Swimming against the rising tide: the use of cetaceans for evaluating the ecological impacts of declining freshwater supplies and global climate change in Bangladesh

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ABSTRACT

The effects of climate change are extremely difficult to predict and monitor because they are complex and operate on broad ecological scales. In biological monitoring, the assessment of complex processes is commonly approached through the use of indicator case-populations or species. These are assumed to integrate changes over time and space, thus reducing random variance of physical measurements, and to be sensitive enough to warn about changes earlier than the usual "spot" measurements. Cetaceans are normally considered to be poor indicators species due to their generalist capacity for adapting to environmental changes. However, the manner by which these large, mobile predators respond to environmental changes (e.g., by altering their movement patterns and foraging behaviour) may be particularly informative for identifying biologically significant environmental attributes, and for monitoring alterations in the spatial and temporal availability of these attributes. These responses may then be used to generate targeted and testable hypotheses, prioritize investigative efforts and identify local aggregations of biological productivity for site-based protection.

The community of cetaceans inhabiting the inshore waterways of the Sundarbans mangrove forest and adjacent coastal waters in Bangladesh is composed of species that distribute themselves according to the physical characteristics in their environment (e.g. salinity, turbidity, depth, and channel configuration). Cetaceans farther offshore in the Swatch-of-No Ground, a 900m+ deep submarine canyon, may also show distinct distributional responses to a decline in the availability of nutrients associated with reduced freshwater discharge and alterations of current patterns that could suppress upwelling. Given that these waters support a diverse and relatively abundant cetacean community that will be dramatically affected by declining freshwater flows and climate change, it is concluded that the animals may be an efficient model for gauging the effects of these anthropogenic threats on the same species elsewhere in their range, and possibly other cetaceans subject to similar environmental pressures. In addition, studies of this cetacean community may provide fundamental insights on the nature and magnitude of more general ecological effects (e.g. changes in the abundance and species composition of lower-level trophic communities) and a basis for developing appropriate management responses. Baseline information and trained local expertise is available, thus offering a solid ground for long-term studies and monitoring.

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INTRODUCTION

Declining freshwater flows and climate change

Human induced climate change is expected to cause major changes in marine ecosystems with some of the most severe impacts occurring in coastal waters (Harley *et al.*, 2006). However, our understanding of the physical processes and the details and magnitude of ecological effects are rudimentary. Critical uncertainties include abrupt modifications in thermohaline circulation and increases in glacial- and sea-ice melt (Alley *et al.*, 2003), and sudden, synergistic biological shifts as ecosystems change from one state to the next (Harley *et al.*, 2006). This general lack of knowledge has potentially catastrophic consequences for biological productivity and diversity, and human welfare. Meanwhile, the general decline in the availability and quality of freshwater also presents a major challenge for biodiversity conservation in freshwater systems (Gleick, 1993). Although climate change is predicted to generally result in increased precipitation, the effects will be spatially and temporally uneven, and declines are expected in some areas (IPCC, 2007). Regardless of projected increases, numerical experiments combining climate change models, water budgets and human population growth indicate that the overall demand for freshwater resources will greatly exceed any positive climate-change related effects (Vörösmarty *et al.*, 2000).

Estuarine systems

Situated at the interface of fresh and marine waters are estuarine systems which, due to their ecotonal and stratified character, support extremely high levels of biological diversity and productivity (Hounde and Rutherford, 1993; Hobbie, 2000). These systems integrate the ecological impacts of what are probably the two greatest environmental challenges of the 21st century: global climate change and declining freshwater supplies. The ecological impacts of climate change and declining freshwater supplies on estuaries will be complex, interactive and far reaching; however, the type of synthetic studies needed for biodiversity conservation (see Hobbie, 2000) have generally been limited to a few temperate systems in the developed word where adequate funds and trained scientists are available.

Submarine canyons

Freshwater flowing into estuaries terminates in underwater rivers or turbidity currents that often erode submarine canyons. These canyons amplify upwelling and, similar to estuaries, are major hotspots of biological production and fisheries catch (Breaker and Broenkow, 1994; Sobarzo *et al.*, 2001). The warming trends associated with human induced climate change will be greater over continental interiors compared to oceans, causing strong convection winds that may result in increased upwelling and nutrient availability. However, increased thermal stratification and a deepening thermocline could also prevent nutrient-rich waters from being upwelled (Roemmich and McGowan, 1995; Harley *et al.*, 2006). The ecological impacts of declining freshwater flows on submarine canyons eroded by, and with sediment fans derived from, riverine induced turbidity currents remain similarly unclear as the effects of climate change, and the two factors may interact synergistically.

Biodiversity conservation in estuaries and submarine canyons

The complex challenges of conserving biological diversity in estuaries and submarine canyons point towards the need for ecological shortcuts. A scattershot approach whereby scientists systematically collect large amounts of biological data over broad

temporal and temporal scales, look for patterns using ordination techniques, and then attempt to detect changes in community structure over time and space, is infeasible in the areas where the negative impacts of global climate change and declining freshwater supplies are potentially the greatest (i.e., world's largest estuaries and associated submarine canyons). One potential ecological shortcut may be to use the adaptive responses of cetaceans.

Cetaceans as indicator species of environmental change

Zacharias and Roff (2001) differentiate between "compositional indicators", which signify a particular habitat, community or ecosystem, and "condition indicators", which are used for biological monitoring of environmental changes resulting from anthropogenic and natural disturbances. At face value, cetaceans make poor compositional or condition indicators. Indeed their life history characteristics are the exact opposite of what are generally considered necessary for scientifically defensible indicators. These characteristics include the occupation of a highly specific ecological niche (see Meffe and Carroll, 1997), whereas cetaceans are generally considered highly adaptable. Indeed, freshwater dolphins often appear to satisfy their life history needs in environmental conditions that are "in every sense marginal" (Reeves and Reijnders, 2002). However, it is the manner by which these species satisfy their life history needs that may give them particular value as informative tools for identifying biologically significant environmental attributes and for monitoring spatial and temporal changes in the availability of these attributes.

As large, mobile predators, cetaceans respond to environmental perturbations by altering their movement patterns and foraging behaviour, which can provide vital information for generating targeted and testable hypotheses, prioritizing investigative efforts and identifying local aggregations of biological productivity for site-based protection. Using the indicator properties of cetaceans (i.e., observable adaptive responses), rather than simple measures of animal presence-absence or relative abundance, turns the concept of indicator species on its head by taking advantage of information contained within the expression of the same characteristics that are generally thought to make them poor indicators – their environmental plasticity.

Information gathered in recent years indicate that the assemblage of cetaceans inhabiting an approximately 120km-wide belt of mangrove channels and adjacent coastal and submarine canyon waters in Bangladesh (Fig. 1) exhibit indicator properties that can be used for modelling the ecological effects of declining freshwater supplies and climate change. Findings could also be translated to other populations of the same species in Asia, and possibly to other cetacean species subject to similar freshwater-supply and climate-change pressures. Here we describe the main characteristics of the cetacean community and mangrove-channel/coastal/submarine-canyon waters in Bangladesh, and discuss the potential of these species for assessing the impacts of declining freshwater supplies and climate change.

CETACEAN COMMUNITY

Freshwater-dependent species

Waterways of the Sundarbans mangrove forest are inhabited by two cetacean species: the Ganges river dolphin (*Platanista gangetica gangetica*) and the Irrawaddy dolphin (*Orcaella brevirostris).* The Ganges river dolphin is an obligate freshwater species that ranges from the upstream, fast-flowing, cool-water reaches of major Himalayan and peninsular tributaries of the Ganges-Brahmaputra-Meghna (GBM) river system to the

mangrove channels of the Sundarbans, and in the comparatively much smaller Karnaphuli River of southern Bangladesh. The range of the subspecies has declined since the nineteenth century when it was mapped by Anderson (1879) especially in the upstream reaches (Sinha *et al.*, 2000; Smith *et al.*, 2001), and it is classified as "endangered" according to IUCN Red List criteria (Smith *et al.*, 2004). Mark-recapture analyses of double concurrent counts made by independent teams during March 2002 indicate that the population in the mangrove channels of the Sundarbans is about 225 individuals (CV = 12.6%) (Smith *et al.*, 2006). The Irrawaddy dolphin is a facultative freshwater species that inhabits near-shore marine (generally limited to estuarine) waters, as well as three large rivers and two marine appended lakes, in South and Southeast Asia (Smith *et al.*, 1997, 2004, 2005). Irrawaddy dolphins are classified by the IUCN as "data deficient," although five geographically isolated populations are classified as "critically endangered" (see Smith and Beasley, 2004a, 2004b, 2004c; Smith, 2004; Kreb and Smith, 2000). Mark-recapture analyses of double concurrent counts made by independent teams during the March 2002 survey cited above generated an abundance estimate of 451 individuals (CV = 9.6%) (Smith *et al.*, 2006).

Coastal species

Coastal waters still affected by freshwater inputs from the Ganges-Brahmaputra-Meghna river system support a taxonomically diverse and relatively abundant cetacean fauna (Fig. 2). Cetacean distribution is closely tied to environmental gradients with Irrawaddy dolphins and finless porpoises (*Neophocaena phocaenoides*) occurring most often in nearshore, shallow, turbid, low-salinity waters and Indo-Pacific hump-backed dolphins (*Sousa chinensis*) in slightly deeper waters where the colour turns from brown to green. A vessel-based, line-transect survey conducted during February 2004 along 1,018km of systematic trackline in nearshore waters resulted in abundance estimates of 5,383 Irrawaddy dolphins (CV = 39.5) and 1,382 finless porpoises (CV = 54.8%; Smith *et al*., 2005). Although an insufficient number of sightings of Indo-Pacific humpback dolphins were made during this survey to estimate abundance, the relative large groups sizes recorded during six sightings (16.2 individuals, SD = 21.9, range = 2-55) implies that the area may be a particularly inportant habitat for the species.

Deep-water species

Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) and Bryde's whales (large form; *Balaenoptera edeni/brydei*) inhabit the deep, clear, high-salinity waters along the rim of the Swatch-of-No-Ground (SoNG), a 900+ m deep submarine canyon lying less than 40 km from the rim of the mangrove forest. Indo-Pacific bottlenose dolphins are generally found in estuaries and along open coasts (Wells and Scott, 2002); however, in Bangladesh the species appears to take advantage of the high productivity created by upwelling currents found along the canyon edge. During the February 2004 survey mentioned above, Indo-Pacific bottlenose dolphins were found straddling fairly shallow (19m) and deep-water (>200m) habitat. The general absence of Indo-Pacific bottlenose dolphins in nearshore waters more strongly affected by freshwater flow probably reflects inter-specific competition with Irrawaddy and Indo-Pacific humpback dolphins and possibly finless porpoises, species that may be better adapted to estuarine conditions. A photo-idenfication study of Indo-Pacific bottlenose dolphins conducted during the winter seasons of 2005/2006 and 2006/2007, resulted in the indentifications of almost 900 individuals and a preliminary abundance estimate using mark-recapture techniques indicate that the population is probably double (i.e. ~1,800 individuals; Mansur, Strindberg and Smith, unpublished).

The common occurrence of Bryde's whales in the SoNG was verified during a study of Indo-Pacific bottlenose dolphins (Mansur, unpublished) with six photo-confirmed (based on the presence of distinct auxiliary head ridges visible on at least one individual in the group) sightings made between 21 January and 15 Feb 2006 and 34 photo-confirmed sightings made between 19 December 2006 and 27 February 2007 (mean group size = 2.9, SD = 2.6, range = 1-15 for all 40 sightings; Smith *et al*., submitted).

Farther offshore in the SoNG, both pantropical spotted dolphins (*Stenellla attenuata*) and spinner dolphins (*S. longirostris)* have been photo-confirmed with two sightings of the former (group size estimates 55 and 250) and 11 sightings of the latter (mean group size = 64.0, SD = 63.3, range = 4-200) made during approximately 541 hours of photo-identification effort for Indo-Pacific bottlenose dolphins in habitat generally closer to the habitat rim (Smith *et al*., submitted). Spinner dolphins in the SoNG appear similar to the large pantropical form of the species (*S. l. longirostris*) rather than the shallow-water dwelling dwarf form *S. l. roseiventris* found in shallow waters of Southeast Asia (see Perrin *et al.* 1989, 1999, 2007).

CETACEAN HABITAT

Mangrove forest waterways

The Sundarbans are the world's largest contiguous mangrove forest encompassing almost 600,000 ha with about 30% composed of a complex network of tidal and fluvial waterways ranging from a few meters to a few kilometres wide. The network is fed almost entirely by the GBM river system (Hussain and Karim, 1994), which, with an annual runoff of 1,400km^3/yr, is the world's third largest (Shiklomanov, 1993). Salinity levels in the Sundarbans are determined primarily by physical forcing from freshwater flows and to a lesser degree by diurnal tides. In recent years, diversion of water upstream in the fluvial system has produced a decrease in fresh-water flow (Smith and Reeves, 2000; Smith *et al.*, 2000). In particular, after construction of the Farakka Barrage in India, significant increases in salinity levels were documented in the Sundarbans (Mirza, 1998a). Also, increased sediment deposition, due to reduced river discharges, has led to the gradual drying up of distributaries that previously contributed to repelling salinity encroachment (Barua *et al*., 1995).

Coastal waters

The coastal waters of Bangladesh are dominated in the west by the Sundarbans mangrove forest and in the east by the massive freshwater input from the GBM mouth. Coastal waters are generally shallow and the 50m contour ranges from 40 to 165km offshore along the south facing coast. The enormous supply of freshwater, sediments and nutrients is circulated by a seasonally reversing, wind-driven, basin-scale gyre, with adjacent meso-scale eddies rotating in the opposite direction (Somayajulu *et al.*, 2003). These combine to produce a highly stratified and productive sea-surface layer in coastal waters.

Submarine canyon waters

The minimum 50m contour distance in coastal waters is located in the far west where the SoNG incises approximately 130km inside the continental shelf in a northeast direction. The canyon has relatively steep walls (12-15°), is cone shaped and ranges from about 40km wide at its mouth in Indian waters to about 6km wide at its head in Bangladeshi waters where the maximum depth is slightly more than 900m. The

SoNG plays an important role in sediment transport, carrying 20-29% of the total load supplied by the GBM system to create the world's largest undersea fan (Michels *et al*., 2003; Subrahmanyam *et al*., 2008).

ENVIRONMENTAL THREATS

Declining freshwater flows

Water is abstracted from the Ganges basin by an extensive network of at least 20 high dams and 21 low-gated dams (barrages) and lost to evaporation from reservoirs and open canals and seepage to recharge groundwater supplies that are generally declining due to intensive extraction by tube wells (Smith and Reeves, 2000; Smith *et al.*, 2000). The most notable flow regulation structure affecting cetaceans in Bangladesh is the Farakka Barrage in India, which divides the overall metapopulation Ganges River dolphins at its approximate geographical centre and diverts flow from the Ganges (Sinha, 2000) that supplies the vast majority of freshwater to the Sundarbans in Bangladesh. The Kobadek and Betna rivers are the only sources of fresh water in the far western portion of the Sundarbans. These rivers have been cut off from the Ganges, probably due to increased sedimentation caused by reduced discharges following construction of the Farakka Barrage, and are currently fed solely by local rainfall (IWM, 2003a). The problem of declining freshwater flow to the Sundarbans will become a much greater threat to dolphins and other aquatic fauna if plans proceed for a collection of large-scale, inter-basin water transfer projects in India (see Ghosh *et al.*, 2003; Patkar, 2004).

Sea-level rise

According simulation models reported by the Intergovernmental Panel on Climate Change (IPCC) average sea-surface temperature will increase by 1.1-6.4°C resulting in a globally averaged sea-level rise of 18-59cm in 2090-2099 (IPCC, 2007). However, these figures could potentially be much higher because the models do not incorporate indirect factors such as carbon-cycle feedback. An alternative semi-empirical model estimated that sea levels could rise by as much as 1.4m over the same period (Rahmstorf, 2007). In the Sundarbans, a 10-45cm sea-level rise has been predicted to cause inundation of about 15% or 750km^2 of the total land mass (Mirza, 1998b), and a rise of 50cm would cause salinity to increase by about 2 ppt during the dry season in the far west, with an increasing extent of sea water intrusion (IWM, 2003b). The ecological effects of sea-level rise have not been rigorously assessed in the fluvial, estuarine, and coastal waters of Bangladesh; however, it is can be expected that altered freshwater and ocean regimes will dramatically change the composition and structure of biological communities and probably result in local species extinctions (Harley *et al.*, 2006).

ENVIRONMENTAL SENSITIVITY

Cetaceans living in freshwater and estuarine systems depend profoundly on the physical characteristics of their environment. Besides having osmotic requirements, they require sufficient freshwater flow to allow movement between deep pools and the availability of hydraulic refuge from high velocity currents (Smith and Reeves, 2000). Ganges and Irrawaddy dolphins in the Sundarbans show distinct distributional responses to salinity and turbidity gradients, tracking their movements from the

southwest to the northeast with declining freshwater flow, which has the same general effects as sea-level rise.

Habitat selection of Ganges River and Irrawaddy dolphins has been investigated using data collected from visual boat-based surveys in waterways of the Sundarbans during the pre-monsoon season, when freshwater flow was approaching its lowest, and during the early post-monsoon season, when freshwater flow was still relatively close to its peak (Smith *et al.*, in press). Generalized Additive Models indicated that Ganges River dolphins selected channel segments characterized by low salinity, high turbidity and moderate depth, while Irrawaddy dolphins were dependent on relatively deep, warm, and clear waters with a relatively high frequency of large and small confluences. However, during the high-water season this latter species selected deep channels, extreme ranges of turbidity, and low salinity. Also, both species exhibited preference for wide sinuous channels with more than two small confluences or at least one large confluence and wide sinuous channels with one or two small confluences (Smith *et al.*, in press).

The broad-scale distribution of Ganges and Irrawaddy dolphins appears thus to be sharply determined by different requirements of salinity, depth and turbidity, but similar requirements related to geomorphology. Due to their obligate dependency on freshwater flow, Ganges River dolphins would be expected to be more affected by declining freshwater flows and sea-level rise compared to Irrawaddy dolphins. On the contrary, Irrawaddy dolphins appear to be more plastic and the above results suggest that the limits to their upstream range are constrained by interspecific competition with the Ganges river dolphin rather than by dependence on salinity; this explanation is given credence by the fluvial distribution of Irrawaddy dolphins in three large rivers of Asia that are not inhabited by Ganges river dolphins (see Smith *et al*., 2007). Since the Irrawaddy dolphin appears to be opportunistic in its ability to take advantage of the benefits of fluvial environments, it can be hypothesized that its response to a decline in the range of Ganges River dolphins would be to take advantage of the weakening of the competitor and extend its range upstream. However, upstream habitat for Irrawaddy dolphins may disappear with increased sedimentation caused by declining freshwater supplies and sea-level rise (Smith *et al.*, in press).

Meanwhile, the availability of the marine habitat for the Irrawaddy dolphin will probably shrink because, in coastal waters, Generalized Additive Models (GAMs) using oceanographic covariate data (depth, salinity, sea surface temperature and turbidity) indicated that the presence of Irrawaddy dolphins was conditionally dependent on low salinity and shallow depth (both significant at $P<0.001$), which explained 36% of the variance in the data (Fig. 3). The selected GAM with the lowest UBRE score using depth and salinity as covariates was then applied to oceanographic data available for the Bay of Bengal on the internet, to create a hypothesized probability surface of Irrawaddy dolphin occurrence. Bathymetry data were taken from the GEBCO Digital Atlas (British Oceanographic Data Centre, 2003) and salinity data from the World Ocean Atlas/Database (National Oceanographic Data Center, 2005) for the month of February. The plot was then compared to the actual sighting locations of the line-transect survey to see if the GAM accurately predicted dolphin occurrence using environmental data obtained from a different source – i.e., the GEBCO Digital Atlas and World Ocean Atlas/Database.

Although additional model validation is needed to quantify how close the probability surface corresponds to the actual locations of Irrawaddy dolphin sightings made during the February 2004 survey, a visual examination of the probability plot (Fig. 4) versus a map of the sighting locations (Fig. 2) indicates that the two roughly

match. Although this analysis should be regarded as preliminary, it does provide support for using Irrawaddy dolphins in Bangladesh as an indicator population to monitor and predict the effects of environmental changes associated with declining freshwater flow and sea-level rise. It was significant that the GAM model pointed to salinity and depth as the most important explanatory covariates because these are sensitive to declining freshwater flow and sea-level rise. Thus, foreseen environmental variation associated with both of these environmental factors is expected to reduce the range of this species at both ends: the offshore range would shrink due to increasing intrusion of marine waters inshore, while upstream habitat could be lost due to a decline in the availability of large and small confluences. Additional sighting and environmental data are currently being obtained from systematic surveys of coastal waters in Bangladesh. These data should allow us to increase the precision of the GAMs and to pursue analyses of other coastal cetaceans, such finless porpoises and Indo-Pacific humpback dolphins.

Less is known about the habitat selection of cetaceans living in coastal waters farther offshore although still affected by freshwater and sediment inputs from the GBM system. These species, including the finless porpoise and Indo-Pacific humpback dolphin, may also exhibit distributional responses to increasing salinity and decreasing turbidity levels, and a possible release from competition with Irrawaddy dolphins. A discriminant analysis of environmental parameters recorded for Irrawaddy dolphins and finless porpoises suggested that depth and salinity best explain the environmental preferences of both species with the latter preferring deeper and more saline waters. Meanwhile at the head of the SoNG, reduced sediment influxes and altered up-welling and circulation patterns may also have profound effects on the probably resident population of Bryde's whales and Indo-Pacific bottlenose, spinner and spotted dolphins that inhabit these waters. Preliminary observations indicate that the distribution of these species is also stratified according to environmental characteristics, with Bryde's whales and bottlenose dolphins in more shallow waters close to the rim of the submarine canyon where upwelling is maximized, followed by spinner and spotted dolphins in more pelagic waters. Distinct distributional responses have been recorded for cetaceans in the submarine canyon of Monterey Bay, California, during the 1997-98 El Ninõ (Benson *et al.*, 2002)

AVAILABILITY OF BASELINE INFORMATION AND FEASIBILITY OF MONITORING

As described above, the abundance, distribution patterns and habitat requirements of both Ganges River and the Irrawaddy dolphins have been extensively researched in the Bangladesh during the last few years (Smith *et al.*, 2001, 2004, 2005, 2006, in press, submitted). A robust database compiled from almost 8,000 sightings of Ganges and Irrawaddy dolphins made by an ongoing cetacean monitoring network established among captains of three nature tourism vessels operated by The Guide Tours Ltd. serves as a baseline for future population monitoring. Moreover, waterways that consistently show the highest density of each species (and randomly selected waterways that support lower cetacean densities) are currently the focus of an intensive study of their physical properties (*e.g.* temperature, salinity, turbidity, channel depth and width, and number of small and large confluences) and biological characteristics (*e.g*. fish and crustacean abundance and diversity).

Data from the open estuarine waters offshore the Sundarbans and deep submarine canyon waters of the SoNG, although not as extensive as inside the mangrove forest, is

also robust. A vessel-based, line-transect survey was conducted during February 2004 along more than 1000km of systematic trackline which resulted in 111 "on-effort" cetacean sightings (Smith *et al.*, submitted). The area is also the focus of periodic line-transect surveys (started in November 2007), which include the systematic collection of environmental data, and fieldwork to compile a photo-identification catalogue of Indo-Pacific bottlenose dolphins, Indo-Pacific humpback dolphins and Bryde's whales, and to obtain biopsy samples for genetic, contaminant and isotope analyses.

From the perspective of local expertise (manpower), the situation offers optimal opportunities for successful monitoring. The Wildlife Conservation Society's Asian Freshwater and Coastal Cetacean Program and the Bangladesh Cetacean Biodiversity Project have jointly made an efficient work of cultivation at all levels: besides having gathered the information on the distribution and abundance of the cetacean species that substantiate the present paper, they have created a network of motivated and trained researchers and graduate students, and have sensitized the local population, from local fishermen, the tourism industry, and high-level government officials, all eager to collaborate. Strong progress has also been made on establishing a protected area network for cetacean diversity in Bangladesh which would provide a mandate for developing a more extensive cetacean research and monitoring program than currently exists.

CONCLUSION

Cetaceans occupying a relatively small area of mangrove channel, open estuarine and submarine canyon waters in Bangladesh exhibit indicator properties that can be used for modelling the potential ecological effects of declining freshwater supplies and climate change. Dedicated studies of these species and their habitat have strong potential for providing fundamental information needed to develop science-based strategies for conserving cetaceans in Bangladesh, and elsewhere where the same or other species are subject to similar freshwater-supply and climate-change pressures.

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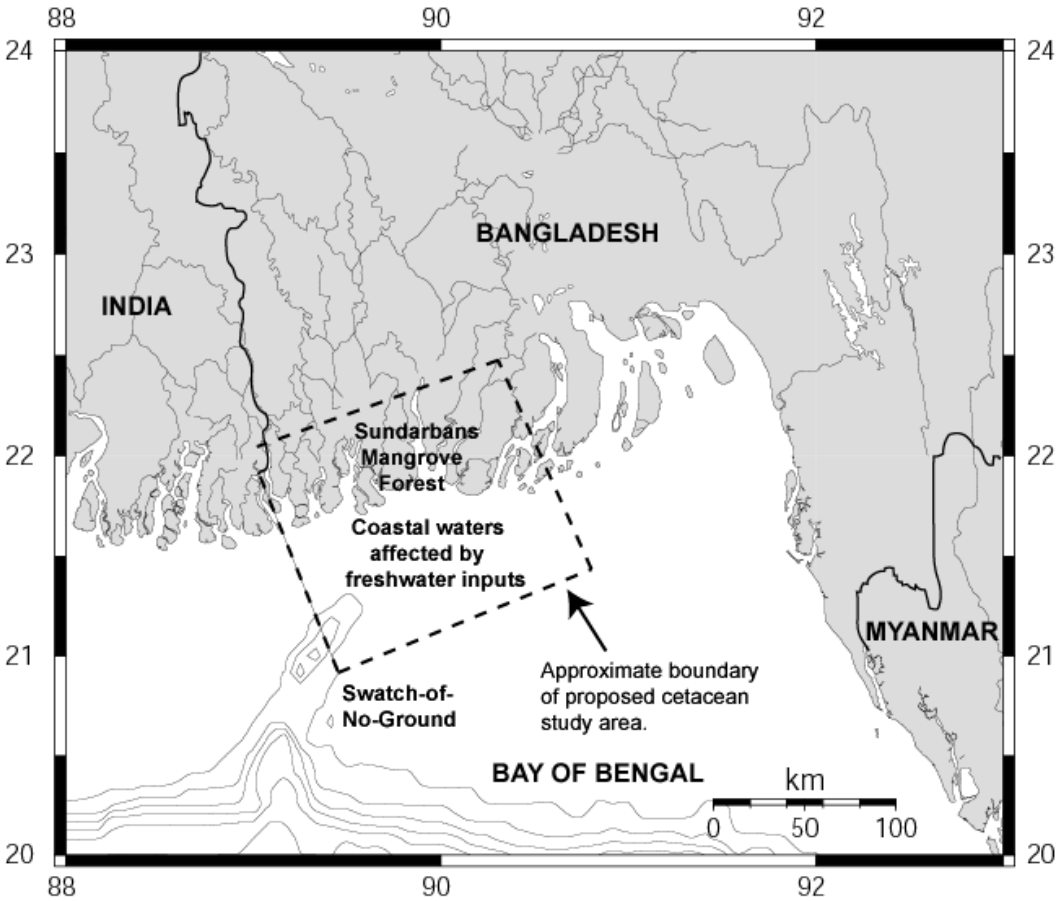


Fig. 1. Map of the Bangladesh showing the proposed cetacean study for evaluating the ecological effects of declining freshwater flows and sea-level rise.

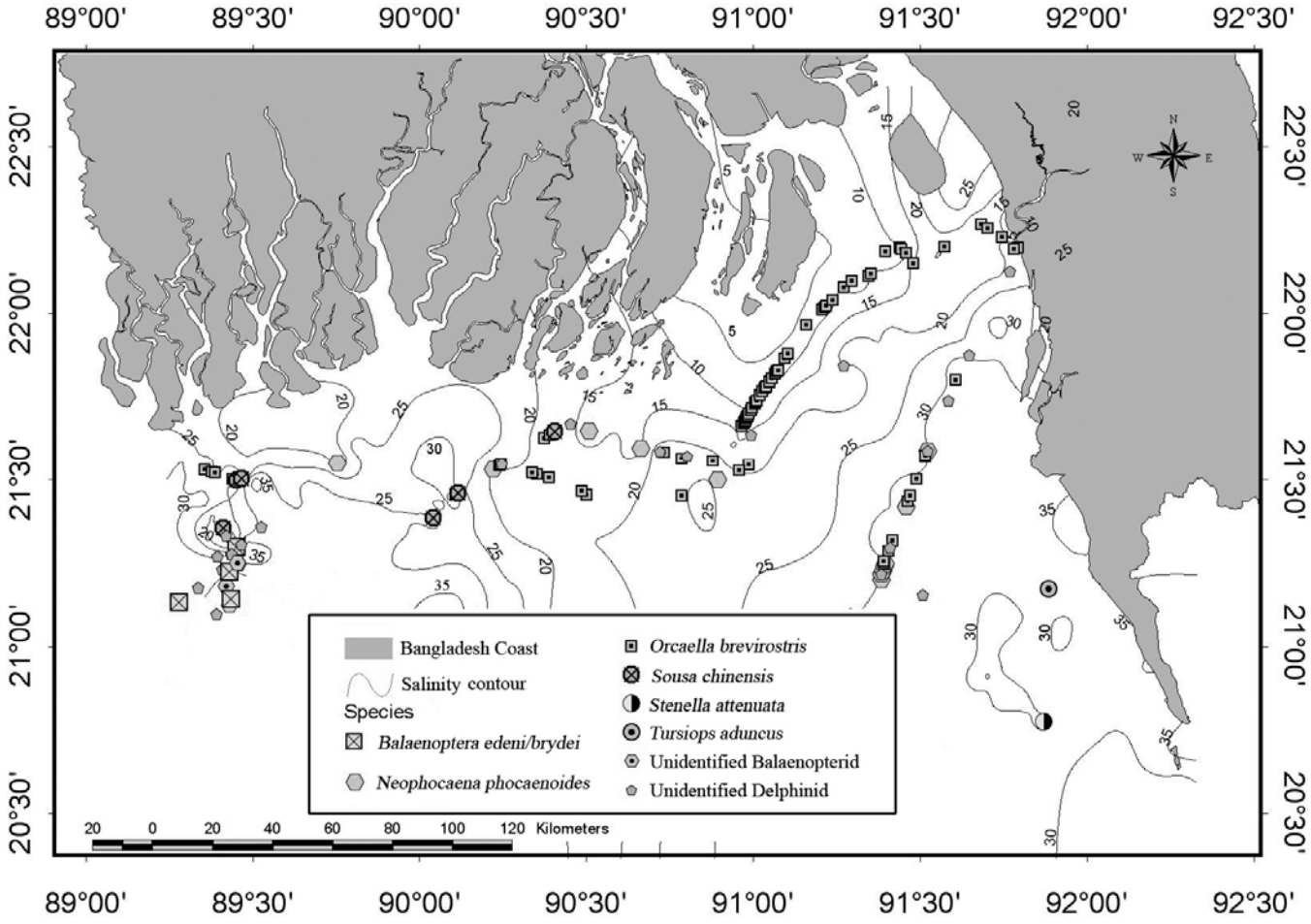
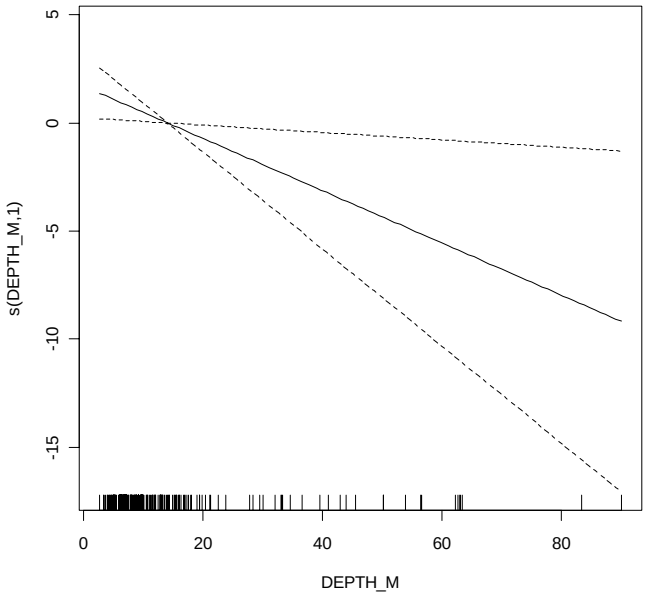


Fig 2. Map of the northern Bay of Bengal showing cetaceans sightings made during a survey of coastal waters in March 2004.



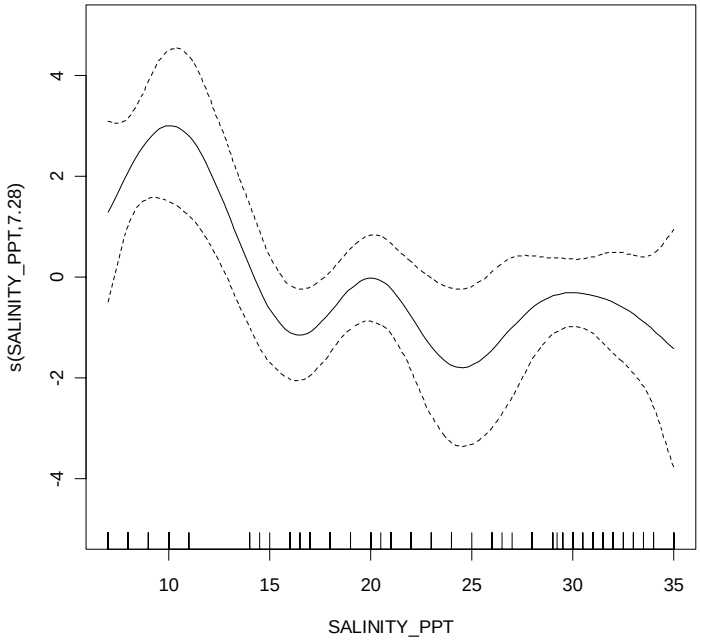


Fig. 3. Results of fitting a binomial logit link Generalized Additive Model (GAM) model to Irrawaddy dolphin presence/absence data with depth (m) and salinity (ppt) as explanatory variables. Estimates (solid lines) and confidence intervals (dashed lines), with a rug plot indicating sighting density along the bottom of the plot, are shown.

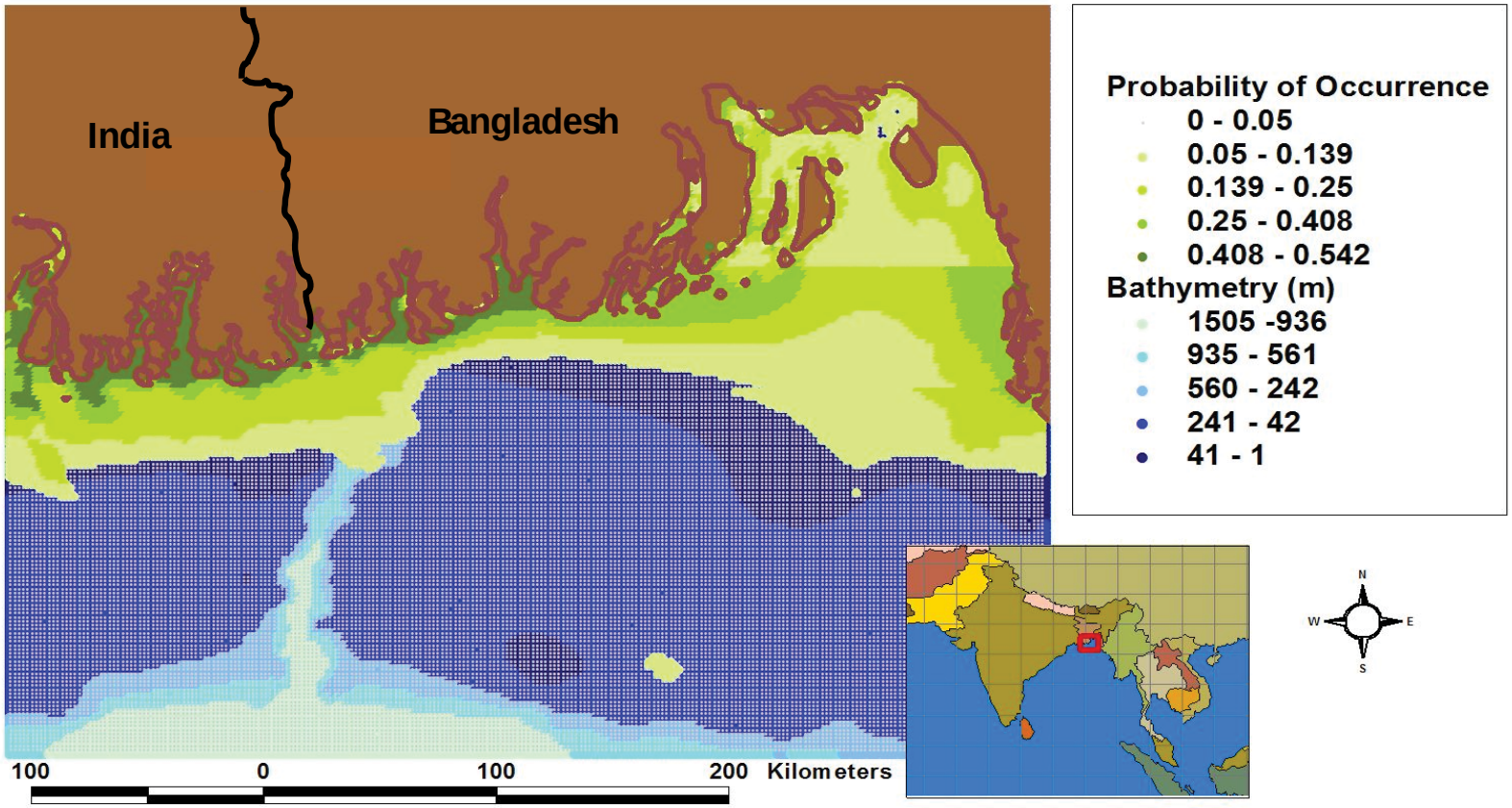


Fig. 4. Prediction of the probability of occurrence of Irrawaddy dolphins based on the best binomial Generalized Additive Model (GAM) with a logit link that included the covariates depth and salinity. The slight discontinuity in the prediction surface is due to the poor resolution of the salinity covariate data.