American Journal of Climate Change, 2016, 5, 133-146
Published Online June 2016 in SciRes. http://www.scirp.org/journal/ajcc
http://dx.doi.org/10.4236/ajcc.2016.52013

Projected Changes in Semi Permanent Systems of Indian Summer Monsoon in CORDEX-SA Framework

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Received 10 February 2016; accepted 27 May 2016; published 31 May 2016

Abstract

The semi-permanent systems such as Seasonal Heat Low (HL), Monsoon Trough (MT), Tibetan Anticyclone (TA), Tropical Easterly Jet (TEJ) and Low Level Jet (LLJ) or Somali jet are observed over Indian region during Indian summer monsoon season (June through September). These systems play a vital role in defining the strength of the Indian summer monsoon rainfall as a whole. Here we evaluate the ability of Consortium for Small-Scale Modeling (COSMO) regional Climate Model (COSMO-CLM), a high resolution regional climate model within the Coordinated Regional Climate Downscaling Experiment for South Asia (CORDEX-SA) framework, to simulate these systems of Indian summer monsoon. The historical runs of the COSMO-CLM for the period 1951-2000 are analysed. Overall the COSMO-CLM is able to simulate these components reasonably well. Possible changes in the position and the strength of these systems and their role in changing rainfall pattern over India are examined to assess the impact of global warming, under the RCP 4.5 simulations towards the end of the century (2051-2100). The analysis shows that the semi permanent systems may not strengthen in the future as compared to the present climate. The summer monsoon rainfall does not show uniform changes over the region. It is likely to enhance over the southern parts of the country, south of 20˚S while it is projected to decrease in the northern parts under the global warming scenario.

Keywords

Summer Monsoon, Semi Permanent Systems, Regional Climate Model, Projected Changes

1. Introduction

Southwest monsoon dominates the climate over the Indian sub-continent. Even now more than 60% of the pop-

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How to cite this paper: Patwardhan, S., Kulkarni, A. and Sabade, S. (2016) Projected Changes in Semi Permanent Systems of Indian Summer Monsoon in CORDEX-SA Framework. *American Journal of Climate Change*, **5**, 133-146.
http://dx.doi.org/10.4236/ajcc.2016.52013

ulation is engaged in the agricultural activities for their livelihood. The agriculture mainly depends on the monsoon rainfall received during the four months June through September. Performance of the monsoon and the spatio-temporal variation in the quantum of seasonal rainfall depends on the so called semi-permanent systems that are seen to be present over the Indian sub continent during summer monsoon season of June through September every year. These systems include Seasonal Heat Low (HL), Monsoon Trough (MT), Tibetan Anticyclone (TA), Tropical Easterly Jet (TEJ) and Low Level Jet (LLJ) or Somali Jet. Krishnamurti and Bhalme (1976) [1] have shown that there exists a quasi-biweekly oscillation in these components of the summer monsoon system.

Findlater (1966) [2] highlighted the existence and importance of the east African low level jet or Somali jet. Findlater (1969 and 1971) [3] [4] confirmed that high-energy flow, in the form of low-level southerly jet streams which had been reported earlier over Kenya, was closely associated with the Inter-Tropical Convergence Zone over the Arabian Sea and western India, and variations in the strength of the stream over Kenya were related to the rainfall which western India received from the south-west monsoon. Joseph and Raman (1966) [5] pointed out the existence of a low level jet stream with core speed of 40 - 60 kts in the monsoon circulation field over south-east Arabian sea and adjoining Peninsular India. The strengthening of the lower tropospheric westerlies in the Arabian sea enhances the monsoon rains along the west coast of India. Desai *et al*. (1976) [6] used the data from Indo-Soviet Monsoon Experiment and confirmed that the active to vigorous monsoon conditions over west coast of India was preceded by the strengthening of Somali jet over the Arabian sea. This jet is known to become the most intense during the months of June, July and August (Krishnamurti and Bhalme, 1976) [1].

The development of a Heat Low (HL) over Indian subcontinent and its location over central regions of Pakistan in July is perhaps the most important causative factor of the monsoon. Heat Low is characterized by anomalously low pressures (3 - 10 hPa lower than the surrounding regions) and is formed due to intense heating of land surface from solar radiation. The low extends only up to 1.5 km above sea level and is overlain by a well marked ridge above. The low pressure in the HL region and the above normal pressures in the peninsula are regarded as favorable for very good monsoon activity over the country. It develops in April-May along with the low-level southwesterly wind regime over the Arabian Sea, almost a month before monsoon arrives over western India (e.g., Ramage, 1966) [7]. It has been observed that the heat low over Pakistan is the deepest in July and not in May. Ramage (1971) [8] has shown that surface pressure at Jacobabad in Pakistan, at the heat low region is inversely related to the monsoon rains over the belt 18˚N to 27˚N. Mean sea level pressure over HL in the month of May has been used as an important predictor of Indian summer monsoon rainfall (Singh *et al*., 1995) [9]. Bollasina and Nigam (2011) [10] have detailed the origin and evolution of heat low over Pakistan region. The strong intensity of the heat low is conducive for good monsoon activity over India.

Monsoon Trough (MT) is regarded as the part of the equatorial trough of the northern summer season over the Indian latitudes. It extends from the seasonal HL over northwest India and neighborhood into the Bay of Bengal. The monsoon disturbances forming over Bay of Bengal region are usually associated with the strengthening of MT over India and in most of the situations herald the active phase of the Indian summer monsoon. It extends up to 6 km above sea level (500-hPa) sloping southwards with height. The position of the trough axis varies on daily scale, which affects rainfall activity over India. The mean position of monsoon trough is along 14˚N. The northward (southward) shift of trough axis, from its mean position, reduces (enhances) the rainfall activity over Indian landmass.

A narrow belt of strong easterly winds is observed between 100 and 200 hPa over southern periphery of India, around 13˚N latitude, throughout the southwest monsoon season (June through September). This is known as Tropical Easterly Jet (TEJ) first observed by Koteswaram (1958) [11]. The jet stream runs from Vietnam to west coast of Africa. TEJ develops due to the influence of continents and oceans on the heat budget of the sub-tropical region. The easterly jet stream over the Peninsular India is the effect of north south thermal gradient during summer. This thermal gradient is effective in reversing the moderately strong westerlies in the lower troposphere into strong easterly current at higher levels. The axis of this jet generally extends from 5˚ - 20˚N during the southwest monsoon season over the Indian sub continent. The strength and the location of the easterly jet stream are often linked with the monsoon activity (Tanaka, 1982) [12]. Interannual variability of the TEJ is closely related to the interannual variability of Indian summer monsoon (Pattanaik and Satyan, 2000) [13]. The deficient (excess) summer monsoon rainfall over India is associated with weaker (stronger) TEJ.

The upper tropospheric (500 hPa) subtropical anticyclone of Asia centered over SE Tibet is known as Tibetan Anticyclone (TA). This high is more marked at 300-hPa and its extent is 70˚ - 110˚E. The heating of the elevated Tibetan Plateau in boreal summer is responsible for the development of the anticyclonic cell over Tibet. This heating accentuates the north-south temperature gradient causing upper tropospheric easterlies to strengthen. Westward shift in the location of Tibetan high, with respect to its normal position, is favorable for the rainfall activity over Indian subcontinent. The equator ward outflow from this anticyclone gains easterly angular momentum and therefore it appears as an easterly jet stream over SE Asia south of 20˚N between 15 hPa and 100 hPa. The TEJ is found in the southern flank of the Tibetan high circulation stretching between South China Sea and Africa, south of 20˚N.

These abovementioned components of summer monsoon over India exist over Indian subcontinent during the four monsoon months of June through September. They play important role in the spatio-temporal variability of monsoon rainfall. Hence to assess their simulation in the regional climate model and the possible changes in these systems under global warming scenario is very crucial. Bucchignani *et al*. (2014) [14] assessed the performance of COSMO-CLM over China. Panitz *et al.* (2014) [15] have analysed COSMO-CLIM simulations over CORDEX-Africa domain. However, this is for the first time, COSMO-CLM is analysed and assessed over CORDEX-SA region for investigating the climate change impacts on monsoonal climate. The COSMO-CLIM simulations are analysed for the period 2001-2050 and 2051-2100. However, the analysis carried out for the period 2001-2050 does not indicate any significant impact of climate change. Hence the results are presented for the period 2051-2100 to indicate the changes in semi-permanent systems in distant future due to global warming.

2 Model and Data

2.1. Model Description and Setup

CORDEX aims to foster international collaboration for generating an ensemble of high-resolution historical and future climate projections on regional scale, by downscaling different Global Climate Models (GCMs) participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al*., 2012) [16].

We have used model simulation from the suite of CORDEX-SA models as this is the most advanced dynamically downscaled data set for the Indian Monsoon region. There are various modeling groups participating in the CORDEX-SA domain, however at present all the parameters required for the present study are available for only one Regional Climate Model (RCM) viz. COSMO-CLM. Hence this study is based on only one RCM.

The CLM (Climate Limited-Area Modeling) Community extended the COSMO-Model to be able to run long-term simulations, the so-called climate mode. The resulting modeling system is called the COSMO-CLM (or CCLM). The COSMO model in Climate Mode (COSMO-CLM or CCLM) is a nonhydrostatic regional climate model developed from the Local Model (LM) of the German Meteorological Service by the CLM-Community. The LM has been developed by the German Weather Service (DWD) for operational weather forecast. Meanwhile it is used and further developed by several other weather services organized in the consortium for small-scale modelling (COSMO). The general goal of COSMO is to develop, improve and maintain a non-hydrostatic limited-area atmospheric model, to be used both for operational and for research applications by the members of the consortium (www.clm.community.eu). Under CORDEX-SA framework, historical and Representative Concentration Pathways (RCP) 4.5 climate experiment runs for CCLM are available for the period 1951-2005 and 2006-2100 respectively, with driving lateral boundary conditions from the European Center HAMburg6 (ECHAM6) model.

2.2. Model Data

Daily simulations of the Historical run of CCLM, for the period of 1951-2000 have been used for model validation. The atmospheric variables used are precipitation, mean sea level pressure, specific humidity as well as the zonal and meridional winds at two levels 850 hPa and 200 hPa. To examine the future changes in monsoonal climate, the RCP4.5 simulations archived at Indian Institute of Tropical Meteorology, Pune, India (http://cccr.tropmet.res.in/cordex/index.jsp) have been used. The model simulations are available at the horizontal resolution of 0.44˚ longitude × 0.44˚ latitude. grid (~50 km × 50 km).

2.3. Observational Data Sets

Zonal and Meridional winds and Mean sea level pressure (MSLP)

The National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis project data sets (Kalnay and Coauthors, 1996) [17] are used for validating the COSMO-CLM model. The gridded reanalysis data are available at a horizontal resolution of 2.5˚ × 2.5˚ for the period from 1948 to present. The three dimensional data set for winds is available on 17 pressure levels. Monthly mean data for Mean Sea Level Pressure, zonal and meridional winds at 850 hPa and 200 hPa during the period 1951-2000 have been used in the present study.

Daily precipitation data from APHRODITE project

The recently introduced Asian Precipitation—Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE) project (Yatagai *et al.*, 2009) [18] provides a long period daily gridded high resolution data set which was prepared by collecting rain-gauge observational data from thousands of stations over the Asian domain. APHRODITE's daily gridded precipitation (APHRO_V1003R1) is a long-term (1951-2007) continental-scale daily product that contains a dense network of daily rain gauge data for Asia including the Himalayas and mountainous areas in the Middle East. APHRO_V1003R1 data sets for Monsoon Asia, Russia and the Middle East (on 0.5˚ × 0.5˚ and 0.25˚ × 0.25˚ grids) are available at http://www.chikyu.ac.jp/precip/. For this analysis we have used the data on 0.25˚ × 0.25˚ lat/long resolution.

3. Results and Discussion

To examine the ability of COSMO-CLM model to simulate summer monsoon rainfall and semi permanent systems during the monsoon season, the historical model simulations are evaluated over fifty years period 1951-2000. Unless the model represents the present climate reasonably well, one can hardly have any confidence in the future projections. For evaluation, all the observed and model simulated parameters have been interpolated on a uniform grid of 0.25 × 0.25 long/lat. The projected changes in the position and the strength of semi-permanent systems towards the end of the century (2051-2100) with respect to 1951-2000 have also been studied.

3.1. Summer Monsoon Precipitation

The rainfall received over Indian landmass during the four summer monsoon months of June to September are vital for the agriculture as well as water resources of the country. Not only quantum, but the spatial as well as temporal distribution of rainfall within the season also plays an important role for the Indian economy. West coast as well as the Northeastern region receives highest rainfall where as northwest India receives the lowest amount of rainfall. The Indo-Gangetic plain and the east central India also receives good amount of rainfall (**Figure 1(a)**). This observed pattern of rainfall is reasonably well captured in the model (**Figure 1(b)**). However model simulates dry bias of more than 4 mm/day over MT region. Rainfall simulation for historical period of 1951-2000 shows wet bias over Jammu and Kashmir region, Northeast and East India (**Figure 1(c)**).

RCP4.5 simulations for the period 2051-2100 are examined to assess the possible change in the quantum and pattern of precipitation under global warming scenario. The model projects 10% - 30% decrease in the summer monsoon rainfall over east central India, Northern states of Northeast India and Northwest India except west Rajasthan (**Figure 1(d)**). Around 5% - 20% increase in seasonal rainfall is projected over southern parts of India, especially south of 20˚N, with more than 20% increase over Kerala. The likely positive changes are also seen over coastal regions of Karnataka and Jammu and Kashmir region.

The specific humidity at surface as well as 850 hPa over Arabian Sea has been analysed to investigate the likely future changes in the moisture content. Model has shown reasonable skill in simulating the specific humidity as compared to Ratna *et al.*, 2014 [19]. RCP4.5 simulations indicate the likely increase in the average moisture over Indian landmass by 11% and 21% at surface and 850hPa respectively (figure not shown).

3.2. Monsoon Indices

Several indices have been proposed to define the strength of the Indian summer monsoon. Parthasarathy *et al.* (1992) [20] defined all-India monsoon index as the area weighted average rainfall over all sub-divisions of India. Webster and Yang (1992) used zonal winds to prepare the index while Goswami (1999) [21] proposed a monsoon circulation index based on meridional winds. This index represents the monsoon Hadley circulation. Wang and Fan (1999) [22] proposed an index based on area averaged outgoing long wave radiation (OLR) averaged over Indian landmass and Bay of Bengal. Here we have computed Goswami wind Index (Goswami *et al.*, 1999) [21] defined as the meridional wind-shear anomaly between 850 hPa and 200 hPa averaged over the region 70˚ - 100˚E and 10˚ - 30˚N and Webster Yang Index to assess the changes in the monsoon circulation in global

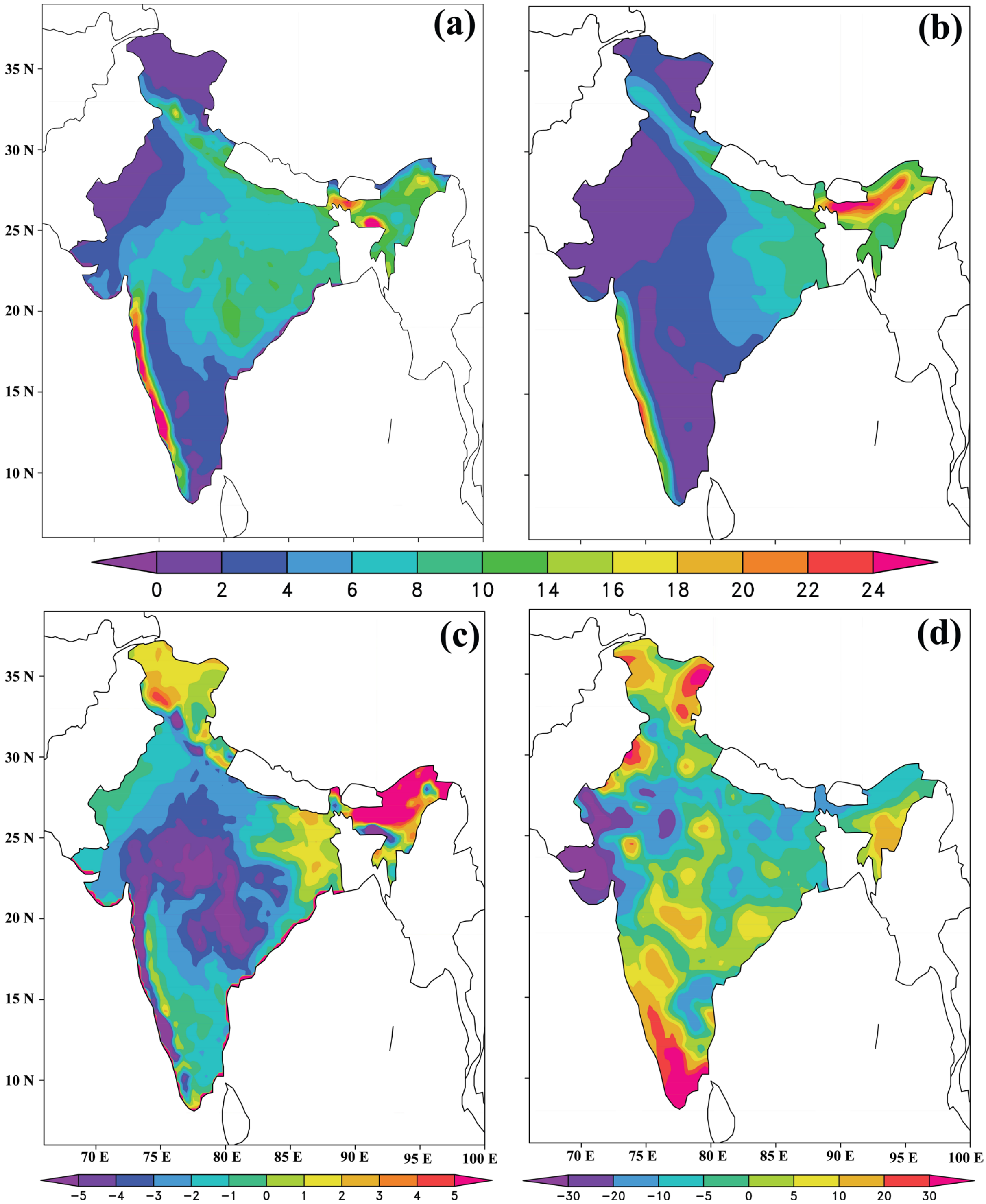


Figure 1. Mean summer monsoon rainfall (June through September, mm/day) over India based on 1951-2000 (a) Observed APHRODITE; (b) Simulated by COSMO-CLM; (c) bias (mm/day); and (d) percentage change for the period 2051-2100 with respect to 1951-2000 under RCP4.5 scenario.

warming scenario. Webster and Yang (1992) [23] proposed a circulation index of the Indian summer monsoon as the zonal wind-shear between 850 and 200 hPa anomaly averaged over 40˚E - 110˚E, 0 - 20˚E. Both the indices have weakened in the future that can be seen from **Table 1** indicating that the monsoon circulation may

Table 1. Projected changes in Goswami Wind Index and Webster Yang Index in 2051-2100 under RCP4.5 scenario with respect to the historical simulation for the period 1951-2000.

	Observed	Historical	RCP4.5
Goswami Wind Index	2.26	2.36	1.81
Trend	Y = 2.66 − 0.016 X	Y = 2.055 + 0.012 X	Y = 1.57 + 0.0094 X
Webster Yang Index	24.29	21.78	20.00
Trend	Y = 25.299 − 0.041 X	Y = 21.343 + 0.017 X	Y = 19.778 + 0.009 X

not intensify under the future scenarios.

The COSMO-CLM model simulates strong positive bias in the meridional monsoon index indicating stronger Hadley circulation in model as compared to observed. However model simulates weak bias in zonal circulation index. Based on 50 years of observed data, both the indices depict significant decreasing trend. The model simulated average indices are comparable with observed, however both indices depict decreasing tendency over fifty years though not statistically significant. Thus the observed significant decreasing trend in both the indices could not be captured by the model (**Figure 2(a)** and **Figure 2(b)**). Under the warming scenario RCP4.5, on an average both the indices have been weakened as compared to the present simulations (**Table 1**). Under RCP4.5 also both the indices depict slightly increasing tendency, however the rate is much smaller than the present century simulations. Under warming scenario both indices have been weakened confirming the weakening of monsoon circulation.

3.3. Seasonal Heat Low (HL)

Low pressure area over northwestern part of India exists from May to September. The normal position of the HL is centred around Jacobabad (Pakistan) and its isobaric value is 998 hPa. Bollasina and Nigam (2011) [10] have shown that HL is deepest in July and not in May.

Figure 3 shows the monthly position of HL in May (**Figures 3 (a)-(c)**), in June (**Figures 3 (d)-(f)**), in July (**Figures 3 (g)-(i)**) and the seasonal HL for the entire monsoon season (June to September) (**Figures 3 (j)-(l)**) for observed, historical and RCP4.5 simulations respectively. The observed lowest pressure over north-west India and Pakistan is around 1002 hPa in May (**Figure 3(a)**) and the area extends up to eastern parts of India. However, the mean position and the mean sea level pressure at HL are very well simulated in the historical runs in May and it extends up to central India. The observations show that the heat low develops gradually from May to July and is strongest in July. The deepening of HL from May to July is very well captured by the model. The seasonal heat low shown in **Figures 3 (j)-(l)**) is shallow as compared to the HL in July as it is deepest in July and weakens comparatively in Aug., and Sept. (figure not shown). However, the pressures associated with the HL region are likely to be more in 2051-2100, more than 1.2 hPa in all the three months: May to July, as compared to the 1951-2000, historical simulations (**Figure 3(c)**, **Figure 3(f)**, **Figure 3(i)** and **Figure 3(l)**), indicating the possible weakening of heat low in future under the global warming scenario.

3.4. Monsoon Trough (MT)

Monsoon trough is an extended low pressure area from the seasonal heat low over northwest India and adjoining area up to the North Bay of Bengal. The position of monsoon trough varies on day-to-day scale and plays an important role in the spatial distribution of seasonal rainfall. When the monsoon trough shifts to the south of its normal position, active phase of monsoon prevails, whereas its northward movement to the foot hills of Himalaya marks the weak phase or break phase of the monsoon (Rao, 1976) [24].

Figure 4 shows the composite observed (a), model simulated (b) and projected (c) seasonal (June to September) mean sea level pressure based on 1951-2000. COSMO-CLM historical simulations show reasonable skill to represent the mean sea level pressure over monsoon trough region (**Figure 4(b)**). However the extent of lowest pressure over NW India is less in historical simulations than the observed (**Figure 4(a)** and **Figure 4(b)**). RCP4.5 simulations show higher sea level pressures over entire monsoon trough region, rise in pressure is more over the HL region (>1.2 hPa) as compared to the eastern end (>0.8 hPa) of monsoon trough (**Figure 4(c)**)

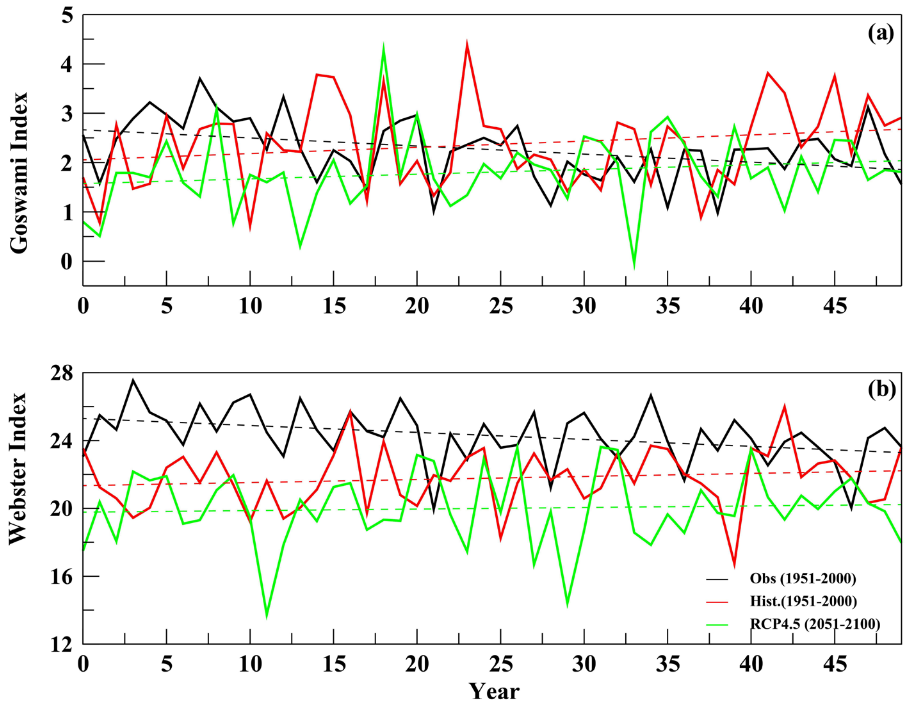
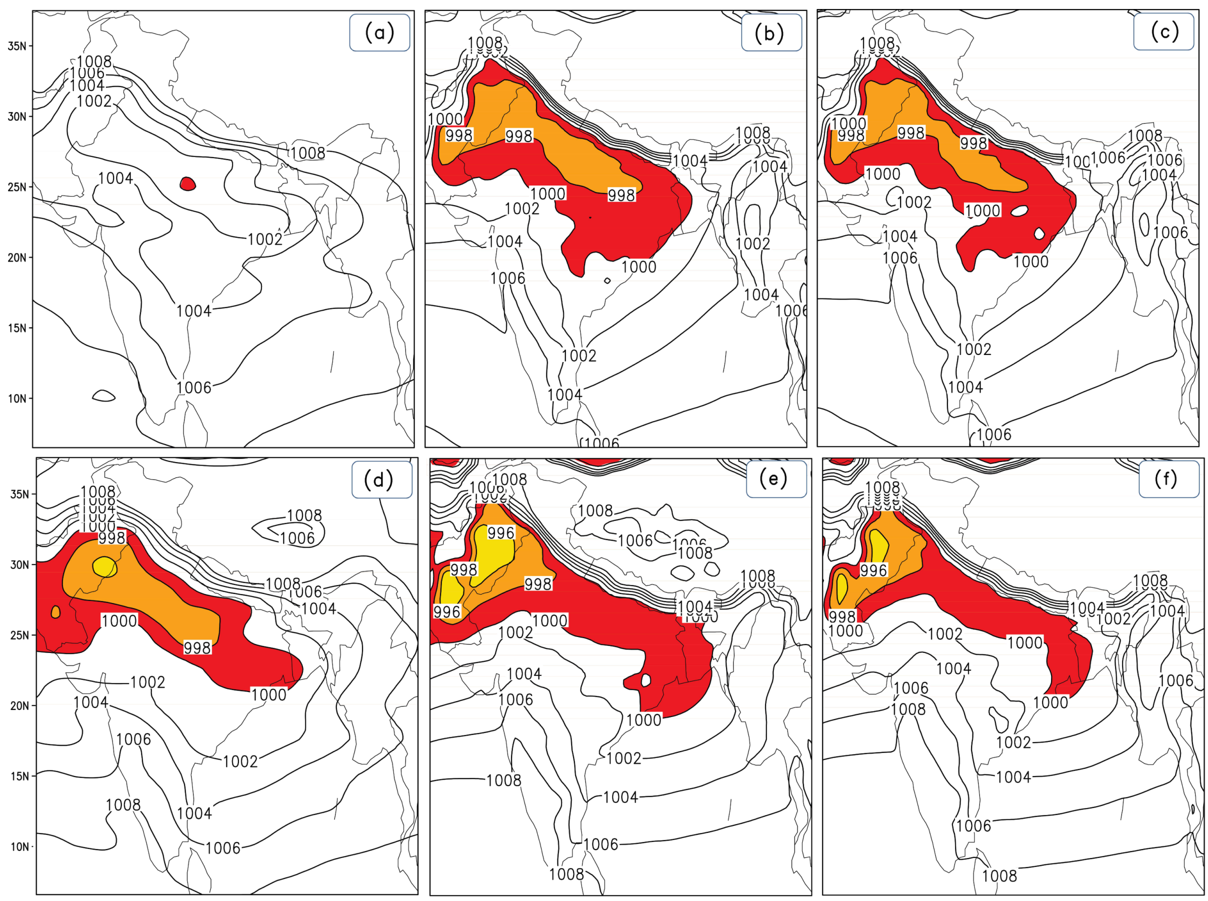


Figure 2. Time series of (a) Goswami Wind Index and (b) Webster Yang Index for observed, historical and RCP4.5 simulations.



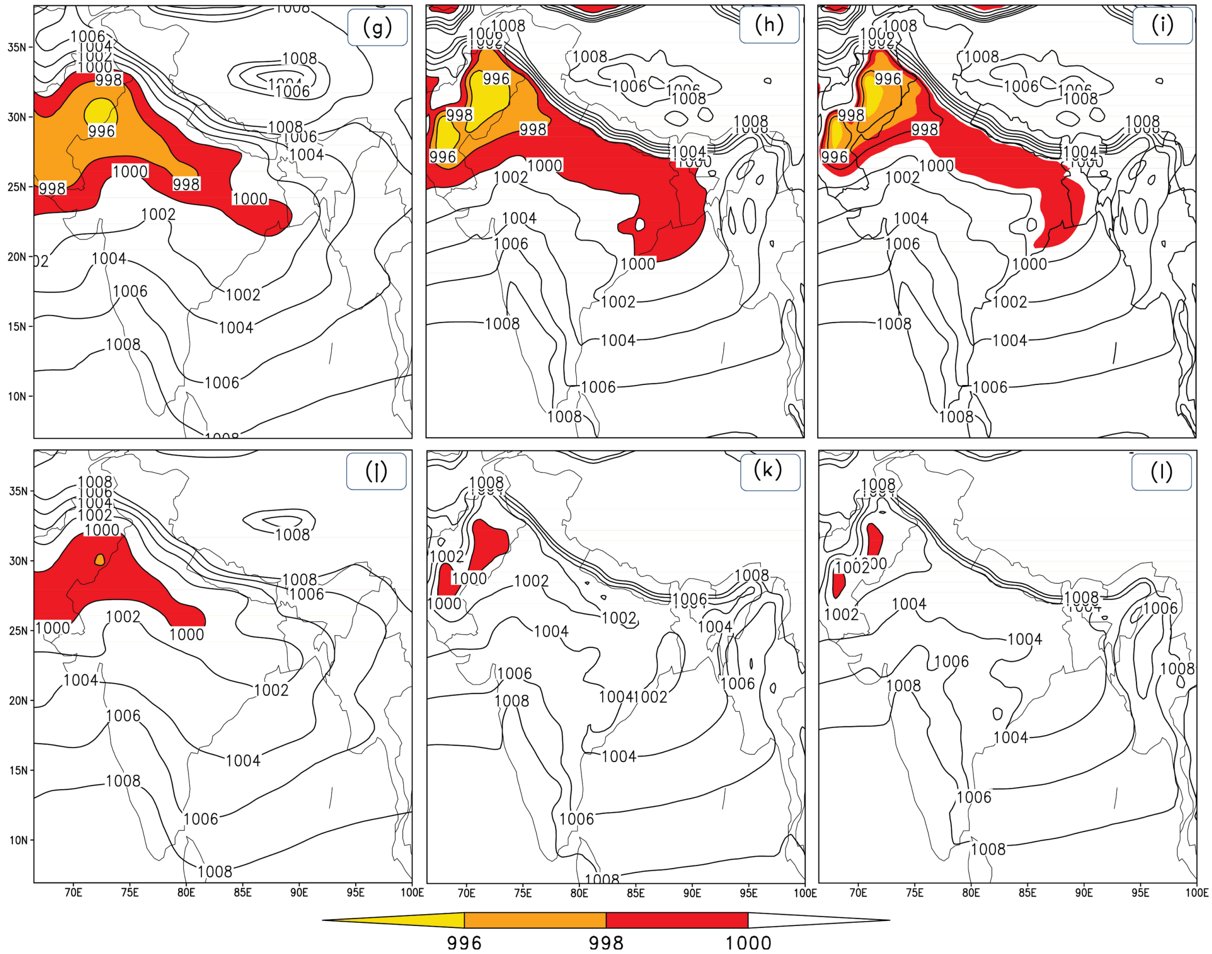
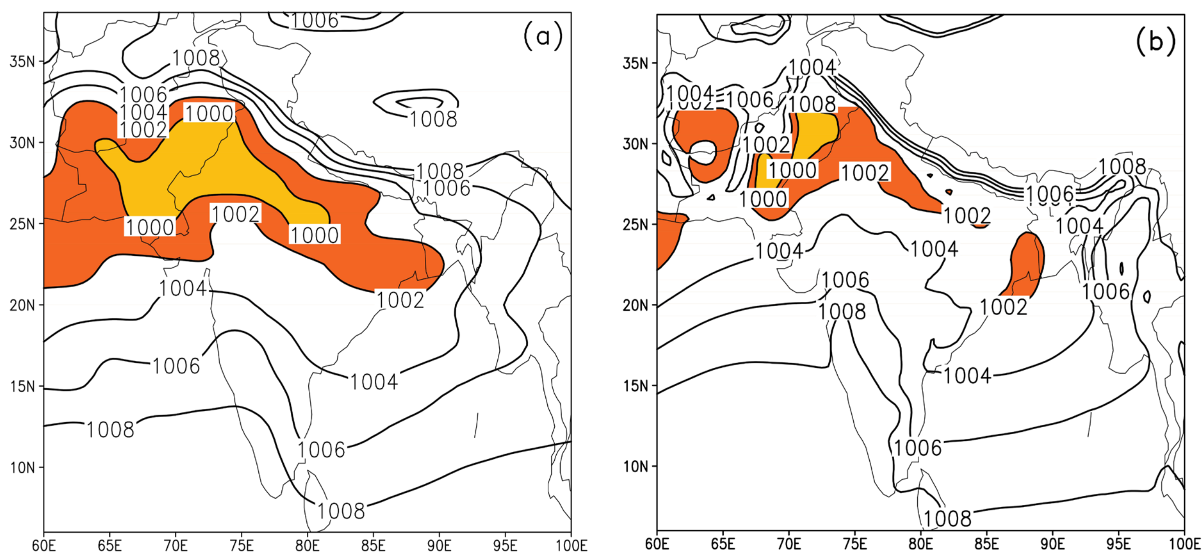


Figure 3. Composite mean sea level pressure (hPa) for the months May, June, July and the season June-September for observed ((a), (d), (g), (j)); historical simulations ((b), (e), (h), (k)) based on 1951-2000 and mean sea level pressure under RCP4.5 ((c), (f), (i), (l)) based on 2051-2100 depicting the heat low over north west India.



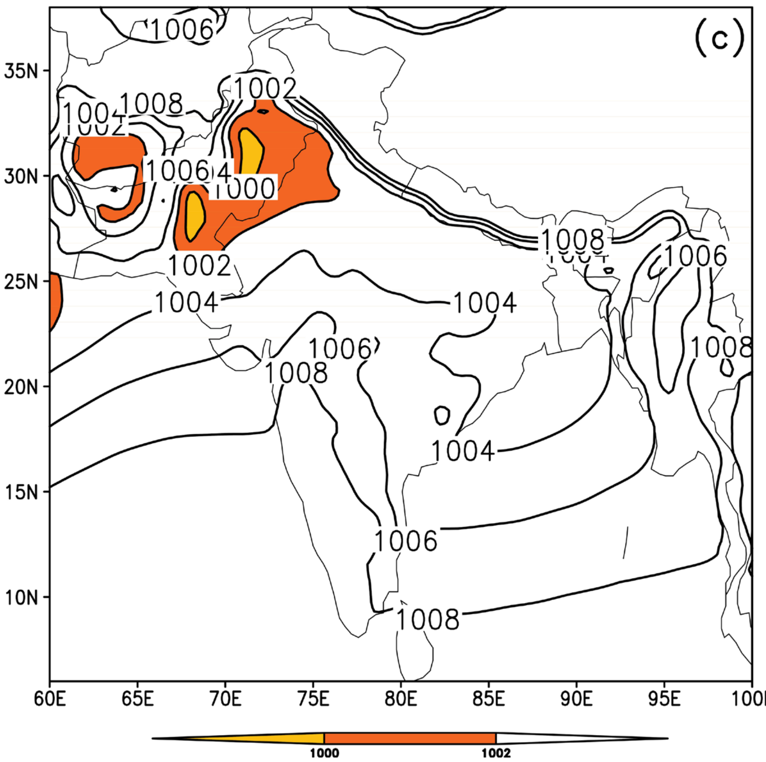


Figure 4. Composite June to September mean Sea level pressure (hPa) pattern based on 1951-2000 over monsoon trough region (a) Observed, (b) Historical for 1951-2000 and (c) RCP4.5 based on 2051-2100.

indicating that the monsoon trough towards the end of the century may not be as deep as in the historical simulations, under climate change scenario. However, there may not be any shift in the position of MT in future.

3.5. Low Level Jet (LLJ)

The cross equatorial flow and the low level jet (LLJ) are very vital components of the summer monsoon at the onset phase and later. The strengthening of the lower tropospheric westerlies in the Arabian Sea is a sign of increase of monsoon rains along the west coast of the Indian Peninsula (south of 20˚N) both at the time of onset and later.

COSMO-CLM historical simulations compared with the observed NCEP/NCAR vector winds show that the LLJ is very well represented in the model as seen from the **Figure 5**. However, the model simulated circulation is stronger than the observed circulation at 850 hPa and also spans the larger area than in observed (**Figure 5(b)**). RCP4.5 simulations do not indicate much change in the strength of the cross equatorial flow during the period 2051-2100 as compared to historical simulations for the period 1951-2000. Also the recurving of westerlies over head Bay of Bengal is not pronounced in future. Hence the monsoon circulation is projected to weaken towards the end of the century as also has been shown in many CMIP5 simulations.

3.6. Tropical Easterly Jet (TEJ)

Upper level winds at 200 hPa are representative of TEJ though the strongest winds are attained at 150 - 100 hPa level. The winds at 100 and 150 hPa level are not available for model simulations. The position as well as the wind speeds at 200 hPa is well represented in the model (**Figure 6(b)**) as compared to observed (**Figure 6(a)**). The model simulates north easterly trade winds over southern Bay of Bengal. However, the TEJ may not be stronger under the RCP4.5 scenario in the period 2051-2100 as seen from the **Figure 6(c)**. The cross equatorial winds as well as the tropical easterly jet diverging from the Tibetan anticyclone are likely to be weaker in RCP4.5 simulation for the period 2051-2100 as compared to the historical period 1951-2000.

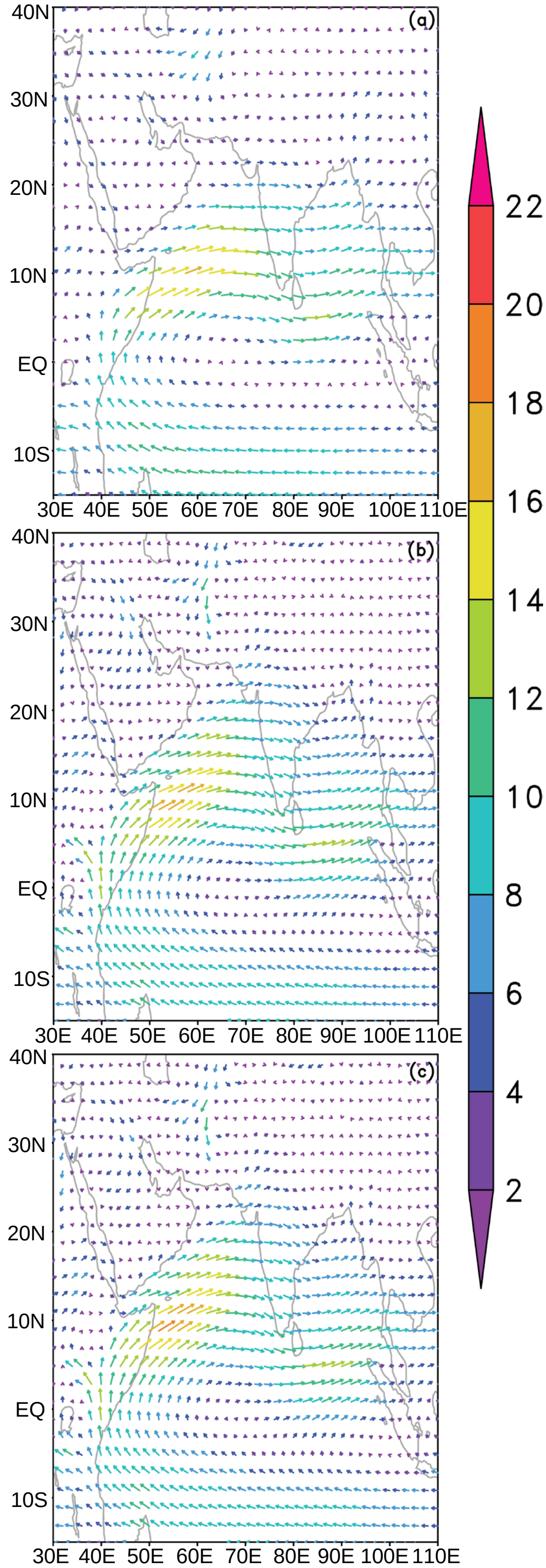


Figure 5. Mean 850 hPa vector winds (m/s) for June through September signifying the LLJ for (a) Observed, (b) historical based on 1951-2000 and (c) Under RCP4.5 based on 2051-2100.

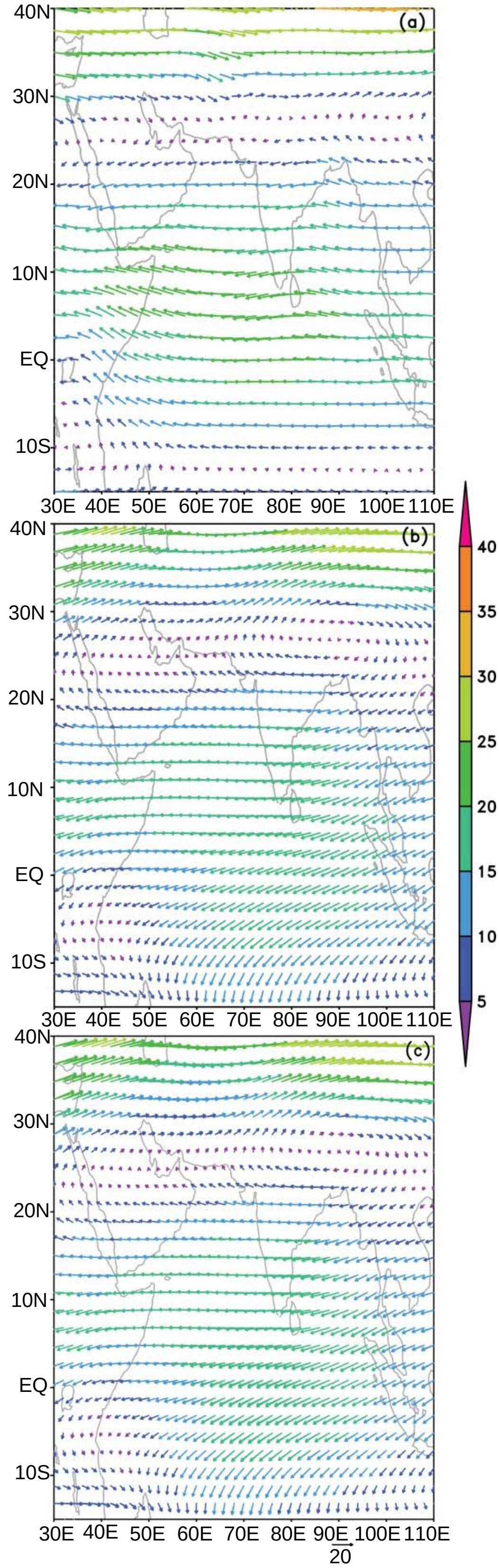


Figure 6. Same as **Figure 5** but for vector winds at 200 hPa depicting TEJ.

3.7. Tibetan Anticyclone (TA)

Tibetan anticyclone is a large anticyclone that has greatest amplitude near 200 hPa during the southwest monsoon season. During monsoon season anticyclone occupies very large area of Tibetan plateau and neighborhood. The normal position of TA at 200 hPa is centered around Lat. 30˚N/Long. 88˚E (Rao, 1976) [24]. It starts moving

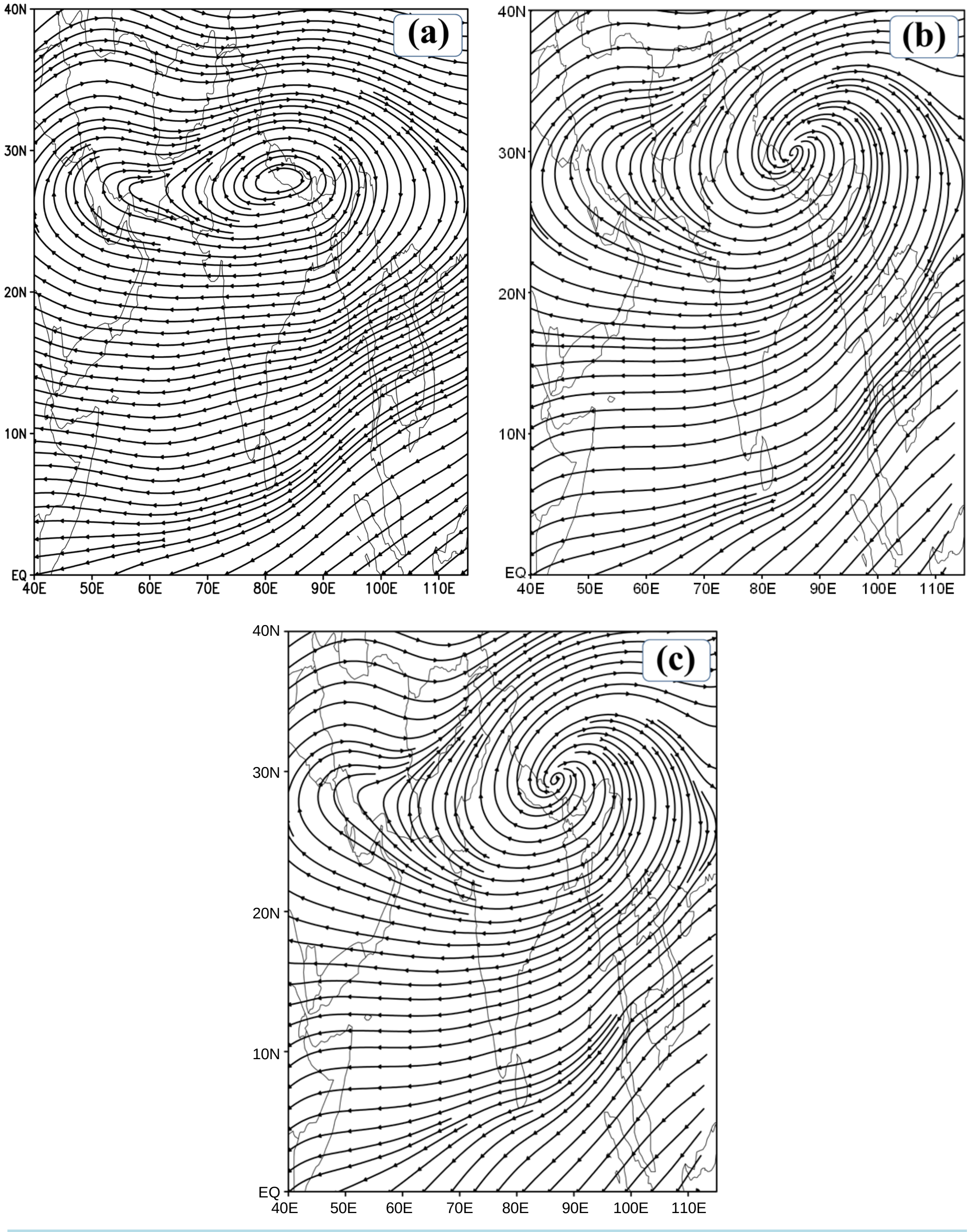


Figure 7. Same as **Figure 5** but for streamlines at 200 hPa signifying the TA.

south southeastwards in September. Change in the position of the TA affects the rainfall associated with the monsoon disturbances along monsoon trough region. Observed TA for the period 1951-2000 using NCEP/NCAR winds at 200hPa compared with the model simulated TA for Jun-August are shown in **Figure 7**. The centre for observed TA is located around lat. 26.6N/long. 80.5E (**Figure 7(a)**) and the historical simulations for the period 1951-2000 shows the centre around lat 30.4N/long. 84.4E (**Figure 7(b)**). The model simulates the centre of TA eastward of its observed position by around 4˚. The future simulations for 2051-2100 show that the TA may be centered around lat. 29.97N/long 87 E indicating southeasterly shift in the centre of TA in future (**Figure 7(c)**). A westward shift from its normal position is favorable for monsoon activity over India however consequences of the shifting the central position to south-eastward is beyond the scope of present study. The east-west extent of TA is however, well simulated by the model in historical as well as RCP4.5 simulations and is comparable with the extent observed.

4. Conclusions

The regional climate model COSMO-CLM under the CORDEX-SA framework is assessed for its ability in simulating the semi-permanent systems of the summer monsoon over India. The historical simulations for the period 1951-2000 are analysed for the validation. The model shows reasonable skill in simulating the semi-permanent systems of the summer monsoon over India. The RCP4.5 simulations for the period 2051-2100 are examined to study the likely changes in the strength and position of these components under the global warming scenario RCP4.5.

The seasonal monsoon rainfall is likely to decrease during 2051-2100, with increase in precipitation over some pockets over Indian landmass. Overall, the semi-permanent systems are likely to be less intense in future as compared to the model historical simulations of 1951-2000. The central pressure over HL as well as over MT region might be more during 2051-2100 under the RCP4.5 scenario. The lower as well as upper tropospheric circulation may not strengthen in the future. In effect the monsoon is projected to decrease over major parts of the country. These results are based on the single model from CORDEX-SA and hence involve a large uncertainty. More models will be analysed when the data is made available.

Acknowledgements

The authors are thankful to the Director, IITM, Pune and Dr. Krishnan, Exe. Director, CCCR, IITM for their support and encouragement. Thanks are due to CORDEX-SA team for providing the simulations for model COSMO-CLM. The graphics have been prepared using GrADS software, the authors are thankful to their team.

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