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ARTICLE

Significant Improvement in Rainfall Forecast over Delhi: Annual and Seasonal Verification

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ABSTRACT

Regional Weather Forecasting Centre (RWFC) New Delhi has the responsibility to issue and disseminate rainfall forecast for Delhi. So it is very important to scientifically verify the rainfall forecast issued by RWFC. In this study rainfall forecast verification of Delhi has been carried out annually and season wise for the period 2011 to 2021. Various statistical parameters such as Percentage Correct (PC), Probability of Detection (POD), Missing Ratio (MR), False Alarm Ratio (FAR), Critical Success Index (CSI), True Skill Statistics (TSS) and Heidke Skill Score (HSS) have been calculated for season wise and annually. A forecast is considered to be improved if PC, POD, CSI, TSS and HSS increase and FAR and MR decrease over a period of time. The author can conclude that annual accuracy of forecast has increased significantly over the period of time from 2011 to 2021, as PC, POD, CSI, TSS and HSS increase and FAR and MR decrease over a period of time. Maximum contribution in the improved forecast has observed in transition season (pre-monsoon season followed by post-monsoon, having rainfall activity mainly in association with thunderstorms), when FAR and MR have decreased drastically.

1. Introduction

Delhi is tremendously affected by severe weather activities such as heavy rainfall during monsoon season; severe thunderstorms, severe heat wave, strong squally wind and dust storm during summer season; dense fog, severe cold wave during winter season. Severe weather effects public life such as human health issues during heat and cold wave conditions, air and surface traffic is very much affected during heavy rain, dense fog and strong squally wind, public property is damaged due to heavy rain etc. In India January and February months fall in winter season, March, April and May months fall in pre-monsoon (Summer Season), June, July, August and September months fall in monsoon season (Rainy Season) and October, November and December months fall in post-monsoon Season.

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Mason [1] discussed about the numerous reasons for performing a verification analysis, there are usually two general questions that are of interest: are the forecasts good, and can we be confident that the estimate of forecast quality is not misleading? In general, the vast majority of verification efforts over the past decades have focused on the calculation of one or more verification scores over a forecast-observation dataset, where the observations usually consist of surface or upper air point observations or analyses onto grids. These methods are sometimes referred to as "traditional verification" to contrast them with more recent developments in verification methodology. Casati [2] has discussed the current issues in forecast verification, reviews some of the most recently developed verification techniques, and provides recommendations for future research. Research and development of new approaches to verification has increased greatly over the last 10 years or so, and has been motivated by several factors, including the availability of new sources of data such as satellite and radar, the desire to generate verification results which are more meaningful to specific users or user groups, the advent of new modelling strategies such as ensembles, and the evolution of models and forecasts to higher spatial and temporal resolution. Nurmi [3] provides some general guidelines, various verification measures for continuous meteorological variables, for binary and multi-category weather events and for probabilistic forecasts. Forecast value and the end user decision making issues associated with forecast verification. Murphy [4] has described differences of opinion exist among forecasters and between forecasters and users—regarding the meaning of the phrase "good (bad) weather forecasts". Three distinct types of goodness are identified. 1) The correspondence between forecasters' judgments and their forecasts (type 1 goodness, or consistency), 2) the correspondence between the forecasts and the matching observations (type 2 goodness, or quality), and 3) the incremental economic and/or other benefits realized by decision makers through the use of the forecasts (type 3 goodness, or value). Each type of goodness is defined and described. In addition, issues related to the measurement of consistency, quality, and value are discussed. Nathan [5] explained a method for determining baselines of skill for the purpose of the verification of rare-event forecasts and examples are presented to illustrate the sensitivity to parameter choices. The Storm Prediction Center's convective outlook slight risk areas are evaluated over the period from 1973 to 2011 using practically perfect forecasts to define the maximum values of the critical success index that a forecaster could reasonably achieve given the con-strains of the forecast, as well as the minimum values of the critical success index that are considered the baseline for skilful forecasts. The annual frequency of skilful daily forecasts continues to increase from the beginning of the period of study, and the annual cycle shows maxima of the frequency of skilful daily forecasts occurring in May and June. Srivastava [6] stated that the rainfall can be estimated with a fair degree of accuracy at desired locations within the range of the Doppler Weather Radar using the radar rainfall products and the developed linear regression model.

Doswell [7] the so-called True Skill Statistic (TSS) and the Heidke Skill Score (S), as used in the context of the contingency, table approach to forecast verification, are compared. It is shown that the TSS approaches the Probability of Detection (POD) whenever the forecasting is dominated by correct forecasts of non-occurrence, i.e., forecasting rare events like severe local storms. This means that the TSS is vulnerable to "hedging" in rare event forecasting.

Rainfall activities over Delhi occurs in association with western disturbances (WD) during winter season, in summer season rainfall occurs due to convective thunder storms, during rainy season it occurs in association with monsoonal flow and in post monsoon season due to thunderstorms associated with WD. Regional Weather Forecasting Centre (RWFC) New Delhi has the responsibility to issue and disseminate warnings for the rainfall and disastrous weather affecting Delhi including National Capital Region (NCR). So, it is very important to scientifically verify the rainfall forecast issued by RWFC.

The main objective of this study is to verify the rainfall forecast issued by Regional Weather Forecasting Centre (RWFC) on day-to-day basis. Verification of Delhi has been carried out annually and season wise for the period 2011 to 2021. Various statistical parameters such as Percentage Correct (PC), Probability of Detection (POD), Missing Ratio (MR), False Alarm Ratio (FAR), Critical Success Index (CSI), True Skill Statistics (TSS) and Heidke Skill Score (HSS) have been calculated for season wise and annually. A forecast is considered to be improving if PC, POD, CSI, TSS and HSS increases and FAR and MR decreases over a period of time.

Data used in this study is described in section 2, Methodology used for forecast verification is described in section 3, Analysis and discussion of rainfall forecast verification has been carried out annually and season wise for the period 2011 to 2021 using various statistical parameters in the Section 4 and finally results are concluded in the section 5.

2. Data

To carry out the verification of forecast 24 hours observed rainfall data has been collected from five obser-

vatories of Delhi, namely Safdarjung, Palam, Ayanagar, Ridge and Lodi Road. These observatories are located within 20 km radius from Safdarjung observatory. 24-hour rainfall forecast has been collected from Regional Weather Forecasting Center (RWFC) New Delhi. Using observed and forecast rainfall data various statistical parameters are calculated and forecast verification is done.

3. Forecast Verification Methodology

To verify the forecast, a contingency table is prepared which shows the frequency of "yes" and "no" forecasts and occurrences. The four combinations are:

*Hit Ev*ent: It means forecast to occur, and did occur

M*iss E*vent: It means forecast not to occur, but did occur

F*alse Alarm: It means* event forecast to occur, but did not occur

C*orrect non-event: It means* event forecast not to occur, and did not occur

The contingency table is a useful way to see what types of errors are being made. A perfect forecast system would produce only *hits* and *correct non-event*, and no *misses* or *false alarms* (Table 1).

Table 1. Contigency Table

Event Forecast	Event Observed		
	Yes	**No**	**Marginal Total**
Yes	Hits	False Alarm	Forecast Yes
No	Miss	Correct Non Event	Forecast No
Marginal Total	Observed Yes	Observed No	Sum Total

Categorical statistics that can be computed from the yes/no contingency table are given below.

3.1 Percentage Correct (PC)

Percentage Correct is the accuracy in (%) using the following formula. *Its range is* 0 to 1 and **Perfect score is** 1. It is simple, intuitive. It can be misleading since it is heavily influenced by the most common category, usually "no event" in the case of rare weather.

$$Accuracy = \frac{hits + correct\ negatives}{total}$$

3.2 Probability of Detection (Hit Rate)

It tells fraction of the observed "yes" events that were correctly forecast. Its range is 0 to 1 and **Perfect score is** 1. It is sensitive to hits, but ignores false alarms. POD is very sensitive to the climatological frequency of the event and good for rare events.

$$POD = \frac{hits}{hits + misses}$$

3.3 False Alarm Ratio (FAR)

It tells the fraction of the predicted "yes" events that actually did not occur. Its range is 0 to 1 and **Perfect score is** 1. FAR is sensitive to false alarms, but ignores misses. FAR is Very sensitive to the climatological frequency of the event.

$$FAR = \frac{false\ alarms}{hits + false\ alarms}$$

3.4 Critical Success Index (CSI)

Also known as *Threat score. It tells how well did the forecast "yes" events correspond to the observed "yes" events. Its range is* 0 to 1 and **Perfect score is** 1. **It** Measures the fraction of observed and/or forecast events that were correctly predicted. Sensitive to hits, penalizes both misses and false alarms. Does not distinguish source of forecast error. Depends on climatological frequency of events (poorer scores for rarer events) since some hits can occur purely due to random chance.

$$TS = \frac{hits}{hits + misses + false\ alarms}$$

3.5 Ttrue Skill Statistic (TSS or HK)

It tells how well did the forecast separate the "yes" events from the "no" events. Its range is 0 to 1 and **Perfect score is** 1. TSS uses all elements in contingency table. The expression is identical to HK = POD - POFD. For rare events HK is unduly weighted toward the first term (same as POD), so this score may be more useful for more frequent events.

$$HK = \frac{(hits)}{hits + misses} - \frac{false\ alarms}{false\ alarms + correct\ negatives}$$

3.6 Heidke Skill Score

It tells what was the accuracy of the forecast relative to that of random chance. Its range is 0 to 1 and **Perfect score is** 1. It Measures the fraction of correct forecasts after eliminating those forecasts which would be correct due purely to random chance.

$$Hss = \frac{(hits + correct\ negatives) - (expected\ correct)_{random}}{N - (expected\ correct)_{random}}$$

where,

$$(expected\ correct)_{random}$$

$$= \frac{1}{N}\left[\begin{array}{l}(hits + misses)(hits + false\ alarms) + \\ (correct\ negatives + misses)(correct\ negatives + false\ alarms)\end{array}\right]$$

3.7 Missing Rate

The fraction or percentage of forecast that result in a miss is called the miss rate. It is defined in terms of Hit Rate or POD, which is described in 3.2:

Missing Rate (MR) = 1- Hit Rate

4. Results and Discussion

In this section analysis and discussion of rainfall forecast verification has been carried out annually and season wise for the period 2011 to 2021 using various statistical parameters.

4.1 Annual Forecast Verification

4.1.1 Percentage Correct (PC)

Figure 1 depicts the percentage correct (PC) forecast during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 percentage correct forecast was 88% and 92% respectively with False Alarm Ratio (FAR) was 0.27 and 0.31 respectively (Figure 3). FAR is quite high when compared with the year 2021 having PC and FAR as 93% and 0.13. In the year 2013 percentage correct forecast was 79%, which has increased to 93% in the year 2021. Thus, the accuracy of forecast for Delhi has increased by 14% in last 8 years. It shows that there is significant improvement in the accuracy of forecast after 2013.

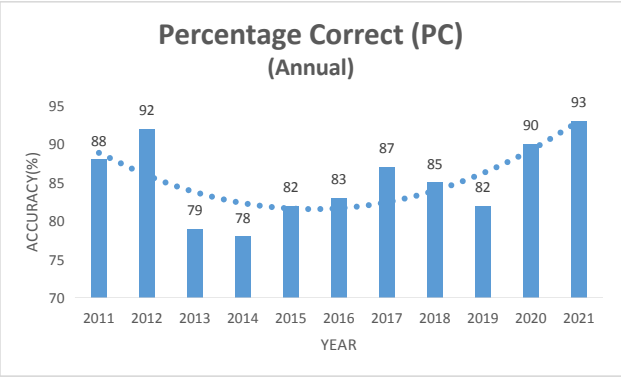

Figure 1. Percentage Correct (PC) for Forecast of Delhi during (2011 – 2021)

4.1.2 Probability of Detection (POD)

The Probability of Detection (POD) for the rainfall event during the period 2011 to 2021 over Delhi is shown in the Figure 2. In the year 2011 and 2012 Probability of Detection (POD) of a rainfall event was around 0.80. In the year 2013 Probability of Detection (POD) was 0.58, which has increased to 0.91 in the year 2021. Thus, the Probability of Detection (POD) for Delhi has increased by 0.33 in the last 8 years. It shows that there is significant improvement in the Probability of Detection (POD) of an event after 2013.

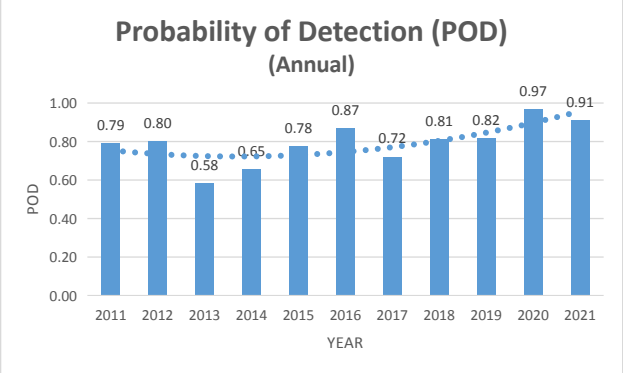

Figure 2. Probability of Detection (POD) for Forecast of Delhi during (2011 – 2021)

4.1.3 False Alarm Ratio (FAR)

Figure 3 illustrates the False Alarm Ratio (FAR) for the rainfall event during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 False Alarm Ratio (FAR) of rainfall event was 0.27 and 0.31 respectively. In the year 2013 False Alarm Ratio (FAR) was very high value 0.62, which has decreased to 0.13 in the year 2021. Thus, the False Alarm Ratio (FAR) for Delhi has decreased by 0.49 in last 8 years. It shows that there is significant decrement in the False Alarm Ratio (FAR) after 2013.

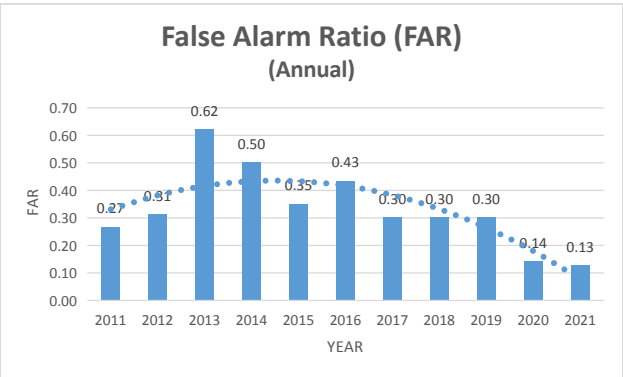

Figure 3. False Alarm Ratio (FAR) for Forecast of Delhi during (2011 – 2021)

4.1.4 Missing Ratio (MR)

The Missing Ratio (MR) for the rainfall event during the period 2011 to 2021 over Delhi is depicted in the Figure 4. In the year 2011 and 2012 Missing Ratio (MR) of a rainfall event was around 0.20. In the year 2013 Missing Ratio (MR) was very heigh value 0.46, which has decreased to 0.09 in the year 2021. Thus, the Missing Ratio

(MR) of an event for Delhi has decreased by 0.37 in last 8 years. It shows that there is significant decrement in the Missing Ratio (MR) after 2013.

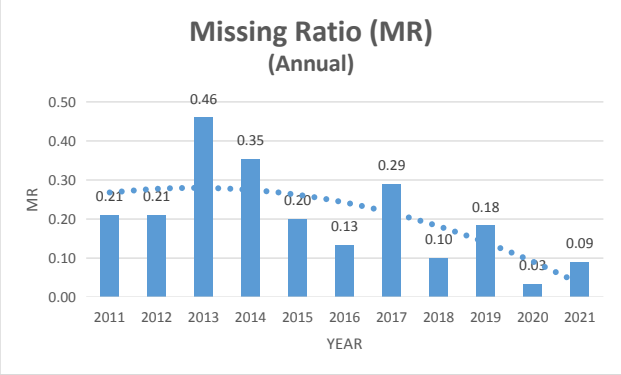

Figure 4. Missing Ratio (MR) for Forecast of Delhi during (2011 – 2021)

4.1.5 Critical Success Index (CSI)

Figure 5 depicts the Critical Success Index (CSI) for the forecast during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 Critical Success Index (CSI) was around 0.60. In the year 2013 Critical Success Index (CSI) was decreased to 0.36, which has increased to 0.81 in the year 2021. Thus, the Critical Success Index (CSI for the forecast of an event for Delhi has significantly increased by 0.45 in last 8 years. It shows that there is significant improvement in the Critical Success Index (CSI) for the weather forecast after 2013.

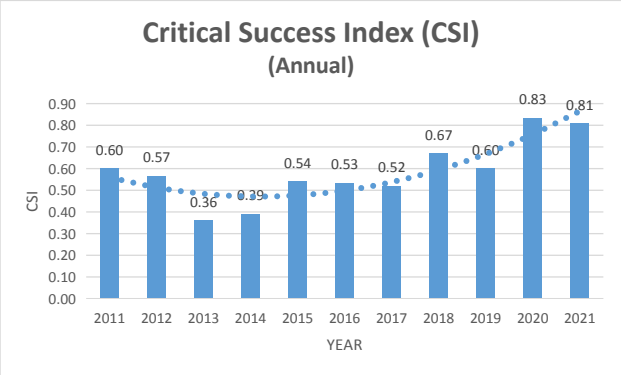

Figure 5. Critical Success Index (CSI) for Forecast of Delhi during (2011 – 2021)

4.1.6 True Skill Statistics (TSS)

Figure 6 depicts the True Skill Statistics (TSS) for the forecast during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 True Skill Statistics (TSS) were 0.61 and 0.68 respectively. In the year 2013 True Skill Statistics (TSS) was decreased significantly to 0.24, which has increased to 0.79 in the year 2021. Thus, the True Skill Statistics (TSS) for the forecast of an event for Delhi has significantly increased by 0.55 in last 8 years. It shows that there is significant increase in the True Skill Statistics (TSS) for the weather forecast after 2013.

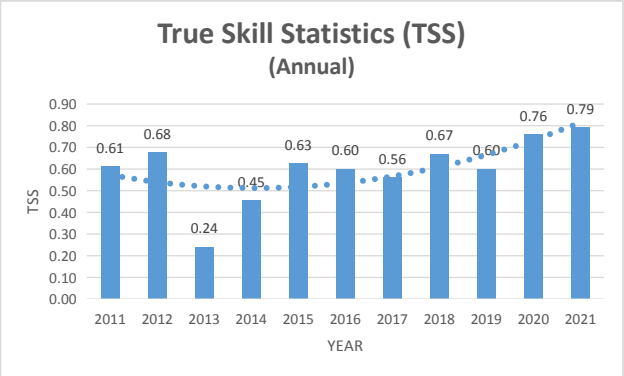

Figure 6. True Skill Statistics (TSS) for Forecast of Delhi during (2011 – 2021)

4.1.7 Heidke Skill Score (HSS)

Figure 7 depicts the Heidke Skill Score (HSS) for the forecast during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 Heidke Skill Score (HSS) were 0.57 and 0.60 respectively. In the year 2013 Heidke Skill Score (HSS) was decreased significantly to 0.25, which has increased to 0.79 in the year 2021. Thus, the Heidke Skill Score (HSS) for the forecast of an event for Delhi has significantly increased by 0.54 in last 8 years. It shows that there is significant increase in the HSS for the weather forecast after 2013.

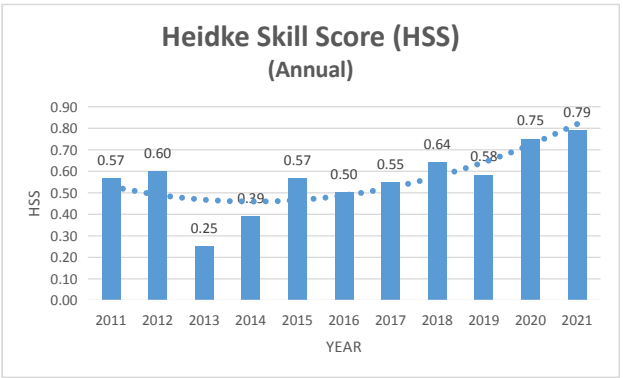

Figure 7. Heidke Skill Score (HSS) for Forecast of Delhi during (2011 – 2021)

Above analysis of PC, POD, FAR, MR, CSI, TSS and HSS for the annual forecast verification for Delhi depicts that PC was higher in the year 2011 and 2012 and again in 2021. But the major difference in these years is that in the year 2021, POD and CSI have significantly increased

and reached up to 0.91 and 0.81 respectively. TSS and HSS also increased significantly in the year 2021 and both reached up to 0.79. Simultaneously FAR and MR have significantly decreased up to 0.13 and 0.9 respectively.

Thus, significant increase in the PC, POD, CSI, TSS and HSS and significant decrease in FAR and MR has been noticed in last 8 years. A forecast is assumed to be improving if PC, POD, CSI, TSS and HSS increases and FAR and MR decreases over a period of time. In this case there is increasing trend in PC, POD, CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement in the forecast during 2011 to 2021.

4.2 Verification of Forecast for Winter Season

4.2.1 Percentage Correct (PC)

Figure 8 depicts the percentage correct (PC) forecast during the period 2011 to 2021 over Delhi during winter season. In the winter season of year 2011 and 2012 percentage correct forecast was 84% and 95% respectively with False Alarm Ratio (FAR) around 0.6 and 0.55 respectively (Figure 10). FAR is quite high when compared with the year 2021 having PC and FAR as 98% and 0.0. In the year 2014 percentage correct forecast was 75%, which has increased to 98% in the year 2021. Thus, the accuracy of forecast for Delhi has increased by 23% in last 7 years during winter season. Figure (8) shows that there is significant improvement in the accuracy of forecast after 2014.

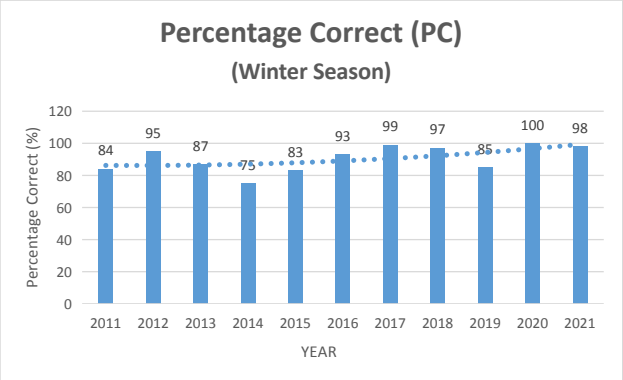

Figure 8. Percentage Correct (PC) for Forecast of Delhi during winter Season (2011 – 2021)

4.2.2 Probability of Detection (POD)

The Probability of Detection (POD) for the rainfall event during the period 2011 to 2021 over Delhi is shown in the Figure 9. In the year 2011 and 2012 Probability of Detection (POD) of a rainfall event was around 0.80. In the year 2013 and 2014 Probability of Detection (POD) was 0.35 and 0.40 respectively, which has increased to 1.0 in the year 2020. Thus, the Probability of Detection (POD) for Delhi has increased by 0.6 in last 6 years. It shows that there is significant improvement in the Probability of Detection (POD) of an event after 2014. In the winter season of the year 2021 POD is reduced to 0.75. Reason for this decrease in POD is that in February 2021 there were only two rainy days, out of which one was predicted correctly and other was missed. Normally 6-7 rainy days are realised in each month of January and February. POD for January 2021 is 1.0, for February 2021 is 0.50 and overall for winter season (2021) is 0.75.

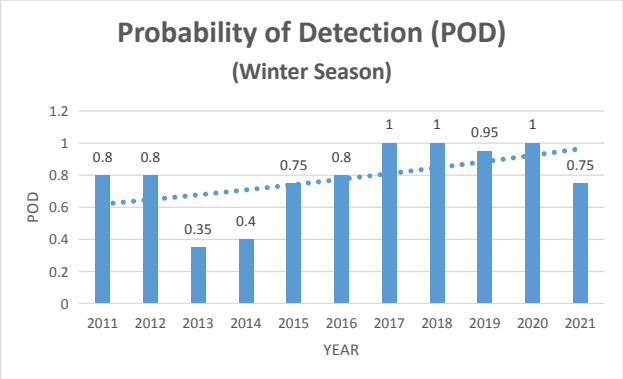

Figure 9. Probability of Detection (POD) for Forecast of Delhi during winter Season (2011 – 2021)

4.2.3 False Alarm Ratio (FAR)

Figure 10 illustrates the False Alarm Ratio (FAR) for the rainfall event during the period 2011 to 2021 over Delhi during winter season. In the year 2011 False Alarm Ratio (FAR) of rainfall event was 0.60. In the year 2013 False Alarm Ratio (FAR) was 0.6, which has decreased to 0.0 in the year 2021. Thus, the False Alarm Ratio (FAR) for Delhi has decreased significantly by 0.6 in last 8 years. It shows that there is significant decrement in the False Alarm Ratio (FAR) after 2011.

4.2.4 Missing Ratio (MR)

The Missing Ratio (MR) for the rainfall event during the period 2011 to 2021 during winter season over Delhi is depicted in the Figure 11. In the year 2011 and 2012 Missing Ratio (MR) of a rainfall event was around 0.20. In the year 2013 Missing Ratio (MR) was very heigh value 0.65, which has decreased to 0.0 in the year 2020. Thus, the Missing Ratio (MR) of an event for Delhi has decreased by 0.65 in last 7 years. It shows that there is significant decrement in the Missing Ratio (MR) after 2013. In the winter season of the year 2021 MR is increased to 0.25 as compared to 2020. Reason for this increase in MR is that

in February 2021 there were only two rainy days, out of which one was predicted correctly and other was missed. Normally 6-7 rainy days are realised in each month of January and February. Missing ratio for January 2021 is 0.0, for February 2021 is 0.50 and overall for winter season (2021) is 0.25.

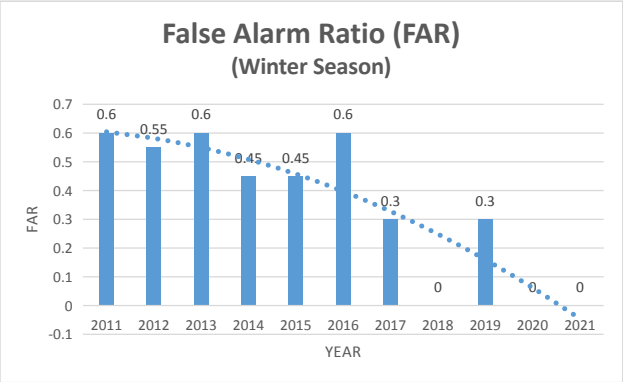

Figure 10. False Alarm Ratio (FAR) for Forecast of Delhi during winter Season (2011 – 2021)

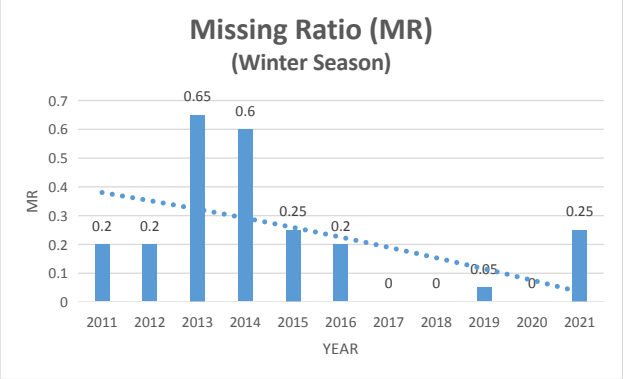

Figure 11. Missing Ratio (MR) for Forecast of Delhi during winter Season (2011 – 2021)

4.2.5 Critical Success Index (CSI)

Figure 12 depicts the Critical Success Index (CSI) for the forecast during the period 2011 to 2021 during winter season over Delhi. In the year 2011 and 2012 Critical Success Index (CSI) was 0.35. In the year 2013 Critical Success Index (CSI) was decreased to 0.25, which has increased to 1.0 in the year 2018 and 2020. Thus, the Critical Success Index (CSI) for the forecast of an event for Delhi has significantly increased by 0.65 in last 8 years. It shows that there is significant improvement in the Critical Success Index (CSI) for the weather forecast after 2013. In the winter season of the year 2021 CSI is decreased to 0.75 as compared to 2020. Reason for this decrease in CSI is that in February 2021 there were only two rainy days, out of which one was predicted correctly and other was missed. Normally 6-7 rainy days are realised in each month of January and February. CSI for January 2021 is 1.0, for February 2021 is 0.50 and overall, for winter season (2021) is 0.75.

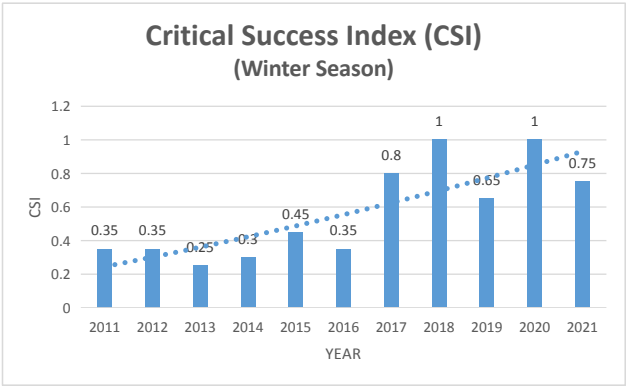

Figure 12. Critical Success Index (CSI) for Forecast of Delhi during winter Season (2011 – 2021)

4.2.6 True Skill Statistics (TSS)

Figure 13 depicts the True Skill Statistics (TSS) for the forecast during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 True Skill Statistics (TSS) were 0.65 and 0.70 respectively. In the year 2013 and 2014 True Skill Statistics (TSS) was decreased significantly to 0.25, which has increased to 1.0 in the year 2020 as compared to year 2013. Thus, the True Skill Statistics (TSS) for the forecast of an event for Delhi has significantly increased by 0.75 in last 7 years. It shows that there is significant increase in the True Skill Statistics (TSS) for the weather forecast after 2013. In the winter season of the year 2021 TSS is decreased to 0 .75 as compared to 2020. Reason for this decrease in TSS is that in February 2021 there were only two rainy days, out of which one was predicted correctly and other was missed. Normally 6-7 rainy days are realised in each month of January and February. TSS for January 2021 is 1.0, for February 2021 is 0.50 and overall for winter season (2021) is 0.75.

4.2.7 Heidke Skill Score (HSS)

Figure 14 depicts the Heidke Skill Score (HSS) for the forecast during the period 2011 to 2021 over Delhi. In the year 2011 and 2012 Heidke Skill Score (HSS) were 0.45 and 0.50 respectively. In the year 2013 Heidke Skill Statistics (HSS) was decreased significantly to 0.20, which has increased to 1.0 in the year 2020. Thus, the Heidke Skill Statistics (HSS) for the forecast of an event for Delhi has significantly increased by 0.8 in last 7 years. It shows that there is significant increase in the Heidke Skill Statistics (HSS) for the weather forecast after 2013. In the win-

ter season of the year 2021 HSS is decreased to 0.75 as compared to 2020. Reason for this decrease in HSS is that in February 2021 there were only two rainy days, out of which one was predicted correctly and other was missed. Normally 6-7 rainy days are realised in each month of January and February. HSS for January 2021 is 0.0, for February 2021 is 0.50 and overall for winter season (2021) is 0.75.

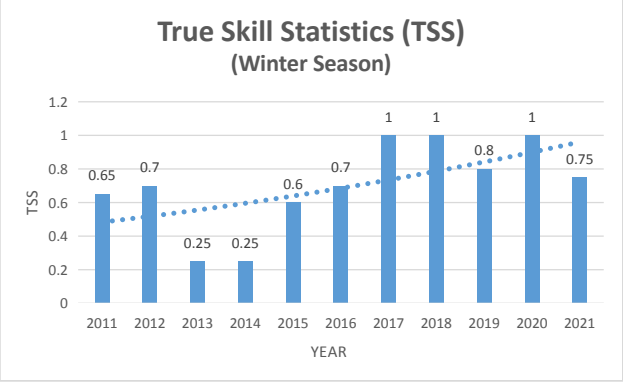

Figure 13. True Skill Statistics (TSS) for Forecast of Delhi during winter Season (2011 – 2021)

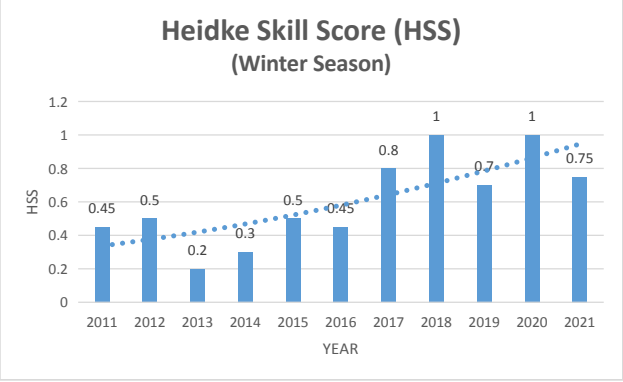

Figure 14. Heidke Skill Score (HSS) for Forecast of Delhi during winter Season (2011 – 2021)

Above analysis of PC, POD, FAR, MR, CSI, TSS and HSS for the winter season forecast verification for Delhi depicts that PC was higher in the year 2011 and 2012 and again in 2021. But the major difference in these years is that in the year 2020, POD and CSI have significantly increased and reached up to 1.0. TSS and HSS also increased significantly in the year 2020 and both reached up to 1.0. Simultaneously FAR and MR have significantly decreased up to 0.0 in the year 2020.

In the year 2021 PC, POD, FAR, MR, CSI, TSS and HSS values were 98%, 0.75, 0.0, 0.25, 0.75, 0.75 and 0.75 respectively. Decrease in POD, CSI, TSS and HSS and increase in MR for the year 2021 is due to the reason that in February 2021 there were only two rainy days, out of which one was predicted correctly and other was missed. Normally 6-7 rainy days are realised in each month of January and February.

Thus, significant increase in the PC, POD, CSI, TSS and HSS and significant decrease in FAR and MR has been noticed in last few years. A forecast is assumed to be improving if PC, POD, CSI, TSS and HSS increases and FAR and MR decreases over a period of time. In this case there is increasing trend in PC, POD, CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement trend in the forecast during 2011 to 2021.

4.3 Verification of Forecast for Pre-monsoon Season

4.3.1 Percentage Correct (PC)

Figure 15 depicts the percentage correct (PC) forecast during the period 2011 to 2021 for pre-monsoon Season over Delhi. In the year 2011 and 2012 percentage correct forecast were 90% and 88% respectively with False Alarm Ratio (FAR) around 0.23 and 0.37 respectively (Figure 17). Trend in Percentage forecast continue to decrease till year 2016, after that it has increasing trend and reached up to 92% in the year 2021 with FAR is 0.20. On comparing year 2011 and year 2021 there is slight increase of 2% in PC and slight decrease of 0.3 in FAR. Thus, the accuracy of forecast for Delhi for pre-monsoon Season has increased by 13% in last 8 years. It shows that there is significant improvement in the accuracy of forecast after 2013.

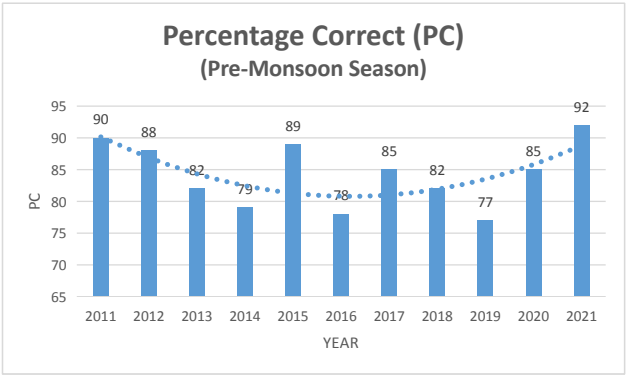

Figure 15. Percentage Correct (PC) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.3.2 Probability of Detection (POD)

The Probability of Detection (POD) for the rainfall event during the period 2011 to 2021 for pre-monsoon Season over Delhi is shown in the Figure 16. In the year 2011 and 2012 Probability of Detection (POD) of a rain-

fall event was 0.73 and 0.63. In the year 2013 Probability of Detection (POD) was 0.30 which was lowest during the period 2011-2021; POD has increased to 0.97 in the year 2021. Thus, the Probability of Detection (POD) for Delhi has increased by 0.67 in last 8 years. It shows that there is significant improvement in the Probability of Detection (POD) of an event after 2013.

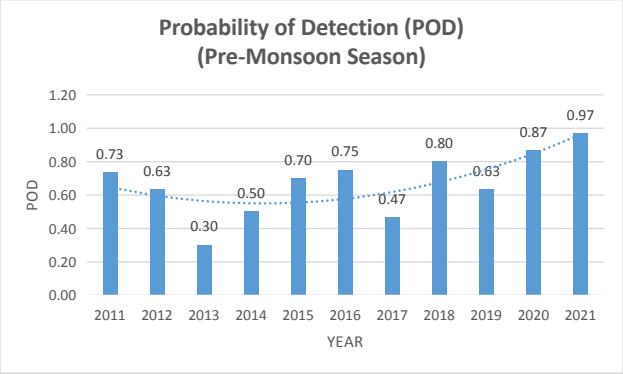

Figure 16. Probability of Detection (POD) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.3.3 False Alarm Ratio (FAR)

Figure 17 illustrates the False Alarm Ratio (FAR) for the rainfall event during the period 2011 to 2021 for pre-monsoon Season over Delhi. In the year 2011 and 2012 False Alarm Ratio (FAR) of a rainfall event was 0.23 and 0.37 respectively. In the year 2013 False Alarm Ratio (FAR) was very high value 0.65, which has decreased to 0.20 in the year 2021. Thus, the False Alarm Ratio (FAR) for Delhi has decreased by 0.45 in last 8 years. It shows that there is significant decrement in the False Alarm Ratio (FAR) after 2013.

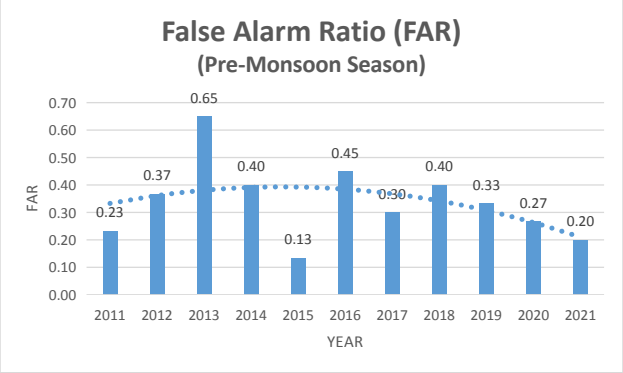

Figure 17. False Alarm Ratio (FAR) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.3.4 Missing Ratio (MR)

The Missing Ratio (MR) for the rainfall events during the period 2011 to 2021 for pre-monsoon Season over Delhi are depicted in the Figure 18. In the year 2011 and 2012 Missing Ratio (MR) of a rainfall event was 0.27 and 0.37 respectively. In the year 2013 Missing Ratio (MR) was very high value 0.80, which has decreased to 0.03 in the year 2021. Thus, the Missing Ratio (MR) of an event for Delhi has decreased by 0.77 in last 8 years. It shows that there is significant decrement in the Missing Ratio (MR) after 2013.

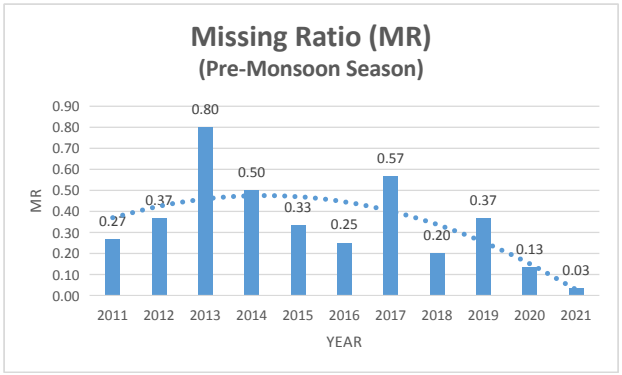

Figure 18. Missing Ratio (MR) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.3.5 Critical Success Index (CSI)

Figure 19 depicts the Critical Success Index (CSI) for the forecast during the period 2011 to 2021 for pre-monsoon Season over Delhi. In the year 2011 and 2012 Critical Success Index (CSI) was 0.60 and 0.40 respectively. In the year 2013 Critical Success Index (CSI) was decreased to 0.15, which has increased to 0.80 in the year 2021. Thus, the Critical Success Index (CSI for the forecast of an event for Delhi has significantly increased by 0.65 in last 8 years. It shows that there is significant improvement in the Critical Success Index (CSI) for the weather forecast after 2013.

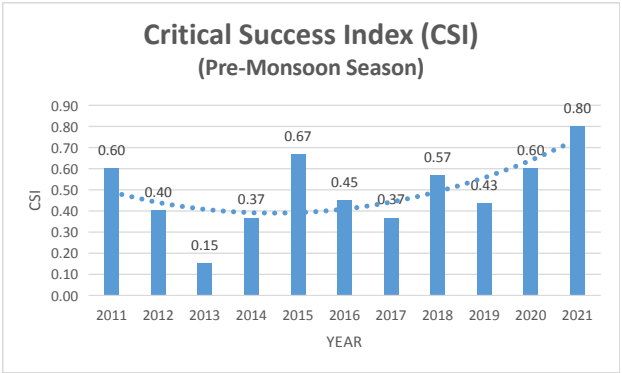

Figure 19. Critical Success Index (CSI) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.3.6 True Skill Statistics (TSS)

Figure 20 depicts the True Skill Statistics (TSS) for the forecast during the period 2011 to 2021 for pre-monsoon Season over Delhi. In the year 2011 and 2012 True Skill Statistics (TSS) was 0.67 and 0.60 respectively. In the year 2013 True Skill Statistics (TSS) was decreased significantly to 0.15, which has increased to 0.87 in the year 2021. Thus, the True Skill Statistics (TSS) for the forecast of the rainfall events for Delhi has significantly increased by 0.72 in last 8 years. It shows that there is a significant increase in the True Skill Statistics (TSS) for the weather forecast after 2013.

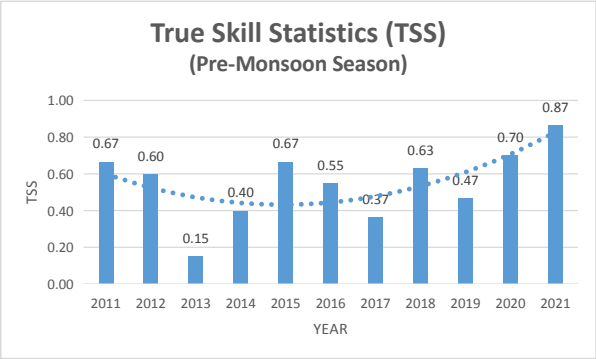

Figure 20. True Skill Statistics (TSS) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.3.7 Heidke Skill Score (HSS)

Figure 21 depicts the Heidke Skill Score (HSS) for the forecast during the period 2011 to 2021 for pre-monsoon Season over Delhi. In the year 2011 and 2012 Heidke Skill Score (HSS) were 0.67 and 0.50 respectively. In the year 2013 Heidke Skill Score (HSS) was decreased significantly to 0.20, which has increased to 0.83 in the year 2021. Thus, the Heidke Skill Score (HSS) for the forecast of an event for Delhi has significantly increased by 0.63 in last 8 years. It shows that there is significant increase in the Heidke Skill Score (HSS) for the weather forecast after 2013.

Above analysis of PC, POD, FAR, MR, CSI, TSS and HSS for the forecast verification for pre-monsoon Season for Delhi depicts that PC was higher in the year 2011, 2012,2015 and again in 2021. But the major difference in these years is that in the year 2021, POD and CSI have significantly increased and reached up to 0.97 and 0.80 respectively. TSS and HSS also increased significantly in the year 2021 and both reached up to 0.87 and 0.83. Simultaneously FAR and MR have also shown decreasing trend and decreased up to 0.20 and 0.03 respectively.

Thus, significant increase in the PC, POD, CSI, TSS and HSS and significant decrease in FAR and MR has been noticed in last 8 years. A forecast is assumed to be improving if PC, POD, CSI, TSS and HSS increases and FAR and MR decreases over a period of time. In this case there is increasing trend in PC, POD, CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement in the forecast during 2013 to 2021.

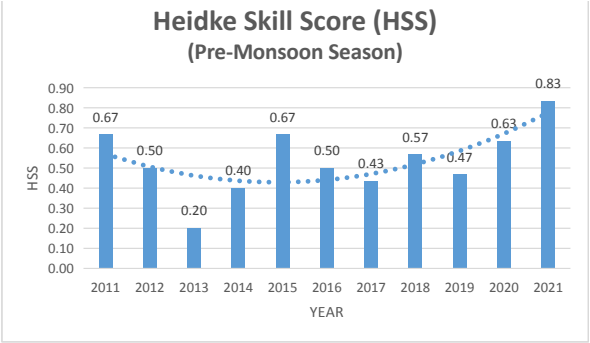

Figure 21. Heidke Skill Score (HSS) for Forecast of Delhi during pre-monsoon Season (2011 – 2021)

4.4 Verification of Forecast for Monsoon Season

4.4.1 Percentage Correct (PC)

Figure 22 depicts the percentage correct (PC) forecast during the period 2011 to 2021 for monsoon Season over Delhi. In the year 2011 and 2012 percentage correct forecast were 80% and 87% respectively with False Alarm Ratio (FAR) 0.1 in both the years (Figure 24). Decreasing trend in Percentage forecast is observed till year 2013, after that it has increasing trend and reached up to 87% in the year 2021 with FAR is 0.2. On comparing year 2011 and year 2021 there is increase of 7% in PC and slight increase of 0.1 in FAR. Thus, the accuracy of forecast for Delhi for pre-monsoon Season has increased by 20% in last 8 years. It shows that there is improvement in the accuracy of forecast after 2013.

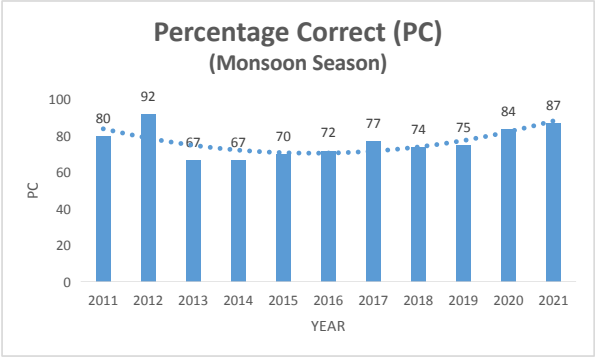

Figure 22. Percentage Correct (PC) for Forecast of Delhi during monsoon Season (2011 – 2021)

4.4.2 Probability of Detection (POD)

The Probability of Detection (POD) for the rainfall event during the period 2011 to 2021 for monsoon Season over Delhi is shown in the Figure 23. In the year 2011 and 2012 Probability of Detection (POD) of a rainfall event was 0.80 and 1.0 respectively. In the year 2013 Probability of Detection (POD) was 0.70 which was lowest during the period 2011-2021; POD in the year 2021 was 0.9. Thus, the Probability of Detection (POD) for monsoon season over Delhi remains close to 0.9 during the period 2011-2021.It shows that there is no large change in the Probability of Detection (POD) of the rainfall in the monsoon season during the study period. The main reason for no large change is that monsoon season is the main rainy season and rainfall occur often, and is well predicted

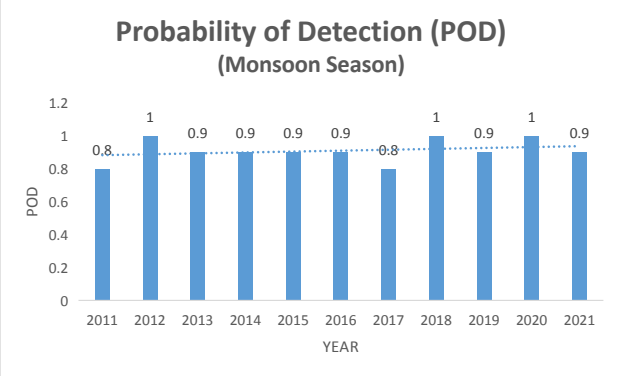

Figure 23. Probability of Detection (POD) for Forecast of Delhi during monsoon Season (2011 – 2021)

4.4.3 False Alarm Ratio (FAR)

Figure 24 illustrates the False Alarm Ratio (FAR) for the rainfall event during the period 2011 to 2021 for the monsoon Season over Delhi. For both In the year 2011 and 2012 False Alarm Ratio (FAR) of the rainfall was 0.1. In the year 2013 False Alarm Ratio (FAR) was very high value 0.7, which has decreased to 0.20 in the year 2021. Thus, the False Alarm Ratio (FAR) for Delhi has decreased by 0.50 in last 8 years. It shows that there is significant decrement in the False Alarm Ratio (FAR) after 2013.

4.4.4 Missing Ratio (MR)

The Missing Ratio (MR) for the rainfall events during the period 2011 to 2021 for the monsoon Season over Delhi are depicted in the Figure 25. In the year 2011, 2014 and 2017 Missing Ratio (MR) of a rainfall event was 0.20. Rest of the years of the period 2011 to 2021, MR is either 0.0 or 0.1. Thus, MR is very low during monsoon season. Overall trend line shows that MR is further decreasing over the years. Reason for decreasing and low values of MR is that rainfall pattern and associated synoptic and atmospheric conditions are well understood during monsoon season.

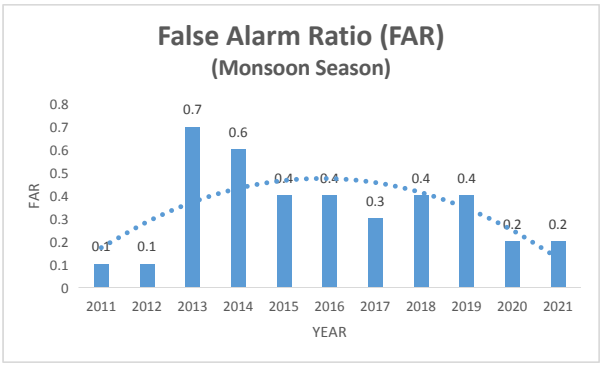

Figure 24. False Alarm Ratio (FAR) for Forecast of Delhi during monsoon Season (2011 – 2021)

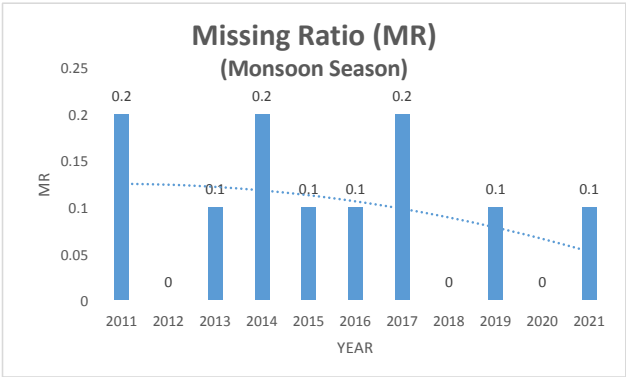

Figure 25. Missing Ratio (MR) for Forecast of Delhi during monsoon Season (2011 – 2021)

4.4.5 Critical Success Index (CSI)

Figure 26 depicts the Critical Success Index (CSI) for the forecast during the period 2011 to 2021 for monsoon Season over Delhi. In the year 2011 and 2012 Critical Success Index (CSI) was 0.70 and 0.90 respectively. In the year 2014 Critical Success Index (CSI) was decreased to 0.4, which has increased to 0.80 in the year 2021. Thus, the Critical Success Index (CSI) for the forecast of rainfall for Delhi has significantly increased by 0.4 in last 7 years. It shows that there is significant improvement in the Critical Success Index (CSI) for the rainfall forecast after 2014.

4.4.6 True Skill Statistics (TSS)

Figure 27 depicts the True Skill Statistics (TSS) for the forecast during the period 2011 to 2021 for monsoon Season over Delhi. In the year 2011 and 2012 True Skill

Statistics (TSS) was 0.5 and 0.70 respectively. In the year 2013 True Skill Statistics (TSS) was decreased significantly to 0.2, which has increased to 0.6 in the year 2021. Thus, the True Skill Statistics (TSS) for the forecast of the rainfall events for Delhi has significantly increased by 0.4 in last 8 years. It shows that there is significant increase in the True Skill Statistics (TSS) for the weather forecast after 2013.

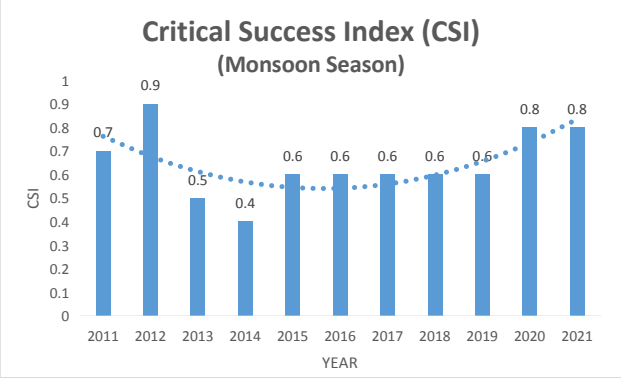

Figure 26. Critical Success Index (CSI) for Forecast of Delhi during monsoon Season (2011 – 2021)

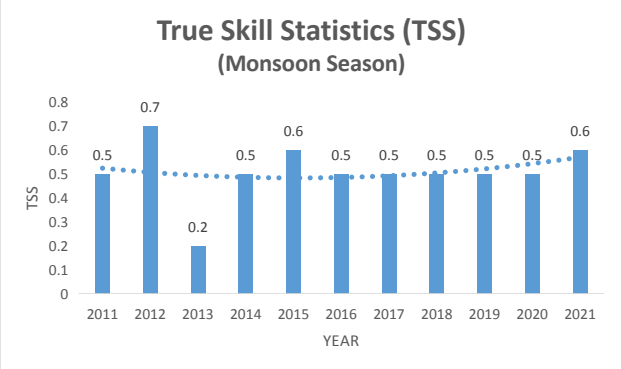

Figure 27. True Skill Statistics (TSS) for Forecast of Delhi during monsoon Season (2011 – 2021)

4.4.7 Heidke Skill Score (HSS)

Figure 28 depicts the Heidke Skill Score (HSS) for the forecast during the period 2011 to 2021 for monsoon Season over Delhi. In the year 2011 and 2012 Heidke Skill Score (HSS) was 0.5 and 0.8 respectively. In the year 2013 Heidke Skill Score (HSS) was decreased significantly to 0.30, which has again increased to 0.6 in the year 2021. Thus, the Heidke Skill Score (HSS) for the forecast of an event for Delhi has significantly increased by 0.30 in last 7 years. It shows that there is significant increase in the Heidke Skill Score (HSS) for the weather forecast after 2014.

Above analysis of PC, POD, FAR, MR, CSI, TSS and HSS for the forecast verification for monsoon Season for Delhi depicts that PC was higher (>80%) in the year 2011, 2012, 2020 and 2021. Above analysis for monsoon season shows that POD is almost similar for the study period. However, trend line of POD indicates slight increase in POD. FAR has decreased significantly after 2013. Trend line of MR is indicating decrease in MR over the years. Trend line of CSI, TSS and HSS shows increasing trend after 2013. Reason for gradual decreasing trend of MR and gradual increasing trend of CSI, TSS and HSS is that during monsoon season rainfall occurs often and also rainfall pattern and associated synoptic and atmospheric conditions are well understood for monsoon season. This shows that there is gradual improvement in the forecast during 2013 to 2021 in monsoon season.

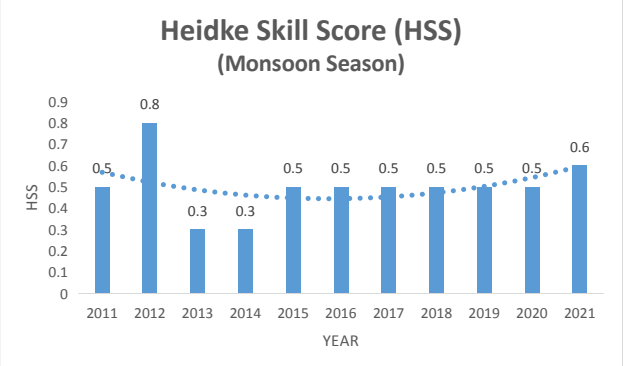

Figure 28. Heidke Skill Score (HSS) for Forecast of Delhi during monsoon Season (2011 – 2021)

4.5 Verification of Forecast for Post-monsoon Season

4.5.1 Percentage Correct (PC)

Figure 29 depicts the percentage correct (PC) forecast during the period 2011 to 2021 for post-monsoon Season over Delhi. In the year 2011 and 2012 percentage correct forecast were 99% and 96% respectively with False Alarm Ratio (FAR) around 0.30 and 0.40 respectively (Figure 31). Trend in Percentage forecast continue to decrease till year 2013, after that it has increasing trend and reached up to 100% and 98% in the year 2020 and 2021 with FAR is 0.0 and 0.05 respectively. On comparing year 2011 and year 2021 PC is almost similar, however significant decrease of 0.30 in FAR is seen. Thus, the accuracy of forecast for Delhi for post-monsoon Season has increased considerably with significant decrease in FAR during last 8 years.

4.5.2 Probability of Detection (POD)

The Probability of Detection (POD) for the rainfall

event during the period 2011 to 2021 for post-monsoon Season over Delhi is shown in the Figure 30. In the year 2011 and 2012 Probability of Detection (POD) of a rainfall event was 1.0 and 0.80. In the year 2013 Probability of Detection (POD) was 0.45 which was lowest during the period 2011-2021; POD has increased to 1.0 and 0.95 in the year 2020 and 2021 respectively. Thus, the Probability of Detection (POD) for Delhi has increased by 0.50 in last 8 years. It shows that there is significant improvement in the Probability of Detection (POD) of an event after 2013.

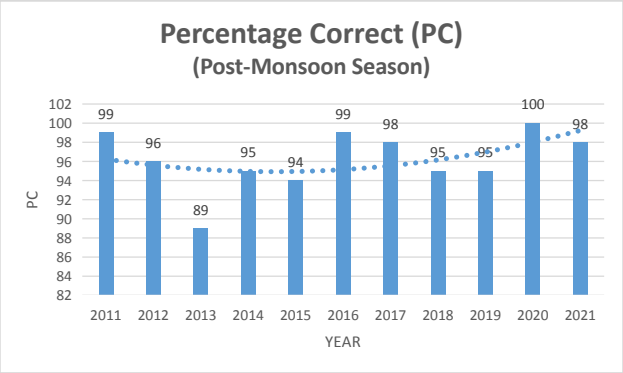

Figure 29. Percentage Correct (PC) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

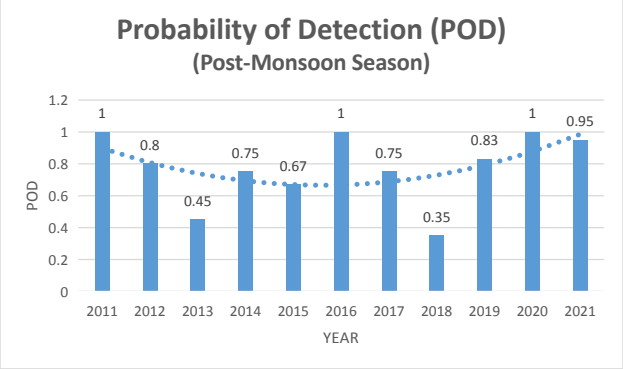

Figure 30. Probability of Detection (POD) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

4.5.3 False Alarm Ratio (FAR)

Figure 31 illustrates the False Alarm Ratio (FAR) for the rainfall event during the period 2011 to 2021 for post-monsoon Season over Delhi. In the year 2011 and 2012 False Alarm Ratio (FAR) of a rainfall event was 0.30 and 0.40 respectively. In the year 2013 and 2014 False Alarm Ratio (FAR) was very high value 0.55, which has decreased to 0.05 in the year 2021. Thus, the False Alarm Ratio (FAR) for Delhi has decreased by 0.50 in last 8 years. Trend line also shows that FAR is decreasing continuously. It shows that there is significant decrement in the False Alarm Ratio (FAR) after 2013.

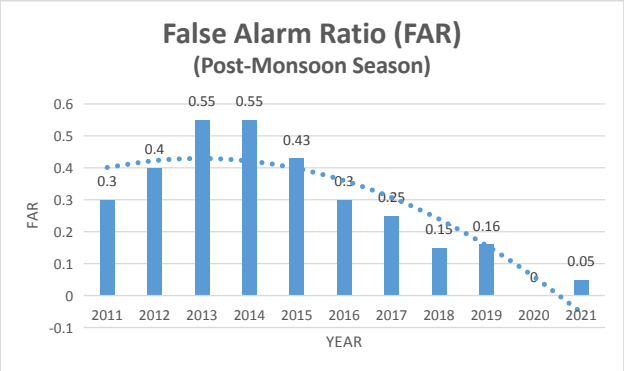

Figure 31. False Alarm Ratio (FAR) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

4.5.4 Missing Ratio (MR)

The Missing Ratio (MR) for the rainfall events during the period 2011 to 2021 for pre-monsoon Season over Delhi is depicted in the Figure 32. In the year 2011 and 2012 Missing Ratio (MR) of a rainfall event was 0.0 and 0.30 respectively. In the year 2013 Missing Ratio (MR) was very high value 0.60, which has decreased to 0.0 and 0.05in the year 2020 and 2021 respectively. Thus, the Missing Ratio (MR) of an event for Delhi has decreased by 0.55 in last 8 years. Trend line also shows that MR is decreasing continuously. It shows that there is significant decrement in the Missing Ratio (MR) after 2013.

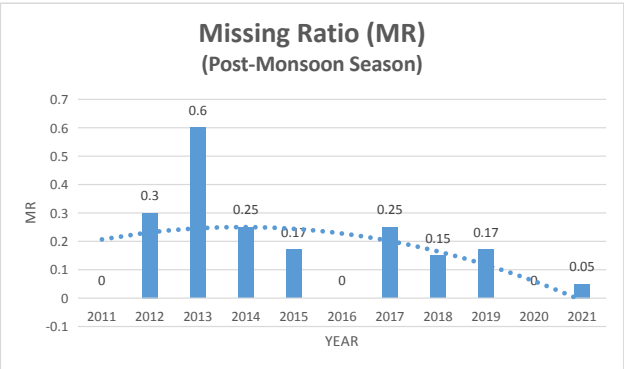

Figure 32. Missing Ratio (MR) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

4.5.5 Critical Success Index (CSI)

Figure 33 depicts the Critical Success Index (CSI) for the forecast during the period 2011 to 2021 for post-monsoon Season over Delhi. In the year 2011 and 2012 Critical Success Index (CSI) was 0.70 and 0.50 respectively. In the year 2013 Critical Success Index (CSI) was decreased to 0.3, which has increased to 1.0 and 0.90 in the year 2020 and 2021 respectively. Thus, the Critical Success Index (CSI for the forecast of an event for Delhi has sig-

nificantly increased by 0.60 in last 8 years. Trend line also shows that CSI is increasing continuously. It shows that there is significant improvement in the Critical Success Index (CSI) for the weather forecast after 2013. Trend line also shows that CSI is increasing continuously.

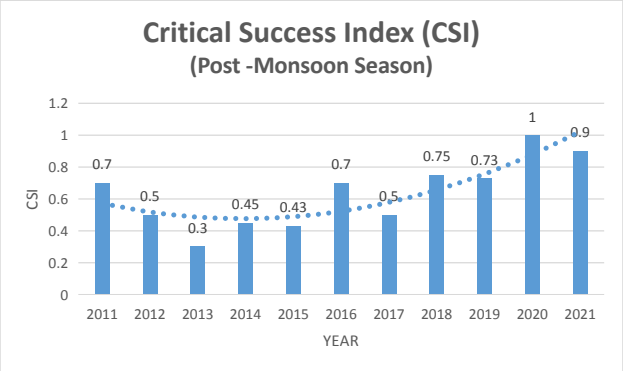

Figure 33. Critical Success Index (CSI) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

4.5.6 True Skill Statistics (TSS)

Figure 34 depicts the True Skill Statistics (TSS) for the forecast during the period 2011 to 2021 for post-monsoon Season over Delhi. In the year 2011 and 2012 True Skill Statistics (TSS) was 1.0 and 0.70 respectively. In the year 2013 True Skill Statistics (TSS) was decreased significantly to 0.35, which has increased to 1.0 and 0.90 in the year 2020 and 2021 respectively. Thus, the True Skill Statistics (TSS) for the forecast of the rainfall events for Delhi has significantly increased by 0.55 in last 8 years. Trend line also shows that TSS is increasing continuously. It shows that there is significant increase in the True Skill Statistics (TSS) for the weather forecast after 2013.

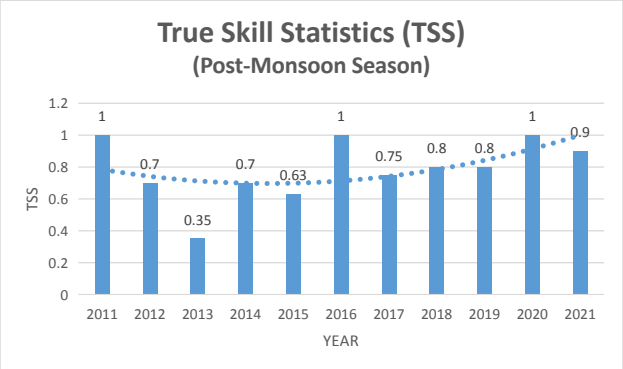

Figure 34. True Skill Statistics (TSS) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

4.5.7 Heidke Skill Score (HSS)

Figure 35 depicts the Heidke Skill Score (HSS) for the forecast during the period 2011 to 2021 for post-monsoon Season over Delhi. In the year 2011 and 2012 Heidke Skill Score (HSS) were 0.80 and 0.60 respectively. In the year 2013 Heidke Skill Score (HSS) was decreased significantly to 0.35, which has increased to 1.0 and 0.90 in the year 2020 and 2021 respectively. Thus, the Heidke Skill Score (HSS) for the forecast of an event for Delhi has significantly increased by 0.55 in last 8 years. Trend line also shows that HSS is increasing continuously. It shows that there is significant increase in the Heidke Skill Score (HSS) for the weather forecast after 2013.

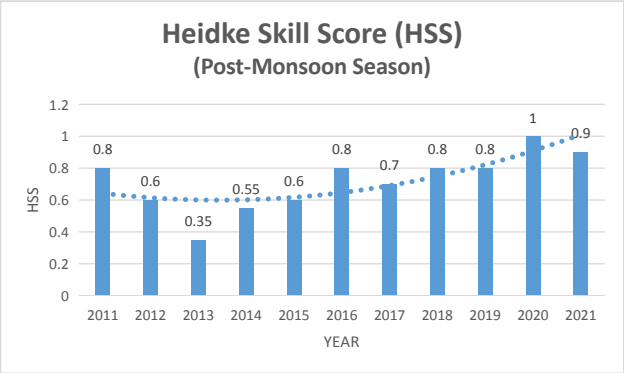

Figure 35. Heidke Skill Score (HSS) for Forecast of Delhi during post-monsoon Season (2011 – 2021)

Above analysis of PC, POD, FAR, MR, CSI, TSS and HSS for the forecast verification for post-monsoon Season for Delhi depicts that PC was higher (>95%) in all the year expect 2013 when it was 89%. CSI, TSS and HSS also increased significantly during the period 2013-2021 reached up to 1.0 and 0.90 in the year 2020 and 2021 respectively. Simultaneously FAR and MR has also shown significant decreasing trend and decreased up to 0.0 and 0.05 in the year 2020 and 2021 respectively.

Thus, significant increase in the CSI, TSS and HSS and significant decrease in FAR and MR has been noticed in last 8 years. A forecast is assumed to be improving if PC, POD, CSI, TSS and HSS increases and FAR and MR decreases over a period of time. In this case there is increasing trend in CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement in the forecast during 2013 to 2021 for the post-monsoon Season.

5. Conclusions

In this study rainfall forecast verification of Delhi for the period 2011 to 2021 has been carried out. Various statistical parameters such as Percentage Correct (PC), Probability of Detection (POD), Missing Ratio (MR), False Alarm Ratio (FAR), Critical Success Index (CSI), True Skill Statistics (TSS) and Heidke Skill Score (HSS) has

been calculated for season wise and annually. A forecast is assumed to be improving if PC, POD, CSI, TSS and HSS increases and FAR and MR decreases over a period of time. Based on the values of these parameters following conclusion are drawn:

Annual: The analysis of various parameters calculated annually depicts that PC was higher in the year 2011 and 2012 and again in 2021. But the major difference in these years (2011-2021) is that in the year 2021, POD, CSI, TSS and HSS has significantly increased and reached up to 0.91, 0.81, 0.79 and 0.79 respectively. Simultaneously FAR and MR has significantly decreased up to 0.13 and 0.9 respectively. This shows that there is significant improvement in the forecast during 2011 to 2021.

Winter: Analysis of various parameters for the winter season depicts that PC was higher in the year 2011 and 2012 and again in 2021. But the major difference in these years is that in the year 2020, POD and CSI have significantly increased and reached up to 1.0. TSS and HSS also increased significantly in the year 2020 and both reached up to 1.0. Simultaneously FAR and MR has significantly decreased up to 0.0 in the year 2020. Thus, there is increasing trend in PC, POD, CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement in the forecast for winter season during 2011 to 2021.

Pre-Monsoon: Analysis of various parameters pre-monsoon Season depicts that PC was higher in the year 2011, 2012, 2015 and again in 2021. But the major difference in these years is that in the year 2021, POD and CSI have significantly increased and reached up to 0.97 and 0.80 respectively. TSS and HSS also increased significantly in the year 2021 and both reached up to 0.87 and 0.83. Simultaneously FAR and MR have also shown decreasing trend and decreased up to 0.20 and 0.03 respectively. For pre monsoon season there is increasing trend in PC, POD, CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement in the forecast during 2013 to 2021.

Monsoon: Analysis for monsoon season shows that POD is almost similar for the study period. However, trend line of POD indicates slight increase in POD. FAR has decreased significantly after 2013. Trend line of MR is indicating decrease in MR over the years. Trend line of CSI, TSS and HSS shows increasing trend after 2013. Reason for gradual decreasing trend of MR and gradual increasing trend of CSI, TSS and HSS is that during monsoon season rainfall occurs often and also rainfall pattern and associated synoptic and atmospheric conditions are well understood for monsoon season. This shows that there is gradual improvement in the forecast during 2013 to 2021 in monsoon season.

Post Monsoon: Analysis of post-monsoon Season for Delhi depicts that PC was higher (>95%) in all the year expect 2013 when it was 89%. CSI, TSS and HSS also increased significantly during the period 2013-2021 reached up to 1.0 and 0.90 in the year 2020 and 2021 respectively. Simultaneously FAR and MR has also shown significant decreasing trend and decreased up to 0.0 and 0.05 in the year 2020 and 2021 respectively. There is increasing trend in CSI, TSS and HSS while decreasing trend in FAR and MR. This shows that there is significant improvement in the forecast during 2013 to 2021 for the post-monsoon Season.

Overall, we can conclude that annually accuracy of forecast has increase significantly during last 8 years. Maximum contribution in the improved forecast has observed in transition season (pre-monsoon season followed by post-monsoon), when FAR and MR has decreased drastically. We can also say accuracy of prediction of rainfall associated with thunderstorms has also increased, as in pre and post monsoon season rainfall activities occurs mainly in association with thunderstorms. The increase in forecast accuracy is mainly attributed to the availability of Doppler weather Radar and satellite images at frequent interval, increased accuracy of Numerical Weather Prediction Models and increased understanding of forecasters.

Author Contributions

Author is Head of Regional Weather Forecasting Center, New Delhi since 2017 and looks after day to day forecasting activities of Delhi as well as North-west India. Author has significant contributions in writing this research paper.

Conflict of Interest

Author has no conflicts of interest to disclose.

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