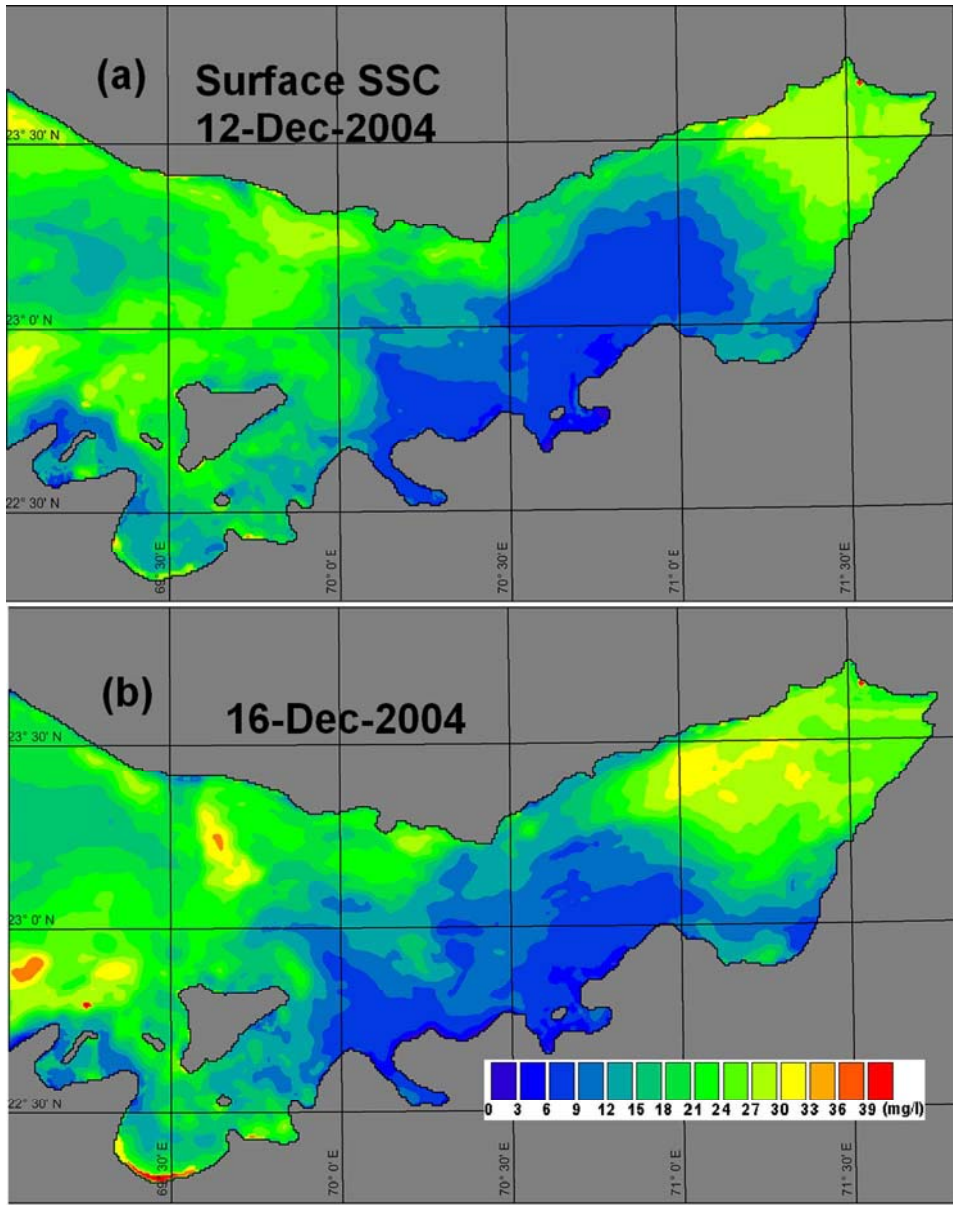


Figure 7 Surface SSC derived from the proposed method
295x372mm (96 x 96 DPI)

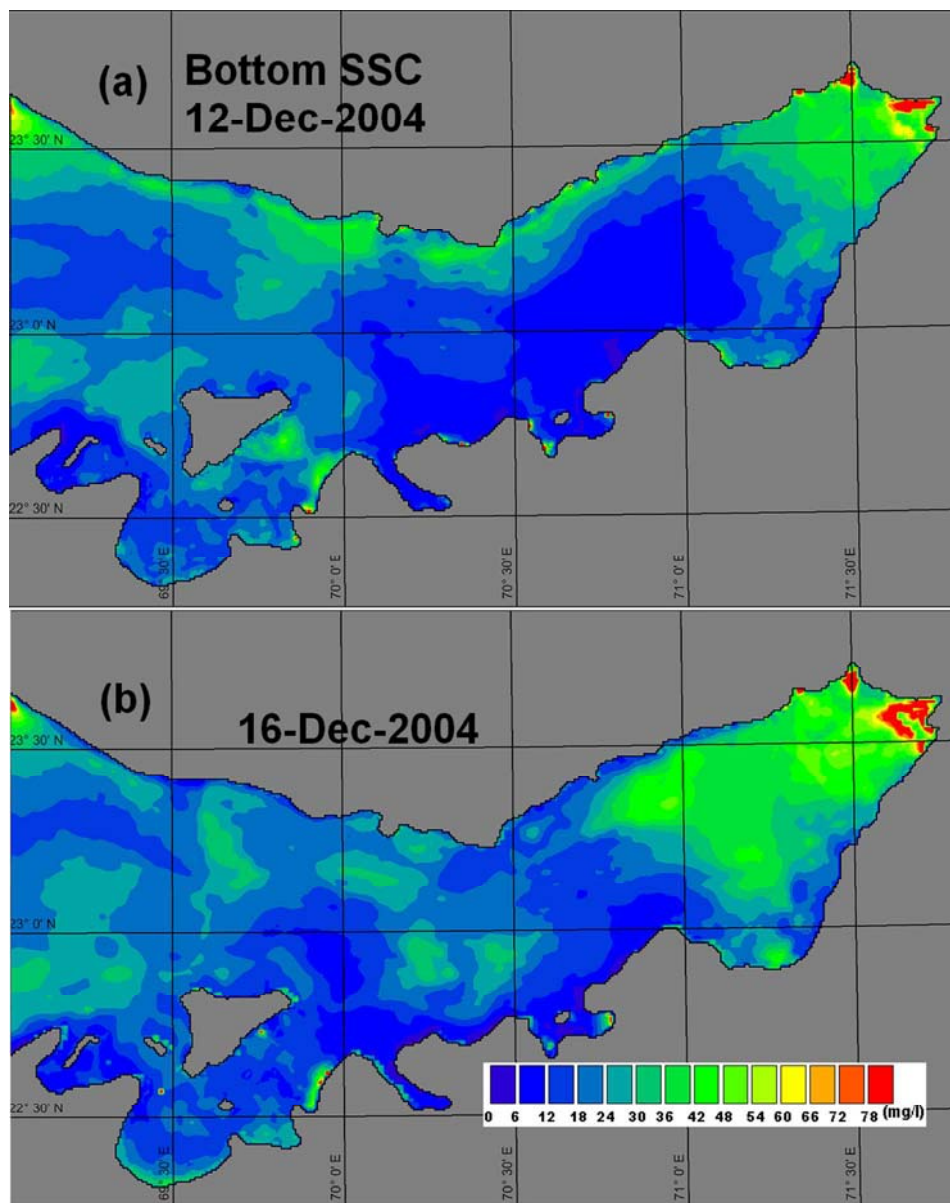


Figure 8 Bottom SSC derived from the proposed method
294x371mm (96 x 96 DPI)

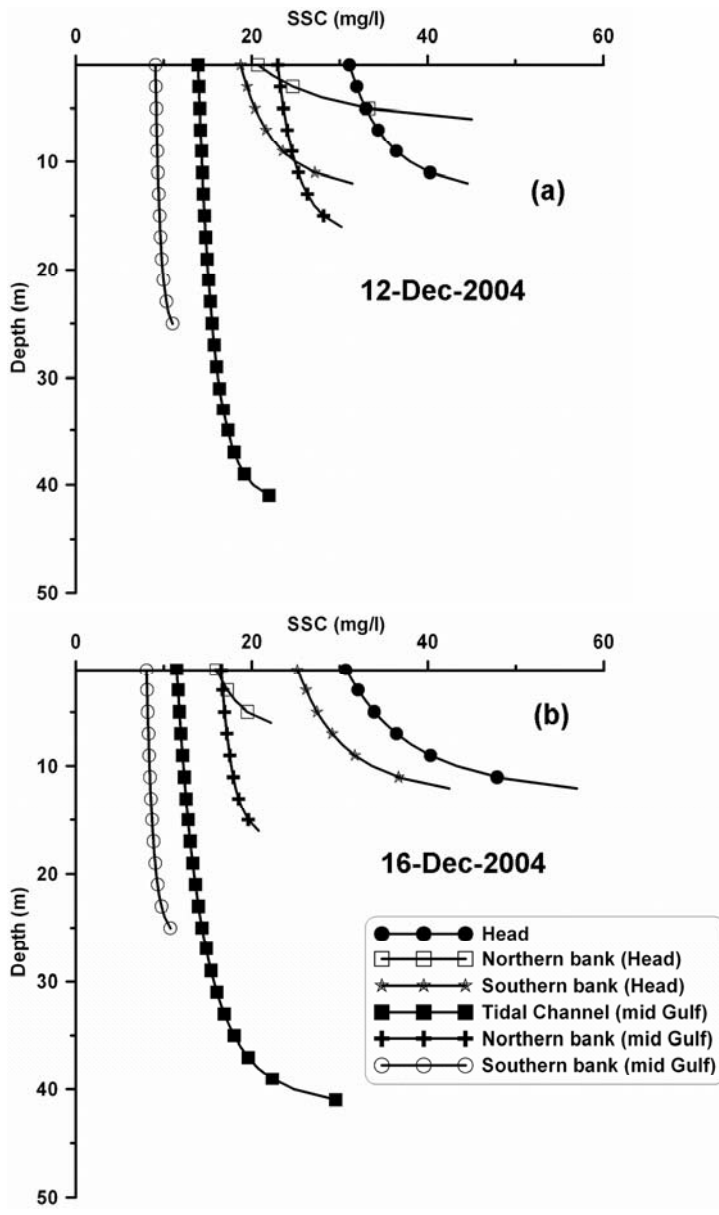


Figure 9 SSC profiles for selected regions within the gulf
325x541mm (96 x 96 DPI)