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Current Trends in the Representation of Physical Processes in Weather and Climate Models

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Editors

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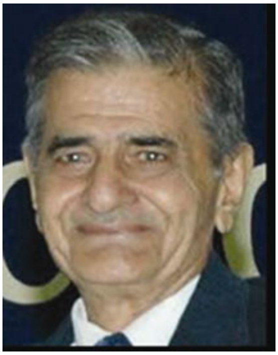

Dev Raj Sikka
(former Director, Indian Institute of Tropical Meteorology, Pune)
(1932–2017)

Foreword

An international workshop on ‘Representation of Physical Processes in Weather and Climate Models’ at IITM, Pune, India, on 13–16 February 2017 was an event of great significance for many reasons. First of all, there is an urgent national need for improving monsoon rainfall forecasts, as monsoon rainfall plays a big role in determining the country’s agricultural production and hence also its gross national product and the state of its economy. There are other related reasons too: droughts, storms and cyclones can cause much destruction, to both human and material. Secondly, the recent availability of much higher computing power for weather forecasting enables Indian scientists now to set their goals higher and expect that the quality of forecasts will have a significant improvement in the near future. Thirdly, there is a great deal of research going on elsewhere in the world that is potentially of immediate relevance to the monsoons, and a detailed discussion of these advances, in India and abroad, can be most useful in identifying newer lines of attack that hold promise.

From these and other points of view, INTROSPECT 2017 appears to have been a very successful meeting. I was unfortunately unable to be present at the meeting, but the availability of material that one can examine on the net has been a great help. The final recommendations made during the panel discussion on 16 February 2017 provide a very useful collection of comments and suggestions made at the meeting by the participants, including specific proposals for future action. These have dealt with a variety of issues, including what kinds of data are currently available and what else needs to be measured or acquired, what new facilities would be required and how one may proceed about it, what frequency of observations is best and other related matters.

The value of collaboration, both within India and with foreign agencies and scientists, was rightly emphasized at the workshop. An annual meet in India would be useful for assessing any improvements in model fidelity since the previous meet. Global inter-comparisons would be valuable, and model outputs should be available, especially to the academic community, to analyse the implications of inter-comparison results. The emphasis on these issues shows how important they are for further progress.

An interesting point that came up during the panel discussion showed concern that, for the limited number of modelling experts India has, perhaps we are using too many modelling and data assimilation tools. Dr. Bechtold felt that two models should really be enough (GFS and UKMO), along with their data assimilation systems. A related question was about whether India should have its own model. Prof. Kinter pointed out that there is no need to start from scratch and it would be better to improve some other model known to be well documented and validated.

At the end, there were a set of unanimous recommendations. One of these was for the formation of a Web-based consortium that would keep MoES institutions and interested academic groups in touch with each other, exchange ideas, have dialogues, etc. An annual workshop in which all model developers in India could get together for discussions and exchange of views is another recommendation. The title for the present meeting, namely INTROSPECT 2017, already implies that more such meetings are intended; it was suggested that a two-to-three-year period between successive meetings might be about right. An advisory committee involving global experts on weather and climate modelling can play a useful role in improving the efforts in India.

It is clear that the 2017 workshop was most effective and successful; it can be a landmark in the history of Indian meteorology if the recommendations at the workshop are all followed. I must congratulate MoES, IITM and all the others, particularly those from abroad, who made the meeting so interesting and useful. It has the potential to trigger systematic and substantial progress in Indian efforts to improve monsoon forecasting in the not too distant future.

Bengaluru, India
February 2018

Roddam Narasimha
Jawaharlal Nehru Centre for
Advanced Scientific Research

Preface

An International Workshop on “Representation of Physical Processes in Weather and Climate Models (INTROSPECT)” was held during 13–16 February 2017 at the Indian Institute of Tropical Meteorology in Pune, India. The workshop focused on the significant advancements made in the field of numerical weather prediction models and the challenges ahead. It brought together eminent scientists from across the globe to discuss the plausible future developments in the representation of unresolved physical processes in high-resolution models. A large number of masters and doctoral students and early career scientists attended the lectures and participated in the tutorial sessions conducted by the senior experts. All the talks and presentations were live-streamed and later uploaded in the website (https://www.tropmet.res.in/introspect/) and IITM youtube. The workshop ended with a consensus recommendation on the representation of physical processes in numerical models which can serve as guidelines for future developments in parameterization of physics in high-resolution weather prediction models. Most of the presentations in INTROSPECT are compiled in this book. The editors thank the authors of each chapter for their excellent summaries of their talks. We hope that this book will be an important reference for students and researchers in the coming decade.

Fort Collins, USA — Prof. David A. Randall
Bengaluru, India — Prof. J. Srinivasan
Pune, India — Prof. Ravi S. Nanjundiah
Pune, India — Dr. Parthasarathi Mukhopadhyay
26 January 2019

Acknowledgements

The convener and organizer of INTROSPECT 2017 gratefully acknowledge the encouragement, guidance and advice of Dr. M. Rajeevan, Secretary, Ministry of Earth Sciences (MoES), Government of India, in organizing the workshop. We are grateful to Director, IITM, Pune, for all the advice and support for organizing the workshop. MoES, Government of India, is thankfully acknowledged for the financial support and all other logistic clearances. We express our gratitude to Dr. Roddam Narasimha for kindly agreeing to write the Foreword of the book. Our special thanks to Dr. R. Krishnan for constant encouragement and support to organize the workshop. We are grateful to all the speakers and authors of the chapters for their valuable contribution. We express our thanks and gratitude to the editors of the book.

Contents

About the Editors

Prof. David A. Randall received his Ph.D. in atmospheric sciences from the University of California, Los Angeles, in 1976. He served as Faculty Member in the Department of Meteorology, Massachusetts Institute of Technology, from 1976 to 1979. Subsequently, he served as Meteorologist at the Global Modeling and Simulation Branch, NASA Goddard Space Flight Center (1979–1988). Since 1988, he has been a member of the faculty in the Department of Atmospheric Science, Colorado State University, where he is currently University Distinguished Professor. He has received prestigious awards including the Jule Charney Award from the American Meteorological Society, 2014; Coordinating Lead Author for the Fourth Assessment of the Intergovernmental Panel on Climate Change, which shared the 2007 Nobel Peace Prize; Fellow, American Geophysical Union, 2002; NASA's Medal for Distinguished Public Service, 2006; the Meisinger Award from the American Meteorological Society, 1994; NASA's Medal for Exceptional Scientific Achievement, 1988; and Fellow, American Meteorological Society, 1986. He has published more than 230 peer-reviewed research papers and 2 books.

Prof. J. Srinivasan is currently Distinguished Scientist at Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru. He received his Ph.D. from Stanford University and then worked as a member of faculty in the Department of Mechanical Engineering, IIT Kanpur, until 1982, when he joined the Department of Mechanical Engineering, Indian Institute of Science, Bengaluru. He worked as NRC Senior Resident Research Associate for NASA in Langley, Virginia, USA, from 1993 to 1995. He subsequently served as Chairman of the Centre for Atmospheric and Oceanic Sciences (1996–2005) and as Chairman of the Mechanical Sciences Division, Indian Institute of Science, Bengaluru (2005–2009). He established the Divecha Centre for Climate Change, Indian Institute of Science, Bengaluru, in 2009 and was its Chairman until 2016. His research interests include monsoon models, monsoon variability, simple climate models, satellite meteorology and renewable energy. He served as Lead Author on the IPCC's Fourth and Second Assessment Reports and as Review Editor on its Third Assessment Report. He is Fellow of Indian Academy of Engineering, Indian National Science Academy, Indian Academy of Sciences and Indian Meteorological Society and has published 140 research papers in peer-reviewed journals.

Ravi S. Nanjundiah received his Doctor of Philosophy in atmospheric sciences from the Indian Institute of Science, Bengaluru, India, in 1992. He worked as Postdoctoral Fellow in the Computer Hardware, Advanced Mathematics and Model Physics (CHAMMP for studying global change) project at the Mathematics and Computer Science Division of Argonne National Laboratory from 1993 to 1995. He has been Faculty Member of the Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, since 1995. He served as Chairman, Centre for Atmospheric and Oceanic Sciences, from 2013 to 2017. Since March 2017, he has been Director of the Indian Institute of Tropical Meteorology, Pune, India. He served as Associate Editor for the Journal of Earth System Sciences (published jointly by the Indian Academy of Sciences, Bengaluru, and Springer) from 2008 to 2014. He was awarded the Sir C. V. Raman Young Scientist Award for the year 2000 in the field of earth sciences and the NVIDIA Innovation Award for the year 2013. He has published over 75 papers in peer-reviewed journals.

Dr. Parthasarathi Mukhopadhyay is currently working as Senior Scientist at IITM, Pune, India. He received his Ph.D. from Savitribai Phule Pune University in 2005 and has since worked extensively in the fields of numerical modelling of mesoscale systems, thunderstorms and tropical cyclones. He has particularly contributed to the development of cloud and convective processes in numerical models. He was awarded the Silver Jubilee Award from IITM, Pune, for the best research paper in 2002 and 2010 and has received the Ministry of Earth Science's Certificate of Merit for outstanding contributions in Atmospheric Science and Technology in 2015. As Adjunct Professor in the Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, he has published 46 papers in peer-reviewed journals.

Model Systematic Errors in the Annual Cycle of Monsoon: Inferences from Process-Based Diagnostics

H. Annamalai

Abstract Forecasting monsoon rainfall using dynamical climate models has met with little success, partly due to models' inability to represent the monsoon precipitation annual cycle accurately. Here, we review and examine the nature and dynamical causes of their biases. We discuss the coupled nature of the monsoon annual cycle from observations and then present errors in multi-model-mean, climatological fields of ocean–atmosphere variables determined from CMIP5. We argue that in CMIP-era models, there is a spatial redistribution in the organization of convection, and precipitation biases are longitudinally oriented with "wet-west" and "dry-east" over the tropical Indian Ocean, with wet (dry) biases prominent over the climatological dry (wet) regions. Irrespective of resolutions and varied physical parameterizations employed in CMIP-era models, the robustness in the biases across the suite of models suggests that multiple processes and their interactions lead to these persistent errors. We review recent literature that addressed the source(s) of model errors and indicate the importance of examining both atmospheric and oceanic fast processes. After discussing the unique nature of observed convection peak during May over the western Indian Ocean, we demonstrate through idealized experiments, how errors in the representation of ocean–atmosphere feedbacks along the equatorial Indian Ocean impact monsoon precipitation errors. We apply process-based diagnostics to identify the relative role of moist and radiative processes and show how systematic errors in certain parameterizations could anchor model biases in precipitation. Despite devoted efforts by the model development teams, persistence of model errors leads us to ask: are there fundamental limits to realistically simulating the monsoon annual cycle? Can a concerted observational and modeling effort enhance models' fidelity in simulating the monsoon? We summarize the pertinent issues on modeling, and limitations on observations to constrain model physics, and stress the need for coordinated activities across diagnostics, modeling, and observational personnel.

Keywords Systematic errors · Processes representation · Fundamental limits

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1 Introduction

a. Background

In South and Southeast Asia, farming and agriculture-related markets employ about two-thirds of the workforce, and therefore, the seasonal-mean monsoon precipitation during boreal summer and winter seasons exerts significant impacts on socioeconomic conditions in the region, particularly with long-lasting imprints on small-scale farmers during years of consecutive drought-like conditions. As such on timescales of days-to-seasons, demands for accurate prediction of spatial distribution of precipitation are increasing. However, skill in spatial average (not to mention spatial distribution) of monsoon precipitation prediction by dynamical climate models remains low (Del Sole and Shukla 2002). One attribution to this low skill is model errors or biases in simulating monsoon annual cycle (Sperber et al. 2013; Annamalai et al. 2017). Identifying the source(s) of model errors and suggesting pathways for model improvements have been very demanding and challenging.

In the past few decades, concerted research from observations, sensitivity experiments with modeling and theory has demonstrated that monsoon results from complex (and yet unknown) interactions among the ocean, atmosphere, and land components of the climate system. Despite focused efforts by model development teams, realistic simulation of the monsoon annual cycle, particularly precipitation characteristics, has met with slow progress. Compared to observations, Fig. 1 summarizes the multi-model-mean (MMM) errors or biases in precipitation (ΔP) over the Asian-Australian monsoon region throughout the annual cycle. Here, biases or errors are defined by differences between the MMM fields from a suite of Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Taylor et al. 2012) and observations. The spatial patterns as well as amplitude of these errors have been persisting for over a decade (Sperber et al. 2013) suggesting that model limitations in multiple processes and their interactions lead to these systematic errors (Annamalai et al. 2017). Briefly, wet bias is noted over the southern tropical Indian Ocean with a local maximum centered at 60°E, and during the course of the annual cycle, the pattern is meandering between 15°S and 10°N. During boreal summer, the structure of the wet bias is prominent all along the low-level climatological cross-equatorial flow path (Annamalai et al. 2017) with the bias core situated over the western Arabian Sea. As regards dry bias, prominent patterns include: (a) the monsoon trough extending from the Indian subcontinent into the central-northern Bay of Bengal during boreal summer, (b) the eastern equatorial Indian Ocean (EEIO) during boreal fall and winter, and (c) parts of Bay of Bengal during all seasons. Compared to observations, modeled wet bias is persistent over the near-equatorial western-southern Indian Ocean, a region that is climatically "dry", and the dry bias is prominent in climatically "wet" spots. In summary, there is a spatial redistribution in convection over the tropical Indian Ocean, and can we identify model processes that cause it?

Identifying the cause(s) for model biases, however, is difficult to assess because intricate interactions among ocean, atmosphere, and land components are recognized to anchor the monsoon; as a result, misrepresentation of a process in one component

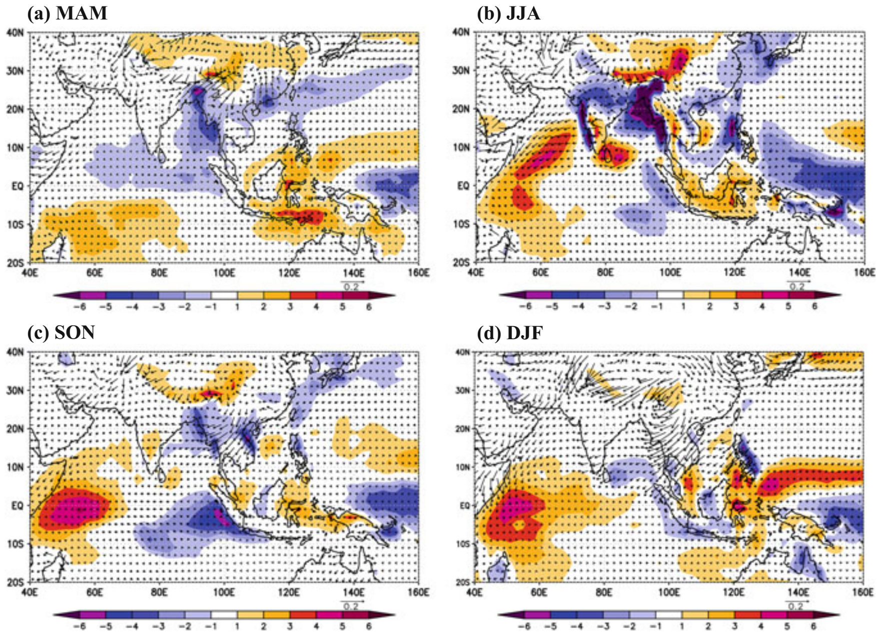

Fig. 1 Seasonal mean climatology difference between CMIP5 multi-model-mean (MMM) and observations of precipitation (shaded, mm/day) and wind stress (N/m^2): **a** March–May; **b** June–August; **c** September–November; and **d** December–February. Reference vector is also given

can lead to errors in other components. Further, in a coupled system, errors generated in one season can amplify due to differing background condition and also persist throughout the annual cycle (Sect. 3). An indicator of the difficulty of the problem is that such model errors have persisted for the last decade, despite considerable efforts to eliminate them.

b. Present study

In this chapter, first we present and discuss the coupled nature of the tropical Indian Ocean-monsoon climate systems, and highlight the role of large-scale air–sea interactions in shaping monsoon precipitation. Second, we discuss the systematic model biases in ocean–atmosphere variables pointing out how errors in one model component could cascade into another. Third, we review recent publications that identify the possible source(s) of model errors, and emphasize the need for realistically representing the coupled processes along the equatorial Indian Ocean (EIO), with particular focus on the oceanic processes during intermonsoon (April–May and October–November) seasons. Fourth, we apply process-based diagnostics specifically vertically integrated moisture and moist-static energy (MSE) budgets to CMIP5 MMM solutions to identify the representation of adiabatic (advection) and diabatic (fluxes of radiation, sensible, and latent heat) sources in priming column MSE. We examine if the error sources are seasonally invariant and ascertain if ΔP are entirely due to ΔSST or not. Finally, we close the chapter by stressing the need for sustained observations of dynamics and thermodynamics of atmosphere and ocean systems to constrain model physics for improved representation of processes that are expected to improve simulation of the monsoon annual cycle.

2 Coupled Nature of the Monsoon—Tropical Indian Ocean Climate Systems

In this section, after summarizing the salient observational aspects of the monsoon annual cycle (Sect. 2.1), we identify coupled ocean–atmosphere processes that anchor the precipitation annual cycle over the tropical Indian Ocean (Sect. 2.2).

2.1 Monsoon Annual Cycle

To a first order, monsoon annual cycle can be viewed as "primarily driven by the seasonal displacement of the Intertropical Convergence Zone (ITCZ), which is anchored by the north-south migration of the Indo-Pacific warm pool (regions where SST is >28 °C)." Figure 2a, b plot observed climatology of SST (contours) and precipitation (color shading) during boreal summer and winter. "During winter, the ITCZ is 'zonally elongated' and resides around the equatorial latitudes while it is 'diagonally oriented' during summer, stretching from central India to the tropical western Pacific. During both seasons, there is intense rainfall (>8 mm/day) only in regions where SST is high (>28 °C), suggesting the latter is a necessary condition for the former (e.g., Graham and Barnett 1987)." The SST/precipitation relationship, however, is not one-to-one, indicating that other factors such as moisture availability in the atmosphere, tropospheric stability (Raymond 2000) and cloud-radiative feedbacks (Stephens et al. 2008) collectively determine column water vapor (CWV) that subsequently impact rainfall intensity (Bretherton et al. 2004; Bretherton 2007). *Do the CMIP-era models realistically represent the processes that determine CWV?* The difficulty lies in the fact that processes involved in priming CWV, amongst others, are moisture–convection, and cloud–radiation feedbacks that are a consequence of convection themselves. Furthermore, orography–flow interactions also contribute to rainfall intensity. More importantly, there are regional differences in the SST/precipitation relationship between the tropical Indian Ocean and west Pacific. *Do climate models capture these regional aspects and represent the diagonally oriented ITCZ during boreal summer?*

Annamalai et al. (2017) note that "during winter (summer), despite southward (northward) displacement of the thermal equator, SST over the Bay of Bengal (Equatorial Indian Ocean) remains warm with values around 28 °C, suggesting the role of oceanic processes in its maintenance. Important aspects of these oceanic pro-

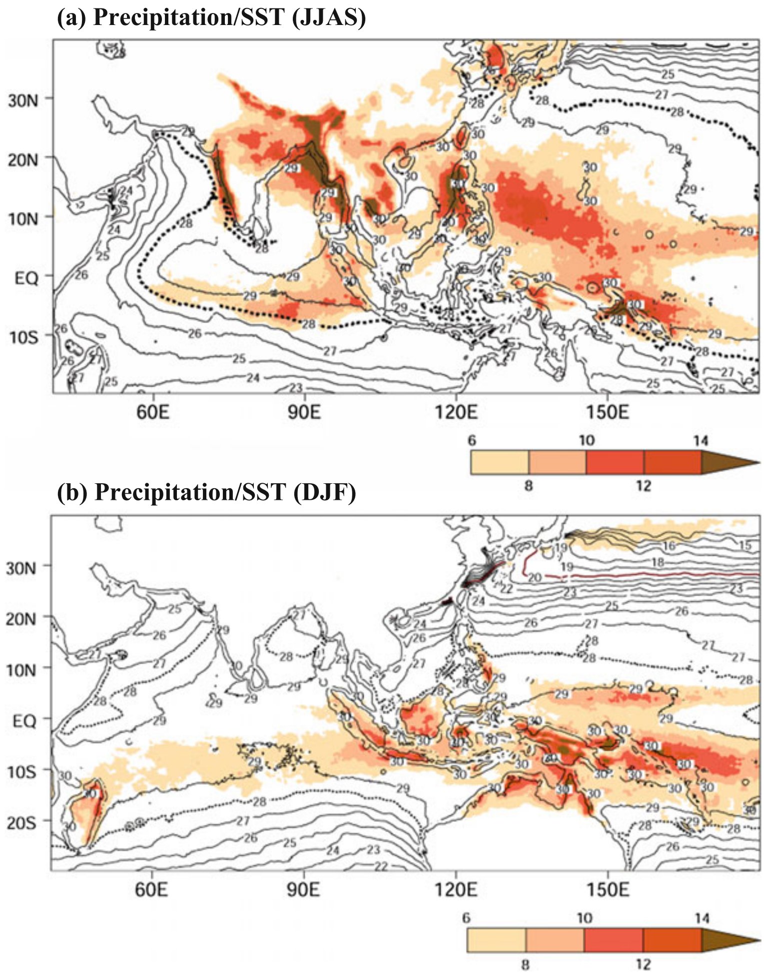

Fig. 2 **a** Boreal summer (June–September) climatology of precipitation (shaded; mm/day) and SST (contours; °C) constructed from TRMM/TMI products (1998–2015), and **b** same as (**a**) but for the boreal winter (December–February) season

cesses, such as upper-ocean stratification and equatorial eastward flowing Wyrtki Jets (WJs)," and their impacts on SST evolution are discussed next.

2.2 *Ocean–Atmosphere Interactions in Shaping Monsoon Precipitation*

In the northern Indian Ocean, there is a remarkable east–west asymmetry in SST and precipitation during the monsoon (Fig. 2a), which to a large extent results from ocean processes. Just prior to the monsoon, SST is the warmest of all the tropical oceans throughout the northern Indian Ocean (Joseph 1990). During the monsoon, there is an intense upwelling of cold water along the Somali and Omani coasts driven by the cross-equatorial low-level (Findlater) jet, and SST drops to about 23–24 °C. Subsequently, horizontal advection by ocean currents, in conjunction with evaporative cooling, cools SST in the central Arabian Sea (McCreary et al. 1993) and these processes limit the westward extension of the warm pool. During summer, SST cooling in conjunction with descent forced by Bay of Bengal convection weakens the rainfall over the Arabian Sea. During winter, lack of upwelling along the Somali and Omani coasts leads to SST being warmer there (Fig. 2b) than during the summer. In Sect. 5.1, we will show how a weakened monsoon circulation in CMIP5 models could be attributed to the modeled wet bias over the western Arabian Sea (Fig. 1b) during summer.

In contrast, SST over the Bay of Bengal remains high because upwelling along the east coast of India is weak or absent (McCreary et al. 1993), and rainfall is much stronger there resulting in upper-ocean salinity and temperature stratifications (Shenoi et al. 2002; Seo et al. 2009). During winter, cold and dry northeasterly monsoon winds are directed away from the Asian continent and due to excessive surface cooling, SST drops to <27 °C over the northern Arabian Sea but remains warm (~28 °C) over the Bay of Bengal (Fig. 2b). The near-surface stratification is impacted locally by the surface freshwater flux (precipitation and river runoff) and remotely through advection. The freshwater thins the surface mixed layer and generates a barrier layer that prevents the entrainment of cold subsurface waters (Lukas and Lindstorm 1991). Furthermore, solar radiation can penetrate the mixed layer to warm the barrier layer, thereby generating temperature inversions (Sengupta and Ravichandran 2001). The maintenance of time-mean SST during winter and spring anchors the ensuing summer monsoon. Observing and modeling details of the thin mixed-layer, upper-ocean stratifications in temperature and salinity, and their collective impact on SST evolution remains a grand challenge (Annamalai et al. 2018).

Quoting from Annamalai et al. (2017), "The equatorial Indian Ocean (EIO) differs from the other equatorial oceans in that it lacks trade winds, owing to the strong atmospheric convection over the eastern EIO and Maritime Continent (Fig. 2a, b). As a consequence, the EIO experiences semiannual westerly winds during the intermonsoon periods when the ITCZ crosses the equator, with a stress magnitude of about 0.4 N/m^2. They force the eastward-flowing WJs (Wyrtki 1973), which attain velocities of the order of 80 cm/s near the surface (Han et al. 1999; Fig. 5a). The WJs carry mass and heat from the western to the eastern EIO and are instrumental in maintaining the warm pool over the eastern EIO (Rao and Sivakumar 2000), so that even during summer warm and wet conditions prevail over the eastern EIO (Fig. 2a).

The WJs are predominantly forced by the near-equatorial winds but modeling studies suggest that salinity-induced barrier layer increases the jet speed by trapping the wind momentum in a thinner mixed layer (Han et al. 1999; Masson et al. 2003). Note that over the eastern EIO, precipitation occurs all year round (Fig. 2). A few points of interest are: (i) during the annual cycle, Bjerknes' feedback occurs along the EIO in which WJs are an important component (Annamalai et al. 2017) and (ii) WJs maintain eastern EIO warm pool that promotes local precipitation that in turn creates a salinity-induced barrier layer, an important process to increase WJ speed itself." We will show that misrepresentation of EIO processes could lead to systematic biases in ocean–atmosphere variables over the tropical Indian Ocean including the dry bias over South Asia during boreal summer (Sects. 4 and 5).

In contrast to the seasonal reversal in the winds over the northern Indian Ocean, the southern Indian Ocean experiences southeasterly trades throughout the annual cycle, and the wind stress curl between the south easterlies in the southern Indian Ocean and westerlies along the EIO implies an upwelling zone between 15°S and 5°S (McCreary et al. 1993) resulting in a shallow thermocline over the southwest Indian Ocean (SWIO; Xie et al. 2002), termed "thermocline ridge". Quoting Xie et al. (2002), "In the tropical oceans, wind-induced upwelling combined with a shallow thermocline results in a minimum in climatological SST and reduced precipitation, features noticeable along the thermocline ridge (Fig. 2a, b)." Nagura et al. (2013) showed that errors in wind stress ($\Delta\tau$; Fig. 1) are the primary candidates for the biases in modeled thermocline ($\Delta D20$), a finding discussed in Sect. 3. Interannual variations in the monsoon onset date are linked to variations in boreal spring SST over the ridge region through their impacts on the poleward migration of the ITCZ (Annamalai et al. 2005), particularly during years after the peak phase of El Niño when fluctuations in thermocline depth and SST are strongly coupled (Xie et al. 2002).

Atmospheric convection, through its effect on the vertical distribution of diabatic heating, influences surface winds that determine oceanic mixed-layer and thermocline processes, and subsequently SST. While high-mean SST through its impact on surface fluxes and CWV is a necessary condition for the occurrence of monsoon convection, in regions of high-mean precipitation such as Bay of Bengal and EEIO, freshwater-forced upper-ocean stratification impacts, perhaps determines SST (Shenoi et al. 2002; Seo et al. 2009). In summary, large-scale air–sea interactions play an active role in the monsoon precipitation annual cycle.

3 Persistent Model Errors over the Asian-Australian Monsoon Region

Here, we begin with a discussion of biases in seasonal-mean ΔP and $\Delta\tau$ over the broader Asian-Australian monsoon (Sect. 3.1) followed by discussions of biases in ocean variables (Sect. 3.2). Then, we interpret the biases in the EIO coupled system (Sect. 3.3).

3.1 Precipitation and Wind Stress Errors

As mentioned in Sect. 1a, in CMIP-era models, there is a spatial redistribution in the organization of convection and precipitation: biases are aligned "wet-west and dry-east" over the tropical Indian Ocean latitudes (15°S–20°N). The wet bias is strongest during fall and winter seasons while the dry bias peaks during summer. Over the annual cycle, the modeled wind stress (also winds in the lower troposphere extending from 1000 to 700 hPa—not shown) shows easterly bias over the northern Indian Ocean extending into parts of South China Sea, with stronger intensity during boreal summer (Fig. 1b) and winter (Fig. 1d) seasons. Easterly bias prevails along the near-equatorial central-eastern Indian Ocean throughout the year with a peak during boreal fall season (Annamalai et al. 2017; Fig. 7a). Over the southern Indian Ocean, modeled southeast trades are also weaker throughout the annual cycle.

In a broader view, the wet-west is dynamically connected with the dry-east by wind biases. For example, the near-equatorial easterly $\Delta\tau$ bias is interpreted as a Kelvin-wave response to positive ΔP over the western EIO (Fig. 1c), and the northeasterly bias associated with anticyclonic circulation features over the northern Indian Ocean is interpreted as a Rossby wave response to negative ΔP over the Bay of Bengal (Fig. 1b). Indeed, irrespective of resolutions and physical parameterizations employed, in almost all CMIP5 models, ΔP and $\Delta\tau$ are robust. It should be mentioned here that dry ΔP noted in boreal summer over the Bay of Bengal (Sperber et al. 2013) is not unique to summer but prevails during all seasons with varying strength (Fig. 1).

Throughout the year, modeled rainfall is stronger over the marginal seas of the Maritime Continent region (10°S–10°S; 100°–140°E), and wet ΔP maximizes in spring with signatures of westerly $\Delta\tau$ (Fig. 1a). During fall and winter seasons, dry ΔP prevails over the island chain of Borneo and Java. Dry ΔP is noted off Philippines for most of the annual cycle. In summary, "wet" bias over the marginal seas and "dry" bias over land are prominent features over the Maritime Continent.

Over the tropical western Pacific longitudes 140°–160°E a latitudinally oriented ΔP pattern, "wet-north and dry-south", is evident. In all seasons, modeled East Asian monsoon front extending from the Korean peninsula to Japan is weaker with dry bias peaking during spring (Fig. 1a). During winter season ΔP is weakly wet over northern Australia (Fig. 1d) but in all seasons and centered on 140°E northerly $\Delta\tau$ is noted. While the dynamical linkage between ΔP and $\Delta\tau$ biases are consistent over the tropical Indian Ocean, for reasons unclear, such linkages are not evident over the tropical western Pacific and Maritime Continent regions.

3.2 SST and Thermocline Depth Errors

While there are both wet and dry ΔP patterns (Fig. 1), throughout the domain (with few exceptions) modeled errors in SST (ΔSST, Fig. 3) and depth of the thermocline ($\Delta D20$, Fig. 4) are cold and deep, respectively. In regions where variations in ther-

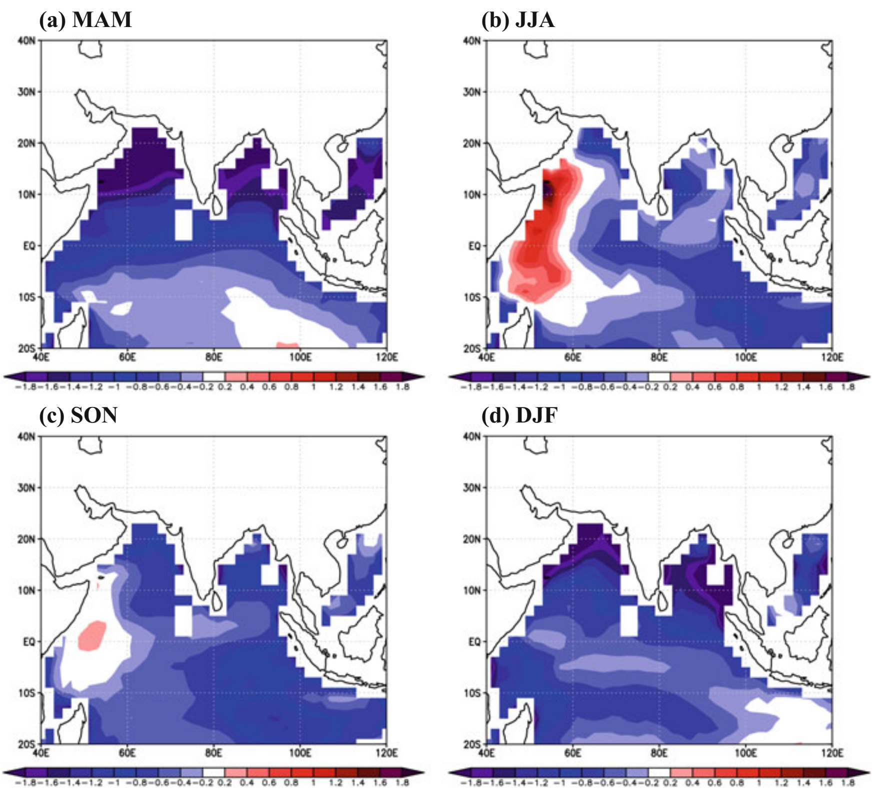

Fig. 3 Seasonal mean climatology difference between CMIP5 multi-model-mean (MMM) and observations of SST (°C): **a** March–May; **b** June–August; **c** September–November; and **d** December–February

mocline depth are known to impact SST, biases in them are physically consistent. They include warm ΔSST and deeper ΔD20 over the western EIO during fall, and along the Somali and Omani coasts during summer, and shallow ΔD20 and cold ΔSST over the EEIO during fall, and weakly positive or near-normal ΔSST along the thermocline ridge over the SWIO.

In CMIP-era models, persistence of northern Indian Ocean ΔSST, particularly those over the Arabian Sea is attributed to model biases in the simulation of winter monsoon circulation (Fig. 1d; Levine et al. 2013; Sandeep and Ajayamohan 2014) while the western Indian Ocean ΔSST during summer and fall seasons is attributed to weakened equatorial WJs during intermonsoon seasons and summer monsoon circulation (Annamalai et al. 2017), issues further discussed in Sect. 3.3. For the cold ΔSST over the Arabian Sea, our interpretation is that the wet ΔP over the near-equatorial southern Indian Ocean during boreal winter (Fig. 1d) forces a stronger local Hadley-type circulation with descent over the subtropical latitudes whose return low-level flow advect cold continental air, leading to excessive surface cooling over

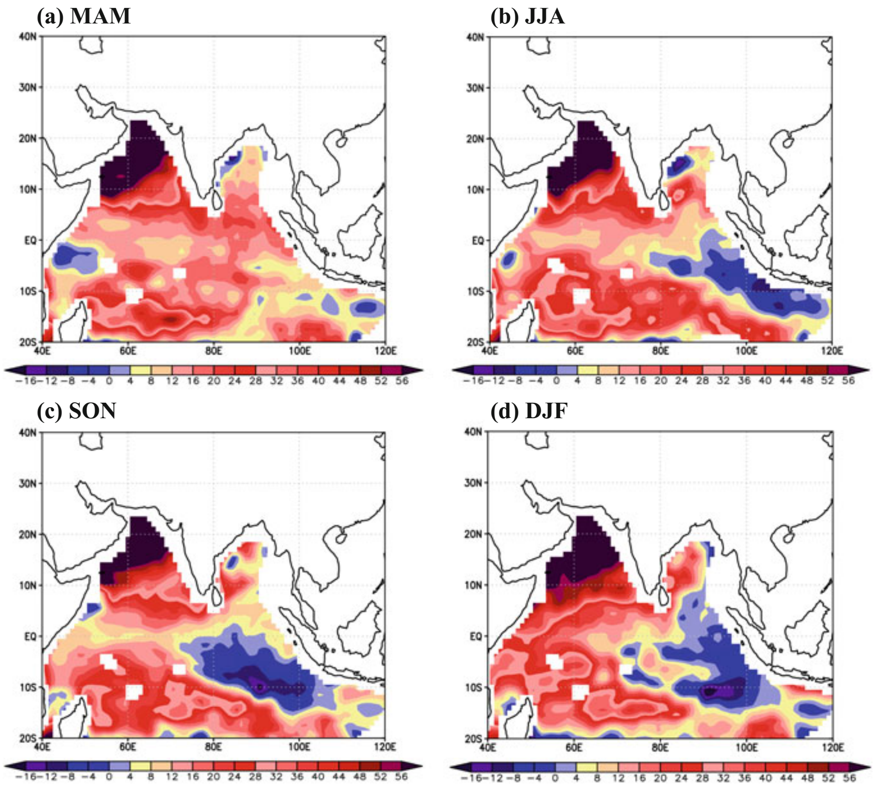

Fig. 4 Seasonal mean climatology difference between CMIP5 multi-model-mean (MMM) and observations of thermocline depth (m) as measured by depth of the 20 °C isotherm: **a** March–May; **b** June–August; **c** September–November; and **d** December–February

the northern Arabian Sea. The source of moist processes that determine wet ΔP is discussed in Sect. 5.2.

Due to persistent easterly bias ($\Delta\tau$) in the EIO and weakened southeast trades leading to a weak wind stress curl and Ekman pumping velocity, ΔD20 in CMIP-era models are deeper by 20–30 m (Fig. 4) over thermocline ridge region (Tozuka et al. 2010; Nagura et al. 2013). In the models, however, the largest ΔD20 occurs over the northern Arabian Sea (Fig. 4), and an examination of MMM mixed-layer depth (see Fig. 1 in Nagura et al. 2018) shows that largest biases (ΔMLT) occur in the northern Arabian Sea. Nagura et al. (2018) examined the processes that account for ΔD20 there. Briefly, their process-based study revealed that in most models ΔMLT influences ΔD20 and variations in ΔMLT are strongly linked to biases in the density stratification (jump) across the bottom of the mixed layer than to surface cooling biases. The density jump is in turn determined primarily by sea-surface-salinity biases (ΔSSS) that are advected into the northern Arabians Sea by the west India coastal current (see their Fig. 12), and the source of ΔSSS is the rainfall deficit associated with the models' weak, summer monsoon (Fig. 1b). Ultimately, then, ΔD20 is linked to deficit of monsoon rainfall over the Bay of Bengal. It suffices to mention here that largest ΔD20 over the northern Arabian Sea is due to nonlocal processes further highlighting the intrinsic difficulties in identifying source of model errors.

3.3 Misrepresentation of the Equatorial WJs and Coupled Processes Along the EIO

WJs transport mass and heat from the western to eastern EIO. Given that the time it takes for an equatorial Kelvin wave to travel the Indian Ocean basin is only a few days, we can expect that errors in wind stress ($\Delta\tau$) will quickly imprint on the simulated WJs. In the CMIP5 models, a direct consequence of the $\Delta\tau$ bias (Fig. 7a) is that both the spring and fall WJs, as measured by the depth-integrated (0–100 m) zonal current at 0°N, 85°E, are weaker by 50–60% compared to observations (Annamalai et al. 2017), and this weakness is apparent everywhere along the equator (compare Fig. 5b and 5a), with biases in the amplitude, phasing, and duration of the WJs; moreover, the summertime westward flow is erroneously strong. The weak WJs and stronger westward flow result in shallow (deep) thermocline biases in the eastern (western) EIO, features that persist for most of the annual cycle (Fig. 4). The errors in WJs and the resultant ΔD20 lead to ΔSST (Fig. 3), and to ΔP locally (Sect. 5) and subsequently onto $\Delta\tau$ along the EIO and the cycle continues leading to erroneous Bjerknes' feedback in the EIO.

4 Possible Sources for Monsoon Precipitation Errors

As mentioned above, it is recognized that complex interactions among the ocean, atmosphere, and land components of the climate system anchor the monsoon annual cycle. In this scenario, the errors in ocean–atmosphere variables are not mutually independent, and errors in one variable (e.g., $\Delta\tau$) can cascade into others (e.g., ΔD20), and errors that develop in one season can persist into the next seasons (e.g., boreal winter Δ SST persisting into the following spring and summer seasons over the Bay of Bengal), and errors are nonlocal in space (e.g., ΔP in Bay of Bengal impacting ΔD20 over the northern Arabian Sea). How do we then reconcile this problem and identify sources of errors, and improve the representation of processes and their interactions in models? Next, we review results from recent studies that attempted to isolate source(s) of model errors.

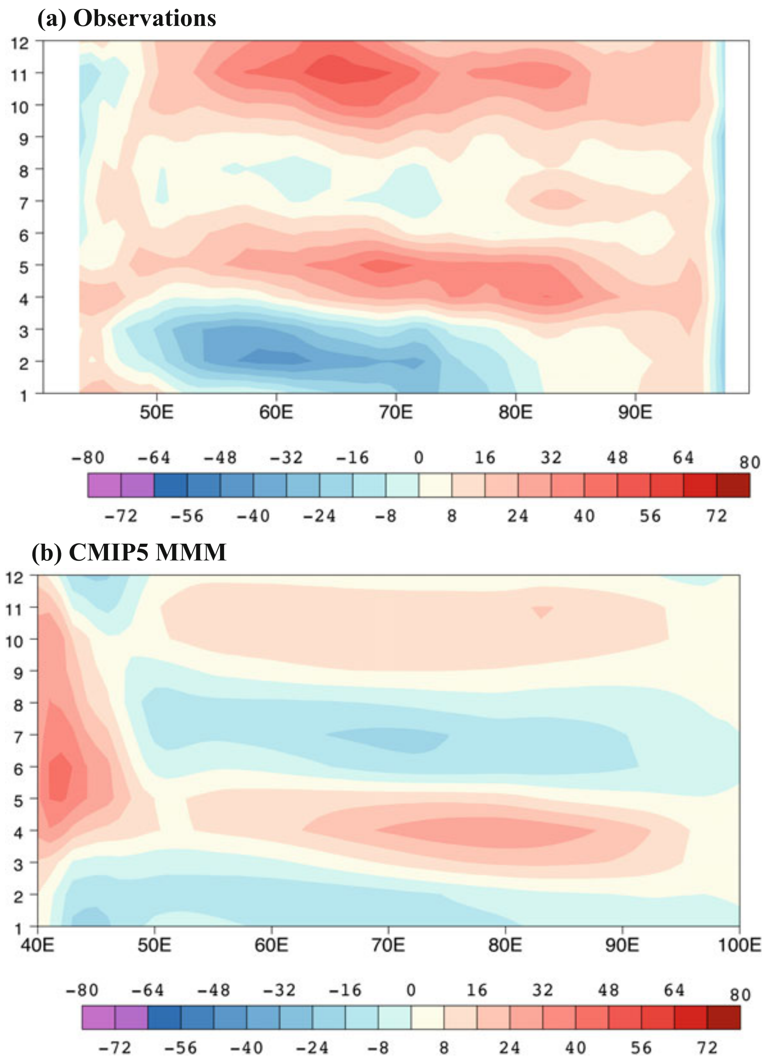

Fig. 5 Monthly evolution (ordinate) of the equatorial (3°S–3°N) zonal current (cm/s) from **a** observations and **b** CMIP5 MMM. The observations used here come from OSCAR product. Adopted from Annamalai et al. (2017)

4.1 Atmospheric Processes

Martin et al. (2010) and Ma et al. (2014) invoked initialized forecast approach as in Numerical Weather Prediction (NWP) to study the development of model errors in the Unified Model and in a suite of models, respectively. Initialized on 01 May, both studies noted a rapid growth of ΔP over the western EIO in the first 5 days of the simulation. The authors suggest that "it is a direct impact of parameterizations and not due to a nonlinear feedback process operating on longer time-scales." Note that NWP forecasts are initialized with "observational estimates" (initial states generated by data assimilation system) and therefore in this experimental setup, biases in SST and large-scale circulation are minimized, paving ways to assess the growth of model errors due to limitations in parameterizations (Klinker and Sardesmukh 1992; Phillips et al. 2004; Rodwell and Palmer 2007). The approach is a promising one.

Bush et al. (2015) incorporated changes to entrainment/detrainment values in the convection scheme of the Unified Model and performed initialized forecasts. While enhanced entrainment effectively reduced ΔP over the western EIO, modeled precipitation showed unrealistic wet bias over the tropical western Pacific. Zhao et al. (2018) reported that the systematic biases over the monsoon region persist in the three generations of the Geophysical Fluid Dynamics Laboratory (GFDL) model versions (from AM2.0 to the latest version AM4.0). In a series of experiments with changes to entrainment rates in AM4.0, particularly incorporating lateral mixing in the deep convective plume to a linear function of free tropospheric column relative humidity, Zhao et al. (2018) note that simulated precipitation increases over the tropical western Pacific for increased entrainment rate. A similar sensitivity to enhanced entrainment in Global Forecast System (GFS) model shows increased precipitation over the near-EIO and decreased precipitation over India (Mapes, 2017 personal communication), further aggravating model systematic errors. One inference is that Asian monsoon is comprised of multiple regional heat sources and given their close proximity to the equator, perturbations to one of the precipitation centers are quickly communicated to others by equatorial waves (Annamalai and Sperber 2005).

In climate models, why do ΔP persist over the western EIO? Let us consider the following scenario. Climatologically, the western EIO receives much less rainfall (dotted line in Fig. 6a) compared to the eastern EIO throughout the annual cycle (thick line in Fig. 6a). An examination of vertical velocity profile (not shown) suggests weak descent (strong ascent) over western (eastern) EIO for the most part of the annual cycle. Therefore, the western EIO is climatically a "dry" region and higher amount of MSE is required to trigger convection and maintain precipitation there. Climatologically during May, observed SST peaks around 30 °C (Fig. 6b) and promotes local evaporation (not shown), and a weak cross-equatorial flow develops (Fig. 6c) and transports moisture from the southern Indian Ocean. These processes lead to the accumulation of CWV in the western EIO. As a result, a local maximum in precipitation (~4 mm/day) is observed (Fig. 6a). Immediately thereafter in June, for reasons given in Sect. 2.2, SST drops to ~26 °C and rainfall decreases subsequently. It is during this "time window" of the annual cycle that the model errors begin to emerge, say wet bias, warm SST over the western EIO, and easterly $\Delta\tau$ in the EIO (Annamalai et al. 2017). Then, due to nonlinear atmospheric feedbacks, ΔP amplify, and the coupled nature of the monsoon-Indian Ocean climate systems anchors its persistence.

Hanf and Annamalai (2018) diagnosed a series of NCAR_CAM4/5 model solutions and reanalysis products. Their budget analyses revealed that after the "burst" of precipitation during late May–early June over the western EIO, accumulation of dry

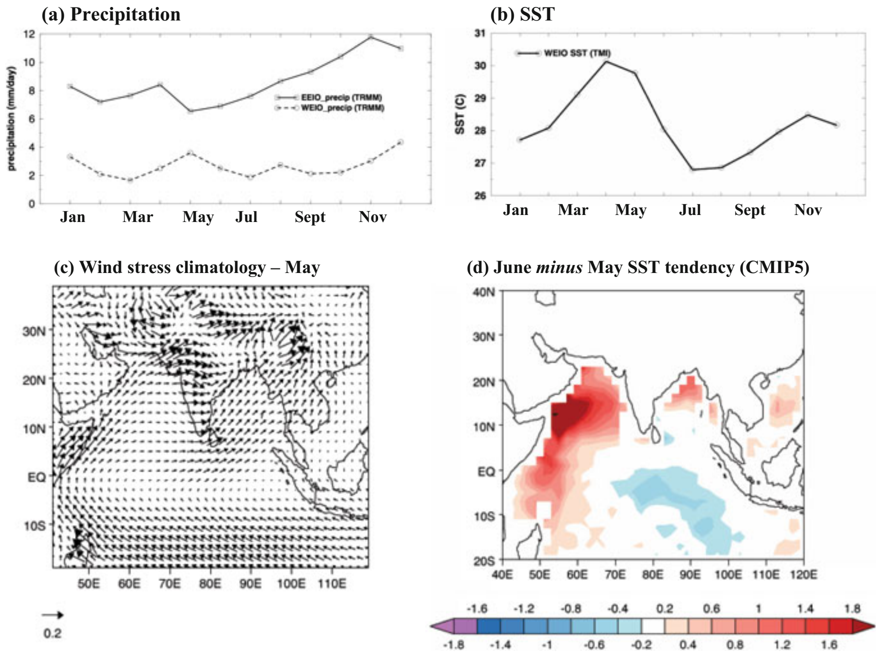

Fig. 6 **a** Observed monthly precipitation (mm/day) climatology averaged over eastern EIO (5°S–5°N; 90–105°E) and western EIO (5°S–5°N; 50–60°E); **b** observed monthly SST (°C) climatology averaged over western EIO; **c** observed wind stress (N/m^2) climatology during May; and **d** June *minus* May SST (°C) tendency bias in CMIP5 MMM. Adopted from Annamalai et al. (2017)

and cold air in the lower troposphere by horizontal advection is the dominant term in anchoring the demise of convection in mid-June. Encouraged by this, Hanf and Annamalai (2018) performed sensitivity experiments by increasing entrainment rates in convection scheme employed in NCAR-CAM4. Their solutions showed a reduction of convective precipitation over the western EIO and an increase of large-scale precipitation along the monsoon trough. In contrast to earlier studies on entrainment sensitivity, their results showed a reduction of model precipitation biases over South Asia.

In cumulus convection schemes, entrainment and detrainment coefficients have notable imprints on cloud properties and precipitation partitioning (Neale et al. 2008; Martin et al. 2010; Zhao et al. 2018), and models whose convection schemes are most responsive to free tropospheric moisture performs better (Lin et al. 2012; Neale et al. 2008). Details of entrainment role on vertical processes and their interactions on moisture–convection and cloud–radiation feedbacks, and precipitation partitioning are discussed in Hanf and Annamalai (2018).

4.2 Model Resolution and Orography

Few studies examined the sensitivity of modeled monsoon precipitation to higher horizontal resolutions. Goswami et al. (2015) and Abhik et al. (2017) performed integrations with CFSv2 coupled model with two horizontal resolutions, viz., ~100 km and ~38 km. In both solutions, ΔP over the tropics and particularly over the monsoon region remain identical, implying insensitivity of ΔP to resolution, at least in this model configuration.

Boss and Hurley (2013) hypothesized that in regions of sharp MSE gradient such as the Hindu Kush (along 73°E) if the height of the model orography is not realistically resolved, then horizontal advection of low MSE air will result in a dry bias over India. In CMIP3/5 models, the average height of orography along 73°E is around 3 km compared to ~5 km in observations. To validate their hypothesis, Boos and Hurley (2013) truncated model orography height in NCAR_CCSM4 to ~1.0 km and their sensitivity run developed a dry bias over India. While encouraging, solutions do not capture the corresponding biases over the western EIO and Bay of Bengal as well as reducing model orography height to ~1.0 km deserves attention.

4.3 Coupled Processes

Annamalai et al. (2017) adopted a different approach. In CMIP5 models, their analysis indicates that an easterly wind stress bias ($\Delta\tau$) along the EIO begins during April–May and peaks during November (Fig. 7a); the severity of the $\Delta\tau$ is that the WJs, eastward-flowing equatorial currents during the intermonsoon seasons (April–May and October–November), are almost eliminated (Fig. 5b). An erroneous, east-to-west SST gradient (warm west and cold east) develops in June. An examination of SST tendency errors (June *minus* May) in CMIP5 MMM clearly shows a warming (cooling) tendency over western (eastern) EIO and the emergence of SST gradient along the EIO (Fig. 6d). The structure of the model errors indicates that they arise from Bjerknes feedback in the EIO. In CMIP5 models, reversed gradient in precipitation along the EIO, and its persistence result from errors in the coupled processes.

To test their hypothesis that the ΔP over South Asia is due to weakened WJs leading to a too strong Bjerknes feedback, Annamalai et al. (2017) forced a coupled model, namely, Coupled model for Earth Simulator (CFES) developed at JAMSTEC, Japan with the easterly $\Delta\tau$ (Fig. 7a) noted along the EIO. In one of the sensitivity solutions where the easterly $\Delta\tau$ is introduced only during intermonsoon seasons (April–May; October–November), the sensitivity run develops westward equatorial currents throughout the year, suppressing the WJs in comparison to the control run (Fig. 7b). The anomalous forcing also excites oceanic Rossby and Kelvin waves that tend to deepen (shallow) the thermocline depth (Fig. 7c) in the western EIO (eastern EIO). In response, warm (cool) SST and wet (dry) conditions develop in each region

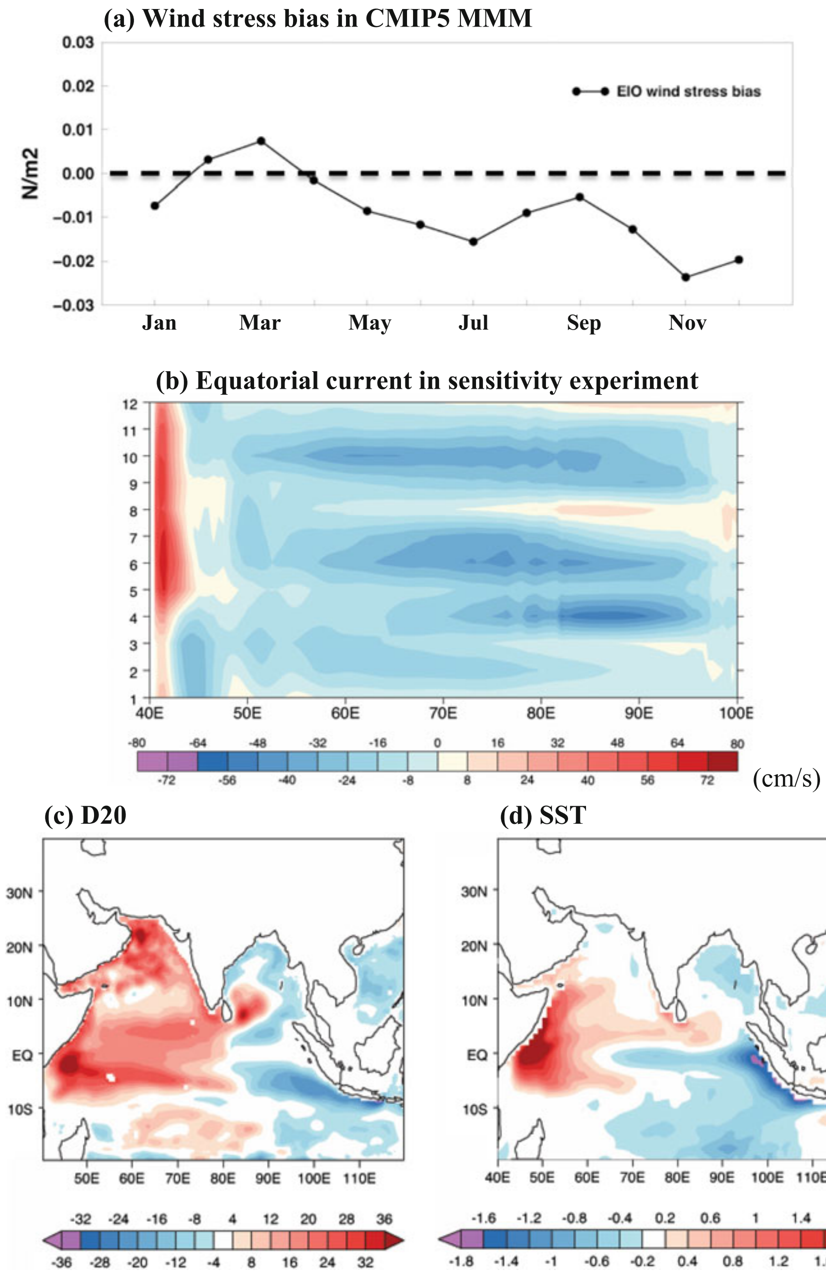

Fig. 7 **a** Equatorial Indian Ocean (3°S–3°N; 40°–100°E) monthly mean wind stress climatology difference between CMIP5 MMM and ERA-INT; **b** monthly evolution (ordinate) of the equatorial (3°S–3°N) zonal current (cm/s) from sensitivity experiment; **c** seasonal (June-September) mean differences in thermocline (m) between CFES_EXP and CFES_CTL; and **d** same as (**c**) but for SST (C). Adopted from Annamalai et al. (2017)