

Why is mean sea level along the Indian coast higher in the Bay of Bengal than in the Arabian Sea?

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Abstract. Levelling observations conducted during the Great Trigonometrical Survey of India (1858–1909) and subsequent observations showed that mean sea level along the coast of India is higher in the Bay of Bengal than in the Arabian Sea, the difference in sea level between Vishakhapatnam and Mumbai (Bombay) being about 30 cm. Using simulations with a $1\frac{1}{2}$ -layer reduced-gravity model, we attribute this to the mean, large-scale wind-forced circulation ($\sim 60\%$) and the alongshore gradient in salinity ($\sim 40\%$). The former (latter) is a consequence of the distribution of wind stress (rainfall) because of the monsoon.

Introduction

The Indian subcontinent divides the north Indian Ocean into two semi-enclosed seas, the Arabian Sea and the Bay of Bengal, both of which encroach onto the equatorial regime of the basin (Figure 1). The Great Trigonometrical Survey of India was carried out during 1858–1909 to map the surface topography of the subcontinent, and was, in its time, the most detailed and accurate survey of its kind ever undertaken. While concluding the survey, Colonel S. G. Burrard, head of the Survey of India, made the following observation [quoted after *Ghildyal and Kumar*, 1984].

“Whilst therefore the levelling operations 1858–1909 have proved that the mean surface of the Arabian Sea and the Bay of Bengal are very nearly at the same elevation, they have also given rise to a suspicion, that the Bay of Bengal may be perhaps slightly higher of the two. It is but a suspicion, the accuracy of the levelling does not warrant us in pronouncing the divergence to be proved. It will be for our successors to show by means of future lines, whether the suspicion is well-founded, or whether the divergence is a result of levelling errors.”

A difference of about 30 cm was noticed between the mean sea level in the Bay of Bengal and that in the Arabian Sea, an observation confirmed subsequently during the “Adjustment of the First Level Net of India” [*Ghildyal and Kumar*, 1984]. The observations show that the mean sea level at Vishakhapatnam (see Figure 1) is 32 cm higher than that at Mumbai (Bombay), and that the mean sea level at Chennai (Madras)

is 17 cm higher than that at Mangalore. The permitted error in levelling over 1080 km, the distance along the levelling lines between Chennai and Mangalore, is 9.8 cm; thus, even after accounting for possible errors in levelling, the mean sea level along the east coast of India is higher than that along the west coast.

Ghildyal and Kumar [1984], in an internal report of the Survey of India, state that “enough levelling data have accumulated to carry forward the investigation from the stage where Colonel Burrard left it for us to complete. The divergence in mean sea level is apparent and this is not due to errors of levelling alone but other factors also.” They compute the difference in sea level for several choices of levelling lines before reaching this conclusion, and suggest, without any quantitative corroboration, that the difference in mean sea level between Chennai and Mangalore is because of “differ-

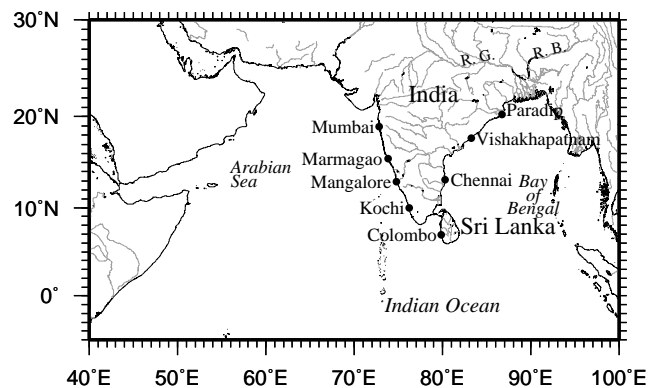


Figure 1. Location of tide-gauge stations. The abbreviations are as follows: R.G., River Ganga, and R.B., River Brahmaputra.

ences in surface salinity, surface temperature, and atmospheric pressure.” However, the differences in atmospheric pressure between the two Indian coasts is less than 1 mbar, accounting for a sea-level difference of less than 1 cm; therefore, the observed difference in sea level must have other causes.

The north Indian Ocean and the Indian subcontinent come under the influence of the monsoon. Monsoonal winds lead to a distinct annual cycle of near-surface circulation and sea level in the basin [McCreary *et al.*, 1993]. Precipitation and evaporation associated with the monsoon lead to a well-defined salinity difference between the Bay of Bengal and the Arabian Sea [Shetye and Gouveia, 1998]. The contributions of wind-forcing and thermohaline effects (owing to the difference in water masses) to the observed differences in mean sea level have not been quantified before. We use a $1\frac{1}{2}$ -layer reduced-gravity model to simulate the effect of these two processes and quantify the contribution of each.

Wind Forced Effect

The model is described in Shankar and Shetye [1997] and Shankar [1998]. Density is constant in the upper layer, which has an initial thickness of 100 m, and the model is forced by the wind-stress climatology of Hellerman and Rosenstein [1983]. The model simulates a mean gradient in sea level along the Indian coast (Figure 2), annual sea level at Vishakhapatnam (Chennai) being higher than that at Mumbai (Mangalore) by about 15 cm (11 cm). Sea level slopes down continuously along the coast from Paradip to Mumbai because the mean alongshore winds blow equatorward (poleward) along the west (east) coast of the subcontinent. Other processes, among them the curl of wind stress and remote forcing from the equatorial Indian Ocean, force an alongshore sea-level gradient in the opposite direction (higher sea level on the west coast), decreasing the gradient caused by the mean alongshore winds alone.

In the simulation described above, the model is forced by a climatology. Monsoon winds, however, are known for their interannual variability. To examine the effect of variability in winds, we increase the wind stress by 20% all over the basin, reflecting a 10% increase in the monsoon winds. The monsoon is a complex phenomenon and a stronger monsoon is unlikely to exhibit such a spatially uniform change in winds, but this experiment still gives an idea of its effect on coastal sea level. Increasing wind stress all over the basin raises sea level along the east coast, but lowers it along the west coast (Figure 2). The 10% increase in the strength of the winds increases the sea level difference between Vishakhapatnam and Mumbai (Chennai and Mangalore) by 13% (11%). Sea level see-saws along the coast of the subcontinent, with the southern tip of Sri Lanka

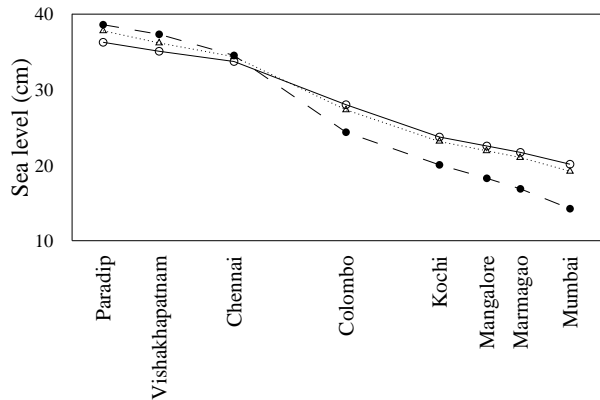


Figure 2. Three model simulations of annual mean sea level (centimeters) along the coast of India: the effect of purely wind-forced circulation (solid line, open circles), of both wind-forced circulation and salinity (dashed line, filled circles), and of increasing wind stress uniformly over the basin (dotted line, triangles). The difference between the dashed and solid lines is a measure of the influence of salinity on coastal sea level, the influence of temperature being negligible, and the difference between the dotted and solid lines is a measure of the effect of a 10% increase in the strength of monsoon winds.

as its pivot.

Thermohaline Effect

Variations in salinity along the Indian coast, due to differences in precipitation, evaporation, and river runoff [Shetye and Gouveia, 1998], have an effect on the seasonal cycle of sea level; hence, constant-density models are incapable of simulating the seasonal cycle of sea level along the Indian coast, though they simulate accurately the seasonal cycle of coastal currents [Shankar, 1998, 2000]. Subannual changes in sea level also are influenced by the variability of monsoon rainfall over India, with river runoff into the northern bay, coastal salinity, and coastal currents playing an intermediate role [Shankar, 1998; Shankar and Shetye, 1999].

We incorporate the effect of thermohaline forcing into the model by prescribing temperature and salinity from monthly climatologies [Levitus and Boyer, 1994; Levitus *et al.*, 1994]. The monthly values of temperature and salinity, averaged over the top 100 m, are interpolated to the model grid and timestep; hence, density in the upper layer now varies in space (horizontally) and time. There exists an alongshore gradient in the vertically-averaged salinity, which is much lower in the Bay of Bengal (Figure 3); variation in temperature is not significant along the coast, except in the northern Arabian Sea.

The alongshore gradient in salinity increases the dif-

ference in mean sea level between Vishakhapatnam (Chennai) and Mumbai (Mangalore) by about 8 cm (5 cm) (Figure 2). This difference increases to 10 cm (7 cm) if data from the Indian coastal region, which do not enter the climatologies of *Levitus and Boyer* [1994] and *Levitus et al.* [1994], are used to modify them [Shankar, 1998]; the salinities observed along the east coast of India [Shetye and Gouveia, 1998] are lower than those in *Levitus et al.* [1994].

The large influx of freshwater into the bay leads to a distinct vertical stratification that is marked by a salinity-induced increase in density over approximately 30–100 m. The strength of the halocline in the bay is among the strongest observed in the world oceans and often sustains temperature inversions when the surface is cooled [Shetye et al., 1996]. Such a stratification has two implications. First, it leads to thinner mixed layers there. Second, sea level fails to be a good proxy for thermocline displacement.

Discussion

The two causes of the observed difference in mean sea level between the east and west coasts of India, wind-forced coastal circulation ($\sim 60\%$) and the salinity gradient along the coast ($\sim 40\%$), are intimately connected to spatial and temporal asymmetries in the distribution of fields associated with the summer and winter monsoons. The wind fields are different in the two seas and along the two coasts of the subcontinent because the Arabian Sea is dominated by the Findlater Jet, which is the western boundary current of the low-level flow of the summer monsoon [Anderson, 1976]. A similar asymmetry exists between the two seasons, with the summer monsoon winds being stronger, leading to a mean alongshore wind stress and to higher sea level along the east coast. The asymmetry is also seen in precipitation, river runoff, and evaporation, the first and second being greater in the Bay of Bengal, and the third being greater in the Arabian Sea. The asymmetry in the atmosphere

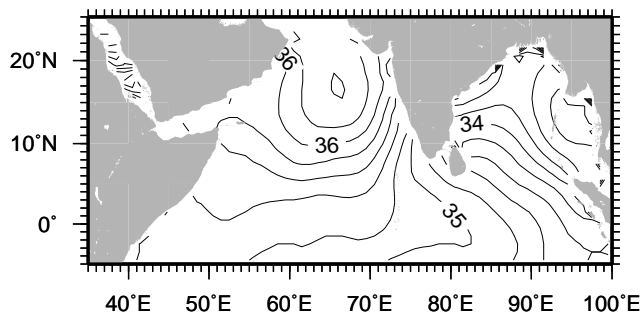


Figure 3. Annual mean salinity, averaged over the top 100 m, in the north Indian Ocean. Contour interval is 0.2 PSU.

is reflected in the underlying ocean, with mixed layers being thinner, and surface temperatures higher, in the bay. That spatial and temporal asymmetries associated with the monsoon determine the sea-level difference between the Bay-of-Bengal and Arabian-Sea coasts of India suggests that this difference could serve as an index of the impact of the monsoon on the ocean.

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