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

V.R. Sherin [a,b], Fabien Durand [c,d,*], Fabrice Papa [c,d], AKM Saiful Islam [e], V.V. Gopalakrishna [f], M. Khaki [g], V. Suneel [h]

[a] *Indo-French Cell for Water Sciences, IRD-IISc, Bangalore, India*
[b] *Indian National Centre for Ocean Information Services, Ministry of Earth Sciences, Hyderabad, India*
[c] *LEGOS, Université de Toulouse, IRD, CNRS, CNES, UPS, Toulouse, 31400, France*
[d] *Laboratório de Geoquímica, Instituto de Geociencias, Universidade de Brasilia, Brasilia, Brazil*
[e] *Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka, 1000, Bangladesh*
[f] *Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India*
[g] *School of Engineering, University of Newcastle, Callaghan, New South Wales, Australia*
[h] *National Institute of Oceanography, Goa, India*

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ABSTRACT

Salinization stands among the most prominent environmental hazards of the largest delta on Earth, the Bengal delta. It has significant impacts on the local societies and the economy. Using an unprecedented collection of *in situ* river salinity records over the Bengal delta, extending from the Hooghly estuary in the west to the Meghna estuary in the east, we report a sudden salinization of the central part of the delta that occurred in 2006–2007. This results in a sudden landward shift of the seasonal march of the salinity front by about 20 km, taking place in the pre-monsoon season. Such a regime shift was never reported before. We investigate the various drivers of this sudden change and identify three possible forcing factors: the decrease in Ganges freshwater discharge, the rise of sea level and the depletion of the groundwater level. These factors may act independently, or in concert. Given the threat of the ongoing climate change and its cohort of adverse effects expected in the course of the 21st century in the Bengal delta, our study contributes to set the observational basis for the development of the next generation of salinization modeling platforms.

1. Introduction

In estuarine and deltaic regions, salinity can be seen as an efficient tracer of the continent-ocean water mass exchanges (Shammi et al., 2017). In the case of low-lying deltaic plains such as the Bengal Delta, salinity exerts a prominent control on the economy and sanitary conditions of the riparian societies. It is widely accepted that, beyond 0.6–1 unit (throughout this paper, salinity unit will be considered without dimension, in the so-called Practical Salinity Scale - PSS), the water is not suitable for drinking purpose (T. Akter et al., 2016a; World Health Organization, 2017). In the Bengal delta, water with salinity in excess of 2 units is not useable for rice fields irrigation (Dasgupta et al., 2018). The recent review of Rahman et al. (2019) emphasized the prominent threat of salinization for the Bengal populations, from the point of view of livelihood, of food security as well as of public health. Chen and Mueller (2018) identified salinization more than inundation as a prominent driver of human migration within as well as outside the Bengal delta. This region is a very energetic hydraulic continuum (Durand et al., 2019), which connects the Ganges-Brahmaputra-Meghna (GBM) river system, third largest discharge to the ocean globally, to the adjoining Bay of Bengal (Fig. 1). This delta comprises the full range of salinity conditions, from pure freshwater injected by powerful rivers in the north to pure seawater (above 33 in the Practical Salinity Scale) at its southern estuarine outlets. The salinity front separating the riverine fresh waters to the downstream Bay of Bengal salty water migrates across the southern part of the delta, over a broad range of timescales (Rahman et al., 2017). The Bengal delta is a macro-tidal area (Tazkia et al., 2017); at intra-daily timescales, the flood tide pushes the salty waters towards the interior delta and the ebb tide pulls them back seaward, typically by several kilometers (Sinha et al., 1999).

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* Corresponding author. LEGOS, Université de Toulouse, IRD, CNRS, CNES, UPS, Toulouse, 31400, France.
E-mail address: fabien.durand@ird.fr (F. Durand).

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Short-duration extremes such as tropical cyclones can similarly induce massive flooding and associated brackish water intrusion in the coastal belt (R. Akter et al., 2016b). On the other side of the temporal spectrum, the long-term sea level rise is known to induce a gradual salinization of the Bengal delta (Mitra et al., 2009; Banerjee, 2013; Shammi et al., 2017). At intermediate timescales, the seasonal alternation of the monsoons is known to modify the salinity distribution over the delta, under the combined influence of the monsoonal variability of the riverine freshwater flow and of the seasonal variability of sea surface height (Sinha et al., 1996; Mirza, 2005; Rahman et al., 2017). At interannual timescales, little is known about the variability of salinity over the delta, primarily on account of the dearth of long enough observational records. Statistical models based on a few pointwise timeseries however suggest a prominent response of the delta salinity pattern to the year-to-year variability of GBM runoff (Mirza, 2005). Similarly, numerical models suggest that the year-to-year variability of the GBM monsoonal runoff can induce marked variability of the whole northern Bay of Bengal salinity (Durand et al., 2011; Akhil et al., 2014). In the context of ongoing climate change, resulting in an expected gradual and continuous rise in eustatic sea level expected during the next decades (Brown et al., 2018), a widespread questioning has recently emerged among the scientific community regarding the long-term evolution of the salinity patterns in the Bengal delta (Clarke et al., 2015; Dasgupta et al., 2015; Payo et al., 2017; Bricheno and Wolf, 2018). These questions are crucial, knowing the primary dependency of the Bengal population on healthy soils and rivers for agriculture. Whereas past studies generally agree about a gradual salinization to be expected primarily in the south-central part of the delta, the quantifications of the salt intrusion and their spatial patterns largely depend on the different methodologies and modeling frameworks used. Dasgupta et al. (2015) for instance drew much more alarming conclusions than Payo et al. (2017) as regards to the magnitude of the long-term salinization to be expected by 2100. Payo et al. (2017) concluded that one key for reconciling the past divergent studies and for reaching more robust conclusions may be to gather observational knowledge, for benchmarking and calibration of the modeling systems in the current climate conditions.

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

The paper is organized as follows. Section 2 presents the datasets we used to analyze our observations. Section 3 presents the seasonal

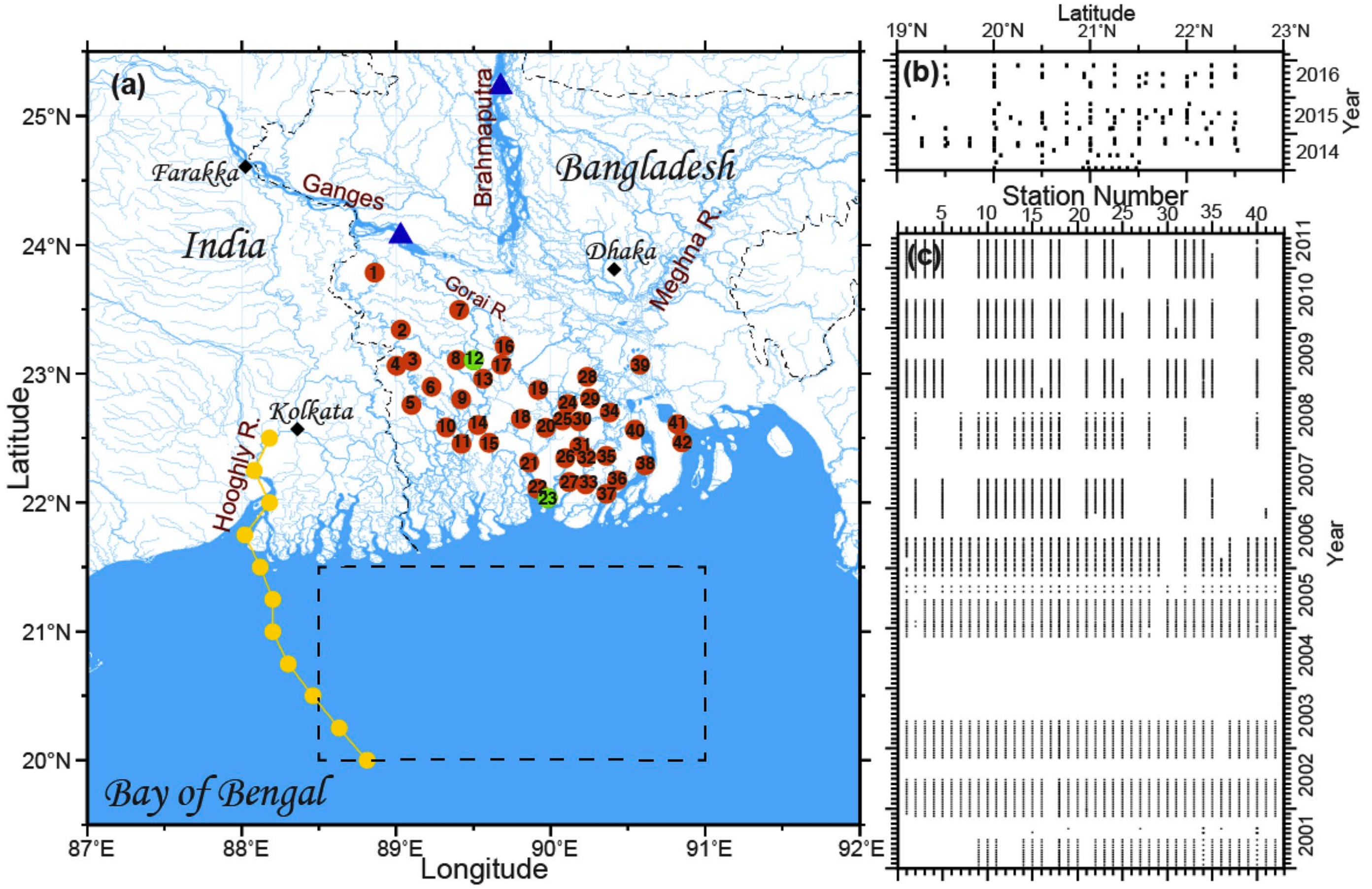

Fig. 1. (a) Distribution of the observation stations. Red bullets show the salinity stations, with station numbers. Green bullets show the stations where we also analyzed water level. Blue triangles show the river gauge locations. The ship track with salinity data locations in Hooghly estuary is in yellow. Other locations discussed in the text (e.g. Farakka dam) are displayed. The dashed box in the ocean features the domain considered for analyzing altimetric sea level data. (b) Spatio-temporal coverage of salinity data in Hooghly River. (c) Spatio-temporal coverage of salinity data for Bangladesh stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

evolution of salinity observed over the delta. In Section 4, we reveal a sudden salinization that took place in the central part of the delta in the mid-2000's, and we analyze the possible factors responsible for this phenomenon. Section 5 concludes our study.

2. Datasets and methods

2.1. Hooghly River salinity

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

2.2. GBM river salinity network in Bangladesh

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

2.3. *In situ* hydrological observations in the GBM delta

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

Table 1
List of salinity stations with their positions.

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

2.4. Groundwater level variations

In the Bengal delta, the rivers exchange water with the surface water reservoirs, with sensible effect on the rivers salinity variability (Nobi and Gupta, 1997; Bhuiyan and Dutta, 2012). In order to investigate the possible role of groundwater in the delta salinity variability, we use groundwater level variations simulated over the delta by Khaki et al. (2018). They used the World-Wide Water Resources Assessment (W3RA) hydrological model of Van Dijk (2010), assimilating data of groundwater storage change obtained from a combination of terrestrial water storage data from the Gravity Recovery And Climate Experiment (GRACE) and surface water storage from multi-satellite dataset (Papa et al., 2015). These outputs were extensively validated and the reader is referred to Khaki et al. (2018) for further details. The modeled groundwater level variations are available over Bangladesh on a monthly basis over 2003–2013. The data were normalized by dividing the time series at each grid point by their standard deviation. Then long-term linear trends were computed on the normalized time series.

2.5. Sea level anomaly

The variability of eustatic sea level is an obvious driver of the salinity variability in the delta. To investigate this effect, we use the merged gridded product of sea level anomaly (SLA) based on multiple satellite missions (T/P, ERS-1/2, followed by Jason-1/2 and Envisat), distributed by Archiving, Validation, and Interpretation of Satellite Oceanographic

(AVISO, https://www.aviso.altimetry.fr/en/data.html). These data have been widely used in countless studies of the northern Bay of Bengal oceanography (e.g. Durand et al. (2008) and references therein). The data are daily, with a spatial resolution of 0.25°. Here, we averaged these data into monthly means, covering the period 2001–2011, and spatially averaged over the northern Bay of Bengal rectangular box (2.25° × 1.25°) shown in Fig. 1a.

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

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

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

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

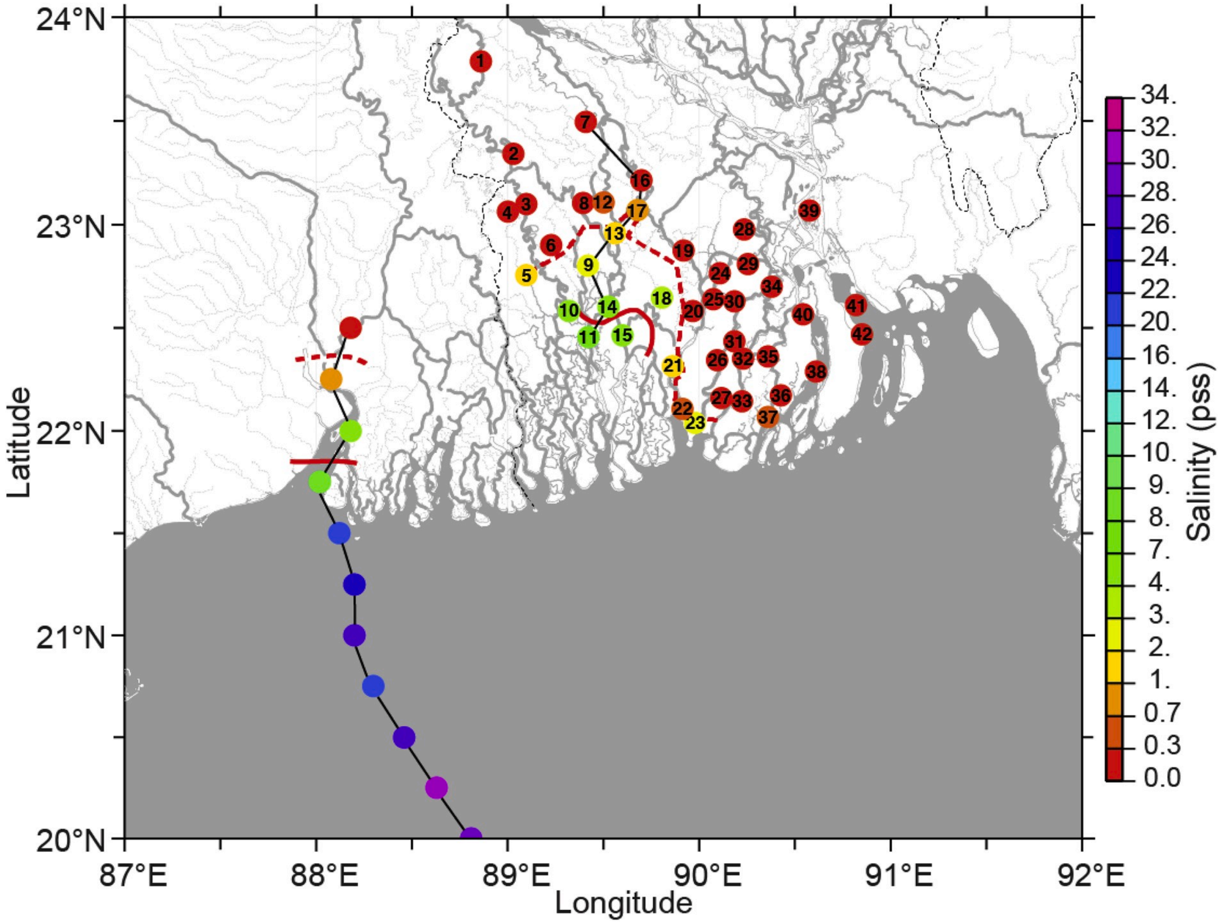

Fig. 2. Long-term mean of salinity at all stations. The red dashed/solid line indicates the climatological position of the 2 units isohaline in April/August, respectively. The thin black lines feature the central and western sections displayed in Fig3a and 3b, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

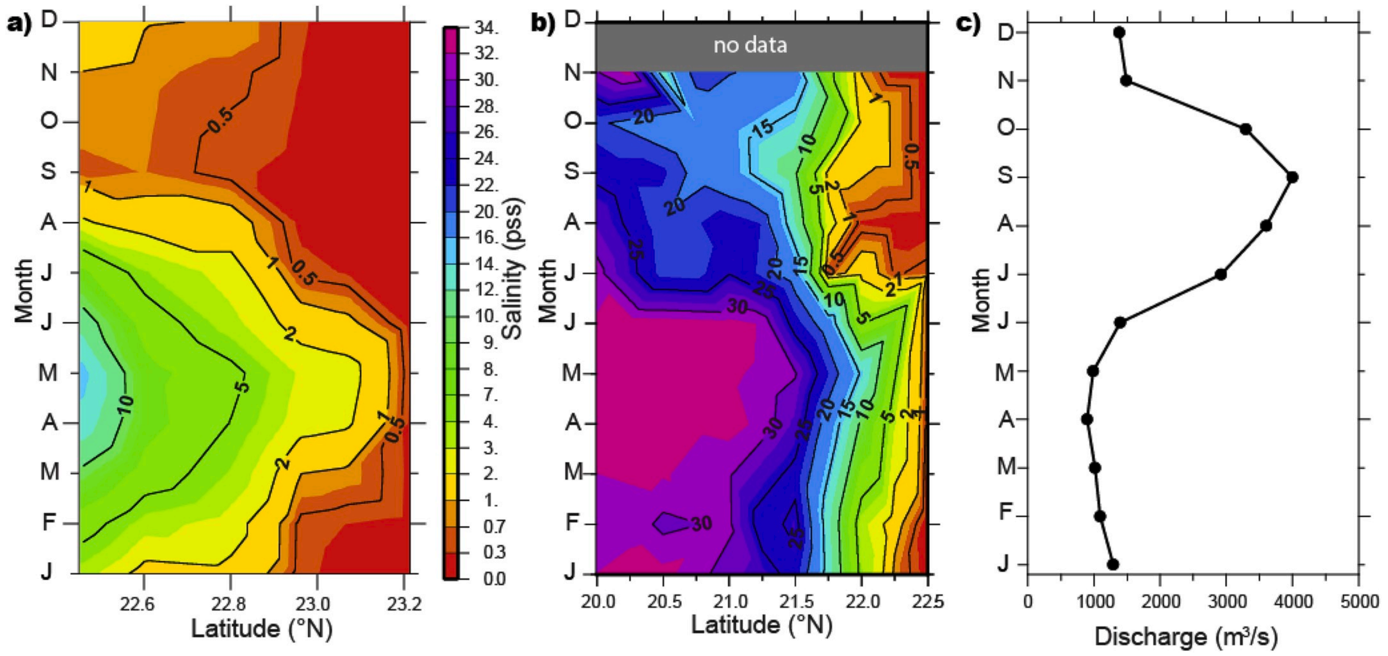

Fig. 3. (a) Latitude-time distribution of the monthly climatology of salinity data for the central section. (b) Latitude-time distribution of the monthly climatology of salinity data for the Hooghly estuary. (c) Evolution of monthly climatology of Hooghly river discharge from Mukhopadhyay et al. (2006).

It is important to investigate specifically the salinity of the Hooghly River (Fig.3b), as the descriptions published so far were based on very limited datasets and numerical modeling, and were largely inconsistent. For the first time, we have access to repeated, synoptic transects, consistently spanning the whole stretch of the estuary and the adjoining oceanic outflow region. Indeed, it was found in the past studies that the river plume, once it has entered the open ocean, is subject to intense mixing with the ambient salty waters, and as such provides a relevant test case for the calibration and validation of estuarine salinity numerical models (Sinha et al., 1999; Durand et al., 2008; Bricheno and Wolf, 2018). For instance, Sinha et al. (1996) reported a moderate salinity intrusion at the mouth of the estuary in the pre-summer monsoon (salinity value of 12 units, in June) whereas Sinha et al. (1999) and Mukhopadhyay et al. (2006) observed much more saline waters there (19 to 23 units). Our dataset shows a clear sign of saline water intrusion in the pre-summer monsoon season, with values around 25 units at the mouth (21.5°N) in May–June. The seasonal evolution of salinity in the Hooghly completely follows the seasonality of the region's hydrology (Fig.3b). In the subsequent monsoon, following the gradual increase of Hooghly river discharge (from 1000 $m^3 s^{-1}$ to 4000 $m^3 s^{-1}$, Fig.3c), salinity decreases at the mouth, down to values close to 10 units in September. Salinity also starts dropping off the mouth. By September, the 20 units isohaline has shifted offshore, to 20°N (more than 100 km off the mouth). The river discharge then starts decaying, with a rapid collapse between October and November, when it stabilizes around 1000 $m^3 s^{-1}$. One month after the peak of the river discharge, in October, salinity starts increasing in the lower Hooghly estuary (south of 22°N) as well as further offshore. By January, the whole fresh plume has disappeared from the open ocean, replaced by salinity values above 20 units offshoreward of the river mouth. The salinity evolution is characterized by an abrupt freshening of the estuary during summer monsoon. Whereas the monsoonal increase of river discharge is rather gradual from June to September, the southern limit of the fresh water zone (salinity inferior to 2 units) suddenly shifts southward in July, from the upstream limit of the estuary (22.5°N) to the mouth of the estuary, 100 km to the south. The short time span of this shift (of order one month, possibly less as our dataset does not resolve intra-monthly timescales) has not been reported before, to the best of our knowledge. At the northern edge of our section, at 22.5°N, the salinity shows weak variability, and consistently remains inferior to 1 unit, even during the low-flow pre-monsoon season (April–May). It is known that the discharge of the Hooghly during April–May is mainly maintained by the diversion of the Ganges river water from the Farakka Barrage to provide sufficient water level heights for ship operations into Kolkata harbour, and prevent its siltation (Mirza, 2005). Tidal rivers east of the Hooghly show higher salinity values, especially during pre-monsoon (Banerjee, 2013). Thus, the low salinity values in the upper Hooghly estuary may be considered as artificially maintained.

4. An abrupt salinization of the Bengal delta in 2006–2007

4.1. Observed shift in river salinity

Beyond the regular, seasonal evolution described in the previous section, intimately linked with the monsoonal cycle, we investigated the pluri-annual variability of our salinity dataset. We restricted our analysis to the decade-long Bangladesh stations, as the Hooghly data sub-set has a relatively shorter time span. Fig. 4a shows the evolution of salinity for few selected stations, for 2001–2011. For all of them, the broad seasonal evolution discussed in Section 3 is seen every year, with low salinity during summer monsoon and in the following months, and higher salinity in pre-monsoon; the amplitude of the seasonal evolution is stronger for the southern stations than for the ones located further inland, as expected. However, it is striking to see that, for the southern stations (#5, 15, 21), the amplitude of the pre-monsoon salinization is much stronger in 2007 and beyond, compared to the pre-2006 period. For instance, at station #15, the yearly peak never exceeds 10 units from 2002 to 2006, whereas it consistently reaches 15 units in every year of the 2007–2011 period. We assess this change by comparing the pre-2006 climatology with the post-2007 climatology, for station #15 (Fig. 5). We can see that, throughout the high-salinity season, the post-2007 monthly values exceed the pre-2006 values by more than one interannual standard deviation. Similarly, at station #21, the yearly peak hardly reaches 1.5 units in 2002–2006 whereas it exceeds 3.5 units in all subsequent years (Fig. 4a). This offset in the magnitude of the seasonal salinization before/after 2006 is observed at all stations located

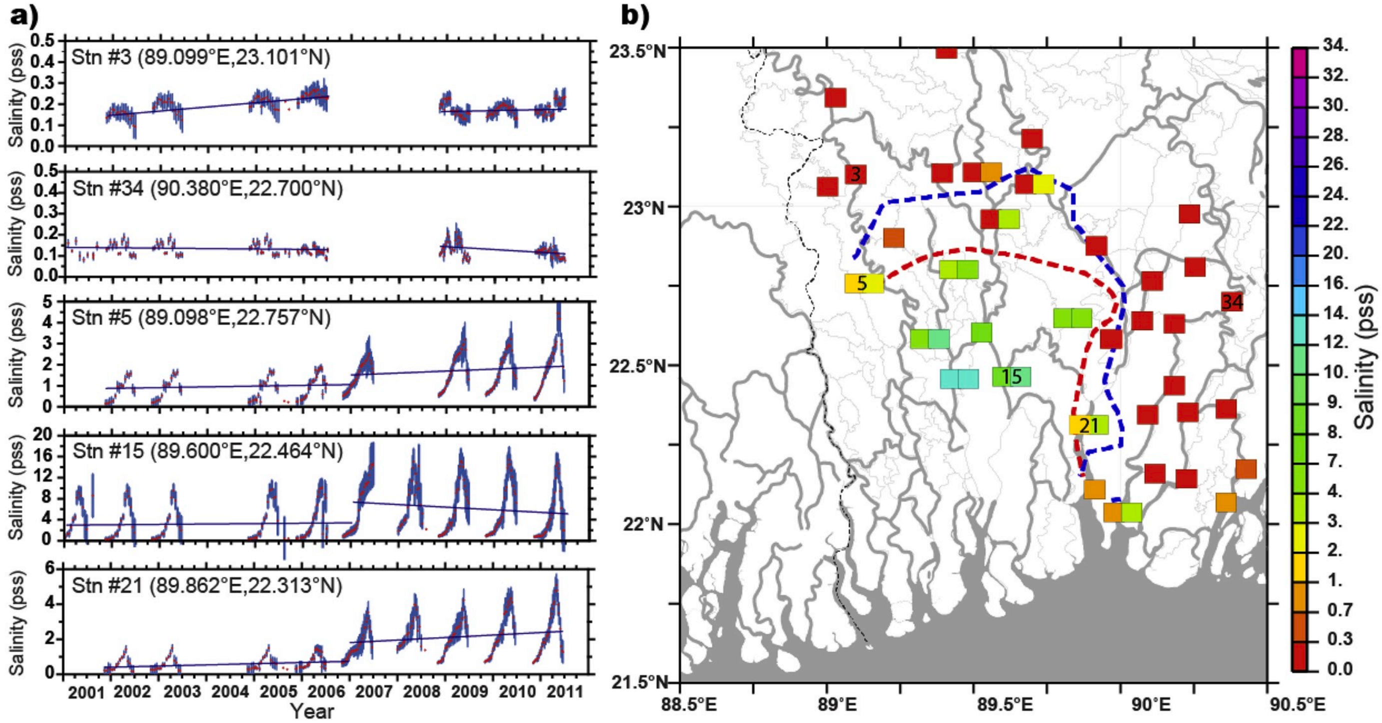

Fig. 4. (a) Timeseries of salinity observed at selected stations (red points). The blue vertical bars in all panels feature the year-to-year standard deviation, computed month-wise, separately over the 2001–2006 period and over the 2007–2011 period. For each of these two periods, we superimpose the linear fit in thin solid line. (b) Salinity climatology in April, with the positions of the pre-2006 (red) and post-2007 (blue) 2 units isohaline. The right-shifted squares in certain stations show the April climatological salinity computed over the post-2007 period only. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

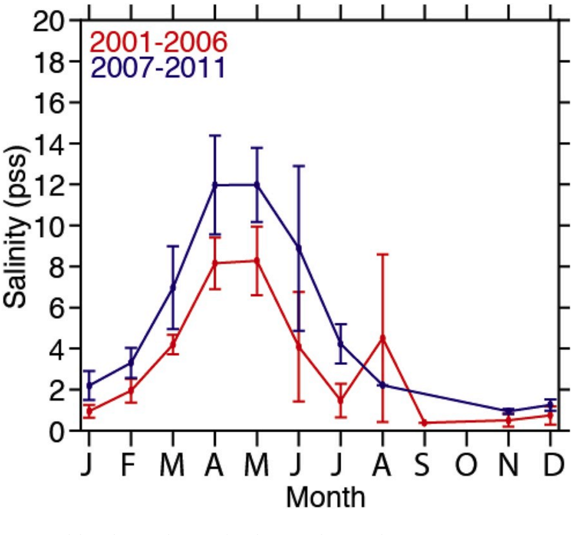

Fig. 5. Monthly climatology of salinity observed at station #15 (89.600°E, 22.464°N), distinguishing the pre-2006 (red) and the post-2007 (blue) periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the crescent-shaped frontal region (Fig. 4b). For these stations, we computed the climatological April salinity (coinciding with the seasonal maximum, for all of them), distinguishing the pre-2006 and post-2007 periods. Clear differences are seen, consistently showing a recent rise in the magnitude of the seasonal salinization, typically amounting to a 50% increase. This is reflected in the linear fits we estimated, separately for the pre-2006 period and for the post-2007 period (Fig. 4a). It is seen that the long-term evolution of the salinity is stable during both periods, for all stations. The pre-2006 and post-2007 mean salinity values are shown in Table 2.

In the post-2007 period, stations #5 and #21 show a moderate increasing trend of +0.1 unit per year, and station #15 shows a moderate decreasing trend of 0.4 unit per year. These values are weak, compared to the shifts of +0.8 unit/+1.7 units/+2.6 units respectively for stations #5, #21 and #15, observed when comparing the pre-2006 mean with the post-2007 mean. In terms of spatial extent of the seasonal intrusion of brackish waters, the shift amounts to a landward retreat of the April 2-unit isohaline by about 20 km, throughout the central part of the delta (between 89°E and 90°E), and could be seen as a potential loss of domain where the water is useable for human needs and for irrigation purpose. This shift, happening in only one season between the 2006 monsoon and the 2007 monsoon, is considerable. In fact, it appears to be commensurate with the 20 km shift of the salinity front that is expected to take place gradually over the same region in the course of the whole 21st century, as a response to global sea level rise (Bhuiyan and Dutta, 2012). Noteworthy, we do not observe any restoration of the salinity to the pre-2006 levels, subsequently. In contrast, the fact that stations #3 and #34 do not show any evidence of regime shift after 2006 reveals that the salinization is restricted to the south and to the west of these, respectively.

4.2. Assessment of the possible forcing factors of the salinity shift

As the abrupt shift revealed by our dataset has never been discussed

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

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

in the literature, we try to shed light on the underlying causative factors, by investigating them sequentially. The past studies revealed that the spatio-temporal evolution of the salinity front in the river network of the Bengal delta results from the competition of various processes, namely the magnitude of the freshwater river discharge, the sea level at the coast and the seepage to/from the adjacent aquifers (Clarke et al., 2015). In addition, human activities like water diversion, polderization (viz. areas enclosed by embankments) and extensive irrigation have the potential to distort the dynamics of the seasonal brackish waters intrusion (Nobi and Gupta, 1997; Mirza, 2005; Bhuiyan and Dutta, 2012). In this section we attempt to document which of these factors might have contributed to the 2006–2007 observed salinity shift. Our goal here is not to quantify the relative importance of the various possible forcing factors, but simply to point which ones are consistent with the observed salinization, and which ones are not.

4.2.1. River discharge

The variability of the flux of fresh water supplied by Ganges, Brahmaputra, and Meghna rivers plays a major role in the overall salinity level in the delta (Mirza, 2005; Rahman et al., 2017). Of these three streams, the western-central part of the delta is mainly fed by the Ganges water only, whereas the fresher eastern delta is fed jointly by the three rivers. The fresh water from Ganges is mainly transported to the central delta region by the Gorai River (Fig. 1) (Rahman and Rahaman, 2017). Fig. 6 shows the monthly climatology of Ganges discharge observed at Hardinge Bridge and Brahmaputra discharge observed at Bahadurabad (see stations location in Fig. 1). The Ganges observing station is located just upstream of the origin of Gorai River. We distinguished the 2001–2006 period and the 2007–2011 period to compute the respective monthly discharge climatologies. For both rivers, the seasonal evolution of the discharge is grossly consistent over both periods, with low flow in January–April and a subsequent increase through the summer monsoon. However, a close examination in the low-flow season reveals significant contrasts. For the Ganges, we observe that all months from January to July show lower discharge in the post-2007 period compared to the pre-2006 period (Fig. 6b). The decrease ranges from 30% (in January) to 10% or less (in subsequent months). The significance of this reduction stems from the fact that the Ganges has to maintain a mean monthly discharge close to 1800 to 2000 m^3/s to contain the salinity within the permissible limit for human consumption during February to April (Mirza, 2005). The climatological discharge at Hardinge Bridge is far inferior to this, being around 1100 to 1600 m^3/s during February–April. Although in pre-2006 period the Ganges discharge is not always within the minimum requirement, this post-2007 drop could have contributed to the sudden salinization. It is reasonable to think that this influence could have reached the south-central part of the delta through the Gorai River network, although no discharge data of the Gorai River are available to confirm this. In contrast, the discharge of Brahmaputra is seen to increase in the post-2007 period compared to pre-2006 period, typically by 10% for all months in the low flow season. This recent excess supply of fresh water –though moderate and within the range of year-to-year variability– may have contributed to keep the eastern part of the delta, including the Meghna estuary, comparatively fresher throughout the decade of observation, with no visible shift in 2006–2007. It has to be noted that, in the downstream part of the delta (station #15), the post-2007 salinization is not restricted to the low-flow season, but also spans the flood season (Fig. 5); however, both river discharges show an increase in the upstream flood discharge (August–September; Fig. 6), in the post-2007 period. This shows that the riverine forcing does not play a role in the salinization observed during the flood season.

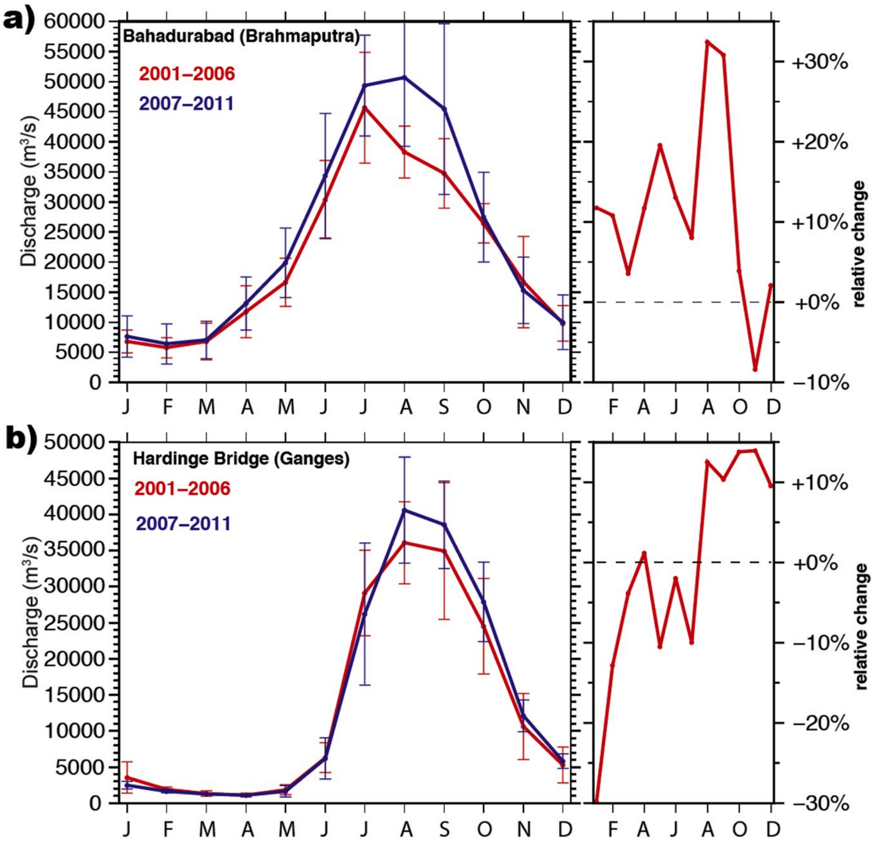

Fig. 6. Monthly climatology of river discharge for the Brahmaputra (top left) and for the Ganges (bottom left), distinguishing the pre-2006 (red) and the post-2007 (blue) periods. The right panels show the corresponding relative change between the two periods, expressed in percent of the pre-2006 values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.2.2. Sea level and river water level

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

4.2.3. Groundwater level

Clarke et al. (2015) reviewed the various processes responsible for the variability of Bengal delta salinity, and pointed towards dry-season irrigation demand and associated depletion of the groundwater level. The seepage of river water towards the adjoining groundwater reservoir was also assessed in the modeling studies of Nobi and Gupta (1997) or Bhuiyan and Dutta (2012), at seasonal and inter-decadal timescales respectively. They concluded that this seepage can significantly alter the march of the salinity front across the Bengal delta. We attempted to assess the possible role of this factor by examining state-of-the-art groundwater reanalysis products. We considered the groundwater data-assimilating modeling product of Khaki et al. (2018) as described in Section 2. Over Bangladesh, this study reported a significant decline in groundwater storage (~32% reduction) for Bangladesh between 2003 and 2013. Fig. 8 shows the map of normalized groundwater level trend for the period 2003–2013. It is seen that there is a general decreasing trend throughout the delta, over our period of interest. This water level depletion is mainly related to excessive irrigation for agricultural purposes in the recent period (Shamsudduha, 2013; Khaki et al., 2018). We extracted two significant and contrasted locations in the model outputs: the region where we observe the shift in salinization in 2006–2007 (south-central delta, purple square on the map in Fig. 8a) and a location to the east of the mouth of Meghna, where no groundwater depletion is seen (south-eastern delta, orange square in Fig. 8a).

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

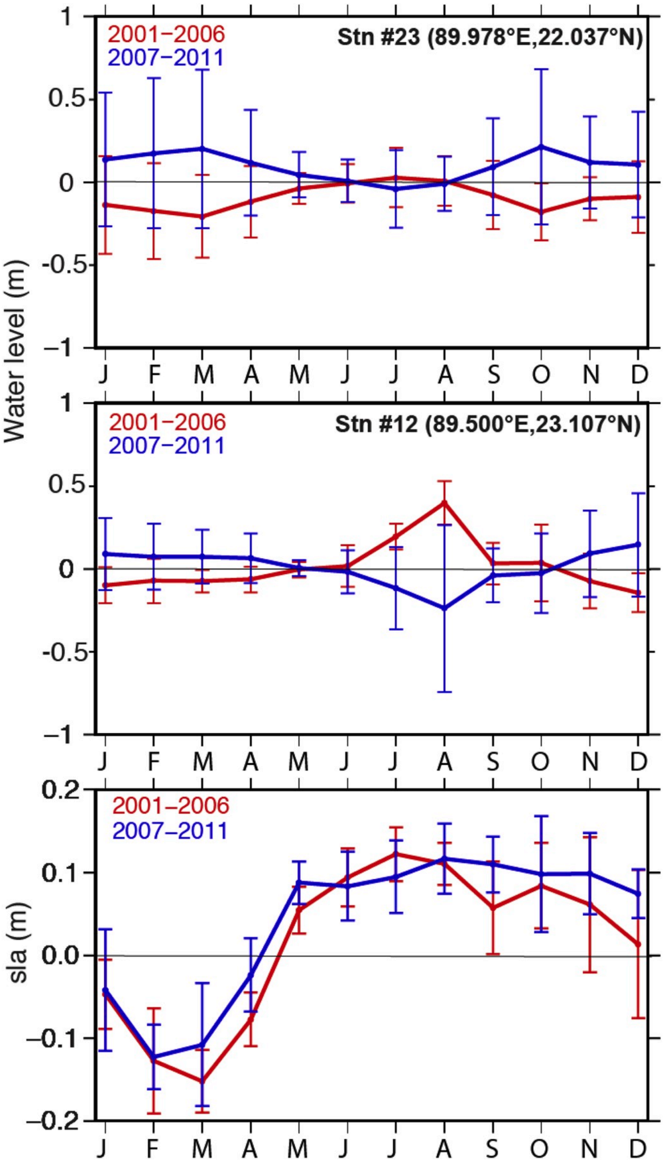

Fig 7. (top) Monthly climatology of river water level observed at station #23, for the pre-2006 (red) and the post-2007 (blue) periods. The monthly climatology of river water level has been removed, for clarity. (middle) Same, for station #12. (bottom) monthly climatology of altimetric sea level averaged over the box displayed in Fig. 1, for the pre-2006 (red) and the post-2007 (blue) periods. The vertical bars in all panels feature the year-to-year standard deviation, computed month-wise.

5. Conclusion

Our study confirms that the large-scale distribution of salinity across the Bengal delta is far from uniform. The saline waters consistently occupy the south-central part of the delta, and are separated from the freshwaters in the upstream part by a sharp salinity front. This front has a crescent shape, extending from the southern part of the Hooghly River in the west, to the Gorai River in the east. Further to the east, the delta is essentially composed of freshwaters. We show that this front migrates landward/seaward during the dry/monsoon season respectively, by 20 to 40 km typically. This pattern of evolution is broadly consistent with

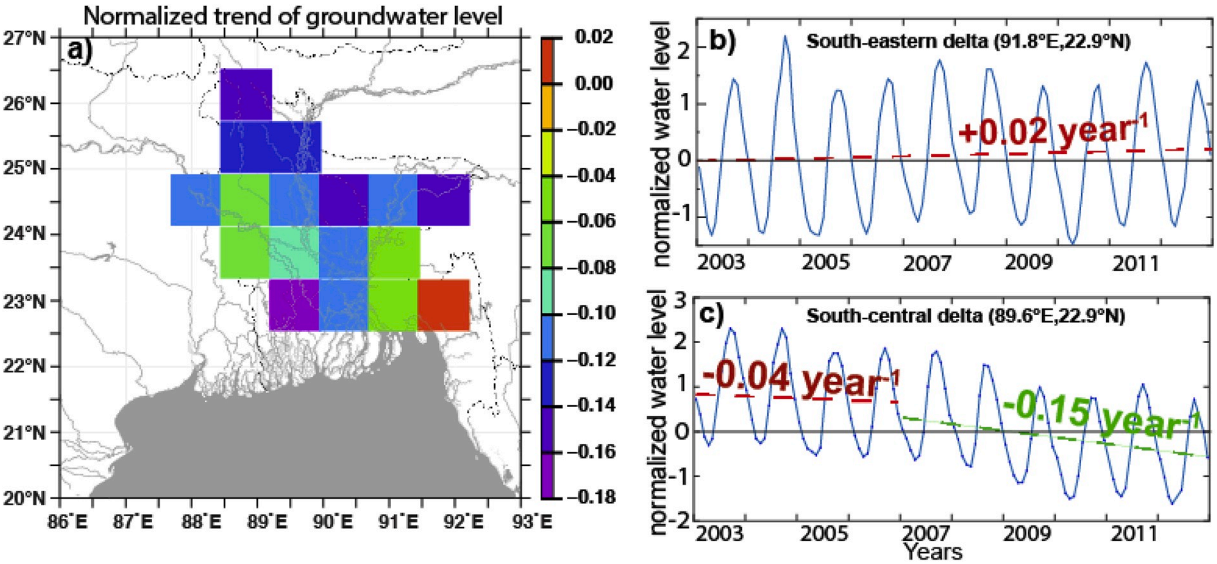

Fig. 8. (a) Normalized long-term trend of groundwater level in the hindcast of Khaki et al. (2018). Timeseries of normalized groundwater level extracted at the two locations showing orange shade (for b) and purple shade (for c) in panel (a). The linear tendency lines are superimposed, along with the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

the previous estimates, although our pluri-annual dataset revealed some marked differences locally with studies based on older and less extended observations. Beyond this periodic sea-saw, we revealed a massive salinity intrusion, which occurred during the 2006–2007 dry season. This intrusion resulted in a landward shift of the salinity front by about 20 km, throughout the central part of the delta. Such a significant shift has never been reported before and is commensurate with the long-term salinization expected to occur in the delta over the whole 21st century, under the effect of the changing climate. By 2011, the last year of available observations, there was still no sign of a subsequent recovery of the delta salinity to the pre-2006 conditions. Since the spatio-temporal evolution of salinity in the river network of the Bengal delta results from the competition of various processes, we tried to identify which factors might have contributed to the 2006–2007 salinity shift, knowing that these factors may act independently or in concert. Over our period of interest, we could document that three possible drivers of this salt intrusion were potential contributors: the decay of Ganges river discharge, the rise of the eustatic sea level in the northern Bay of Bengal, and the depletion of the groundwater level in the central part of the delta. Beyond these processes, rapid-onset events such as cyclonic surges and associated coastal flooding of salt water, essentially unresolved by the temporal sampling of our dataset, need to be assessed in view of the results reported here.

Our study presents a relevant test-case for the development, calibration and validation of the future generation of numerical models of the salinization of the delta. In the context of drastic environmental changes expected to occur over the delta in a changing climate, added to the profound impact of the local human activity on the water resource, such models are strongly needed. In particular, it is needed to ascertain the exact processes possibly responsible for the salt intrusion we report, among the three factors we identified. Only models capable of realistically hindcasting such a phenomenon may be used to forecast the details of the evolution of the delta salinity over the 21st century. As our assessment of the salinization factors we identified is essentially qualitative, our study calls for an integrated modeling framework, considering the hydrodynamical continuum (rivers-estuaries-ocean) as well as its coupling with the groundwater compartment, as our observations suggest that none of these hydrological components should be excluded a priori.

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

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

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

Declaration of Competing interest

All authors declare having no financial nor personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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