Evaluating forecasts for Indian Summer Monsoon Precipitation using the Navy Earth System Model

Erin Roberson

Department of Earth and Atmospheric Sciences

Metropolitan State University of Denver

Abstract

Accurate seasonal forecasts rely heavily on the prediction of precipitation amounts. This is especially true for the Indian Summer Monsoon (ISM), which accounts for the majority of India’s annual rainfall and drives the nation’s agricultural industry. The Navy Earth System Model (NESM) is an air-sea coupled model using the Navy Global Environmental Model (NAVGEM) and Global Ocean Forecast System (GOFS). NESM model forecasts are compared to the observed precipitation over the region. Verification for ISM seasonal rainfall amounts is performed through graphical comparison and standard statistical relationships during the peak ISM months (July and August) in 2014, 2015, and 2016. The results showed significant dry bias over the Deccan Plateau, a major agricultural region for India, and the Arabian Sea coast, the region which typically receives the most rainfall during the ISM season.

Introduction

Water is an important element for all agricultural activities. This is especially true for the South Asian country of India where approximately 69% of the population lives in rural areas and contributes to the nation’s agricultural industry (Registrar General of India 2011). Farms often source water through irrigation practices or it can be provided the “natural” way by rain. 55% of India’s farmland is in fact rainfed and not irrigated (National Rainfed Area Authority Planning Commission 2012), which means the majority of the country’s farmland heavily relies on precipitation. The majority of India’s annual precipitation occurs during the nation’s monsoon season called the Indian Summer Monsoon (ISM). The ISM occurs during the boreal summer

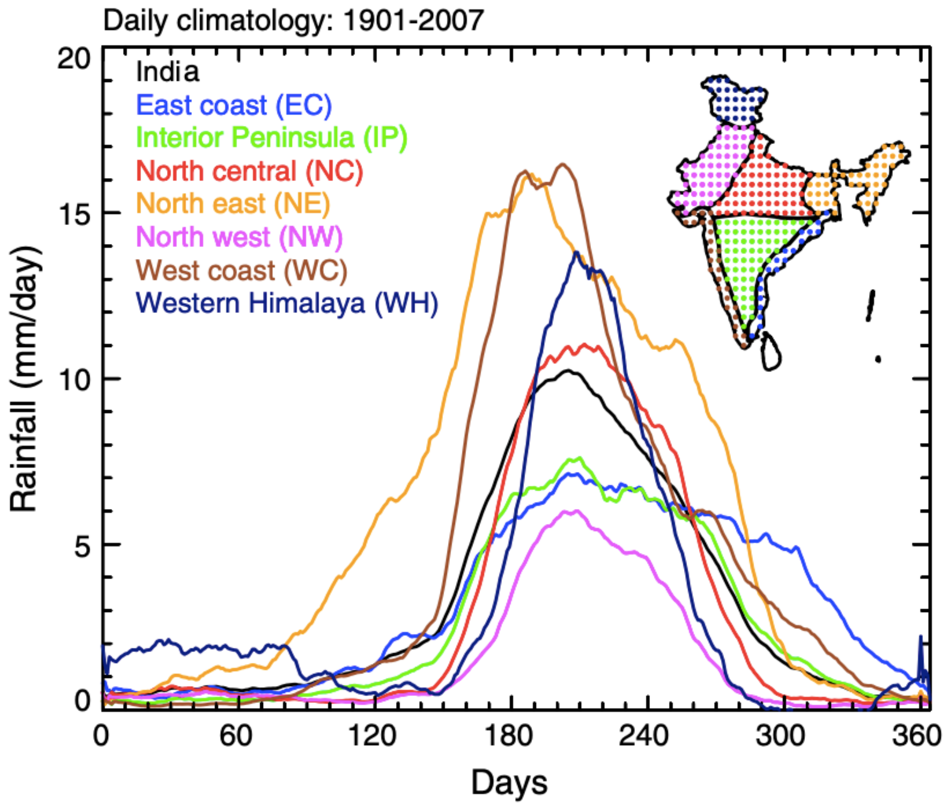

***Figure 1**: Daily Rainfall Climatology for India and for each individual region (Kishore et al. 2016).*

between the months of June and September and is responsible for not only feeding farmland directly but also replenishing groundwater. Consequently, 91% of India's groundwater is used for agricultural irrigation (Ministry of Water Resources 2014). Freshwater demand from agriculture will continue to rise due to increasing population, making ISM rainfall an important water management issue with impacts on the nation's food security (Barik et al. 2017).

Human activities could further exacerbate freshwater availability in India. A study from Paul et al (2016) found large-scale deforestation contributes to a decrease in ISM rainfall by weakening the return of water to the atmosphere through evapotranspiration. Being driven by the thermal gradient between the land surfaces and surrounding oceans, ISM rainfall could also be weakened by the ocean warming attributed to anthropogenic climate change (Roxy et al. 2015). However, others have suggested manmade global warming could increase and intensify rain over the region leading to life-threatening flooding (Goswami et al. 2006; Wang et al. 2013). The dynamics coupled with spatial and temporal variability of ISM rainfall make it difficult to forecast. ISM rain totals can range from 160 mm/yr to 1800 mm/yr, with the west coast (Arabian Sea coast) and northeast (surrounding Bangladesh) regions receiving the most annual precipitation (Kishore et al. 2016). **Figure 1**, from Kishore et al, shows the daily rainfall climatology from 1901-2007 for the entire country and broken down into seven regions that experience similar ISM precipitation. As stated, the regions that receive the most rainfall during the ISM season are the West Coast and Northeast. Both see the most precipitation in July during what is considered the peak of ISM season (July-August). The Western Himalaya and North Central regions also receive higher than average ISM rainfall but both peak later between July and August (Kishore et al. 2016). The North Central region is also worth noticing since it encompasses states where the majority of wealth comes from land cultivation, otherwise known as agrarian economies.

Predicting ISM precipitation, although not simple due to many influences (Crétat et al. 2017), would greatly benefit India since it influences its economy, food security, environmental health and security, and disaster preparedness. Barik et al. (2017) concluded seasonal and extended range forecasts could be an important tool for India's water agencies to improve management practices by reducing groundwater exploitation and controlling demand (Barik et al. 2017). For this study, extended range forecasts will be compared to observations of ISM rainfall over three summers to assess the capabilities of the Navy Earth System Model (NESM).

Data

1. *Navy Earth System Model*

The Navy Earth System Model (NESM) is a coupled atmosphere-ocean model that combines the Navy Global Environment Model (NAVGEM) (Hogan et al. 2014) and the Global Ocean Forecasting System (GOFS) (Metzger et al. 2014). The model offers both hindcast and forecast daily precipitation accumulations spanning 1999-2016 (Kirtman et al. 2017). It is initialized four times weekly for 45 day runs (Janiga et al. 2018). For this study, the NESM hindcast data is used for 1^{o}x1^{o} (latitude x longitude) global gridded precipitation. Model hindcasts were made available through the Subseasonal Experiment (SubX), which produced seventeen years of reinitialized forecasts using 7 global models to benefit research in subseasonal forecasting (Kirtman et al. 2017). All archived and real-time data is open for public use through the Data Library of the International Research Institute for Climate and Society, Columbia University (Kirtman et al. 2017).

2. *Global Precipitation Climatology Centre*

The Global Precipitation Climatology Centre (GPCC) data are monthly gridded precipitation observations based on in-situ gauge measurements across the globe. It currently uses approximately 80,000 stations and produces a monthly precipitation total for each latitude by longitude grid point (Schneider et al. 2018). For this study, the 1^{o}x1^{o} grid was chosen to match the NESM grid, but the observations are half a degree off from the model data. Although introduced here, the handling of this issue is discussed later in the methodology section. The GPCC was originally established in 1989 at the request of the World Meteorological Organization (WMO) to fill a need for long-term global precipitation analyses and has fulfilled those requests by providing data from 1891-2016 (Schneider et al. 2018). The organization is operated under the National Meteorological Society of Germany as a part of the nation's contributions to the World Climate Research Programme (WCRP) and Global Climate Observing System (GCOS) (Schneider et al. 2018). Data is made available to the public online through NOAA's Earth System Research Laboratory Physical Science Division.

Methodology

This paper focuses on the peak monsoon months for three consecutive years. Observations of July through August in 2014, 2015, and 2016 are compared to NESM hindcast for those months. 2014 and 2015 were both dry monsoon years for India, with each receiving 12% and 14% less than average, respectively (India Meteorological Department 2016). In 2016 ISM rainfall totaled to only 3% less than average, making it an average monsoon season (India Meteorological Department 2017). Keeping with the suggestions of better extended range forecasts from Barik et al and SubX, 7-day and 14-day forecasts are examined. The reinitialized conditions for NESM hindcasts have not improved predictions past 2 weeks (Janiga et al. 2018) and therefore, these lead times should represent the best extended range forecast from the model. NESM predicts daily total precipitation which differs from the monthly GPCC rainfall observations. In order to make a direct comparison, the model precipitation is summed over the entire month at each grid point. The calculated monthly precipitation amount is then statistically examined against the observations using bias, mean square error (MSE), and correlation. Bias and MSE are plotted geographically for the entire South Asia region between 6º-32º N latitude and 66º-98º E longitude. Since GPCC data is based solely on land gauges, all NESM forecasts over ocean are removed in the comparison process. The 1ºx1º grid size is quite large and the resulting images are grainy. Although not aesthetically pleasing, smoothing was not applied because it is the most accurate representation of the data. Grid point alignment issues were handled by “rounding” the observations up a degree. For example, the 20ºN, 78ºE NESM grid point is evaluated against the 19.5ºN, 77.5ºE observation grid point. As one could expect, this may affect the results of this paper. However, once the comparison data was plotted onto a map of India, the placement of the bias and MSE pattern aligned with discrepancies shown by the precipitation patterns discussed in **Figure 2**. All data handling and analysis is performed using the R statistical programming language in the integrated development environment called RStudio.

Results and Discussion

1. Total Precipitation

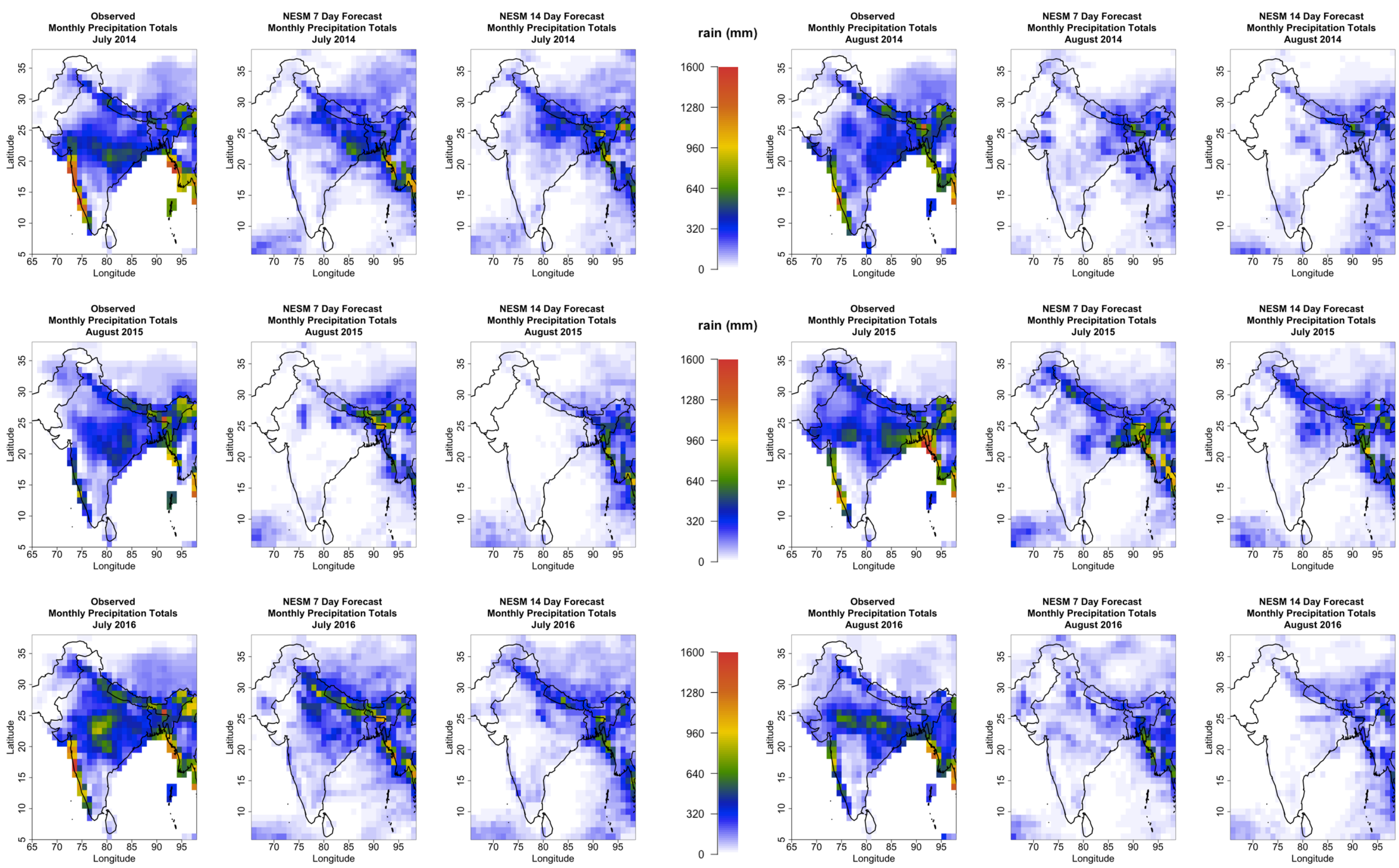

Figure 2*: Total monthly precipitation is plotted for observations, 7-day NESM, and 14-day NESM in July (left column) and August (right column) of 2014 (top row), 2015 (middle row), and 2016 (bottom row).*

Monthly precipitation observations for the entire South Asia region are plotted in **Figure 2**. The first row shows 2014 observations and forecasts for each month. The first (fourth) image in row one is the July (August) 2014 observations from GPCC. The two images following are the 7-day and 14-day NESM forecasts. A substantial difference between the model and observational rainfall totals exists in central and eastern India for both months in 2014. Although the 7-day forecasts do register some of the high precipitation values seen in the observations on the Myanmar coast, both lead times completely miss the high rainfall on the West Coast. This problem persists for each year studied and is concerning because the region is expected to receive the greatest ISM precipitation. In the middle row, July and August observations for 2015 show high rain totals in the West Coast, North East and North Central regions of India. NESM once again inaccurately predicts the rainfall in these areas. However, there is significant improvement between the 14-day and 7-day forecast in in the North East section for both months, an area of the country which typically receives high ISM rainfall. The final row has the observations and NESM predictions for 2016, an average year for ISM rainfall. Both July and August of 2016 show high precipitation centers over the North Central region which were not present in the previous 2 years. Considering this region is also the center for the nation's agricultural industry, missing a forecast in the area could have economic costs. Interestingly, there is an overestimation of precipitation between the 14-day and 7-day forecasts over the Himalaya Mountains in Nepal for 2016. This was unique to this year like the precipitation over Central India.

2. *Bias*

Precipitation bias between the NESM forecasts and observations are shown in **Figure 3**. Areas in blue indicate a positive (wet) bias while areas in red are negative (dry) bias. For all years, dry bias dominates India. The strongest negative bias is on the Arabian Sea (West) coast and is consistent across each summer for both lead times. Another consistent dry bias exists on the Bangladesh and Myanmar coast. Both are in regions of warm coastal waters and this suggests the NESM has issues with moisture advection off the ocean surface and/or tropical convection during the ISM. However, further study would be required to confirm this claim. In the July 2014 bias plots, an expansive wet bias stretches across the North Central and North East regions,

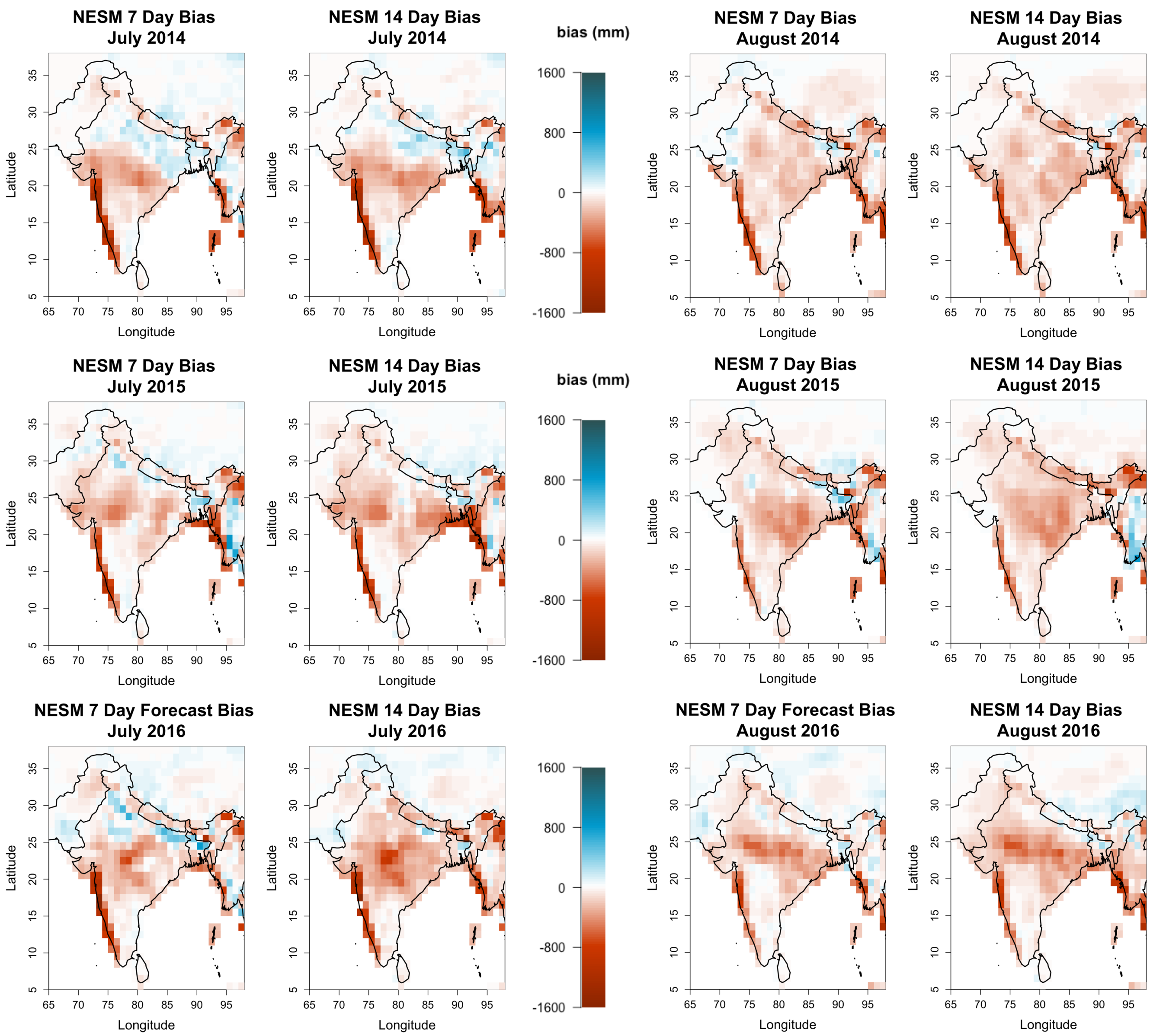

Figure 3*: Precipitation bias is plotted for the study period with red indicating less than average (dry bias) and blue meaning greater than average (wet bias).*

paralleling the Ganges River Valley. This area is important for agricultural activities and especially emergency management services since many citizens of India live along the river. A positive bias occurs similarly in August of 2016 but covering less area. The strongest wet bias across the entire period of study is in July 2016 along Nepal's southern border with India. It is co-located with the topographical change of the Himalayas which could be the cause of the

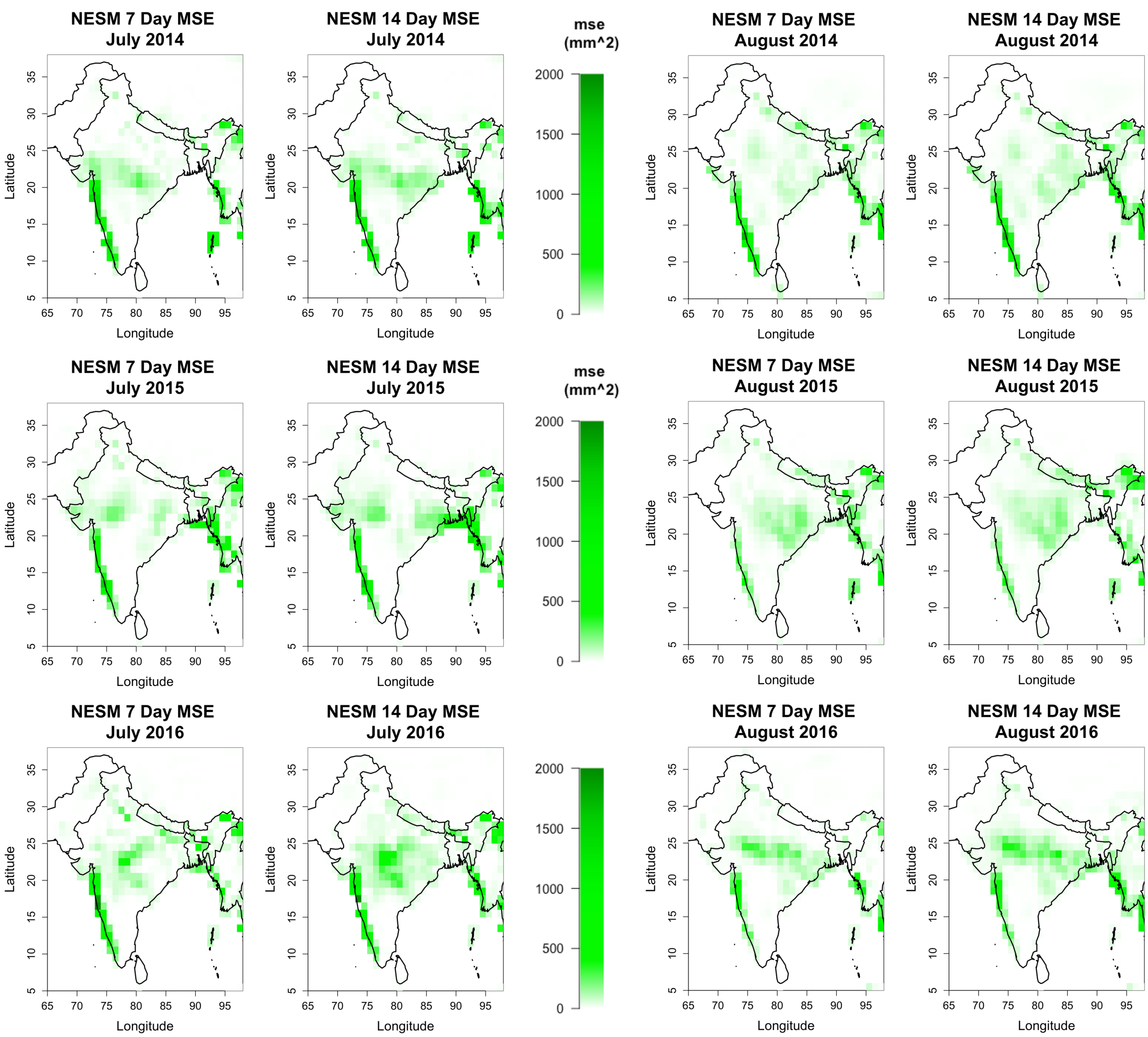

***Figure 4**: MSE is plotted for the study period with increasing green color indicating greater squared deviations from the observations.*

discrepancy between the model and observations. NESM has the smallest bias in the Interior Peninsula region. For each summer, the regional bias is typically dry but tends to have the least bias compared to other regions.

3. Mean Square Error

The model MSE for each lead time is plotted over the South Asia region in **Figure 4**. Darker colors represent greater squared deviations from the observations. Once again, these plots highlight the model error on the West Coast. This region has very large MSE for all months studied with the exception of August 2016 which only has much smaller errors on the Arabian Sea coast. **Figure 3** also showed prominent dry biases there across all three summers, suggesting

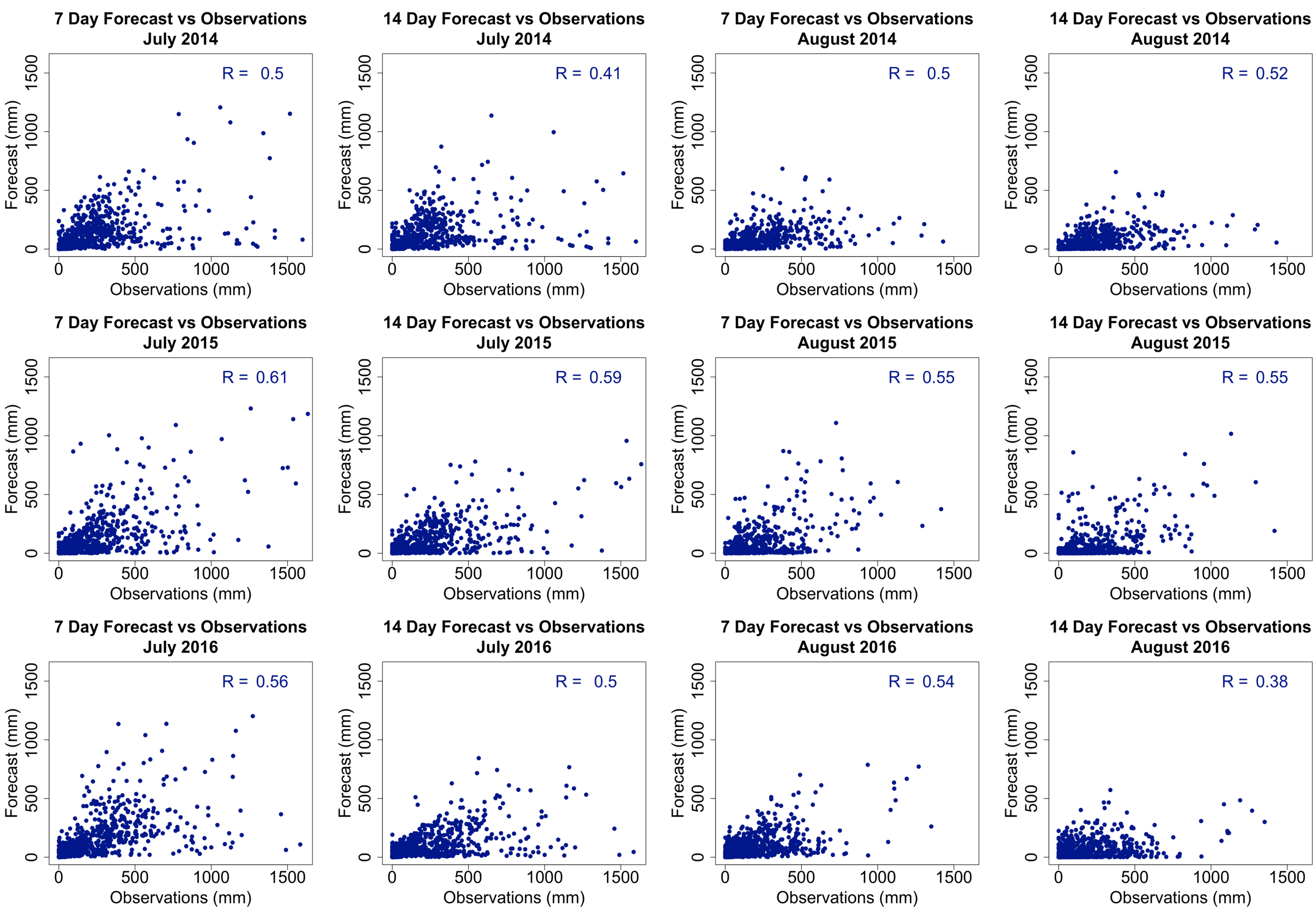

***Figure 5**: Scatterplots for model rain totals vs observations. R values are correlations for each lead time and month.*

that these errors greatly affect the performance of the model. For the entire study, the North Central region also has mid to high MSE with the greatest errors in the 2016 summer. The corresponding dry bias during the 2016 average ISM season again suggests another source of error for NESM. Over the Myanmar coast, MSE are all related to dry bias with the exception of the August 2015 plots, where the southern tip of the country received less rainfall than predicted. Other than this case, the majority of the wet bias areas in **Figure 3** have been diminished in the calculation of MSE, indicating the wet bias is affecting the model much less than the dry.

4. *Correlation*

Figure 5 shows scatterplots of forecast amounts versus observed rainfall at individual grid points for every month studied. Each plot also displays correlation (R) values for the precipitation data. At first glance, the data is simply not correlated. The lead times are quite long though, and in this context, low correlations are expected. Given that anticipation, NESM does well matching observations below 500 mm with many points clustered in the bottom left of the plots. Above that threshold, however, the model performs poorly with frequent observations over 500 mm being underestimated and giving further confirmation of the dry bias seen in **Figure 3**. The inaccuracy is especially visible in the August 2016 14-day plot where none of the forecast amounts are above 500 mm. In general, there is little to no improvement in correlation between the 14-day and 7-day leads due to the persistent dry bias. This is also evident in **Figure 4** where MSE is generally the same between both the lead times. There is, however, a substantial improvement between the 14- and 7-day forecast for both July 2014 and August 2016. **Figure 4** graphically shows the recovery in terms of a decrease in MSE on the Myanmar coast and Central India. Although, the increased correlation could also be the result of NESM also overestimating rainfall during those months since each show more widespread wet bias in **Figure 3**.

Conclusion

After comparing rainfall totals from the NESM hindcasts to observations, the NESM is clearly deficient in its representation of ISM precipitation. ISM rainfall in India's Arabian Sea coast and Deccan Plateau regions are both heavily under predicted during the study period. The Deccan Plateau is home to the nation's agricultural industry, making it a preeminent location for precipitation forecasts. Extended range forecasts are especially important for this region to better prepare water managers and farmers. In this vein, the NESM does poorly, especially during an average ISM precipitation year (2016). The Arabian Sea coast typically experiences the most precipitation during the ISM, but the NESM rainfall predictions were some of the lowest in the entire South Asia region. This could indicate major issues representing coastal rainfall, which involves dynamic atmospheric-oceanic surface interactions. However, it is also possible that these biases are due to misrepresentation of the pattern. In this study, precipitation data is used solely to explore model performance. In further research, surface winds and sea level pressure should also be included to diagnose whether NESM shortfalls are due to pattern variation. Errors can be further defined by calculating the model vs observation correlations per region and determining how the model handles specific topographies/climates. Another deficiency of this study is the short period of analysis. Additional investigation into NESM and ISM rainfall predictions would benefit from increasing the number of years investigated.

References

Barik, Beas, et al., 2017: "Water–food–energy nexus with changing agricultural scenarios in India during recent decades." Hydrology and Earth System Sciences 21.6: 3041.

Crétat, J., Terray, P., Masson, S. et al., 2017: “Indian Ocean and Indian summer monsoon: relationships without ENSO in ocean–atmosphere coupled simulations.” Clim Dyn 49: 1429, https://doi.org/10.1007/s00382-016-3387-x.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. & Xavier, P. K., 2006: “Increasing trend of extreme rain events over India in a warming environment.” Science 314, 1442–1445.

Hogan, T.F., M. Liu, J.A. Ridout, M.S. Peng, T.R. Whitcomb, B.C. Ruston, C.A. Reynolds, S.D. Eckermann, J.R. Moskaitis, N.L. Baker, J.P. McCormack, K.C. Viner, J.G. McLay, M.K. Flatau, L. Xu, C. Chen, and S.W. Chang, 2014: “The Navy Global Environmental Model.” Oceanography 27(3):116–125, https://doi.org/10.5670/oceanog.2014.73.

India Meteorological Department, 2016: “Rainfall Statistics – 2014.” Ministry of Earth Sciences, ESSO/IMD/HS/R.F.Report/01(2016)/19.

India Meteorological Department, 2016: “Rainfall Statistics – 2015.” Ministry of Earth Sciences, ESSO/IMD/HS/R.F.Report/04(2016)/22.

India Meteorological Department, 2017: “Rainfall Statistics – 2016.” Ministry of Earth Sciences, ESSO/IMD/HS/R.F.Report/01(2017)/23.

Janiga, M.A., C. J. Schreck, J.A. Ridout, M. Flatau, N.P. Barton, E.J. Metzger, and C.A. Reynolds, 2018: “Subseasonal Forecasts of Convectively Coupled Equatorial Waves and the MJO: Activity and Predictive Skill." Mon. Wea. Rev., 146, 2337–2360, https://doi.org/10.1175/MWR-D-17-0261.1.

Kirtman, B. P., Pegion, K., DelSole, T., Tippett, M., Robertson, A. W., Bell, M., … Green, B. W., 2017: "The Subseasonal Experiment (SubX) [Data set]." IRI Data Library, https://doi.org/10.7916/D8PG249H.

Kishore, P., Jyothi, S., Basha, G., Rao, SVB, Rajeevan, M., Velicogna, I., & Sutterley, TC., 2016: "Precipitation climatology over India: validation with observations and reanalysis datasets and spatial trends." Climate Dynamics, 46(1-2), 541-556. http://dx.doi.org/10.1007/s00382-015-2597-y.

Metzger, E.J., O.M. Smedstad, P.G. Thoppil, H.E. Hurlburt, J.A. Cummings, A.J. Wallcraft, L. Zamudio, D.S. Franklin, P.G. Posey, M.W. Phelps, P.J. Hogan, F.L. Bub, and C.J. DeHaan, 2014: "US Navy operational global ocean and Arctic ice prediction systems." Oceanography 27(3):32–43, https://doi.org/10.5670/oceanog.2014.66.

Ministry of Water Resources, 2014: "Dynamic Ground Water Resources of India (As on 31st March 2011)." Central Ground Water Board, River Development & Ganga Rejuvenation,GoI, Faridabad (July), 299.

National Rainfed Area Authority Planning Commission, 2012: "Prioritization of Rainfed Areas in India." Study Report 4, NRAA, New Delhi, India, p. 100.

Paul, S., Ghosh, S., Oglesby, R., Pathak, A., Chandrasekharan, A., and Ramsankaran, R., 2016: "Weakening of Indian Summer Monsoon Rainfall due to Changes in Land Use Land Cover." Sci. Rep., 6, https://doi.org/10.1038/srep32177.

Registrar General of India, 2011: "Census: Instruction manual for houselisting and housing census." New Delhi.

Roxy, M. K., Ritika, K., Terray, P., Murtugudde, R., Ashok, K., and Goswami, B. N., 2015: "Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient." Nat. Commun., 6, 7423, https://doi.org/10.1038/ncomms8423.

Schneider, Udo; Becker, Andreas; Finger, Peter; Meyer-Christoffer, Anja; Ziese, Markus, 2018: "GPCC Full Data Monthly Product Version 2018 at 1.0°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historical Data." DOI: 10.5676/DWD_GPCC/FD_M_V2018_100

Wang, B. et al., 2013: "Northern Hemisphere summer monsoon intensified by mega-El Niño/southern oscillation and Atlantic multidecadal oscillation." Proc. Natl Acad. Sci. USA 110, 5347–5352.