

1 **Forecasting transboundary river water elevations from space**

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15 Abstract

16 Over 90% of Bangladesh's surface water is generated upstream of its border, yet no real-time
17 information is shared by India (the upstream country) with respect to two major
18 transboundary rivers, the Ganges and Brahmaputra. This constraint limits operational
19 forecasts of river states inside Bangladesh to lead times of no more than three days.
20 Topex/Poseidon satellite altimetry measurements of water levels in India, combined with in-
21 situ measurements inside Bangladesh allow extension of this lead time. We show that for both
22 rivers, it is practically feasible to forecast water elevation anomalies during the critical
23 monsoon season (June to September) near the Bangladesh border with an RMSE of about
24 0.40 m for lead times up to 5-days. Longer 10-day forecasts have higher errors (RMSE
25 between 0.60 m and 0.80 m) but still provide useful information for operational applications.
26 These results demonstrate the tremendous potential of satellite altimetry for transboundary
27 river management.

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29 1. Introduction

30 Two hundred and fifty-six major river basins, covering 45% of the global land area exclusive
31 of Antarctica and Greenland, are split between two or more countries [Wolf *et al.*, 1999]. The
32 absence of information sharing among some riparian nations has led to numerous tensions in
33 the past [Balthrop and Hossain, 2010]. A classic case of uncoordinated management of
34 transboundary flooding occurs in the Ganges-Brahmaputra River basins. More than 90% of
35 surface water flowing through Bangladesh comes from the countries upstream - mostly India
36 [Nishat and Rahman, 2009]. Hydrological measurements on the Ganges and Brahmaputra
37 Rivers are viewed as sensitive by India, and no treaty provides for sharing of such data
38 between the two nations at operational time scales [Balthrop and Hossain, 2010]. For this

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39 reason, water elevation (WE) forecasts in the interior and southern parts of Bangladesh are
40 limited to lead times of two to three days [*Ahmad and Ahmed*, 2003]. Increasing this lead time
41 would be very valuable both for disaster preparedness and agricultural water management.

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43 Previous studies have shown that combination of rainfall satellite measurements and
44 modeling can successfully forecast streamflow in Bangladesh [*Nishat and Rahman*, 2009;
45 *Hopson and Webster*, 2010; *Webster et al.*, 2010]. In particular, *Hopson and Webster* [2010]
46 and *Webster et al.* [2010] developed a daily 1-15-day flood forecasting system for
47 Bangladesh, based on statistically adjusted (with satellite observations) quantitative
48 precipitation forecasts from the European Centre for Medium-Range Weather Forecasts
49 (ECMWF). This system has successfully forecasted floods since 2004, with an accuracy of ± 1
50 day in flood onset and retreat [*Webster et al.*, 2010]. However, *Hopson and Webster* [2010]
51 highlight that “if river flow measurements higher up in the catchment were available and
52 could be routed downriver to the forecast location, errors in rainfall-runoff modeling ... could
53 be reduced”. Satellite altimetry observations have the potential to provide such information.
54 *Birkinshaw et al.* [2010] have used both in-situ and altimetry WE time series on the Mekong
55 basin, combined with hydrologic modeling to forecast discharge downstream. However, in
56 their approach satellite altimetry is one of several data sources, and the impact of the lead time
57 in the context of water management was not investigated. Here we show the potential for
58 satellite altimetry to extend forecast lead time in a case where it is the only source of upstream
59 river stage data.

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61 2. The Brahmaputra and Ganges Rivers

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62 The locations of the Ganges and Brahmaputra rivers and the political boundaries of the
63 riparian countries are shown in Figure 1. The drainage area of the Ganges basin is about
64 1,065,000 km². It is shared among China, India, Nepal and Bangladesh. The Brahmaputra has
65 a drainage area of about 574,000 km² and is shared among China, India, Bhutan and
66 Bangladesh [*Nishat and Rahman, 2009*].

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68 The upstream-most in-situ gauges in Bangladesh used in this study are located at Hardinge
69 Bridge on the Ganges and at Bahadurabad on the Brahmaputra (Figure 1). WE (referenced to
70 the Public Work Department, PWD datum of Bangladesh Government) have been collected
71 by the Bangladesh Water Development Board (BWDB) and Institute of Water Modeling
72 (IWM, Bangladesh). They are daily (some days missing) and are available from
73 January 2000 to September 2005. Figure 2 shows in-situ WE time series measured at the
74 Bahadurabad (Figure 2.a) and Hardinge Bridge (Figure 2.b) gauges for all years available in
75 the period of record. The Brahmaputra can be considered unregulated with no major hydraulic
76 structures, whereas the Ganges is highly regulated with at least 34 dams and diversion points
77 in India and Nepal [*Hopson and Webster, 2010*]. The hydraulic structures are intended
78 primarily for use during the dry season and do not act as a control structure to regulate flow
79 during the monsoon season [*Jian et al., 2009*]. At Bahadurabad and at Hardinge Bridge, the
80 mean annual (monsoon season) discharges are around 16,800 m³.s⁻¹ (39,400 m³.s⁻¹) and 7,100
81 m³.s⁻¹ (24,300 m³.s⁻¹), respectively. The transboundary region of Meghna is relatively smaller
82 than Ganges and Brahmaputra to have a significant impact on forecasting of WE inside
83 Bangladesh and has not been considered in this study.

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85 3. Methodology

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86 We used estimates of WE in India derived from the Topex/Poseidon (T/P) satellite nadir
 87 altimeter to forecast WE at Bahadurabad and Hardinge Bridge. T/P WE were computed by the
 88 Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) and were
 89 downloaded from the HydroWeb data base (<http://www.legos.obs->
 90 [mip.fr/en/soa/hydrologie/hydroweb/](http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/)). T/P was a joint National Aeronautics and Space
 91 Administration (NASA) and Centre National d'Etudes Spatiales (CNES) satellite mission
 92 launched in August 1992, with a 10-day repeat period. In September 2002, the T/P orbit was
 93 changed due to the launch of a new satellite altimeter (JASON-1), which defines the T/P
 94 HydroWeb period of record from 1993 to mid-2002. Nadir altimeters like T/P measure WE
 95 only in a vertical plane, i.e. along the satellite's ground track (shown in Figure 1); therefore,
 96 relatively few locations on each river are observed. The locations (referred as "virtual
 97 stations") of the T/P measurements on the Ganges and the Brahmaputra in India are shown in
 98 Figure 1. The overlapping time period of T/P with in-situ WE measurements is January 2001
 99 to August 2002 at Hardinge Bridge and January 2000 to August 2002 at Bahadurabad. Table
 100 1 shows the distance between each T/P virtual station (VS) used in this study and the in-situ
 101 gauge on the river, along with the number of observations available in the T/P time series, the
 102 mean time between two consecutive observations, and the river drainage area at the VS.
 103 These four VS were selected to span a range of distances from the in-situ gauges and to have
 104 a maximum number of observations. Temporal gaps in T/P time series arise from instrument
 105 errors, inaccurate atmospheric corrections, and errors due to the retracking of the data and
 106 interaction with the surrounding land.

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108 Correlations between the in-situ WE anomalies (h_{insitu}) measured at the gauge locations and
 109 the upstream T/P WE anomalies in India (h_{alti}) k days earlier were computed as follows:

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$$110 \quad Corr_h(k) = \frac{cov[h_{insitu}(t), h_{alti}(t+k)]}{stdev[h_{insitu}(t)] \cdot stdev[h_{alti}(t+k)]} \quad (1)$$

111 where k is the lead time, t corresponds to the date for which $h_{alti}(t+k)$ is available (for the few
 112 days when $h_{insitu}(t)$ is missing, it was linearly interpolated from the closest measurement in
 113 time), cov is the covariance, stdev is the standard deviation and $Corr_h$ is the correlation
 114 coefficient between the two time series. The lead time k was allowed to vary from 0 to 40
 115 days. For each of these lead times, a linear fit was computed to relate the water surface
 116 elevation at the in-situ gauge and the water level at the VS k days earlier.

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118 4. Forecasting Brahmaputra River WE anomalies

119 On the Brahmaputra River, correlations between in-situ and upstream T/P WE anomalies are
 120 quite high (> 0.9) for lead time up to 25 days over the entire time period; however, this is
 121 somewhat misleading as much of the correlation is due to the high and almost concurrent
 122 seasonality of WE. For this reason, we computed correlations, for various lead times, only
 123 over the monsoon period (June to September) when floods occur. For this period, all
 124 correlations for lead times below 10 days are highly significant ($p < 0.05$). As expected, the
 125 highest correlations are for VS n°166_1, which is the closest to Bahadurabad. In-situ and
 126 upstream T/P WE anomalies remain significantly correlated (above 0.9 for VS n°166_1 and
 127 0.8 for VS n°242_1 during the monsoon period) for a lead time around 5 days. Correlations
 128 for lead times less than 10 days, correlations remain above 0.8 for VS n°166_1, but decrease
 129 substantially for lead times greater than 5 days.

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131 For each VS and for lead times less than 5 days, the RMSE between the T/P forecasts and the
 132 in-situ measurements for the monsoon period is lower than or near 0.40 m with a minimum

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133 around 3 days (which corresponds to the maximum correlation). At lead times greater than 5
134 days, RMSE increases significantly and tends to stabilize for lead times above 10 days at
135 around or slightly above 0.50 m for VS n°166_1 and 0.70 m for VS n°242_1.

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137 Figures 3.a and 3.b show the in-situ (blue curve) and forecasted WE anomalies at the gauge
138 location from T/P VS n°166_1 (red triangles) for a 5-day and a 10-day lead time, respectively.
139 These results are very encouraging as the forecast is quite close to the observation. On the
140 other hand, it should be noted that some local maxima (like the one in August 2000) are
141 slightly underestimated in the forecasted time series. This might be due to satellite
142 measurement errors, errors in the T/P-in situ WE regression and the fact that the methodology
143 used does not explicitly account for inflows between the location of the virtual and real
144 gauges.

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146 5. Forecasting Ganges River WE anomalies

147 During the monsoon, the correlation for VS n°014_1 (located 530 km upstream of the gauge,
148 Table 1) is maximum for lead time around 5 days and then decreases (it is below 0.9 for lead
149 times above 10 days). As VS n°116_2 is farther upstream from the gauge (1560 km, Table 1),
150 the correlation is lower (still above 0.9 for lead times between 8 and 13 days) and is highest
151 for a 10-day lead time. For lead times greater than 14 days, the correlation decreases and is
152 similar to that for VS n°014_1. The different timing in the occurrence of the maximum
153 correlation between the two VS is due to the large distance (above 1000 km) between them.
154 As for the Brahmaputra River, RMSE during the monsoon period between in-situ and forecast
155 WE anomalies from T/P data has a minimum around the same lead time that maximizes the
156 correlation. For VS n°014_1 the RMSE is minimum at around 0.40 m for a 5-day lead time

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157 and remains between 0.40 m and 0.60 m for lead times below 10 days, beyond which, RMSE
158 increases significantly. For VS n°116_2, the RMSE is higher, and its minimum value is
159 around 0.90 m for a 14-day lead time. This was expected due to the greater distance to the
160 gauge.

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162 Figures 3.c and 3.d show the in-situ and forecasted WE anomalies at the gauge location from
163 T/P VS n°014_1 for a 5-day and a 10-day lead time, respectively. As for the Brahmaputra
164 River, the forecasts remain very close to the in-situ measurements.

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166 6. Discussion

167 Our results clearly show that T/P forecasts follow well the rising and receding trends in
168 observed water surface elevation with modest bias. The persistence of high correlations
169 between upstream and downstream WE anomalies for a range of practically useful lead times
170 and the relatively low RMSE, compared to the differences in WE between low and high flows
171 (around 6 m at Bahadurabad and 8 m at Hardinge Bridge, Figure 2), are encouraging. We
172 believe that the relatively high forecast skill is due to the fact that even though the VS are far
173 upstream (see Table 1), most of the runoff that reaches Bangladesh is generated far upstream,
174 and the relationship between upstream and downstream water levels is affected primarily by
175 channel processes. The Brahmaputra drainage area is around 506,000 km² at Bahadurabad and
176 345,000 km² at the 550 km upstream T/P VS n°242_1 (Table 1). On the Ganges, the drainage
177 area is 944,000 km² at Hardinge Bridge and 756,900 km² at T/P VS n°014_1 530 km
178 upstream (Table 1). Therefore, WE are less sensitive to local and short-term precipitation
179 events and remain correlated over long distances. Combined with the higher impact of human
180 activity, this could also explain higher RMSE on the Ganges: as its mean annual discharge is

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181 two times lower than that of the Brahmaputra, it is more affected by high frequency
182 variations. For each VS, the ratio between the distance to the in-situ gage and the lead time
183 which gives the maximum correlation is around 1 m.s^{-1} , the same order as the rivers' velocity
184 [Jian *et al.*, 2009]. Because T/P data are not available after 2006, data from the new nadir
185 altimeter Jason-2, launched in 2008 on the same orbit than T/P, would need to be used for real
186 time forecast observations. The time latency of Jason-2 Interim Geophysical Data Record is
187 around 2 days and the retracking of this product can be done immediately, which means that
188 near real time forecast is feasible.

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190 The current good quality of the forecast might even be improved using ancillary satellite data,
191 such as precipitation or river width estimates. In addition, more accurate satellite-based WE
192 measurements would help to better detect peaks in WE. This could be done by retracking
193 altimeter measurements as suggested by Lee *et al.*, [2009]. Moreover, the low time resolution
194 in the T/P time series could be addressed by combining forecasts from different VS and using
195 multiple satellite altimeters. Errors on these multi-source forecasts will vary in time
196 depending on the altimeter and the VS used.

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198 The future Surface Water and Ocean Topography (SWOT) wide swath altimeter (a
199 NASA/CNES mission, planned for 2019), will provide much improved forecast coverage (in
200 both geographic extent, and the size of rivers for which coverage will be provided) and
201 accuracy. SWOT will provide 2-D maps of WE along a 120 km wide swath with a 100 m
202 horizontal resolution and a 10 cm minimum vertical accuracy (usually better) [Rodríguez,
203 2009], providing 2 to 4 observations on the study domain per repeat period (22 days),
204 allowing a much more precise forecast of flooding or low flow events.

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206 Furthermore, the approach presented in this paper can augment alternative approaches, like
207 that of *Webster et al.* [2010], that seek to improve forecast lead times by incorporating long
208 lead probabilistic precipitation forecast information into streamflow forecasts. We also
209 foresee a future pathway by which altimetric information from planned satellites like SWOT
210 can be incorporated into hydrodynamic models.

211

212 7. Conclusions

213 For both the Ganges and Brahmaputra rivers, it is possible to forecast WE anomalies during
214 the monsoon season from upstream nadir altimeter measurements of WE anomalies with a
215 lead time at least 5 days longer than is currently feasible, with RMSE around 0.40 m. 10-day
216 forecasts during the monsoon season are also feasible, although with RMSE between 0.60 m
217 and 0.80 m, depending on the river and the VS used. Our results demonstrate that satellite
218 altimeter data have a huge potential to improve forecasting of WE anomalies at the
219 Bangladesh borders and, therefore, could provide valuable information for flood forecast
220 systems needed for downstream nations in large transboundary river basins more generally.
221 Combining satellite altimetry measurements with weather, hydrological, and hydrodynamic
222 forecast methods offers the potential to further extend forecast lead times. The use of multiple
223 altimeter measurements, along with ancillary satellite observations can help to constrain
224 forecast errors. We also emphasize the limitations of current generation satellite altimeters,
225 which were primarily designed for oceanographic applications and are limited by their
226 relatively infrequent repeat periods (10 days for Topex/Poseidon) and relatively inaccurate
227 measurements of river heights. The proposed wide swath SWOT mission is expected to

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228 improve greatly both forecast accuracy and time sampling of rivers and may well represent a
229 major breakthrough in the ability of downstream countries to manage riverine hazards.

230

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242

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274 Figure Legends

275

276 Figure 1. Map of the study domain. Ganges basin (red hatched area) and Brahmaputra basin
277 (magenta hatched area) boundaries come from HYDRO1k. Locations of measurements from
278 the satellite nadir altimeter Topex/Poseidon on the Ganges and the Brahmaputra rivers
279 (available on HydroWeb) are represented, respectively, by red and purple dots (yellow lines
280 correspond to the satellite ground tracks). Green dots correspond to the furthest upstream in-
281 situ gauges in Bangladesh. The background topography used in this map is the ETOPO1
282 topography dataset. Lakes, rivers and political boundaries come from the CIA World Data
283 Bank II.

284

285 Figure 2. In-situ water elevation time series measured on the Brahmaputra at Bahadurabad (a)
286 and on the Ganges at Hardinge Bridge (b).

287

288 Figure 3. (a) Measured water elevation anomaly time series at Bahadurabad (blue) and the
289 T/P virtual station n°166_1 forecasted water elevation anomalies at the gauge location for a 5-
290 day lead time (red triangles). (b) Similar plot for 10-day lead time T/P virtual station n°166_1
291 forecasted water elevation anomalies. (c) Measured water elevation anomaly time series at
292 Hardinge Bridge (blue) and the T/P virtual station n°014_1 forecasted water elevation
293 anomalies at the gauge location for a 5-day lead time (red triangles). (d) Similar plot for 10-
294 day lead time T/P virtual station n°014_1 forecasted water elevation anomalies. Plots of the
295 linear fit between time-lagged T/P and in-situ time series used to compute these forecasts are
296 included in the auxiliary materials.

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297 Table Legend:

298 Table 1. Distance from the in-situ gauge, number of observations, mean and median time
299 between two consecutive observations and river drainage area (from HYDRO1k) for each
300 Topex/Poseidon virtual station (from HydroWeb) on the Ganges and Brahmaputra rivers.
301 Forecasts using time series from virtual stations in bold are shown in Figure 3.

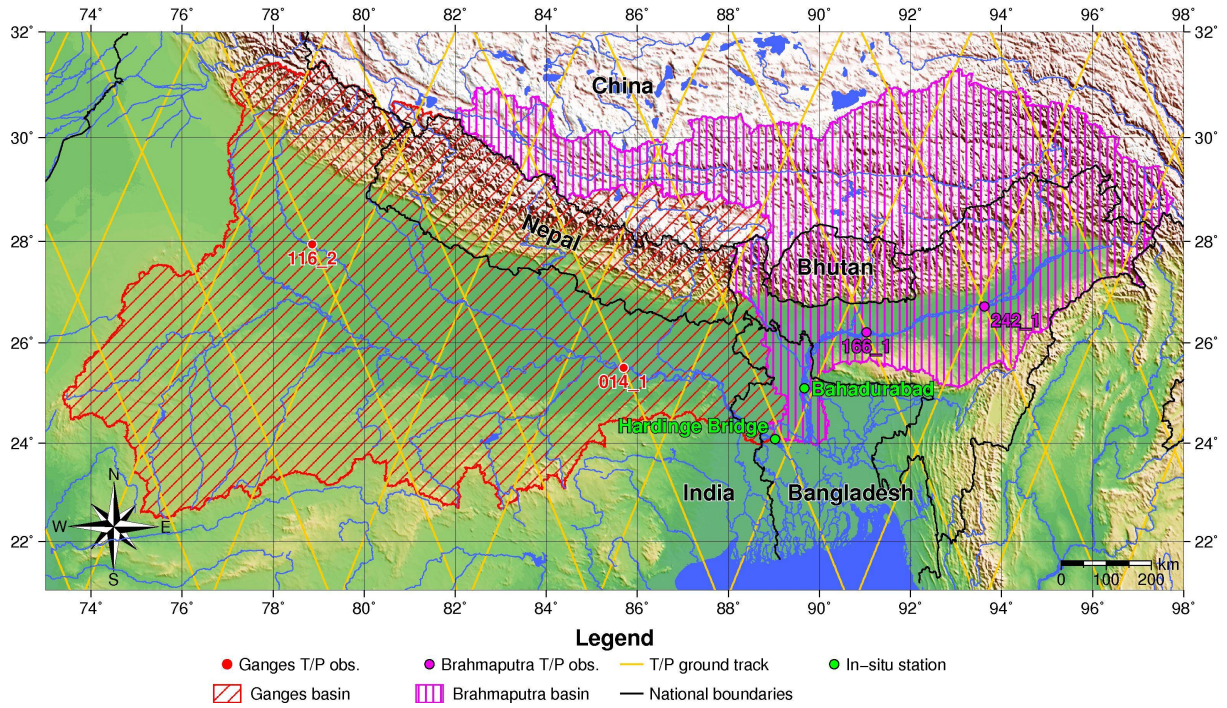
302 Table

303 Table 1. Distance from the in-situ gauge, number of observations, mean and median time
304 between two consecutive observations and river drainage area (from HYDRO1k) for each
305 Topex/Poseidon virtual station (from HydroWeb) on the Ganges and Brahmaputra rivers.
306 Forecasts using time series from virtual stations in bold are shown in Figure 3.

T/P Virtual station	River	Distance to the gauge (km)	Number of obs.	Mean/median time btw obs. (days)	Drainage area (km ²)
166_1	Brahmaputra	250	58	16/10	408,500
242_1	Brahmaputra	550	71	14/10	345,100
014_1	Ganges	530	25	22/20	756,900
116_2	Ganges	1560	49	12/10	38,400

307 Figures

308 Figure 1:



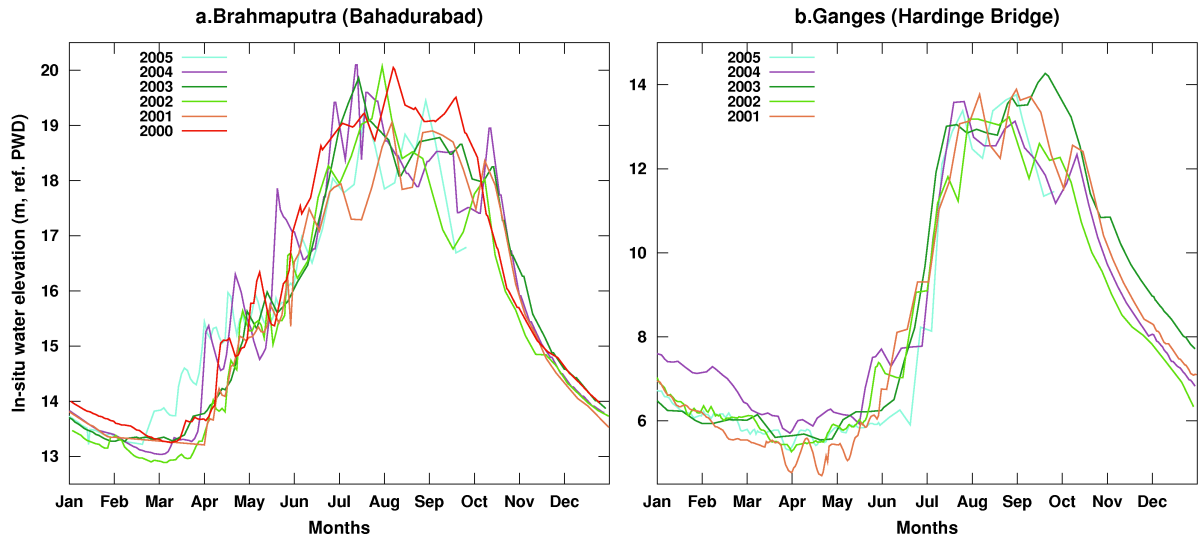
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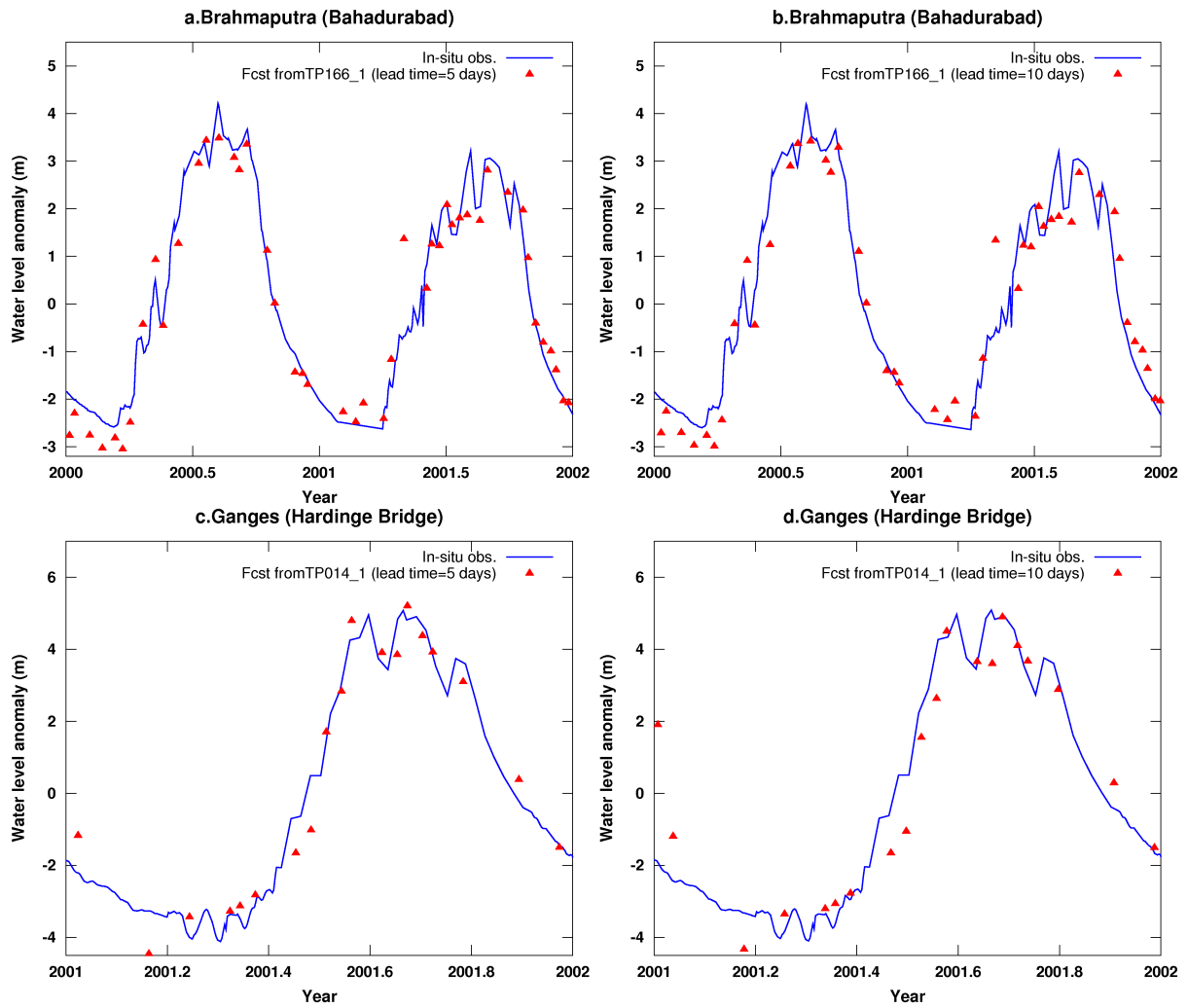
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310 Figure 2:



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312 Figure 3:



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