The Role of Local Topography and Sea Surface Temperature on Summer Monsoon Precipitation over Bangladesh and North-East India

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Keywords: Asian monsoon, Rainfall, Topography, Bangladesh, Bay of Bengal, Moisture flux

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Abstract

Bangladesh receives most of its precipitation from June to September in the form of rainfall as a part of the Asian summer monsoon system. Bangladesh is a relatively flat region, surrounded by the southern Himalayas and Meghalaya Plateau in the north, Arakan Mountains in the east, and the Bay of Bengal (BOB) in the south. Although several studies have investigated the mechanisms that drive the Asian monsoon precipitation, very few studies have focused on the monsoon precipitation in Bangladesh. This study investigated the influence of the topography of the surrounding regions and sea surface temperature on the summer monsoon precipitation of Bangladesh and the surrounding regions. Using observed data, we showed that moisture convergence near the mountains contributes to the precipitation of Bangladesh, whereas the BOB acts as a source of moisture. A strong low-level jet carries the moisture inland as the land–sea thermal contrast intensifies the wind circulation during the summer. Three differently forced simulations of the Euro-Mediterranean Centre on Climate Change coupled climate model (CMCC CM2) were analysed to investigate the influence of the surrounding region's topography and sea surface temperature on the summer monsoon precipitation. The low-resolution simulation showed no spatial variability of precipitation and dry bias due to the overly smooth topographical representation of mountains. The high-resolution coupled simulation, with a better representation of topography, improved the moisture convergence at the foothills and precipitation bias. The high-resolution prescribed sea surface temperature further improved the precipitation bias by intensifying the low-level jet that transports moisture over Bangladesh.

1. Introduction

As part of the South Asian Monsoon system, Bangladesh receives 70-75% of its annual precipitation as rainfall from June to September months (June-July-August-September or JJAS) (Ahmed 1993; Ahmed et al. 2020) (Fig. 1). Bangladesh is a flat region occupied by the Ganges-

Brahmaputra-Meghna delta and surrounded by the Arakan Mountains in the east, Meghalaya Plateau in the northeast, and southern foothills of the Himalayas in the north (Fig. 2a). Realistic simulation of Bangladesh's seasonal mean monsoon (June-September) has proven to be a challenging task for state-of-the-art climate models due to many factors, including the surrounding complex topography, large sea surface temperature (SST) variability in the BOB, and representation of the convection in the state-of-the-art climate models (Lucas-Picher et al. 2011; Xie et al. 2006). The northeast region of Bangladesh (i.e., the Sylhet division) and its surrounding regions (Cherrapunjee, Mawsynram, and Meghalaya Plateau of India) is the wettest region on earth (Murata et al. 2017). The zonal distribution of observed precipitation also shows that Bangladesh's southeastern and northwestern regions receive the most precipitation during the summer monsoon (Fig. 1c). The latest General Circulation Models (GCM)s still have significant precipitation biases over these regions, mainly in low-resolution climate models (Oouchi et al., 2009; Cherchi and Navara, 2007). A low vertical and horizontal resolution in simulations do not adequately represent the actual complex variations in the topography of the earth's surface. In the atmosphere, moist air needs to reach the cloud condensation level to form precipitation. Uplift is a forcing mechanism that can transport boundary layer moisture to the cloud condensation level in the atmosphere. The natural lifting mechanisms include differential surface heating and air mass boundaries (fronts and dry lines), whereas the mechanical lifting mechanism includes steep topography such as mountains. Due to coarse spatial resolution, most GCMs cannot represent correct orographic lifting, resulting in an erroneous precipitation simulation.

The role of topography in modulating the South Asian monsoon has been studied widely (Hahn and Manabe 1975; Chakraborty et al. 2006; Gill 1980; Yanai and Li 1994; Kitoh 2002; Privé and Plumb 2007a, b; Goswami 2010; Prokop and Walanus 2015). Hahn and Manabe (1975) investigated the role of mountains in South Asian monsoon circulation. They used a numerical climate model with 11 vertical levels, 270 km horizontal resolution, and prescribed SST to explore the contribution of local mountains to the global atmospheric circulation pattern. Two sets of experiments were done in their study to compare with the observations: (1) South Asian monsoon simulation with Asian mountains present, and (2) without Asian mountains in the climate model. Results showed that the South Asian summer monsoon was well simulated with mountains present in the climate model compared to the numerical experiment with no mountains. The low-level

circulation (1000hPa geopotential height) showed a strong low-pressure circulation near the Tibetian Plateau with mountains present. In contrast, there was no clear pattern of the low-pressure system over South Asia without mountains in the Hahn and Manabe (1975) experiments. However, these experiments were done in a GCM with a low horizontal and vertical resolution. The surrounding topography of Bangladesh (e.g., Meghalaya Plateau and Arakan mountains), or elsewhere, was unaccounted for even in the experiments with mountains. As a result, no intense precipitation was generated over Bangladesh and its surrounding regions (e.g., Meghalaya Plateau) during the summer monsoon, where observed data shows a high intensity of summer monsoon precipitation.

Investigating the role of the Tibetan Plateau on local precipitation, Boos and Kuang (2010) found that diabatic heating over the Tibetan Plateau intensifies the precipitation near the southern edge of the Himalaya range. The Himalayan range supports a strong monsoon circulation by preventing the mixing of dry extratropical air into the warm and moist air over continental India. Later, Boos and Hurley (2013) showed that the Coupled Model Intercomparison Project Phase (CMIP) 3 and 5 models exhibit common biases in thermal structure over South Asia during the Boreal summer monsoon season due to an overly smooth topographic representation in the climate models. Recently, Acosta and Huber (2020) showed that high-resolution climate models accurately represent the topographic and atmospheric dynamics interactions. The Himalayas and the Tibetan Plateau play an important role in redirecting moisture convergence to produce local orographic precipitation, while the SST gradient mainly govern large-scale circulations, advecting water vapor onshore regardless of the topographical feature. Focusing on the northeastern region of the Himalayas, Gu et al. (2020) further confirmed that a high-resolution Regional Climate Model (RCM) simulation significantly decreases precipitation bias over the Brahmaputra River basin. The convective system is a crucial mechanism that contributes to the monsoon precipitation in a region like Bangladesh and its surrounding regions by interacting with the local topography (Romatschke et al. 2010; Goswami et al. 2010; Medina et al. 2010). Convective cells associated with the BOB depression evolve into mesoscale convective systems near the eastern Himalayas to be lifted by the local topography triggering precipitation (Medina et al. 2010). Using the Weather Research and Forecasting (WRF) model, Konduru & Takahashi (2020) showed that the diurnal cycle and precipitation variation over the Indian monsoon region significantly depends on the

horizontal resolution of simulation compared to the convection scheme used in the model. Besides the representation of orography, slowly varying local and remote SST patterns are also crucial for a realistic representation of monsoons in GCM's (Shukla, 1981).

Several studies have shown that the North Indian Ocean (the Arabian Sea and the BOB), Atlantic, and Pacific Ocean SST play a role in modulating Indian summer monsoon precipitation variability (Breitenbach et al. 2010; Kumar et al. 2013; Preethi et al., 2010; Roxy 2014; Cherchi et al., 2018; Ratna et al., 2016; Feng et al., 2018; Singh et al., 2019). Rao and Goswami (1988) found that the correlation between monsoon precipitation and SST is not static rather it varies throughout the season. They also noticed a strong positive correlation during pre-monsoon, a significantly negative correlation during post-monsoon, and a small correlation during peak monsoon. Goswami et al. (2016) found that the ocean components of most current coupled models fail to reproduce the BOB's upper ocean thermal structure because of a poor representation of mixing between highly fresh and stratified regions. High-resolution and high-frequency observations are required to understand the interaction between Indian Ocean dynamics and Indian summer monsoon precipitation (George et al., 2016; Goswami et al., 2016). Roxy (2014) found a statistically significant relationship between SST and a linear increase in precipitation up to 31 ^{o}C for the Asian summer monsoon. The study quantified a ~2 mm/day increase in rainfall for a 1 ^{o}C increase in SST. Kumar et al. (2013) found that different reanalysis data show a varying degree of strength in the SST-precipitation relationship. The influence of SSTs on the precipitation of Bangladesh and its surrounding regions is also documented in several studies (Salahuddin et al., 2006; Wahiduzzaman et al., 2021). Alapaty et al. (1995) found that Indian Summer Monsoon precipitation is sensitive to the SST distribution of the BOB. Their study found that there is approximately a 20% increase in the evaporation and a 10% increase in the precipitation with the observed SST compared to the model's SST. The authors also noticed a one to two-degree increase in the SST over some parts of the BOB and the Arabian Sea, leading to a pressure drop of 2 to 3 hPa and increased wind speed. Yang et al. (2017) show that an atmospheric river connected to the BOB leads to extreme precipitation over northern India during the summer monsoon season.

Krishnamurthy and Goswami (1999) found a strong relationship between the interdecadal variability of the Indian summer monsoon precipitation and interdecadal variations of multiple

ENSO indices. In an interannual timescale, Chowdhury (2003) showed that seasonal flooding over Bangladesh is significantly related to the Southern Oscillation Index (SOI) instead of El-Nino Southern Oscillation (ENSO). Chowdhury (2003) found that a positive phase of the SOI leads to dry conditions over Bangladesh, whereas the negative phase is linked with wet conditions over Bangladesh. Ahmed et al. (2017) investigated long-term precipitation trends over Bangladesh during the summer monsoon season and analyzed the relationship between precipitation over Bangladesh and SST modes of variability, such as Indian Ocean Dipole (IOD) and ENSO, and noticed that a positive phase of IOD has a significant relationship with the summer monsoon precipitation of Bangladesh. Mishra et al. (2017) found a linkage between phases of the Madden–Julian Oscillation (MJO) and precipitation over the Meghalaya plateau. Phase 1 and 2 of the MJO circulation creates a strong moisture convergence near the Meghalaya plateau, leading to intensified precipitation over northeast India and the northern Bangladesh region during the summer monsoon. Several studies have also reported that changes in soil moisture contribute to the pre-monsoon and monsoon precipitation variation over Bangladesh (Ono & Takahashi, 2016; Sugimoto & Takahashi, 2017)

Several studies have investigated precipitation variability over Bangladesh using Regional Climate Models (RCMs). RCMs have relatively higher resolution compared to GCMs. However, RCMs lack two-way interactions with the large-scale circulation, in contrast to GCMs. This property of RCMs can lead to model biases in the local atmospheric circulation and precipitation. Using large ensembles of RCM simulations, Picher et al. (2011), Nowreen et al. (2015), and Rimi et al. (2019) showed that there are significant dry biases present all over Bangladesh with maximum bias over the north-east and southeast regions. A study conducted by Islam et al. (2008) found that an RCM overestimates precipitation in the pre-monsoon and winter seasons. In contrast, it underestimates the precipitation in the monsoon season using the Providing Regional Climates for Impacts Studies (PRECIS) model. After analyzing the results of RCMs, Feng and Fu (2006) concluded that RCMs improve the simulation of the spatial pattern of precipitation but not the intensity. Since RCMs use initial and lateral boundary conditions from a GCM, a significant part of the uncertainty of the RCM-simulated precipitation can be traced back to input from the GCM (Syed et al., 2014). Therefore, proper representation of topographic features and reliable GCM boundary conditions for RCMs can help in simulating the long-term precipitation climatology over this region.

Although several studies have shown how precipitation during the summer monsoon is a unique feature over Bangladesh and its surrounding regions, very few studies have focused on the physical mechanisms that drive the climatological summer monsoon precipitation over Bangladesh and its surrounding regions (Rafiuddin et al. 2010; Abdullah et al. 2020). Most studies have focused on extreme precipitation events on short timescales that don't necessarily determine the seasonal mean precipitation of the region. Studies that explore the influence of local topography on local precipitation lack attention to the northeastern and southern parts of Bangladesh and focus broadly on the Indian summer monsoon. Within the common framework of forcing RCMs with GCM boundary conditions, it is crucial to understand what generates precipitation variability over Bangladesh in the first place.

The objective of the study is to understand the role of the topography and SST in summer monsoon precipitation over Bangladesh and its surrounding regions in hierarchical climate model simulations from CMIP6 experiments. The organization of this paper is structured as follows: section (2) describes the various datasets and their evaluation methodologies, section (3) presents results, and section (4) provides a detailed discussion of the findings of the study and compares them to other published studies. Finally, section (5) summarizes the key findings of this study.

2. Data and Methodology

We analyzed various observational and numerical model simulated datasets, including observed gridded precipitation, topographic distribution, and various GCM datasets under the CMIP6 project. This study examined 34 years of common data for calculating model biases, and the observed data were interpolated to the model's resolution to find model biases.

To explore the characteristics of the summer monsoon precipitation over Bangladesh, we used the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) observed high resolution gridded dataset version 2 (Funk et al. 2015, Montes et al. 2021). CHIRPS uses 0.05° resolution satellite imagery and in-situ station data to create gridded precipitation time series spanning 50° South to 50° North, and data from 1981 to the near present. To test our hypothesis

about the precipitation mechanism, we used observed SST data HadISST (Rayner et al., 2003). For the zonal wind U, meridional wind V, and specific humidity q, the reanalysis dataset ERA5 is used in this study (Hersbach et al. 2020). The observed surface height of the topography of Bangladesh and its surrounding regions was collected from Global Multi-resolution Terrain Elevation Data (GMTED2010) to make a comparison with the model's topography (Fig. 2a) (Danielson, J.J., Gesch 2011). The resolution of the surface height topography data is 0.008^{o}x0.008^{o}.

To further investigate the contribution of local topography and SST, we used present-day climate simulation of GCM CMCC CM2 (Cherchi et al. 2019), which participates in the CMIP6 project (Eyring et al. 2016). The CMCC CM2 is a global coupled model primarily based on the Community Earth System Model (CESM) project (http://www.cesm.ucar.edu), and is developed and maintained by the Euro-Mediterranean Centre on Climate Change (CMCC) to understand global climate variability and climate change.

To quantify the influence of local topography versus SST we used three model simulations of CMCC CM2 from CMIP6 project: (1) a coupled simulation with low resolution (Lowres) atmosphere (1^{o}x1^{o}) and high-resolution ocean (0.25^{o}x0.25^{o}), (2) a coupled simulation with high-resolution (Highres) atmosphere (0.25^{o}x0.25^{o}) and high-resolution ocean (0.25^{o}x0.25^{o}), and (3) a AGCM simulation with high-resolution (Highres SST) atmosphere (0.25^{o}x0.25^{o}) and prescribed observed SST (HadISST 0.25^{o}x0.25^{o}). The Lowres simulation was taken from the CMIP6 Historical run, the Highres simulation was taken from the CMIP6-HighresMIP Hist-1950 run, and the Highres SST simulation was taken from the CMIP6-HighresMIP highresSST-present run. Compared to the Lowres simulation, the HighresMIP model simulations (Highres and Highres SST) have a higher resolution of topographical features (Haarsma et al., 2016). The Lowres coupled run uses the Community Atmospheric Model 4 as the atmospheric model with 30 vertical levels and the NEMO3.6 as the ocean model. The Highres coupled run uses a similar configuration, except the atmospheric model is in a higher resolution with a better-resolved topography. The Highres SST is an AGCM run where the ocean is prescribed SST from observed HadISST data with a high-resolution atmospheric model. All three simulations use the same aerosol, land surface, and ocean bio-geochemistry model.

Gao et al. (2012) investigated the sensitivity of moisture flux convergence to the choice of model grid resolution and found that a high-resolution model better simulates moisture flux convergence on the windward side of the mountains because of a more realistic representation of hydrodynamic instabilities. Seager et al. (2007) considered the vertically integrated moisture flux convergence as the net precipitation in the long term. Given the complex topographic distribution of the Himalayas, Arakan mountains, and the Meghalaya Plateau, it is imperative to investigate the role of model resolution to moisture flux convergence and precipitation climatology over Bangladesh and its surrounding regions. We computed the Vertically Integrated Moisture Flux (VIMF) as seen in Equation 1 (Darand and Pazhoh, 2019).

$$VIMF = \frac{1}{g}\int_{Ps}^{Pt}\left(\frac{\partial uq}{\partial x}+\frac{\partial vq}{\partial y}\right).dP \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where q is the specific humidity, P_s is surface pressure (in our study 1000 hPa), P_t is the pressure at the atmospheric level up to which lower troposphere moisture flux is calculated (in our study 700 hPa), u and v are the x- and y-components of the wind, respectively, and g is the acceleration due to gravity. The unit of VIMF is kg $m^{-2}s^{-1}$. A positive value of VIMF indicates that the moisture is spreading out or diverging, and a negative value suggests the moisture is concentrating or converging.

Earlier studies show that the Vertically Integrated Moisture Transport (VIMT) flux from the Indian Ocean supplies a significant amount of moisture for the Asian summer monsoon precipitation (Chansaengkrachang et al., 2018; Ullah and Gao, 2012; Fasullo and Webster 2003). The moisture for the monsoon precipitation over Pakistan primarily originates from the Arabian Sea, and the BOB plays a secondary role (Ullah and Gao, 2012). In contrast, the BOB is the dominant source of moisture for precipitation in Bangladesh. The VIMT from the Arabian sea contributes minimally to the precipitation over Bangladesh because most of the humidity directed in the northeasterly direction condense and precipitate on the windward side of the Western Ghats mountains and over it. Thus, our study focused on assessing the VIMT from the BOB, and we calculated the VIMT (Equation 2) as defined by Fasullo and Webster (2003).

$$VIMT = \int_{surface}^{700\,mb} q\,\boldsymbol{U}.dP\,, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (2)$$

Where q is the specific humidity and **U** is the wind vector.

Finally, we achieved our research objective of finding the isolated influence of the SST and topography on the summer monsoon precipitation of Bangladesh by analyzing CCMC CM2 from CMIP6 HighresMIP simulations forced with different resolutions of topography and prescribed SST.

3. Results

3. 1. Observed Summer Monsoon Precipitation over Bangladesh

During JJAS, there are three maximum precipitation regions over Bangladesh (Fig. 2a). The northeastern part of Bangladesh (the Sylhet division and the surrounding Indian states) receives the maximum precipitation during the summer monsoon, along with the northwestern region of Bangladesh (northern Rangpur division) and their surrounding Indian regions. The other region of Bangladesh that receives excessive precipitation during the summer monsoon is southeastern Bangladesh (Chittagong division) and its surrounding regions (Arakan state, Myanmar and Tripura, and Mizoram states of India). The unique precipitation pattern over Bangladesh and its surrounding regions during both annual mean and JJAS mean is primarily dominated by the surface topographical features (Fig. 1 & Fig. 2). In other words, the three maximum precipitation regions of Bangladesh are directly associated with nearby mountains. For example, the northeastern region of Bangladesh receives >25 mm/day precipitation during the summer monsoon, and the pattern of precipitation is associated with the area of the Meghalaya Plateau. The magnitude of the precipitation maxima over the northwestern region is nearly 22 mm/day precipitation during the summer monsoon and is associated with the southern Himalayan Mountain range (Fig. 2). The high precipitation band over Bangladesh's southeastern and eastern parts depicts 20-25 mm/day precipitation. It is associated with the mountain band over the Myanmar and Indian state, known as Arakan Mountains.

The VIMF divergence from ERA5 reanalysis showed that areas of high precipitation over Bangladesh and its surrounding regions result from strong lower tropospheric moisture convergence (Fig. 2b). The topography of the mountain bands forces the lower tropospheric moisture flux convergence over northern and northeastern Bangladesh, thus generating high precipitation. The VIMF also diverges in the lower troposphere over the BOB, located in the south of Bangladesh (Fig. 2b). The strong divergence of moisture flux over the BOB acts as a source of moisture that is transported by the low-level jet (LLJ) stream to the mountainous regions. The 925 hPa wind circulation shows that lower-level air travels from the southwest of the BOB to the northern part of Bangladesh, and then moves toward the northeast and northwest of Bangladesh near the southern Himalayan mountains. The Meghalaya plateau and south Himalayan Mountain range block the lower-level wind circulation and force moist air to converge and get lifted due to mechanical lifting, leading to precipitation (Fig 2b). The Arakan mountain and Meghalaya Plateau form a concave geometry with vertex over the Sylhet division (Fig. 2a). The Himalayas and Arakan mountain range lie along the northern and eastern borders (perpendicular and parallel) of Bangladesh. Due to the distinct geometry of these three regions, the LLJ coming from the BOB intersects at three different angles. It contributes to the moisture convergence over maximum precipitation regions of northern and northeastern Bangladesh. The LLJ reaches a climatological maximum during the local summer monsoon due to a maximum land-sea thermal contrast. The near-surface temperature and lower troposphere air temperature increases faster than the ocean due to the local monsoon heating and relatively higher ocean heat capacity during JJAS. This process creates a higher land-sea thermal contrast during the summer monsoon that drives the LLJ stream and transports moisture along with it. The lower-level wind circulation of the LLJ is parallel to the Arakan mountains. A stronger VIMT (Fig 2c) and weaker moisture convergence over the southeast region of Bangladesh suggest that the precipitation maxima over southeastern Bangladesh are due to a direct moisture convergence rather than the topographical features of the region.

3. 2. Numerical Experiments Decomposing the Influence of Topography & SST

The seasonal cycle of the domain-averaged precipitation of Bangladesh is shown in the Fig. 4. The result shows the Highres significantly improves the seasonal cycle of the precipitation, whereas the Highres SST further improves the seasonal cycle compared to the Lowres CMCC CM2

simulation. The total area-averaged monthly mean precipitation and the peak of seasonal cycles are enhanced in the Highres SST simulations compared to the Lowres and Highres model simulations. Onset, cessation, and length of the rainy season of the summer monsoon are also improved in the Highres SST model simulation as compared to the other two model simulations. This comparison suggests that the SST has significant influence over the summer monsoon precipitation. However, the magnitude of the seasonal precipitation is still underestimated when compared to the observations. The CMCC CM2 climate model shows significantly different summer monsoon precipitation climatology over Bangladesh with specific configurations (Figs. 3, 4, & 5). The Lowres simulation shows no clear precipitation maxima over Bangladesh with 4-6 mm/day precipitation (Fig 5a), due to a nonexistent topographical feature over the regions that surrounds Bangladesh (Fig. 3a). In contrast, the Highres model simulation shows a spatial variability of precipitation with maxima over the Meghalaya Plateau that extends to the northeastern part of the Bangladesh (Sylhet division), precipitation maxima over the northwest of Bangladesh (over Indian state, near southern Himalayan Mountain range), and maxima over the southeastern part of Bangladesh that extends to the Arakan mountains (Fig. 5b). The Highres model shows a better spatial pattern of precipitation distribution than the Lowres due to a better topographic resolution (Fig. 3b). Seasonal mean precipitation is increased over the flat land of Bangladesh from 4 mm/day to ~10 mm/day in Highres model simulations (Fig. 5b), as compared to the Lowres model simulation (Fig. 5a). In the Highres SST, spatial precipitation pattern is further improved especially in the southern and southeastern Bangladesh region.

The bias in the precipitation simulation of the CMCC CM2 model simulation when compared to the observation shows that the Lowres model has the maximum model bias in both the spatial pattern and magnitude of precipitation over Bangladesh and its surrounding regions (Fig. 5d). The Lowres model simulation shows an underestimation of precipitation with a maximum bias of 15 mm/day over northeastern Bangladesh (Fig. 5d). The precipitation bias is maximum near the Arakan Mountains and Meghalaya Plateau, where climatological precipitation has an observed maximum (Fig. 5a). The Highres model simulation's precipitation bias is significantly lower than the Lowres simulation (Fig. 5e). The Highres simulation still shows significant precipitation biases over northeastern and southeastern Bangladesh in regions of heavy climatological precipitation (Fig. 5e). These dry biases in the Highres are due to the false maxima (wrong maximum

precipitation region) of precipitation on the Highres simulation over these two regions, especially over the northeastern Bangladesh (Fig. 5e). Observations show maximum precipitation over the northeastern districts of Bangladesh (Sylhet division) (Fig. 2a), whereas the CMCC CM2 produces maximum precipitation over India near the Meghalaya Plateau (Fig. 3b, 5b, & 5e). The Highres simulation of the CMCC CM2 shifts the precipitation maximum towards the north over the northeastern Bangladesh (Fig. 3b & 5b). This particular model bias occurs due to the Meghalaya Plateau not being well-represented in the Highres model simulation (Fig. 2b & Fig. 3b). The Highres SST simulation shows significantly lower summer monsoon precipitation bias in the southeastern Bangladesh than the Lowres and Highres coupled simulations (Fig.5f). Reduction of the precipitation bias over the southeastern Bangladesh in the Highres SST compared to Highres coupled model simulations suggest that the SST in the BOB and tropical ocean system plays an important role in the summer monsoon precipitation simulation in Bangladesh. Interestingly, the precipitation bias pattern is similar in the Highres SST and Highres simulation due to the same model topography (Fig. 5f).

In this section, we have analyzed VIMF convergence and transport to understand the role of the topography of the surrounding regions and SST in the simulation of seasonal mean precipitation over Bangladesh. There is a significant bias (compared to the observation) in the VIMF over almost all of Bangladesh and its surrounding regions (Fig. 6 & 7). Due to a lack of well-resolved topography, the Lowres simulation shows a maximum bias in the moisture flux in terms of spatial pattern and magnitude (Fig. 6a & 6d). The Highres simulates a more realistic moisture flux convergence due to a better topography; however, the magnitude of the moisture flux is still significantly underestimated (Fig. 6b & 6e). A similar bias pattern in the VIMF convergence is seen in the Highres SST simulation (Fig. 6c & 6f). The similarity in VIMF convergence in the Highres coupled and Highres SST indicates that moisture flux convergence near the mountains of the surrounding regions is mostly dominated by the topography rather than the SST variability. Interestingly, over the northeastern Bangladesh and surrounding regions in the CMCC CM2 produces a strong moisture convergence only over the Meghalaya plateau, which results in a false precipitation maximum in the model (Fig. 6e). These false precipitation maxima are also present in the Highres SST, as both simulations use similar atmospheric model resolution and topography (Fig. 6f). However, the intensity of the moisture transport in the Highres SST due to a realistic

SST is related to a better LLJ circulation and higher moisture content (Fig. 6f). The VIMT of the CMCC CM2 simulations is shown in Fig. (7). The precipitation bias over Bangladesh and its surrounding regions is also due to a model bias in the simulation of low-level moisture transported from the BOB over land (Fig. 7). The Lowres simulation shows underestimated moisture transport over almost the entire Bangladesh land regions (Fig. 7a & 7d), and overestimated moisture transport on the east side of the mountains in the surrounding regions due to an overly smooth representation of the local topography. In the Highres coupled model simulation, the underestimation of moisture transport over the Bangladesh land region remains similar. However, the overestimation of moisture transport is improved in the east of the mountains of the surrounding regions due to an improved topographical representation. The Highres SST produces stronger moisture transport, leading to a lowest precipitation bias over Bangladesh especially in the southern and southeastern regions than in the Lowres and Highres simulations during JJAS (Fig. 7 d, e, & f). The intensity of the precipitation bias is decreased in the Highres SST simulation compared to the Highres coupled simulation over the southern and southeastern part of Bangladesh. This suggests that the precipitation intensity bias is driven by the bias in the SST over BOB.

Results show that the coupled model simulations (Lowres and Highres) have warmer SST over the BOB compared to the observed SST (Fig. 8). This SST bias in the coupled CMCC CM2 runs (Lowres and Highres) leads to a weaker land-sea thermal contrast that leads to a weaker LLJ (Fig. 8a, 8b). The bias in the 925 hPa circulation shows that wind anomalies are in the opposite direction of the climatological summer monsoon LLJ circulation (Fig. 8a, 8b, 8d, & 8e). The prescribed SST simulation (Highres SST) still shows a 925hPa wind bias. However, it overestimates the wind speed compared to observations and contributes to the stronger moisture transport (Fig. 8c & 8f). The moisture transport over Bangladesh is still underestimated in the Highres SST simulation. Overall, seasonal mean precipitation is improved incrementally with a realistic representation of the topography of the surrounding regions and climatological BOB SST variability.

4. Discussion

Bangladesh is in a unique geographical location in the tropical to the subtropical region that receives most of its precipitation during the summer monsoon. Three regions of Bangladesh receive maximum precipitations during the summer monsoon: northeastern (Sylhet division), northwestern (northern Rangpur state near southern Himalaya), and southeastern (Chittagong division) Bangladesh and surrounding regions. In this study, we have used three present-day climate simulations of CMCC CM2 from CMIP6 experiments to understand the influence of local topography and SST on summer monsoon precipitation over Bangladesh and its surrounding regions. The Lowres coupled simulation uses a low atmospheric model resolution with a coarse topography (1x1 degree). The Highres coupled simulation uses a relatively higher resolution atmospheric model that uses a more realistic high-resolution topography (0.25x0.25 degree). The Highres SST simulation uses the same atmospheric resolution as Highres simulation, except it has a prescribed observed SST.

Precipitation maximum regions of Bangladesh are directly associated with the mountains of the surrounding regions. The southern Himalayan Mountain range and Meghalaya Plateau block the southwesterly wind that carries moisture and produces strong convergence that leads to precipitation maxima. The band of the Arakan mountains acts as a local forcing to the precipitation over the Myanmar region by blocking the low-level winds associated with the LLJ stream and directly forcing local moisture convergence. However, the precipitation maxima over southeastern Bangladesh (coastal region) are mostly due to inland moisture transports from BOB. Although mountains play a crucial role in forcing the moisture to precipitate by convergence, the BOB plays a significant role as a source of moisture for precipitation over Bangladesh. The moisture flux divergence and 925hPa circulation revealed that the moisture content is carried from the northern BOB by the LLJ circulation. During the summer monsoon, these winds are stronger due to a monsoonal differential heating that creates a stronger land-sea thermal contrast and drives the circulation with moisture content towards northern Bangladesh.

The CMCC CM2 model simulations show the influence of the topography and SST on summer monsoon precipitation over Bangladesh. Compared to observations, the Lowres simulation shows almost no peaks in the spatial distribution of precipitation over the northeastern part of Bangladesh due to a lack of topographical features in the model. The Highres simulation has a better (higher

resolution) topography and simulates a better precipitation climatology than the Lowres. However, the Highres coupled model simulation still shows significant precipitation bias over climatological maximum precipitation regions of Bangladesh. The prescribed SST run (Highres SST) has significantly less bias in the precipitation over Bangladesh compared to the coupled Lowres, and Highres model runs. Interestingly, the pattern of the precipitation bias is very similar between the Highres coupled, and the Highres prescribed SST run. The similarity in precipitation patterns suggests that the pattern of precipitation bias is primarily due to local topography. In contrast, the bias in magnitude is primarily due to the SST bias in the model.

The Highres and Highres SST model simulations still show significant precipitation bias compared to observations. The maximum precipitation and moisture convergence region of northeastern Bangladesh is especially shifted toward Indian states instead of Bangladesh, which creates a false precipitation maximum. It suggests that the model still requires a more realistic high-resolution topography to improve the simulation of precipitation climatology over Bangladesh, especially in the northeastern region.

This study shows that the low-resolution model simulations can lead to a large monsoon precipitation bias in regions like Bangladesh, where local topography plays a significant role. As a result, a realistic SST simulation in the model alone is not enough to produce realistic monsoon precipitation over Bangladesh and its surrounding regions. This suggests that a higher resolution GCM with realistic topography can significantly improve the local climate prediction and climate change projection.

5. Conclusion

We have analyzed CMCC-CM2 GCM simulations from CMIP6 experiments to understand the importance of the local topography of surrounding mountains and SST in simulating summer monsoon precipitation over Bangladesh and its surrounding regions. Our main results are summarized as follows:

1. By analyzing observed data and CMCC-CM2 model simulations, our study shows that the summer monsoon precipitation over Bangladesh is forced by the SST over BOB and surrounding mountains near Bangladesh. The moisture content generated from the BOB carried by the LLJ converges near local mountains to precipitate which creates three distinct maximum precipitation regions over Bangladesh.

2. The climatological summer monsoon precipitation simulation of Bangladesh in a GCM is sensitive to the choice of the horizontal resolution of the GCM simulation. Even with the standard GCM model horizontal resolution (1x1 degree), the latest generation of climate models fails to simulate. Overall, patterns and magnitudes of climatological precipitation are improved in simulations with realistic local topography.

3. The BOB also plays a significant role as a source of moisture for precipitation over Bangladesh. The prescribed SST run (Highres SST) has significantly less bias in the precipitation over Bangladesh compared to the coupled Lowres and Highres model runs. It implies that the SST in the BOB and tropical ocean system contributes to the summer monsoon precipitation over Bangladesh.

4. Total area-averaged monthly mean precipitation, the peak of the seasonal cycle, onset, cessation, and the length of the rainy seasons are improved in the Highres SST simulations as compared to the Lowres, and Highres model simulations. This result suggests that the SST of BOB drives the seasonal monsoon system over Bangladesh (Fig. 4).

5. Overall, our result suggests that the pattern of precipitation bias is primarily due to the local topography. Whereas, the bias in the magnitude is primarily due to the SST bias in the model.

The Highres SST simulations still produce a significant dry bias over Bangladesh even when forced with the observed SST. This result shows that the CMCC CM2 model has less low-level moisture content present over the BOB compared to observations during the summer monsoon.

Further investigation is needed to understand why the CMCC CM2 underestimates the summer monsoon moisture content over the BOB.

In conclusion, the current study highlights the importance of higher spatial model resolution and realistic representation of the BOB SST variability in climate models in reproducing the properties of monsoon precipitation over Bangladesh and its surrounding regions.

Acknowledgments

We would like to thank Dr. Natalie J. Burls (George Mason University) for her initial contribution to the idea of the manuscript.

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Figures:

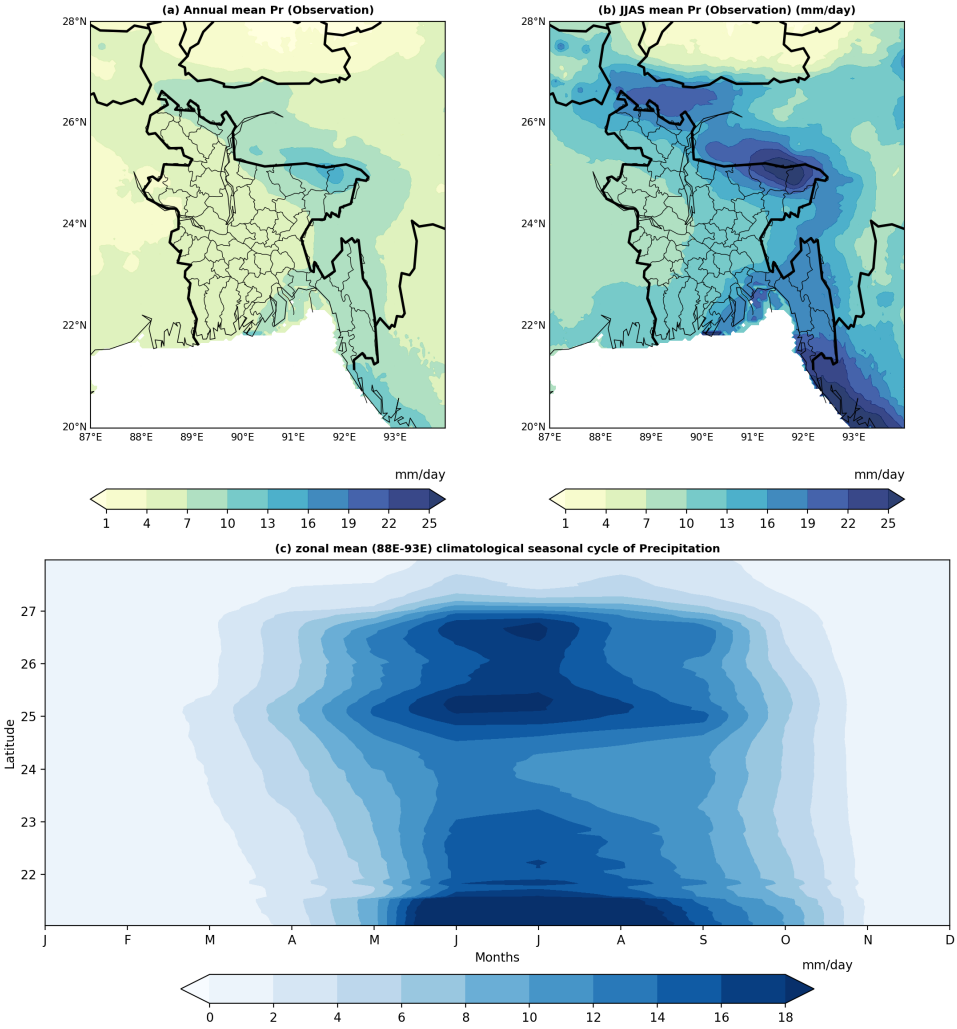

Fig. 1 Precipitation climatology (years 1981-2014) of (a) Annual mean, (b) JJAS mean, and (c) zonal mean (average over 88E-93E) seasonal cycle of Chirps v2 observed data as a function of latitude (units: mm/day).

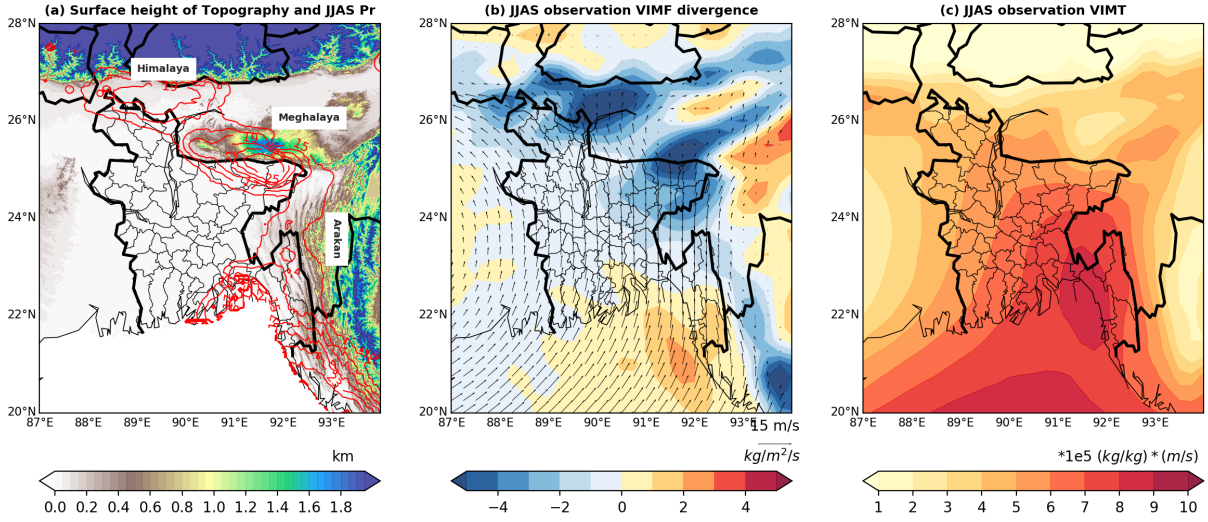

Fig. 2 (a) Height of topography of Bangladesh and its surrounding regions (units: km), and the JJAS observed precipitation is contoured as red lines in mm/day. (b) JJAS mean ERA-5 vertically integrated moisture flux (VIMF) divergence (1000-700 hPa) (units: kg/m^2/s) is shown in shaded color, and 850hPa wind circulation is shown as a vector (units: m/s) (years mean 1981-2014). VIMF positive values show divergence, and negative values show the convergence of vertically integrated winds. (c) JJAS mean ERA-5 vertically integrated moisture transport (VIMT) (1000-700 hPa) (units: 1e5 * kg/kg * m/s)

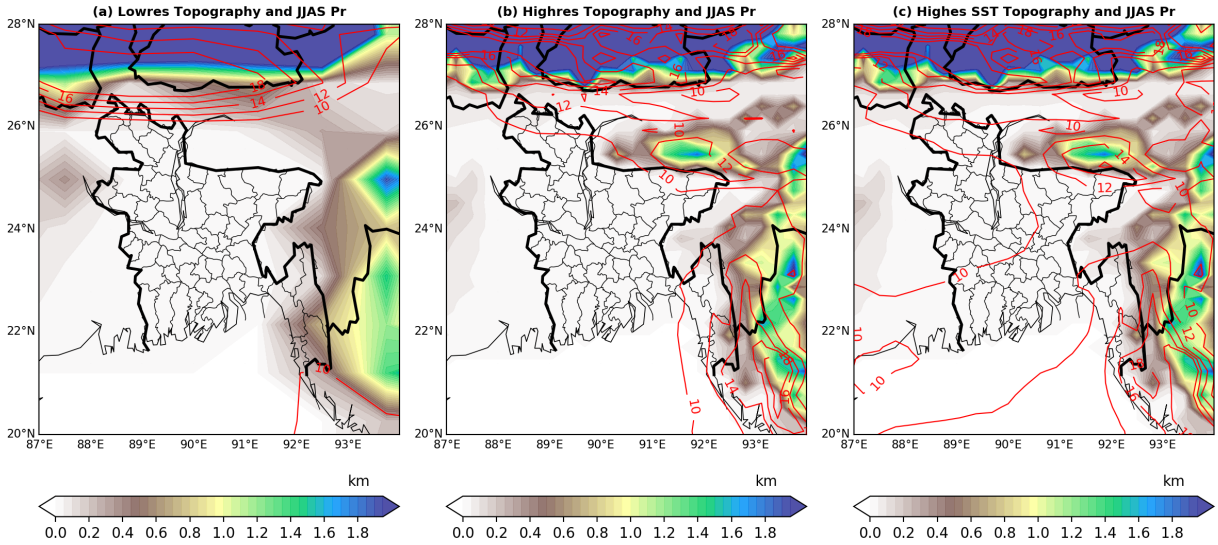

Fig. 3 Model topography in shaded color and 34 years (1981-2014) JJAS mean precipitation contoured in red-colored for (a) Lowres, (b) Highres, and (c) Highres SST (units: mm/day). The topography map shows no existence of the Meghalaya Plateau on the CMCC CM2 Lowres simulation.

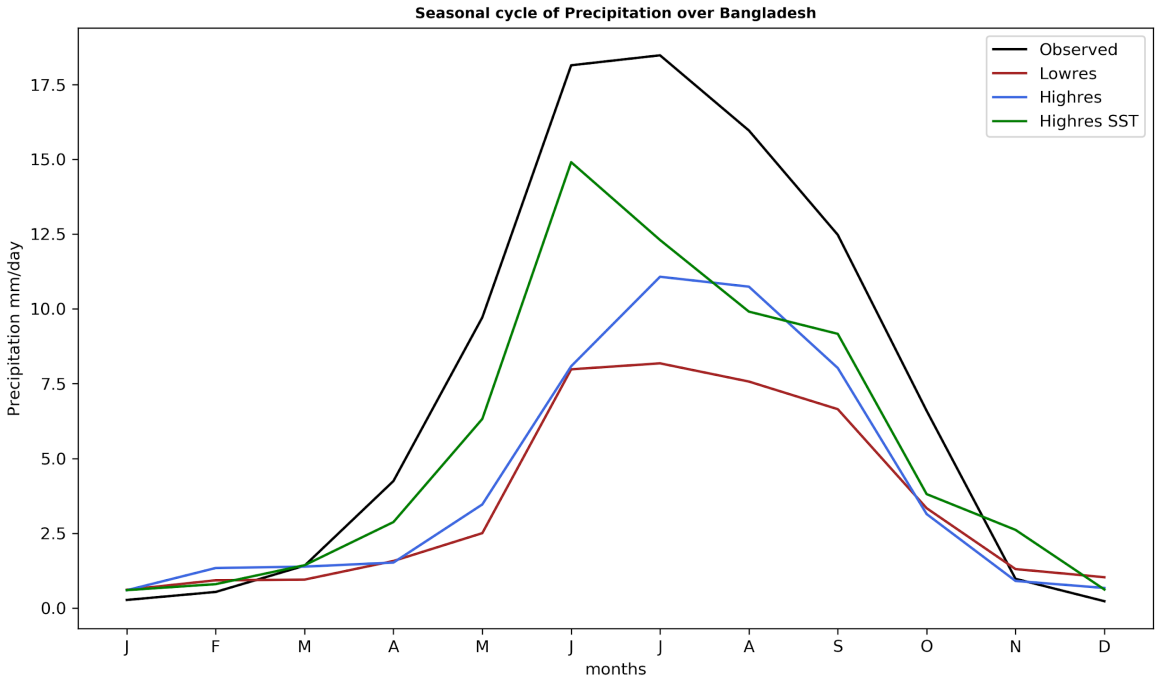

Fig. 4 Climatological (mean over 1979-2014) monthly seasonal cycle of precipitation over Bangladesh is shown for observation (black colored), CMCC CM2 Lowres (brown colored), CMCC CM2 Highres (blue colored), and CMCC CM2 Highres SST (green colored) (units: mm/day).

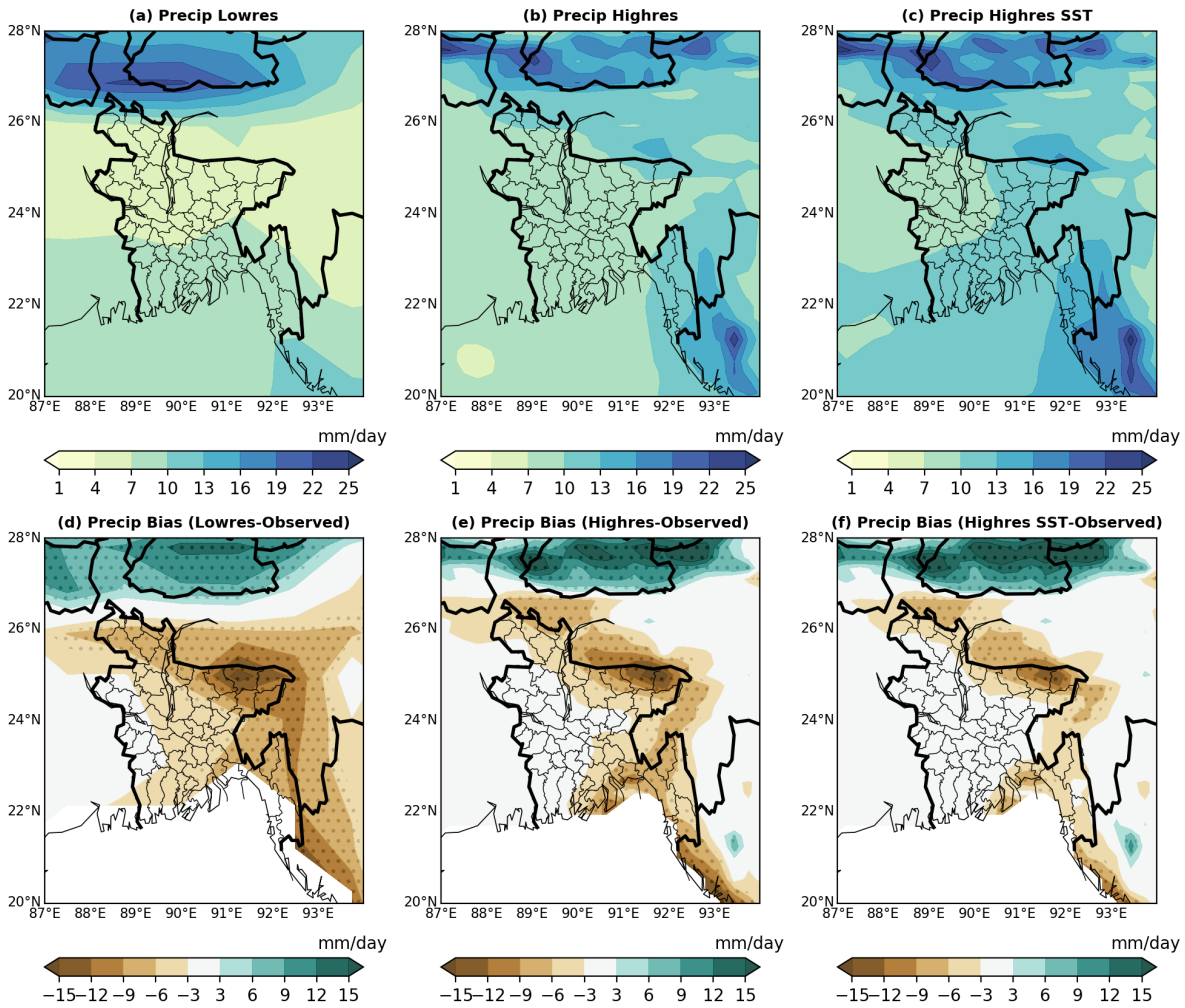

Fig. 5 JJAS mean precipitation climatology of CMCC CM2 for (a) Lowres, (b) Highres, and (c) Highres SST (units: mm/day). The precipitation bias in the CMCC CM2 simulations is shown for (d) Lowres - Observed, (e) Highres - Observed, and (f) Highres SST - Observed. Units are in mm/day. Precipitation bias plots are stippled at a 95% significance level calculated using a 2-sided student t-test for the difference of means.

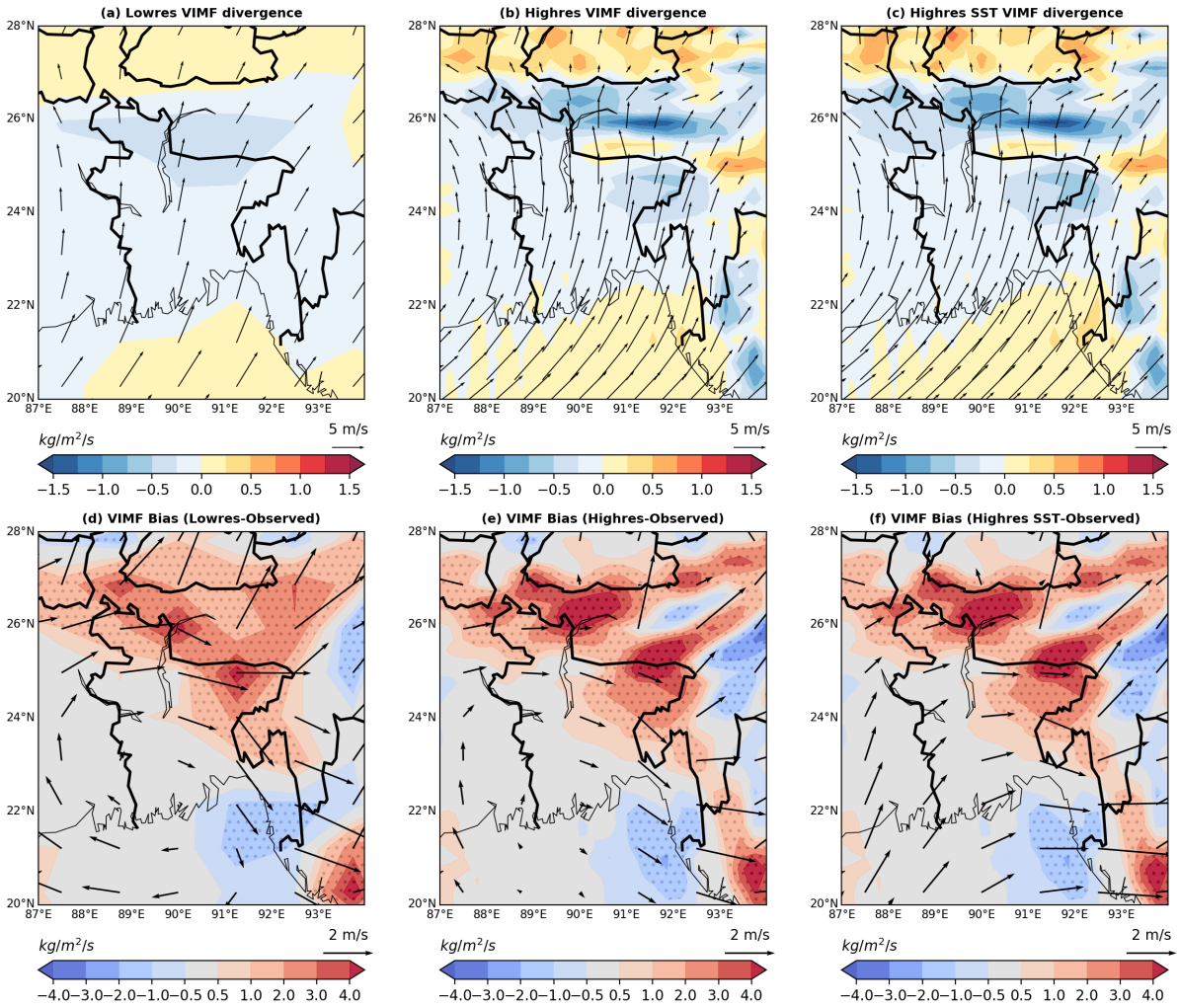

Fig. 6 JJAS mean climatological mean (1981-2014) vertically integrated moisture flux convergence (VIMF) (1000-700hPa) (units: kg/m^2/s) shown as shaded color and 925hPa wind circulation (units: m/s) shown as vector for CMCC CM2 (a) Lowres, (b) Highres, and (c) Highres SST. The VIMF bias (as shaded color) (units: kg/m^2/s) and 925hPa wind bias (units: m/s) (as vector) in the model simulation compared to observation is shown for (d) Lowres - Observation, (e) Highres - Observation, and (f) Highres SST - Observation. VIMF bias differences are stippled at a 95% significance level calculated using a 2-sided student t-test for the difference of means.

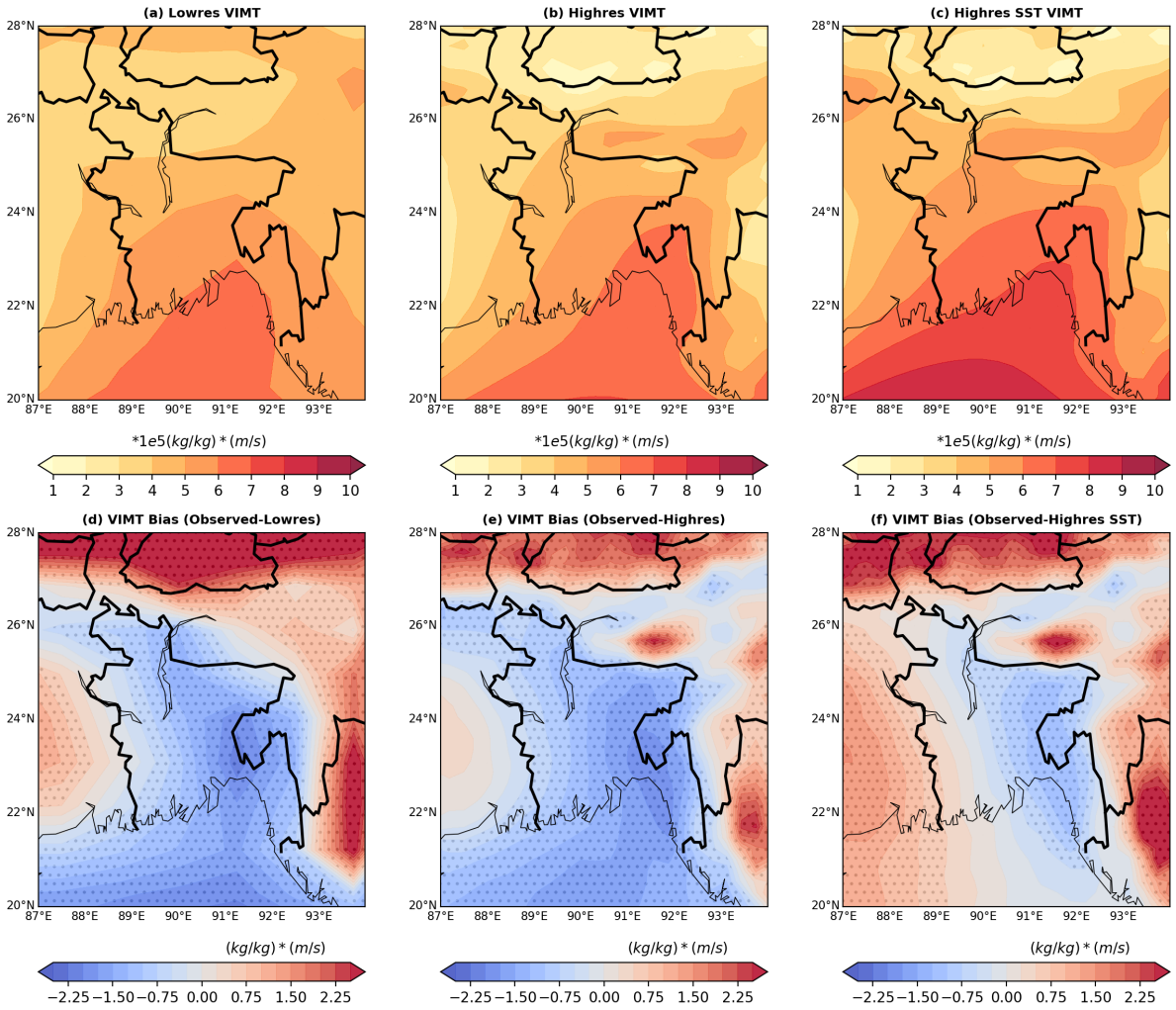

Fig. 7 JJAS means climatological vertically integrated moisture transport (VIMT) is shown for (a) Lowres, (b) Highres, and (c) Highres SST (units: 1e5* kg/kg * m/s). The VIMT bias (units: kg/kg * m/s) in the model simulation compared to observation is shown for (d) Lowres - Observation, (e) Highres - Observation, and (f) Highres SST - Observation. VIMT bias differences are stippled at a 95% significance level calculated using a 2-sided student t-test for the difference of means.

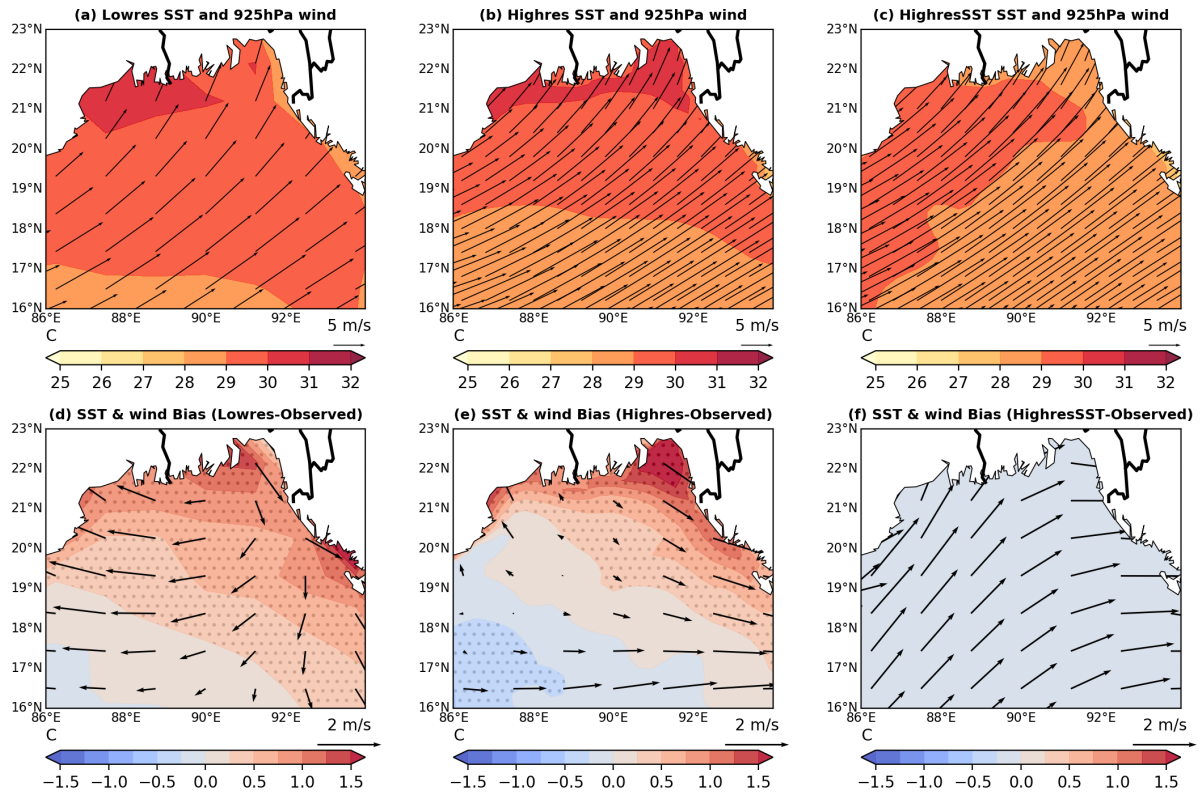

Fig. 8 JJAS climatological mean (1981-2014) SST for CMCC CM2 (a) Lowres, (b) Highres, and (c) Highres SST. The SST bias (units: C) and 925hPa wind bias (units: m/s) (as vector) in the model simulation compared to observation is shown for (d) Lowres - Observation, (e) Highres - Observation, and (f) Highres SST - Observation. SST bias differences are stippled at a 95% significance level calculated using a 2-sided student t-test for the difference of means.