

A One Year Comparison of Radar and Pressure Tide Gauge at Goa, West Coast of India

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Abstract:

At many locations absolute pressure gauges are used to obtain sea level data. Therefore, knowledge of the other physical processes which effect the sea level measurements at the coast is very important to insert the required corrections. Data from the radar and an absolute pressure gauge are obtained over a period of one year from test site at Verem, Goa, India. The variance of difference between the radar and absolute pressure gauge is 15.9 cm², which reduces to 5.7 and 4.0 cm² respectively when measured atmospheric pressure and density variations are introduced for obtaining sea level from absolute pressure gauge. The regression analysis indicates that atmospheric pressure, water density and rainfall can account the difference individually upto 71%, 33% and 27% respectively. The aim of the study is to quantify the effects of atmospheric and oceanographic variables while measuring sea level using pressure gauges. The radar gauge has advantages over other type of gauges with regard to easy installation, maintenance and also sea level measurements are absolute and could be given precedence in future applications.

Keywords: Sea-level, Radar and Pressure gauges, Comparison, Variability

1. Introduction

Information about mean sea level and its variability is essential for wide variety of practical (e.g. engineering, navigation, risk to coastal areas, defense etc) and scientific applications. Considering the historically known vulnerability of the Indian coasts to storm surges (Joseph and Prabhudesai, 2005) and the recently felt threat of tsunamis, including the powerful December 2004 global tsunami (Titov *et al.*, 2005, Joseph *et al.*, 2006, Prabhudesai *et al.*, 2008) real-time reporting of sea-level, sea-state, and surface meteorological information has become all the more important for multi-hazard monitoring and warning purposes.

The classical and most reliable method of measuring the sea level is by tide staff, but it is also prone to manual errors. Subsequently, the float based tide gauges (Forrester, 1983) have been used extensively for long time. However, such systems require supporting structures, shelters and regular maintenance. The pressure gauge systems found widespread use to indirectly obtain the sea level by measuring the subsurface pressure, which required knowledge of atmospheric pressure (in case of absolute pressure sensor), seawater density and gravitational acceleration to make the conversion from pressure to sea level. In spite of the above lacuna, the instruments have many practical advantages as sea level recorders. The most commonly used types are pressure sensor gauges (differential/absolute) in which sensors are mounted directly in the sea. In late 1990s, radar devices, which were mainly used in process technology, were introduced into hydrometry. The Federal Institute of Hydrology (BfG) made the first investigation at the beginning of 2000 and since then different tests are being undertaken under both laboratory and field conditions (Woodworth and Smith, 2003; Miguez *et al.*, 2005; Blasi, 2009 etc).

In this paper, we present the results of the field test to evaluate and strengthen the suitability of radar gauges as an instrument for sea level measurements. The study is also to evaluate the effects of atmospheric pressure, water density and rainfall while estimating the sea level using absolute pressure sensors. In section-2, we briefly describe the theory of pressure and radar gauge systems; section-3 describes the means and data and section-4 describes the results of analysis.

2. Theory and Method

There are fundamentally four types of sea level measuring technology (IOC, 2006) in common use are (1) A stilling well and float (2) Pressure system (3) Acoustic system and

(4) Radar system. We will briefly describe the principle of operation of Pressure and Radar system in this section, as they are the focus of our present study:

2.1 Pressure System:

These systems measures sub-surface pressure (Fig.1a) instead of sea level according to the law:

$$h = \frac{(P - P_a)}{\rho \times g} \quad (1)$$

where, h= height of sea level above the pressure sensor, p = measured sub-surface pressure, p_a= atmospheric pressure, ρ= water density and g= gravitational acceleration.

The most commonly used types are the Pneumatic Bubbler Gauges (Pugh, 1972) and Pressure Sensor Gauges in which sensors are mounted directly in the sea. The pressure sensor in differential mode experience's (p - p_a), making the measured pressure directly proportional to the required sea level. However, the absolute transducer provides, total pressure including sea level and atmosphere pressure. Therefore, an additional barometer is required to monitor the atmospheric pressure, which is also a valuable parameter for oceanographic studies, and thus the two-transducer option is most frequently employed. All pressure transducers are sensitive to temperature and needs to have an in-built temperature sensor to compensate thermal drifts, else it is important to monitored sensor temperature, so as to incorporate corrections independently.

Apart from gravity, the knowledge of the water density 'ρ' is important in estuarine waters, where the density may change during a tidal cycle or seasonally. In such cases, the density corrections need to be incorporated during post processing. However, in the locations where the water is well mixed, it can be considered constant.

2.2 Radar Gauges

The radar sensor is positioned (Fig.1a) well above the highest expected sea level (also the highest expected wave to avoid damages to the unit) and measures the distance from this point to the air/sea interface. Radar gauges fall into two categories. (1) Measures changes in sea level by monitoring the time-of –flight of a radar pulse from the sensor to the sea surface and back to the unit. (2) The other type of radar gauge transmits 'Frequency Modulated Continuous Wave' (FMCW), which gets mixed with the reflected wave from the

sea surface and is used to determine the phase difference between the two waves to obtain the range. The radar gauge has many advantages over traditional systems (IOC, 2006), as it makes a direct measurement of sea level. The effects of density and temperature variations, even in the atmosphere, are unimportant.

3. Data description

Sea level and surface meteorological parameters are collected at Goa (Fig.1b). Weather data are collected by an automatic weather station (AWS), installed on the building of National Institute of Oceanography at a height of ~48 m w.r.t. mean sea level (sensor evaluation described by Mehra, *et al.*, 2005). Sea level is measured using a real-time reporting pressure (Honeywell, Inc.) and radar (OTT, Kalesto) tide gauge at Verem, near the mouth of the Mandovi estuary (Fig. 1 and Table 1). The distance between the tide-gauge and the weather station is ~5.1 Km. The observed parameters and the periods covered are shown in Table 1.

Table 1. Summary of the Observations from 24th September, 2007 to 30th April, 2009^c :

| Measured Variable | Station | System | Depth/ Height (m) |
|--|-------------------------|----------------|----------------------|
| Sea level, SST | " | Pressure Gauge | -1.0 |
| Sea level | Verem ^a | Radar Gauge | +4.0 |
| Water density | " | CTD | 0 to -3 |
| Air pressure, Air temperature and rainfall | Dona Paula ^b | AWS | + 48.1 |

^a The sea level and sea surface temperature (SST) data are collected from the Verem Jetty. For the pressure gauge (Radar gauge) the depth (height) is given with respect to the local chart datum.

^b The surface meteorological parameters are collected from the terrace of NIO building. The AWS height is given with respect to the mean sea level.

^c The local time is Indian Standard Time (IST), which is 05:30 hr ahead of GMT.

The surface meteorological parameters used in present study (Fig. 1a) such as barometric pressure and air temperature are sampled every 10 seconds and averaged for

10 minutes duration to generate data series every 10 min, which were then filtered using a convolution filter with a Hanning window of 24 points. The rain fall is measured using a tipping bucket sensor for every 10 minute recording interval. In the present, study the total rain fall for five days has been used.

Sea level is measured at Verem near the mouth of the Mandovi estuary (Fig. 1 and Table 1). The tide-gauge instruments were described in detail by Prabhudesai *et. al.*,2006. A pressure sensor based tide gauge has been in operation since October 2005 and a radar tide gauge was installed, in addition, in September 2007. The pressure gauge also provided the sensor's (Honeywell, Inc.) compensation temperature as an output and has been used as sea surface temperature (Mehra *et. al.*, 2008). The data is sampled at 2 Hz frequency for five minute duration (600 samples), averaged and then recorded in the data-logger every five minute. In the present study the data is sub sampled for 10 minutes to synchronize with the surface meteorological parameters.

The radar gauge (Fig.1a) is positioned ~4m above the chart datum, a Kalesto instrument which transmits FMCW pulse within a $\pm 5^\circ$ cone, with a range accuracy claimed by the manufacturer to be ± 1 cm over the measuring range of 1.5 m to 30 m. The distance between the radar and pressure gauge is ~50 m. The radar gauge records at 5 minute interval and samples are obtained 1 minute prior to the recoding interval over a 30 second window. Therefore, the measurements of radar gauge corresponding to the pressure gauge are in a narrow window of 30 second of the 4th minute of the recording duration of 5 minute. If there is no significant sea level variability within the 5 minute duration, then the two systems would report similar estimates. For our data comparisons, we have sub sampled the data every 10 minutes. The water density is obtained by using CTD (Seabird) at least twice in a month at the test site.

Fig.2a shows the unfiltered tide data from 24th September 2007 to 30th April 2009, reported by the two systems with a tidal range up to 250 cm with fortnightly variation. Almost all the gaps in the time series shown in Fig.2a are due to outages in the pressure gauge. The semidiurnal, spring and neep tides are clearly depicted in Fig.2b from September to December 2008. When the tidal signal was removed from the sea level records using the TASK [Bell et al., 1998] tidal analysis and prediction program to obtain the sea level residuals (SLR). Table 2 shows some of the main tidal constituents determined from the radar and pressure gauge form January 2008 to March 2009. The main diurnal, semidiurnal and fortnightly tides are almost identical (± 1 mm). However,

exception is the annual (Sa) and semi-annual (Ssa) for which the amplitude differ by 3.3 cm and 0.7 cm respectively. This could reflect to some extent the seasonal changes in density in the river and also due to the limited data series of ~ 1 year.

While comparing the measurements from radar and pressure gauge, apart from their systematic errors, the main systematic error for the pressure gauge comes from the assumption for the value of the product of the average density of sea water and the local acceleration due to gravity. Joseph *et.al.*, 2002, reported in a study at Marmugao Port, Goa from June 1995 to July 1998, that the surface water density varied between 1.020-0.996 gcm⁻³. During June-July the density dipped to 1.000±0.005 gcm⁻³ and increased to 1.020 gcm⁻³ by September and remained at this level till May. Then, it sharply decline to 1.000±0.005 gcm⁻³ by June. The effective density used at Verem, Goa is 1.020 gcm⁻³, g=980.665 cms⁻² and atmospheric pressure is obtained from AWS. However, this $\nabla\rho=(1.020-0.995)=0.025$ gcm⁻³ could lead to an under-estimation by 2.45% in sea level by the pressure gauge.

4 Results

4.1 Data comparison:

We now, turn to the analysis of the difference between the measurements from the radar and pressure gauge. The Radar gauge can be considered as reference gauge because it measures the true sea level and effects of density, atmospheric pressure and temperature (water/air) are unimportant. In this section, we aim to estimate the effect of the oceanographic and surface meteorological parameters over the measurements made using the absolute pressure gauges in an estuarine system. It will also strengthen our understanding about the performance of pressure sensors, as at many remote locations availability/measurement of other required variables may not be feasible. Fig. 3a shows the difference obtained as:

$$d_1 = S_{RG} - S_{PG} \quad (2)$$

where S_{RG} = Sea level (cm) measured by Radar gauge

S_{PG} =Sea level (cm) measure by Pressure gauge, assuming a mean

atmospheric pressure=1004.5 mb, $\rho=1.020$ gcm⁻³ and g=980.665 cms⁻².

The d_1 as shown in Fig.3a varies between -7 to 18 cm and shows a seasonal variability with minimum during January (~ -3 cm) and maximum during July ($\sim +10$ cm). This variation also stems out due to inverse dependence of d_1 over the atmospheric pressure (anomaly) as shown in Fig. 3b with a significant correlation coefficient 'r' of ~ -0.85 (Table 3). The atmospheric pressure shows seasonal variability with maximum during January 1006.7 (1007.5) mb for the year 2008 (2009) and the minimum during July (1001.09) mb 2008. The range being 6.5 mb. These changes would imply a sea level change of ~ 6.5 cm with opposite phase in pressure gauge.

The water density (Fig. 3c) is another parameter over which the sea level measurements by the pressure gauge inversely depends (equation-1). The water density is low during June-August (~ 1.000 gcm⁻³) and remains ~ 1.020 during other period having coefficient of correlation ~ -0.58 with d_1 . The water density is also affected by the rain fall as the measurement location is in an estuary. The total rainfall during five days is shown Fig. 3d, predominantly appears during south-west monsoon (June-September). The significant correlation coefficient between d_1 and rainfall is low ~ -0.53 , indicates a strong water density variation due rainfall.

However, the water density also depends upon the water temperature (SST, Fig. 3e) ($r=0.45$). Water temperature (SST) shows a more complicated seasonal variability with a period of higher values in April-May ~ 31.9 °C and a period of lower values in August ~ 27.1 °C 2008, with a range of ~ 4.8 °C (Fig. 5f). A second period of elevated temperature can be found in November. The air temperature shows a similar pattern to the water temperature (Fig. 3f) but with higher variability in December – February period.

The effect of atmosphere pressure and water density over the pressure gauge measurements is shown Fig. 4 and listed in table 4. The difference d_1 (Fig. 4a) as defined in equation-2, reflects the seasonal and monthly variations with a variance of ~ 15.9 cm². When the measured atmospheric pressure is used in the equation-1, the difference obtained d_2 (Fig. 4b) reduces the variance to 5.7 cm² with frequencies of semidiurnal and higher order, owing to the fact that the density at the site varies throughout the tidal cycle, with largest at high water (Prandle *et al.*, 1990). Fig 4c shows the difference d_3 , when along with atmospheric pressure, the measured density (Fig. 3c) is also applied in the equation-1, resulting in a variance of ~ 4.0 cm². The effect of rain is clearly evident as listed in Table 4. The variance of the d_2 during rainy period Sept-Dec 2007 & June-October 2008 days is 4.3 & 5.2 cm² respectively. However, this reduces drastically to 0.7 & 0.1 during non-rainy

periods such as Jan-May 2008 & Nov-April 2009 respectively. However, there is a marginal reduction in variance of d_2 even after using the measure density during rainy periods 4.0 & 3.8 cm^2 . This may be due to the low sampling rate of water density measurements which is also affected by the tidal cycle in the study area.

4.2 Multiple regression analysis:

Linear multiple regression models could be used to improve the sea level measurements from the pressure gauge in the absence of measured water density by using the other surface meteorological parameters as:

$$\begin{aligned} d_1 &= d_e + \varepsilon \\ d_e &= B_0 + B_1AP + B_2AT + B_3RF + B_4SST\dots \end{aligned} \quad (3)$$

where d_1 is as per equation-2, d_e is the estimated difference using independent variables such as atmospheric pressure (AP), air temperature (AT), Rain fall (RF), water temperature (SST) etc and ε is the difference due to systematic errors and other effects which cannot be explained by these parameters. How well the model describes the dependant parameter d_1 is assessed by looking at the percentage of variance explained by the model. The independent parameters were added one at a time. Only where, an independent parameter increased the variance explained 'var_e', significantly, it was retained in the model.

$$\text{var}_e = \left(1 - \frac{\text{variance}(d_1) - \text{variance}(d_e)}{\text{variance}(d_1)}\right) \times 100, \quad (4)$$

The regression was performed over the whole period with d_1 as dependent parameter and Table 5 shows that 'AP' and water density 'DN' accounted upto 71% and 33% of variability as these variables are directly involved in the estimation of sea level using pressure gauges (equation-1). The rainfall could account upto 27.6% in d_1 when used as an independent parameter. The other variables such as SST, AT or difference of SST-AT has negligible effect. All the above variables, if used in equation-3 are able to explain the variance up to 80 %.

In most of our measurements, we deploy AWS along with the tide gauge and hence atmospheric pressure is available in the near vicinity of the tide gauge. Therefore, it would be worth using rainfall data for improving the measurements of the pressure gauge corrected for atmospheric variation, then in such a case the difference would be d_2 . Fig. 5 shows d_2 (black) and d_2-d_e (red) where the d_e is estimated using d_2 as dependent parameter and rainfall as independent variable (with coefficient of regression as $b_0=0.053 \text{ cm}$, and

$b_1=0.022$ cm/mm. The variance of d_2 is ~ 5.7 cm² and there is marginal improvement in the variance (~ 4.86) of d_2-d_e .

Conclusions

This report has described a comparison of radar and pressure gauge along with the surface meteorological parameters at Goa, West Coast of India. The influence of environmental variables over the measurements from the pressure gauge have been evaluated. From the available data, we conclude that both the systems function well most of the time and produces similar tidal constituents. However, during rainy period the pressure gauge may under-estimated the measurement due to density variations.

It is worth mentioning that the present site developed, measures the sea level in a completely different way than the traditional float or bubbler gauges. The system does not need expensive buildings on site, such as stilling well and intake pipes. All is done, using a simple supporting structure to mount the sensors, powered by solar energy and communicating data (using cellular modems) automatically at base server in NIO. However, these features could present some drawback, if the sites are exposed to harsh environment and lacks security. Therefore, they may not be suitable at all locations, however with proper prior survey; we have been able to operate the network of such stations (see <http://inet.nio.org/>) successfully.

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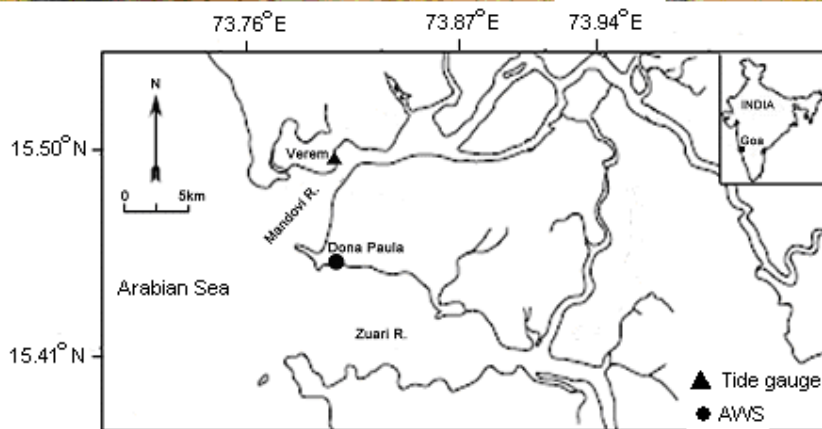


Figure 1. [a] Sea-level (Pressure and Radar) gauges at Verem, Goa. [b] Map of the study region of Goa, the West Coast of India.

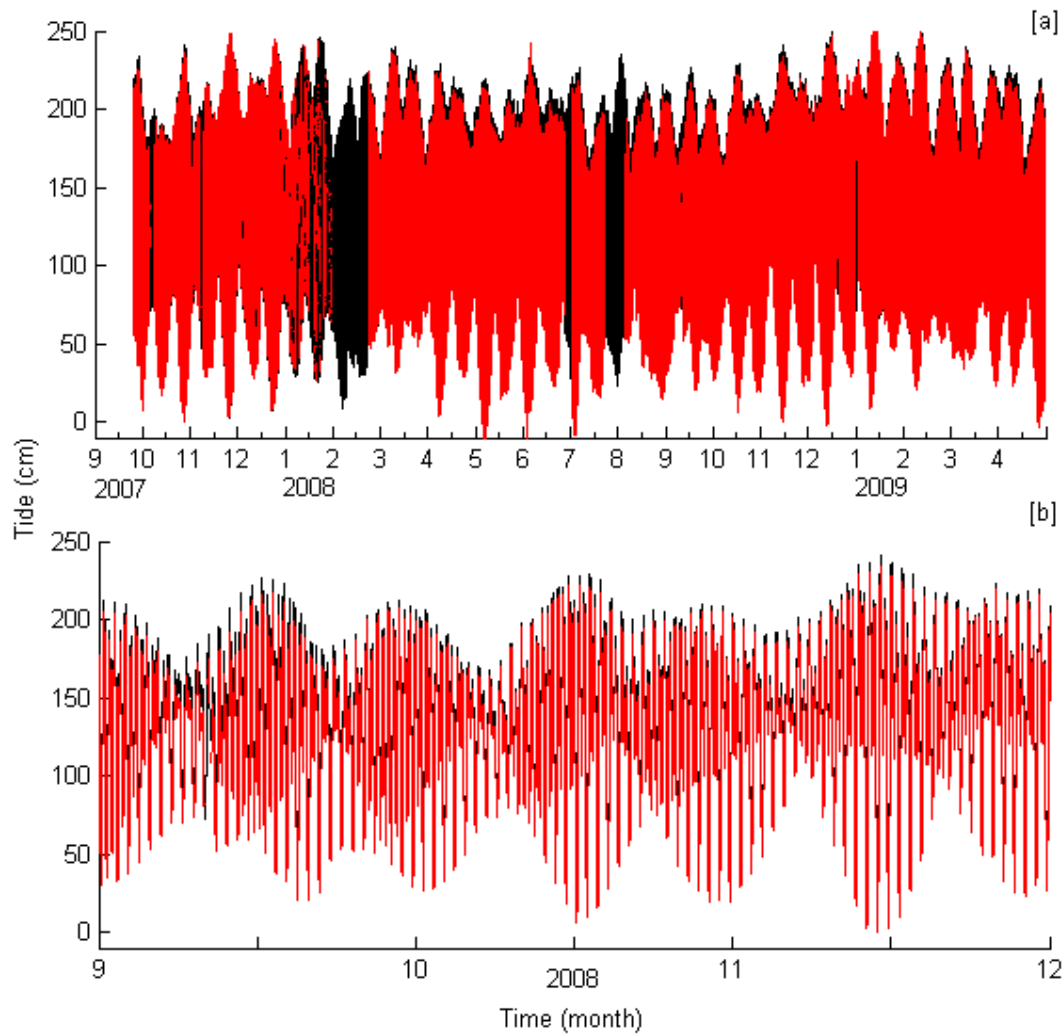


Figure 2. The tides in Goa, the West Coast of India. [a] Time series of tidal data from Radar (black) and Pressure (red) gauges from 24th September, 2007 to 30th April, 2009. [b] Tidal data from September to December 2008, showing the semi-diurnal nature along with spring and neap tides.

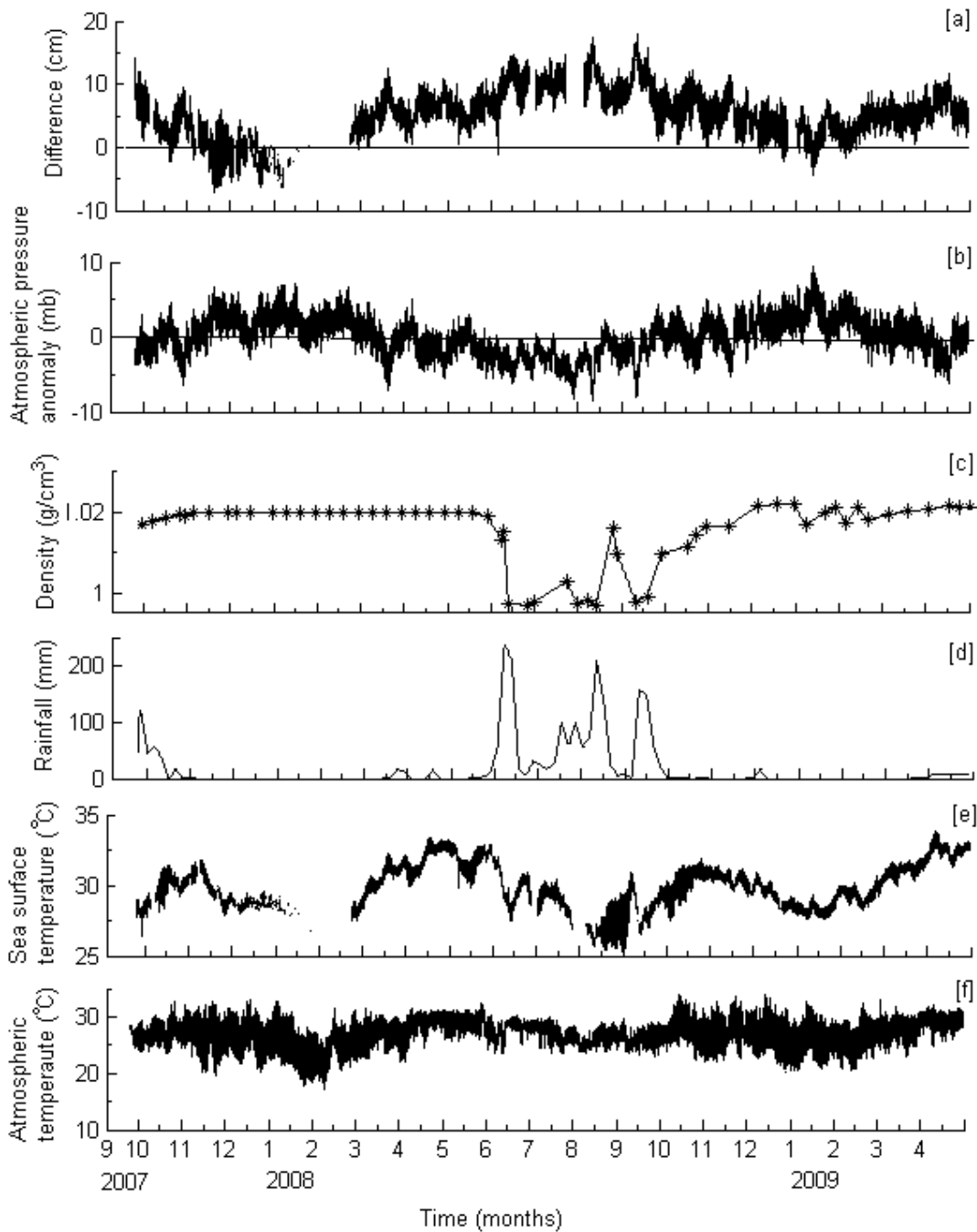


Figure 3. Time-series measurements from September 2007 to April 2009 at Verem, Goa, India. [a] difference [b] atmospheric pressure anomaly [c] Water density [d] Total rain fall for five days [e] Water temperature and [f] Atmospheric temperature.

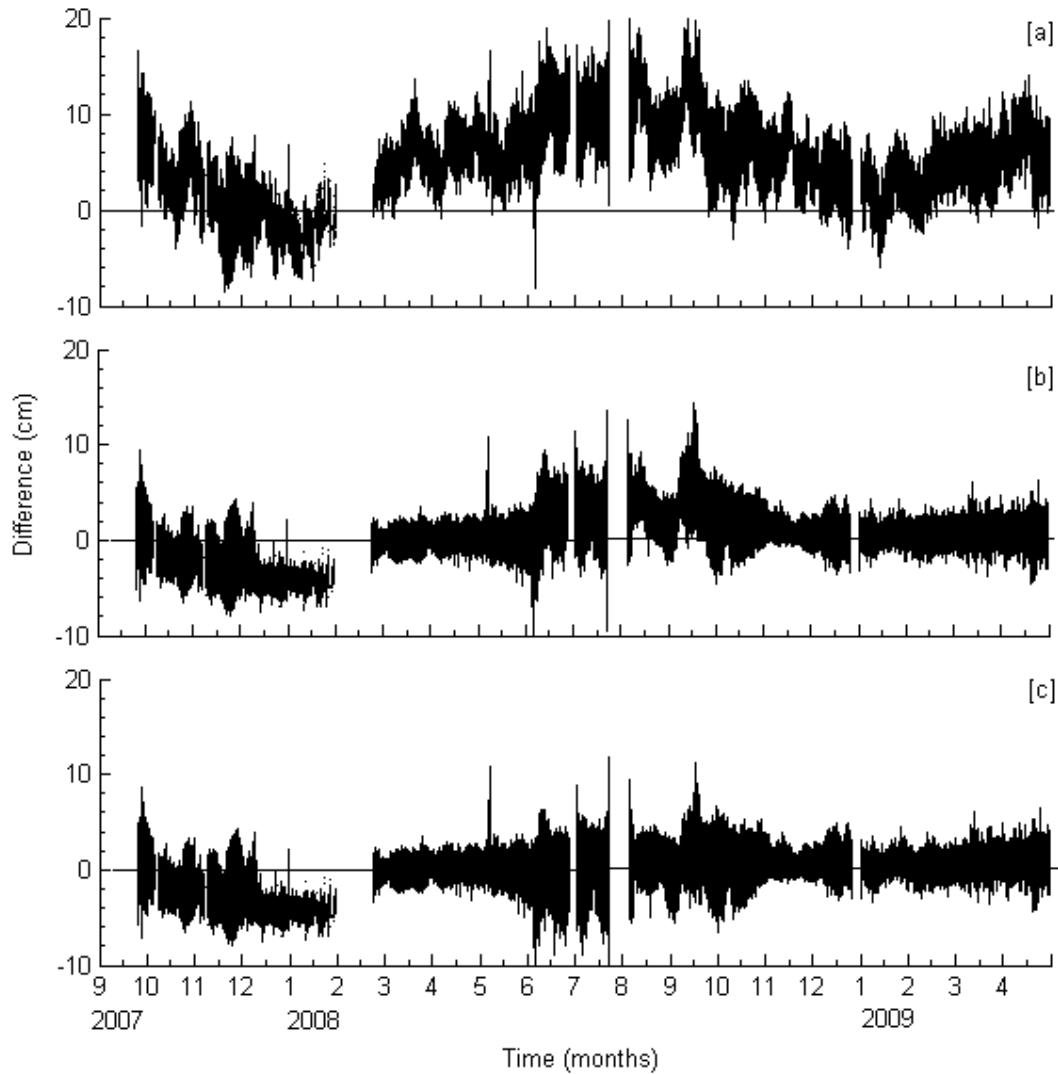


Figure 4. Difference between radar and pressure gauge as per equation-2. [a] Difference d_1 with mean barometric pressure and density $\rho=1.020 \text{ gcm}^{-3}$ used in equation-1. [b] Difference d_2 with measure barometric pressure and density $\rho=1.020 \text{ gcm}^{-3}$ used in equation-1. [c] Difference d_3 with measure barometric pressure and density used in equation-1.

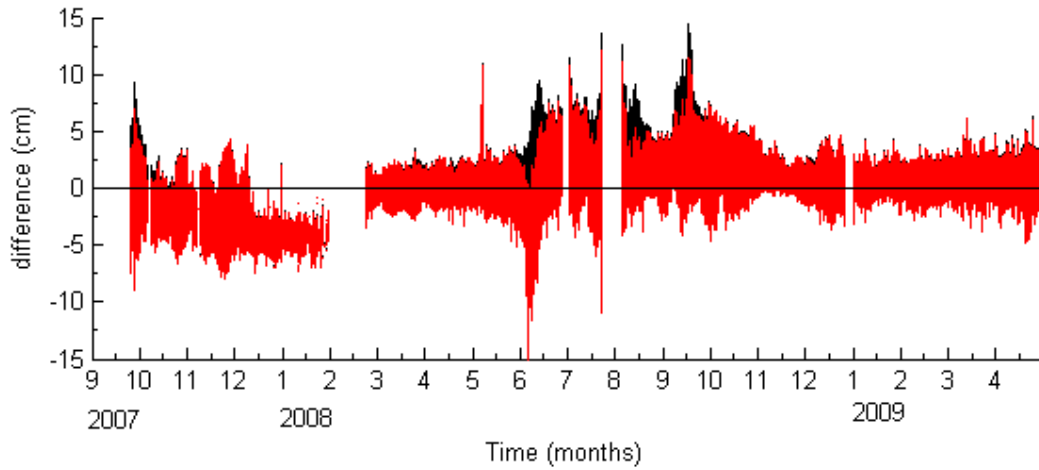


Figure 5. Shows d_2 (black) and d_2-d_e (red) where the d_e is estimated using d_2 as dependent parameter and rainfall as independent variable.

| Tide | Radar | | Pressure gauge | |
|------|--------|---------|----------------|---------|
| | H (cm) | G (deg) | H (cm) | G (deg) |
| SA | 5.1 | 290.4 | 8.4 | 303.6 |
| SSA | 1.3 | 121.8 | 0.6 | 185.9 |
| MSF | 0.8 | 287.4 | 0.9 | 286.5 |
| MF | 1.2 | 40.4 | 1.1 | 36.5 |
| O1 | 14.8 | 53.4 | 14.8 | 53.4 |
| M1 | 1.0 | 74.9 | 1.0 | 76.6 |
| K1 | 29.7 | 55.5 | 29.8 | 56.0 |
| M2 | 51.5 | 314.1 | 51.6 | 314.7 |
| S2 | 17.9 | 352.1 | 17.9 | 352.8 |

Table 2. Tidal constituents (amplitude H and Phase lag G) determined during January 2008 to February 2009 from Radar and Pressure gauge.

r: Correlation Coefficient between various parameters at 95% confidence interval for the entire data.

| | | | | | | |
|--------------------------------|------|--------------|--------------|--------------|-------------|-------------|
| | Diff | AP | DN | RF | SST | AT |
| Diff | 1.00 | -0.85 | -0.58 | 0.53 | -0.02 | 0.10 |
| AP | | 1.00 | 0.45 | -0.47 | -0.16 | -0.21 |
| DN | | | 1.00 | -0.57 | 0.45 | 0.04 |
| RF | | | | 1.00 | -0.37 | -0.09 |
| SST | | | | | 1.00 | 0.47 |
| AT | | | | | | 1.00 |
| p: significance of correlation | | | | | | |
| Diff | 1 | 0 | 0 | 0 | 0 | 0 |
| AP | | 1 | 0 | 0 | 0 | 0 |
| DN | | | 1 | 0 | 0 | 0 |
| RF | | | | 1 | 0 | 0 |
| SST | | | | | 1 | 0 |
| AT | | | | | | 1 |

Table 3. The correlation coefficients 'r' between the various parameters 95% confidence interval. If P(I,j) is small, say less than 0.05, then the correlation R(i,j) is significant. Note: Diff- Difference; AP- Atmospheric pressure; DN- Water density; RF- Rain fall; SST- Sea surface temperature and AT- Air temperature.

| Sr. No. | Duration (days) | Variance of difference (Radar gauge-Pressure gauge) in cm ² . | | |
|---------|-----------------|--|----------------|----------------|
| | | d ₁ | d ₂ | d ₃ |
| 1 | Sept-Dec 07 | 13.27 | 4.38 | 4.02 |
| 2 | Jan-May 08 | 5.19 | 0.71 | 0.71 |
| 3 | June-Oct 08 | 10.68 | 5.25 | 3.85 |
| 4 | Nov-April 09 | 6.71 | 0.98 | 1.0 |

Table 4. Seasonal variability of the difference between radar and pressure gauge.

| Sr. No. | Variable | var _e (%) |
|---------|---------------------|----------------------|
| 1 | AP | 71.4 |
| 2 | DN | 33.5 |
| 3 | RF | 27.6 |
| 4 | SST | 0.09 |
| 5 | AT | 1.0 |
| 6 | Tdiff | 1.68 |
| 7 | All above variables | 80.7 |

Table 5. Percentage variability explained by various variables for difference d₁.

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