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Recent salinity intrusion in the Bengal delta: Observations and possible causes

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► **To cite this version:**

V.R. Sherin, Fabien Durand, Fabrice Papa, Akm Saiful Islam, V.V. Gopalakrishna, et al.. Recent salinity intrusion in the Bengal delta: Observations and possible causes. *Continental Shelf Research*, 2020, 202, pp.104142 -. 10.1016/j.csr.2020.104142 . hal-03490695

HAL Id: hal-03490695

<https://hal.science/hal-03490695>

Submitted on 22 Aug 2022

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38

39 Keywords: salinization, Bengal, Ganges-Brahmaputra-Meghna, sea level rise

40

41 **1. Introduction**

42

43 In estuarine and deltaic regions, salinity can be seen as an efficient tracer of the continent-
44 ocean water mass exchanges (Shammi et al., 2017). In the case of low-lying deltaic plains such as
45 the Bengal Delta, salinity exerts a prominent control on the economy and sanitary conditions of the
46 riparian societies. It is widely accepted that, beyond 0.6 - 1 unit (throughout this paper, salinity unit
47 will be considered without dimension, in the so-called Practical Salinity Scale - PSS), the water is
48 not suitable for drinking purpose (Akter et al., 2016; WHO, 2017). In the Bengal delta, water with
49 salinity in excess of 2 units is not usable for rice fields irrigation (Dasgupta et al., 2018). The recent
50 review of Rahman et al. (2019) emphasized the prominent threat of salinization for the Bengal
51 populations, from the point of view of livelihood, of food security as well as of public health. Chen
52 and Mueller (2018) identified salinization more than inundation as a prominent driver of human
53 migration within as well as outside the Bengal delta. This region is a very energetic hydraulic
54 continuum, which connects the Ganges-Brahmaputra-Meghna (GBM) river system, third largest
55 discharge to the ocean globally, to the adjoining Bay of Bengal (Fig. 1). This delta comprises the
56 full range of salinity conditions, from pure freshwater injected by powerful rivers in the north to
57 pure seawater (above 33 in the Practical Salinity Scale) at its southern estuarine outlets. The salinity
58 front separating the riverine fresh waters to the downstream Bay of Bengal salty water migrates
59 across the southern part of the delta, over a broad range of timescales (Rahman et al., 2017). The
60 Bengal delta is a macro-tidal area (Tazkia et al., 2017); at intra-daily timescales, the flood tide
61 pushes the salty waters towards the interior delta and the ebb tide pulls them back seaward,
62 typically by several kilometers (Sinha et al., 1999). Short-duration extremes such as tropical
63 cyclones can similarly induce massive flooding and associated brackish water intrusion in the
64 coastal belt (Akter et al., 2016). On the other side of the temporal spectrum, the long-term sea level
65 rise is known to induce a gradual salinization of the Bengal delta (Mitra et al., 2009; Banerjee,
66 2013; Shammi et al., 2017). At intermediate timescales, the seasonal alternation of the monsoons is
67 known to modify the salinity distribution over the delta, under the combined influence of the
68 monsoonal variability of the riverine freshwater flow and of the seasonal variability of sea surface
69 height (Sinha et al., 1996; Mirza, 2005; Rahman et al., 2017). At interannual timescales, little is
70 known about the variability of salinity over the delta, primarily on account of the dearth of long
71 enough observational records. Statistical models based on a few pointwise timeseries however
72 suggest a prominent response of the delta salinity pattern to the year-to-year variability of GBM

73 runoff (Mirza, 2005). Similarly, numerical models suggest that the year-to-year variability of the
74 GBM monsoonal runoff can induce marked variability of the whole northern Bay of Bengal salinity
75 (Durand et al., 2011; Akhil et al., 2014). In the context of ongoing climate change, resulting in an
76 expected gradual and continuous rise in eustatic sea level expected during the next decades (Brown
77 et al., 2018), a widespread questioning has recently emerged among the scientific community
78 regarding the long-term evolution of the salinity patterns in the Bengal delta (Clarke et al., 2015;
79 Dasgupta et al., 2015; Payo et al., 2017; Bricheno and Wolf, 2018). These questions are crucial,
80 knowing the primary dependency of the Bengal population on healthy soils and rivers for
81 agriculture. Whereas past studies generally agree about a gradual salinization to be expected
82 primarily in the south-central part of the delta, the quantifications of the salt intrusion and their
83 spatial patterns largely depend on the different methodologies and modeling frameworks used.
84 Dasgupta et al. (2015) for instance drew much more alarming conclusions than Payo et al. (2017) as
85 regards to the magnitude of the long-term salinization to be expected by 2100. Payo et al. (2017)
86 concluded that one key for reconciling the past divergent studies and for reaching more robust
87 conclusions may be to gather observational knowledge, for benchmarking and calibration of the
88 modeling systems in the current climate conditions.

89 Indeed, in spite of the above-mentioned studies, it appears that there is, even today, a lack of
90 observed data of the salinity variability across the Bengal delta, over the recent period. This may
91 partly explain the inconsistencies found among the above cited past salinity modeling studies.
92 Indeed, most of the *in situ* databases generally used are classified and/or partial, having only a short
93 time span (typically one year or less) and typically covering only one side of the India-Bangladesh
94 border. The objective of the present study is to present and analyze a consolidated, pluri-annual *in*
95 *situ* archive of rivers salinity, covering the whole Bengal delta. The Bangladesh part of our dataset
96 spans over one decade (2001-2011), and only a small subset of it has been analyzed up to now
97 (Rahman et al., 2017). The India part of our dataset, extending along the Hooghly River estuarine
98 region, covers three years (2014-2016); such a coverage is unprecedented over the area. The latter
99 dataset consists of primary data collected under this study.

100 The paper is organized as follows. Section 2 presents the datasets we used to analyze our
101 observations. Section 3 presents the seasonal evolution of salinity observed over the delta. In
102 Section 4, we reveal a sudden salinization that took place in the central part of the delta in the mid-
103 2000's, and we analyze the possible factors responsible for this phenomenon. Section 5 concludes
104 our study.

105

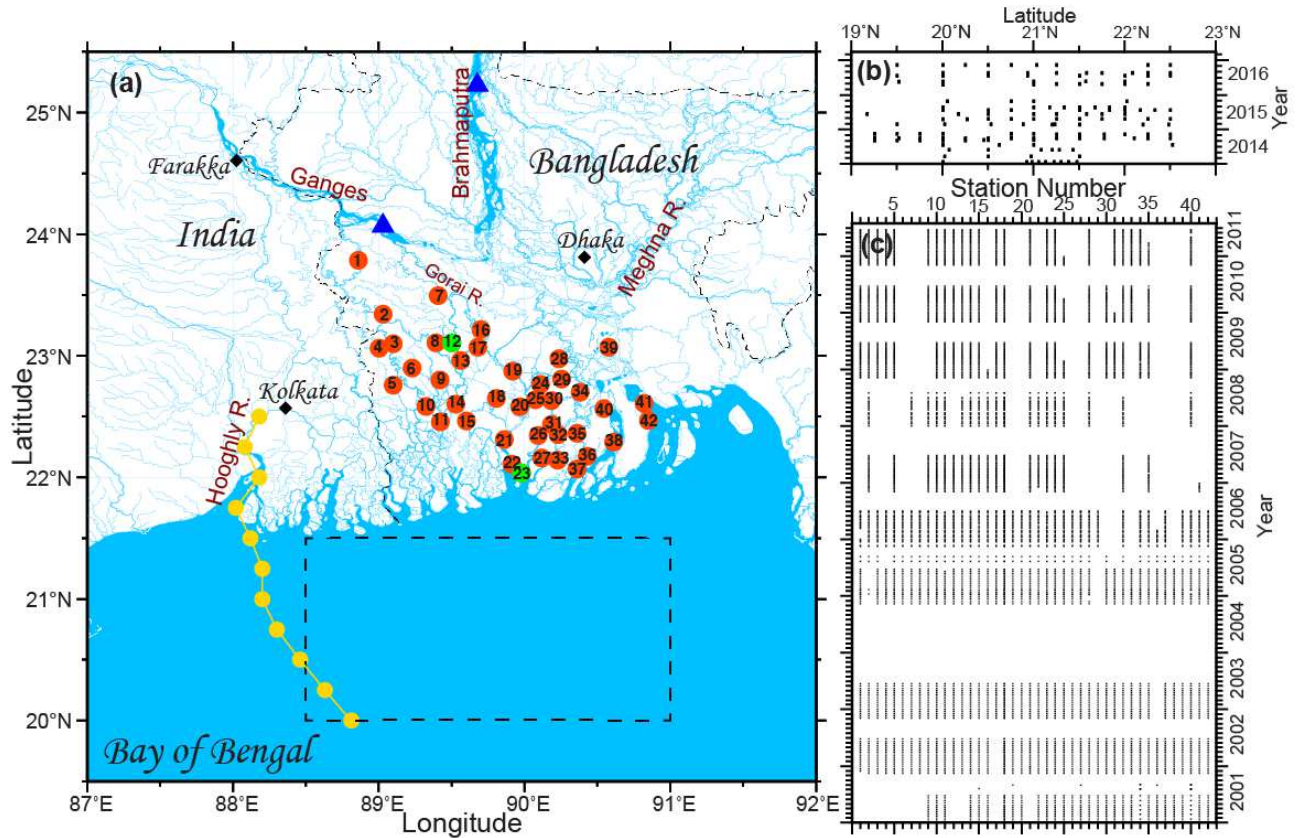
106 **2. Datasets and methods**

107

108 **2.1 Hooghly River salinity**

109 We use primary data of repeated shipborne salinity sections that were surveyed between the
110 head of Hooghly estuary (Kolkata harbour) and the open ocean, 150 km off the mouth of the
111 Hooghly (Fig. 1a). These sections were surveyed from bucket samples collected onboard passenger
112 ships plying between Kolkata harbour (at the head of Hooghly estuary) and Port Blair (in the
113 Andaman Islands). The open-ocean part of this original dataset was already used in the past studies
114 of Chaitanya et al. (2015) and Sherin et al. (2018). Bucket salinity samples were collected every 25
115 km on a typically monthly basis (though not strictly regularly) along the Hooghly River estuary,
116 between early 2014 and late 2016 (Fig. 1b). Salinity samples were subsequently analyzed following
117 standard international procedures using a Guild Line 8400 Autosol salinometer. After standard
118 quality control procedures were applied, we gridded the data along the transect on a grid with
119 uniform spatial resolution of 0.25°.

120



121 **Figure 1.** (a) Distribution of the observation stations. Red bullets show the salinity stations, with station numbers.
122 Green bullets show the stations where we also analyzed water level. Blue triangles show the river gauge locations.
123 The ship track with salinity data locations in Hooghly estuary is in yellow. Other locations discussed in the text
124 (e.g. Farakka dam) are displayed. The dashed box in the ocean features the domain considered for analyzing
125 altimetric sea level data. (b) Spatio-temporal coverage of salinity data in Hooghly River. (c) Spatio-temporal
126 coverage of salinity data for Bangladesh stations.
127

128

129

130 **2.2 GBM river salinity network in Bangladesh**

131 We use conductivity samples collected at 42 river stations in the GBM river network in
132 Bangladesh, as shown in Fig. 1a. The locations of the stations are provided in Table 1. River
133 salinity data have been collected from Bangladesh Water Development Board (BWDB) for
134 academic research in collaboration with the Institute of Water and Flood Management (IWFM) of
135 Bangladesh University of Engineering and Technology (BUET). From 2001 to 2011, electrical
136 conductivity of the rivers water was measured in situ from November to June, approximately 4
137 times per month on average, both during high tide and low tide (Fig. 1c). We then converted the
138 conductivity values to salinity following the UNESCO equation (Lewis and Perkin, 1981). In the
139 absence of temperature data at the time of conductivity data collection, we assumed the water
140 temperature was identical to the seasonal climatology of sea surface temperature of the northern
141 Bay of Bengal (90.5°E;21.5°N) in the North Indian Ocean Atlas climatology (Chatterjee et al.,
142 2012), at the time of collection. We checked that our results remain robust if this prescribed
143 temperature varies within an acceptable range. The temporal sampling at the various stations is
144 quite similar, with each year continuous records from the post-monsoon season (November) to the
145 following monsoon onset (July), and little or no data in the monsoon season. One exception is the
146 mid-2003 to late-2004 period, when no data are available. Monthly mean values of salinity were
147 then computed at each station using averaged high tide and low tide salinity.

148

Stn No.	Longitude (°E)	Latitude (°N)	Name
1	88.860	23.787	Hatboalia
2	89.030	23.342	Tahirpur
3	89.099	23.101	Jhikargacha
4	89.003	23.062	Navaron
5	89.098	22.757	Benarpota
6	89.228	22.901	Keshabpur
7	89.408	23.496	Magura
8	89.393	23.105	Afraghat
9	89.420	22.801	Dumuria
10	89.321	22.583	Paikgacha
11	89.422	22.457	Nalianala_Hadda
12	89.500	23.107	Gobrahat
13	89.560	22.960	Gazirhat
14	89.527	22.603	Chalna
15	89.600	22.464	Mongla
16	89.699	23.214	Bhatiapara
17	89.678	23.070	Bardia
18	89.807	22.648	Bagerhat
19	89.918	22.876	Patgati
20	89.966	22.582	Pirojpur
21	89.862	22.313	Rayenda

22	89.912	22.108	Chardoani
23	89.978	22.037	Patharghata
24	90.108	22.766	Swarupkati
25	90.074	22.640	Kawkhali
26	90.093	22.344	Bamna
27	90.117	22.159	Barguna
28	90.235	22.976	Gournadi
29	90.254	22.809	Uzirpur
30	90.183	22.630	Jhalokati
31	90.183	22.436	Betagi
32	90.230	22.352	Mirzaganj
33	90.225	22.143	Amtali
34	90.380	22.700	Barisal
35	90.360	22.362	Patuakhali
36	90.428	22.173	Galachipa
37	90.359	22.068	Gulbunia
38	90.610	22.289	Dasmunia
39	90.576	23.069	Nilkamal
40	90.543	22.566	Dhulia
41	90.820	22.611	Daulatkhan
42	90.850	22.469	Tajumuddin

Table 1. List of salinity stations with their positions

149

150

151 **2.3 *In situ* hydrological observations in the GBM Delta**

152 To analyze the relationship between salinity variability and freshwater supply from the
153 upstream delta, we use *in situ* river water level and river discharge observations over the GBM in
154 Bangladesh collected by the Bangladesh Water Development Board (BWDB)
155 (<http://www.bwdb.gov.bd/>). The water level data consist of measurements collected daily at 2
156 stations of the salinity network (Fig. 1a), viz. stations #12 and #23, over the period 2001-2011. The
157 discharge data consist of daily time series, covering 2001-2014, of the Ganges and Brahmaputra
158 observed at the two basin outlet stations before the confluence of the two rivers, as shown in Fig.
159 1a: the Hardinge Bridge station (24.07°N;89.03°E) for the Ganges, and the Bahadurabad station
160 (25.15°N;89.70°E) for the Brahmaputra. We computed monthly averages from the daily timeseries.

161

162 **2.4 Groundwater level variations**

163 In the Bengal delta, the rivers exchange water with the surface water reservoirs, with
164 sensible effect on the rivers salinity variability (Nobi and Gupta, 1997; Bhuiyan and Dutta, 2012).
165 In order to investigate the possible role of groundwater in the delta salinity variability, we use
166 groundwater level variations simulated over the delta by Khaki et al. (2018). They used the World-
167 Wide Water Resources Assessment (W3RA) hydrological model of Van Dijk (2010), assimilating

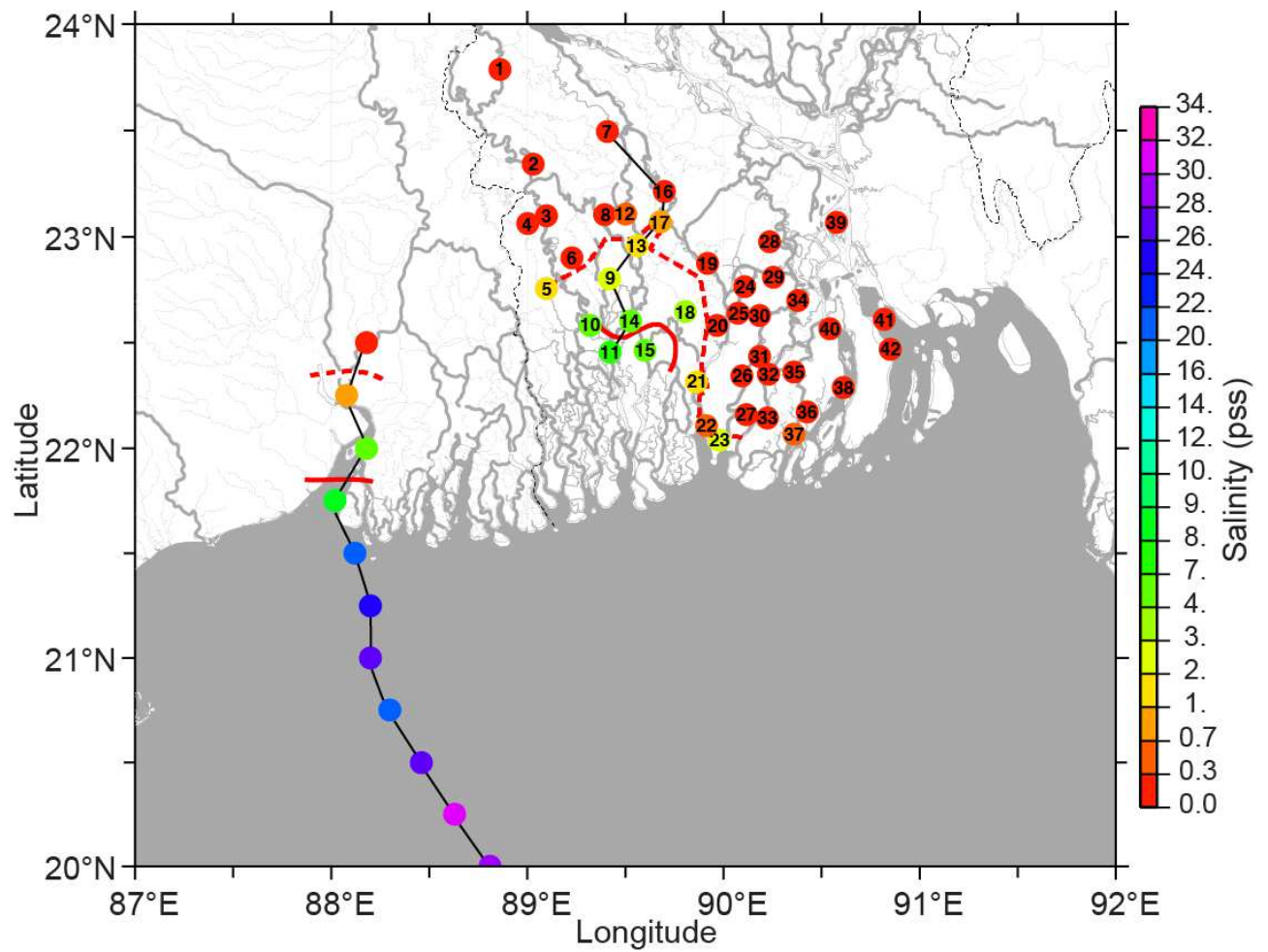
168 data of groundwater storage change obtained from a combination of terrestrial water storage data
169 from the Gravity Recovery And Climate Experiment (GRACE) and surface water storage from
170 multi-satellite dataset (Papa et al., 2015). These outputs were extensively validated and the reader is
171 referred to Khaki et al. (2018) for further details. The modeled groundwater level variations are
172 available over Bangladesh on a monthly basis over 2003-2013. The data were normalized by
173 dividing the time series at each grid point by their standard deviation. Then long-term linear trends
174 were computed on the normalized time series.

175

176 **2.5 Sea level anomaly**

177 The variability of eustatic sea level is an obvious driver of the salinity variability in the
178 delta. To investigate this effect, we use the merged gridded product of sea level anomaly (SLA)
179 based on multiple satellite missions (T/P, ERS-1/2, followed by Jason-1/2 and Envisat), distributed
180 by Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO,
181 <https://www.aviso.altimetry.fr/en/data.html>). These data have been widely used in countless studies
182 of the northern Bay of Bengal oceanography (e.g. Durand et al. (2008) and references therein). The
183 data are daily, with a spatial resolution of 0.25° . Here, we averaged these data into monthly means,
184 covering the period 2001-2011, and spatially averaged over the northern Bay of Bengal rectangular
185 box ($2.25^\circ \times 1.25^\circ$) shown in Fig. 1a.

186



187

188 **Figure 2.** Long-term mean of salinity at all stations. The red dashed/solid line indicates the
 189 climatological position of the 2 units isohaline in April/August, respectively. The thin black lines
 190 feature the central and western sections displayed in Fig3a and 3b, respectively
 191

192 **3. Mean and seasonal evolution of salinity over the Bengal delta**

193

194 Fig. 2 shows the long-term mean salinity observed over the delta. The salinity is well
 195 contrasted at the scale of the delta, with a sharp, crescent-shaped separation between fresh waters
 196 (salinity less than 0.3 unit, stations #6-8-16-19-20-22, and all other stations located to the north and
 197 east of these) in the northern and eastern part, and salty waters (salinity superior to 2 units, stations
 198 #5-9-13-18-21-23 and all other stations located to the south of these) in the south-central part. The
 199 salinity level in the western part of southwestern Bangladesh, which mainly receives water from the
 200 Gorai River, remains generally higher than the eastern part fed by more powerful rivers such as the
 201 Brahmaputra, Meghna and their tributaries. The annual mean salinity in the Hooghly river transect
 202 also shows a frontal region, with values less than 0.3 unit at the northern edge of the section
 203 (22.5°N, Kolkata harbour) and values superior to 4 units 50 km further to the south, southward of
 204 22°N.

205 On account of its socio-economic relevance (Dasgupta et al., 2017), the position of the 2-
206 units isohaline is also displayed, both for the April and August climatological conditions. These two
207 months respectively correspond to the landward/seaward extreme positions of this isohaline, during
208 its seasonal migrations. The 2-units isohaline can be considered as a good proxy of the salinity front
209 (Bricheno and Wolf, 2018; Fig. 3ab). Over the central part of the delta, its seasonal march extends
210 over about 30 to 50 km in the north-south direction (between stations #10-11-14-15 in August-
211 September and stations #5-6-13 in April-May; Fig 3a), and over about 10 km in the east-west
212 direction (between stations #15-18 in August and stations #20-21 in April). A more precise
213 characterization of the front migrations is however not possible, given the limited spatio-temporal
214 resolution of our observing network. Over the inner Hooghly estuary, the seasonal march of the 2-
215 units isohaline is of the same order, with a landward migration of about 50 km from August to
216 April, and vice-versa from April to August.

217 The mean and seasonal picture captured by our dataset is grossly in line with the previously
218 published descriptions (Sinha et al., 1996, 1999; Mirza, 2005; Mukhopadhyay et al., 2006; Mitra et
219 al., 2009; Clarke et al., 2015; Rahman et al., 2017; Shammi et al., 2017). The forcing factors of this
220 seasonally-evolving pattern have been studied by numerical modeling (Sinha et al., 1996, 1999;
221 Nobi and Gupta, 1997; Bhuiyan and Dutta, 2012) or statistical modeling (Mirza, 2005). From these
222 past studies, it appears that three factors can play a role in the variability of delta salinity: the
223 variability of sea level, of the tidal amplitude and of the freshwater discharge from the rivers.
224 Brackish waters progress landward in the delta when sea level increases and/or when the tidal
225 amplitude increases and/or when the rivers discharge decreases. In addition, this simple picture can
226 be significantly distorted due to water seepage between the rivers and the adjoining aquifers (Nobi
227 and Gupta, 1997; Bhuiyan and Dutta, 2012; Payo et al., 2017).

228 It is important to investigate specifically the salinity of the Hooghly River (Fig.3b), as the
229 descriptions published so far were based on very limited datasets and numerical modeling, and were
230 largely inconsistent. For the first time, we have access to repeated, synoptic transects, consistently
231 spanning the whole stretch of the estuary and the adjoining oceanic outflow region. Indeed, it was
232 found in the past studies that the river plume, once it has entered the open ocean, is subject to

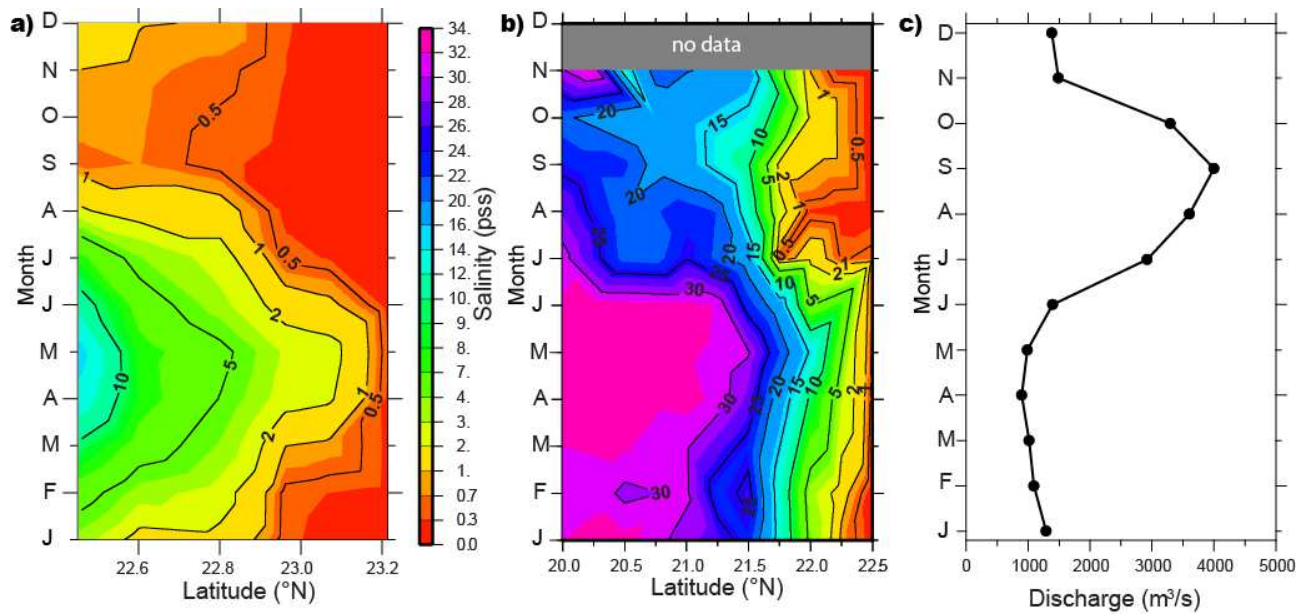
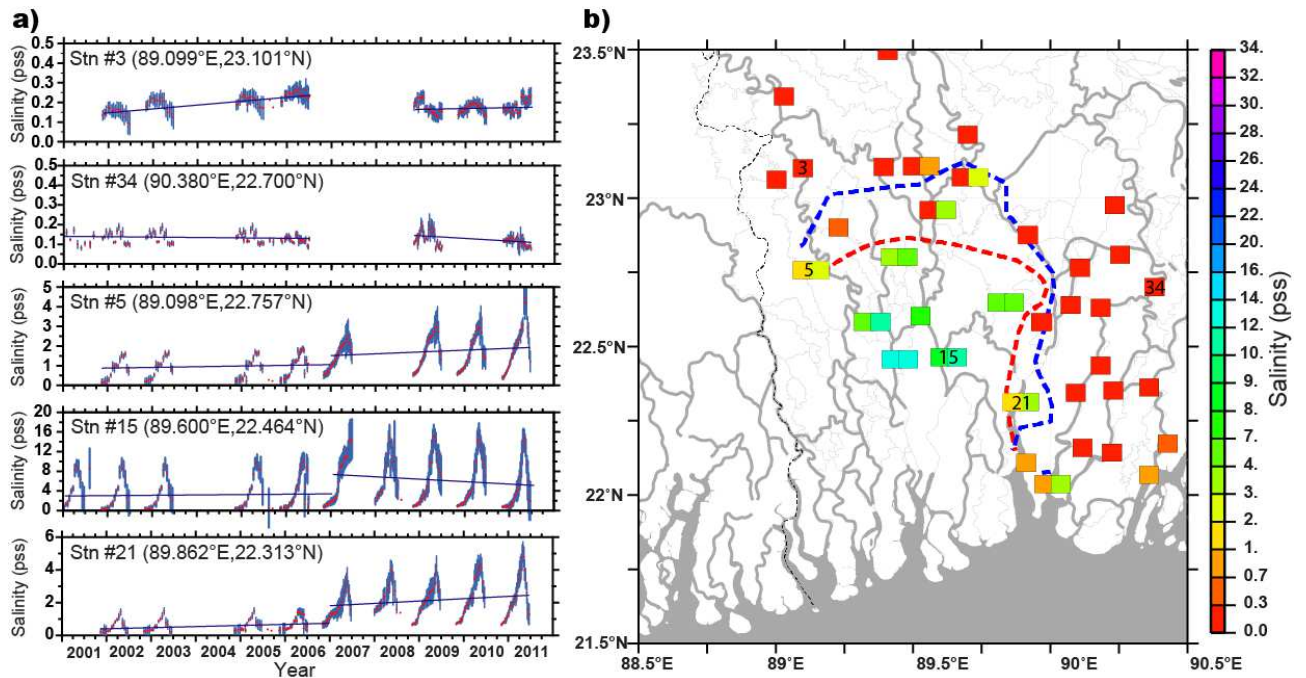


Figure 3. (a) Latitude-time distribution of the monthly climatology of salinity data for the central section. (b) Latitude-time distribution of the monthly climatology of salinity data for the Hooghly estuary. (c) Evolution of monthly climatology of Hooghly river discharge from Mukhopadhyay et al. (2006).

233
 234
 235
 236
 237
 238 intense mixing with the ambient salty waters, and as such provides a relevant test case for the
 239 calibration and validation of estuarine salinity numerical models (Sinha et al., 1999; Durand et al.,
 240 2008; Bricheno and Wolf, 2018). For instance, Sinha et al. (1996) reported a moderate salinity
 241 intrusion at the mouth of the estuary in the pre-summer monsoon (salinity value of 12 units, in June)
 242 whereas Sinha et al. (1999) and Mukhopadyay et al. (2006) observed much more saline waters there
 243 (19 to 23 units). Our dataset shows a clear sign of saline water intrusion in the pre-summer
 244 monsoon season, with values around 25 units at the mouth (21.5°N) in May-June. The seasonal
 245 evolution of salinity in the Hooghly completely follows the seasonality of the region's hydrology
 246 (Fig.3b). In the subsequent monsoon, following the gradual increase of Hooghly river discharge
 247 (from 1000 m³.s⁻¹ to 4000 m³.s⁻¹, Fig.3c), salinity decreases at the mouth, down to values close to
 248 10 units in September. Salinity also starts dropping off the mouth. By September, the 20 units
 249 isohaline has shifted offshore, to 20°N (more than 100 km off the mouth). The river discharge then
 250 starts decaying, with a rapid collapse between October and November, when it stabilizes around
 251 1000 m³.s⁻¹. One month after the peak of the river discharge, in October, salinity starts increasing in
 252 the lower Hooghly estuary (south of 22°N) as well as further offshore. By January, the whole fresh
 253 plume has disappeared from the open ocean, replaced by salinity values above 20 units
 254 offshoreward of the river mouth. The salinity evolution is characterized by an abrupt freshening of
 255 the estuary during summer monsoon. Whereas the monsoonal increase of river discharge is rather
 256 gradual from June to September, the southern limit of the fresh water zone (salinity inferior to 2
 257 units) suddenly shifts southward in July, from the upstream limit of the estuary (22.5°N) to the
 258 mouth of the estuary, 100 km to the south. The short time span of this shift (of order one month,
 259 possibly less as our dataset does not resolve intra-monthly timescales) has not been reported before,

260 to the best of our knowledge. At the northern edge of our section, at 22.5°N, the salinity shows
 261 weak variability, and consistently remains inferior to 1 unit, even during the low-flow pre-monsoon
 262 season (April-May). It is known that the discharge of the Hooghly during April – May is mainly
 263 maintained by the diversion of the Ganges river water from the Farakka Barrage to provide
 264 sufficient water level heights for ship operations into Kolkata harbour, and prevent its siltation
 265 (Mirza, 2005). Tidal rivers east of the Hooghly show higher salinity values, especially during pre-
 266 monsoon (Banerjee, 2013). Thus, the low salinity values in the upper Hooghly estuary may be
 267 considered as artificially maintained.



268
 269 **Figure 4.** (a) Timeseries of salinity observed at selected stations (red points). The blue vertical bars in all panels feature
 270 the year-to-year standard deviation, computed month-wise, separately over the 2001-2006 period and over the 2007-
 271 2011 period. For each of these two periods, we superimpose the linear fit in thin solid line. (b) Salinity climatology in
 272 April, with the positions of the pre-2006 (red) and post-2007 (blue) 2 units isohaline. The right-shifted squares in
 273 certain stations show the April climatological salinity computed over the post-2007 period only.
 274

275 **4. An abrupt salinization of the Bengal delta in 2006-2007**

276 277 **4.1 Observed shift in river salinity**

278 Beyond the regular, seasonal evolution described in the previous section, intimately linked with the
 279 monsoonal cycle, we investigated the pluri-annual variability of our salinity dataset. We restricted
 280 our analysis to the decade-long Bangladesh stations, as the Hooghly data sub-set has a relatively
 281 shorter time span. Fig. 4a shows the evolution of salinity for few selected stations, for 2001-2011.
 282 For all of them, the broad seasonal evolution discussed in Section 3 is seen every year, with low
 283 salinity during summer monsoon and in the following months, and higher salinity in pre-monsoon;
 284 the amplitude of the seasonal evolution is stronger for the southern stations than for the ones located
 285 further inland, as expected. However, it is striking to see that, for the southern stations (#5, 15, 21),

286 the amplitude of the pre-monsoon salinization is much stronger in 2007 and beyond, compared to
 287 the pre-2006 period. For instance, at station #15, the yearly peak never exceeds 10 units from 2002
 288 to 2006, whereas it consistently reaches 15 units in every year of the 2007-2011 period. We assess
 289 this change by comparing the pre-2006 climatology with the post-2007 climatology, for station #15
 290 (Fig. 5). We can see that, throughout the high-salinity season, the post-2007 monthly values exceed
 291 the pre-2006 values by more than one interannual standard deviation. Similarly, at station #21, the
 292 yearly peak hardly reaches 1.5 units in 2002-2006 whereas it exceeds 3.5 units in all subsequent
 293 years (Fig. 4a). This offset in the magnitude of the seasonal salinization before/after 2006 is
 294 observed at all stations located in the crescent-shaped frontal region (Fig. 4b). For these stations, we
 295 computed the climatological April salinity (coinciding with the seasonal maximum, for all of them),
 296 distinguishing the pre-2006 and post-2007 periods. Clear differences are seen, consistently showing
 297 a recent rise in the magnitude of the seasonal salinization, typically amounting to a 50% increase.
 298 This is reflected in the linear fits we estimated, separately for the pre-2006 period and for the post-
 299 2007 period (Fig. 4a). It is seen that the long-term evolution of the salinity is stable during both
 300 periods, for all stations. The pre-2006 and post-2007 mean salinity values are shown in Table 2.

301

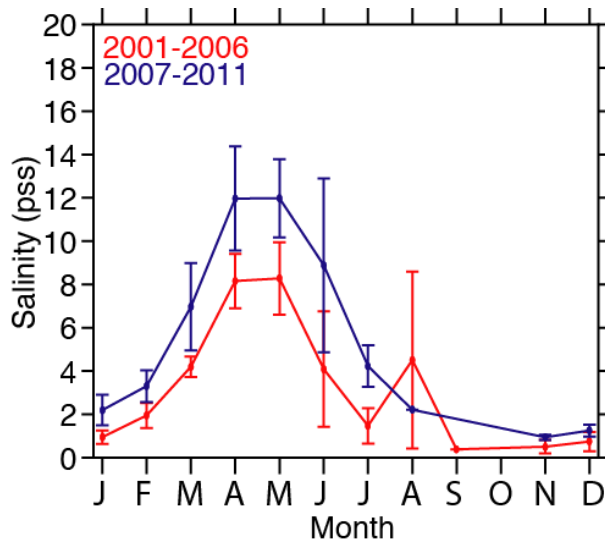
Stn No.	2001-2006 mean salinity	2007-2011 mean salinity
5	0.9	1.7
15	3.5	6.1
21	0.6	2.1

302 Table 2. Pre-2006 and post-2007 mean salinity values for selected stations.

303

304 In the post-2007 period, stations #5 and #21 show a moderate increasing trend of +0.1 unit per year,
 305 and station #15 shows a moderate decreasing trend of 0.4 unit per year. These values are weak,
 306 compared to the shifts of +0.8 unit / +1.7 units / +2.6 units respectively for stations #5, #21 and #15,
 307 observed when comparing the pre-2006 mean with the post-2007 mean. In terms of spatial extent of
 308 the seasonal intrusion of brackish waters, the shift amounts to a landward retreat of the April 2-unit
 309 isohaline by about 20 km, throughout the central part of the delta (between 89°E and 90°E), and
 310 could be seen as a potential loss of domain where the water is usable for human needs and for
 311 irrigation purpose. This shift, happening in only one season between the 2006 monsoon and the
 312 2007 monsoon, is considerable. In fact, it appears to be commensurate with the 20 km shift of the
 313 salinity front that is expected to take place gradually over the same region in the course of the whole
 314 21st century, as a response to global sea level rise (Bhuiyan and Dutta, 2012). Noteworthy, we do
 315 not observe any restoration of the salinity to the pre-2006 levels, subsequently. In contrast, the fact

316 that stations #3 and #34 do not show any evidence of regime shift after 2006 reveals that the
317 salinization is restricted to the south and to the west of these, respectively.



318

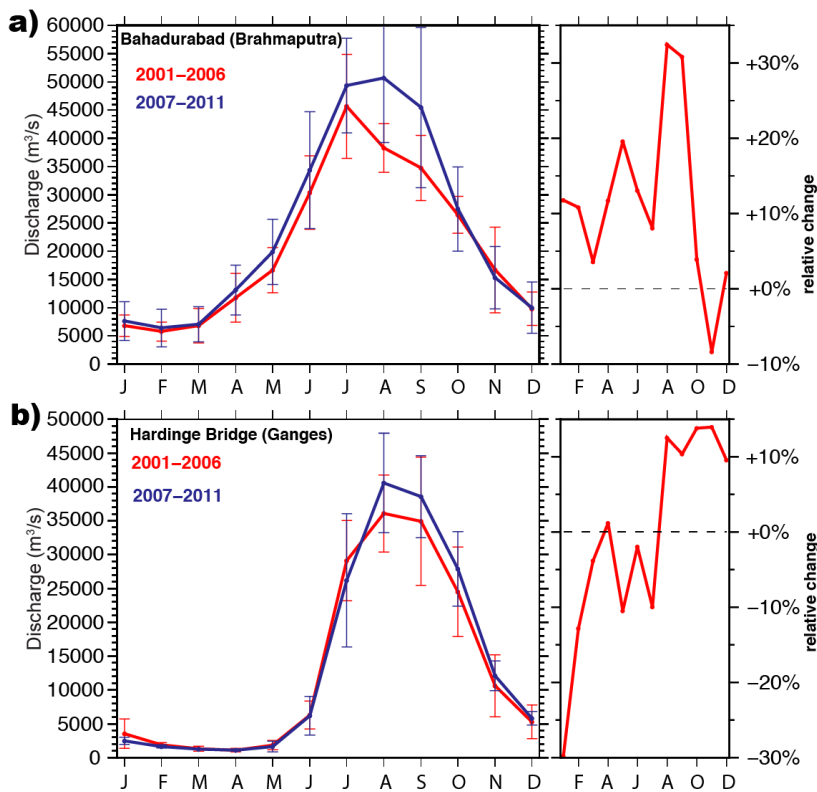
319 **Figure 5.** Monthly climatology of salinity observed at station
320 #15 (89.600°E, 22.464°N), distinguishing the pre-2006 (red)
321 and the post-2007 (blue) periods.

322

323 **4.2 Assessment of the possible forcing factors of the salinity shift**

324 As the abrupt shift revealed by our dataset has never been discussed in the literature, we try to shed
325 light on the underlying causative factors, by investigating them sequentially. The past studies
326 revealed that the spatio-temporal evolution of the salinity front in the river network of the Bengal
327 delta results from the competition of various processes, namely the magnitude of the freshwater
328 river discharge, the sea level at the coast and the seepage to/from the adjacent aquifers (Clarke et
329 al., 2015). In addition, human activities like water diversion, polderization (viz. areas enclosed by
330 embankments) and extensive irrigation have the potential to distort the dynamics of the seasonal
331 brackish waters intrusion (Nobi and Gupta, 1997; Mirza, 2005; Bhuiyan and Dutta, 2012). In this
332 section we attempt to document which of these factors might have contributed to the 2006-2007
333 observed salinity shift. Our goal here is not to quantify the relative importance of the various
334 possible forcing factors, but simply to point which ones are consistent with the observed
335 salinization, and which ones are not.

336



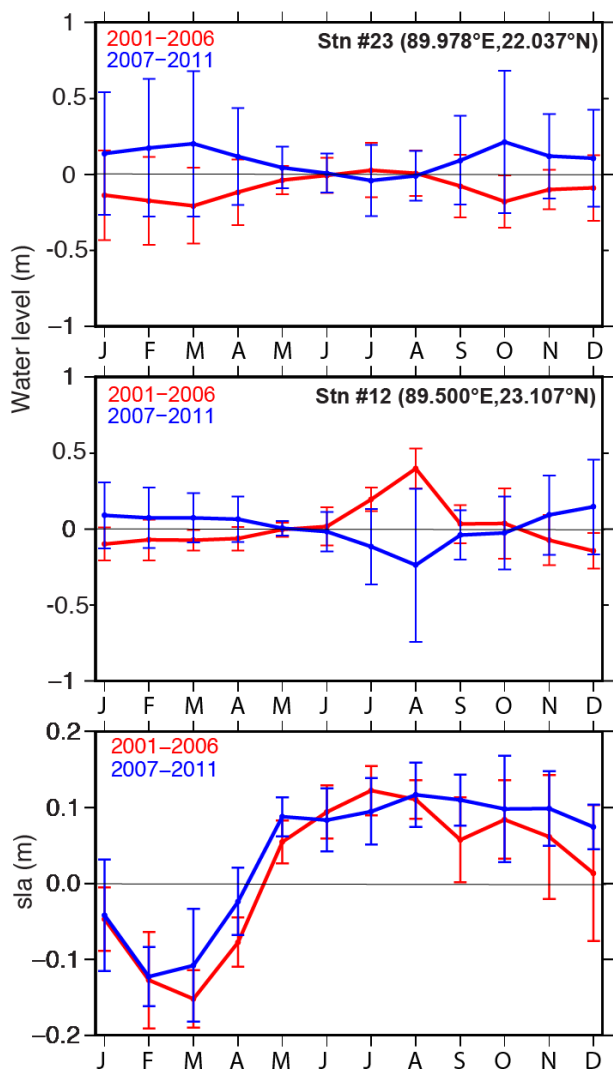
337

338 **Figure 6.** Monthly climatology of river discharge for the Brahmaputra (top left) and
 339 for the Ganges (bottom left), distinguishing the pre-2006 (red) and the post-2007
 340 (blue) periods. The right panels show the corresponding relative change between the
 341 two periods, expressed in percent of the pre-2006 values.
 342

343 4.2.1. River discharge

344 The variability of the flux of fresh water supplied by Ganges, Brahmaputra, and Meghna rivers
 345 plays a major role in the overall salinity level in the delta (Mirza, 2005; Rahman et al., 2017). Of
 346 these three streams, the western-central part of the delta is mainly fed by the Ganges water only,
 347 whereas the fresher eastern delta is fed jointly by the three rivers. The fresh water from Ganges is
 348 mainly transported to the central delta region by the Gorai River (Fig. 1) (Rahman and Rahaman,
 349 2017). Fig. 6 shows the monthly climatology of Ganges discharge observed at Hardinge Bridge and
 350 Brahmaputra discharge observed at Bahadurabad (see stations location in Fig. 1). The Ganges
 351 observing station is located just upstream of the origin of Gorai River. We distinguished the 2001-
 352 2006 period and the 2007-2011 period to compute the respective monthly discharge climatologies.
 353 For both rivers, the seasonal evolution of the discharge is grossly consistent over both periods, with
 354 low flow in January-April and a subsequent increase through the summer monsoon. However, a
 355 close examination in the low-flow season reveals significant contrasts. For the Ganges, we observe
 356 that all months from January to July show lower discharge in the post-2007 period compared to the
 357 pre-2006 period (Fig. 6b). The decrease ranges from 30% (in January) to 10% or less (in subsequent
 358 months). The significance of this reduction stems from the fact that the Ganges has to maintain a
 359 mean monthly discharge close to 1800 to 2000 m³/s to contain the salinity within the permissible
 360 limit for human consumption during February to April (Mirza, 2005). The climatological discharge

361 at Hardinge Bridge is far inferior to this, being around 1100 to 1600 m³/s during February – April.
 362 Although in pre-2006 period the Ganges discharge is not always within the minimum requirement,
 363 this post-2007 drop could have contributed to the sudden salinization. It is reasonable to think that
 364 this influence could have reached the south-central part of the delta through the Gorai River
 365 network, although no discharge data of the Gorai River are available to confirm this. In contrast, the
 366 discharge of Brahmaputra is seen to increase in the post-2007 period compared to pre-2006 period,
 367 typically by 10% for all months in the low flow season. This recent excess supply of fresh water –
 368 though moderate and within the range of year-to-year variability– may have contributed to keep the
 369 eastern part of the delta, including the Meghna estuary, comparatively fresher throughout the
 370 decade of observation, with no visible shift in 2006-2007. It has to be noted that, in the downstream
 371 part of the delta (station #15), the post-2007 salinization is not restricted to the low-flow season, but
 372 also spans the flood season (Fig. 5); however, both river discharges show an increase in the
 373 upstream flood discharge (August-September; Fig. 6), in the post-2007 period. This shows that the
 374 riverine forcing does not play a role in the salinization observed during the flood season.



375

376 **Fig 7.** (top) Monthly climatology of river water level observed at station #23, for the pre-2006 (red)
 377 and the post-2007 (blue) periods. The monthly climatology of river water level has been removed,

378 for clarity. (middle) Same, for station #12. (bottom) monthly climatology of altimetric sea level
379 averaged over the box displayed in Fig. 1, for the pre-2006 (red) and the post-2007 (blue) periods.
380 The vertical bars in all panels feature the year-to-year standard deviation, computed month-wise.

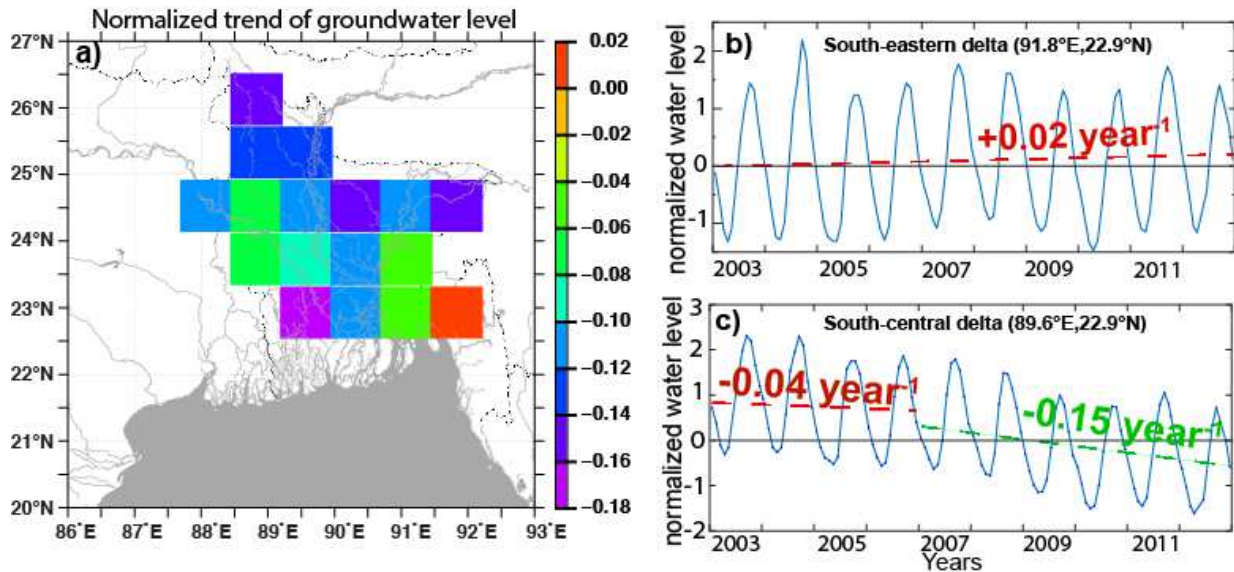
381 382 4.2.2 Sea level and river water level

383 Sea level rise was also identified as a prominent driver of Bengal delta salinization (Bricheno et al.,
384 2016; Rahman et al., 2017). So as to infer the potential role of sea level on the 2006-2007 salinity
385 shift, Fig. 7 shows two *in situ* tide gauge records (displayed in green in Fig. 1), along with sea level
386 anomaly from spaceborne altimetry in the northern Bay of Bengal (black box in Fig. 1). For both
387 the datasets, a clear upward shift in sea level is observed in the pre-monsoon season (December to
388 May), typically of 20 cm at the southern station (station #23), 15 cm at the northern station (station
389 #12), and 5 cm in altimetry. These shifts are significant, as they lie outside the bounds of the year-
390 to-year variability, both for *in situ* gauges and for altimetry. Strictly speaking, the two observational
391 systems do not monitor the same variable, as the *in situ* gauges measure the relative sea level
392 (including the contribution of possible vertical land motions at the gauging site), whereas altimetry
393 measures eustatic sea level. This said, vertical land motions are known to be at most of order a few
394 mm/year over the Bengal delta (Pethick and Orford, 2013). This is at least one order of magnitude
395 inferior to the shifts observed by both the *in situ* tide gauges and altimetry. This water level rise
396 could have induced a significant salinity intrusion going in hand with the decrease in the river
397 discharge. Station #23 being close to the coast, its similarity with the altimetric sea level is quite
398 natural. However, station #12 exhibiting similar water level rise suggests that this may be due to the
399 ingress of seawater. We can rule out the increase in river water level being due to river runoff there,
400 as during the same period we noted a lower discharge. The mid-2000's sea level rise evidenced from
401 altimetry is not restricted to the Bengal coast, but concerns the whole Northern Indian Ocean
402 (Srinivasu et al., 2017). It is part of a large-scale re-distribution of ocean heat, possibly involving
403 the whole Indo-Pacific basin (Lee et al., 2015).

404 405 4.2.3 Groundwater level

406 Clarke et al. (2015) reviewed the various processes responsible for the variability of Bengal delta
407 salinity, and pointed towards dry-season irrigation demand and associated depletion of the
408 groundwater level. The seepage of river water towards the adjoining groundwater reservoir was also
409 assessed in the modeling studies of Nobi and Dasgupta (1997) or Bhuyian et al. (2012), at seasonal
410 and inter-decadal timescales respectively. They concluded that this seepage can significantly alter
411 the march of the salinity front across the Bengal delta. We attempted to assess the possible role of
412 this factor by examining state-of-the-art groundwater reanalysis products. We considered the
413 groundwater data-assimilating modeling product of Khaki et al. (2018) as described in Section 2.
414 Over Bangladesh, this study reported a significant decline in groundwater storage (\square 32% reduction)

415 for Bangladesh between 2003 and 2013. Fig. 8 shows the map of normalized groundwater level
 416 trend for the period 2003–2013. It is seen that there is a general decreasing trend throughout the
 417 delta, over our period of interest. This water level depletion is mainly related to excessive irrigation
 418 for agricultural purposes in the recent period (Shamsudduha, 2013; Khaki et al., 2018). We
 419 extracted two significant and contrasted locations in the model outputs: the region where we
 420 observe the shift in salinization in 2006-2007 (south-central delta, purple square on the map in Fig.
 421 8a) and a location to the east of the mouth of Meghna, where no groundwater depletion is seen
 422 (south-eastern delta, orange square in Fig. 8a).



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Fig 8. (a) Normalized long-term trend of groundwater level in the hindcast of Khaki et al. (2018). Timeseries of normalized groundwater level extracted at the two locations showing orange shade (for b) and purple shade (for c) in panel (a). The linear tendency lines are superimposed, along with the corresponding values of the tendencies. For (c), we computed separately two tendency lines, over 2003-2006 and over 2007-2012.

429 The 2003-2012 timeseries of the hindcast water level are displayed in Fig. 8bc. Both locations show
 430 a prominent seasonal cycle, with low water table in the dry season, and high water table during and
 431 after monsoon. What is striking is the regularity of this seasonal cycle in the south-eastern delta,
 432 with a moderate long-term rise of the water level over this decade, compared with the prominent
 433 negative trend seen in the south-central delta. The decreasing trend is 3-4 times stronger in the post-
 434 2007 period compared to the pre-2006 period. Based on possible influence of seepage on the salt
 435 and freshwater exchanges evidenced in the Bengal in the above-cited studies, the evolution seen in
 436 the hindcast of Khaki et al. (2018) has the potential to influence the sudden salinization we
 437 observed in 2006-2007. Indeed, groundwater storage depletion can significantly impact
 438 groundwater contribution to river stream during pre-monsoon with large groundwater baseflow
 439 reduction, as reported for instance in Mukherjee et al. (2018).

440
 441

5. Conclusion

442

443 Our study confirms that the large-scale distribution of salinity across the Bengal delta is far
444 from uniform. The saline waters consistently occupy the south-central part of the delta, and are
445 separated from the freshwaters in the upstream part by a sharp salinity front. This front has a
446 crescent shape, extending from the southern part of the Hooghly River in the west, to the Gorai
447 River in the east. Further to the east, the delta is essentially composed of freshwaters. We show that
448 this front migrates landward/seaward during the dry/monsoon season respectively, by 20 to 40 km
449 typically. This pattern of evolution is broadly consistent with the previous estimates, although our
450 pluri-annual dataset revealed some marked differences locally with studies based on older and less
451 extended observations. Beyond this periodic sea-saw, we revealed a massive salinity intrusion,
452 which occurred during the 2006-2007 dry season. This intrusion resulted in a landward shift of the
453 salinity front by about 20 km, throughout the central part of the delta. Such a significant shift has
454 never been reported before and is commensurate with the long-term salinization expected to occur
455 in the delta over the whole 21st century, under the effect of the changing climate. By 2011, the last
456 year of available observations, there was still no sign of a subsequent recovery of the delta salinity
457 to the pre-2006 conditions. Since the spatio-temporal evolution of salinity in the river network of
458 the Bengal delta results from the competition of various processes, we tried to identify which
459 factors might have contributed to the 2006-2007 salinity shift, knowing that these factors may act
460 independently or in concert. Over our period of interest, we could document that three possible
461 drivers of this salt intrusion were potential contributors: the decay of Ganges river discharge, the
462 rise of the eustatic sea level in the northern Bay of Bengal, and the depletion of the groundwater
463 level in the central part of the delta. Beyond these processes, rapid-onset events such as cyclonic
464 surges and associated coastal flooding of salt water, essentially unresolved by the temporal
465 sampling of our dataset, need to be assessed in view of the results reported here.

466 Our study presents a relevant test-case for the development, calibration and validation of the
467 future generation of numerical models of the salinization of the delta. In the context of drastic
468 environmental changes expected to occur over the delta in a changing climate, added to the
469 profound impact of the local human activity on the water resource, such models are strongly
470 needed. In particular, it is needed to ascertain the exact processes possibly responsible for the salt
471 intrusion we report, among the three factors we identified. Only models capable of realistically
472 hindcasting such a phenomenon may be used to forecast the details of the evolution of the delta
473 salinity over the 21st century. As our assessment of the salinization factors we identified is
474 essentially qualitative, our study calls for an integrated modeling framework, considering the
475 hydrodynamical continuum (rivers-estuaries-ocean) as well as its coupling with the groundwater

476 compartment, as our observations suggest that none of these hydrological components should be
477 excluded a priori.

478 The observed sudden intrusion of the salinity front inside the delta may have had profound
479 implications in terms of land use and agricultural practices. These remain to be analyzed, in light of
480 the above findings.

481 Obviously, the observational coverage of our dataset leaves the eastern edge of Indian
482 territory (between 88.5°E and 89°E) completely void. Knowing the ecological value of this
483 mangrove region (Mirza, 2005), the challenges that this unique ecosystem will face in the context of
484 climate change need to be documented. It is also unfortunate that the salinity data collection effort
485 in the Hooghly estuary started too late to monitor the years of regime shift we report on the central
486 part of the delta (2006-2007). These issues call for the implementation of a sustained observing
487 network over this area, ideally covering the entire delta.

488 Finally, the salinization of the Bengal delta and the various potential forcing factors we
489 identified (sea level rise, depletion of riverine freshwater discharge and depletion of the water table)
490 are issues of relevance for the other tropical deltas as well, as they are known to face -at least partly-
491 similar environmental changes (Becker et al., 2019, and references therein). Our study calls for
492 similar investigations in these vulnerable regions.

493

494 **Acknowledgements**

495 SVR, FP and FD were supported by the CNES-TOSCA program via the BANDINO project and by
496 the French research agency (Agence Nationale de la Recherche; ANR) under the DELTA project
497 (ANR-17-CE03-0001). SVR, FP and FD were hosted by IFCWS-IRD-IISc, Bangalore, India during
498 part of this work. FD was hosted by LIENSs - Université de La Rochelle, France during part of this
499 work. The Ministry of Earth Sciences (MoES), Government of India supported the collection of *in*
500 *situ* data collected in the indian sector of the Bengal delta. We thank Bangladesh Water
501 Development Board (BWDB) for providing water level, discharge and river water salinity data. The
502 authors thank all the project staff for their efforts in collecting these data.

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