CHAPTER 7

MODELLING TEMPERATURE AND SALINITY
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7.1 Temperature and salinity characteristics

The Gulf of Kachchh is also known as an inverse estuary where high salinities are observed at the upstream regions. Measurements indicate salinities of the order of 40 PSU in the eastern regions off Navlakhi and Kandla while in the western parts salinity varies from 37.2 to 37.8 PSU. Across the western boundary the GoK waters interact with the warm Arabian Sea waters while in the eastern parts little Rann of Kachchh feeds the Gulf with cold, high salinity waters from the upstream areas. River influx into the Gulf is almost negligible as the surrounding regions receive scanty rainfall (~40cm per year).

The climate of the surrounding land is arid or semi arid nature; severe drought conditions recur frequently in the region. Because of higher concentration of salt in the seawater, a number of Salt Works are located in the region, which produce an average of 6.9 million tons of salt annually. One of the severe problems faced by the surrounding areas is contamination of drinking water due to salinity ingress. An average distance of 5.0 to 7.5 km from the coastline is adversely affected by salinity ingress (Barot, 1996). Studies related to the salinity characteristics of GoK attain greater importance in this context.

Modelling studies have been carried out to understand the temperature salinity variability in Gulfs, bays etc. Omstedt and Axell (2003) modelled salinity and temperature fields in the in Gulf of Bothnia, Gulf of Finland, and Gulf of Riga by using a coupled sea ice-ocean Baltic Sea model, forced by meteorological parameters. Using 3D model Horiguchi et al. (2001) simulated the seasonal cycle of temperature and salinity in the Tokyo bay. The above models reproduced the temperature-salinity fields very closely to the observed values.

Neither field measurements nor modelling studies related to the temperature-salinity fields are reported in the literature for GoK. Hence, in order to understand the temperature and salinity variability, their distributions the field data as well as model results are analysed. The results of the analysis are presented in the next section.

7.2 Modelling of temperature and salinity fields

Though GoK is generally known to be well mixed, the results obtained from CTD and RCM measurements points to the fact that there could be vertical circulation driven
by the density stratification. The current structure obtained from moored Doppler Current
Meter (DCM12) off Sikka (Fig.7.2.1) suggests that there is intensification in the surface
layer due to wind effect and strong currents are present in the subsurface layer during
ebb currents. The temperature-salinity distributions obtained from CTD profiles
explained in chapter 4, show that in general the Gulf waters are vertically well mixed,
vertical gradients are observed in the temperature and salinity fields at some locations
especially in the eastern part where a high saline, coldwater tongue is seen in the
subsurface layer. Also, temperature inversions are noticed in the southwestern region.
These temperature-salinity changes could induce stratification, which cannot be
modeled using vertically integrated 2D model. In order to accommodate the vertical
gradients in the temperature-salinity distribution, 3D modelling is necessary. Hence, the
hydrodynamic model MIKE3 numerical modelling system has been used. It simulates
unsteady 3D flow, taking into account density variations in addition to wind and tidal
forcings.

In the formulation of 3D model, the conservation of mass, momentum, and
temperature-salinity are included. For momentum conservation, the Reynolds-averaged
Navier-Stokes equation in 3D is used with the effects of turbulence and variable density.
The equations for mass, momentum and temperature-salinity conservation, used in
MIKE3 (MIKE3 user guide) are as follows:

\[
\frac{1}{\rho C_s^2} \frac{\partial P}{\partial t} + \frac{\partial u_j}{\partial x_j} = SS
\]

7.1

\[
\frac{\partial u_j}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_i} + 2\Omega_y u_j = \frac{1}{\rho} \frac{\partial P}{\partial x_i} + g_i + \frac{\partial}{\partial x_j} \left( V_T \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} k \right) + u_i SS
\]

7.2

\[
\frac{\partial S}{\partial t} + \frac{\partial}{\partial x_j} (S u_j) = \frac{\partial}{\partial x_j} \left( D_s \frac{\partial S}{\partial x_j} \right) + SS
\]

7.3

\[
\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j} (T u_j) = \frac{\partial}{\partial x_j} \left( D_T \frac{\partial T}{\partial x_j} \right) + SS
\]

7.4

where \( \rho \) is the local density of the fluid, \( C_s \) is the speed of sound in sea water,
\( u_i \) the velocity in the \( x_i \) direction, \( \Omega_y \) the Coriolis parameter, \( P \) the fluid pressure, \( g_i \) the
gravitational acceleration, \( V_T \) the turbulent eddy viscosity, \( \delta \) the Kronecker's delta, \( k \) the
turbulent kinetic energy, \( S \) and \( T \) the salinity and temperature, \( D_s \) and \( D_T \) the associated
dispersion coefficients and \( t \) denotes the time. SS refers to the respective source/sink
terms and thus differs from equation to equation. The salinity, temperature and pressure are used to derive the density through the UNESCO definitions (UNESCO, 1981).

Eqs. 7.1 and 7.2 are the hydrodynamic (HD) equations and 7.3 and 7.4 are the advection-dispersion (AD) equations for salinity and temperature. Eqs. 7.1 and 7.2 are solved using the HD module and Eqs. 7.3 and 7.4 are solved using the AD module. The HD module of MIKE3 makes use of Alternating Direction Implicit (ADI) technique to integrate the equations for mass and momentum conservation in space–time domain by discretizing the equations on the Arakawa C-grid aiming at a second order accuracy on all terms, i.e. second order in terms of the discretization error in a Taylor series expansion.

7.3 Simulation of currents, temperature and salinity using 3D model

The bathymetry file prepared earlier for 2D simulation was used in the 3D model with 15 vertical levels, each level with a vertical thickness of 4m. Tides along the western open boundary were prescribed using predicted tides at Dwarka and Godia and for the eastern open boundary predicted tides at Navlakhi are used. For vertical eddy viscosity coefficient, k-ε Smagorinsky scheme has been applied (Smargorinsky, 1963; Mellor and Yamada, 1982). A constant value of 0.15 has been used for the bottom friction and average values of measured temperature and salinity are used to prescribe the initial and boundary conditions. Measured wind speed, wind direction, relative humidity and air temperature (explained in Chapter 4) are also used in the model to estimate heat flux. A constant value of 4 mm d⁻¹ is assumed for evaporation (Desa et al., 2002). In order to simulate the currents, temperature and salinity fields, model runs have been taken for the month of November 2002.

7.3.1 Model sensitivity analysis

Model runs have been carried out to check the sensitivity of the model to heat flux variations by comparing the model results obtained for two case studies: (i) without heat flux and (ii) with heat flux. The model simulated salinity and temperature (T-S values) extracted at 3 test points located in the western, central and eastern Gulf, responded significantly when heat flux is included.
7.3.2 **Simulation of currents using 3D model**

The current vectors simulated for the top 5 layers (thickness 4m each) are given in Figs 7.3.1. The vertical distribution of u-component along an east-west section passing through the centre of the Gulf are shown in Fig.7.3.2a&b. The current components and water levels simulated by the model are compared with the measurements taken at LOC2 and LOC5. (Figs.7.3.3 & 7.3.4). The u & v components of modeled currents showed very good agreement with the measurements at LOC2 and LOC5 at the surface level.

7.3.3 **Temperature salinity structure**

In order to verify the model results, the simulated temperature and salinity fields are extracted at the location, 22°41'48"N:69°43'49"E off Mundra where time series CTD profiles were taken on 13-14 November 2002. The vertical variations of temperature and salinity off Mundra (grid 229,108) for the model run period 5-25 November 2002 is given in Fig. 7.3.5. The results indicated that the model results did not stabilize during this period; though the temperature—salinity values exhibited variations with the tides, the temperature showed a decreasing trend and salinity an increasing trend after each tidal cycle. After 30 November, the temperature and salinity values stabilized and exhibited oscillations similar to that observed in the measured data. The values extracted from this point onwards are used for verifying the model results. The model salinity values off Mundra settle in the range 39.3–39.9 PSU from 30 Nov onwards (Fig. 7.3.6). The average temperature over tidal cycles shows continuous decrease throughout the simulation period. Similar variations have been noticed in the time series measurements of salinity and temperature off Mundra (Fig.4.1.1a) during winter. The model results obtained after Nov 30 have been used for verification of the results.

Fig.7.3.6 shows model simulated temperature and salinity off Mundra at different depth levels such as surface, 4m, 8m, 12m, and 16 m for the period 30 Nov to 8 Dec 2002. The temperature-salinity distribution at different depths measured by CTD has been already discussed in chapter 4 (Fig.4.1.14). Both temperature and salinity exhibit oscillations associated with the semidiurnal tide. Temperature and salinity show flood-ebb variability with warm, less saline flood waters and cold, high saline ebb waters. As seen in the measurements, temperature inversions are also noticed in the modelled results. It is apparent from the observed as well as modelled temperature-salinity fields that the temperature is almost homogeneous; salinity variations of ~1 PSU contribute to the vertical density gradients, more than the temperature.
Figs. 7.3.7 and 7.3.8 show the model simulated salinity and temperature at the top layer during flood and ebb tides on 8 Dec 02, after 30 days of simulation. Both the temperature and salinity patterns agree very well with the patterns obtained from the CTD profiles (Figs. 4.1.7 and 4.1.8). One of the important features reproduced by the model (Fig. 7.3.7) is the westward advection of the high salinity tongue from the eastern region between 69°45' and 70°15'E. This feature is clearly noticeable in the horizontal salinity distribution obtained from CTD data (Fig. 4.1.8). The central Gulf is characterized with saline front of 38.5 PSU, which advects eastward during flood tide and westward during ebb tide. This oscillation is seen off Mundra (Fig. 7.3.7). A comparatively less saline tongue (37.8 PSU) is seen advecting eastward from the west across 69°15'E in the central Gulf. Temperature simulated by the model showed colder waters covering the entire Gulf except the western and central channel where comparatively warm waters are noticed (Fig. 7.3.8). The warm waters from the west advect eastward during flood tide and the cold waters from the east advect towards west during ebb.

A vertical section is selected running from the mouth to head of the Gulf to explain the variability of temperature and salinity along the east west axis of the Gulf. A section passing from west to east through the central deep channel has been taken for this purpose (Fig. 7.3.9). It is evident that stratification is present in the eastern and western Gulf, but the central Gulf is vertically homogeneous. In the eastern parts cold and high saline waters are present in the subsurface layers while warm and less saline water are present in the deeper layers of the western Gulf. A typical salinity pattern simulated at five different layers is given in Fig. 7.3.10.

### 7.4 Comparison between model and measurements

CTD profiles measured off Mundra for every hour during 13-14 November 2002 show that the salinity varies between flood and ebb tides in the range 38.7 and 39.0 PSU in the upper 20 m layer (Fig. 4.1.14). As the modeled temperature and salinity did not stabilize during this period, the values obtained from the model after 30 Nov 02 have been used for comparison with the measured data. During this period, the modeled salinity values in the upper 20 m layer vary between 39.3 and 39.9 PSU (Fig. 7.3.6). Temperatures measured by CTD vary between 27.2°C and 27.8°C during 13-14 November 2002. However, the modeled temperature values showed much lower values of temperature, varying between 25.0 and 25.8 during 30 Nov-8 Dec 2002. The model results exhibit reduction in temperature from November to December due to the onset of
winter. Very low temperatures (~22-23°C) have been observed off Mundra during winter period (Fig. 4.1.1a).

The vertical and horizontal temperature-salinity distributions revealed the presence of a tide-driven thermohaline front in the central Gulf. The frontal zone is characterized with a homogeneous salinity of 38.5 PSU and temperature of 26.5-27°C. The existence of a 'Dynamic Barrier' has been identified in this region which separates the Gulf into two water bodies with distinct circulation characteristics (Vethamony et al., 2005).
Fig. 7.2.1 Time-series of current u-components (cm/s) measured at six levels off Sikka, Gulf of Kachchh using DCM12 acoustic current meters. The depth levels are surface, 4m, 7m, 10m, 13m, and 16m. Dotted line indicates model results.
Fig. 7.3.1 Model simulation of currents in the upper five layers of 4m thickness
Fig. 7.3.2 3D model simulated vertical section of u-component of the (a) ebb current and (b) flood current on 17.11.02
Fig. 7.3.3 Comparison between currents (modeled & measured) and tides (modeled and predicted using the tidal constituents of nearest the tide gauge station): (a) u-component of currents, (b) v-component of currents and (c) water level at location LOC2 during November 2002.
Fig. 7.3.4 Comparison between currents (modeled & measured) and tides (modeled and predicted using the tidal constituents of nearest the tide gauge station): (a) u-component of currents, (b) v-component of currents and (c) water level at location LOC5 during November 2002
Fig. 7.3.5 Model simulated (a) salinity and (b) temperature off Mundra for the simulation period 6-30 November 2002.
Fig. 7.3.6 Model simulated (a) salinity and (b) temperature off Mundra for the simulation period, 30 November-9 December 2002.
Fig. 7.3.7 Simulation of salinity in the Gulf of Kachchh during (a) flood tide and (b) ebb tide
Fig. 7.3.8 Simulation of temperature in the Gulf of Kachchh during (a) flood tide and (b) ebb tide.
Fig. 7.3.9 Model simulated (a) salinity and (b) temperature along a vertical section from the mouth to head of the Gulf (along grid 100).
Fig. 7.3.10 Model simulation of salinity in the upper five layers of 4m thickness.