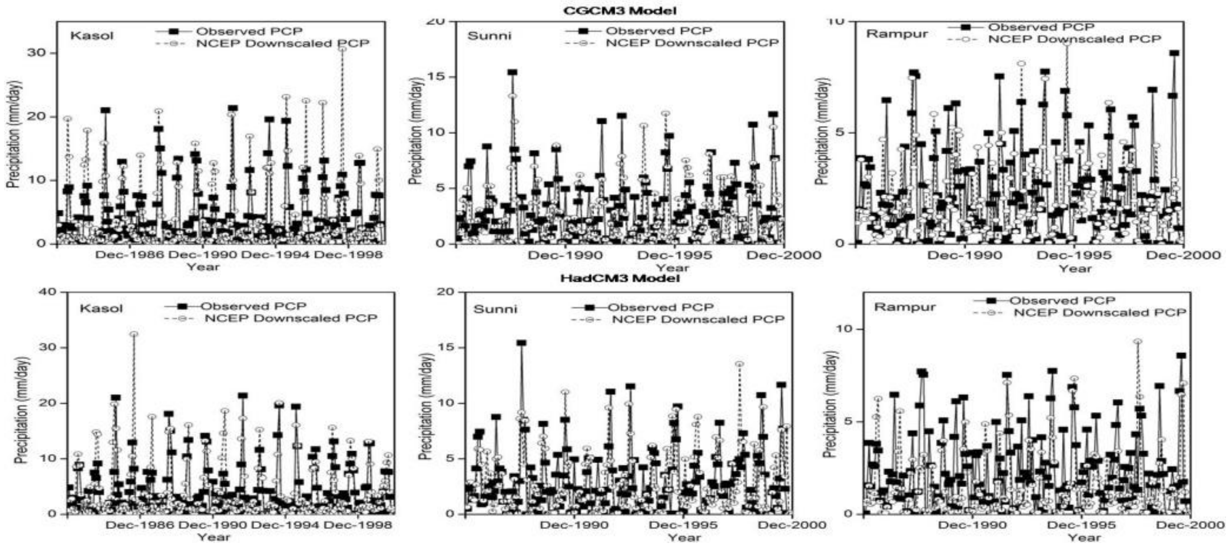

Figure 3: Comparing observed and downscaled values of precipitation for all three stations during validation for CGCM3 and HadCM3 models

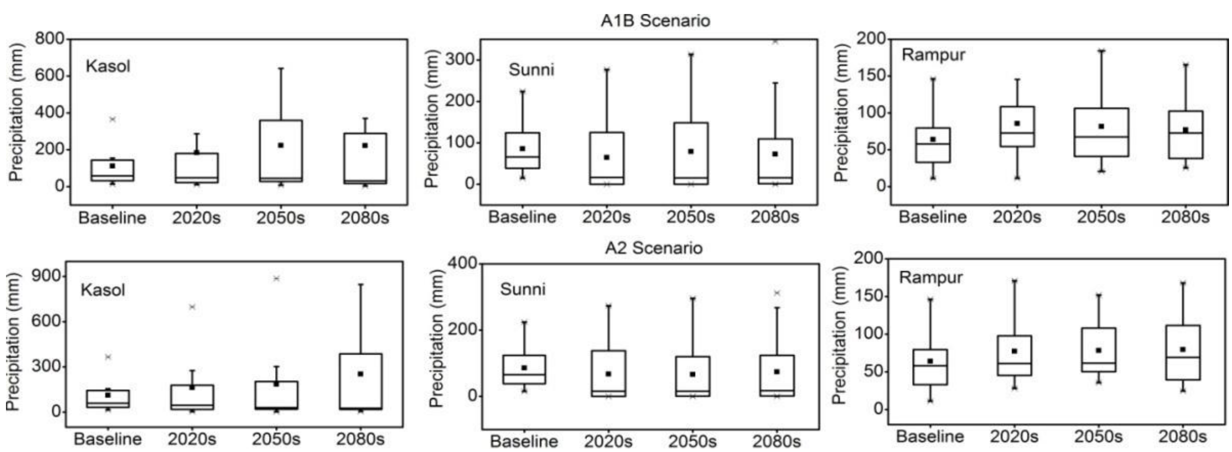

Figure 4: Box plots results from SDSM based downscaling model for the projected precipitation (CGCM3 model). The horizontal line in the middle of the box represents median value while darkened square represents mean value of precipitation data

5.2. Spatial and Temporal Patterns of Downscaled Precipitation for Future Periods

The calibrated SDSM model is used to downscale and generate future scenarios of precipitation from predictors of CGCM3 (SRES A2 and A1B) and HadCM3 (SRES A2 and B2) models in the study region. The pattern of downscaled precipitation is investigated for future periods with a box plot. For this study, the future period is grouped into three time slices; 2020's (2011–2040), 2050's (2041–2070) and 2080's (2071–2099) and each corresponds to span of 30 year periods respectively. The downscaled precipitation is compared with baseline precipitation (1970-2000) to observe change in patterns of precipitation.

The projected precipitation for the future periods (2020's, 2050's and 2080's) has been shown in Figure 4 for the CGCM3 model.

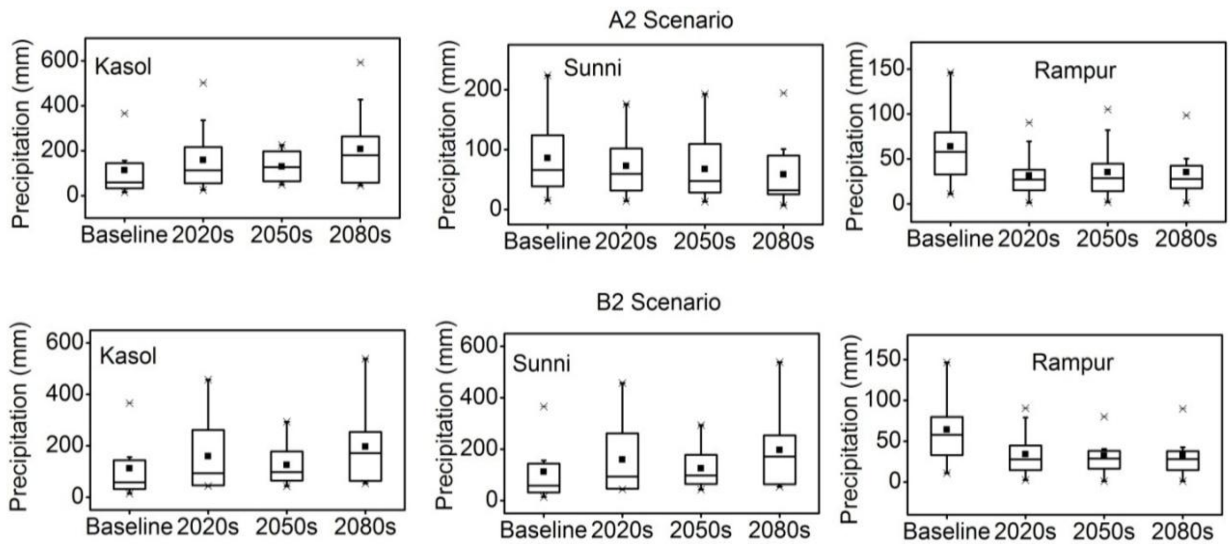

Figure 5: Box plots results from SDSM based downscaling model for the projected precipitation (HadCM3 model). The horizontal line in the middle of the box represents median value while darkened square represents mean value of precipitation data

The increase in future precipitation has been observed at Kasol and Rampur while decrease has been found at Sunni for SRES A2 and SRES A1B scenarios. An overall increase of 5.67%, 8.52% and 18.25% has been computed in mean annual precipitation in the study area under A1B scenario during 2020's, 2050's and 2080's whereas it is 9.21%, 11.23% and 13.91% under A2 scenario respectively. The increase in projected precipitation is higher for A2 scenario as compared to A1B scenario.

The results obtained from HadCM3 model is shown in Figure 5. The decline in amount of simulated precipitation has been found at Sunni and Rampur whereas increase at Kasol for SRES A2 and SRES B2 scenarios. The net change in amount of mean annual precipitation has been computed over study area under SRES A2 and SRES B2 scenarios. The results show increase in magnitude of precipitation under A2 and B2 scenarios for 2080's and decrease for 2050's respectively. This has been found 5.24% under A2 scenario and 4.57% under B2 scenario for 2080's and 3.77% under A2 and 4.08% under B2 for 2050's. For 2020's, no change in mean annual precipitation has been noticed under A2 whereas it is 0.92% under B2 scenario. The poor results obtained during calibration and validation suggests that predictors of HadCM3 model are not well simulated. Further, these are unable to capture regional climate dynamics and hence, poorly projected by SDSM model as compared to CGCM3 model.

The seasonal patterns of projected precipitation have been studied and presented in Table 5 for CGCM3 model. The large increase in projected precipitation has been found at Kasol and significant decrease at Sunni during JJA (June, July, August) periods. The unexpected results have been observed at Rampur. The increase in projected precipitation has been shown during JJA periods for A1B emission scenario and decrease for A2 scenario accordingly. The model predicts increase in projected precipitation under SON (September, October, November) periods for all three stations.

Table 5: Change in projected precipitation during different seasons for CGCM3 model

Station	Season	Change in Precipitation (cm)					
		SRES A2 Scenario			SRES A1B Scenario		
		2020's	2050's	2080's	2020's	2050's	2080's
Kasol	DJF	-0.76	-1.95	-2.74	0.41	1.42	2.14
	MAM	-2.48	-2.79	-2.69	1.25	2.24	2.70
	JJA	19.15	28.75	49.24	25.90	29.90	41.68
	SON	4.13	5.01	12.24	4.78	18.54	7.24
Sunni	DJF	1.27	0.06	0.38	0.50	2.13	0.50
	MAM	-3.40	-3.36	-3.39	3.52	3.56	3.43
	JJA	-10.73	-10.46	-8.42	10.07	7.85	9.26
	SON	5.37	5.97	6.63	5.33	6.50	7.98
Rampur	DJF	1.42	0.44	7.26	1.29	1.74	1.22
	MAM	3.63	8.92	4.40	0.20	1.20	1.81
	JJA	-0.18	-6.24	-5.83	5.29	4.23	2.17
	SON	0.47	2.60	0.41	1.91	2.27	3.60

Table 6: Change in projected precipitation during different seasons for HadCM3 model

Station	Season	Change in Precipitation (cm)					
		SRES A2 Scenario			SRES B2 Scenario		
		2020's	2050's	2080's	2020's	2050's	2080's
Kasol	DJF	19.37	5.11	37.75	18.72	2.39	36.73
	MAM	22.13	6.22	9.99	24.04	6.59	8.78
	JJA	-23.99	-6.99	-23.52	-24.52	-5.84	-23.06
	SON	1.03	2.48	13.78	0.57	2.13	11.38
Sunni	DJF	-0.023	-2.02	-3.37	-0.65	-1.51	-2.23
	MAM	4.78	3.22	0.89	4.55	2.78	2.61
	JJA	-7.98	-6.86	-6.62	-6.57	-5.14	-6.34
	SON	-1.89	-1.60	-1.87	-1.83	-1.77	-1.80
Rampur	DJF	-3.19	0.20	-2.91	-3.20	-3.01	-3.16
	MAM	-2.30	-1.94	-2.21	-1.66	-2.19	-2.36
	JJA	-5.02	-4.32	-4.12	-4.85	-5.14	-4.92
	SON	-2.41	-2.13	-2.12	-2.32	-2.23	-2.20

On contrary, the projected precipitation obtained from HadCM3 model (Table 6) show significant differences in results that are obtained from CGCM3 model. The amount of precipitation is reduced significantly during JJA periods at Kasol. The decrease in projected precipitation has been observed for future periods at Sunni and Rampur respectively.

6. CONCLUSION

In the present paper, a multiple regression based statistical downscaling tool popularly known as SDSM 4.2 is successfully applied to downscale and generate future scenarios of precipitation from predictors of CGCM3 and HadCM3 models in a part of North-Western

(N-W) Himalayan region, India. The change in projected precipitation has been studied for the time periods; 2020's, 2050's and 2080's for SRES A2 and A1B scenarios (CGCM3 model) and for SRES A2 and B2 scenarios respectively. The seasonal patterns of precipitation are also examined and changes with respect to baseline period are shown.

The results of precipitation downscaling using SDSM are found to be poor for HadCM3 model as compared to CGCM3 model. The results obtained from CGCM3 model predict an overall increase in precipitation while decrease in precipitation is predicted by HadCM3 model for the future periods in the region. Based on the analysis of results, CGCM3 model has been found better for simulation of precipitation in comparison to HadCM3 model.

APPENDIX: 1

Abbreviations used in Table 1

Predictors	Description
msl	Mean sea level pressure
p_f	Surface air flow strength
p__v	Surface meridional velocity
p__z	Surface vorticity
p_th	Surface wind direction
pzh	Surface divergence
p5_f	500 hpa airflow strength
p5_u	500 hpa zonal velocity
p5_v	500 hpa meridional velocity
Predictors	Description
p500	500 hpa geopotential height
p5zh	500hpa divergence
p8_z	850 hpa vorticity
p8_th	850 hpa wind direction
s850	Relative/Specific humidity at 850 hpa
p8zh	850 hpa divergence
rhum	Near surface relative humidity
shum	Surface specific humidity
temp	Mean temperature at 2 m

REFERENCES

Anandhi, A., Shrinivas, V.V., Nanjundiah, R.S., Kumar, D.N., 2008. Downscaling precipitation to river basin in India for IPCC SRES scenarios using support vector machine. *International Journal of Climatology* 28 (3), 401-420.

Bardossy, A., Bogardi, I., Matyasovszky, I., 2005. Fuzzy rule-based downscaling of precipitation. *Theoretical and Applied Climatology* 82 (1-2), 119–129.

Basistha, A., Arya, D.S., Goyal, N.K., 2009. Analysis of historical changes in rainfall in the Indian Himalayas. *International Journal of Climatology,* 29 (4), 555-572.

Bhutiyani, M. R., Kale, V. S., Pawar, N. J., 2007. Long-term trends in Maximum, minimum and mean annual air temperatures across the northwestern Himalaya during the twentieth century. Climatic Change, 85, 159-177.

Carter, T.R., La Rovere, E.L, Jones, R.N., Leemans, R., Mearns, L.O., Nakicenovic, N., Pittock, A.B., Semenov, S.M., Skea J., 2001. Developing and applying scenarios. In J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken & K.S. White (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (pp. 145-190), Cambridge University Press, Cambridge.

Chen, S.-T., Yu, P.-S., Tang, Y.-H., 2010. Statistical downscaling of daily precipitation using support vector machines and multivariate analysis. *Journal of Hydrology* 385 (1-4), 13-22.

Dubrovsky, M., Buchtele, J., Zalud, Z., 2004. High-frequency and low frequency variability in stochastic daily weather generator and its effect on agricultural and hydrologic modelling. *Climatic Change* 63 (1-3), 145–179.

Farooq, A.B., Khan, A.H., 2004. Climate change perspective in Pakistan. In A. Muhammed & L. Stevenson (Eds.), Proceedings of Capacity Building APN Workshop on Global Change Research, (pp39-46), Islamabad, Pakistan.

Fowler, H.J., Kilsby, C.G., O'Connell, P.E., 2000. A stochastic rainfall model for the assessment of regional water resource systems under changed climatic conditions. *Hydrology and Earth System Sciences* 4 (2), 261–280.

Ghosh, S., 2010. SVM-PGSL coupled approach for statistical downscaling to predict rainfall from GCM output. *Journal of Geophysical Research* 115, D22102.

Ghosh, S., Mishra, C., 2010. Assessing hydrological impacts of climate change: modeling techniques and challenges. The *Open Hydrology Journal* 4, 115-121.

Giorgi, F., 1990. Simulation of regional climate using a limited area model nested in a general circulation model. *Journal of Climate* 3(9), 941–963.

Gosain, A.K., Rao, S., Arora, A., 2011. Climate change impact assessment of water resources of India. Current Science, 101(3), 356-371.

Hewitson, B. C., Crane, R.G., 1996. Climate downscaling: techniques and application. *Climate Research 7* (2), 85–95.

Hua, C., Jing, G., Wei, X., Guo, S., Xu, C.-Y., 2010. Downscaling GCMs using the Smooth Support Vector Machine Method to predict daily precipitation in the Hanjiang Basin. *Advances in Atmospheric Sciences* 27 (2), 274–284.

http://loki.qc.ec.gc.ca/DAI/predictors-e.html [Last accessed date 3/02/2012].

http://www.cics.uvic.ca/scenarios/index.cgi [Last accessed date 3/02/2012].

Jain, S. K., 2012. Sustainable water management in India considering likely climate and other changes. *Current Science* 102(2), 117-188.

Jones, R.G., Murphy, J.M., Noguer, M., 1995. Simulation of climate change over Europe using a nested regional climate model. I. Assessment of control climate, including sensitivity to location of lateral boundaries. *Quarterly Journal of the Royal Meteorological Society,* 121(526), 1413–1450

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C.,, Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society,* **77**(3), 437–471.

Kim, J. W., Chang, J. T., Baker, N. L., Wilks, D. S., Gates, W. L., 1984. The statistical problem of climate inversion: Determination of the relationship between local and large-scale climate. *Monthly Weather Review*, 112 (10), 2069–2077.

Kumar, V., Jain, S.K., 2010. Trends in rainfall amount and number of rainy days in river basins of India (1951–2004). *Hydrology Research,* 42(4), 290–306.

Kumar, V., Singh, P., Jain S.K., 2005, (April). Rainfall trends over Himachal Pradesh, Western Himalaya, India. In G.N., Mathur, A.S., Chawla, & R.L., Chauhan (Eds),Conference Proceedings, Development of Hydro Power Projects – A Prospective Challenge (II-63-II-71), organized by CBIP & HPSEB, Shimla, New Delhi, India.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A., Wilby, R.L., 2007. A daily weather generator for use in climate change studies. *Environmental Modelling and Software,* 22(12), 1705–1719.

Lapp, S., Sauchyn, D., Toth, B., 2009. Constructing scenarios of future climate and water supply for the SSRB: Use and limitations for vulnerability assessment. *Prairie Forum (Guest Issue),* 34(1), 153-180.

Mason, S.J., 2004. Simulating Climate over Western North America Using Stochastic Weather Generators. *Climatic Change,* 62(1-3), 155–187.

Pant, G.B., Rupa, Kumar, R.R., Borgaonkar, H.P., 1999. Climate and its long-term variability over the western Himalaya during the past two centuries. In S.K., Dash, & J., Bahadur, (Eds). *The Himalayan Environment* (pp. 171-184), New Age International (P) Ltd., Publishers: New Delhi, India.

Raghavan, S.V., Vu, M.T., Liong, S.Y., 2012. Assessment of future stream flow over the Sesan catchment of the Lower Mekong Basin in Vietnam. *Hydrological Process,* 26 (4), 3661-3668, doi: 10.1002/hyp.8452

Raje, D., Mujumdar, P. P, 2011. A comparison of three methods for downscaling daily precipitation in the Punjab region. *Hydrological Process,* 25(23), 3575-3589.

Rupa Kumar, K. R., Sahai, A. K., Krishna, K. K., Patwardhan, S. K., Mishra, P. K., Revadkar, J. V., Kamala, K., Pant, G. B., 2006. High resolution climate change scenario for India for the 21st century. *Current Science* 90 (3), 334–345.

Shrestha, A.B., Wake, C.P., Dibb, J.E., Mayyewski, P.A., 2000. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large-scale climatology parameters. *International Journal of Climatology* 20(3), 317–327.

Tripathi, S., Srinivas, V.V., Nanjundiah, R.S., 2006. Downscaling of precipitation for climate change scenarios: a support vector machine approach. *Journal of Hydrology* 330 (3–4), 621–640.

von Storch, H., Langenberg, H., Feser, F., 2000. A spectral nudging technique for dynamical downscaling purposes. *Monthly Weather Review* 128 (10), 3664–3673.

Wilby, R.L., Hassan, H., Hanaki, K., 1998. Statistical downscaling of hydrometeorological variables using general circulation model output. *Journal of Hydrology* 205 (1-2), 1-19.

Wilby, R.L., Hay, L.E., Leavesly, G.H., 1999. A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River Basin, Colorado. *Journal of Hydrology,* 225 (1-2), 67–91.

Wilby, R.L., Dawson, C.W., Barrow, E.M., 2002. SDSM - a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software,* 17(2), 147-159.

Wilby, R.L., Dawson, C.W., 2007. SDSM User Manual- A Decision Support Tool for the Assessment of Regional Climate Change Impacts. *Retrieved from https://copublic.lboro.ac.uk/cocwd/SDSM/main.html* [Last accessed date 17.11.2011.

Wilby, R. L., Wigley, T. M. L., 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21(4), 530–548.

Xu, Y.C., 1999. From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. *Progress in Physical Geography,* 23(2), 229–249.

Xu, Z., Gong, T., Liu, C., 2008. Decadal trends of climate in the Tibetan Plateau – regional temperature and precipitation. *Hydrological Processes,* 22 (16), 3056–3065.

Zhao L, Ping C L, Yang D Q *et al*., 2004. Change of climate and seasonally frozen ground over the past 30 years in Qinghai-Tibetan plateau, China'. *Global and Planetary Change,* 43, 19–31.