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HISTORICAL AND FUTURE TRENDS IN THE ONSET, WITHDRAWAL, AND DURATION OF THE INDIAN SUMMER MONSOON IN THE NORTHEASTERN INDIAN SUBCONTINENT

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Abstract Historical (1976–2006) and future (2071–2100) trends in the onset, withdrawal and duration of the Indian summer monsoon were assessed under changing climatic conditions. First, historical precipitation data (APHRODITE) observed over the Indian subcontinent were analyzed to identify trends in the onset, withdrawal, and duration of the monsoon. In some regions, an earlier onset, increased duration, and delayed withdrawal were identified historically. These trends in the onset and duration were significant in the northeastern Indian subcontinent. Several climate models from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) could capture the past trends detected in the observation data, and five models were selected to analyze the future period. The future projections of the CMIP5 models under the RCP8.5 scenario had similar trends for the monsoon onset, withdrawal, and duration, albeit with weak statistical significance. The results suggest that the trends toward an earlier onset and delayed withdrawal observed in the past would continue and the duration would increase in the future.

Keywords: monsoon, onset, withdrawal, duration

1. Introduction

Traditionally, the monsoon is defined as a seasonal reversing wind that is accompanied by corresponding changes in precipitation (Ramage 1971). Currently this terminology is used for tropical and subtropical seasonal reversals in atmospheric circulation and precipitation (Trenberth *et al.* 2000). On a large scale, the process can be simply described as a thermally driven sea breeze that is modified by the earth's rotation (Trenberth *et al.* 2000). Differential heating of the Indian subcontinent and Tibetan Plateau during boreal spring draws moist air from the Indian Ocean, generating the southwest Indian summer monsoon (ISM) (Webster 1987). The major characteristics of monsoon phenomena are the total rainfall, onset, withdrawal, and duration. The onset of the monsoon is considered the beginning of the rainy season when a sudden increase in rainfall is observed. The withdrawal of the monsoon corresponds to the retreat of the rainy season.
The ISM affects water availability over India. The summer monsoon between June and September contributes 80% of the annual rainfall in south Asia (Turner and Annamalai 2012). Variability in

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the onset and duration of the summer monsoon strongly controls water resources, agriculture, economics, ecosystems, and human mortality throughout south Asia (Marshall 2010). Agriculture is the backbone of the Indian economy, and most of the India's population depends on cereal and pulse production. Agriculture is also a major supplier of raw materials for industry (Kumar *et al.* 2004). Therefore, arrangements to deal with variation in the timing, intensity, and duration of the monsoon are necessary (Turner and Annamalai 2012). Except for the southeast region, the rainy season over India lasts from June to September. Central India receives a considerable amount of rainfall in July and August, between 10 and 15 mm/day. The climb to the peak rainfall during June is more gradual in the central region. Except for the southeast region, the rainfall over all regions decreases rapidly during the withdrawal phase of the summer monsoon in September (Krishnamurthy and Shukla 2000). The ISM undergoes periods of enhanced and reduced rainfall over a large part of India; this intraseasonal variation is called the "active" and "break" monsoon phases (Krishnan 1999). Rainfall over this region consists of fluctuations on an intraseasonal scale between active phases with much rainfall and weak phases or breaks with little rainfall. Because uneven spatial and temporal distribution of rain can adversely affect agriculture, prediction of the intraseasonal variation in the ISM is very important (Rajeevan *et al.* 2010).

The monsoon is very sensitive to global warming (Kitoh *et al.* 2013), and the current enhancement of greenhouse gas emissions worldwide could aggravate the complexity and severity of the ISM (Sharmila *et al.* 2015). Projections of future variability in the ISM are essential for sustainable economic development and future adaptations in the Indian subcontinent (Sharmila *et al.* 2015). Some studies have reported that the onset of the ISM was earlier in the late twentieth century (Kajikawa *et al.* 2012; Bollasina *et al.* 2013), whereas some other studies of the onset and withdrawal have had inconsistent findings, as delayed onset (Sabeerali *et al.* 2012) and early withdrawal (Sahana *et al.* 2015) after 1976/1977-time margin. Kitoh and Uchiyama (2006) and Kitoh *et al.* (2013) analyzed changes in the Asian summer rainy season at the end of the twenty-first century with global warming using daily precipitation data projected by climate models. The results projected an earlier onset, later withdrawal, and longer duration over some parts of India. Previous studies (Ananthakrishnan *et al.* 1981; Matsumoto 1997) considered long term averaged precipitation to determine the onset and withdrawal dates. However, few studies have examined the trends in monsoon onset, withdrawal and duration, and the idea on trends under a future warming environment is unclear. As this research analyzes long term historical and future trends, it would be a good guide to assess the future trends in such warming environment.

2. Methods

For this study, the period from 1976 to 2005 is considered historical, and from 2071 to 2100, the future. After analyzing the trend over the subcontinent, northeastern part was selected for the further analysis. Target domain is 22.75–26.75°N 85.25–91.25°E (Figure 1). This area includes northeastern India and part of Bangladesh. APHRODITE precipitation data (Yatagai *et al.* 2012), which are available for 1951–2006 in the Asia Monsoon region, were used as the observational data.

Several methods were used by previous researchers to identify monsoon onset and withdrawal in previous studies, such as a sudden, persistent increase in rainfall (Ananthakrishnan *et al.* 1981; Matsumoto 1997) or the zonal wind component (Cheang and Tan 1988; Syroka and Toumi 2004; Kiguchi and Matsumoto 2005). Matsumoto (1997) defined the onset (withdrawal) of the summer rainy season as the first (last) pentad when the mean pentad precipitation exceeds the annual mean pentad precipitation (Pm = (Annual precipitation)/73) in at least three consecutive pentads after (before) decreasing in at least three consecutive pentads. This objective method was utilized in this research and using this objective method, the onset and withdrawal were identified in each year. The APHRODITE and model simulation data were analyzed to check whether the models were capable of tracking trends in the onset and withdrawal during the historical period. The same analysis was done to analyze future variability in the monsoon. The climatological patterns of precipitation during the historical and future periods were compared to identify any projected changes in the precipitation pattern in the future. The Mann–Kendall test (Kendall 1974) was used to assess the historical and future trends.

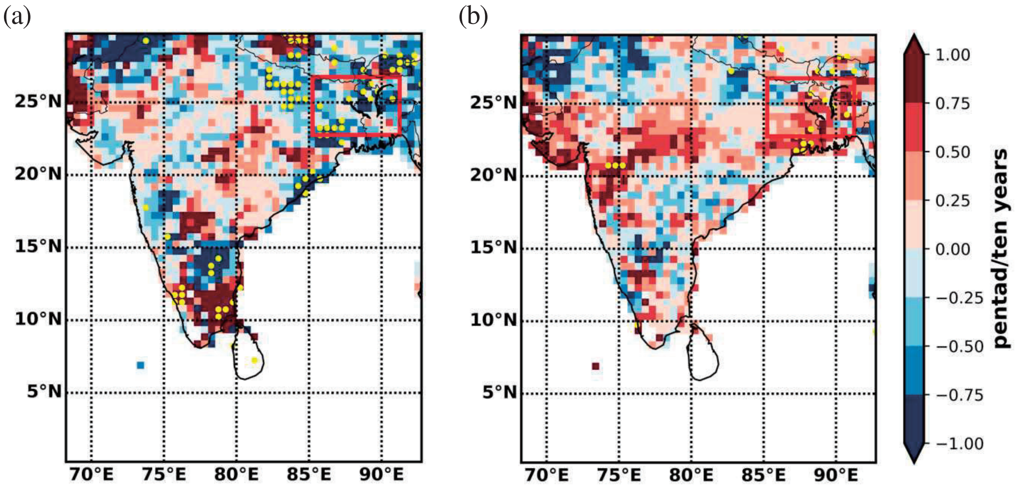

Fig. 1 Trend in the (a) onset and (b) withdrawal (pentad per decade) during 1960–2006 The boxed region (22.75–26.75°N 85.25–91.25°E) was selected for this analysis. Yellow dots indicate trends that are significant at the 0.05 level.

To analyze the future trends in onset, withdrawal, and duration, Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulation results under the RCP 8.5 scenario were analyzed. Suitable models for the analysis were selected according to their performance in the selected region. To compare model performance, climatological monthly precipitation (1976–2005) was used, and the accuracy was evaluated using the root mean square error (RMSE), Nash–Sutcliff efficiency coefficient (NSE), and Pearson product moment correlation coefficient (R). The performance of each model was compared using above parameters and based on this evaluation suitable models were selected for the analysis.

3. Results and Discussion

This study first analyzed the observational data to identify trends in the onset and withdrawal for the entire Indian subcontinent. The analysis indicated that the northeastern area had earlier onset and later withdrawal. The boxed region in Figure1 was subjected to further analysis as it showed earlier onset and later withdrawal. Inside the region trends were significant according to

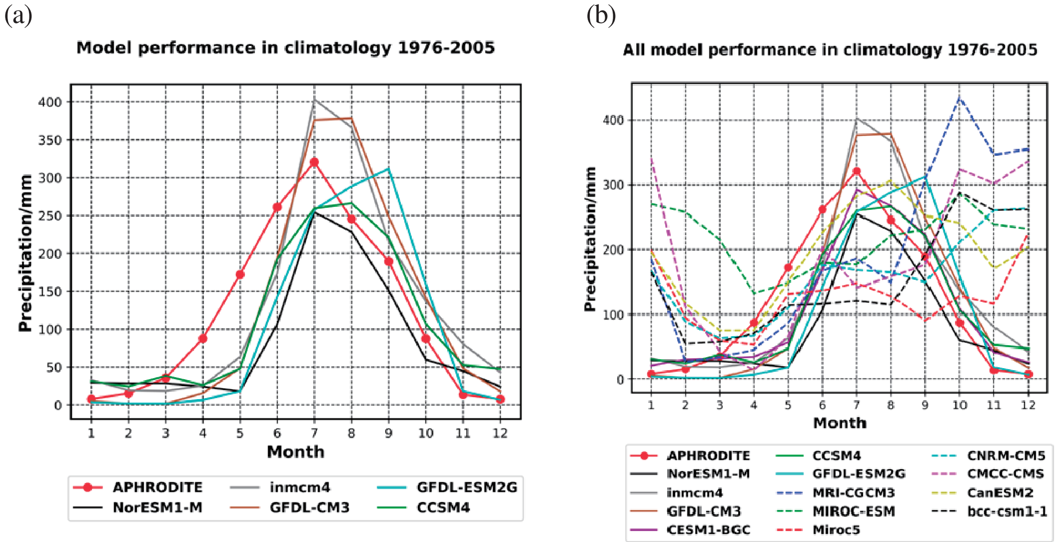

Fig. 2 (a) Climatological comparison of the APHRODITE precipitation and output of five selected models during the historical period (1976–2005). (b) Climatological comparison of the APHRODITE precipitation and all the analyzed models.

the result given by the Mann–Kendall test.

Based on the performance in the target domain for 1976–2005, six models which could able to perform the climatology (Figure 2), were selected for the analysis (Table 1). The performance of each model was compared using above described three parameters and the result is mentioned in Table I. Six models were selected as they have high correlation (R), high Nash-Sutcliff efficiency (NSE) and least root mean squire error (RMSE) compared to the observations. Figure 2 is a graphical interpretation of the observed climatology and the simulated climatology in historical period. However, according to data availability limited the analysis to five models, excluding CESM1-BGC.

Figure 3 compares the historical and future climatology. All models except NorESM1-M predicted that the peak monthly precipitation would increase in the future. NorESM1-M model, showed small reduction in the peak monthly precipitation. Considering the APHRODITE data and model outputs, there was a lag in the model outputs in both the historical and future periods. The monsoon indices based on the model outputs were later than the real monsoon based on observed data. Most likely the models may not simulate the pre-monsoon precipitation well. Figure 4 shows the observed trends and simulated trends during historical and future periods. In Table 2 those trends were tabulated in pentads per ten years scale. With the observed data, the onset tended to come earlier and the withdrawal come later, increasing the duration of the monsoon. During this historical period the onset came one pentad earlier every decade, and the withdrawal was delayed by half a pentad every decade (Table II). In the historical period, four models showed earlier onset, whereas only the model CCSM4 showed later onset (Table II). For the future period, NorESM1-M and incm4 showed a later onset, whereas the other three models showed an earlier trend. Considering withdrawal during the historical period, CCSM4, incm4, NorESM1-M showed earlier withdrawal, and GFDL-ESM2G and GFDL-CM3 showed a later withdrawal. In the future, incm4 and NorESM1-M show an earlier withdrawal, GFDL-ESM2G, CCSM4, and GFDL-CM3

(a) (b)

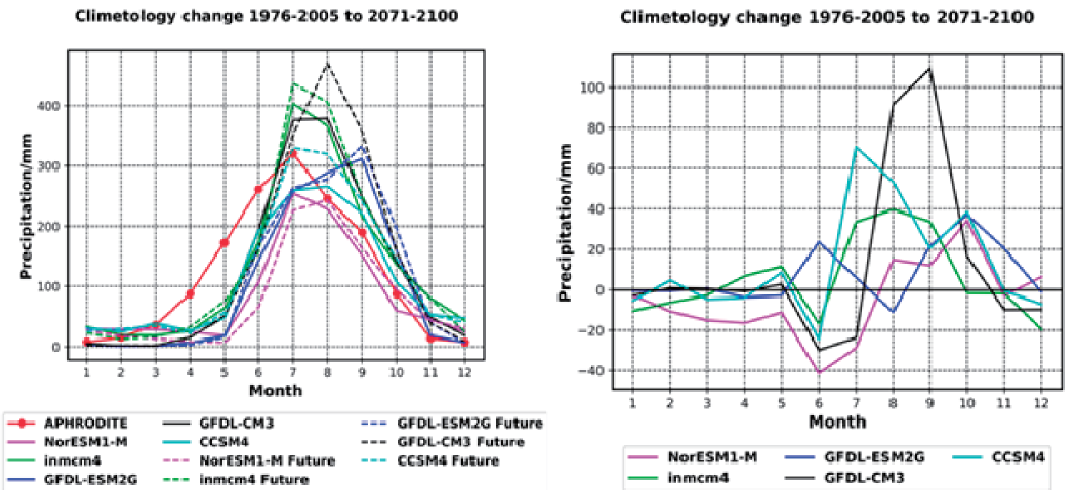

Fig. 3 (a) Historical and future climatology and (b) difference between the future and historical climatology. Thin and dotted lines indicate historical and future trends, respectively.

Table 1 Comparison of model performance in the target domain using the indicators (selected models are marked with stars)

	R	NSE	RMSE
bcc-csm1-1	0.63	-0.03	109.92
CanESM2	-0.24	-0.95	151.07
CCSM4*	0.88	0.76	52.67
CESM1-BGC*	0.90	0.79	49.30
CMCC-CMS	-0.29	-2.04	188.50
CNRM-CM5	-0.06	-0.54	134.04
GFDL-CM3*	0.88	0.61	67.55
GFDL-ESM2G*	0.79	0.49	77.26
inmcm4*	0.86	0.61	67.40
Miroc5	-0.05	-0.24	120.47
MIROC-ESM	-0.49	-1.37	166.27
MRI-CGCM3	-0.06	-2.00	187.42
NorESM1-M*	0.83	0.57	71.09

showed a later trend.

When considering the significance of the simulated trends in Table 2, the APHRODITE precipitation data showed a trend toward earlier onset at the 15% significance level during the historical period, and trend toward a longer duration at the 20% significance level. Only the incm4 model showed a future trend to earlier withdrawal (at the 15% significance level) and shorter duration (at the 25% significance level). But as incm4 showed negative trends in withdrawal in both the historical and future periods, this result was not consistent with the trends in the observation data. The significant trends in observations were not well simulated by all model simulations. Thus, all models could not perform the historical trends in onset, withdrawal and duration, some perform either one or two or all trends during past and future time periods. Both GFDL-CM3 and GFDL-ESM2G models were able to perform all historical trends fairly well. Trends performed by this model were close to the observed trends, and future projections of this models would be a good guidance for a realistic future estimation. Due to this reason, assessment on the future trends based on these two models would be reasonable. This identified early onset during historical period is consistence with the results of experiment carried out by Kajikawa *et al.* (2012).

This research analyzes the trends in onset, withdrawal, and duration simulated by models compared to the observations in past and examine the future. Though precipitation simulated by models are not exact as observed one, it was believed that is relatively robust against the quantitative bias.

4. Conclusion

Several, but not all, of the CMIP5 general circulation models (GCMs) simulated the ISM in the selected domain well. Models which were capable to simulate ISM well in selected domain were

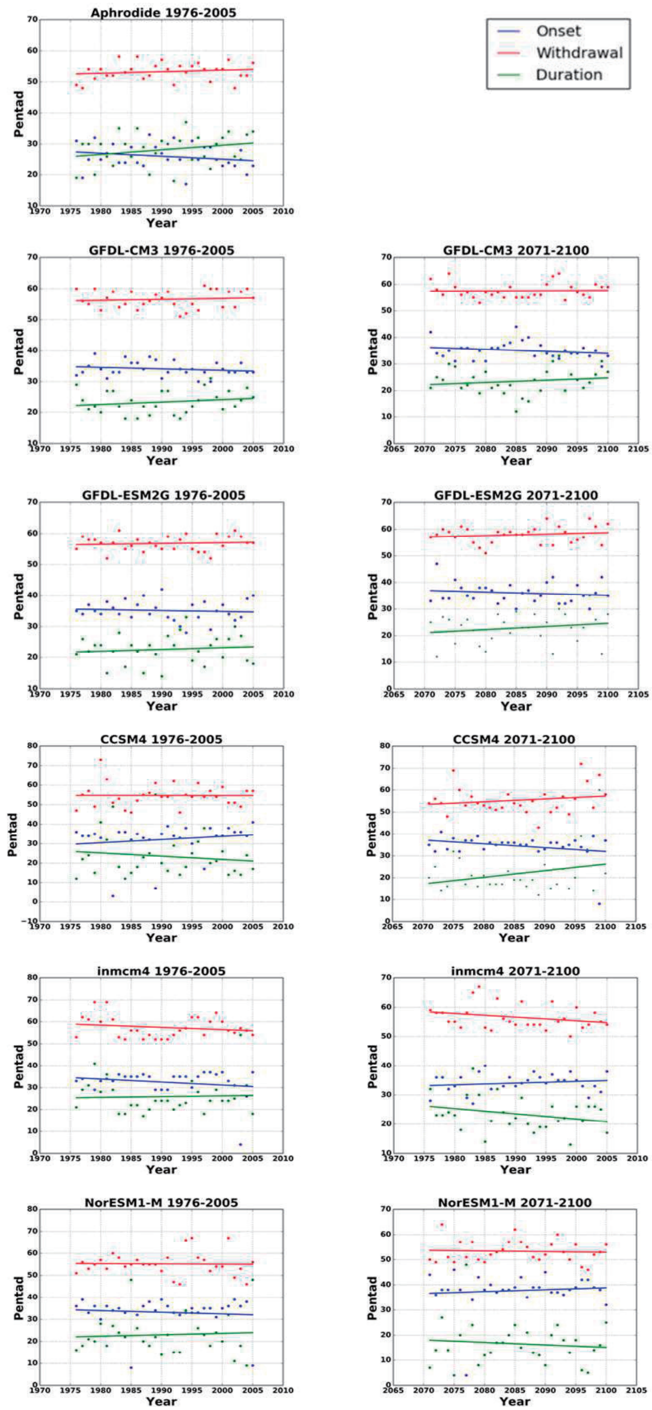

Fig. 4 Trends in the APHRODITE data and comparison of the historical and future trends in monsoon onset, withdrawal, and duration with models.

selected for detailed analysis, based on the comparison of climatological mean monthly rainfall. Some of the GCMs could simulate all three parameters (i.e., the onset, withdrawal, and duration), while others could simulate only one or two. Among these models GFDL-CM3 and GFDL-ESM2G showed good agreement with the historical trends in onset, withdrawal, and duration (Figure 4 and Table 2). Future projections of this two models are more reliable in future assessments. Projections of both of this GCMs under the RCP 8.5 scenario showed that the past trends observed in the monsoon onset, withdrawal, and duration would persist in the future. To sum up the result of this study, in future the trend of monsoon onset will be early, and withdrawal will be later and as a result the duration will become longer in the northeastern Indian subcontinent.

Table 2 Trends in the onset, withdrawal, and duration in the historical (1976–2005) and future (2071–2100) periods. +++/- - -; Significant at 0.15 level, ++/- -; Significant at 0.20 level, +/-; Significant at 0.25 level in Mann–Kendal trend test

	Pentad per 10years					
	Onset		Withdrawal		Duration	
	historical	Future	historical	future	historical	future
APHRODITE	-1.00^{---}		0.50		1.50^{++}	
CCSM4	1.98	-1.70	-0.56	1.30	-2.54	3.00
GFDL-CM3	-0.50	-0.80	0.30	0.10	0.80	0.90
GFDL-ESM2G	-0.30	-0.60	0.30	0.60	0.60	1.20
inmcm4	-1.12	0.60	-1.50	-1.20^{---}	-0.38	-1.80^{-}
NorESM1-M	-0.57	0.70	-0.43	-0.20	0.14	-1.00

These results imply that it is necessary to consider adaptive measures for the possible social and environmental impacts caused by future changes in the ISM. Ensemble simulations using multiple models should increase the statistical significance of the results and reduce the uncertainty of the model projections. In trend analysis, it is necessary to divide into decadal variability and long-term trend. For that, the trend of seasonal march of ISM during historical period will be analyzed using more longer dataset in future.

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References

Ananthakrishnan, R., Pathan, J. M. and Aralikatti, S. S. 1981. On the northward advance of the

ICTZ and the onset of the southwest monsoon rains over the southeast Bay of Bengal. *Journal of Climatology* **1**: 153–165.

Bollasina, M. A., Ming, Y. and Ramaswamy, V. 2013. Earlier onset of the Indian monsoon in the late twentieth century: the role of anthropogenic aerosols. *Geophysical Research Letters* **40**: 3715–3720.

Kajikawa, Y., Yasunari, T,, Yoshida, S. and Fujinami, H. 2012. Advanced Asian summer monsoon onset in recent decades. *Geophysical Research Letters* **39**: 1–5.

Kendall, M. G. Rank Correlation Methods 4th edn (London: Griffin).

Kiguchi, M. and Matsumoto, J. 2005. The rainfall phenomena during the pre-monsoon period over the Indochina Peninsula in the GAME-IOP year, 1998. *Journal of the Meteorological Society of Japan* **83**: 89–106.

Kitoh, A., Endo, H., Krishna, K. K., Cavalcanti, I.F.A., Goswami, P. and Zhou, T. 2013. Monsoons in a changing world: a regional perspective in a global context. *Journal of Geophysical Research: Atmospheres* **118**: 3053–3065.

Kitoh, A., Uchiyama, T. 2006. Changes in onset and withdrawal of the East Asian summer rainy season by multi-model global warming experiments. *Journal of the Meteorological Society of Japan* **84**: 247–258.

Krishna, K. K., Rupa, K. K., Ashrit, R. G., Deshpande, N. R. and Hansen, J. W. 2004. Climate impacts on Indian agriculture. *International Journal of Climatology* **24**: 1375–1393.

Krishnamurthy, V. and Shukla, J. 2000. Intraseasonal and interannual variability of rainfall over India. *Journal of Climate* **13**: 4366–4377.

Krishnan, R. 1999. Dynamics of breaks in the Indian summer monsoon. *Journal of the atmospheric sciences* **57**: 1354–1372.

Marshall, J. 2010. Unintelligent design. *Architectural Record* **198**: 18.

Matsumoto, J. 1997. Seasonal transition of summer rainy season over Indochina and adjacent monsoon region. *Advances in Atmospheric Sciences* **14**: 231–245.

Rajeevan, M., Gadgil, S. and Bhate, J. 2010. Active and break spells of the Indian summer monsoon. *Journal of earth system science* **119**: 229–247.

Ramage, C. 1971. Monsoon Meteorology. *International Geophysics Series* **15**: 296.

Sabeerali, C. T., Rao, S. A., Ajayamohan, R. S, and Murtugudde, R. 2012. On the relationship between Indian summer monsoon withdrawal and Indo-Pacific SST anomalies before and after 1976/1977 climate shift. *Climate Dynamics* **39**: 841–859.

Sahana, A. S., Ghosh, S., Ganguly, A. and Murtugudde, R. 2015. Shift in Indian summer monsoon onset during 1976/1977. *Environmental Research Letters* **10**: 054006.

Sharmila, S., Joseph, S., Sahai, A. K., Abhilash, S, and Chattopadhyay, R. 2015. Future projection of Indian summer monsoon variability under climate change scenario: an assessment from CMIP5 climate models. *Global and Planetary Change* **124**: 62–78.

Syroka, J. and Toumi, R. 2004. On the withdrawal of the Indian summer monsoon. *Quarterly Journal of the Royal Meteorological Society* **130**: 989–1008.

Trenberth, K. E., Stepaniak, D. P. and Caron, J. M. 2000. The global monsoon as seen through the divergent atmospheric circulation. *Journal of Climate* **13**: 3969–3993.

Turner, A. G. and Annamalai, H. 2012. Climate change and the South Asian summer monsoon. *Nature Climate Change* **2**: 587–595.

Webster, P. J. 1987. The elementary monsoon. *Monsoons*. 3–32.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N. and Kitoh, A. 2012. Aphrodite constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society* **93**: 1401–1415.