Ganga-Brahmaputra river discharge from Jason-2 radar altimetry: An update to the long-term satellite-derived estimates of continental freshwater forcing flux into the Bay of Bengal

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[1]   This paper discusses the use of Jason-2 radar altimeter measurements to estimate the Ganga-Brahmaputra surface freshwater flux into the Bay of Bengal for the period mid-2008 to December 2011. A previous estimate was generated for 1993–2008 using TOPEX-Poseidon, ERS-2 and ENVISAT, and is now extended using Jason-2. To take full advantages of the new availability of in situ rating curves, the processing scheme is adapted and the adjustments of the methodology are discussed here. First, using a large sample of in situ river height measurements, we estimate the standard error of Jason-2–derived water levels over the Ganga and the Brahmaputra to be respectively of 0.28 m and 0.19 m, or less than ~4% of the annual peak-to-peak variations of these two rivers. Using the in situ rating curves between water levels and river discharges, we show that Jason-2 accurately infers Ganga and Brahmaputra instantaneous discharges for 2008–2011 with mean errors ranging from ~2180 m³/s (6.5%) over the Brahmaputra to ~1458 m³/s (13%) over the Ganga. The combined Ganga-Brahmaputra monthly discharges meet the requirements of acceptable accuracy (15–20%) with a mean error of ~16% for 2009–2011 and ~17% for 1993–2011. The Ganga-Brahmaputra monthly discharge at the river mouths is then presented, showing a marked interannual variability with a standard deviation of ~12500 m³/s, much larger than the data set uncertainty. Finally, using in situ sea surface salinity observations, we illustrate the possible impact of extreme continental freshwater discharge event on the northern Bay of Bengal as observed in 2008.

1. Introduction

[2] Continental freshwater runoff or discharge is a key parameter of the global water cycle and of major importance for the evaluation of water balance at catchment scale. It also plays an important role in the climate variability as it provides significant freshwater inflow to the ocean that can impact ocean circulations and sea-air interactions regionally.

[3] In the recent decades, satellite remote sensing techniques have become an important complementary tool of in situ measurements and modeling simulations for hydrology investigations (*Alsdorf et al.* [2007], *Crétaux et al.* [2005], *Papa et al.* [2006, 2008a, 2010a, 2010b], and *Azarderakhsh et al.* [2011], among others). Some hydraulic variables can be now measured reliably from satellites [*Alsdorf et al.*, 2007; *Papa et al.*, 2008b, 2010a, 2010b] and satellite altimetry (TOPEX-Poseidon (T-P), ERS-1/2, GFO, ENVISAT and Jason-2 missions) is now routinely used to monitor stage variations of large rivers, lakes, wetlands and floodplains, providing time series covering almost two decades (see works by *Birkett* [1998], *Birkett et al.* [2002], *Crétaux et al.* [2005], and *Frappart et al.* [2008, 2011], among others). In parallel, several investigations have demonstrated the capability of using these sensors locally for estimating freshwater discharge in large rivers (still limited to rivers with a width of few kilometers), including the Ob River [*Kouraev et al.*,

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2004], several sites along the Amazon River [*Zakharova et al.*, 2006; *Leon et al.*, 2006] or in Chari/Ouham confluence near the Lake Chad [*Coe and Birkett*, 2004]. Recently, *Papa et al.* [2010a] used a combination of T-P, ERS-2 and ENVISAT altimetry-derived river heights along with daily in situ river discharge measurements to produce a monthly data set of Ganga-Brahmaputra river discharge for 1993–2008. Indeed, using the rating curve methodology, i.e., the relationship between river water levels and in situ river discharges, *Papa et al.* [2010a] used the three sources of altimetric data to estimate the river water levels and accurately infer the instantaneous Ganga (hereafter (G)) and Brahmaputra (hereafter (B)) discharges. For instance, the mean error on the estimated instantaneous discharge derived from altimetry ranged from ∼15% (∼4700 m³s) using T-P over the Brahmaputra for 1993–2001 to ∼36% (∼9000 m³/s) using ERS-2 over the Ganga for 1995–2002. The combined Ganga-Brahmaputra monthly discharges for 1993–2008, with a mean error of ∼17% (∼2700 m³/s), meet the 15%–20% range of acceptable accuracy for discharge measurements. The upscaled monthly discharge at the river mouths produced for oceanographic investigations exhibited a marked seasonal and interannual variability, and represents now an unprecedented source of information for the climate research community in order to quantify continental freshwater forcing flux into the northern Indian Ocean. Indeed G-B, the third largest freshwater outlet to the world ocean just after the Amazon and the Congo Rivers, accounts for ∼25% of the total amount of freshwater received by the Bay of Bengal (BoB) [*Sengupta et al.*, 2006], a key region for the tropical and global climate system and the Asian monsoon [*Sengupta et al.*, 2008].

[4] This data set can be used to force Indian Ocean circulation models in order to simulate the inflow of freshwater in the BoB, and to assess its influence on ocean salinity. *Durand et al.* [2011] showed that this impact is strong compared to other forcing factors in the northern part of the bay. Moreover, they showed that extreme discharge anomalies are exported through the southern boundary and can penetrate into the southeastern Arabian Sea. This exchange of continental freshwater between Bay of Bengal and Arabian Sea had already been put forward in a seasonal climatological context [*Han and McCreary*, 2001; *Jensen*, 2001]. The availability of the multiyear G-B discharge data set allowed extending the validity of this concept to interannual timescales. Besides, *Durand et al.* [2011] showed that the interannual variability of G-B discharge induces a significant variability of the upper ocean temperature, hereby suggesting a possible impact on the climate variability of the region. In the new context of unprecedented availability of global and complementary sources of routine salinity observations, i.e., the Argo project, the recent launch of the satellite Aquarius in 2010, following the one of SMOS in 2009, there is now a recognition of the need for long-term and accurate estimates of fresh water flux to the Bay of Bengal to understand their impacts on the ocean salinity and circulation as well as on sea-air interactions [*Vinayachandran et al.*, 2012, and references therein].

[5] The present study has two main objectives: first, we will demonstrate the capability of using Jason-2 radar altimeter over the Ganga and the Brahmaputra Rivers for estimating river level height variations and discharge; second, we will present an updated of the comprehensive data

set of monthly mean altimetry-derived G-B river discharge at the river mouths to 2011, which will be freely available to the scientific community.

[6] Section 2 will present the data sets used in this study, consisting of in situ height and discharge measurements, satellite altimetry observations and in situ Sea Surface Salinity (SSS) observations in the northern Bay of Bengal. In section 3, we will discuss the methodology and the limitations of estimating river discharge using satellite-derived water levels height and rating curve methodology. Then we use the rating curves (in situ and satellite-derived) for computing Ganga and Brahmaputra discharges with Jason-2 satellite data, discuss the uncertainties and present the updated monthly discharge estimates over almost two decades, 1993–2011 using T-P/ERS-2/ENVISAT/Jason-2 altimetry measurements. Then, we will present the total Ganga-Brahmaputra altimetry-derived monthly discharge data set at the river mouths from 1993 to 2011 for oceanographic applications. In order to illustrate the possible impact of continental freshwater discharge on the surrounding ocean, we will then compare the year-to-year evolution of the satellite-derived G-B discharge with a new in situ SSS data set.

2. Data Sets

2.1. Ganga-Brahmaputra In Situ River Heights and Discharges

[7] In this study we have access to hydrological observations in the Ganga-Brahmaputra Rivers in Bangladesh made by the Bangladesh Water Development Board (BWDB) (http://www.bwdb.gov.bd/). These data are collected at the two basin outlet stations before the two rivers meet, as shown in Figure 1: the Hardinge Bridge station (hereafter G, 24.07°N; 89.03°E) for the Ganga and the Bahadurabad station (hereafter B, 25.15°N; 89.70°E) for the Brahmaputra. Here, we will use three different types of in situ measurements:

[8] 1. Daily Ganga and Brahmaputra discharge data derived from water levels measured at both staging stations and converted into discharge using stage-discharge relationships (rating curves, presented in section 3). These data sets (Figure 2), already used by *Papa et al.* [2010a], extend from 1993 to mid-2002 for the Ganga (with a significant gap from early 2000 through early 2001, as well as at the beginning of 2002) and from 1993 to 2004 for the Brahmaputra (with few days not available in October and November 2003 and in September 2004). These discharge data are also called "in situ discharge," although they are not direct discharge measurements. Indeed for these periods of time, we do not have access to the original water level data used to infer the discharge.

[9] 2. *Papa et al.* [2010a] had access to 152 direct measurements of Ganga water level made infrequently at Hardinge in 2007. Nine of these measurements were coincident in time with ENVISAT observations and the comparison between the two data sets showed a very good agreement with a correlation of 0.96 and a standard error of 0.26 m. This value, consistent with the accuracy of altimeter measurements obtained over other large rivers is much smaller than the range of variability of the river height of ∼7 m. For the present study, we have now access to large samples of in situ river height measurements made both at Hardinge and Bahadurabad stations: 858 infrequent measurements for the
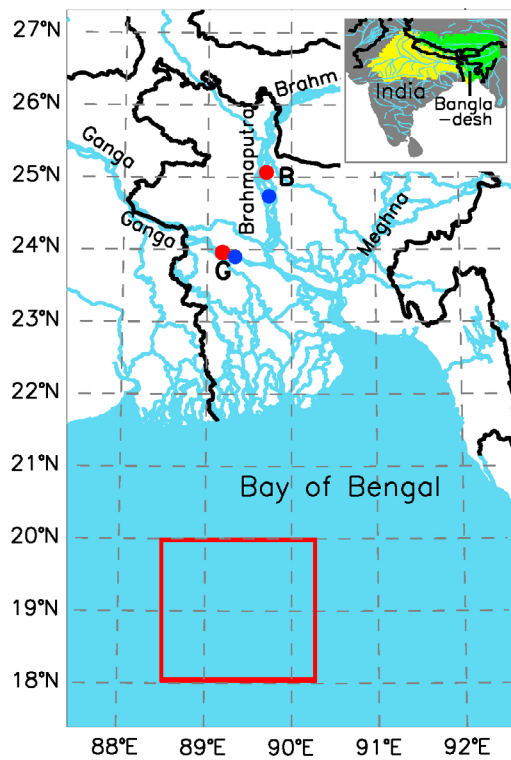
Figure 1. Map of the region of interest showing the Ganga and Brahmaputra Rivers flowing through India and Bangladesh into the Bay of Bengal. The thick black lines are the political borders. The locations of the two in situ gauging stations in Bangladesh, Hardinge (G) and Bahadurabad (B) are displayed with red circles. The virtual stations, i.e., the intersections between Jason-2 altimeter ground tracks and each river are shown with blue circles. The inset map shows the Ganga (yellow) and the Brahmaputra (green) rivers catchments areas. The red box ([18°N–20°N] × [88.5°E–90.3°E]) in the Bay of Bengal shows the boundaries of the region where in situ Sea Surface Salinity (SSS) observations are available.

Figure 2. Time series of in situ discharge (a) of the Ganga River at Hardinge Bridge station and (b) of the Brahmaputra River at Bahadurabad station. For the period 1993–2002 at Hardinge, and for 1993–2004 at Bahadurabad, daily discharge data derived from water levels are shown (see text for details). For the period 2006–2011 at Hardinge and for the period 2008–2011 at Bahadurabad, the dots show the observations of measured river discharge.

Ganga from May 2006 to August 2011 and 102 infrequent measurements for the Brahmaputra from January 2008 to August 2011. They will be discussed later in Figure 3.

[10] 3. Along with the in situ river height measurements, 858 coincident observations of measured river discharge (not estimated from stage-discharge relationships) are available for the Ganga from May 2006 to August 2011, as well as 102 coincident observations of "measured" river discharge for the Brahmaputra from January 2008 to August 2011. These data are displayed in Figure 2.

[11] The accuracy of these three sources of measurements is not known. However, even if it is still difficult to measure the depth and velocities, and consequently the true discharge of large rivers like the Ganga and the Brahmaputra [*Chowdhury and Ward*, 2004], typical accuracy of river discharge measurements is assumed to be in the range of 10 to 20% [*Fekete et al.*, 2000].

[12] In the following, we will refer either to the Ganga River or the Hardinge station using the letter G while the letter B will refer to the Brahmaputra River or the Bahadurabad station. The discharge and the river height at Hardinge on the Ganga
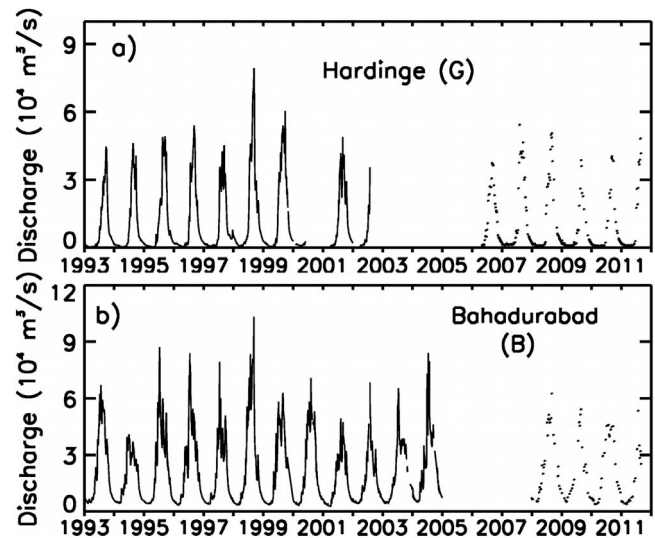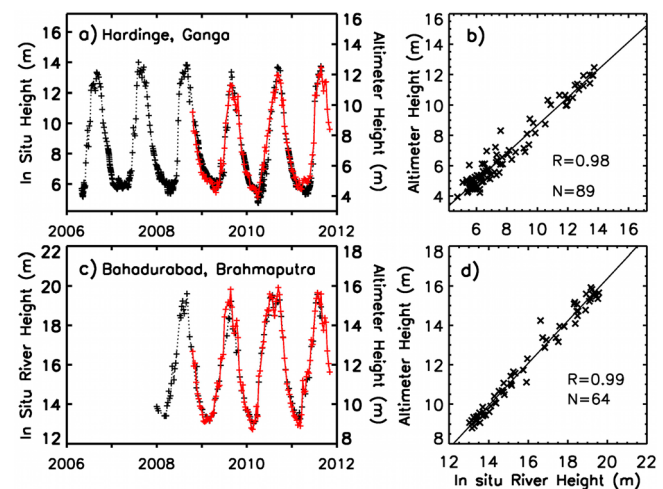

Figure 3. (a) Time series of in situ river level height measurements at Hardinge Bridge H_G (2006–2011, black plus sign with dotted line) compared to altimeter-derived river level height for the virtual station of the Ganga River $H_{J-2/G}$ (red plus sign with solid line) every 10 days from Jason-2 for mid-2008–December 2011. (b) Scatterplot of Jason-2 altimeter-derived river heights $H_{J-2/G}$ versus the in situ river height over the Ganga H_G. The linear correlation coefficient (R) and the number of points (N) are indicated. The solid line shows the linear regression between both variables. (c and d) Same as Figures 3a and 3b for the Brahmaputra River (Bahadurabad Station).

will be named Q_G and H_G respectively while the discharge and the river height at Bahadurabad on the Brahmaputra will be called Q_B and H_B respectively.

2.2. Observations From Satellite Radar Altimetry Over the Ganga and the Brahmaputra

[13] Radar altimeters onboard satellites are initially designed to measure the ocean surface topography by providing along-track nadir measurements of water surface elevation. For a complete description of altimetry and the construction of surface water level time series over the oceans (or ice sheets), we refer to *Fu and Cazenave* [2001]. The technique can be summarized as follows: altimeters emit a pulse at the nadir to Earth and receive the echo back after it is reflected by the observed surface. Assuming that the pulse is propagating at the speed of light, a precise measurement of the round-trip time between the satellite and the Earth's surface gives the distance between the satellite and the surface called range R. However, as electromagnetic waves travel through the atmosphere, they are decelerated and corrections related to the delayed propagation through the atmosphere or the interaction with the ionosphere need to be applied. Given that the satellite altitude Hsat with respect to a reference ellipsoid is known accurately by precise orbitography calculation, the height H of the observed reflector with respect to the geoid is given by

$$H = Hsat - R + Ci + Cd + Cw + Cs + Cp, \qquad (1)$$

where Ci is the correction for delayed propagation through the ionosphere, Cd (d for dry) and Cw (w for wet) are corrections for delayed propagation in the atmosphere, accounting respectively for pressure and humidity variations, and Cs and Cp, the solid and polar tides respectively, are part of the corrections applied due to the solid Earth tides and crustal vertical motions.

[14] For continental water studies, radar altimeter water level data have been long shown to be precise enough and are now used for systematic monitoring of large rivers, lakes, wetlands and floodplains [*Birkett*, 1998; *Birkett et al.*, 2002; *Crétaux et al.*, 2005]. There are now various databases that provide time series of water stages in the great basins of the world such as the HYDROWEB database from LEGOS (available at http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/ [*Crétaux et al.*, 2011]) or the River&Lake from ESA (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main [*Berry et al.*, 1997, 2004]). *Papa et al.* [2010a] used water levels coming from three altimeter satellites to infer Ganga-Brahmaputra river discharge time series: 10 day T-P–derived Ganga and Brahmaputra river level heights available from 1993 to 2001, along with 35 day ERS-2 and ENVISAT derived river level height time series for the period 1995–2002 and 2002–2008 respectively.

[15] The observations from Jason-1, launched in 2001 as the follow-up mission of T-P, had different on-board processing and additional filtering which removed most of the altimeter data over continental surfaces and thus cannot be used for hydrological study. Since mid-2008 Jason-2, the Jason-1 follow-up mission, is acquiring data again over inland water bodies. Jason-2 is a high-precision radar altimeter operating in Ku band (13.6 GHz) and C band (5.3 GHz) with a ground footprint of approximately 2–4 km depending on surface roughness. Jason-2 has the same orbital configuration as the original T-P orbit (before the T-P orbit was changed in 2001) with a ~10 day repeat cycle and an inter-track spacing at the equator of ~350 km sampling the 66°N–66°S latitudinal domain. In this study, we select for Jason-2 the same "virtual stations," i.e., the intersections between the satellites ground tracks and the Ganga and Brahmaputra rivers, as the ones from T-P [*Papa et al.*, 2010a], which are the nearest virtual stations to the Hardinge and Bahadurabad gauging stations. The virtual station on the Ganga (23.92°N; 89.33°E) is located ~25 km downstream of G and the one on the Brahmaputra (24.74°N; 89.70°E) is located ~40 km downstream of B. They are shown in Figure 1. At these locations, the river width for low/high water stages is 2/5 km for the Ganga and 4/8 km for the Brahmaputra.

[16] For these virtual stations, we derive Jason-2 time series of the water stage variations for each pass using the Virtual Altimetry Station software (VALS, 2010, Virtual Altimetry Station Software, version 0.6.2, available at www.mpl.ird.fr/hybam/outils/logiciels_test.php). VALS is a Java-based toolbox that was developed to interactively select altimetry data at the virtual stations and apply the corrections individually to satellite passes [*Santos da Silva et al.*, 2010]. The Jason-2 altimetric observations we use come from the Centre de Topographie des Océans et de l'Hydrosphère (CTOH 2008), a French observation service that distributes the geophysical data records provided by the space agencies (AVISO-CNES in the case of Jason-2 satellite), with additional parameters. The VALS data processing has three steps and is described in detail by *Santos da Silva et al.* [2010, 2012]. The first step consists of a rough selection of the region using imagery from satellite such as Google Earth or the GeoCover Landsat Thematic Mapper orthorectified mosaics (available from the MrSID Image Server at https://zulu.ssc.nasa.gov/mrsid/mrsid.pl). The second step consists of refining the selection in a cross-sectional view. The third step consists of the computation of master points per pass. Following the conclusions of *Frappart et al.* [2006], the median value instead of the mean value is computed for each pass using the data subset selected in the second step. In order to estimate the range R (equation (1)), several tracker algorithms can be used to best fit the highly variable time distribution of the echo energy bounced back by the very different types of surfaces in the satellite field of view. Comparing the performances of several existing algorithms (OCEAN, Ice-1, Ice-2…) for continental hydrology, *Frappart et al.* [2006], or more recently *Santos da Silva et al.* [2010] concluded that the Ice-1 algorithm, primarily designed for ice sheets, provided the most robust estimated water stages on rivers and lakes. Therefore, here we use the range values calculated by the Ice-1 retracking algorithm. Finally, river height water levels are referenced to the Earth Gravitational Model EGM2008 [*Pavlis et al.*, 2008] with respect to WGS 84 reference (National Geospatial-Intelligence Agency, The World Geodetic System 1984, http://earth-info.nga.mil/GandG/wgs84/).

[17] It is important to point out here that, in terms of single river level height measurements, there are several other factors, beside the choice of a certain tracker to retrieve the altimetric range or the river width, that could introduce uncertainties in the height measurements: for instance, the precision of the estimated satellite orbit or the uncertainties in data sets used to correct atmospheric contributions can also have a non-

negligible impact. However, uncertainties/errors due to these factors will not be evaluated nor discussed in this study.

[18] We use the following nomenclature to refer to the altimetry-derived river height from Jason-2 over the Ganga and the Brahmaputra: $H_{J-2/G}$ and $H_{J-2/B}$ respectively. These time series as well as other satellite-altimeter–derived time series over the Ganga-Brahmaputra are available freely on the HYDROWEB-LEGOS website.

2.3. Evaluation of Jason-2 Radar Altimetry Over the Ganga-Brahmaputra

[19] Figure 3 shows the Jason-2–derived times series of water level height at G and B estimated in section 2.2 ($H_{J-2/G}$ and $H_{J-2/B}$) and the comparison with the in situ river height measurements H_G and H_B. Since altimeter-derived water level heights are expressed with respect to a geoid model, note that there is no common height reference when compared to in situ water level heights, resulting in a natural difference in absolute values.

[20] Consistent with Figure 2, a large seasonal cycle is observed with annual height variations exceeding 8 m for both rivers. Times series (every 10 days for $H_{J-2/G}$ and $H_{J-2/B}$, infrequent but typically 3 to 4 times per month on the average for H_G and H_B) show a very good agreement (Figures 3a and 3c) and have a similar behavior in the peak-to-peak height variations. Over the Ganga, from 2008 to 2011, there are 89 dates where measurements are simultaneously available (defined as plus or minus two days apart) for $H_{J-2/G}$ and H_G. Similarly, for the Brahmaputra, there are 64 measurements simultaneously available for $H_{J-2/B}$ and H_B from 2008 to 2011. Figures 3b and 3d show the relationship between the satellite-derived river height and the in situ observations, confirming the good agreement between the two data sets with a correlation of 0.98 (p-value (hereafter, p) < 0.01) and 0.99 (p < 0.01) for G and B, respectively. The estimated standard error is 0.28 m for G and 0.19 m for H, typically in the range of accuracy of altimetric observations over large rivers (10–20 cm for instance over the Amazon [*Birkett et al.*, 2002; *Frappart et al.*, 2006]) or similar to the 0.26 m found using ENVISAT over the Ganga in work by *Papa et al.* [2010a]. Note that this accuracy strongly depends, among other factors, on the width of the river and on the morphology of the riverbanks. In general, the accuracy is reduced over narrower rivers and/or in presence of vegetation. At our virtual stations G and H, the width of the river channel is always larger for the Brahmaputra than for the Ganga, which might explain in part the better accuracy of the river height measurements over the Brahmaputra than over the Ganga.

[21] Moreover, flow cross-sectional area typically varies on short spatial scales and it is therefore not expected that in situ and altimetry-derived values reach a perfect fit, especially in the case where the virtual stations are located 25 to 40 km from the gauging stations. We performed a simple regression analysis between the two data sets and found that

$$H_{J-2/G} = H_G * 1.04 + 0.86 \qquad (2)$$

and

$$H_{J-2/B} = H_G * 0.94 + 4.97, \qquad (3)$$

showing that for these two cases the dynamic of the flow at the gauging station and at the virtual station are quite similar with regression coefficient close to 1. These relationships will be used in the section 3 when estimating radar altimeter-derived discharges.

2.4. In Situ Salinity Observations in the Bay of Bengal

[22] In order to illustrate the possible impact of G-B discharge variability on the ocean salinity, we will use an in situ sea surface salinity (SSS) data set in section 3.4. This unprecedented source of SSS observations in the BoB consists of water samples collected by a passenger ship plying between Kolkata (India mainland located at 22.6°N, 88.4°E) and Port Blair (Andaman Islands in the Bay of Bengal located at 12.5°N, 92.75°E). The boundaries of the area in the Bay of Bengal where in situ SSS observations are available for our study are shown in Figure 1. The data set spans the September 2006–May 2011 period, with typically a monthly to bimonthly frequency (6 to 13 cruises per year, depending on the year considered). During each cruise, an onboard scientific observer collects surface seawater samples (bucket samples) every 50 km. The samples are subsequently analyzed for SSS following standard international procedures, using a Guild Line 8400 Autosal salinometer. This ensures a typical accuracy of SSS data of about 10^{-2} units.

3. Ganga and Brahmaputra River Discharge From Altimetry

3.1. Methodology: Rating Curve and Limitations

[23] Even if several direct measurement approaches exist (including current meter or Acoustic Doppler Current Profiler (ADCP)), the routine and operational measurement of discharge in medium to large rivers is generally based on indirect approaches. The most common one is based on the conversion of water stages into discharges using a one-to-one stage-discharge relationship or rating curve [*Rantz et al.*, 1982]. In practice, this rating curve is derived on the basis of a number of simultaneous stage and discharge measurements at a river location. A measure of stage at any time is then directly converted into discharge by means of the developed rating curve. This relationship is specific to each gauging station and its development is regulated by different national and international standards.

[24] Ideally, the goal for in situ discharge measurement accuracy is within 5% of the true value. However, in practice, given the difficulties to measure the depth and velocities (and consequently the true discharge), particularly in large and strong-flowing rivers, the community agrees that a 15–20% accuracy is generally acceptable. It is important to note here that several factors can influence over time the transformation from stage to discharge and thus can alter gradually or abruptly the rating curve equation. These factors include the dynamics of the riverbed itself, but also anthropogenic factors such as land use change, withdrawal for water use, or new contributions from artificial water storage reservoirs. In general, the reinstallation of gauges and related bathymetric surveys can frequently be required and the rating curve has to be recalibrated with appropriate frequency. This is particularly important for rivers such as the Ganga and the Brahmaputra Rivers, which carry large
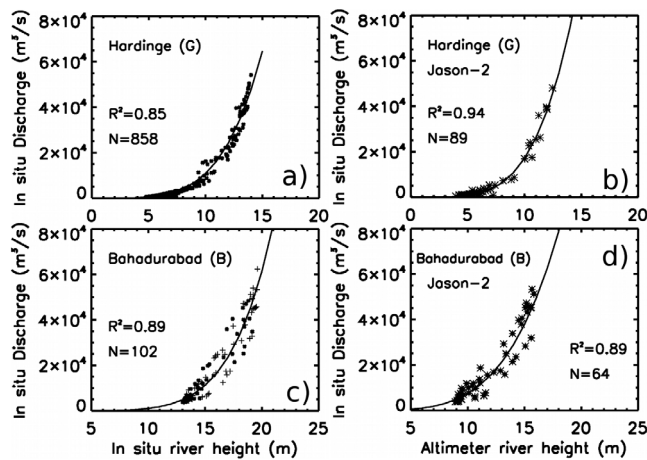
Figure 4. Rating curves (see text for details), i.e., the scatterplot showing the relationship between river height and river discharge. (a) Scatterplot (H_G-Q_G) for 858 measurements during 2006–2011 between in situ river height and in situ river discharge for the Ganga at Hardinge. (b) Scatterplot ($H_{J-2/G}$-Q_G) of in situ river discharge observations versus Jason-2 altimeter-based river height measurements for Hardinge, Ganga. (c) Scatterplot (H_B-Q_B) for 102 measurements during 2008–2011 between in situ river height and in situ river discharge for the Brahmaputra at Bahadurabad. Plus signs represent measurements made during the river height rising period and crosses represent measurements made during the river height decreasing period. (d) Scatterplot ($H_{J-2/B}$-Q_B) of in situ river discharge observations versus Jason-2 altimeter-based river height measurements for Bahadurabad, Brahmaputra. In each figure, the number of points (N) and the correlation coefficient (R) are indicated. The solid lines show the regression relation (power law function).

volumes of floodwater and sediments and may experience morphological changes. However, *Mirza* [2003] studied the evolution of the rating curves at Hardinge and Bahadurabad from 1966 to 1992 and showed that the Ganga and Brahmaputra Rivers were in dynamic equilibrium during this period and that the rating curves previously developed in 1966 were still valid to at least 1992.

[25] Using the described rating curve methodology, two different approaches can be considered to retrieve the river discharge using satellite-derived water level data. In general, it is difficult to get access to the official rating curves or to long time series of in situ water level measurements overlapping the satellite altimeter measurements. Therefore, one practical approach consists of establishing direct relationships between the altimeter-derived water levels at the satellite-river intersection and the in situ observed discharges. As we did not get access to in situ (or official) rating curves at that time, this approach was successfully adopted at G and B for three altimeter missions by *Papa et al.* [2010a]. The same technique was also used with success in several other studies over the Ob River in Siberia [*Kouraev et al.*, 2004] or the Amazon [*Zakharova et al.*, 2006]. The second approach consists of using the official rating curve constructed using several simultaneous direct measurements of river height and river discharge. The altimetry-derived water

level measurements can then be converted into discharges using the in situ rating curve. In the present study we will consider both approaches and evaluate their differences.

[26] The rating curves methodology using altimetry-derived measurements of river stages has some well-known limitations. Both approaches rely first on the availability of ground-based observations (discharge and/or stage) to construct the rating curves. As already mentioned, such in situ observations are most of the time not available to the scientific community, because they are considered sensitive data to national security or simply because the number of gauging stations was dramatically reduced over the last decade due to economic constraints. When they are available, stream gauges are rarely located along the satellite altimeter track or within the altimeter footprint, but more typically within ~100 km, which can introduce spurious effects in the relationship altimeter/in situ observations. As already mentioned, another limitation resides in the fact that the original relation river height–discharge is assumed to be static over time (permanent control) and might not be valid over a long period of time (shifting control). In parallel, the rating curve methodology can be considered adequate for all rivers under steady-flow conditions. Under unsteady-flow conditions, when flood waves show a marked kinematic behavior, such approach can leads to the formation of a hysteretic rating curve also known as the loop-rating curve. This implies that the steady-flow rating curve is no longer sufficient and adequate to describe the real stage-discharge relationship and may lead to errors in discharge estimation that can be greater than 15%. Another significant error can also be produced by the extrapolation of the rating curve beyond the range of measurements used for its derivation. This is generally the case for large anomalous flooding events that were not observed during the establishment of the rating curve. Finally, as discussed by *Papa et al.* [2010a] and more in details by *Papa et al.* [2012], a major drawback in the use of altimetric measurements to monitor river stages and discharges is the temporal frequency of observations. In situ gauges provide observations daily or twice daily, which is a temporal sampling intervals needed for studies related to hydrological processes or to evaluate flood risk. This is not the case for the satellites with a 10 day repeat cycle for T-P or Jason-2.

[27] Nevertheless, despite all the limitations mentioned above, the use of radar altimeter and rating curve methodology to estimate river discharge for studies related to climate is still extremely valuable as a complement to ground-based observations. It also provides valuable information where traditional gauge data can be irregular and difficult to obtain.

[28] Figure 4 shows the rating curves (hereafter called H-Q diagrams) at G and B. Figure 4a gives the relation H_G-Q_G constructed using the in situ river height (H_G) and the in situ river discharge (Q_G) measured simultaneously at the Hardinge gauging station during 2006–2011 (Figures 2a and 3a). Figure 4b shows the $H_{J-2/G}$−Q_G diagrams, constructed using 89 measurements made during 2008–2011 between Jason-2 altimetry-derived water level height ($H_{J-2/G}$) and in situ river discharge (Q_G). Figures 4c and 4d show H_B-Q_B (using 102 simultaneous in situ measurements made during 2008–2011) and $H_{J-2/B}$−Q_B (using 64 measurements made during 2008–2011), respectively.
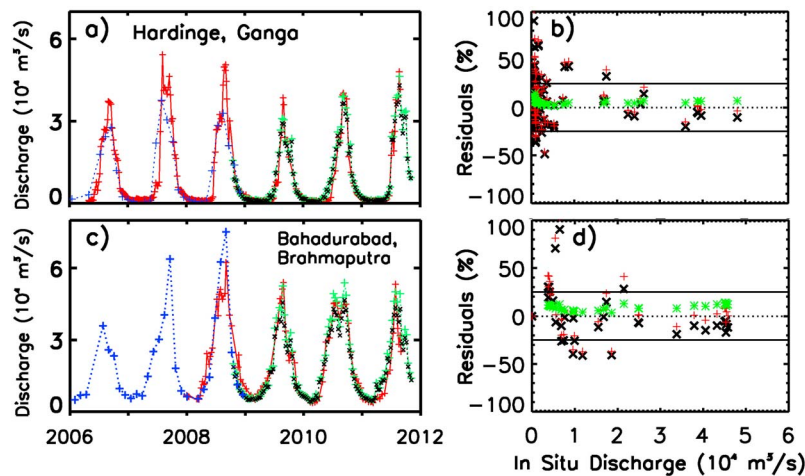
Figure 5. Time series of satellite altimeter-derived discharges and in situ observed discharges and evaluation. (a) River discharge estimates from Jason-2 using the in situ rating curve from Figure 4a ($Q_{J-2/Gi}$, green plus signs) and using the altimeter-derived rating curve from Figure 4b ($Q_{J-2/Gs}$, black cross signs) compared to in situ discharge observations (red plus, solid line) for Hardinge, Ganga. The blue line with plus sign is the river discharge from ENVISAT ($Q_{ERS/G}$ for 2006–2008, every 35 days) as in Figure 8 from *Papa et al.* [2010a]. (b) Percent residual as function of in situ discharge: scatter diagrams of error residuals of the Jason-2 altimeter-derived instantaneous discharge (shown as a percent of the in situ discharge Q_G) versus the in situ discharge at Hardinge, Ganga. The black crosses are for $Q_{J-2/Gs}$ and the red plus signs are for $Q_{J-2/Gi}$. Also shown as green star signs are the differences between as $Q_{J-2/Gi}$ and $Q_{J-2/Gs}$ (in percent of $Q_{J-2/Gi}$) versus Q_G. (c and d) Same as Figures 5a and 5b for the Brahmaputra at Bahadurabad (i.e., $Q_{J-2/Bi}$, $Q_{J-2/Bs}$, Q_B and $Q_{ENV/B}$).

[29] First, one can note that, for both G and B stations, the in situ rating curve and the satellite-derived rating curve show a similar pattern. Despites the limited amount of measurements used to construct $H_{J-2/G}-Q_G$ and $H_{J-2/B}-Q_B$ (89 and 64 data respectively), both diagrams show a tight H-Q relationship. However, during the summer flood period of 2007 and 2008 (Figures 1 and 2), prior to the launch of Jason-2, there are anomalous events of large discharges and stages which cannot be captured in $H_{J-2/G}-Q_G$ and $H_{J-2/B}-Q_B$ compared to H_G-Q_G and H_B-Q_B. In such case, the extrapolation of the satellite-derived rating curve beyond the range of measurements used for its construction might generate strong uncertainties in the altimeter-derived estimated discharge. The H_B-Q_B plot (Figure 4c) and the $H_{J-2/B}-Q_B$ plot (Figure 4d) for the Bahadurabad station are both more scattered than the diagrams for Hardinge. We tried to analyze the diagram H_B-Q_B into different hydrological regimes by separating the period of flood falling (crosses) and flood rising (plus signs), to assess the relevance of a loop-rating curve. In such case, discharges estimated at the same river stage during the rising flood period and the recession flood period are different. However, the analysis was not conclusive and we argue that this higher dispersion has its main cause in higher uncertainties in the measurements of in situ river discharge at B due to the difficulties to accurately observed discharge in large and mighty river. Despite the more scattered diagram at B, the regression analysis between the two quantities is thus done considering a single curve. *Callède et al.* [2001] show that, in large river such as the Amazon, the uncertainties related to the use of a single curve for complex stage-discharge relationships are nevertheless small compared to other sources of error.

[30] For each H–Q diagram of Figure 4, we perform a single regression analysis to obtain the best fitting rating curves. H_G-Q_G, H_B-Q_B, $H_{J-2/G}-Q_G$ and $H_{J-2/B}-Q_B$ are approximated by power law functions.

3.2. Jason-2–Derived Instantaneous Discharge Estimates

[31] Using both in situ (H_G-Q_G and H_B-Q_B) and satellite-derived ($H_{J-2/G}-Q_G$ and $H_{J-2/B}-Q_B$) rating curves at G and B, discharge time series are estimated every 10 days for the period 2008–2011 using Jason-2–derived river water levels.

[32] Nevertheless, before using $H_{J-2/G}$ and $H_{J-2/B}$ with H_G-Q_G and H_B-Q_B, we need to adjust the satellite-derived water level heights to H_G and H_B. Indeed, as discussed in section 2.3, there is a small difference in the seasonal amplitude between $H_{J-2/G}$ and H_G (resp. between H_B and $H_{J-2/B}$) due to the difference in flow cross-sectional area at the in situ station and the virtual altimetry station. We assume here the conservation of flow between these two locations (no inflow from tributaries and lateral inflow negligible) and we adjust therefore $H_{J-2/G}$ to H_G in terms of seasonal amplitude and offset (resp. H_B to $H_{J-2/B}$) by simple linear regression using the slope-intercept coefficients estimated in section 2.3.

[33] The Jason-2–derived discharge estimates for Hardinge using H_G-Q_G is called $Q_{J-2/Gi}$, with "i" for in situ, and the ones using $H_{J-2/G}-Q_G$ is called $Q_{J-2/Gs}$, with "s" for satellite. They are displayed in Figure 5a along with Q_G for 2006–2011 and the ENVISAT-derived 35 day discharge time series $Q_{ENV/G}$ from *Papa et al.* [2010a] for 2006–2008.

Figure 5c shows the same time series for Bahadurabad with $Q_{J-2/Bi}$, $Q_{J-2/Bs}$, Q_B and $Q_{ENV/B}$. The residuals for $Q_{J-2/Gi}$, $Q_{J-2/Gs}$, $Q_{J-2/Bi}$, $Q_{J-2/Bs}$ (i.e., the differences between altimetry-derived discharge and simultaneous in situ discharges, expressed as percent of the in situ discharge value) as a function of in situ discharge values are shown in Figures 5b and 5d.

[34] Figures 5a and 5c clearly show excellent agreement between the Jason-2 satellite-derived discharges and the in situ discharges, in terms of seasonal and interannual (limited to three years) variations with low/high flow season well depicted. For Hardinge, $Q_{J-2/Gi}$ and $Q_{J-2/Gs}$ gives a correlation with Q_G of 0.99 and 0.98 respectively (n = 89). For the Brahmaputra, these values are 0.99 and 0.97 (n = 64). Even if the comparison is made for a limited sample of three years, the year-to-year variations of $Q_{J-2/Gi}$ and $Q_{J-2/Gs}$ are in good agreement with Q_G as well, with as an example, the larger discharge values obtained during the high-flow season of 2011 for the Ganga. For the Brahmaputra, $Q_{J-2/Bi}$ and $Q_{J-2/Bs}$ also capture well the double peak of the summer 2010 as seen on Q_B. The rmsd (root mean square difference) between $Q_{J-2/Gi}$ and Q_G is 1458 m^3/s while the one between $Q_{J-2/Gs}$ and Q_G is a little larger with 1652 m^3/s. The rmsd between $Q_{J-2/Bi}$ and Q_B is of 2180 m^3/s and the one between $Q_{J-2/Bs}$ and Q_B is of 2431 m^3/s. Figures 5b and 5d show that the residual error for individual 10 day estimates for G and B is generally less than ±25% of the in situ discharge. More than 64% (resp., 80%) of the $Q_{J-2/Gi}$ and $Q_{J-2/Gs}$ (resp., $Q_{J-2/Bi}$ and $Q_{J-2/Gs}$) are within 15% of in situ Q_G (resp. Q_B). We further estimate that the mean error (that we defined as the mean of absolute value of the residuals) of instantaneous $Q_{J-2/Gi}$ (resp., $Q_{J-2/Gs}$, $Q_{J-2/Bi}$, $Q_{J-2/Bs}$) is ~13% (resp., 14%, 6.5% and 7.5%) and thus well within the range (10–20%) of errors acceptable for discharge measurements. These values are comparable and even better than the mean error on the estimated instantaneous discharge found in work by *Papa et al.* [2010a] that ranged from ~15% (~4700 m^3/s) using TOPEX-Poseidon over the Brahmaputra for 1993–2001 to ~36% (~9000 m^3/s) using ERS-2 over the Ganga for 1995–2002. The mean error of instantaneous $Q_{J-2/Gi}$ and $Q_{J-2/Gs}$ is even reduced to less than 10% when only discharges over 5000 m^3/s are considered. Indeed, during the low-flow season, from December to April, the altimeter has more difficulties to accurately retrieve the river level height variations when the river is narrower (~2 km for the Ganga during low-water season) and consequently low discharge with the residual error that can be greater than 30% in relative values.

[35] Figures 5a and 5c also show a new independent evaluation/validation of the ENVISAT-derived 35 day discharge time series $Q_{ENV/G}$ and $Q_{ENV/B}$ from *Papa et al.* [2010a] for the period 2006–2008. $Q_{ENV/G}$ and $Q_{ENV/B}$ were used to estimate the discharge 2002–2008 in the 1993–2008 time series but, because no in situ data were available at that time, only a simple indirect evaluation was made using precipitation estimates from the Global Precipitation Climatology Products (GPCP). $Q_{ENV/G}$ and $Q_{ENV/B}$ were calculated using rating curves based on the relationship between ERS-2–derived river water level heights and Q_G and Q_B during 1995–2001 [*Papa et al.*, 2010a]. The in situ observation time series confirm what was suggested by the ENVISAT-derived discharges and the basin-scale precipitation analysis: 2007 and 2008 represent two large

anomalous years in terms of discharge in the period 2006–2011, especially marked by the noticeably large peak for the Brahmaputra in 2008. Overall, $Q_{ENV/G}$ and $Q_{ENV/B}$ are in good agreement with the in situ discharges observations, even if the annual peak flow in 2008 is underestimated for Hardinge and overestimated for Bahadurabad.

[36] To complete the evaluations, Figure 5b (resp. 5d) also show the difference between $Q_{J-2/Gi}$ and $Q_{J-2/Gs}$ (in percent of $Q_{J-2/Gi}$) as a function of Q_G (resp. $Q_{J-2/Bi}$, $Q_{J-2/Bs}$, Q_B). For all estimates, $Q_{J-2/Gi}$ (resp. $Q_{J-2/Bi}$) is always larger than $Q_{J-2/Gs}$ (resp. $Q_{J-2/Bs}$), with a mean absolute difference of ~6% for Hardinge and 10% for Bahadurabad. For both stations, the differences between both estimates are larger for the lowest and the highest flows of Q_G and Q_B, with in general larger differences for B. For Q_G (resp., Q_B) below 10,000 m^3/s or above 35,000 m^3/s differences are above in general ~10%. The largest values are found at B with ~15% difference for the 5th largest discharge (>45,000 m^3/s). These differences, although within acceptable ranges, confirm one of the limitations of the use of rating curves and the extrapolation beyond the range of measurements used for their construction. Indeed, as seen in Figure 4, the number of measurements during the high flows used to construct the rating curve is 5 to 6 times larger for H_G-Q_G, (resp., H_B-Q_B) than for $H_{J-2/G}$-Q_G (resp., $H_{J-2/B}$-Q_B) and leads to larger uncertainties in the regression analysis. For high water flows, the $Q_{J-2/Gi}$ and $Q_{J-2/Bi}$ perform much better than $Q_{J-2/Gs}$ and $Q_{J-2/Bs}$. $Q_{J-2/Gi}$ and $Q_{J-2/Bi}$ are thus the estimates we will retain to construct the monthly data set in next sections.

[37] Finally, there will be a possibility of using the current results to retrieve river discharge variations using future Jason-2 measurements and extend the time series beyond 2011 (for periods when in situ data are not available for comparisons), thus we further assess the robustness of the rating curves methodology by testing their sensitivity. For instance, while constructing the in situ rating curves for G, we removed a year (for instance 2006) from the in situ record and used only the data for the remaining years (2007–2011). The 2006 Jason-2–based river discharges using the new rating curve are then compared to Q_G for 2006. The same computations are repeated for each available year of the record, for G and B. We found that the standard deviation of the residuals is in the same order of magnitude (not shown) as the standard deviation of the residuals calculated when the entire record is used to construct H_G-Q_G and H_B-Q_B. This conclusion gives confidence in the use of these diagrams to further extend the time series in the future with nevertheless the hypothesis that the rating curve will remain static for a certain period of time.

3.3. Ganga-Brahmaputra Monthly Discharge Variations and Their Aggregated Estimates at the River Mouth for Oceanographic Applications

[38] Monthly discharges for G and B for the period 1993–2011 are presented using multiple radar altimeters missions. For the period 1993–2008, we use the estimates from *Papa et al.* [2010a] which are a combination of T-P–derived discharges for 1993–2001, ERS-2–derived discharges for 2002 and ENVISAT-derived discharges for 2003–2008.

[39] For 2009–2011, we now update the data set by estimating the monthly mean discharge obtained by averaging
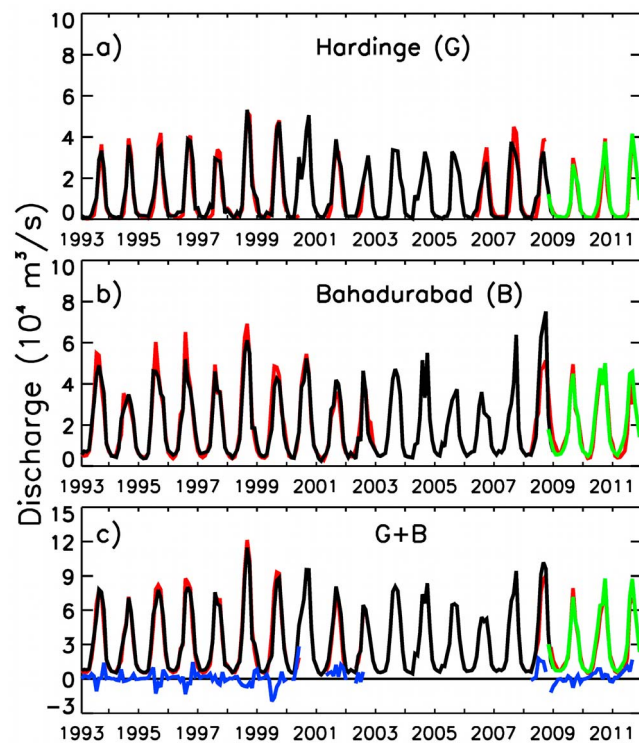
Figure 6. Time series of monthly river discharges derived from radar altimetry 1993–2011 (black line, using TOPEX-Poseidon, ERS-2 and ENVISAT as by *Papa et al.* [2010a], green line using Jason-2, this study) and compared to in situ streamflow (red line) (a) for the Ganga at Hardinge (Q_G in situ data available from 1993 to mid-2002 and from 2006 to mid-2011) and (b) for the Brahmaputra at Bahadurabad (Q_B in situ data available from 1993 to mid-2004 and from 2008 to 2011). (c) $Q_{ALT/G+B}$ for the combined discharge of the two rivers G + B (Q_{G+B} in situ data available from 1993 to mid-2002 and from 2008 to 2011). The blue curve shows the residuals (the difference between $Q_{ALT/G+B}$ and Q_{G+B}, when in situ discharge available).

all available instantaneous discharges $Q_{J-2/Gi}$ and $Q_{J-2/Bi}$ within a month. We choose to use the estimates derived from the in situ rating curve as they perform better for high water flow as discussed in section 3.2. No adjustment between the various discharge time series over 1993–2011 is done. The altimetry-derived discharge for 1993–2011 is called $Q_{ALT/G}$ for the Ganga and $Q_{ALT/B}$ for the Brahmaputra. The total discharge of the combined rivers G + B obtained by summing the two individual discharges is called $Q_{ALT/G+B}$.

[40] The various times series of monthly river discharge for G, B and G + B for the period 1993–2011 are displayed in Figure 6, and compared with the monthly mean time series of in situ river discharge when available (Q_G, Q_B and Q_{G+B}). The residuals between $Q_{ALT/G+B}$ and Q_{G+B} are shown in Figure 6c. Because, we already discussed the year 1993–2008 in details in work by *Papa et al.* [2010a], we will mainly focused here on the new results obtained using Jason-2 for 2009–2011.

[41] Figure 6 confirms that the monthly satellite-derived estimates, in particular the new ones from Jason-2, and in situ river discharges agree well in the seasonal and the

interannual variations (Figures 6a and 6b). For G and B and their aggregate estimates, the year-to-year variations of the peak flow are well captured with differences smaller than 15%. The total river discharge of the Ganga-Brahmaputra river system (Figure 6c) has a prominent seasonality with maximum values generally in August/September and shows large year-to-year variations in the magnitude of the peak. For the period 1993–2011 the mean aggregate discharge is $\sim$32000 m^3/s with a standard deviation of $\sim$28000 m^3/s. The annual maximum monthly discharge has a mean value of $\sim$82000 m^3/s and a standard deviation $\sim$14000 m^3/s for 1993–2011. Over the full-length record, the largest yearly peak of $Q_{ALT/G+B}$ occurs in August and September 1998 with $\sim$115000 m^3/s ($\sim$120000 m^3/s from in situ data) and the lowest occurs in 2006 with $\sim$54000 m^3/s (no in situ data to compare with).

[42] For 2009–2011, more than 85% of the $Q_{ALT/G+B}$ are within 15% of in situ Q_{G+B} values and the standard deviation of the residuals (blue curve) for 2009–2011 is 2900 m^3/s ($\sim$2700 m^3/s for 1993–2001). The mean error (defined as the mean of absolute value of the residuals) of monthly $Q_{ALT/G+B}$ is 16% for 2009–2011 ($\sim$17% for 1993–2011), and confirms, as expected, that the altimeter-derived monthly discharge data set meets the requirements of acceptable accuracy (15–20%) and that these requirements are kept for the extended data set when using Jason-2.

[43] Following the approach proposed by *Papa et al.* [2010a], we adjust the altimetry-derived discharge $Q_{ALT/G+B}$ to represent the continental freshwater flux at the river mouths flowing into the Bay of Bengal, the key factor for studies related to the nearby ocean.

[44] In general, past studies that needed an accurate estimate of continent-to-ocean freshwater flux of Ganga-Brahmaputra [*Durand et al.*, 2007; *Vinayachandran and Kurian*, 2007] used available runoff climatology such as the ones from *Vörösmarty et al.* [1996], *Fekete et al.* [2000], *Dai and Trenberth* [2002] or *Dai et al.* [2009], typically estimated using a combination of a climate-driven water balance model and, when available, in situ river discharge data. Here, in order to adjust our data set to represent the flow at the river mouth, we use the climatology from *Fekete et al.* [2000] shown in Figure 7a (red curve), along with the climatology of $Q_{ALT/G+B}$ for 1993–2011 (black curve). As expected, the $Q_{ALT/G+B}$ climatology compares extremely well with the climatology of Q_{G+B} (blue line). The climatology of $Q_{ALT/G+B}$ has values slightly lower than the estimates of *Fekete et al.* [2000], mainly explained by the fact that the latter integrates the entire Ganga and Brahmaputra watersheds and includes the contribution of local tributaries and precipitation downstream of Hardinge and Bahadurabad, comprising the discharge of the Meghna River that can amount to about 10% of Q_{G+B}.

[45] The ratio between the mean $Q_{ALT/G+B}$ climatology and the mean of the *Fekete et al.* [2000] climatology is of 120.5%, a coefficient that we apply to $Q_{ALT/G+B}$ interannual monthly time series to get the so-called "$Q_{ALT/G+B}$ scaled," i.e., the Ganga-Brahmaputra river discharge at the river mouth. Its climatology is shown in Figure 7a (green curve) and the time-varying monthly Ganga-Brahmaputra river discharge at the river mouth for 1993–2011 is displayed in Figure 7b. When compared to the repeated climatology from work by *Fekete et al.* [2000] (red line), "$Q_{ALT/G+B}$ scaled"
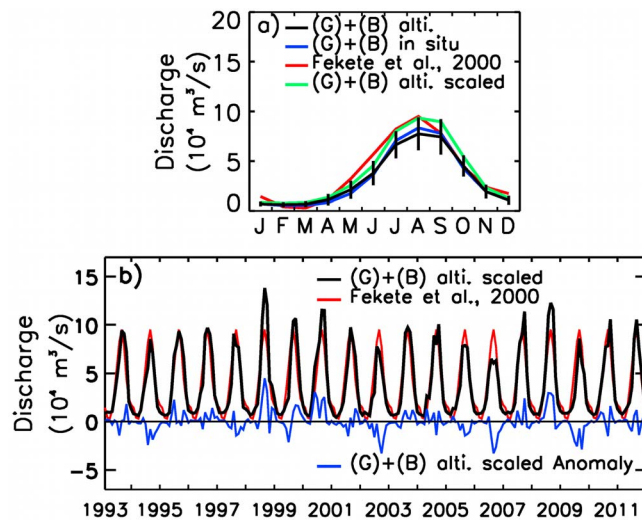
Figure 7. (a) The black line is the monthly climatology of the sum of the two discharges (G and B) derived from radar altimetry ($Q_{ALT/G+B}$ for 1993–2011); the vertical bars show the monthly evolution of its interannual variability, defined by plus or minus one standard deviation; the blue line is the monthly climatology of the sum of the two discharges (G and B), Q_{G+B} derived from in situ measurements (1993–2001 and 2008–2010); the red line is the monthly climatology of the Ganga and Brahmaputra rivers discharge at the river mouth estimated by *Fekete et al.* [2000]; the green line is the same as the black line, after applying a scaling factor of 120.5% (see the text for details). (b) Monthly variations of the satellite-derived Ganga-Brahmaputra River discharge (black line) at the river mouth (i.e., "$Q_{ALT/G+B}$ scaled") during 1993–2011, superimposed on the repeated climatology of *Fekete et al.* [2000] (red line). The blue line shows the deseasonalized anomalies (obtained by subtracting the 19 year mean monthly value from individual months) of $Q_{ALT/G+B}$ scaled.

shows a large interannual variability with a standard deviation of their difference of ∼12500 m³/s, equivalent to the standard deviation of their difference over 1993–2008 [*Papa et al.*, 2010a], and much larger than the data set uncertainty. The nonseasonal variability of "$Q_{ALT/G+B}$ scaled" is also displayed in Figure 7 (1993–2011 mean annual cycle was

removed to obtain the deseasonalized anomalies). It shows large interannual variations, annual peak-to-peak variability as large as 50,000 m³/s and periods of consecutive years of large anomalous events (1997–2001 and 2006–2009) that could strongly impact the buildup of negative and positive anomalies in the sea surface salinity. $Q_{ALT/G}$, $Q_{ALT/B}$, $Q_{ALT/G+B}$ and "$Q_{ALT/G+B}$ scaled" are freely available to the scientific community upon request to the authors (visit www.legos.obs-mip. fr/papa).

3.4. Impact of Year-to-Year Variations of Ganga-Brahmaputra Discharge Variations on Northern Bay of Bengal SSS

[46] The new "$Q_{ALT/G+B}$ scaled" data set represents an unprecedented and valuable information for investigations of the BoB freshwater budget, the climate of the area and its variability. Here we provide a simple illustration of the relevance of this multiyear discharge data set for the better understanding of the BoB freshwater budget. Figure 8 shows the time evolution "$Q_{ALT/G+B}$ scaled" for 2006–2011 along with the corresponding evolution of observed SSS in the northern BoB. The SSS time series was computed by averaging all available in situ samples over the box [18°N–20°N] × [88.5°E–90.3°E] (see Figure 1 for the location of the box), a region highly exposed to the direct influence of the G-B freshwater plume [e.g., *Durand et al.*, 2011, and references therein]. For each transect, the typical number of available samples is about five. Figure 8 shows that SSS basically mirrors the seasonal evolution of G-B discharge, with low salinity of the Bay of Bengal surface waters (typically inferior to 31 units) following the high-discharge season, and a saltening (up to about 32–32.5 units) in the low-discharge season. This basic evolution is repeated each year but with marked interannual variations as the magnitude of the freshening greatly differs from year to year. Noticeably, the year 2008 shows a maximal freshening of more than 6 units (from 32.4 in May 2008 to 25.6 in August–September 2008). This freshening occurs simultaneously with the highest anomaly of G-B discharge over the period 2006–2011, observed in June–September 2008, with values reaching 120 000 m³.s⁻¹, suggesting that G-B discharge can partly contribute to the observed large-scale salinity anomaly in the BoB. Nevertheless, G-B discharge is not the only parameter controlling the SSS evolution in the Bay of Bengal, as other forcing factors such as precipitation, evaporation at air/sea interface
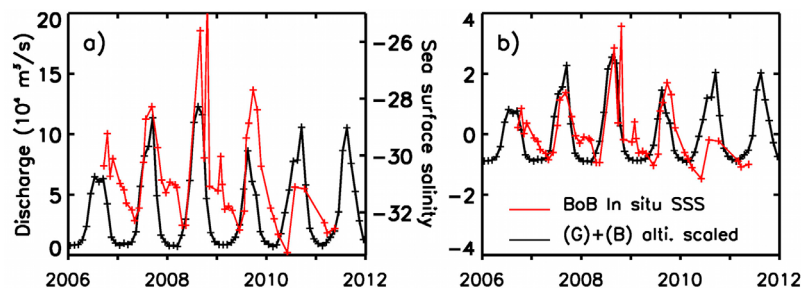

Figure 8. (a) Correspondence between the monthly variations of the satellite-derived Ganga-Brahmaputra river discharge (black line, left axis) at the river mouth (i.e., "$Q_{ALT/G+B}$ scaled") during 2006–2011 and the Bay of Bengal in situ sea surface salinity (red line, right axis). (b) Anomalies (obtained by subtracting the record mean value from individual value). Note that for visual purposes and for both Figures 8a and 8b, the SSS values are multiplied by −1.

and transport by oceanic circulation are also contributing to the SSS budget [*Durand et al.*, 2011]. Observations during 2010 indeed show a moderate freshening in the BoB, whereas G-B discharge has quite high values, $\sim$100,000 m^3.s^{-1}, during July–September 2010. Carrying out a thorough freshwater budget of the northern BoB and fully understanding the impact G-B discharge is clearly beyond the scope of the present paper, as it would require the setup of a dedicated numerical framework. However, the availability of our multiyear G-B discharge data set over almost two decades is a major step forward for future studies and to prescribe continental freshwater forcing flux in ocean circulation models.

4. Conclusion

[47] This study reports the use of Jason-2 radar altimeter observations to estimate the surface freshwater discharge of the Ganga-Brahmaputra river system into the Northern Indian Ocean for the period 2009–2011. The results represent an important update to the long-term satellite-derived estimates of continental freshwater forcing flux into the Bay of Bengal that were previously generated for 1993–2008 using river water level heights derived from TOPEX-Poseidon, ERS-2 and ENVISAT radar altimeters. Indeed, long-term, comprehensive and accurate estimate of G-B river discharge, the third largest freshwater outlet to the world ocean after the Amazon and the Congo Rivers, is central to better understand the Bay of Bengal regional climate variability and its impact on Asian monsoon. Nineteen years (1993–2011) of the new estimates of Ganga-Brahmaputra surface freshwater discharge into the Bay of Bengal is now available.

[48] First, we derive Jason-2 time series of water stage variations using the Virtual Altimetry Station software (VALS) for two virtual stations over the Ganga and the Brahmaputra for the period mid-2008 to December 2011. For both rivers, a large seasonal cycle is observed with annual height variations exceeding 8 m. Comparisons between satellite-derived and in situ river height measurements show a good agreement (R > 0.98 for both rivers for 2008–2011) and we estimated the standard error of 0.28 m for G and 0.19 m for H, i.e., less than 4% of the peak-to-peak yearly of variability of these two rivers and typically in the range of accuracy of altimetric observations over large rivers.

[49] Second, we apply the rating curve methodology to retrieve G and B river discharge using Jason-2–derived water level data. Two different approaches are considered and evaluated. One approach consists of establishing direct relationships between the altimeter-derived water levels at the satellite-river intersection and the in situ observed discharges. The second approach consists of using the official in situ rating curves constructed using simultaneous direct measurements of river height and river discharge. Using both approaches, Jason-2–derived water level measurements are then converted into instantaneous discharges every 10 days. Results show that Jason-2 satellite-derived discharges are in good agreement with the in situ discharges in terms of seasonal variations, with low/high flow season well depicted over the years. Jason-2 accurately infers Ganga and Brahmaputra instantaneous discharges with mean errors ranging from $\sim$2180 m^3/s (6.5%) over the Brahmaputra to $\sim$1458 m^3/s (13%) over the Ganga. We also conclude that, in general, the use of the in situ rating curve approach leads to better results that when the satellite-derived ones are considered. The limitations of the rating curve methodology as well as the limitations of the use of radar altimeter over large rivers and to retrieve the discharges are also discussed in details throughout the manuscript.

[50] The monthly Ganga, Brahmaputra and their aggregated discharges are presented for the period 1993–2011. For each river basin and their combined discharge, the seasonal and the interannual variations are well depicted with the annual low/high peak flows well captured. The combined Ganga-Brahmaputra monthly discharges meet the requirements of acceptable accuracy (15–20%) with a mean error of $\sim$16% when using Jason-2 only (for 2009–2011), in the same order of magnitude of the mean error of $\sim$17% found for 1993–2011 when using the suite of satellite altimeters.

[51] We then present the Ganga-Brahmaputra monthly discharge upscaled to the climatological estimates of *Fekete et al.* [2000] to represent the continental surface freshwater flux at the river mouths into the Bay of Bengal. The data set shows a marked interannual variability with annual peak-to-peak variability that can be as large as 50,000 m^3/s and a standard deviation over the record of $\sim$12500 m^3/s, much larger than the data set uncertainty.

[52] This unique data set over almost two decades, freely available to the scientific community represents an unprecedented source of information. First, it removes a crucial obstacle to significantly progress on several fundamental scientific questions related to the climate and its variability in the Bay of Bengal and surrounding continents. For instance, we briefly present a possible oceanographic interpretation of our G-B discharge data set, by comparing the year-to-year evolution of our discharge estimate with that of northern Bay of Bengal SSS. It shows the co-occurrence in 2008 of the highest oceanic freshening and of the highest freshwater river flux anomaly and suggests that the G-B discharge is a plausible candidate to explain (at least partly) the observed BoB large-scale salinity anomaly. Carrying out a thorough freshwater budget of the northern Bay is clearly beyond the scope of the present paper, as it requires the setup of a dedicated numerical framework. However, the availability of our multiyear G-B discharge data set is a major step forward toward such studies. Given the recognized implications of upper Bay of Bengal salinity stratification in the air-sea interactions of the area [e.g., *Vinayachandran et al.*, 2012], and on the Asian climate in general, we believe our study will allow to better address key oceanographic and scientific questions.

[53] Second, this new long-term data set will offer new opportunities to analyze other hydrological parameters over India and Bangladesh, such as continental freshwater storage variations [*Shamsudduha et al.*, 2012; *Tangdamrongsub et al.*, 2011; *Papa et al.*, 2008b; *Prigent et al.*, 2012]. It will also be useful for future hydrological studies in order to assess land surface model performances [*Decharme et al.*, 2012] or to study the influences of hydroclimatic variables on societal issues such as the transmission cycles of cholera in the Bengal Delta region [*Akanda et al.*, 2011].

[54] Finally, the Ganga-Brahmaputra river discharge data set will be soon extended to more months using current Jason-2 observations, with a possible goal of retrieving the satellite-derived discharge in near real time with a delay of

only few weeks. The observations of SARAL-AltiKa, the future Indo-French radar altimeter to be launched by the end of 2012, will be also used to provide a permanent update of this long-term satellite-derived estimate of continental freshwater forcing flux into the Bay of Bengal.

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