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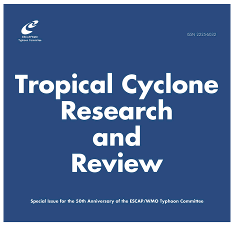

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Forcing ocean model with atmospheric model outputs to simulate storm surge in the Bangladesh coast

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Abstract: Tropical cyclones are devastating hazards and have been a major problem for the coastal population of Bangladesh. Among the advancements in atmospheric and oceanic prediction, accurate forecasting of storm surges is of specific interest due to their great potential to inflict loss of life and property. For decades, the numerical model based storm surge prediction systems have been an important tool to reduce the loss of human lives and property damage. In order to improve the accuracy in predicting storm surge and coastal inundation, recent model development efforts tended to include more modeling components, such as meteorology model and surface wave model in storm surge modeling. In this study, we used the outputs of an atmospheric model to force the ocean model for simulating storm surges in the Bay of Bengal with particular focus on the Bangladesh coast. The ability of the modeling system was investigated simulating water levels in the Bangladesh coast of two tropical cyclones Sidr (2007) and Aila (2009). The effectiveness of the model was verified through comparing the obtained computational outputs against tide gauge data. The cyclone tracks and intensities reproduced by the atmospheric model were reasonable, though the model had a tendency to overestimate the cyclone intensity during peaks and also close to coast. The water levels are reproduced fairly well by the ocean model, although errors still exist. The root mean square errors in water level at different gauges range from 0.277 to 0.419 m with coefficient of correlation (R^2) between 0.64 to 0.97 in case of Sidr and 0.209 to 0.581 m with R^2 0.62 to 0.98 for Aila. The overall coupled modeling system is found to be useful with reasonable accuracy and precision, though there are spaces for improvement. Higher-resolution modeling approaches are recommended to gain more skills.

Keywords: Tropical cyclone, Storm surge, One-way coupling, Bay of Bengal

1. Introduction

Storm surges associated with severe tropical cyclones are among the world's most devastating and destructive natural hazards (Dube et al. 2008; Needham et al. 2015; Peduzzi et al. 2012). The massive destruction and loss of human life associated with a tropical cyclone can be attributed mainly to the sudden inundation and flooding of the coastal areas produced by storm surges hazards (Dube et al. 2008; Peduzzi et al. 2012). They cause heavy loss of life and property, damage to the coastal structures and the losses of agriculture, livestock and coastal aquaculture which lead to annual economic losses in affected countries (Chaumillon et al. 2017). Storm surges may drive the saline water up to 160 km inland into Bangladesh (Snead 2010) which have been cause of increase in water and soil salinity in the surge affected areas (Bricheno and Wolf 2018; Salehin et al. 2018). Periodic storm surge flooding is also significant for vertical infiltration of saltwater (Huizer et al. 2017) and leads to salinity intrusion in the coastal aquifers of Bangladesh (Zahid et al. 2018). Thus storm surges cause huge loss and damage to agricultural crops and drinking water supply systems in the coastal Bangladesh by salinity intrusion (Brammer 2014; Rabbani et al. 2013).

Tropical cyclone induced surges have been major problem for the coastal population of Bangladesh. The Bay of Bengal is producing on average 5.5 tropical cyclones per year (Chowdhury et al. 2012) and a super storm with devastating damage in every 2-3 years (Alam and Dominey-Howes 2015). It consistently experiences the world's highest surges, with on an average five surges ≥5 m per decade (Needham et al. 2015). 59% of global tropical cyclones that have killed at least 5000 people occurred in this basin (Needham et al. 2015). The destruction from the tropical cyclone induced storm surge affects all the countries in the rim, in particular east coast of India, Bangladesh and Myanmar. Amongst them Bangladesh suffering most from storm surges (Dube et al. 1997; Murty et al. 1986). The main factors contributing to disastrous surges in Bangladesh are given below and how these factors together affect the physics and height of surges are shown in Figure 1.

1. Paths of tropical cyclones, and locations of landfall (Islam and Peterson 2009),
2. Bathymetry - shallow continental shelf (Krien et al. 2016),
3. Coastal geometry - wide continental shelf with a funneling effect (As-Salek 1998),
4. Atmospheric convergence of the bay (Luis and Pandey 2004),
5. High astronomical tides (Murty and Henry 1983),
6. Densely populated , low lying and poorly protected coastal area (Ali 1996), and
7. Huge river discharge with innumerable number of tidal creeks and inlets (Brammer 2014).

The trends derived from recent observations show that there are reasons for concern. Both observations and climate predictions anticipate that, although possibly decreasing in the mean, tropical cyclones will move towards a substantial intensification (Sobel et al. 2016; Young et al. 2011). Mei et al. (2015) have predicted that the mean intensity of tropical cyclones will increase from Category 3 (currently) to Category 4 by 2100. Even if coastal storms do not increase in frequency and intensity, because of sea-level rise, storm surge may have more of an impact over time (Neumann et al. 2015). A key global problem is the high concentration of human populations near the coast and in low-laying coastal areas (Wong et al. 2014). As sea level rises and climate change impacts coastal regions, extreme events will become more common (more surge-driven flooding and thus more urban infrastructure).

Among the advancements in atmospheric and oceanic prediction, accurate forecasting of extreme weather events is of specific interest due to their great potential to save lives and money (Paul 2009). There seems to be a consensus that high-quality predictions of extreme events like storm surge and flooding caused by tropical cyclone could substantially contribute to avoiding or minimizing human and material damages and losses (Kay et al. 2015; Wolf 2009). In recent years, early warning systems based on storm surge prediction models (e.g., WMO 2011) contributed to reduce the loss of human lives and property damage caused by storms surge (Paul 2009). While in recent years progress has been achieved in modeling capabilities, many crucial aspects of coupling are still to be explored and defined, both in terms of physics and more so as implementation in operational models (Cavaleri et al. 2007). In order to improve the accuracy in predicting storm surge and coastal inundation, recent model development efforts tended to include more modeling components, such as meteorology and surface wave. The state-of-the-art storm surge models (e.g., WMO 2011) are getting higher resolution in time and space, the atmosphere and ocean are coupled more frequently, sharing more fields (Brown et al. 2016).

In the Bay of Bengal, numerical simulation of storm surge due to land falling tropical cyclone was pioneered by (Das 1972). Das et al. (1974) further improved the model by incorporating tides in addition to the atmospheric forcing as boundary forcing. Afterward, several studies carried out numerical modeling for predicting storm surges in the Bay of Bengal, some of them focused on Bangladesh coast (e.g.; Dube et al. 1997; Dube et al. 1985, 1986; Flather 1994; Johns and Ali 1980; Johns et al. 1981; Johns et al. 1983; Murty et al. 1986; Roy 1995). Some of the more recently studies (e.g.; Debsarma 2009; Dube et al. 2009; Dube et al. 2013; Hussain and Tajima 2016; Krien et al. 2017; Kumar et al. 2011; Lewis et al. 2014; Pattanayak et al. 2016; Paul et al. 2016; Rahman et al. 2017) demonstrated the capability of numerical models in reproducing storm surges. The chronology of literature demonstrated that shallow-water numerical models are capable of reproducing storm surges to within an error of 50 cm.

Despite these achievements, storm surge modeling in the Bangladesh Coast remains a very challenging topic. In Bangladesh, storm surge forecasting is being carried out as a part of operational tropical cyclone forecasting (Sobel and Pillai 2018). Distinct numerical models representing the ocean, separate from those used to forecast the tropical cyclone itself, are used to predict the surge which are drive by atmospheric forcing from parametric models.. The greatest source of uncertainty in storm surge forecasts, which limits the lead time, is uncertainty in atmospheric forcing. Uncertainties relative to atmospheric input data is one of the reasons. Accurate representation of wind forcing and mean sea level pressure is important for modeling storm surges (Bricheno et al. 2013). The Bay of Bengal suffers from a dearth of in-situ observations. Hence, as most of the above stated studies, wind and pressure fields during cyclone events have to be estimated from parametric models. Uncertainties arise from the choice of the parametric model (Lin and Chavas 2012) and input parameters, such as cyclone track, intensity, or size translate into large uncertainties in the prediction of storm surges. Though these observations remain valid for hindcast studies comparison between best track data provided by several meteorological agencies show systematic discrepancies because of the use of different data and operational techniques (Krien et al. 2017). Analyzing the data provided by different agencies Lewis et al. (2013) found tens of kilometers track difference at landfall with timing error of several hours, resulting in discrepancies of several meters on water level. This indicates the importance of mesoscale forcing towards the prediction of storm surge amplitude (Dube et al. 2009). Atmospheric mesoscale models such as the Advanced Research Weather Research and Forecasting model (ARW-WRF) (Skamarock et al. 2008) hereafter referred to as WRF, can be used to improve the meteorological forcing of surge prediction. There is now a unique opportunity to further improve surge forecasts by using a mesoscale model for wind and pressure fields. The motivation for this study was to explore ways of improving coastal surge forecasting in the Bay of Bengal by improving the atmospheric forcing.

With the advancement of high resolution atmospheric mesoscale models the forecast of track and wind speed of tropical cyclone are substantially improved. However, storm surge prediction skills in the Bay of Bengal area have not similarly improved due to uncertainties related to atmospheric input data, lack of available high-quality and high-resolution bathymetric data in shallow areas, lack of available high-quality water level records during cyclones and also lack of knowledge with regards to several physical processes, such as atmosphere-ocean momentum exchange, especially under strong wind regime and in shallow waters (Krien et al. 2017). For this purpose, we simulated the storm surges associated with severe tropical cyclones over the Bay of Bengal with the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) (Holt and James 2001) using meteorological forcing from WRF outputs. The both models are already well established (e.g., Mohanty et al. (2010) found that WRF perform well for the Bay of Bengal tropical cyclones, and Kay et al. (2015) found good performance of POLCOMS in the Bay of Bengal for extreme sea level).

The performance of a one-way coupled POLCOMS-WRF storm surge modeling system is demonstrated in the present study. A brief description of the modeling system, experimental design and statistical methods used in the study are presented in section 2. The results of both atmospheric and ocean models are discussed in section 3. The main findings of the study have been concluded in section 4.

2. Materials and methods

2.1. The modeling system

Two well-established models have been used for the study. The atmospheric model used in the study is the WRF and for the ocean component of this study, the 3D tide and surge model POLCOMS is used. The outputs from the atmospheric model were used to drive the ocean models in a one-way coupled / forced mode. Figure 1 shows the flow chart of modeling system used in the study.

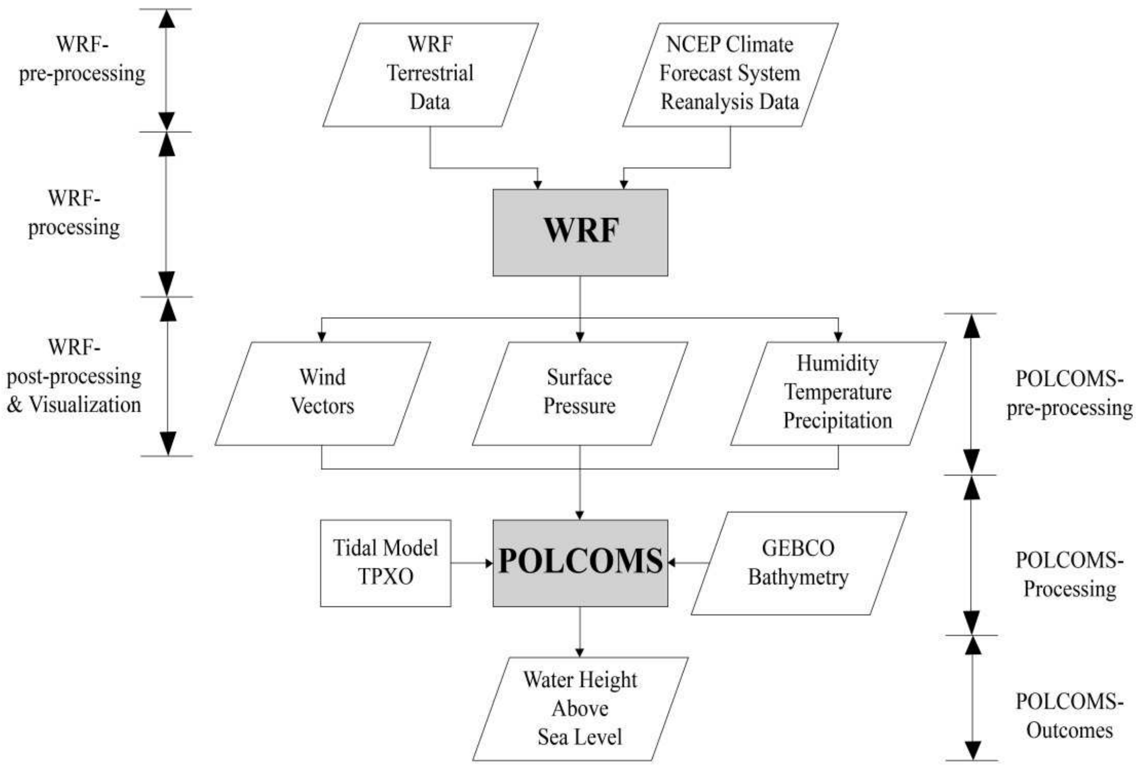


Figure 1. Model schematic diagram

2.1.1. Atmospheric model - WRF

The WRF is a fully compressible, non-hydrostatic mesoscale model with hydrostatic option (Janjic 2003). The model solves the three-dimensional Euler equations using terrain-following hydrostatic-pressure vertical coordinates to simulate meso- and micro-scale atmospheric variables and staggered Arakawa-C grid. The present version of WRF (Skamarock et al. 2008) is portable in a parallel computing environment. The WRF model has found wide application in variety of problems that resolves physical processes having wide spatial scale resolutions. The model physics in WRF takes into account cloud microphysics, surface layer physics, land surface model, boundary layer, long and short wave radiation components. The detail description of the current version of WRF (Version 3) with model equation has been described by Skamarock et al. (2008).

We are using a dynamical downscaling approach, to generate high frequency, high-resolution atmospheric forcing from WRF. This will improve the surface boundary condition of the POLCOMS model, and there for the prediction of storm-surge. The global atmosphere model provides lateral boundary data, then the nested WRF model downscales this to output hourly winds and pressures more suitable for regional surge forecasting. The dynamical downscaling approach also improves the representation of coastline / orography features, thus improving coastal forecasts (Bricheno et al. 2013).

A 12 km resolution grid is defined over the Bay of Bengal (Figure 2), which is initialized and forced by the global analyses model, National Centers for Environmental Prediction Final (NCEP FNL) data. NCEP FNL produces every six hours at 00, 06, 12 and 18 Coordinated Universal Time (UTC) at 1 X 1 degree spatial resolution. The model was run to get outputs in every hour reinitializing the forcing from global data in every 24 hours daily to avoid excessive drift. The model was run for 12 h for spin up and then further 24 h for outputs. The atmospheric planetary boundary layer (PBL) was represented by 12 sigma levels below the 850-hPa level, with the lowest level set at 38 m above ground level . We considered that such vertical configuration can correctly reproduce atmospheric dynamics in a complex coastal area. It should also be noted that in stormy conditions and complex topography (Tenerife) Marrero et al. (2009) found a lack of sensitivity to the number of vertical levels. The meteorological model is configured with 32 vertical sigma levels, and the top of the atmosphere is set as 50 hPa.

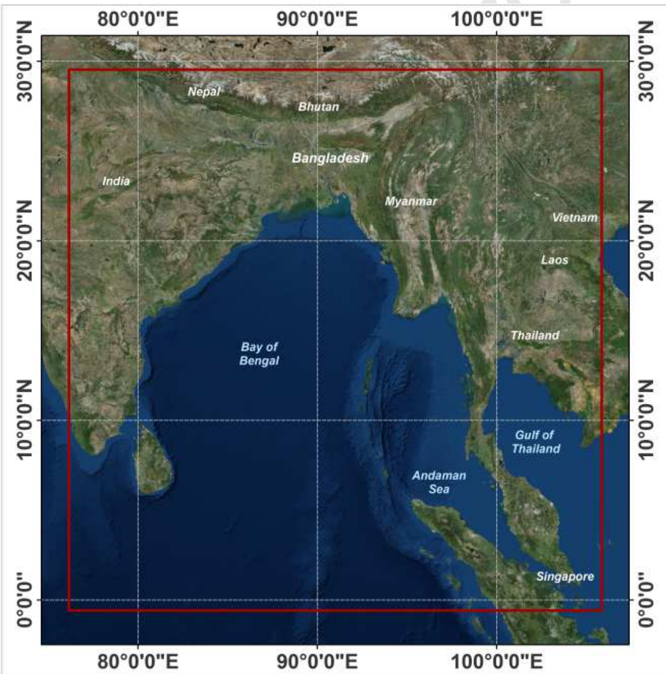


Figure 2. WRF model domain

Intensity and track are highly sensitive to the model physics. Srinivas et al. (2013) found that the combination of Kain–Fritsch (KF) cumulus scheme (Kain 2004) convection Lin microphysics (Lin et al. 1983), the Yonsei University planetary boundary layer (Hong et al. 2006) and NOAH land surface physics (Ek et al. 2003) options provide the best physics for operational forecasting with least errors. The microphysics scheme is set as Ferrier (new Eta), Lin microphysics and WSM 6-class graupel scheme, and the Cumulus Parameterization was defined by Kain-Fritsch (new Eta) scheme, NOAH land surface physics (Ek et al. 2003); and Betts-Miller-Janjic. Details of model configuration are shown in Table 1.

2.1. 2. Ocean model - POLCOMS

The 3D coupled tide surge model, POLCOMS is used for the ocean component of the study. POLCOMS is a three-dimensional baroclinic Arakawa B-grid model designed for the study of shelf sea processes and ocean-shelf interaction. The model solves the momentum and scalar transport equations for oceanographic applications with realistic topography, bathymetry and forcing. The underlying hydrodynamics in POLCOMS are the shallow water equations with the hydrostatic and Boussinesq approximations. This limits model applicability to flows where the vertical acceleration is small and in practice this imposes a minimum horizontal resolution; simulation can be made at resolutions finer than this but at no benefit to the solution. As a rough guide this can be taken as half the maximum water depth (Holt and James 2001). The system has been structured to allow its execution on parallel and serial computers (Ashworth et al. 2004).

Table 1. Details of the WRF model

Dynamics	Non hydrostatic
Data	NCEP FNL
Output frequency (h)	1
Grid size	277kmx294kmx32
Resolution	12 km
Covered area	0-30 N, 75 – 105 E
Map projection	Mercator
Horizontal grid system	Arakawa-C grid
Integration time step	150 s
Vertical coordinates	Terrain-following hydrostatic pressure vertical co-ordinate with 51 vertical levels
Time integration scheme	Third order Runga-Kutta scheme
Spatial differencing scheme	Sixth order center differencing
PBL scheme	Yonsei University planetary boundary layer model
Surface layer parameterization	Noah land surface scheme
Microphysics	1. Ferrier (new Eta); 2. Lin microphysics; and 3. WSM 6-class graupel scheme
Short wave radiation	Dudhia scheme
Long wave radiation	RRT
Cumulus Parameterization (cu_physics)	1. Kain-Fritsch (new Eta) scheme ; 2. Grell-Devenyi ensemble; and 3. Betts-Miller-Janjic

The model was set up over the region shown in Figure 3. The spatial resolution was 0.1° in longitude and latitude (about 11 km) and the domain extended to 200 km inland to the north. The model was run on a structured mesh grid. There were 40 vertical levels at each grid point, distributed using an s-coordinate method. Topographic and bathymetric data defining the region were obtained from General Bathymetric Chart of the Oceans (GEBCO) data on a global 30 arc-second grid available at http://www.gebco.net. A minimum water depth of 10m was imposed to avoid the implementation of wetting and drying at the coast; hence the complex shape of the delta's coastline can only be represented approximately.

Tidal forcing is built into POLCOMS through forcing at the open ocean boundary. The 8 leading harmonic components were used: Q1, O1, P1, K1, N2, M2, S2 and K2. Elevation and current boundary conditions were derived from a tidal model (TPXO) (Egbert and Erofeeva 2002), and nodal factors and date corrections were applied within the model (Le Provost et al. 1995). Kay et al. (2015)

conducted a thorough analysis of simulated tide with similar model set up (0.1 degree horizontal resolution, forced water level to 10m, and global bathymetry) and found reasonably good agreement in the Ganges–Brahmaputra–Meghna delta. Relying on their findings this study did not investigate the skill of current modeling set up in simulating only the tides the Bangladesh coast. This manuscript build on this, by considering the coupling between tide and surge. It is important to combine the non-linear interactions of tide and surge, in order to make an accurate prediction. The timing of cyclone arrival, related to the state of the tide can have major impact on the height of total water level (Williams et al. 2016).

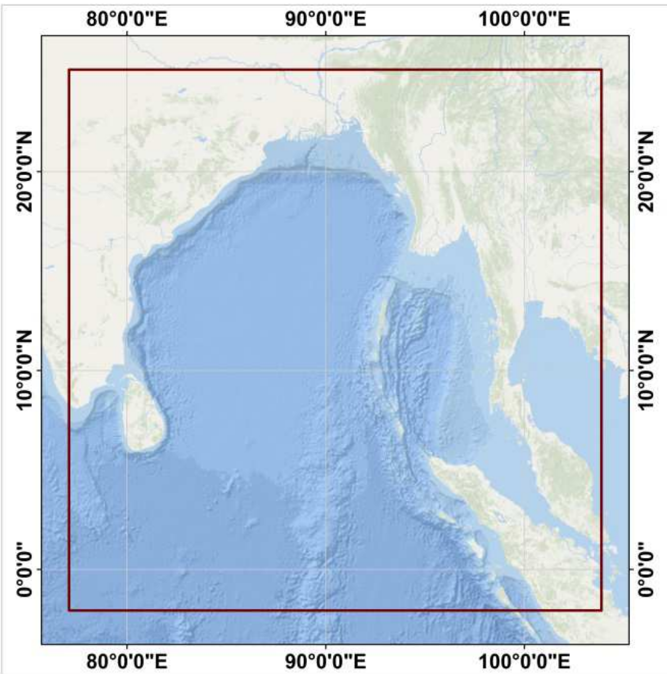


Figure 3. POLCOMS domain in the Bay of Bengal

Meteorological forcing is provided through the application WRF at the ocean surface in every hour. The meteorological variables used are 10-m winds, mean sea level pressure, 2-m surface temperature and clouds. The POLCOMS and WRF model resolution were held constant throughout the study.

2.2 Tropical cyclones chosen for simulation

Two recent severe tropical cyclones Sidr (2007) and Aila (2009) were taken to analyze and compare model simulated results with observation. Cyclone Sidr and Aila are excellent candidates to test storm surge model in the Bangladesh coast as they are the most recent and best observed and documented extreme event that caused surge in the Bangladesh coast during the last decades. They have also been used as a test case for regional storm surge models by a number of authors (Deb et al. 2011; Debsarma et al. 2014; Dube et al. 2009; Gayathri et al. 2016; Kanase and Salvekar 2015; Krien et al. 2017; Lewis et al. 2013; Rahman et al. 2017).

2.2.1 Cyclone Sidr (2007)

On 15 November 2007, Cyclone Sidr struck the south-west coast of Bangladesh with winds up to 240 kilometers per hour. The category-4 storm was accompanied by surge levels (total water level) up to 6 meters in some areas, breaching coastal and river embankments, flooding low-lying areas and causing extensive physical destruction (ITJSCE 2008). High winds and floods also caused damage to housing, roads, bridges, and other infrastructure. Electricity and communication were knocked out, and roads and waterways became impassable. Drinking water was contaminated by debris and many sources were inundated with saline water from tidal surges, and sanitation infrastructure was destroyed (GoB 2008). Over 3000 people died, and extensive damage occurred to roads, bridges, houses, livestock, and crops.

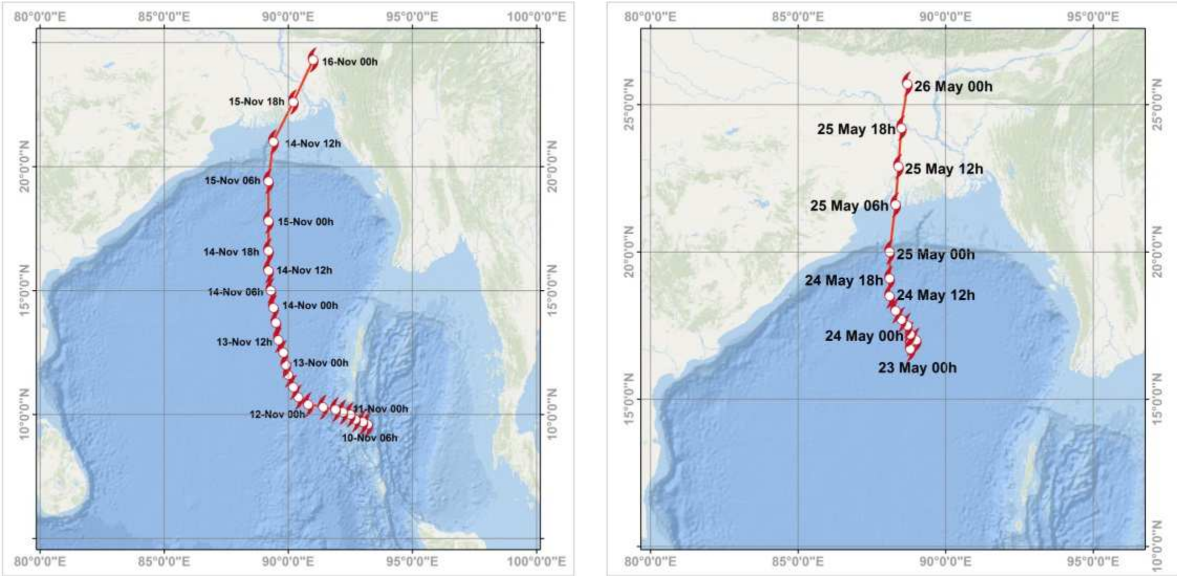
A well-defined low pressure area was located over the southeast Bay of Bengal at 0000 UTC of 11 November 2007, which concentrated into a depression at 0900 UTC of 11 November and lay centered at latitude 10.0° N, longitude 92.0°E about 200 km south-southwest of Port Blair and intensified into deep depression at 1800 UTC of the same day. Moving in a northwesterly direction, the system intensified into a cyclonic storm at 0300 UTC of 12 November. Thereafter, the system rapidly intensified into a severe cyclonic storm at 1200 UTC and into a very severe cyclonic storm (167 km/h) at 1800 UTC on 12 November. The system continued to move in a northwesterly direction until 0000 UTC of 13 November. Afterwards the system moved in a northerly direction up to 1200 UTC of 15 November and then started to move north-northeastwards. It maintained the same intensity (167 km/h) from 1800 UTC on 12 November to 0000 UTC on 15 November. The system further intensified to 213 km/h at 0300 UTC on the same day and crossed the west Bangladesh coast around 1700 UTC near latitude 21.7°N, longitude 89.8°E with the same intensity. After landfall the system weakened into cyclonic storm at 2100 UTC of 15 November. The system further weakened into depression at 0300 UTC and remained depression until 0600 UTC on 16 November. Figure 4 (a) shows the observed track of Cyclone Sidr.

2.2.2 Cyclone Aila (2009)

Aila, a category 1 cyclone, with a wind speed of 120 km/h hit south western coastal districts of Bangladesh on 25 May 2009, killing 190 people, affecting more than 3.9 million people (Khatun et al. 2017) across the 11 coastal districts, disrupting their livelihoods, and destroying infrastructure. According to a report from the Bangladesh Meteorological Department, a low formed over Southwest Bay and adjoining area on 21 May 2009. It moved northwards and further intensified into a well-marked low and a depression over Southwest Bay and adjoining West Central Bay on 23 May. Afterward on the same day, it changed its direction and moved north-northeastwards and intensified further into a deep depression, which then developed into the cyclonic storm called Aila on 24 May and about 0800 UTC of 25 May the system started to cross West Bengal-Khulna in Bangladesh coast near Sagar island in India and then moved continuously northwards. At about 1200 UTC of May 25, the central position of the system was positioned over Kolkata (India) and adjoining Bangladesh. The observed track of cyclone Aila is shown in Figure 4 (b).

Aila experienced rapid intensification while approaching the coast retaining its intensity level of Severe Cyclonic Storm for more than 12 h after the landfall. It is notable that Aila was the only cyclone in the past two decades to cross West Bengal coast during the pre-monsoon season. Aila resulted in storm surge about 3 m for the Bangladesh region and exceeding 2 m along the Indian coast. The astronomical tide during time of landfall ranged between 4 and 5 m, and the cumulative effects from storm surge resulted in a total water level elevation exceeding 4 m that severely inundated the onshore regions. The loss of human life about 175 in Bangladesh and was about 100 in India (Gayathri et al. 2016).

Tropical cyclones form in the Bay of Bengal during pre-monsoon season mostly hit the Bangladesh or Myanmar coast. Cyclonic disturbances that develop during this season have a high probability of reaching a severe cyclonic stage (Singh et al. 2000). The trajectory of both Sidr and Aila followed almost the northward direction towards the head Bay of Bengal as shown in the Fig. 4a and 4b, which is the usual climatology track for cyclones that have cyclogenesis in the southeast Bay of Bengal (Sahoo and Bhaskaran 2015).



(a) **(b)**

Figure 4. Observed track of selected cyclones. The time shown is in Coordinated Universal Time. (a) Sidr (2007) (b)AILA (2009).

2.3 Data and statistical methods

To validate the models, a range of data has been used. Numerical results of WRF are evaluated against estimated/observed data provided by both Joint Typhoon Warning Center (JTWC) and India Meteorological Department (IMD). The estimated/observed intensity and the position of the tropical cyclone were obtained from International Best Track Archive for Climate Stewardship data (Knapp et al. 2010). It provides the basic cyclone data pertaining to geographical coordinates of cyclone eye location (latitude and longitude); maximum wind speed; central pressure; radius of maximum winds, etc., at every 6-h interval from both sources.

Accurate measurements of water levels that can be used to validate numerical models are unfortunately still rather scarce near the landfall area. Bangladesh Inland Water Transport Authority (BIWTA) is primarily responsible to measure tidal water level in Bangladesh. BIWTA collects such data every hour at different coastal and island stations through tide staffs (tide gauges consisting of a vertical graduated pole from which the height of tide at any time can be read directly) and automatic gauges. These data are generally referred to local chart datum. However, except at a few stations the relation between chart datum and public works datum are not available. Moreover, it is observed from the data record that in most cases water level data are not available due to bad weather during severe cyclonic periods. Therefore, thoroughly comparison of water levels with observed ones at each station is restricted due to scarcity of authentic time series of observed data. To validate the model simulated results with observed data, data from tide gauges located at Hiron Point, Khepupara and Chachanga were used. Figure 5 shows the location of tide gauges used for this study. To correct for datum the observed tidal data were adjusted by the local mean water level which is averaged from extended data; Heron Point (- 1.85m), Khepupara (- 2.315 m, averaged for 14 years of observed data), Charchanga (- 2.149 m from 21 years).

To analyze the model performance the coefficient of correlation (R^2), Root Mean Square Error (RMSE), and percentage model bias (p-bias) were calculated. The RMSE presents an absolute error for the model data, R^2 is an indicator of how much of the variance is explained by the correlation, and p-bias provides a measure of whether the model is systematically over or under predicting the measured data.

For the R^2 the square of the Pearson Correlation Coefficient (Hunt 1986) was used. The RMSE of a model prediction with respect to the estimated variable D_n is defined as the square root of the mean squared error:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(M_n - D_n)^2}{N}}, \tag{1}$$

where M_n is observed values and D_n is modelled values at time *n*.

The p-bias is defined as,

$$p - bias = 100\frac{\sum_{n=1}^{N}(M_n - D_n)}{\sum_{n=1}^{N}(D_n)}, \tag{2}$$

The model prediction is represented by M, D represents the measured data, and N is the total number of data points used to calculate the cost function.

Figure 5. Location of tide gauge used data from to evaluate storm surge elevation results

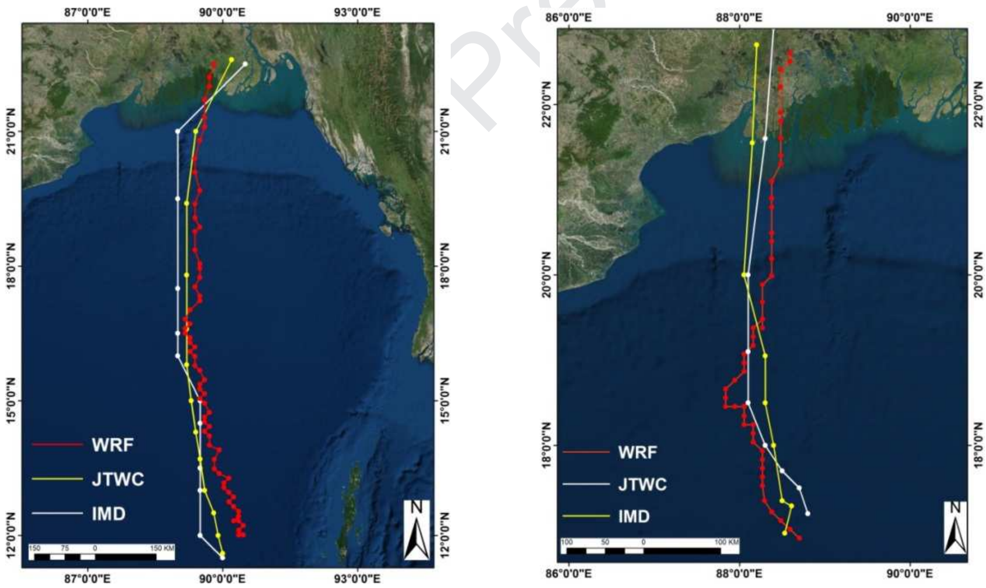
3. Results

3.1 Atmospheric modeling

The results from WRF simulation of severe tropical cyclones Sidr and Aila are presented in this section. The Bay of Bengal suffers from a dearth of in-situ observations of wind and pressure patterns during cyclone events. Nevertheless, JTWC and IMD estimate basic cyclone data at every 6 hours. Observed and simulated tracks of cyclones Sidr and Aila are presented in Figure 6(a) and 6(b). The cyclone eyes of the numerical results are the point to be the minimum value of the pressure at the sea level. The vector displacement errors (VDE) of cyclone track (geographical distance) are calculated from latitudinal and longitudinal displacements.

WRF simulation performs well in predicting the track propagation of Sidr with vector displacement errors of 34.5 km from JTWC data and 46.7 km from IMD data. However, there are some track errors due to temporal displacements. There is a time lag in passing through the same point in just before the cyclone landfall because of slightly slower transition speed of movement of cyclone by WRF model. The WRF simulated landfall was 2 hour later than that of the JTWC observed cyclone. Akter and Tsuboki (2012) and Srinivas et al. (2013) also found delay in WRF simulated landfall time and argue that because of having more recurvature than is normal.. If we assume that the cyclone moves linearly and with a constant translation speed between the two locations given in the best track data before and after the landfall it is at around 17 h UTC (Krien et al. 2017). However, ITJSCE (2008) reported the cyclone landfall time at 18h30 UTC. The observed data shows that the cyclone Sidr change it direction toward northeast rapidly just before landfall. However, this rapid change in wind direction just before landfall of cyclone Sidr has not been reproduced by the WRF model. Topographic effects reducing wind speed at rivers (Ruel et al. 1998) could be a good candidate to explain the changes of direction (Krien et al. 2017) which was not represented in the model due to the 12km resolution not capturing complex coastal features.

The WRF simulated track of cyclone Aila was also fairly accurate with 18 km and 26 km displacement error to JTWC and IMD best track data respectively. The numerical model simulated track of cyclone Aila have biased to east side of the observed track. When the system approaches the land, the track simulated from WRF detours further from the observed track (Fig. 5b). The WRF model simulated track of Aila showed a maximum track displacement error of ∼28 km with JTWC, and ∼42 km with IMD. Though RMSE of VDE is found to be 18 km to JTWC and 26 km to IMD tracks, the time error is acceptable (~1h).



(a) (b)

Figure 6. Compares of WRF simulated tracks and observed tracks of JTWC and IMD. WRF data are hourly interval and the observational data are in 6 hourly interval: (a) Cyclone Sidr and (b) Cyclone Aila.

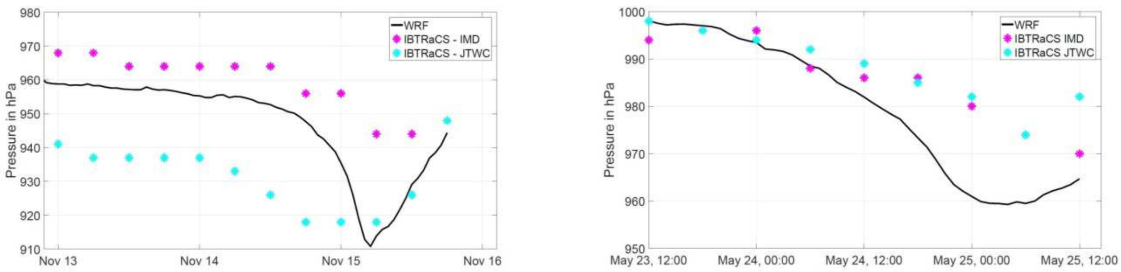
In the current study cyclone tracks were found better compare to some other studies. For example, in case of Sidr Pattanayak and Mohanty (2010) found a vector displacement error of 54 km from IMD observation, Akter and Tsuboki (2012) found 70 km displacement when compared with the observed positions of JTWC, Srinivas et al. (2013) observed track distances of around 100 km using the meteorological model WRF. On the other hand, in case of Aila Deb et al. (2011) found 30 km track displacement along with the IMD track, Debsarma et al. (2014) found vector displacement error 66.6 km throughout the passage of cyclone till the landfall. Atmospheric model simulated track is influenced by model initialization. The closer initialization time, the more accurate track is produced. As the WRF model was re-initialized in every 24 hours it avoided excessive drift in model and gave more accurate tracks.

Cyclone intensity has been evaluated in terms of minimum sea level pressure at the cyclone central (MSLP) and maximum sustain wind at 10m above sea surface (MSW). WRF model was able to capture the intensity of tropical cyclone Sidr and Aila reasonably with observation, though the model had a tendency to overestimate the intensity of MSLP during peak and close to coast.

Figures 7(a) and 7(b) show the MSLP at the sea level of cyclone Sidr and Aila. Cyclone Sidr attained the lowest estimated center pressure of about 910 hPa before the landfall, which is close to JTWC's estimation, however far lower than IMD estimation. In case of Aila, the MSLPs were underestimated by the WRF model compare to both JTWC and IMD data. Before the landfall lowest center pressure of Aila was found to be about 965 hPa.

Quantitative evaluation of the MSLP compared with data for IMD and JTWC for cyclone Sidr is presented in the Table 2. The R^2 values reflected that WRF gives consistent results for MSLP with reasonable RMSEs (9.23 hPa compare to IMD data and 12.5 hPa compare to JTWC data). Interestingly, WRF simulated MSLPs of cyclone Sidr have less than 2% p-bias with negative p-bias for IMD and positive p-bias for JTWC. Which mean that the WRF simulated central pressure is in between the estimation of the two institutes' estimation. Srinivas et al. (2013) found that WRF had tendency to overestimate the cyclone intensity, with mean errors ranging from -2 to 15 hPa for MSLP. Pattanayak et al. (2016) showed that the advancement of data assimilation techniques indeed improves the skill of the WRF models and in case of Sidr found RMSE for central sea level pressure below 4.5 hPa.

Quantitative evaluation of the MSLP of cyclone Aila compared with data for IMD and JTWC is presented in the Table 3. The R^2 values reflected that WRF model gives consistent results for MSLP of cyclone Aila. The RMSE of MSLP was 5.53 hPa compare to IMD estimation and 8.15 hPa compare to JTWC data. Negative p-bias (- 0.5%) suggest that WRF model was slightly overestimated the intensity of cyclones Aila. The tendency for overestimation could be due to biases in the model. However, Debsarma et al. (2014) found that WRF simulation underestimated the intensity of cyclone Aila and argued because of weak representation of the system in the initial field of global atmospheric model FNL data sets. In this study the drawback was overcome by re-initializing the model daily as the global model included data assimilation capability and tracks are more accurate in the model. Frequent reinitializing model avoids excessive drift and improves accuracy of simulated cyclone intensity (Skamarock et al. 2008). However, because of frequent reinitializing in a relatively coarse grid the WRF model could evolve too strongly to overestimate the MSLP particularly during strong wind conditions. The overestimate of these peaks could be reduced by increasing model resolution (Bricheno et al. 2013).



(a) **(b)**

Figure 7. WRF model simulated MSLP at the cyclone central of cyclone Sidr and Aila compare to the estimation of JTWC and IMD. (a) Cyclone Sidr and (b) Cyclone Aila

Table 2 The R^2 value, RMSE and p-bias for WRF model simulated MSLP of cyclone Sidr comparing with IMD and JTWC data (N=18)

R^2		RMSE (hPa)		p-bias (%)	
IMD	*JTWC*	*IMD*	*JTWC*	*IMD*	*JTWC*
0.566	*0.759*	*9.23*	*12.5*	*-1.8384*	*1.1057*

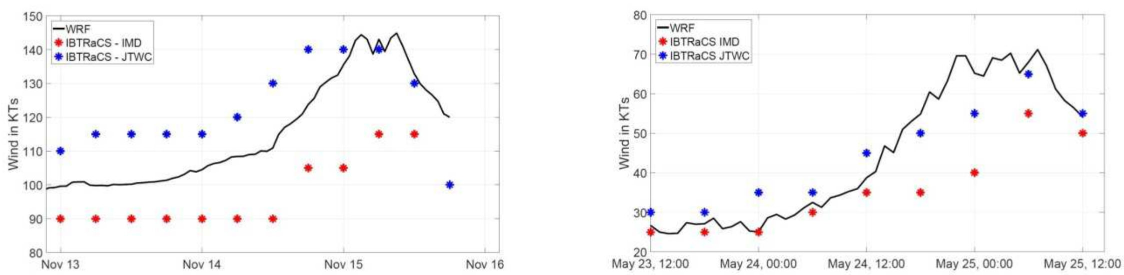
Table 3 The R^2 value, RMSE and p-bias for WRF model simulated MSLP of cyclone Aila comparing with IMD and JTWC estimation (N=12)

R^2		RMSE (hPa)		p-bias (%)	
IMD	*JTWC*	*IMD*	*JTWC*	*IMD*	*JTWC*
0.888	*0.757*	*5.53*	*8.15*	*-0.5712*	*-0.407*

The maximum surface wind speeds of cyclone Sidr and Aila have been presented in Figure 8(a) and 8(b). The WRF model simulated MSW during the peak of cyclone Sidr was more than 140 KTs. The R^2 value, RMSE and p-bias for MSW comparing with IMD and JTWC estimation for cyclone Sidr are presented in Table 4. The R^2 values reflected that WRF model gives consistent results for MSW with RMSE of about 7.06 KTs compare to IMD estimation and 10.1 KTs compare to JTWC estimation.

The WRF model simulated cyclone Aila was most intense just before landfall with MSW about 70.5 KTs. The R2 value, RMSE and p-bias for WRF model simulated MSW of cyclone Aila comparing with IMD and JTWC estimation are presented in Table 5. The R^2 values reflected that WRF gives consistent results for maximum surface wind with about 10 KTs mean error.

The WRF model simulated most of the features (arrival time, high winds and low pressure) of the cyclones Sidr and Aila with reasonable accuracy.



(a) (b)

Figure 8. WRF model simulated MSWs of cyclone Sidr and Aila compare to the estimation of JTWC and IMD. a) Cyclone Sidr and b) Cyclone Aila

Table 4. The R^2 value, RMSE and p-bias for WRF model simulated MSW of cyclone Sidr comparing with IMD and JTWC estimation (N=18)

R^2	RMSE (KTs)	p-bias (%)

IMD	JTWC	IMD	JTWC	IMD	JTWC
0.924	*0.839*	*7.06*	*10.1*	*22.9735*	*-6.4713*

Table 5. The R^2 value, RMSE and p-bias for WRF model simulated MSW of cyclone Aila comparing with IMD and JTWC estimation (N=12)

R^2		RMSE (KTs)		P-bias (%)	
IMD	JTWC	IMD	JTWC	IMD	JTWC
0.704	*0.676*	*10.1*	*10.6*	*22.0825*	*-2.3340*

3.2 Ocean model results

The results from numerical simulation of tropical cyclone induced storm surges in the Bangladesh coast are presented in this sub-section. The water levels are reasonable reproduced by POLCOMS with RMSE of hourly water level ranging from 0.419 - 0.277 m.

Figure 9 shows POLCOMS modeled and observed water levels associated with the cyclone Sidr for the three locations at Hiron Point, Khepupara, and Charchanga. Maximum water level at Hiron Point was computed 1.83 m whilst BIWTA's total maximum observed water height was 1.55m. POLCOMS predicted maximum water level at Khepupara was 4.54 m. Tide gauges at the Khepupara station stopped working during the peak surges of cyclone SIDR. ITJSCE (2008) estimated 4.7 m water level close to the tide gauge of Khepupara which compare well with the numerical results. A maximum water level of 1.6 m was found from the numerical results for Charchanga, where value of 1.8 m was measured by tide gauges.

A strong recession in the surges of Sidr occurred after 14.00 UTC on 15th November at Hiron Point (Fig. 8a), earlier than in any other locations and about 3 h before landfall of the storm. The location of the tide gauge at Hiron Point is west of the SIDR track, hence in a region where the storm surge is not the strongest. The recession takes place due to backwash of water from the shore towards the sea. In fact, Hiron Point is situated left (west) of the cyclone path and so the direction of the anti-clock wise circulatory wind becomes southerly (i.e., offshore) at Hiron Point long before the storm reaches the coast and thus driving the water towards the sea and reducing the surge at the coast.

There is a low water level just after the surge peak and a high water level 3 hours later, close to high tide at the Hiron Point, which have not been reproduced by the numerical model. This is may be because of the rapid change in wind direction and intensity in Hiron Point just before land of cyclone Sidr which has not been captured by the atmospheric model WRF and the surface wind is overestimated in the models during the cyclone journey inland. Significant phase differences in the surge characteristics were found (Fig. 8). Hiron Point exhibited a fair match in both surge amplitude and phase. Cyclone Sidr arrives at Hiron Point (located on the left side of the track near the landfall location) during the ebb tide at 1800 UTC, travels toward the central coast and reaches Charchnage during the flood tide at 2100 UTC.

R^2 value, RMSE, and p-bias for the model data with the tide gauge measured data of the three stations are presented in Table 6. The water levels at Hiron Point and Khepupara where surges occurs have poorer R^2 correlation than the other one. These two stations have also higher RMSE and p-bias. In all cases p-bias are positive that mean model overestimate surge level.

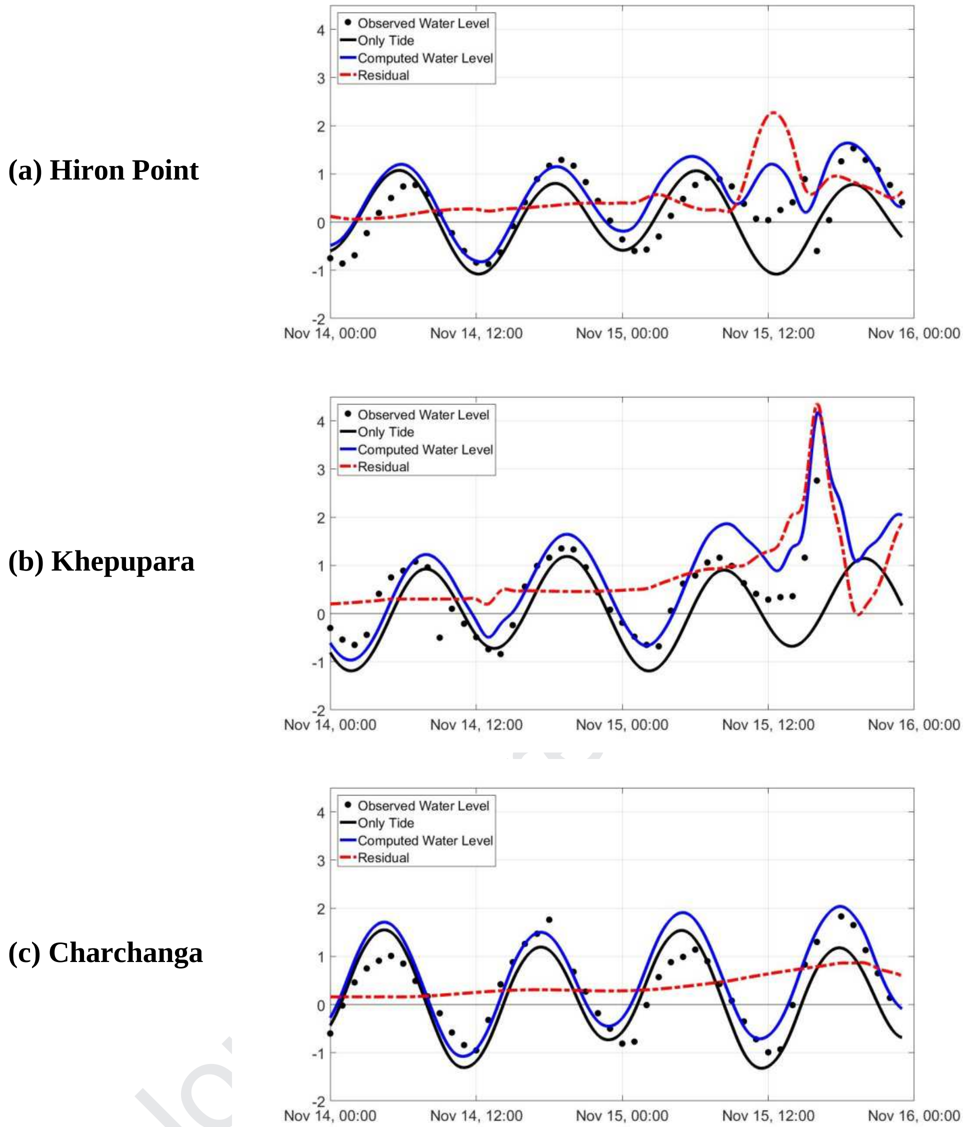


Figure 9. Computed water elevation and observed data referred to mean sea level from the sea level center during Cyclone Sidr at the three locations; a. Hiron Point; b. Khepupara; and c. Charchanga. The black lines are water levels from the tide only run of respective location and the red dotted lines are surge residuals (total water level minus tide only water level).

Table 6 R^2 value, RMSE, and p-bias for tide plus surge elevation at four locations during the cyclone Sidr

Tide Gauge Station	**R^2**	**RMSE (m)**	**p-bias (%)**
Hiron Point	0.637	0.419	34.3237
Khepupara	0.663	0.449	29.9015
Charchanga	0.841	0.317	24.1089

The closer to the landfall location the larger error was found. Krien et al. (2017) found RMSE of water level ranging from 0.59-0.64 m during cyclone SIDR with a new wave-current coupled modeling system with improved bathymetric and topographic data (Krien et al. 2016). They drive the storm surge model with idealized pressure and wind fields however still get good result because of wave integration and improved bathymetric data. Dube et al. (2009) computed maximum surge of about 6.8 m to be near Mongla Port with a vertically integrated numerical storm surge prediction model of Dube et al. (1994). They used the cyclonic storm as the sole driving force for the dynamical processes in the sea, however, have not included the tides and wave setup. Thus the model of Dube et al. (2009) provided larger errors and overestimated the surge level. Using a vertically integrated shallow water model Rahman et al. (2017) computed water levels due to the nonlinear interaction of tide and surge associated with cyclone Sidr. According to them, the results simulated by the model were satisfactory with observed data and found 3.9m and 5.6m at Hiron Point and Khepupara respectively. However, the interaction of wind stress with tide and surge and wave breaking conditions were not taken into account. By integration of these factors, the model results of Rahman et al. (2017) could be further improved. They also found that using a very fine mesh scheme can reduce the errors.

Figure 9 shows POLCOMS simulated and observed water levels associated with the cyclone Aila for the three locations. During the cyclone Aila, the peak water levels were at Hiron Point. The model computed maximum water level about 2.5 m at the Hiron point location where as the BIWTA's observed heights water level was also almost the same. Maximum simulated water level at Khepupara was just below 2.5 m.

Figure 9 (b) shows that the model simulated water levels do not agree with the observations. , A closer look to the observation data shows that there is a lot of missing value and no data during the peak surge. We assume that the tide gauge at Khepupara was not functioning during cyclone Aila. The highest surge elevation of 1.7m was found from the numerical results for Charchanga, where value of 1.75 m was measured by tide gauges. Differences in surge amplitude were evident as Aila approached its landfall location. For the locations Hiron Point and Khepupara the difference between astronomical tide and storm-tide was more than 1.0 m (Figure 9) when the cyclonic system approached towards the coast. Another notable feature is the phase difference in resurgence time at most of the locations. The water levels at central coast were constantly higher for storm tide simulation prior (almost 2 days) to landfall. The build-up of water level is evident increasing to about 1.0 m according to the present model simulations during the landfall time. As in case of Sidr, surge characteristics of Aila also showed phase difference. The surge amplitude decreased as one progress from west to east, proportional to relative distance of locations from Aila track. The surge amplitude at locations Hiron Point is comparatively higher than other locations, with a smaller resurgence time.

Using ADCIRC model Gayathri et al. (2016) found that the water level was 3 m along the western parts of Bangladesh. ADCIRC is a widely used to understand the storm surge characteristics for the global ocean basins, however, according to Gayathri et al. (2016) the model overestimated water level during Aila and did not capture the presence of numerous river drainage systems with several tidal creeks along coastal stretches in the Sundarban region. Rahman et al. (2013) also overestimated total water level due to tide surge interaction during Aila and found 3.61m maximum water level in Bangladesh coast. Rahman et al. (2017) further improved the model of Rahman et al. (2013) using a very fine mesh scheme and found 3.02 m water level. Very Fine Mesh Scheme could capture wind stress representation better.

(a) Hiron Point

(b) Khepupara

(c) Charchanga

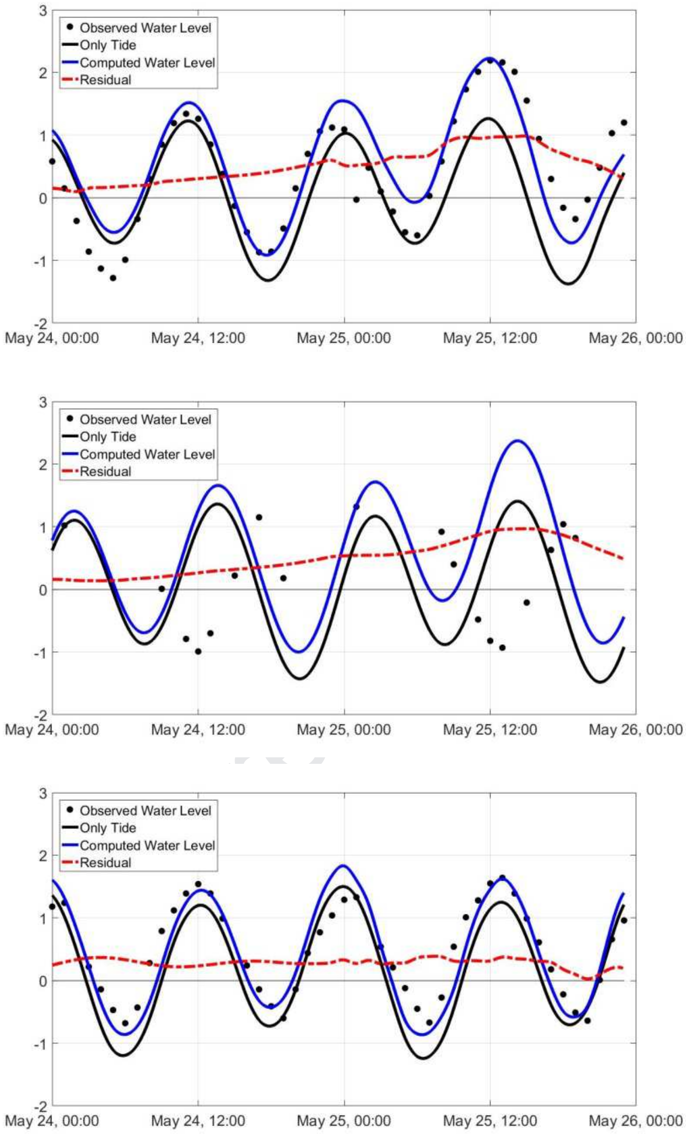


Figure 9. Computed tidal water elevation and observed data referred to mean sea level from the sea level center during cyclone Aila at the three stations; a) Hiron Point; b) Khepupara; and c) Charchanga. The black lines are water levels from the tide only run of respective location and the red dotted lines are surge residuals (total water level minus tide only water level).

It may be observed that, the maximum surge level is increasing with time as the storm approaches towards the coast and finally there is a recession. However, computed peak water levels due to the interaction of tide and surge associated with the storm Aila are found to be less in comparison with those of the cyclone Sidr. The main reason behind the fact may be the wind speed, which is found to be justified by that the intensity of the cyclone Sidr was double than that of the cyclone Aila during crossing the coast.

R^2 value, RMSE, and p-bias for the model data with the tide gauge measured data of two stations (Hiron Point and Charchanga) are presented in Table 7. As the tide gauge at Khepupara was not functioning well during cyclone Aila numerical results were not evaluated. Here the surge water level at Hiron Point has lower R^2 correlation than the other two stations. Hiron Point has also higher

RMSE and p-bias. In Charchanga the value of p-bias is negative that mean model underestimated surge levels. Underestimation of MSLP and overestimation of MSW.

Table 7 R2 value, RMSE, and p-bias for tide plus surge elevation at four stations during the cyclone Aila

Tide Gauge Station	R^2	RMSE	p-bias
Hiron Point	0.619	0.581	47.6093
Charchanga	0.869	0.262	-20.3861

The surge residual elevation shows the interaction effects between the tide and the surge. The surge is reduced by the tide–surge interaction during low tide; the maximum residuals at Hiron Point were predicted during low tide though. It may be observed that, the maximum surge level is increasing with time as the storm approaches towards the coast and finally there is a recession. The highest storm surge residuals during cyclone Sidr were obtained at Khepupara during the landfall time (Fig. 8). The surge amplitude was 2.20 m at Hiron point, 4.35 m at Khepupara reducing to 1.70 m at Charchenga at the time of landfall of cyclone Sidr. Compared to any other regions in the Bangladesh coast the Sundarban poses a major challenge to determine the extent of surge residuals owing to complex coastline geometry and numerous tidal creeks (Krien et al. 2016). The POLCOMS configuration used in our study has a minimum water depth of 10m, and did not go into the rivers. This may explain some tidal some biases in the model results. Using high resolution bathymetric data can improve the model simulation in such complex morphological coast (Krien et al. 2017). The phase differences are indicative of shallow water effects, with surge generation modulated by water depth. Tides are generally not well reproduced by numerical models if bottom topography is not represented well (Krien et al. 2016). As the water depth was constrained to be at least 10 m in this highly complex costal area it may be that these interactions are not properly represented. In addition, at low spatial resolution, the sharp transition in bottom roughness when moving from land to sea cannot be captured. Lower resolution implies an orography smoothing and an underestimation of the surface roughness.

Maximum skew surges for the both cyclone Sidr and Aila are shown in the Table 8. A skew surge is the difference between the maximum observed water level and the maximum predicted tidal level regardless of their timing during the tidal cycle. There is one skew surge value per tidal cycle ("Storm surge climatology – Skew surges"). The skew surge contains the true meteorological contribution to the surge, whereas the non-tidal residual contains the meteorological contribution, in addition to harmonic prediction errors or timing errors and non-linear interactions, which can artificially bias the surge ("Storm surge climatology – Skew surges"). an event with a high skew surge but which occurred at neap tide is still significant. False positives, in which a surge is predicted but does not in fact occur, are also important to study.

Table 8 Maximum residuals and skew surges during cyclone Sidr and Aila

Location	Sidr		Aila	
	Max. Residual (m)	Skew Surge (m)	Max. Residual (m)	Skew Surge (m)
Hiron Point	2.20	0.83	1.83	1.06
Khepupara	4.35	3.00	0.98	0.96
Charchanga	0.86	0.86	0.40	0.38

4. Discussions

Tide-surge interaction reaches a maximum 1-2 hours after the low tide in case of Sidr (Figure 8) and incase of Aila the interaction was consistent with tide (Figure 9). Table 8 shows that during Sidr, a large screw surge was has been found at the Khepupara but relatively a small screw at the Hiron Point station. It is because the tide gauge at Hiron Point is located to the left of the cyclone track where the storm surge is not the strongest. The surge rise timing in the model simulated water levels occurred sooner than observed because of delaying the landfall time in the atmospheric model. The miss match of timing can be address by calculating skew surges for a good prediction of maximum water level at surge peak. The large positive p-bias in Table 6 which interpret overestimation of surge by the model can be address by skew surge. For operational forecasting accurate estimation of water levels is important. Nonetheless, false positives, in which a surge is predicted but does not in fact occur, are also important to study should be handled carefully.

In the Bangladesh coast, astronomical tides interact non-linearly with surges (Antony and Unnikrishnan 2013; Zhang et al. 2010). The interactions are found to amount to be tens of centimeters. They can even exceed one meter locally, especially close to the landfall area, in rivers, or in the north-eastern part of the submarine delta were the tidal range is the highest. Conversely, wind stress is less efficient in producing surges at high tide, when the water level is 2–4 m higher (Krien et al. 2017). In shallow water areas with a large tidal range, the nonlinear effects of tide-surge interaction are important (Wolf 2009). This phenomenon can lead to enhanced surges preferably at low rising tide (rather than low or ebb tide) because of phase alteration of the tidal signal (Horsburgh and Wilson 2007). Indeed, a positive surge induces an increase of tidal phase speed enhances storm tide. In the current study, a significant part of the tidal contribution to the total water level is expected to be offset by tide-surge interactions, which significantly tempers the traditional view that a cyclone would induced much higher (resp. lower) destructions if landing at high (resp. low) tide. Moreover, observations of tides and surges are generally made at coastal tide gauges, although these locations are not always ideal for model validation since they may experience local effects by being in ports or estuaries rather than reflecting open sea conditions (Wolf 2009). Presence of numerous river drainage systems with several tidal creeks along coastal stretches in the southwest Bangladesh coast had enabled surge propagation into the river systems. Tides need to be computed explicitly and accurately in storm surge models in the head Bay of Bengal to capture tide-surge interactions properly (Krien et al. 2017).

Another shortcoming of the current study is that wave contribution to the total surge is disregarded. The modeled surge is sensitive to atmosphere–wave interaction. Several studies including waves in numerical models were conducted for cyclones hitting the northern Bay of Bengal (e.g.; Bhaskaran et al. 2013; Murty et al. 2014), and concluded that a significant part of total surge can be attributed to wave setup (Murty et al. 2014). Although the continental shelf is wider and shallower in the Bangladesh coast, its exact contribution to total surge might be significant (Deb and Ferreira 2016). In POLCOMS the drag coefficient increases with wind speed (Brown and Wolf 2009), and simulated water levels are sensitive to the way in which waves are represented by the model (Bricheno et al. 2013).

Driving the ocean model with higher-resolution meteorological forcing has a large impact on modeled surge elevation and wave height (Bricheno et al. 2013). In order to complete the air–sea interaction, the effect of the sea state on the atmosphere must be considered in terms of heat, mass flux exchange and wave roughness in subsequent studies (Geetha and Balachandran 2014; Nelson et al. 2014). However, in this study the components of atmosphere and ocean have been considered separately. But this is a little artificial as the meteorology is driving the ocean processes, and there are feedbacks. One important feedback effect of surface wave roughness occurs on the atmospheric boundary layer, resulting in an increase in surface roughness, which leads to a reduction in wind speed. Furthermore, the heat flux exchange may be an important factor in the air–sea interaction. A strong storm usually causes a strong mixing and cooling effect on the ocean (Nelson et al. 2014; Wu et al. 2007). The cold sea surface temperature then causes the storm to be weakened (Wu et al. 2007). Bottom physics are also important factors in the shallow area during the storm surge (Yoon and Jun 2015). Calculating wave-induced bottom stress in the coupled wave–current model could improve storm surge prediction. The concept of radiation stresses was not included in this study, which explains the phenomenon of wave set-up because the gradient of stresses is not sufficiently resolved in the coarser grid model system. However, the concept of radiation stresses is effective on the small scale for simulating storm surge in near-coastal areas and applying run-up.

In some basins huge amounts of observational data are available and can be assimilated to provide relatively accurate wind and pressure fields (e.g., Bunya et al. 2010). In the Bay of Bengal, in-situ observations are significantly lackings, so wind and pressure patterns during cyclone events have to be estimated. This study shows that using a 12km resolution model to downscale global NCEP wind and pressure to hourly resolution is a good solution. The performance of the model in hindcasting historical cyclone Sidr and Aila was reasonable with some shortcomings. One of the shortcomings is atmospheric model resolution. High resolution atmospheric model improves the representation of storms, producing sharper mesoscale features as well as better representing convective events (Mass et al. 2002). As tropical cyclones arise from multi-scale processes high-resolution is required to capture the representation of storms explicitly and producing sharper mesoscale features (deep low pressures and high winds (Bricheno et al. 2013)). Various studies have identified the need for good spatial resolution of the storm to get the maximum wind correct (e.g., Cavaleri 2009; Krien et al. 2017) in order to get accurate water level forecasts.

5. Conclusions

The northern Bay of Bengal, particularly Bangladesh coast is home to some of the deadliest cyclones recorded during the last decades. Storm surge models developed for this region significantly improved in recent years, but they still fail to predict patterns of coastal flooding with sufficient accuracy. Accurate representation of wind forcing and mean sea level pressure is important for modeling storm surges. This is especially important for complex coastal zone areas like Bangladesh coast. In the study, the ability of a new, state-of-the-art ocean-atmosphere coupled storm surge modeling system was investigated to simulate water levels in the Bay of Bengal with particular focus on Bangladesh Coast. The effectiveness of the model was verified through the obtained computational outputs. The model is found to reproduce surge elevation with reasonable accuracy and precision, although errors still exist and there is still room for improvement.

Skill is gained through forcing the ocean model with wind and pressure fields from atmospheric model. The use of the weather data from atmospheric model WRF was found to generally increase the accuracy of water level in the Bangladesh coast by up to 40 cm in places compare to other studies. WRF model is able to simulate some salient features such as maximum sustained wind, central pressure and movement. The atmospheric model results of 12 km resolution were then applied to the ocean model. To use the modeling system for operational forecast of storm surges in the Bangladesh coast required some sorts of improvement. More works are needed to improve the accuracy and precision of simulated water levels to communicate with the decision makers and as demonstrated in this study we in the right direction by adding more process in numerical modeling system. The findings of this study suggest more high-resolution atmospheric model run could improve the surge forecast. It would be interesting to extend this research with higher-resolution WRF simulation to see the response of the modeled surge when forced with increased resolution meteorological forcing. Another improvement would come from the inclusion of flooding and drying in the model, and improved bathymetry in the shallow coastal area to better forecast the storm surge.

Current storm surge forecasts in Bangladesh which are carried out as a part of tropical cyclone forecasting are essentially deterministic rather than probabilistic. For emergency preparedness and to develop mitigation strategies proper analysis of the storm surges and their accurate and precise forecasts are very important. Storm surge forecasts can be much improved by employing tight ocean-atmospheric couple models as the research has clearly demonstrated. On the whole, there is a strong need for a deeper, more detailed coupling, in terms of the physics, between the atmospheric, ocean and wave models.

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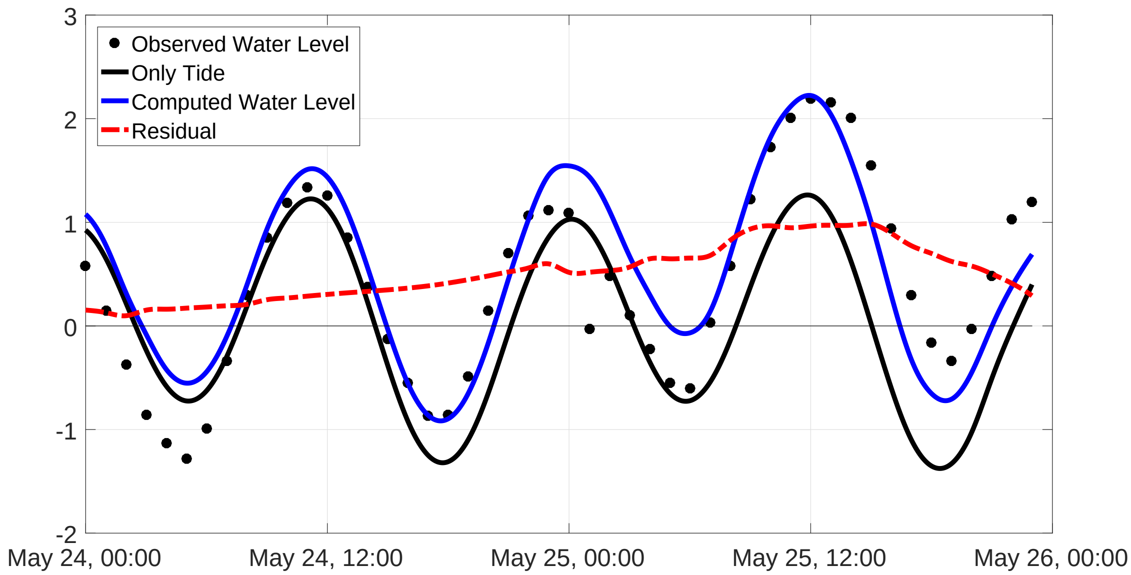

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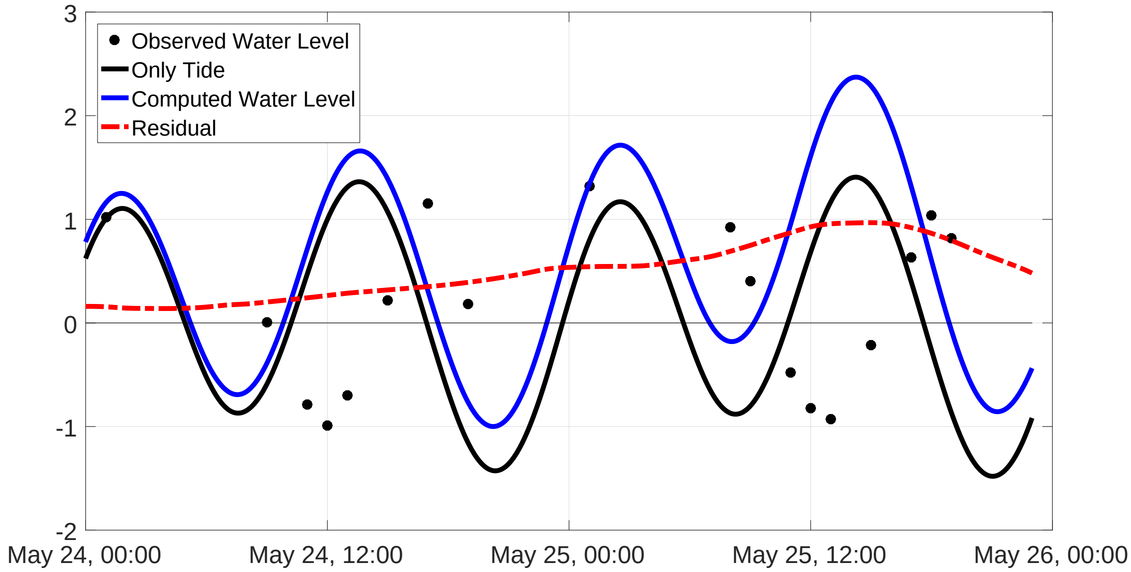

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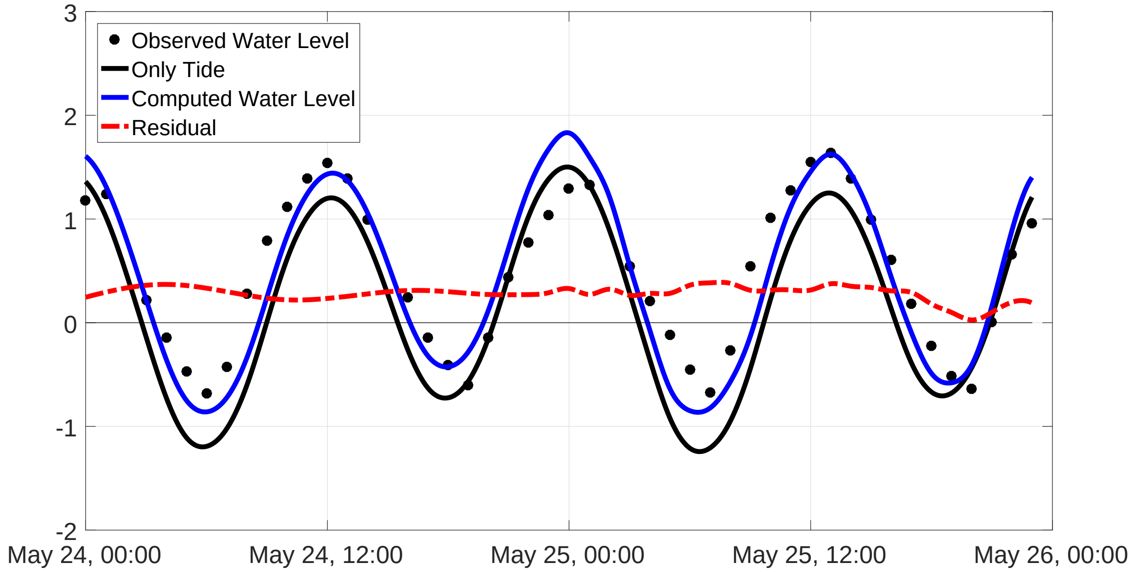

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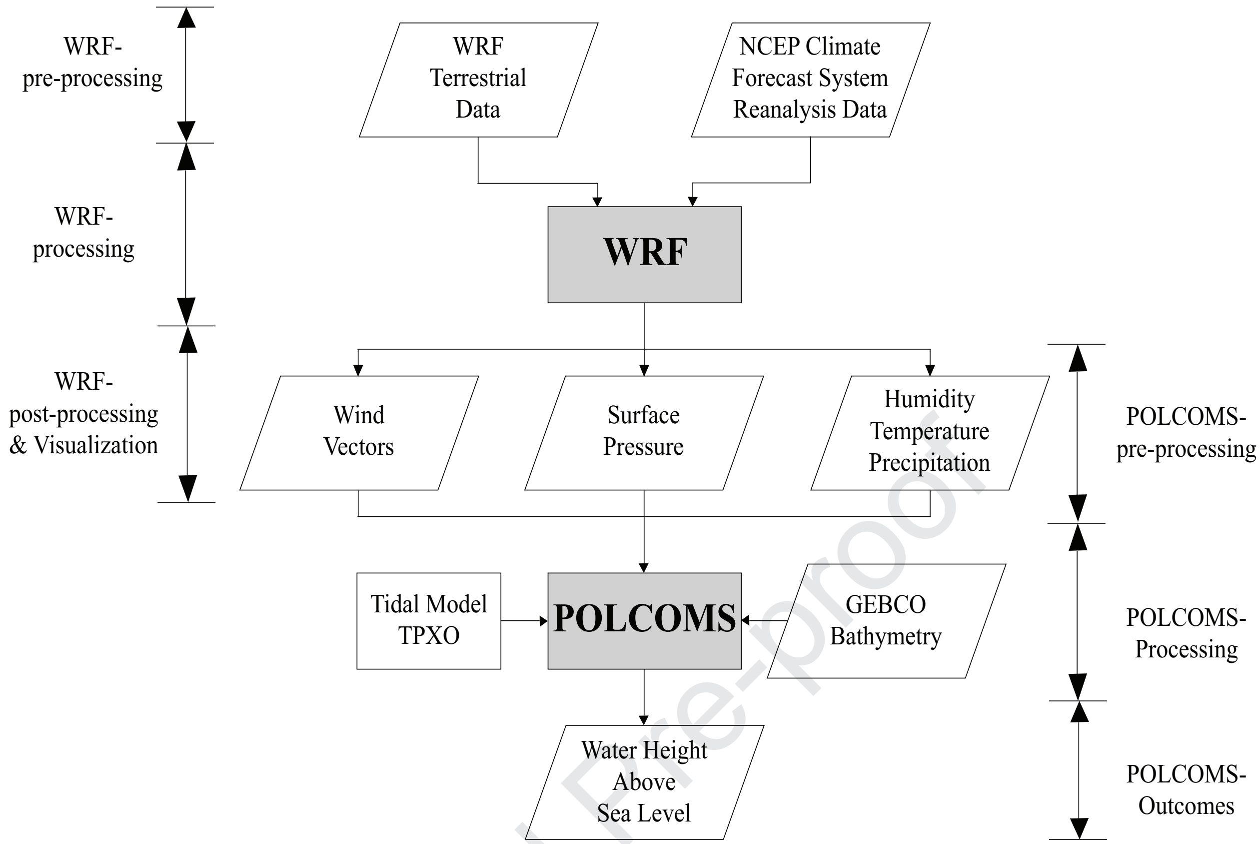
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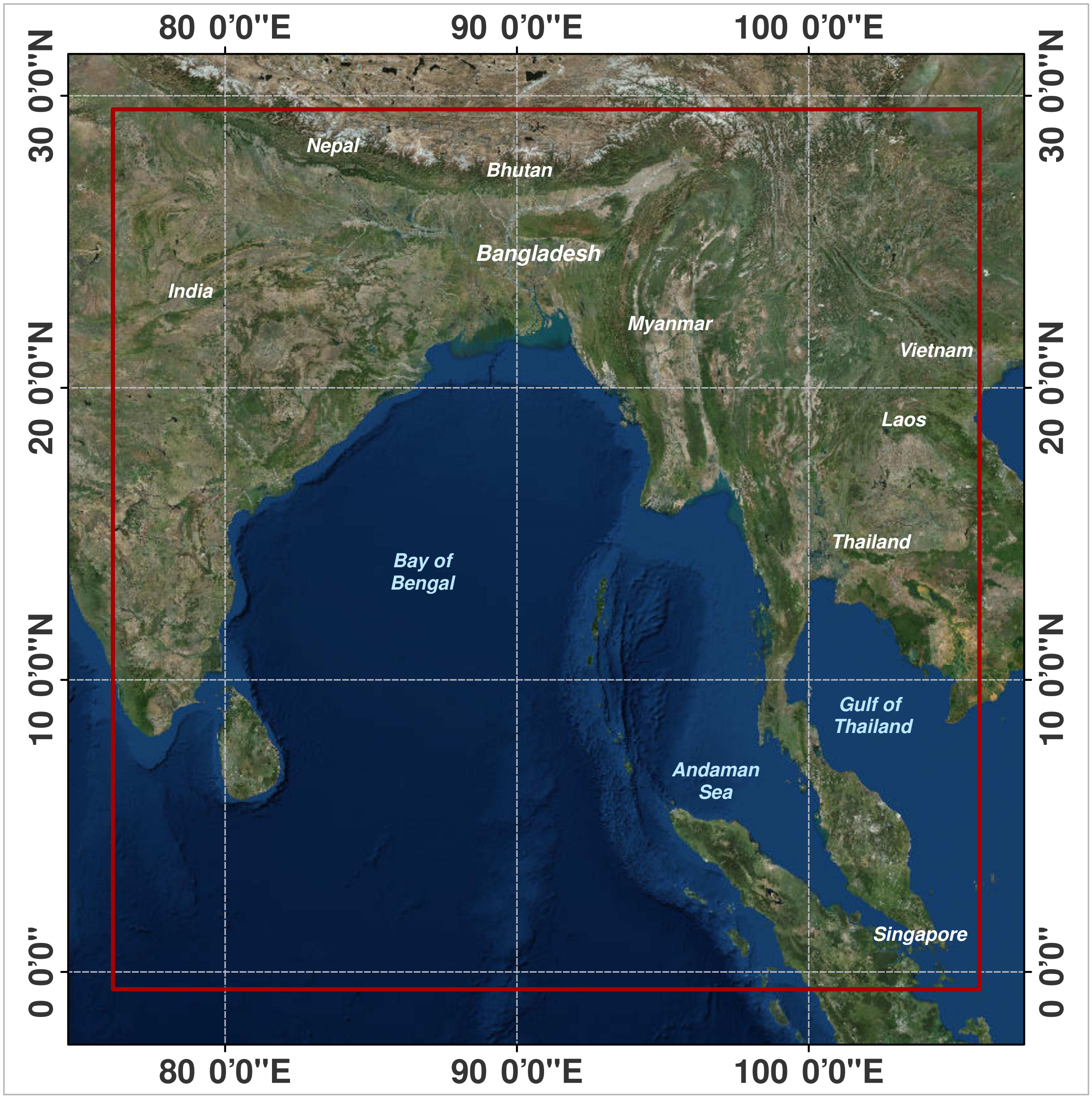
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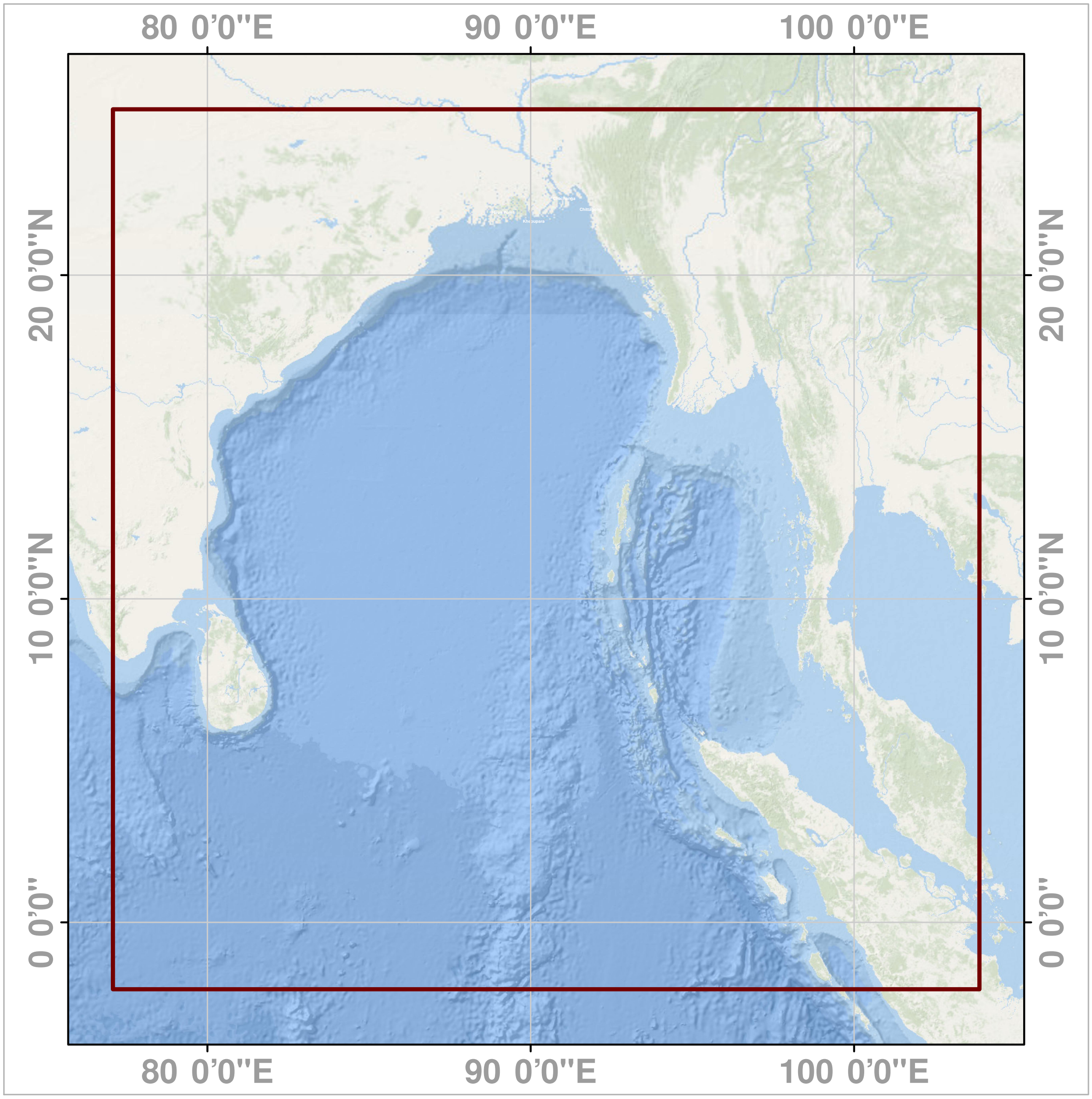
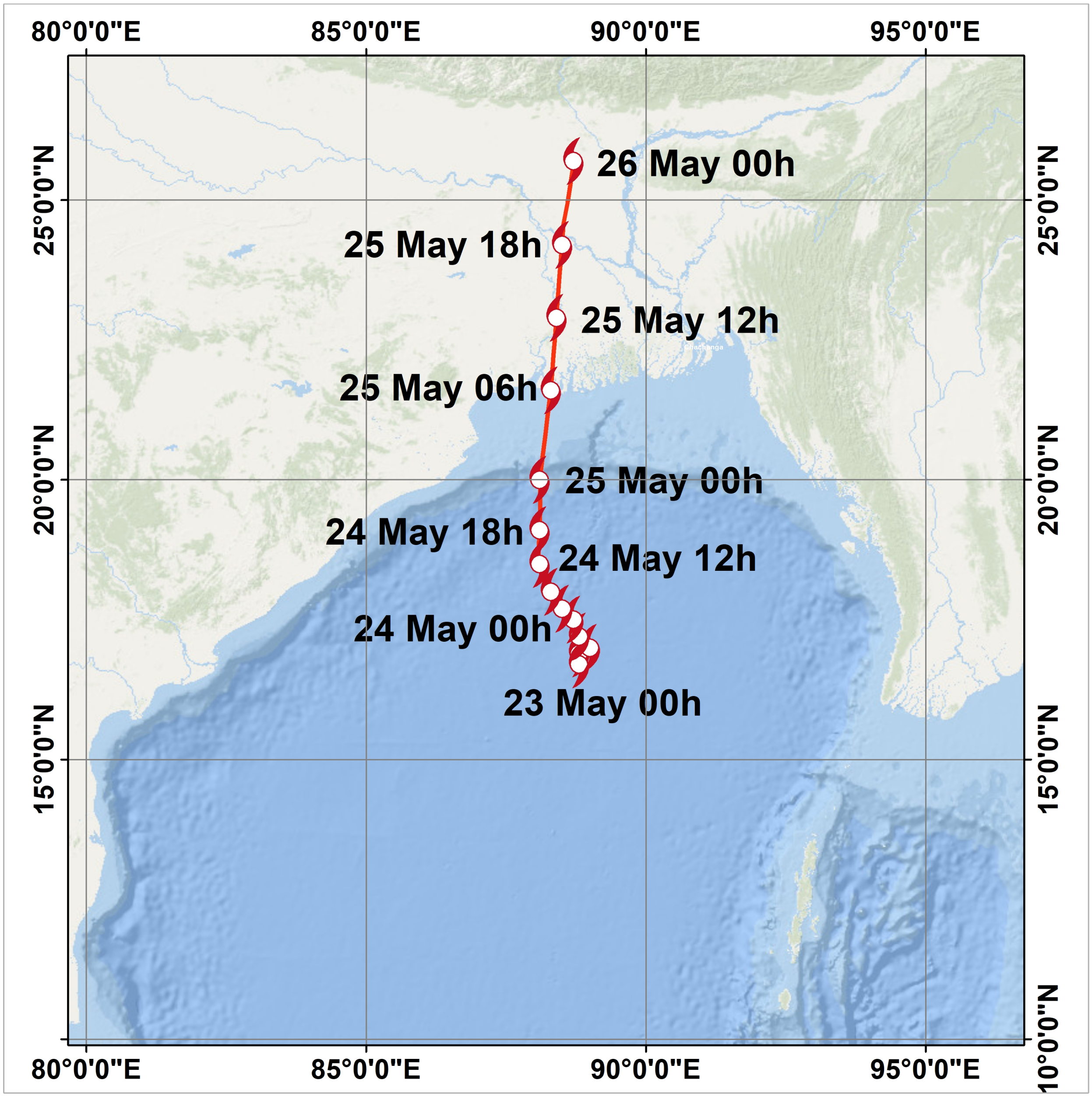
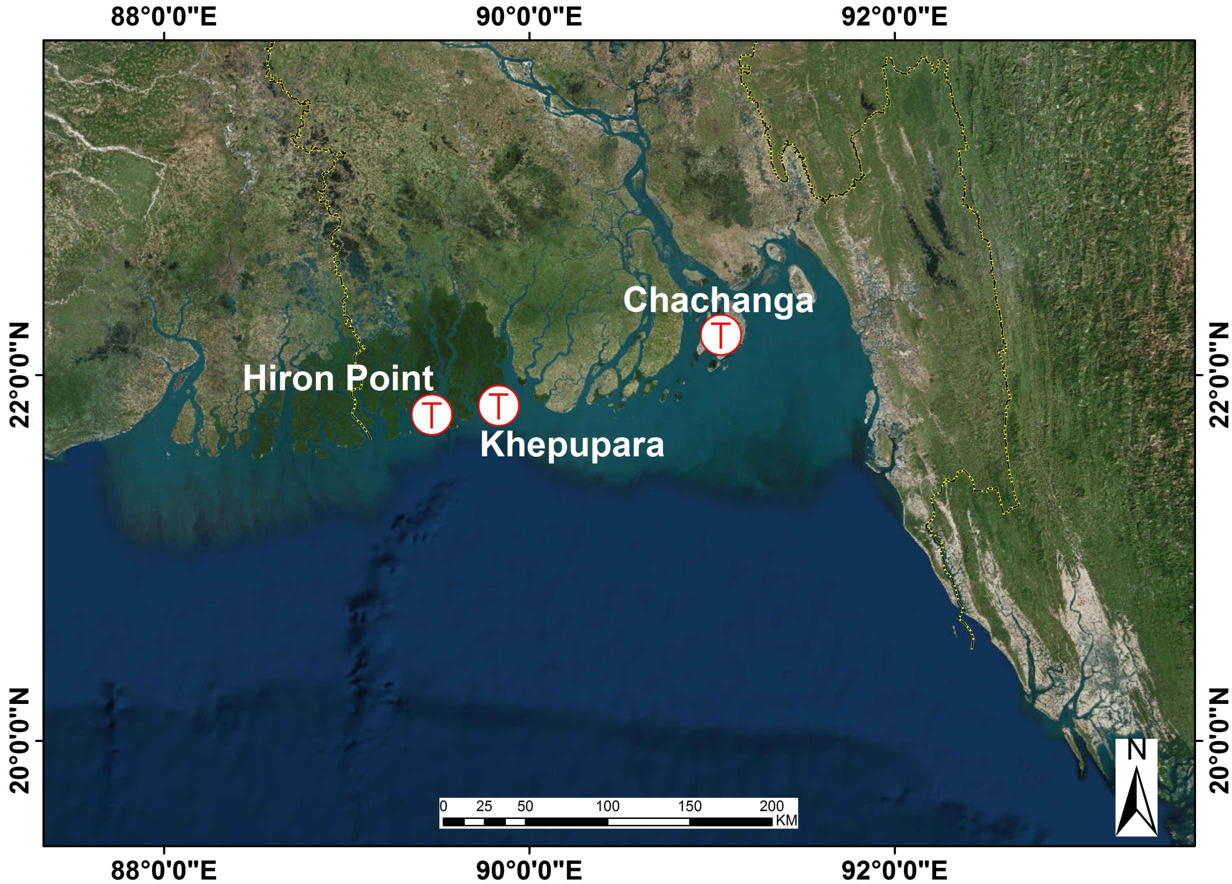
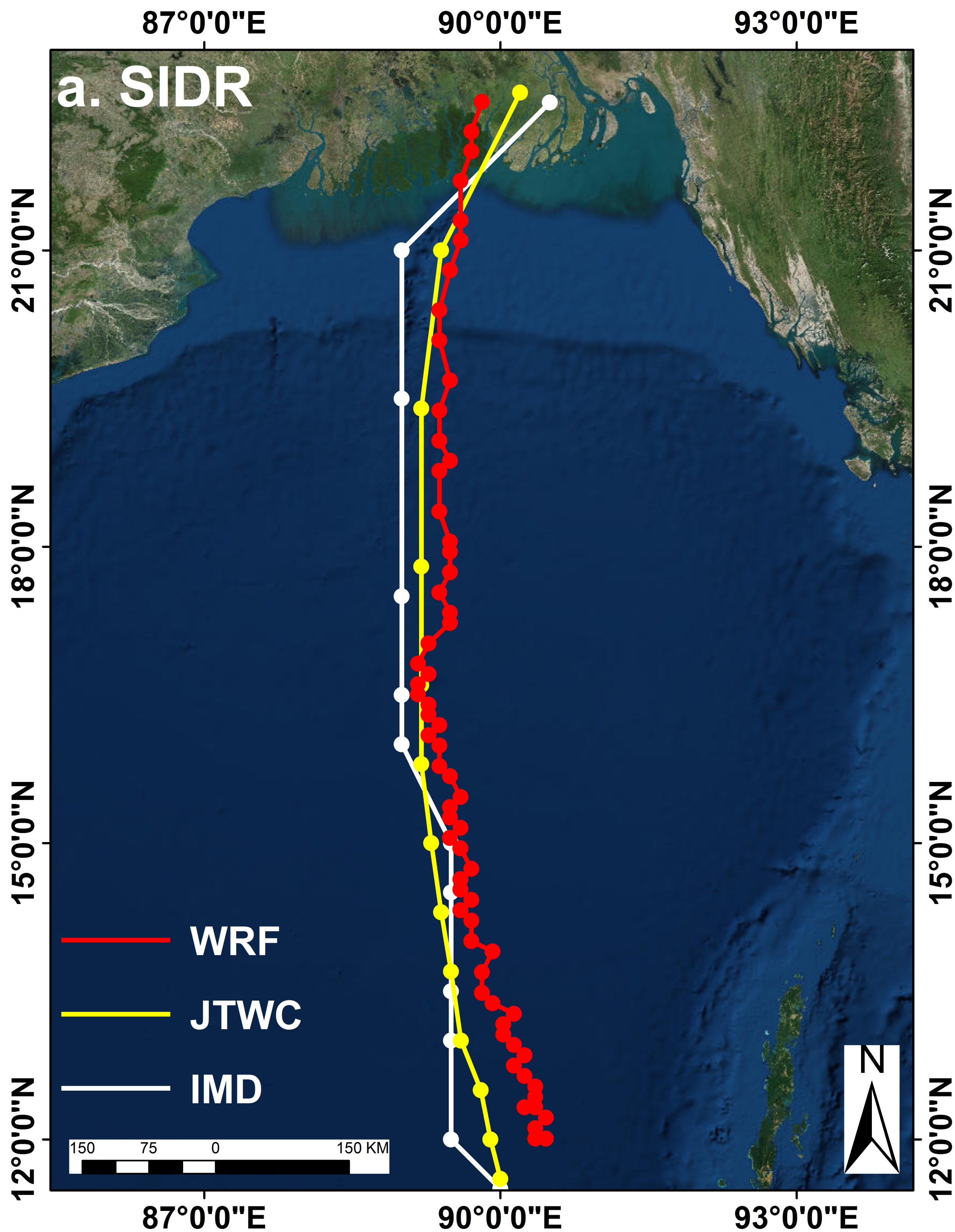
Andaman Sea
Singapore

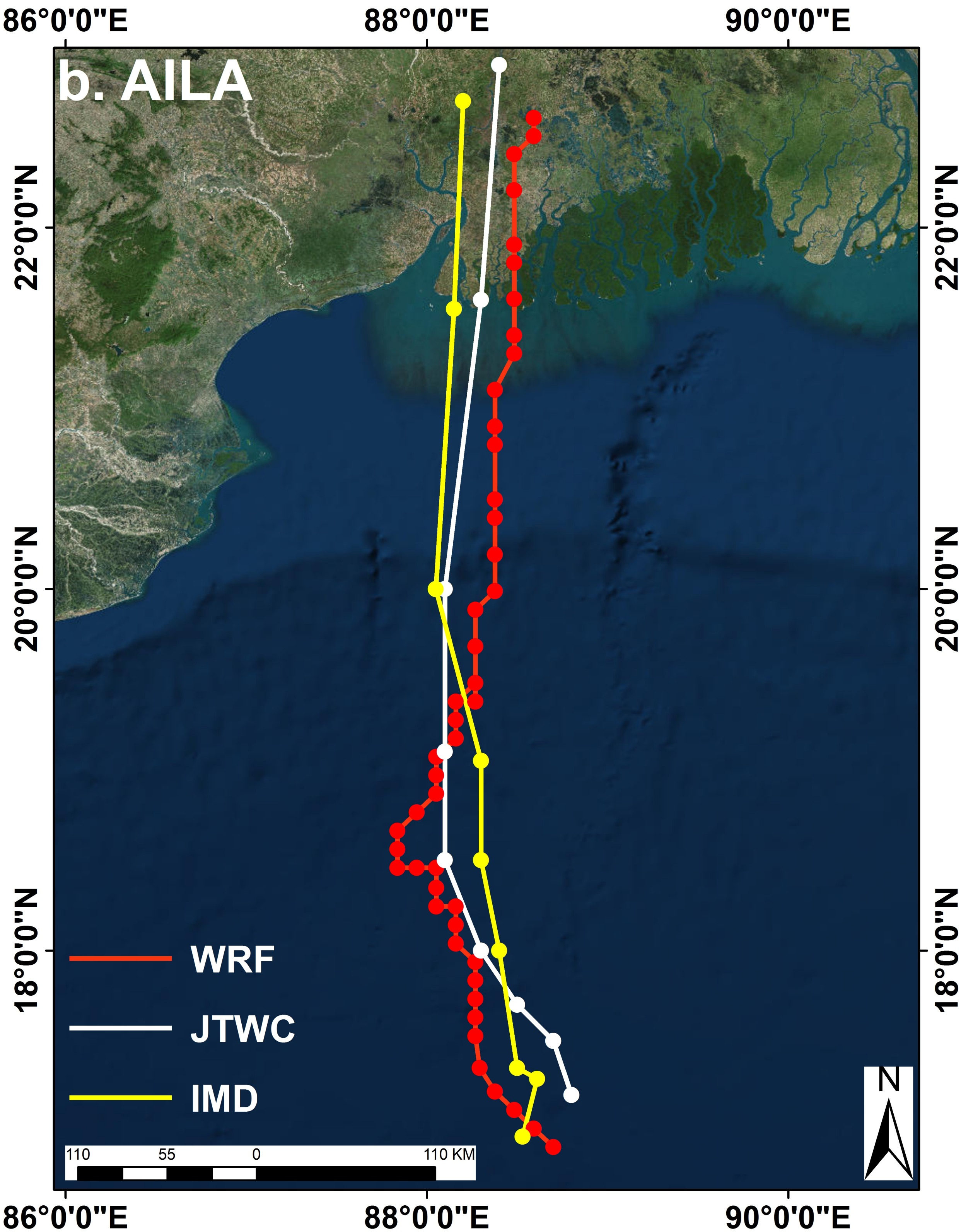

80 0'0"E
90 0'0"E
100 0'0"E
20 0'0"N
10 0'0"N
0 0'0"

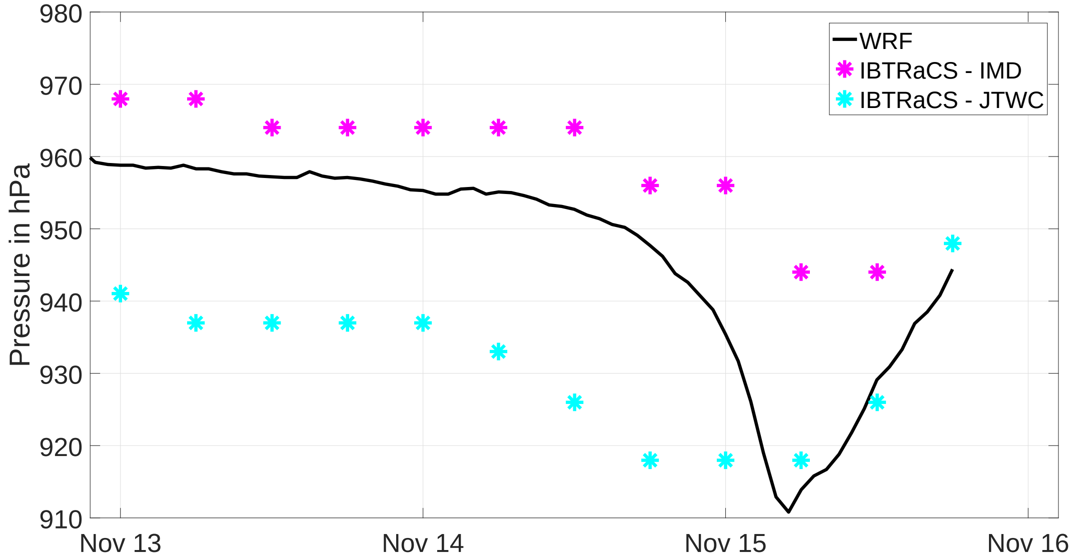

80°0'0"E
85°0'0"E
90°0'0"E
95°0'0"E
100°0'0"E
20°0'0"N
15°0'0"N
10°0'0"N
16-Nov 00h
15-Nov 18h
14-Nov 12h
15-Nov 06h
15-Nov 00h
14-Nov 18h
14-Nov 12h
14-Nov 06h
14-Nov 00h
13-Nov 12h
13-Nov 00h
11-Nov 00h
12-Nov 00h
10-Nov 06h

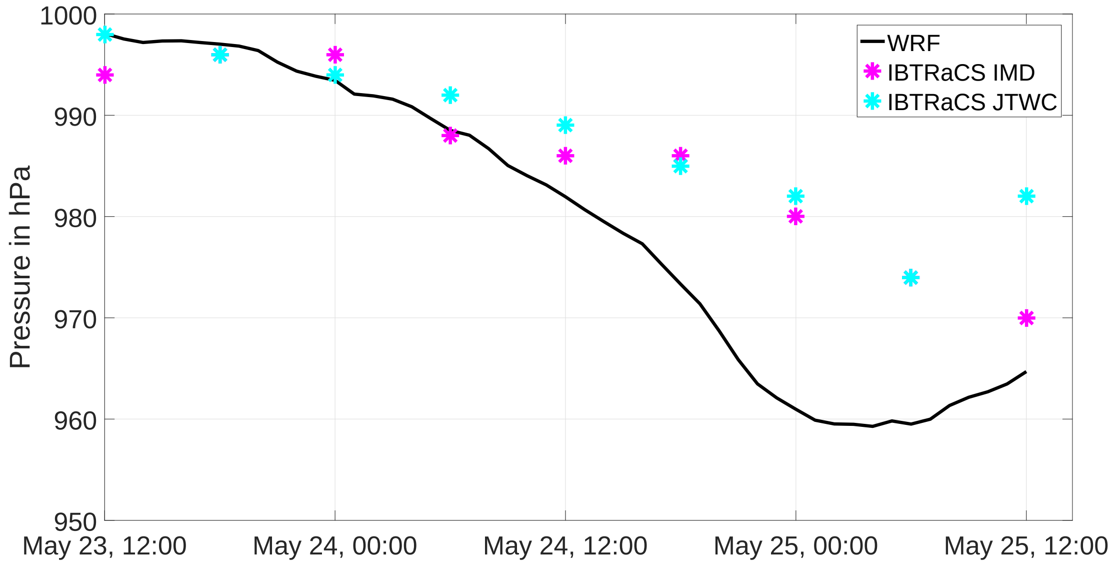

80°0'0"E
85°0'0"E
90°0'0"E
95°0'0"E
25°0'0"N
20°0'0"N
15°0'0"N
10°0'0"N
26 May 00h
25 May 18h
25 May 12h
25 May 06h
25 May 00h
24 May 18h
24 May 12h
24 May 00h
23 May 00h

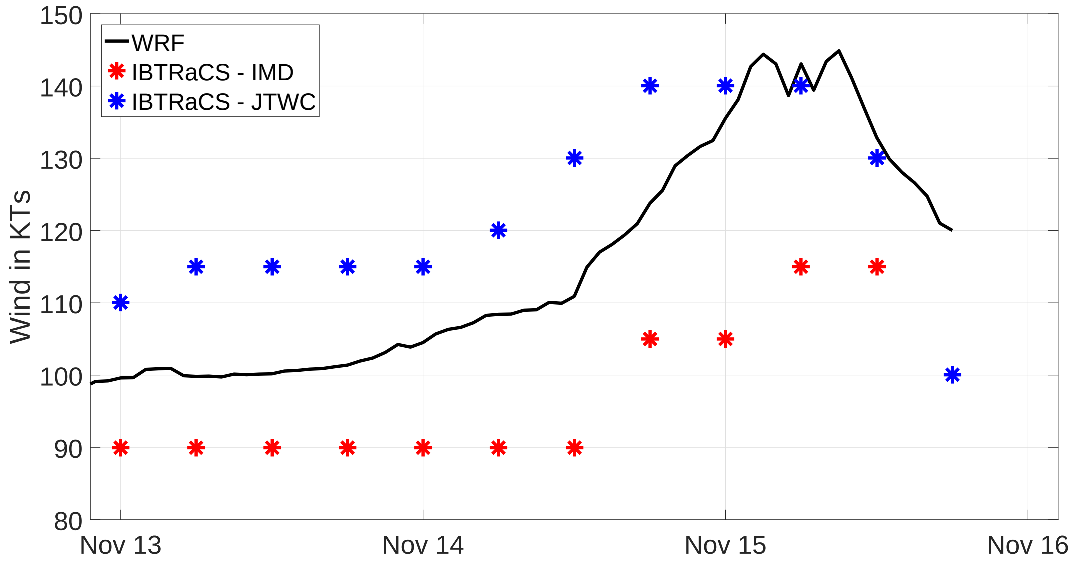

88°0'0"E
90°0'0"E
92°0'0"E
22°0'0"N
20°0'0"N
Chachanga
Hiron Point
Khepupara
0 25 50 100 150 200
KM
N

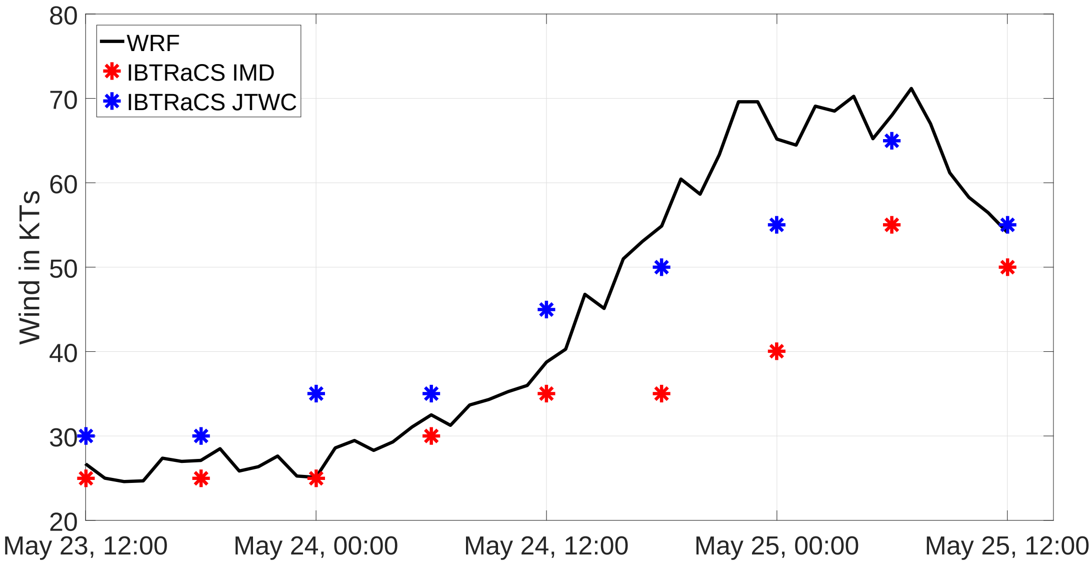

a. SIDR
87°0'0"E
90°0'0"E
93°0'0"E
21°0'0"N
18°0'0"N
15°0'0"N
12°0'0"N
WRF
JTWC
IMD
150
75
0
150 KM
N


86°0'0"E
88°0'0"E
90°0'0"E
22°0'0"N
20°0'0"N
18°0'0"N
b. AILA
WRF
JTWC
IMD
110
55
0
110 KM
N

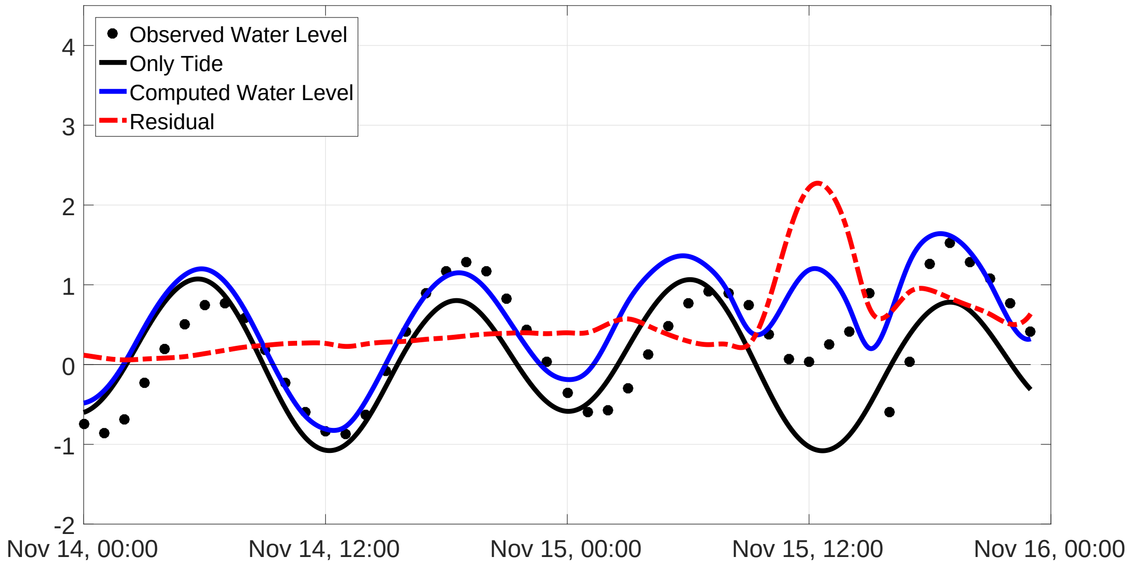

980
970
960
950
940
930
920
910
Pressure in hPa
Nov 13
Nov 14
Nov 15
Nov 16
WRF
IBTRaCS - IMD
IBTRaCS - JTWC


1000
990
980
970
960
950
Pressure in hPa
May 23, 12:00
May 24, 00:00
May 24, 12:00
May 25, 00:00
May 25, 12:00
WRF
IBTRaCS IMD
IBTRaCS JTWC

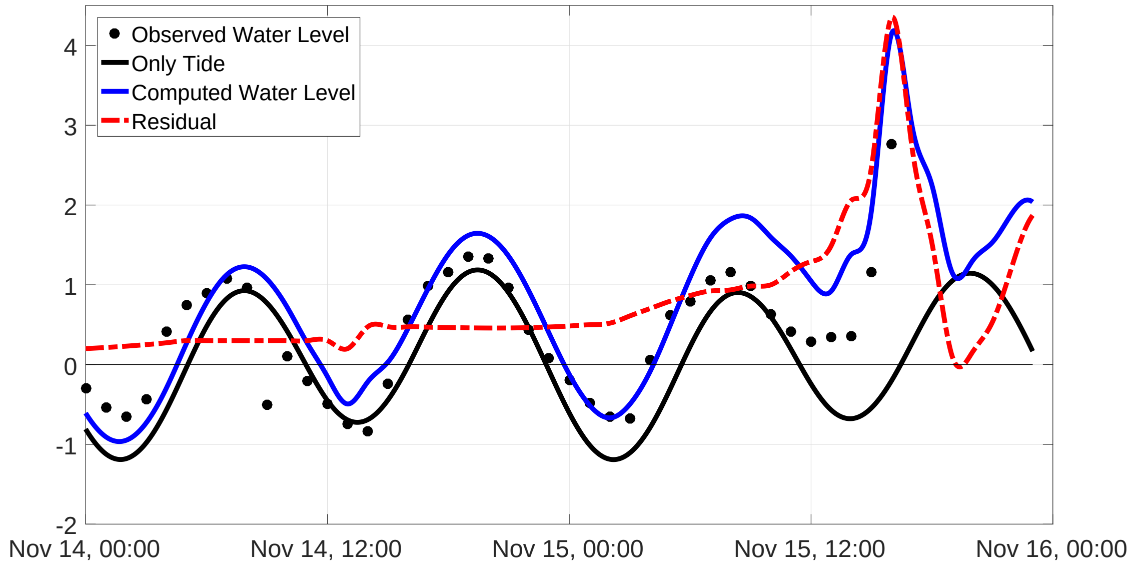

WRF
IBTRaCS - IMD
IBTRaCS - JTWC
Wind in KTs
150
140
130
120
110
100
90
80
Nov 13
Nov 14
Nov 15
Nov 16



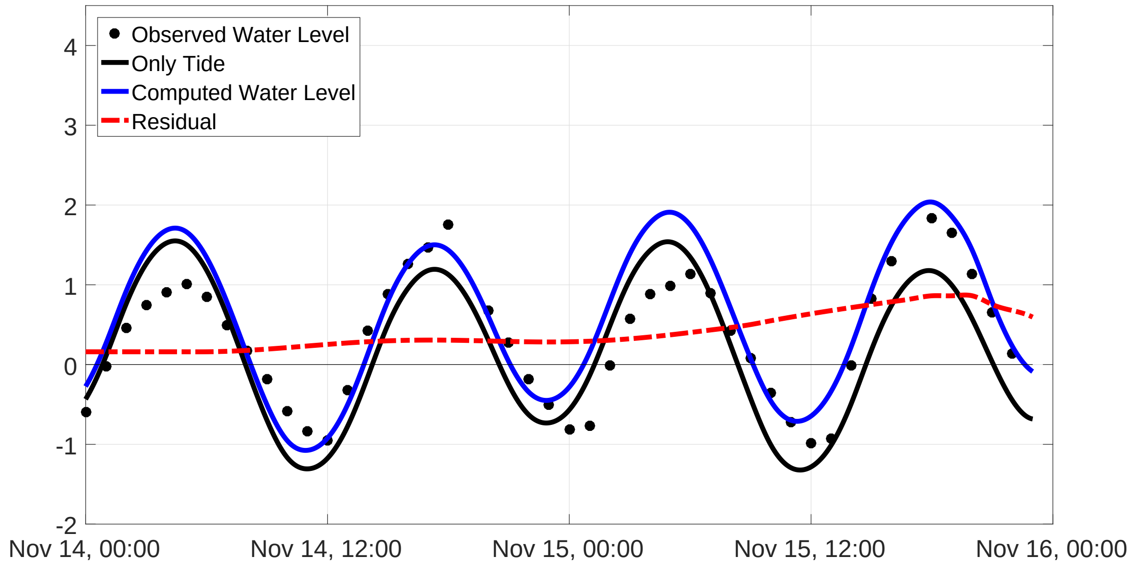
80
70
60
50
40
30
20
Wind in KTs
WRF
IBTRaCS IMD
IBTRaCS JTWC
May 23, 12:00
May 24, 00:00
May 24, 12:00
May 25, 00:00
May 25, 12:00



Observed Water Level
Only Tide
Computed Water Level
Residual
4
3
2
1
0
-1
-2
Nov 14, 00:00
Nov 14, 12:00
Nov 15, 00:00
Nov 15, 12:00
Nov 16, 00:00



Observed Water Level
Only Tide
Computed Water Level
Residual
4
3
2
1
0
-1
-2
Nov 14, 00:00
Nov 14, 12:00
Nov 15, 00:00
Nov 15, 12:00
Nov 16, 00:00



Observed Water Level
Only Tide
Computed Water Level
Residual
4
3
2
1
0
-1
-2
Nov 14, 00:00
Nov 14, 12:00
Nov 15, 00:00
Nov 15, 12:00
Nov 16, 00:00