The Value Addition of Dynamic Downscaling the South Asian Summer Monsoon from a Global Reanalysis using a Regional Coupled Ocean-Atmosphere Model

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Abstract

In this study we present the results of a Regional Coupled ocean-atmosphere Model (RCM) simulation of the South Asian Summer Monsoon (SASM) forced by global atmospheric and oceanic reanalysis at 20 km grid spacing over a period of 25 years (1986-2010). The RCM shows a more realistic alignment of the simulated rainfall along the orographic features of the domain. Furthermore, the RCM simulates the observed feature of convection over continental SASM region being more vigorous with dominance of mixed warm and cold phase hydrometeors in contrast to the dominance of the warm rain process in the neighboring tropical oceans. Similarly, the upper ocean features of contrasting mixed layer and thermocline depths between the northern and equatorial Indian Ocean are also simulated in the RSM-ROMS. Intra-Seasonal Oscillation (ISO) of the SASM at 10-20 and 20-70 days are simulated in the RSM-ROMS with many of the observed features captured like the latter frequency band being of higher amplitude and the meridional propagation being slower in Bay of Bengal compared to that over Arabian Sea. Additionally, RSM-ROMS shows 12.3 Monsoon Low Pressure Systems (LPS) per season that is comparable to 14.6 per season from observations. Furthermore, the intraseasonal contrasts of LPS between the wet and dry spells of ISO is also reproduced in the RSM-ROMS. The simulation of mesoscale LPS and its intraseasonal variability by the RCM amidst its reasonable fidelity of the SASM climatology clearly demonstrates the value addition of downscaling a global reanalysis at 2.5° (~277-km) to 20-km grid spacing.

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Keypoints:
1) The regional climate model displays robust intraseasonal variability with verifiable meridional propagation
2) The intraseasonal variations of the monsoon low pressure systems in the regional climate model simulation verify reasonably with observations
3) The regional climate model shows the observed contrast of convection with warm rain process dominating over ocean compared to that over land

Abstract

In this study we present the results of a Regional Coupled ocean-atmosphere Model (RCM) simulation of the South Asian Summer Monsoon (SASM) forced by global atmospheric and oceanic reanalysis at 20 km grid spacing over a period of 25 years (1986-2010). The RCM shows a more realistic alignment of the simulated rainfall along the orographic features of the domain. Furthermore, the RCM simulates the observed feature of convection over continental SASM region being more vigorous with dominance of mixed warm and cold phase hydrometeors in contrast to the dominance of the warm rain process in the neighboring tropical oceans. Similarly, the upper ocean features of contrasting mixed layer and thermocline depths between the northern and equatorial Indian Ocean are also simulated in the RSM-ROMS. Intra-Seasonal Oscillation (ISO) of the SASM at 10-20 and 20-70 days are simulated in the RSM-ROMS with
many of the observed features captured like the latter frequency band being of higher amplitude and the meridional propagation being slower in Bay of Bengal compared to that over Arabian Sea. Additionally, RSM-ROMS shows 12.3 Monsoon Low Pressure Systems (LPS) per season that is comparable to 14.6 per season from observations. Furthermore, the intraseasonal contrasts of LPS between the wet and dry spells of ISO is also reproduced in the RSM-ROMS. The simulation of mesoscale LPS and its intraseasonal variability by the RCM amidst its reasonable fidelity of the SASM climatology clearly demonstrates the value addition of downscaling a global reanalysis at 2.5° (~277-km) to 20-km grid spacing.

Plain Language Summary

The South Asian Summer Monsoon (SASM) climate represents an amalgam of variations across spatio-temporal scales over a region with unique topographic and bathymetric features. As a result, the SASM climate offers stiff challenges for numerical climate models to simulate its climate. In this study we evaluate the added value of the Regional Climate Model (RCM) in downscaling the SASM climate from a 2.5° x 2.5° global reanalysis to 20 km grid spacing. Besides displaying reasonable fidelity of simulating the mean climate of the SASM, the RCM demonstrates significant skill in capturing the observed features of the intra-seasonal oscillations of the SASM and its iconic meridional propagation. Furthermore, at 20 km, the RCM simulates the seasonal and intraseasonal activity of the monsoon low pressure systems that is comparable to observations. Therefore, the RCM of this study clearly demonstrates its added value to the driving global reanalysis in the simulation of the SASM climate, its intra-seasonal variations, and the seasonal and intra-seasonal activity of the monsoon low pressure systems.

1 Introduction

The South Asian Summer Monsoon (SASM) is one of the most significant sources of terrestrial convection, which exhibits a robust seasonal cycle and is often construed as a significant part of the atmospheric general circulation. The inter-play between the atmosphere and ocean in the evolution of the SASM is significant that manifest at their interface and in the free troposphere and below the ocean surface (Loschnigg and Webster 2000; Wang et al. 2003, 2004; Wu and Kirtman 2005; Kumar et al. 2005; Misra 2008). For example, several studies have suggested that air-sea interaction as displayed by the correlations between atmospheric fluxes and SST is unique to the tropical Indian Ocean and plays an important role in the variations of the SASM (Krishnamurti et al. 1988; Sengupta et al. 2001; Wu et al. 2008). Similarly, other studies (e.g., Loschnigg and Webster 2000; Noska and Misra 2016) suggest that the interhemispheric transport of heat in the ocean and in the atmosphere balance each other out, regionally over tropical Indian Ocean with the seasonal evolution of SASM.

The sub-seasonal variations of the SASM are significant and is argued to be dominant over other temporal scales of variation (Webster et al. 1998).
ster and Hoyos (2004) suggest that intra-seasonal variations of the SASM have larger impact on agricultural productivity and water management than inter-annual variations of the seasonal anomalies. In contrast, Moron et al. (2012) concluded that SASM is dominated by the interannual timescales with the sub-seasonal variations playing a dominant role during neutral monsoon years. The intra-seasonal variations of the SASM is identified to have two distinct scales of variations with periodicity that is centered around 45 days (often referred as Boreal Summer Intra-Seasonal Oscillation [BSISO]) and 20 days (often referred as Quasi-Biweekly Mode [QBM]) (Murakami 1976; Krishnamurti and Bhalme 1976; Yasunari 1979, 1980, 1981; Sikka and Gadgil 1980; Krishnamurthy and Shukla 2007). A major difference between the BSISO and QBM besides their disparate time scales is their propagating characteristics. BSISO originates from the equatorial Indian Ocean and propagates northward while the QBM originates from northwest tropical Pacific and propagates northwestward through Bay of Bengal (BoB) to central India. More recently, Karmakar et al. (2021) showed that the genesis of Monsoon Depressions (MD) is far more prevalent in the active phases of the BSISO than during its inactive spells. Interestingly, it was found that the Monsoon Lows (ML) were insensitive to the phase of the BSISO.

Despite the familiarity of the SASM phenomenon, the simulation and prediction of the SASM continues to be a challenge. For one, the multi-scale interactions involved in the evolution of the SASM is complex and yet to be fully understood. The role of the local scales of the cumulonimbus clouds to the view of the SASM as a shift of the ITCZ from the equatorial Indian Ocean to the continental region with quasi-divergent planetary circulations make SASM an amalgam of many spatio-temporal scales (Meehl 1987; Webster et al. 1998; Goswami 2005; Chen et al. 2019, 2021). Secondly, the anharmonic variations of the sub-seasonal variations of the SASM have been a significant shortcoming of many climate models across generations of model development (Slingo et al. 1996; Kang et al. 2002; Rajendran and Kitoh 2006; Ajayamohan et al. 2011; Mandke et al. 2020). More recently attempts at simulating the SASM and more importantly its intraseasonal variations at comparatively higher resolutions than global models have been made from regional climate models with limited success (e.g., Bhaskaran et al. 1998; Bhat et al. 2012, Samala et al. 2013; Maharana and Dimri 2016). It should be noted that most of these regional climate modeling studies of the SASM have been conducted using regional atmospheric models. In some instances where a coupled ocean-atmosphere regional model has been deployed, the lateral boundary conditions to the regional ocean model use climatological monthly mean boundary conditions and/or use some form of flux correction (e.g., Samala et al. 2013, Zou and Zhou 2016). In contrast, the high-resolution regional climate modeling studies conducted with coupled air-sea interactions of the SASM in Misra et al. (2017, 2018) and in this study use more realistic boundary conditions for the ocean that vary on monthly time scale. These regional climate modeling studies with realistic boundary conditions and coupled air-sea interactions have shown initial promise in simulating the sub-seasonal
variations of the SASM. In this study we are presenting the results of the verification of a 25-year simulation of the SASM conducted with a regional climate model at 20 km grid spacing that includes air-sea coupling. This study is novel in that it is one of the longest integrations conducted at 20 km grid resolution for this region (Fig. 1) with a regional coupled air-sea climate model. The resolution and length of the regional climate model integration in this study allows us to also examine the weather extremes of the Monsoon Low Pressure Systems (LPS) and its variations, which was missing from our earlier studies (Misra et al. 2017, 2018).

The concept of the added value of the regional climate model relative to its global driving data has been thoroughly reviewed in many of the earlier studies (Leung et al. 2003; Di Luca et al. 2015; Torma et al. 2015; Ciarlo et al. 2021). These studies suggest that the added value could be evaluated in multiple ways including by way of comparing quantitative metrics for model performance/fidelity, qualitative comparison of simulated fields with observations and simulating processes and phenomenon that are unresolved in the driving model. In this study we adopt all of these techniques to demonstrate the added value of the regional climate model to the driving global reanalysis.

2 Model Description

The model used for this study is the Regional Spectral Model-Regional Ocean Modeling System (RSM-ROMS). RSM-ROMS has been adopted in several climate studies (e.g., Li et al. 2012, 2014; Ham et al. 2016; Misra et al. 2018). The RSM is the atmospheric component and ROMS is the oceanic component of the regional coupled ocean-atmosphere modeling system. RSM is based on spectral core using sine and cosine series to solve the primitive equations (Juang and Kanamitsu 1994). The RSM also uses a spectral damping scheme to reduce climate drift, and which also allows for larger than conventional nesting ratios (Kanamaru and Kanamitsu 2007). In the RSM there are 28 vertical, terrain following \( \frac{p}{\rho} \) levels reaching up to ~2hPa. A brief outline of the physics adopted in RSM for this study is provided in Table 1.

Table 1: Outline of the physics in RSM

<table>
<thead>
<tr>
<th>Physical parameterization</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow convection</td>
<td>Tiedtke (1983)</td>
</tr>
<tr>
<td>Deep convection</td>
<td>Moorthi and Suarez (1992)</td>
</tr>
<tr>
<td>Shortwave radiation</td>
<td>Chou and Lee (1996)</td>
</tr>
<tr>
<td>Longwave radiation</td>
<td>Chou and Suarez (1994)</td>
</tr>
<tr>
<td>Boundary layer</td>
<td>Hong and Pan (1996)</td>
</tr>
<tr>
<td>Land surface</td>
<td>Ek et al. (2003)</td>
</tr>
<tr>
<td>Gravity wave drag</td>
<td>Alpert et al. (1988)</td>
</tr>
<tr>
<td>Clouds (explicit)</td>
<td>Zhao and Carr (1997)</td>
</tr>
</tbody>
</table>
ROMS is a free surface, terrain following primitive equation regional ocean model (Haidvogel et al. 2000; Scheptekin and McWilliams 2005). There are 30 vertical levels in ROMS. The parameterizations used in ROMS include local closure schemes based on the level 2.5 turbulent kinetic energy equations (Mellor and Yamada 1982), boundary layer formulation is based on the nonlocal closure scheme (Large et al. 1994), second order biharmonic horizontal diffusion (Ezer et al. 2002), and generic length-scale parameterization (Umlauf and Burchard 2003).

RSM and ROMS are coupled on identical spatial grids at 20-km grid spacing so that interpolations at their interface and the use of flux coupler is avoided. The coupling interval between RSM and ROMS is 1 hour. No flux correction is applied throughout the integration of RSM-ROMS.

3 Experiment Description and Verification Datasets

A single 25 year integration is conducted with RSM-ROMS over the period of 1986-2010 over the domain indicated in Fig. 1. The resolved model topographic and bathymetric features are also shown in Fig.1. The grid spacing at 20km of RSM-ROMS can resolve many topographical and bathymetric features including the coastal shelves, mesoscale mountain ridges and valleys. The integration is forced at the lateral boundaries of RSM with NCEP-DOE reanalysis (R2; Kanamitsu et al. 2002) and the lateral boundaries of ROMS is forced with Simple Ocean Data Assimilation v2.2.4 (SODA; Carton and Giese 2008). The R2 reanalysis is available at 2.5° grid spacing while SODA is made available at 0.5° grid resolution. The initial conditions of the RSM atmosphere and land surface were obtained from R2 for the corresponding date of the start of the integration. Similarly, the initial conditions for ROMS are obtained from SODA. These initial conditions were interpolated to the RSM-ROMS grid at 20 km grid spacing.

In this study we verify several variables from RSM-ROMS with many different sources of observation listed in Table S1 (supplementary material). There are few cases when the validation datasets do not match with the integration period of RSM-ROM. However, in such instances the non-overlapping period of the climatological mean between the observation and RSM-ROMS is not critical because the climatology of the model is verified. The seasonal climatology is computed over the months of May-June-July-August-September (MJJAS) season. The extended 5-month season is so chosen to include the earlier onset of the monsoon in South Asia (e.g., Thailand, Cambodia, Myanmar).

4 Results

i) Seasonal Climatology of upper air and surface meteorological variables

The observed seasonal climatological rainfall in Fig. 2a suggests strong topographic influence. For example, the observed rainfall in Fig. 2a shows a maximum along the Western Ghats, in northern BoB, along the northeast Indian Hills, foothills of the Himalayas, the Arakan Yoma and the Bilauktaung Ranges in Myanmar and along the Annamite Range in Laos. There are other moderate
maxima of rainfall like over the Vindhya Range in central India and off the Banjaraan Titiwangsa Range in Sumatra that clearly mark the influence of the orography on the summer monsoon climatological rainfall (Fig. 2a). Similarly, the rain shadow area in southeastern part of India and over Sri Lanka is another manifestation of the orographic influence, which receives less than a tenth of what falls over the Western Ghats or over the Northeast Indian Hills (Fig. 2a; Fletcher et al. 2018). These spatial characteristics of the observed MJJAS climatological rainfall are reasonably captured in the RSM-ROMS simulations (Fig. 2b), especially in relation to R2 reanalysis (Fig. 2c). The pattern correlation coefficient (PCC) of rainfall of RSM-ROMS with respect to IMERG is 0.81 over land and 0.72 over the ocean. The relatively high resolution of the RSM-ROMS simulation at 20 km is certainly helping in focusing the rainfall near orographic features. However, over the Arakan Yoma region, the simulation (Fig. 2d) like the R2 reanalysis (Fig. 2e) produces a wet bias along coastal Myanmar and a dry bias over the adjacent BoB. But more generally, the rainfall bias over land is reduced in RSM-ROMS compared to R2 reanalysis with the exception over the Himalayas, parts of China, Malay Peninsula and Sumatra. Over the oceans, the dry bias of the RSM-ROMS simulation (Fig. 2d) is more extensive (especially over BoB) and the wet bias over southwestern Indian Ocean is more severe than in R2 reanalysis (Fig. 2e). But the rainfall bias in and around Sri Lanka is significantly reduced in RSM-ROMS in relation to R2 reanalysis.

The observed climatology of the MJJAS precipitable water shows a familiar large-scale meridional gradient of decreasing precipitable water from the equatorial Indian Ocean to the Tibetan Plateau and a large-scale positive zonal gradient from the western coast of India across to BoB (Fig. 3a). However, this negative meridional gradient of precipitable water is interspersed with a maximum over the northern BoB and the Gangetic-Brahmaputra Plain (GBP; Fig. 3a). The RSM-ROMS simulation shows these observed gradients although the maxima over the BoB and the GBP is underestimated relative to the observations (Fig. 3b). This climatological maximum of precipitable water over BoB and GBP and the positive zonal gradient in peninsular India are significantly diminished in the R2 reanalysis (Fig. 3c). However, R2 reanalysis preserves the observed broad scale negative meridional gradient of the precipitable water between the equatorial Indian Ocean and the Tibetan Plateau (Fig. 3c). The comparison of the systematic errors indicates that the bias of the precipitable water is reduced both over land, especially over the orographic features like the Himalayas and the Vindhya Ranges in central India in RSM-ROMS (Fig. 3d) relative to the corresponding moist bias over the Himalayas and across central India in R2 reanalysis (Fig. 3e). The dry bias over the oceans in RSM-ROMS is however higher than in R2 reanalysis (Fig. 3e). Interestingly, the dry bias in RSM-ROMS is uniform across land and ocean (Fig. 3d) unlike in R2 reanalysis (Fig. 3e).

The observed characteristics of rainfall of the Indian Summer Monsoon (ISM) reveal that some of the most intense deep convection as witnessed by the frequency of lightning flashes occurs along the Western Ghats, GBP, and the
Himalayan Foothills (Murugavel et al. 2021). Furthermore, observations from satellites confirm that thunderstorms in tropical oceans are weaker than those over tropical land surface (Nesbitt et al. 2000; Zipser et al. 2006). Similarly, Mohr et al. (1999) using passive microwave satellite data showed that ice scattering signatures over land were consistently stronger than over the oceans. It is conjectured that the large difference in the vigor of the convection, between tropical land and ocean could be a result of smaller entrainment rates for land convection (Lucas et al. 1994; Petersen and Rutledge 1998; Zipser 2003). In addition to strong updrafts, lightning activity is engendered by presence of supercooled liquid water and high concentration of frozen hydrometeors (Avila and Caranti 1994; Williams et al. 2005). Therefore, lightning activity is often used as an indicator of deep convective cells in cloud systems (Lang and Rutledge 2002; Carey et al. 2003). In Figs. 4a and b we show the MJJAS climatological mean of the vertically integrated cloud water mixing ratio between surface to free cooling level (signifying warm rain process) and from free cooling level to top of the atmosphere (signifying cold rain process) in the RSM-ROMS simulation as a proxy to the observed lightning activity (Fig. 4c). The cloud water mixing ratio serves as the best proxy from the RSM-ROMS simulation for the presence of hydrometeors above the freezing level since it is the only prognostic water species variable in its cloud microphysics scheme (Zhao and Carr 1997). Therefore, from comparing Figs. 4a and b, and noting the relative abundance of cloud water mixing ratio above the freezing level in Fig. 4b from the RSM-ROMS simulation it is apparent that deep convection in MJJAS and or lightning activity is more likely over land than in the oceans as the observations would suggest (Fig. 4c). Furthermore, by examining the relative abundance of frozen hydrometeors (Fig. 4b), the lightning activity in the RSM-ROMS simulation is more likely and frequent in the Western Ghats, Vindhya Range, Northeast Indian Hills, the Himalayan Range, the Arakan Yoma and the Bilauktang Range in Myanmar and over parts of China than over the rest of the domain as the observations suggest (Fig. 4c). The observed lightning strokes in Fig. 4c suggests that BoB has far more lightning activity than the rest of the oceans, which is not as apparent from the distribution of the frozen hydrometeors in the RSM-ROMS simulation (Fig. 4b).

The observed 850hPa wind climatology of the MJJAS season shows the westerlies over the equatorial Indian Ocean, the strong southwesterlies associated with the Findlater Jet and the monsoon trough residing over the BoB (Fig. S1a; in supplementary material). The RSM-ROMS reproduces these features (Fig. S1b), albeit with a bias of weaker winds of the Findlater Jet and the downstream maximum off the southeastern coast of Sri Lanka. Furthermore, the monsoon trough over the BoB is also weak in the simulation (Figs. S1b and d). The R2 reanalysis also show similar features with comparable bias as in the RSM-ROMS simulation (Figs. S1c and e).

ii) Seasonal Climatology of upper ocean variables

The characteristic warm SST across equatorial Indian Ocean and the cold SST
along the coastal western Indian Ocean (Fig. 5a) is reasonably well replicated in the RSM-ROMS simulation (Fig. 5b). These SST patterns are associated with the weak westerlies along equatorial Indian Ocean and the strong southwesterlies in the western Arabian Sea (AS; Fig. S1). In addition, the wetter and drier conditions that dictate the freshwater influx in equatorial Indian Ocean and western AS shoal and further deepen mixed layer depth, respectively. The climatological positive zonal gradient of SST along the equatorial Indian Ocean (Fig. 5a) is also simulated in the RSM-ROMS (Fig. 5b), albeit, with the gradient being stronger in the latter. The systematic errors of SST in the RSM-ROMS show a warm bias across the eastern Indian Ocean and Gulf of Thailand and along the equatorial Indian Ocean (Fig. 5c).

The simulation of the mixed layer depth as diagnosed from the density profile (Monteguet et al. 2004) from RSM-ROMS is compared with corresponding seasonal climatology from Argo in Figs. 6a-c. The Argo observations clearly show the contrasting deeper mixed layer depths over the western AS and the shallower mixed layer depths along the equatorial Indian Ocean and BoB (Fig. 6a). The RSM-ROMS simulation in Fig. 6b picks this contrast rather weakly. This is largely on account of the underestimation of the mixed layer depth in the western AS (Fig. 6c). The depth of the thermocline as diagnosed by the depth of the 20°C isotherm shows that equatorial Indian Ocean has less heat content compared to AS and the BoB (Fig. 6d). This feature is replicated in the RSM-ROMS simulation (Fig. 6e). Furthermore, the AS displays a higher ocean heat content than the BoB (Fig. 6d), which is also demonstrated in the RSM-ROMS simulation (Fig. 6e). Although the bias of the excess heat content across the domain in the RSM-ROMS simulation is apparent (Fig. 6f).

In summary, the verification of the seasonal climatology shows the value addition of RSM-ROMS in downscaling a coarse resolution global reanalysis like R2. For example, the fine scale features of the topographic rainfall, contrast of the convective activity between ocean and land as witnessed from the relative distribution of frozen hydrometeors, reduction in the systematic bias of precipitable water over orographic features in addition to highlighting the contrasts of the upper ocean thermal contrast between the AS and BoB lays some of the foundation for arguing in favor of downscaling R2 reanalysis using RSM-ROMS for the SASM. By way of the inclusion of air-sea coupling in RSM-ROMS, a comprehensive and dynamically consistent dataset of the atmosphere and ocean is generated for the SASM that is otherwise available only for the atmosphere or for the ocean from the R2 or the SODA reanalysis products, respectively. We also show quantitatively, the fidelity of the SASM climatology in the RSM-ROMS simulation by way of the Taylor diagram in Fig. 7.

Fig. 7 shows that the pattern correlation coefficients of all the variables displayed are well over 0.69 for both over land and ocean except for mixed layer depth (0.45), which suggests that RSM-ROMS generally captures the spatial heterogeneity of the variables reasonably well. Similarly, the standardized variance is in the vicinity of 1.00 for majority of variables except for SST, precipitation,
and zonal wind at 850 hPa, again suggesting that the temporal variability of the variables at interannual scales is comparable to the corresponding observed values. The RMSE of the variables in Fig. 7 for both over land and ocean is a relatively small fraction of the total field shown earlier in Figs. 2-6. Although the RMSE is averaged across the domain. Even the moisture variables like precipitation and precipitable water, that have large spatial and temporal variations appear with reasonably small RMSE.

iii) Intraseasonal Variations

The intraseasonal oscillation with its quasi-periodic dry and wet spells is one of the iconic features of the ISM. Using the Multi-Channel Singular Spectrum Analysis (MSSA; Ghil et al. 2002) we extract the QBM at 10-20 day and BSISO modes at 20-70 day time scales after pre-filtering the daily anomalies of precipitation with a moving 5-day mean to remove very high frequency variability (Karmakar and Misra 2020). Additionally, a bootstrap technique to assess the statistical significance of the isolated ISO from 1000 red noise surrogates following Allen and Robertson (1996) is applied to the MSSA. To understand the evolution of the oscillation, a phase composite based on the phase angle of the space time empirical orthogonal functions and principal components from MSSA which lies in the range of 0 to 2\(\pi\) is equally divided into eight equal intervals. In the case of QBM and BSISO, each of the phase composites will have a duration between ~1.25 to 2.5 days and ~2.5 to 8.75 days, respectively.

The spatio-temporal evolution of the QBM in precipitation in terms of the phase composites derived from MSSA is shown from observations (Fig. 8a) and RSM-ROMS simulation (Fig. 8b) using the QBM signal area averaged over central India (16°N-26°N and 75°E-85°E). The first row of four panels (or the first four phase composites of QBM) in Fig. 8a indicate wet spell over BoB and central India replaced by a dry spell over the same region in the bottom row of four panels (or the last four phase composites of QBM) in Fig. 8a. Similarly, the wet and dry spells of the QBM are indicated in the phase composites of the RSM-ROMS simulation (Fig. 8b). The differences in the phase composite of the QBM in RSM-ROMS simulation from observations are apparent in the amplitude and location of the precipitation anomalies. For example, in Fig. 8b, the strongest wet and dry spell anomalies of precipitation are located over central India in contrast to the observed anomalies over the open waters of BoB. However, the peak amplitude of the anomalies is observed in Phases 2 and 3 for the wet and Phases 6 and 7 for the dry spell anomalies both in observations (Fig. 8a) and model simulation (Fig. 8b).

The meridional propagation characteristics of the QBM is highlighted by the Hovemöller (phase-latitude) diagram shown in Figs. 8c-f. Over the AS (zonally averaged between 65°E-75°E), the observations in Fig. 8c clearly indicate the northward propagation of QBM by the tilt of precipitation anomalies extending across latitudes. This northward propagation is faster over the AS (Figs. 8c and d) with the tilt of the anomalies being far more diminished relative to the prominent tilt signifying slower northward propagation over the BoB longitudes.
However, unlike the observations, the meridional propagation over the AS is over a shorter latitude span in RSM-ROMS (Fig. 8d) compared to observations (Fig. 8c) and the anomalies in BoB south of 12°N are much weaker in RSM-ROMS (Fig. 8f) compared to observations (Fig. 8e).

The phase composites of BSISO are shown in Figs. 9a and b, which are significantly stronger than the QBM composite anomalies (Figs. 8a and b). Once again, the phase composites in Figs. 9a and b are based on the BSISO signal area averaged over central India (16°N-26°N and 75°E-85°E). The propagation of the BSISO in the observations is apparent in Fig. 9a with Phases 1, 2, 3, and 4 marking essentially wet spell over the latitudes of the Indian subcontinent, southeast Asia while marking a dry spell over the Indian Ocean at latitudes south of ~8°N. In Phases 5, 6, 7, and 8 the precipitation anomalies change sign with wet spell south of 8°N and dry spell north of this latitude (Fig. 9a). The RSM-ROMS simulation produces these observed features of the BSISO in Fig. 9b with the amplitude of the anomalies slightly weaker than observations. The RSM-ROMS simulation also correctly shows the amplitude of the BSISO anomalies to be stronger than those of the QBM anomalies. An important feature of the BSISO is the northwest-southeast tilt, which is a result of the faster propagation of the convection anomalies in the AS relative to BoB (Karmakar and Misra 2020). This tilt in the BSISO anomalies is apparent both in the observations and in the RSM-ROMS simulation (Figs. 9a and b). The meridional phase propagation characteristics of the BSISO indeed indicate that the northward propagation over the AS longitudes (Figs. 9c and d) is faster than in the BoB (Figs. 9e and f). These propagation characteristics of the BSISO have been the “Achilles heel” for most climate models including the latest round of CMIP6 models (Konda and Vissa 2022). However, the simulation tends to significantly diminish the BSISO anomalies north of 20°N over the AS while extending robustly further north over BoB in comparison to observations.

iv) Monsoon Low Pressure Systems

LPS is a major component of the SASM, contributing nearly half of the total seasonal rainfall in large parts of South Asia (Hunt and Fletcher, 2019; Yoon & Chen, 2005). In South Asia, weaker LPS are typically called Monsoon Lows (ML; wind speeds about 8.5 m/s with one closed isobar of mean sea level pressure (MSLP)) and stronger ones are called Monsoon Depressions (MD; wind speeds are in the range 8.5-13.4 m/s with two or three closed isobars of MSLP at 2hPa interval). Typically, we observe about 14 LPS over the ISM of which, about 10 are ML, 2.5 are MD, and 1.5 are deep depressions (> 13.4 m/s with two or three closed isobars of MSLP at 2hPa interval; Sikka 2006). Hurley and Boos (2015) further revised these figures using ERA-Interim analysis (Dee et al. 2011) to suggest that on average during the ISM there are about 16 LPS with ~ 4 MD, and fewer than 1 deep depression. More recently, Vishnu et al. (2020) compared five other global reanalyses including ERA5. They noted some diversity in the LPS counts across reanalysis. But ERA5 was found to have closest match to the analysis of LPS following Sikka (2006). Furthermore, Vishnu et al. (2020)
notes an improvement in the seasonal cycle of the LPS in ERA5 relative to other reanalysis when verified with the seasonal cycle of LPS in Sikka (2006).

The TempestExtremes algorithm of Ullrich and Zarzycki (2016) is used to track the LPS from the ERA5 reanalysis and RSM-ROMS during June to September over the 25 year period from 1986 to 2010 (Fig. 10). We used data at 6-hourly interval for estimating the LPS track information. The LPS are detected based on the 850hPa geopotential criteria as mentioned in Vishnu et al (2020), in which they consider the ML/MD as a disturbance to have 850hPa geopotential that increases by 125 m$^2$s$^{-2}$ from the center minimum within a radius of 10° (Figs. 10a and b). Additionally, the tracks are considered only if it achieves an 850hPa relative humidity of at least 85% for at least 1 day (average of the 4-time steps of 6 hourly interval of data) and a surface geopotential of less than 8000 m$^2$s$^{-2}$. ML in Figs. 10d and e are categorized by further considering the 10-meter wind speeds, which are less than or up to 8.5 m/s with one closed isobar of MSLP. MD in Figs. 10g and h are further based on 10-m wind speeds greater than 8.5 m/s and with greater than two closed isobars of MSLP at 2hPa interval.

Over the 25 year period from 1986 to 2010, 366 and 307 LPS were detected with an average of 14.6 per season and 12.3 per season in ERA5 (Fig. 11a) and in the RSM-ROMS simulation (Fig. 10b), respectively. The track densities of the LPS in RSM-ROMS (Fig. 10b) shows the familiar northwest-southeast orientation extending from the head of BoB to northern India (Fig. 10a). However, RSM-ROMS simulation clearly underestimates LPS over the head of BoB and in the AS while overestimating over Northeastern Hills of India and over Myanmar (Fig. 10c). Similarly, the total number of ML were 227 and 156 with a seasonal average of 9.1 and 6.3 in the ERA5 (Fig. 10d) and in the RSM-ROMS simulation (Fig. 10e), respectively. The underestimation of the ML in the head of BoB, along the foothills of Himalayas and over AS in the RSM-ROMS simulation are apparent in Fig. 10f. The total number of MD in ERA5 is 139 with a seasonal average of 5.5 (Fig. 10g) and in RSM-ROMS simulation it is 151 with a seasonal average of 6.0 (Fig. 10h). The underestimation of the MD in the RSM-ROMS simulation is largely over the head of the BoB and in the AS with an overestimation along the foothills of Himalayas (Fig. 10i). But the relatively lower bias in the counts of MD compared to that of ML in the RSM-ROMS simulation suggests that the likelihood of ML becoming MD is much higher in the model, especially over central India. The underestimation of the LPS in head of BoB and in AS despite the warm bias of SST and relatively weak bias of the 850hPa winds in the RSM-ROMS simulation, could be related to errors in the zonal shear emanating from the westerly bias in the tropical easterly jet (not shown). The tropical easterly jet is weak in the R2 reanalysis that is further amplified in the RSM-ROMS simulation. The strong westward zonal wind shear of the SASM is found to be critical for the development of LPS (Goswami et al. 1980; Sandeep and Ajayamohan 2014; Praveen et al. 2015), which unfortunately happens to be comparatively weak in the RSM-ROMS simulation (not shown). Nonetheless, the verification of these statistics of the seasonal activity of the LPS
from the RSM-ROMS simulation is extremely encouraging given the disparity in reanalysis (Vishnu et al. 2020) and in global models (Praveen et al. 2015).

Several studies have indicated a dominating influence of the BSISO on the LPS (Yoon and Chen 2005; Chen and Weng 1999; Goswami et al. 2003; Krishnamurthy and Ajayamohan 2010; Karmakar et al. 2021). Krishnamurthy and Ajayamohan (2010) indicate that there are nearly twice as many LPS days during active relative to the break phases of the BSISO. In Fig. 11 we show the composite difference of the track density of the LPS between the wet and dry spells of the BSISO from ERA5 and the RSM-ROMS simulation. The wet and dry spells of BSISO are based on the eight phases from MSSA over central India from IMERG observations (2001-2020) and ERA5 data sets for the corresponding periods are used to develop the LPS composites in Figs. 11a-c. Similarly, a comparable 20 year period (1991 to 2010) from RSM-ROMS simulation are used to develop the composite track density of LPS in Figs. 11d-f based on the wet and dry phases of the BSISO. In both ERA5 and RSM-ROMS the wet spells of the BSISO produce a higher track density of LPS (i.e., a greater number of LPS per 1° x 1° grid) than in the dry spells over central India and over the head waters of BoB (Fig. 11). However, the model simulation displays a much smaller difference of the LPS track density between the wet and dry spells of the BSISO over BoB and AS compared to ERA5. This is largely because the model has a bias of producing far fewer LPS over the oceans than ERA5 (Fig. 10). Furthermore, the larger difference of the LPS track density between wet and dry spells of the BSISO is over central India in the model, which is further inland than in ERA5. But the negative difference of the track density along the foothills of the Himalayas suggesting higher LPS activity during the dry spell of the BSISO over central India is well simulated in the model.

5 Conclusion

Generating a 20 km rendition of the SASM climate from a 2.5° x 2.5° global reanalysis that hosts a variety of temporal variations across many spatial scales poses a stiff challenge. In this study RSM-ROMS, a regional coupled ocean-atmosphere model at 20 km grid spacing forced at the lateral boundaries with R2 atmospheric and SODA ocean reanalysis is assessed for its fidelity in simulating the features of the SASM. This paper highlights that at 20 km grid spacing, many of the topographic and bathymetric features of the domain appear realistic albeit with their gradients best approximated at the discretized resolution of the regional model. The RSM-ROMS simulation shows reasonable fidelity of the seasonal climate of SASM. Like, the sharp topographic features of rainfall, the contrast of the convective activity between largely warm rain process in the ocean and mixed warm and cold rain process over land as witnessed from the distribution of frozen and unfrozen hydrometeors and reduction in the systematic bias of precipitable water over orographic features relative to R2.

The coupling of the atmosphere to the ocean in RSM-ROMS provides the added benefit of resolving the air-sea interactions, which is considered very important for the simulation of the SASM. The RSM-ROMS simulation clearly displays fi-
delity in describing the large-scale patterns of the upper ocean thermal structure that is consistent with the atmospheric forcing. For example, the shallow mixed layer and warmer SST in the equatorial Indian ocean that receives significant precipitation with weak surface westerlies in contrast to the deeper mixed layer and colder SST in the western AS under drier conditions and strong southwes-
terlies are nicely replicated in the downscaled simulation.

The fidelity of the SASM mean climate in the RSM-ROMS simulation provides confidence to further examine the sub-seasonal scales and extremes (like LPS) of the SASM. The intraseasonal oscillations of the SASM has been a difficult challenge for many climate models to simulate given its two distinct timescales of the BSISO (20-70 days) and QBM (10-20 days), their robust propagation, and their influence on LPS. The RSM-ROMS simulation impressively reproduces all these features including the northwest-southeast tilt of the BSISO with a clear modulation of the LPS at the intraseasonal scales. The LPS of the SASM form in a high vertical shear environment and largely intensify inland, confounding usual theories of tropical cyclone development and reproduced in the RSM-
ROMS simulation.

The added value of the RSM-ROMS simulation of the SASM to the R2 global reanalysis is amply demonstrated in this paper. The intra-seasonal variations of the SASM and its defining features are important in defining their influence on the LPS. At 2.5° x 2.5°, the R2 reanalysis is simply too coarse to resolve the LPS and therefore the RSM-ROMS simulation clearly demonstrates its added value from permitting them at 20 km spatial resolution with reasonable season-
al statistics. However, the successful simulation of such mesoscale features by a regional climate model amidst a reasonable simulation of the large-scale, complex SASM climate is also a reason for the defining features of the intrasea-
sonal variations of the SASM to be simulated in RSM-ROMS. For example, the northwest-southeast tilt of the BSISO is associated with the northwestward track of the LPS (Karmakar and Misra 2020; Karmakar et al. 2021). Similarly, the contrast in convection between BoB and central India is associated with the strengthening and propagation of the LPS inland. Such intricate relationships are not discernible in R2 reanalysis on a 2.5° x 2.5° grid.

From this study, we show that this RSM-ROMS simulation would be an ideal platform to launch intensive diagnostic studies to understand the BSISO’s and their influence on LPS. Furthermore, given the fidelity of RSM-ROMS in simulating SASM as demonstrated from this work, future studies with RSM-ROMS forced with global model projections of the future climate would be of significant interest to understand the changes in some of these SASM features.

Acknowledgments

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Data Availability Statement
The IMERG rainfall from NASA was obtained from https://gpm.nasa.gov/data/directory. The NASA water vapor project’s precipitable water data was obtained from https://doi.org/10.5067/NVAP-M/NVAP_CLIMATE_LAYERED-PRECIPITABLE-WATER_L3.001. The ERA5 reanalysis data was from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, the mixed layer depth from Argo was obtained from http://mixedlayer.ucsd.edu/ and the SODA v2.2.4 ocean reanalysis data was obtained from https://iridl.ldeo.columbia.edu/SOURCES/.CARTON-GIESE/.SODA/.v2p2p4/?Set-Language=en. The data from the RSM-ROMS integration and analysis scripts necessary to generate the figures in the manuscript are available from vmisra@fsu.edu.

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**Figure Captions**

**Figure 1:** The regional domain of RSM-ROMS with bathymetry and topography (m) shown at 20 km grid spacing with the identification of some of the salient topographic and bathymetric features.

**Figure 2:** The climatological seasonal (May-June-July-August-September) mean precipitation (mm day$^{-1}$) from a) IMERG, b) RSM-ROMS, and c) R2 reanalysis and the corresponding systematic errors (mm day$^{-1}$) of d) RSM-ROMS and e) R2 reanalysis. Only statistically significant values at 95% confidence interval according to t-test is shaded in (d) and (e).

**Figure 3:** The climatological seasonal (May-June-July-August-September) mean precipitable water (kg m$^{-2}$) from a) ERA5, b) RSM-ROMS, and c) R2
reanalysis and the corresponding systematic errors of c) RSM-ROMS and d) R2 reanalysis. GBP in (a) is Gangetic-Brahmaputra Plains referred in the text. Only statistically significant values at 95% confidence interval according to t-test is shaded in (d) and (e).

**Figure 4:** The vertically integrated, seasonal mean (May-June-July-August-September [MJJAS]) climatology of the cloud water content (kg kg\(^{-1}\)) between (a) cloud base and freezing level and (b) between freezing level and cloud top from RSM-ROMS. The corresponding MJJAS climatology of lightning flashes from observations are shown in (c).

**Figure 5:** The climatological seasonal (May-June-July-August-September) mean SST (°C) from a) OISSTv2 and b) RSM-ROMS. c) The corresponding systematic errors from RSM-ROMS. Only statistically significant values at 95% confidence interval according to t-test is shaded in (d) and (e).

**Figure 6:** The climatological seasonal (May-June-July-August-September) mean depth (m) of the (a, b) mixed layer (d, e) 20°C isotherm from (a) Argo, (d) SODA reanalysis, and (b, e) RSM-ROMS. The corresponding systematic errors in the depth of the (c) mixed layer and the (f) 20°C isotherm from the RSM-ROMS simulation. Only statistically significant values at 95% confidence interval according to t-test is shaded in (f).

**Figure 7:** Taylor diagram of the 25-year climatology of May-September mean from RSM-ROMS simulation for precipitation (pr), precipitable water (pwat), zonal wind at 850 hPa (u850) and at 200 hPa (u200), meridional wind at 850 hPa (v850) and at 200 hPa (v200), for a) land points of the regional domain and b) additionally for SST, mixed layer depth (MLD), depth of the 20°C isotherm (20CIso) for ocean points of the regional domain. Here, IMERG, ARGO, and SODA are used as the reference data set for precipitation, MLD, and 20CIso, respectively. ERA5 is used as the reference dataset for the remaining variables. The values of the pattern correlation (PCC), ratio of the standardized variances of model to observations (Ratio), and root mean square error (RMSE) are tabulated.

**Figure 8:** The phase composite diagram of QBM precipitation anomalies (mm day\(^{-1}\)) based on April-October period from (a) IMERG and (b) RSM-ROMS. Stippled regions indicate anomalies are significant at 5% level using a randomization test following Allen and Robertson (1996). The phase composites are created using area averaged QBM signal over central India (16°N-26°N and 75°E-85°E). The Hovmöller diagram showing the propagation of the precipitation anomalies of the 10-20 days QBM over (c, d) Arabian Sea (AS; zonally averaged between 65°E-75°E) and (e, f) Bay of Bengal filtered (zonally averaged between 85°E-95°E) from (c, e) IMERG and (d, f) RSM-ROMS simulation.

**Figure 9:** The phase composite diagram of BSISO precipitation anomalies (mm day\(^{-1}\)) based on April-October period from (a) IMERG and (b) RSM-ROMS. Stippled regions indicate anomalies are significant at 5% level using a randomization test following Allen and Robertson (1996). The Hovmöller
diagram showing the propagation of the precipitation anomalies of the BSISO over (c, d) Arabian Sea (AS; zonally averaged between 65°E-75°E) and (e, f) Bay of Bengal filtered (zonally averaged between 85°E-95°E) from (c, e) IMERG and (d, f) RSM-ROMS simulation.

**Figure 10**: The track density of the Monsoon Low Pressure Systems (LPS) during June to September measured as number of LPS per 1° x 1° grid as diagnosed from a) ERA5, b) RSM-ROMS simulation, and c) the corresponding bias of RSM-ROMS over the period of 1986-2010. Similarly, the track density of Monsoon Lows (ML) from d) ERA5, e) RSM-ROMS, and f) corresponding bias of RSM-ROMS. The track density of Monsoon Depressions (MD) from g) ERA5, h) RSM-ROMS, and i) the corresponding bias of RSM-ROMS. The inset table in (a, b, d, e, g, and h) provide the seasonal statistics of the total number (Total) of LPS, Monsoon Lows (ML), Monsoon Depressions (MD) and their seasonal average (Avg).

**Figure 11**: The composite track density of the Monsoon Low Pressure Systems (LPS) measured as number of LPS per 1° x 1° grid for (a, d) wet spells and (b, e) dry spells of the BSISO and their corresponding difference (c, f) wet-dry from (a, b, c) ERA5 and (d, e, f) RSM-ROMS simulation.
Supplementary Material

The Value Addition of Dynamic Downscaling the South Asian Summer Monsoon from a Global Reanalysis using a Regional Coupled Ocean-Atmosphere Model

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### Table S1: Details of the verification datasets used in the study

<table>
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<tr>
<th>Variable</th>
<th>Source</th>
<th>Purpose</th>
<th>Spatial resolution</th>
<th>Period used in the study</th>
</tr>
</thead>
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<td>Rainfall</td>
<td>IMERG (Huffmann et al. 2019)</td>
<td>Verification of seasonal mean, interannual and intraseasonal variations over both land and ocean</td>
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<tr>
<td>Lightning strokes</td>
<td>WWLLN</td>
<td>Verification of frozen precipitable water</td>
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<tr>
<td>Upper air variables</td>
<td>ERA-5 (Hersbach et al. 2019)</td>
<td>Verification of seasonal mean 850hPa winds, precipitable water</td>
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<tr>
<td>SST</td>
<td>OISSTv2 (Reynolds et al. 2007)</td>
<td>Verification of seasonal mean SST and rainfall-SST relationship</td>
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<td>Mixed layer depth</td>
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<td>Verification of seasonal mean mixed layer depth</td>
<td>1° x 1°</td>
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<td>Depth of the 20°C isotherm in the ocean</td>
<td>SODA reanalysis (Carton and Giese 2008)</td>
<td>Verification of the depth of the seasonal mean 20°C</td>
<td>0.5° x 0.5°</td>
<td>1986-2010</td>
</tr>
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Figure S1: The climatological seasonal (May-June-July-August-September) mean 850hPa winds (m s\(^{-1}\)) from a) ERA5, b) RSM-ROMS, and c) R2 reanalysis. The corresponding systematic errors from c) RSM-ROMS and d) R2 reanalysis. Only statistically significant values at 95% confidence interval according to t-test is shown in (d) and (e).