

Physical processes in the Gulf of Kachchh: A review

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Received 20 August 2010; revised 21 December 2010

A brief review of various physical processes acting in the Gulf of Kachchh (GoK), which have prominent roles in Gulf dynamics, is presented in this article. The eddies present in the GoK confirm that they are permanent features of the GoK circulation. Accurate estimation of residual currents and eddies in an active industrial coastal zone like the Gulf of Kachchh is important because of its potential applications with respect to discharge of pollutants. Though GoK is considered as a well-mixed system, recent studies revealed that only the central Gulf is well mixed. Stratification in temperature and salinity is noticed in the eastern Gulf, where a cold and high saline tongue is observed in the subsurface layers. Model results indicated the effect of seasonally changing winds the circulation. During southwest monsoon, the predominant westerly winds enhance the flood currents by about 20% and reduce the ebb currents significantly. In spite of semi-arid climate and lack of major rivers flowing into it, the Gulf is highly turbid with suspended sediment concentrations (SSC) during October-November 2002 ranging between 0.5 mg l^{-1} and 674 mg l^{-1} .

[Keywords: Physical processes, Gulf of Kachchh, Circulation, Eddies, Suspended sediment concentration]

Introduction

The Gulf of Kachchh (GoK) is a semi-enclosed basin located in the northern part of west coast of India (Fig.1). It is one of the two highly energetic, macro-tidal systems of the northeastern Arabian Sea with tidal ranges reaching upto 7.2 m. GoK has a length of ~180 km; width decreases from ~70 km in the west to about a few hundred of meters at Navlakhi and Kandla near the head. Further eastward, it narrows down to form a salt marsh known as the Little Rann of Kachchh. The bottom topography of GoK is very complex, and the depth varies from ~60m near the mouth to ~15m in the central and western parts. GoK has grown in economic importance due to rapid industrial development in recent years. Fertilizer, chemical, cement and power plants, minor and major ports, oil refineries and salt works are the major industries, which make use of GoK waters¹. Most of these activities are concentrated along the southern shore of GoK, where eco-sensitive areas like Marine Sanctuaries (MS) and Marine National Parks (MNP) are located. The northern coast, located to west of Mundra, is characterized with sand dunes and sandy beaches; the southern coast is interwoven with mudflats and small inlets. Across the western open boundary, GoK waters interact with the northern Arabian Sea, while the upstream eastern regions bring in high saline waters through the shallow and narrow creeks, and thereby make the gulf an inverse estuary.

Though GoK waters are used by the industries, it is very rich in its biodiversity as the waters are found to be healthy². The southern gulf is famous for mangroves, coral reefs, sea grass, sea weeds and many species of red, green and brown algae. In order to protect this unique ecosystem and its flora and fauna, an area of 458 km² of the southern gulf is declared as Marine Sanctuary and another 163 km² as category-II Marine National Park. These regions host a variety of marine life including sea snakes, dolphins and endangered species of sea turtles. In spite of intensive efforts to protect the ecosystem, the corals in the region are showing signs of deterioration and depletion. In order to preserve the ecosystem, it is necessary that industrialization be balanced through an integrated approach using modelling and monitoring, which can keep the coastal environment healthy.

Temperature profiles reveal a nearly homogeneous water column in the Gulf, caused by factors such as mixing associated with strong tidal currents, uneven bottom topography and lack of fresh water discharges. Temperature distribution shows linear variation from mouth to head during summer and winter. The horizontal salinity variation from mouth (36.6 psu off Okha) to head (41.0 psu off Kandla) is very remarkable, and the highest observed in the Indian coastal region. Tides in the Gulf are predominantly semi-diurnal. The mean spring tidal range increases from mouth to head: 3.06 m at Okha,

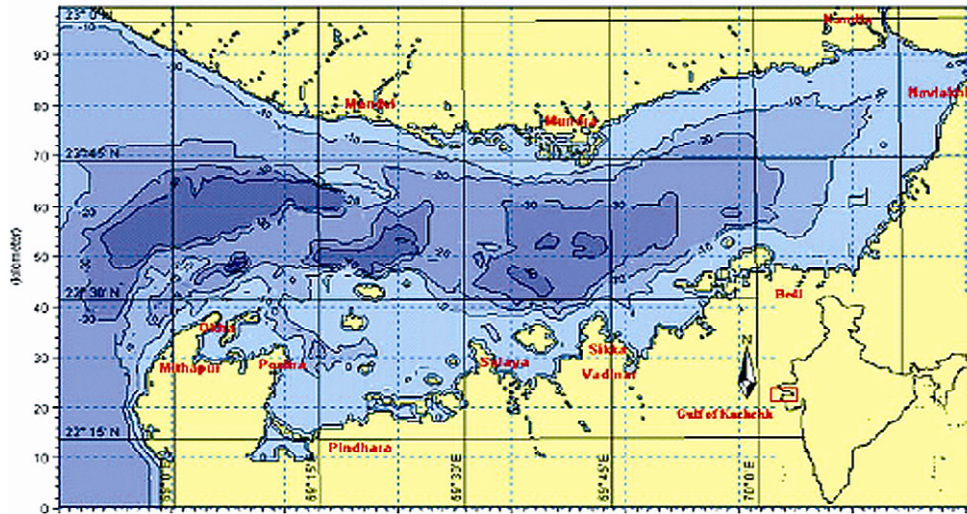


Fig. 1—The major morphological features of Gulf of Kachchh (P. Vethamony *et al.*, 2005).

Table 1—Seasonal variability of the maximum and minimum current components u and v obtained from model results at three select locations (wind speed and current components are in ms^{-1}) in the GoK

Period	Wind speed (ms^{-1})	Wind direction	Location					
			Mundra		Vadinar		Sikka	
			u-max (ms^{-1})	v-max (ms^{-1})	u-max (ms^{-1})	v-max (ms^{-1})	u-max (ms^{-1})	v-max (ms^{-1})
North-East Monsoon	3.5	NNE(337°)	1.16	0.31	0.60	0.13	0.96	0.37
Pre-Monsoon	4.5	WNW(292°)	0.96	0.23	0.45	0.10	0.73	0.28
South-West monsoon	6.5	SSW(247°)	1.30	0.45	0.64	0.17	1.01	0.50

4.67 m at Sikka, 5.82 m at Kandla and 6.43 m at Navlakhi. Bathymetry, funnel shape of the Gulf, coastal configuration and orientation of the coast are the reasons for amplification of tides. Currents in the Gulf are driven mainly by tides, except during a short spell (July-August) when the surface currents are influenced by monsoon winds¹. In general, surface currents vary from 0.75 to 1.25 ms^{-1} at the mouth to 1.5 to 2.0 ms^{-1} at the head and reach to a maximum of 2.5 ms^{-1} in the central channel.

Materials and Methods

As a part of the project on 'Integrated Coastal and Marine Area Management (ICMAM) Plan for the Gulf of Kachchh', extensive field data collection programme was conducted by the National Institute of Oceanography, Goa in collaboration with ICMAM Project Directorate, Chennai during 2002-2003. These data have been analysed and used in the studies reviewed here. Data on winds, temperature, salinity, currents, tides, waves, suspended and bed sediments, optical properties of the water column, flora and fauna, water quality, coastal ecology and

meteorological parameters collected earlier for various studies have been used. The wind field over the gulf undergoes seasonal changes coinciding with the change of monsoons in the Indian Ocean. Mean winds are utilized to simulate currents during north-east monsoon, pre-monsoon and south-west monsoon. Recording Current Meter (Model: RCM7; Make: Aanderaa, Norway) data measured during different periods, viz., December 1992 to February 1993, March 1994 and June-July 1996 representing NE monsoon, pre-monsoon and SW monsoon have been used for model validation².

Results and discussions

Seasonal circulation

Recording current meters were deployed at 5m and 10m from the bottom, where the total water depth was 15m and the measured values of u and v current components at 10m above the bottom were used for comparison with the model results. Seasonal variability of the maximum and minimum current components u and v obtained from model results are given in Table-1. The residual currents estimated after

removing the tides from the measured data, were of the order of 0.11 to 0.09 ms^{-1} , and exhibited an oscillatory motion with diurnal period associated with the diurnal change of winds.

Current speed and direction measured at two depths, 5 and 20m from the bottom, were resolved into u and v components and the mean u and v have been compared with the model results. Though the simulation was carried out for a period of 1 month, the results are presented only for the period of current measurements. Seasonal changes in the maximum and minimum current components obtained from model results are given in Table-1. The effect of wind forcing is manifested in the residual currents. During pre-monsoon, the winds are weak and consistently of westerly direction. The model simulated tidal currents during spring ebb and flood show an apparent increase in the u component by about 10% in the absence of wind forcing. However, during neap, the tidal currents show a reduction upto 20% compared to the measured currents, suggesting that wind forcing is more effective during neap than spring phase.

Assuming a constant wind representing southwest monsoon period, model runs were carried out to simulate the currents and the results are compared with water levels and currents measured off Sikka during June–July 1996. The surface elevation and currents obtained from the model and measurements are presented in Fig-2. As the 2D model results

represent averaged current flux, the measured $u-v$ components are vertically averaged before comparing it with the model results. The model flood currents show very good agreement with the measured values, while the ebb currents are slightly overestimated in the model. Measurements show that currents in the upper layer increase significantly under the influence of southwest monsoon winds. Another model study conducted earlier revealed that currents are of the order of 1.0 m/s off Sikka during the same period, and both ebb and flood currents showed nearly the same magnitudes³. However, a flood-ebb inequality is clearly visible with spring flood current reaching a maximum of 1.17 ms^{-1} , and ebb current of 0.87 ms^{-1} . This inequality can be attributed to the forcing due to the southwesterly winds. In order to analyse the wind effect, the residual currents after removing the tidal component have been analysed². The u and v components of residual currents are always positive, showing a northeastward wind-driven current. The u -component varies between 0.26 and 0.50 ms^{-1} and v -component shows a maximum of 0.37 ms^{-1} (Fig-2). For a typical neap and spring, the u -components of the current are shown in Fig-3. The u -component of measured current indicates an apparent increase by about 20% over the modelled tidal current during spring flood and a reduction of about 20% is noticed during ebb. It is evident from the results that the effect of wind forcing on tidal currents is very significant

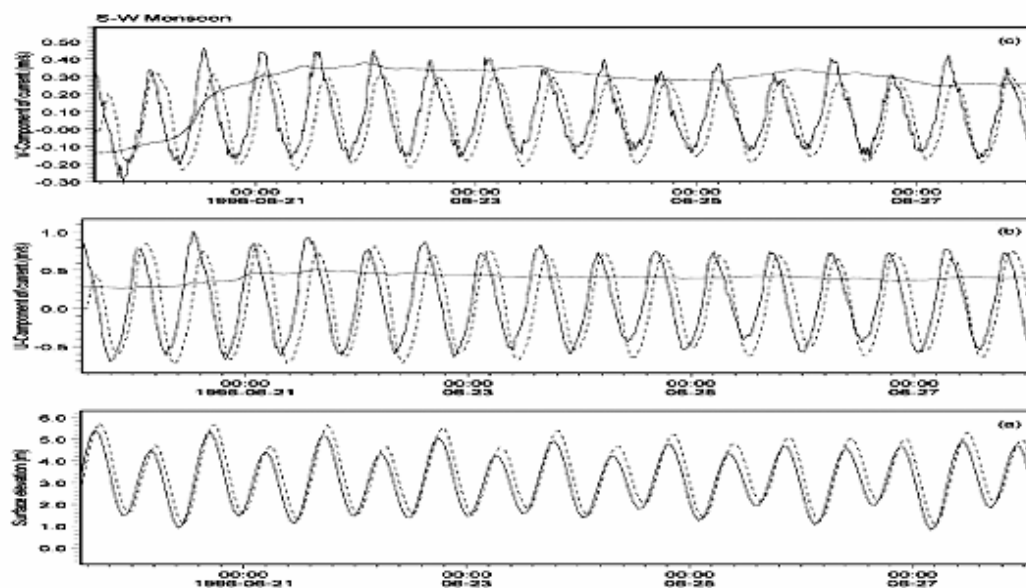


Fig. 2—Comparison between measured and modelled

(a) surface elevation

(b) current U-Component and (c) current V-Component during S-W Monsoon off GoK (M. T. Babu *et al.*, 2005).

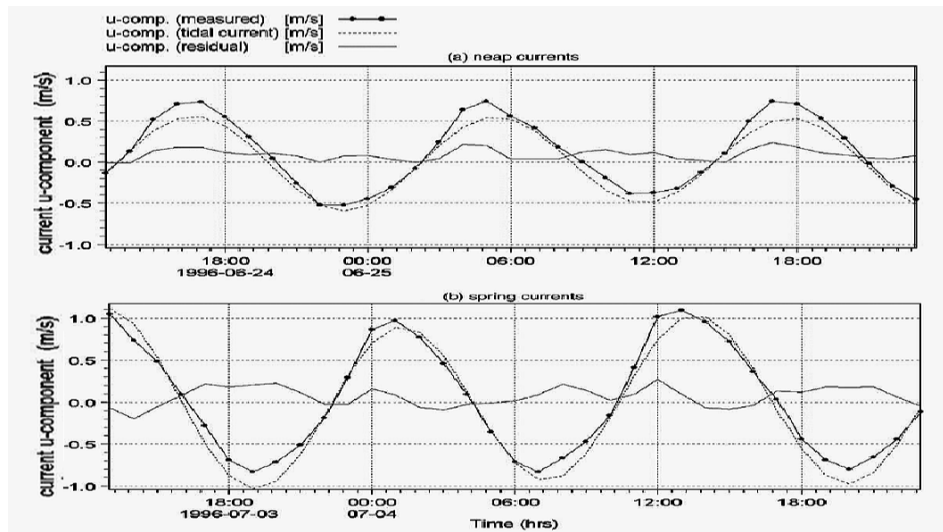


Fig. 3—U-component of measured, tidal and residual currents for (a) neap tide and (b) spring tide off Sikka, GoK during southwest monsoon period (M. T. Babu *et al.*, 2005).

and it varies between spring and ebb phases of the tide. Also the currents intensify during NE monsoon period as well as SW monsoon period when the winds become stronger. The transition period between NE and SW monsoons exhibit comparatively relaxed residual currents.

Residual currents

Knowledge of residual currents is important in understanding the net transport of pollutants or material discharged into the coastal environment. The residual velocity field (March 1994) computed from the model results shows the existence of three distinct eddies with diameter varying between 10 and 20 km in the western half of the gulf (Fig-4). It may be noted that the residual eddies are seen in the western gulf where irregular bathymetry with abrupt shoals such as Ranwara and Investigator reef are located (Fig-1). A maximum phase delay of 80° occurs when the M2 tide propagate over this area to cover a horizontal distance of about 140 km from the mouth to head. The study suggests that any ecological modelling system must include wind forcing as the net transport of pollutants and their residence time depend largely on the residual currents. Accurate estimation of residual currents and eddies in an active industrial coastal zone like the Gulf of Kachchh is important because of its practical applications related to discharge of pollutants.

Tidal circulation and eddies

In the eastern half of the Gulf, the circulation shows a net transport towards Kandla (along the northern rim of the Gulf) with a tendency to form a

clockwise circulation. On the contrary, in the western Gulf, the residual circulation presents anti-clockwise eddies of different sizes, except one clockwise eddy in the northern Gulf (off Mandvi). It is evident from that the net transport from the open ocean into the Gulf is through the southern side of the mouth, and the net outward transport is through the northern side, forming an anti-clockwise circulation in the western part (Fig-5). Tidal eddies shed by coastal features such as coral reefs and islands play a vital role in transporting materials. Incidentally a qualitative validation to the eastward flow along the northern rim of the eastern Gulf was obtained when a wave rider buoy deployed off Mundra got detached from the mooring and started drifting. After a period of one month it was located off Kandla (70°E). The path of wave rider buoy and the time taken to reach Kandla match very well with that of particle released off Mundra.

Thermohaline structure

Though GoK is considered as a well-mixed system, the study reveals that only the central Gulf is well mixed. Horizontal and vertical distributions of temperature–salinity fields obtained from various studies show vertical gradients in the eastern Gulf off Navlakhi and Kandla, where a cold and high saline tongue is seen advecting along the subsurface layers. These high-density waters in the sub-surface layers lead to stratification, which in turn produces a vertical current system driven by density gradients. Salinity variations in GoK indicates the characteristic feature of an inverse estuary with values (36.60 psu)

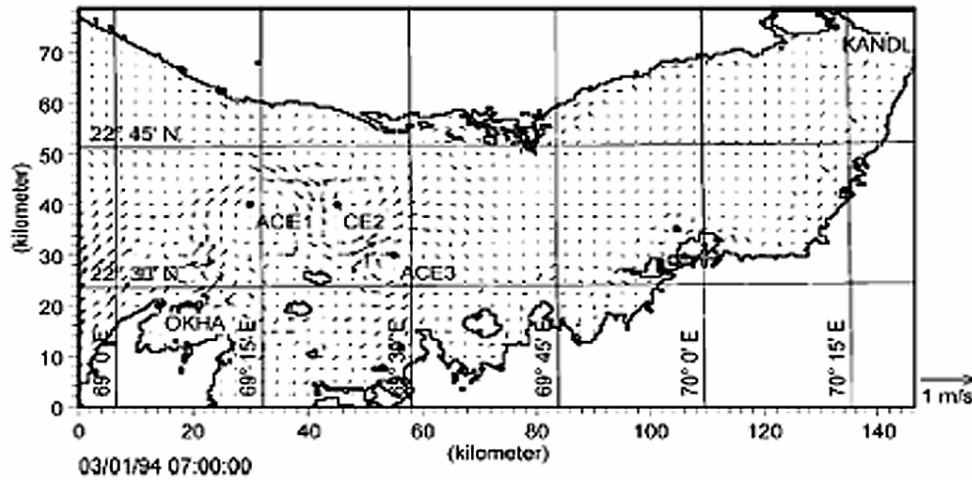


Fig. 4—Residual flow field in the Gulf of Kachchh based on modelled current components depicting the residual eddies in the western gulf (ACE1 and ACE3 are anti-cyclonic and CE2 is cyclonic) (M.T. Babu *et al.*, 2005).

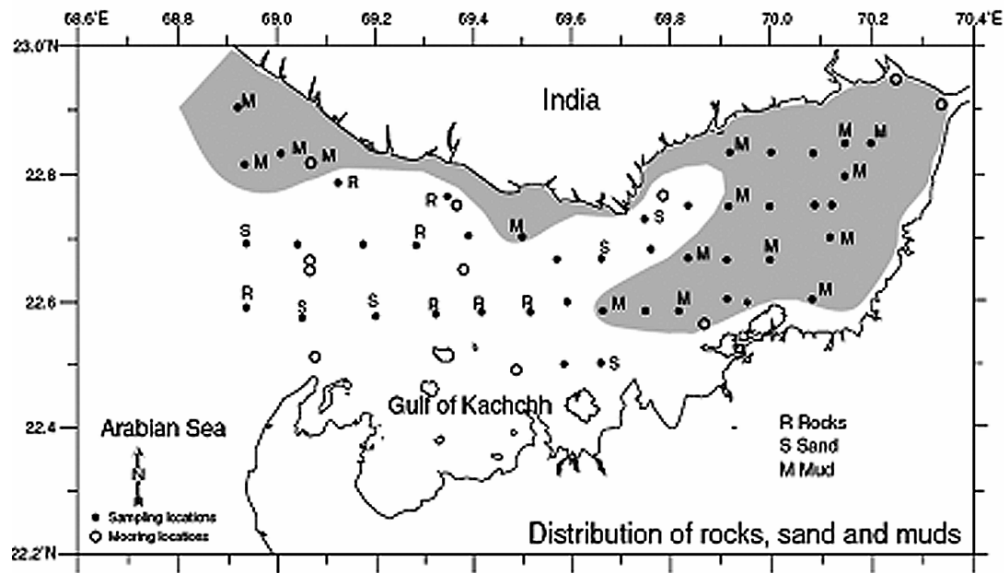


Fig. 5—Distribution of fine-grained sediments (silt and clay) within Gulf of Kachchh. (Ramaswamy *et al.*, 2007)

increasing from the mouth towards the upstream regions where high values >41.0 psu are noticeable. The model simulated temperature and salinity fields exhibit semidiurnal oscillations similar to that of field observations. Model results show cold, high saline waters advecting from the east during ebb forming a transition zone, which oscillates with tides. A high salinity tongue is seen in the bottom layer, indicating a westward flowing bottom current. This transient zone plays a vital role in the pollutant transport.

Sediment transport and dispersal

Since there are no major rivers discharging sediment directly into the Gulf, suspended matter

distribution can be related to sea floor sediment distribution, strength of tidal currents and bathymetry. Primary control on suspended sediment concentration (SSC) seems to be availability of fine grained sediments on the sea floor as high SSC are observed along the northern coast and head of the Gulf, where the sea floor has a mud cover (Fig-5). Kunte *et al.* (2003) have noticed higher SSC values near the head of the Gulf where tidal currents are maximum⁴. Higher SSC is also noticed near the shoals present within the Gulf. Presence of numerous shoals (eg. the Gupur, Ranwar shoals and Investigator Reef) near the mouth of the Gulf leads to increase in speed of tidal

currents due to constriction. Stronger currents and shallow bathymetry lead to higher SSC near shoals.

The geometry of the Gulf is such that the tide enters into it across the western boundary and propagates eastwards. As the Gulf width decreases in the mid-Gulf and coastal orientation changes abruptly thereafter the water flow direction changes and deflects towards north, forming a dynamic barrier across Sikka–Mundra section⁵. One branch of this northern flow contributes to the westward flow (outflow of the Gulf), and the other branch to the eastward flow, both along the northern rim of the Gulf. Result of dispersal of sediments at three locations in the centre of the Gulf is shown.

The clear water patch with low turbidity ($SSC < 10 \text{ mg l}^{-1}$) covers an area of about 1000 km^2 in the mid-Gulf. This is also observed in satellite imageries of this area as a persistent feature present throughout the year. The main reasons for low turbidity in this area are deeper depths, rocky headlands which obstruct tidal currents and distance from mud flats and fine sediment deposits. Current measurements near the head of the Gulf, off Bedi in the central Gulf and off Navlakhi in the eastern Gulf during pre-monsoon show that flood-currents are stronger than ebb-currents⁶. Strong flood currents result in piling up of sediments in the mud flats at the head of the Gulf. Although previous studies have shown that bulk of the suspended sediment near the head of the Gulf is delivered by numerous tidal creeks present within the tidal mud flats⁷ model studies show that the tidal currents should lead to net piling of sediments in the tidal mud flats.

Earlier studies have shown that sediments in the Gulf have been largely derived from the Indus River^{8,9,10}. The issue of how the Indus sediments have reached the Gulf has been ascribed to the eastward flowing summer monsoon currents transporting the Indus River discharge into the Gulf. It is now recognized that the damming of the Indus River has drastically reduced the sediment delivery to the Arabian Sea from over 400 million tons in the 19th century to less than 40 million tons¹¹. The present active delta is less than 100 km wide and examination of satellite images during the monsoons show only a small plume off the Indus river mouth.

Giosan *et al.*, have studied the anthropogenic changes to the Indus delta due to reduction of sediment supply of the Indus river¹². Until 1954, the shoreline off the Indus river has been stable or advancing. However, following the 80% reduction in

sediment discharge the deltaic shoreline along the central delta coast started to recede at average rates of $\sim 50 \text{ m year}^{-1}$. The abandoned delta shore towards the SE and NW portion of the Indus river mouth remained largely progradational. The SE portion of the delta has been prograding at an even greater rate than before with sediments derived from the eroded central portion of the delta. The process of sediment supply to the Gulf of Kachchh via tidal erosion of the abandoned delta is still active. Satellite images show that the Indus deltaic material, especially off the Kori creek is being re-suspended and transported to the Arabian Sea.

Tidal processes, especially settling lag effects help in import of fine grained sediments into high tidal areas¹³. The main source of sediments to the Gulf appears to be re-suspended material from the Kori and other creeks in the eastern part of the Indus delta. Sediment input to the Gulf is mainly from the northern side of the Gulf. These sediments are transported along the northern coast by the strong EW-currents. As mentioned previously, model studies indicate that the current pattern opposes transport of sediment towards the central and southern portion of the Gulf. This explains the lack of significant sediment cover in the central and southern Gulf. Chamyal *et al* have shown that the Greater Rann of Kachchh, the Little Rann of Kachchh and Gulf of Khambat were interconnected by a shallow sea and the entire area was inundated during 6000 to 2000 BP¹⁴. During this period, the inundated areas received sediments directly from the Indus and other rivers and sediments in the Rann of Kachchh are relict Indus deltaic sediments.

Acknowledgments

This review article is prepared from the papers referred in the text. We are thankful to the authors of those papers. This is NIO contribution No 4878.

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