Satellite-based technique for nowcasting of thunderstorms over Indian region

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India experiences severe thunderstorms during the months, March–June. But these systems are not predicted well, mainly due to the absence of mesoscale observational network over Indian region and the expert system. As these are short lived systems, the nowcast is attempted worldwide based on satellite and radar observations. Due to inadequate radar network, satellite plays the dominant role for nowcast of these thunderstorms. In this study, a nowcast based algorithm ForTracc developed by Vila *et al.* (Weather Forecast 23:233–245, 2008) has been examined over the Indian region using Infrared Channel (10.8 μm) of INSAT-3D for prediction of Mesoscale Convective Systems (MCS). In this technique, the current location and intensity in terms of Cloud Top Brightness Temperature (CTBT) of the MCS are extrapolated. The purpose of this study is to validate this satellite-based nowcasting technique for Convective Cloud Clusters that helps in optimum utilization of satellite data and improve the nowcasting. The model could predict reasonably the minimum CTBT of the convective cell with average absolute error (AAE) of <7 K for different lead periods (30–180 min). However, it was underestimated for all the lead periods of forecasts. The AAE in the forecasts of size of the cluster varies from about $3 \times 10^4 \text{ km}^2$ for 30-min forecast to $7 \times 10^4 \text{ km}^2$ for 120-min forecast. The mean absolute error in prediction of size is above 31–38% of actual size for different lead periods of forecasts from 30 to 180 min. There is over estimation in prediction of size for 30 and 60 min forecasts (17% and 2.6% of actual size of the cluster, respectively) and underestimation in 90 to 180-min forecasts (–2.4% to –28%). The direct position error (DPE) based on the location of minimum CTBT ranges from 70 to 144 km for 30–180-min forecast respectively.

Keywords. Thunderstorm; MCS; CTBT; INSAT-3D; nowcast.

1. Introduction

Thunderstorm activity is one of the most severe weather hazard affecting India and neighbourhood, mainly during the months March–June (Srinivasan *et al.* 1973; Tyagi 2007). Meteorologists monitor the atmosphere for signs of severe thunderstorms

development. They issue a severe thunderstorm warning for areas where conditions are favourable for the formation of severe storms as per standard operation procedure (India Meteorological Department (IMD) 2012). The horizontal size of a thunderstorm varies between a few kilometres and a few hundred kilometres and its time-scale

from a few minutes to a few hours (Asnani 1993). The thunderstorm activity is greatly governed by the overall synoptic scale disturbances (Srinivasan *et al.* 1973).

The low level moisture and instability, and environmental conditions like horizontal and vertical wind shear, lower level vorticity, upper level divergence, triggering synoptic condition like trough, cyclonic circulation, low pressure systems, upper level trough/ridges etc. lead to thunderstorm activity (Srinivasan *et al.* 1973; Asnani 1993; IMD 2012). The field forecaster using the forecast based on synoptic charts as a guideline delineates the areas of a watch for development of thunderstorms. One has to depend heavily on reports of actual development of cumulonimbus clouds, thunderstorms, line squall etc. and their movement, observed by current weather stations or radar for purposes of operational warnings (such as thunderstorm warning for airfield and nowcast for a city). In this regard satellite imagery is also used to help track the movement of weather systems that might generate thunderstorms. Large scale thunderstorms usually occur in association with mesoscale convective systems (MCS) as observed through satellite. During March–June, MCS cover areal extent of 1000–10,000 km² with life span of 1–3 hrs on many occasions (Tyagi *et al.* 2012; Goyal *et al.* 2014).

The monitoring and prediction of the MCS is attempted worldwide on nowcasting basis. The RADAR based nowcasting application software, 36 Warning Decision Support System Integrated Information (WDSS-II) developed by National Severe Storms Laboratory (USA) in collaboration with Oklahoma University (WDSS-II; Lakshmanan *et al.* 2007) is used in IMD for real-time. The WDSS-II provides a platform to play with weather data from multiple Radars and multiple sensors for detection of thunderstorms. The WDSS-II has been installed in IMD at eight stations (Sen Roy *et al.* 2014). Due to limited stations, the coverage area is less. Another mesoscale model, Advance Regional Prediction System (ARPS) has also been attempted by IMD (Srivastava *et al.* 2010). These MCS are not forecasted well because of the absence of mesoscale observational network over Indian region and suitable expert system to cover the entire country. As there is inadequate radar network, satellite plays the dominant role for nowcast of these thunderstorms. In this study, a nowcast based algorithm ForTracc developed by Vila *et al.* (2008) is validated to predict

MCS over Indian region using Infrared Channel (10.8 μm) of INSAT-3D. In this technique, the current location and intensity in terms of Cloud Top Brightness Temperature (CTBT) of the MCS are extrapolated. The purpose of this study is to validate this satellite based nowcasting technique for convective cloud clusters that helps in optimum utilization of satellite data and improves the nowcasting.

The observational and synoptic features of the severe thunderstorm/convective activities over Indian region and the characteristics of the satellite based nowcasting technique used for nowcasting of thunderstorms and convective cells is presented and discussed in section 2. The performance of the nowcast technique for the prediction of the severe thunderstorm/convective activities are analyzed and presented in section 3. The broad conclusion of this study is presented in section 4.

2. Data and methodology

A satellite based nowcast technique *viz.* Forecast and Tracking of Active Cloud Clusters (ForTraCC) developed by Vila *et al.* (2008) has been tested by Goyal *et al.* (2016) based on case study of intense thunderstorm activity over Bihar on 21 April, 2015. To have more robust assessment, 11 representative cases of convective activity over Indian region during the months (March–June) 2014 and 2015 (Ray *et al.* 2014, 2015). The details of 11 cases are given in table 1. The cases which caused intense thunderstorm activity along with rainfall/hailstorm have been considered (figure 1). The cases represent different thunderstorm prone regions of India like southern peninsula, east and northeast India. The above data collected from Ray *et al.* (2014, 2015) and the weekly weather reports published by National Weather Forecasting Centre, IMD, New Delhi have been considered in this study. For the validation of the nowcast technique, half hourly satellite images of channel Thermal Infrared (TIR) (10.8–11.5 μm) of INSAT-3D with spatial resolution of 4×4 km² has been considered to create nowcast up to next 180 min (every half hourly, table 2). The flowchart of this technique implemented in IMD is shown in figure 2.

The algorithm (Vila *et al.* 2008) for nowcasting of severe weather based on satellite imageries has been implemented in the IMD (Goyal *et al.* 2016). The algorithm is based upon the extrapolation technique that allows for the tracking of

Table 1. Characteristics of thunderstorm activity considered in study.

Sl. no.	Date of occurrence	Time of origin (UTC)	Areal extent lat.(°N)/long.(°E)	Maximum area (km ²)	Lowest C _T BT (K)	Synoptic systems	Weather
1	02 Jun 2014	1200	7.6–16.9/73–80.3	464195	180.2	A trough in lower level from south Madhya Pradesh to south Tamil Nadu across interior Karnataka	Heavy rainfall over Rayalseema, Telangana, Tamil Nadu and Pondicherry
2	07 May 2014	1030	16–20.4/72.1–74.4	76401	181.2	Trough from northwest Madhya Pradesh to center of well-marked low pressure are over south Kerala and neighbourhood	Heavy rainfall over coastal Karnataka and north & south interior parts of Karnataka
3	07 May 2014	1030	8–12.7/71.3–77.7	215569	183.1	Well-marked low pressure are over south Kerala and neighbourhood	Very heavy rainfall over coastal Kerala and heavy rainfall over interior parts of Kerala
4	18 Mar 2015	0900	19.3–22.1/25.7–89.6	88547	211.3	Upper air cyclonic circulation over Chhattisgarh, Odisha and neighbourhood extending up to 0.9 km amsl on 15th & 16th	Hailstorm coupled with rain over east Odisha
5	26 Mar 2015	1200	27.4–31.1/75.4–79.7	104277	204.1	Upper air cyclonic circulation over Jharkhand and neighbourhood extending up to 1.5 km amsl	Moderate rainfall over Jharkhand
6	03 Apr 2015	1200	24.4–31.1/72–78	404446	194.9	Western disturbance as an upper air cyclonic circulation over north Pakistan and adjoining Jammu and Kashmir extending up to 2.1 km amsl with trough along 72°E. Induced cyclonic circulation up to 1.5 km amsl over west Rajasthan and neighbourhood	Moderate rainfall over west Rajasthan, west Uttar Pradesh, heavy rainfall over east Rajasthan
7	04 Apr 2015	0900	23.6–28.8/88–95.1	198565	184.6	Upper air trough at 1.5 km amsl runs from west Madhya Pradesh to Tripura with embedded cyclonic circulation over Bangladesh	Heavy rainfall over Assam and Meghalaya, Moderate rainfall over West Bengal
8	05 Apr 2015	0730	22.9–24.8/90.1–94	49652	192.1	Upper air trough at 1.5 km amsl runs from west Madhya Pradesh to Tripura with embedded cyclonic circulation over Bangladesh	Sub-Himalayan West Bengal isolated heavy rain, Gangetic West Bengal, Assam and Meghalaya moderate rain

Table 1. (Continued.)

Sl. no.	Date of occurrence	Time of origin (UTC)	Areal extent lat.(°N)/long.(°E)	Maximum area (km ²)	Lowest CTBT (K)	Synoptic systems	Weather
9	21 Apr 2015	1400		42020	180.1	Circulation are Assam and Meghalaya upto 0.9 amsl with trough extending to North Bengal Chhattisgarh across Gangetic West Bengal and Jharkhand	Moderate rainfall over Bihar
10	27 Apr 2015	1700	26.1–30.4/79.1–82.7	117742	211	Cyclonic circulation of northwest Madhya Pradesh up to 1.5 km amsl	Heavy rainfall over Sub-Himalayan West Bengal. Moderate rainfall over Gangetic West Bengal, Jharkhand, Bihar. East and west Uttar Pradesh
11	28 Apr 2015	1700 (27Apr 2015)	25.5–29.3/81.8–84.4	73594	214.5	Cyclonic circulation of northwest Madhya Pradesh up to 0.9 km amsl	Heavy rainfall over Bihar and Sub-Himalayan West Bengal. Moderate rainfall over Jharkhand and east Uttar Pradesh

MCS radiative and morphological properties (Vila and Machado 2004). Using the infrared satellite data, based on CTBT, the algorithm is capable of forecasting evolution of the above said physical properties up to 360 min. The studies by Goyal *et al.* (2016) have shown that the accuracy of the nowcast product is very less beyond 180 min and hence nowcast is issued for 180 min by IMD at present.

The features of the algorithm are discussed below:

- (i) Following Maddox (1980) and Machado and Laurent (2004), an MCS with size $\geq 2400 \text{ km}^2$ and temperature threshold $\leq 235 \text{ K}$ (-38°C) is detected.
- (ii) Successive images of MCS were applied on the statistical module to identify morphological and radiative parameters of each MCS. Tracking technique is applied on MCS overlapping areas between successive images according to Machado *et al.* (1998), Vila and Machado (2004).
- (iii) MCS evolution in previous time steps were incorporated into a forecast model (Vila *et al.* 2008).

By considering the following three parameters, the forecast process is carried out. These parameters are:

- MCS displacement estimation.
- MCS area evolution based on the linear regression.
- MCS minimum brightness temperature temporal rate, also based on the linear regression.

A statistical method is used to estimate the brightness temperature of the MCS. It is hypothesized that the size evolution is linearly followed by a cloud-top variation with time ($\Delta T = \delta T_{\text{min}} / \delta t$), where T is cloud top brightness temperature and T_{min} is minimum cloud top brightness temperature. A linear relationship is performed between normalised area of expansion, ΔE and ΔT , which is also applied to the forecast procedure in order to obtain the evolution of the minimum temperature. The criteria for tracking the MCS, i.e., (i) area of cloud cluster $\geq 2400 \text{ km}^2$ and (ii) CTBT $\leq -38^\circ\text{C}$ has been applied for tracking of cloud clusters for every half an hour (Goyal *et al.* 2016). The results were analysed for the half hourly forecasts available from the model in the actual scenario based on INSAT-3D observations. Since the forecast imageries contain the CTBT of cloud cluster,

Figure 1. Cases of thunderstorm activity under study and their area of occurrence.

performance of the technique was calculated by comparing the predicted minimum CTBT, location of minimum CTBT, location of the mid-point of the cloud clusters and area of the cloud clusters with the actual. The results are presented and discussed in section 3.

3. Results and discussion

3.1 Comparison of predicted and actual CTBT

Since we are taking brightness temperature as principal parameter for the nowcasting, so the comparison of the minimum CTBT of forecast convective cell with that of actual convective cell is carried out by plotting the scattered diagram and by

calculating average absolute error (AAE) and root mean square error (RMSE) in minimum CTBT.

Figure 3 shows the scatter diagram of the observed and forecast minimum CTBT. Good agreement between the observed and forecasted values is observed for 30 and 60 min lead periods. The correlation coefficient (CC) between forecast and actual minimum CTBT is 0.8 up to 180 min. Gradual decrease in forecast skill is observed with increase in time.

Figure 4(a) shows the AAE of minimum CTBT for every 30, 60, 90, 120, 150 and 180 min. It is found that the model could predict reasonably the minimum CTBT of the convective cell with AAE of < 7 K for different lead period. The AAE for 30, 60, 90, 120, 150 and 180 min are 3.6, 4.8, 5.6, 6.0,

Table 2. Number of forecast verified for the cases of thunderstorms considered in the study.

Sl. no.	Date of the event	Area of origin convective cell	Number of forecasts issued with different lead periods (min)						Total
			30	60	90	120	150	180	
1	02 Jun 2014	Tamil Nadu and south AP	3	3	3	3	3	3	18
2	07 May 2014	SW Maharashtra	3	3	3	2	1	0	12
3	07 May 2014	North Kerla adjoining Karnataka	3	3	3	2	1	0	12
4	18 Mar 2015	Odisha	3	3	3	3	3	3	18
5	26 Mar 2015	West Bengal	2	2	2	2	2	2	12
6	03 Apr 2015	Rajasthan	3	3	3	3	2	1	15
7	04 Apr 2015	Bangladesh adjoining SHWB and Assam	4	4	4	4	4	4	24
8	05 Apr 2015	Bangladesh	3	3	3	3	3	3	18
9	21 Apr 2015	North Bihar adjoining Nepal	5	5	4	3	2	1	20
10	27 Apr 2015	NW UP adjoining Nepal	2	2	2	2	2	2	12
11	28 Apr 2015	East UP adjoining Nepal	4	4	4	4	4	3	23
Total			35	35	34	31	27	22	184

Figure 2. Automized flow chart of satellite-based nowcast technique in IMD.

6.3 and 6.6 K, respectively. As shown in figure 4(a), the error gradually increases with increase in lead period of forecast. Similarly, the RMSE of minimum CTBT (figure 4b) for 30, 60, 90, 120, 150 and 180 min are 4.4, 6.0, 6.9, 7.1, 7.8, and 8.3 K, respectively.

From table 3, it can be found that there is a negative bias in the forecast of minimum CTBT. Otherwise, the minimum CTBT is underestimated

for all the lead periods of forecast from 30 min to 180 min. It endorses the earlier findings of Vila *et al.* (2008). However, the negative bias is less than 1% of the actual minimum CTBT up to 120 min forecast and increases thereafter with increase in lead period. Considering the absolute mean difference in forecast and actual minimum CTBT, it varies from 1.9% of actual CTBT for 30 min forecasts to 2.91% for 120 min forecasts.

Figure 3. The observed and forecast CTBT of MCS during the validation period for (a) 30 min, (b) 60 min, (c) 90 min, (d) 120 min, (e) 150 min, and (f) 180 min forecast. CC: Correlation coefficient. CCs significant at 95% level of confidence are highlighted.

ARPS model is developed by University of Oklahoma, USA and is validated for Indian region by [Srivastava *et al.* \(2010\)](#). By assimilating the radar data of DWR, the model provides forecast for 6 hrs in the interval of 1 hr. According to the studies by [Srivastava *et al.* \(2010\)](#), the model underestimates the intensity by about 5 dBz.

WDSSII is an expert system used for operational nowcasting over Indian region. It utilizes DWR data to provide forecast up to 2 hrs. [Sen Roy *et al.* \(2014\)](#) have demonstrated that the error in nowcasting by this system is mostly in respect

of location as well as the intensity of the cells. The overall error is minimum in the monsoon season and maximum during April–June.

3.2 Comparison of predicted and actual area of cloud cluster

The area of cluster is defined as the area covered by the cluster with CTBT of 235 K or less; the cluster with area of $>2400 \text{ km}^2$ has been considered for the study. A good agreement is observed

Figure 4. (a) Average Absolute Error (AAE) and (b) Root Mean Square Error (RMSE) in the prediction of minimum CTBT for the lead period of 30–180 min.

Table 3. Mean bias (Δ) and absolute bias of the size (expressed in % to show the relative variations in size) and minimum temperature. Each row represents different lead periods (minutes).

Lead period (min)	Mean $\Delta T_{\min}(\%)$ K	Absolute mean $\Delta T_{\min}(\%)$ K	Mean Δ size (%) km^2	Absolute mean Δ size (%) km^2
30	−0.29	1.86	16.69	31.99
60	−0.55	2.42	2.56	35.00
90	−0.75	3.03	−2.39	35.10
120	−0.56	2.91	−12.69	38.14
150	−1.0	3.25	−18.93	38.58
180	−1.57	3.19	−27.95	36.83

$$\Delta T_{\min} = \frac{\text{Forecast } T_{\min} - \text{Actual } T_{\min}}{\text{Actual } T_{\min}} \times 100, \quad \Delta \text{size} = \frac{\text{Forecast size} - \text{Actual size}}{\text{Actual size}} \times 100.$$

between actual and forecasted area of cloud clusters as shown in scatter diagram (figure 5). The correlation coefficient of >0.9 is observed up to 180 min. The correlation decreases with increase in lead period.

The AAE and RMSE in the forecast of size of the cluster are calculated and presented in figure 6. It clearly shows that the error increases with increase in lead period. The AAE varies from about $3 \times 10^4 \text{ km}^2$ for 30 min forecast to $7 \times 10^4 \text{ km}^2$

for 120 min forecast in terms of AAE. It varies from 4×10^4 to $11 \times 10^4 \text{ km}^2$ in terms of RMSE. From table 3, there is positive bias or overestimation in prediction of size for 30 and 60 min forecasts, i.e., 17% and 2.6% of actual size of the cluster respectively. There is negative bias or underestimation in 90 to 180 min forecasts, i.e., −2.4% to −28% respectively. The mean absolute error in prediction of size is above 31–38% of actual size for different lead periods of forecasts from 30 to 180 min.

Figure 5. The observed and forecast size of MCS during the validation for (a) 30 min, (b) 60 min, (c) 90 min, (d) 120 min, (e) 150 min, and (f) 180 min forecast. CC: Correlation coefficient. CCs significant at 95% level of confidence are highlighted.

Comparing the AAE as percentage of actual value of minimum CTBT and size, the minimum CTBT is better predicted than the size of cluster (table 3). It also endorses the earlier findings of Vila *et al.* (2008). While the actual size decreases, the actual minimum CTBT increases. Otherwise, with the decrease in size, the intensity of the cluster also decreases. Considering the forecast parameters, when the forecast size decreases the forecast minimum CTBT increases or the intensity of the cluster decreases.

3.3 MCS size and temperature evolution

The evolution of the forecast parameters like forecast minimum CTBT and forecast size of the MCS has been compared to actual minimum CTBT and size of the MCS for individual cases. The objective is to find out whether there is any relationship between the size and intensity of the cluster.

Figure 7 shows the size and minimum temperature evolution for a single MCS present at 0100 UTC of 27 March 2015. Solid lines represent the

Figure 6. (a) Average Absolute Error (AAE) and (b) Root Mean Square Error (RMSE) in the prediction of size of cloud cluster for the lead period of 30–180 min.

Figure 7. Size and minimum temperature evolution for single MCS of 27th March 2015 at 0100 UTC.

observed values for both parameters, while dotted lines represent the forecast obtained with satellite based nowcast tool for different time leads. The minimum CTBT is underestimated in the forecast. The forecast size of the MCS almost

agrees with the actual upto 90 min and then it is underestimated. Similar findings have also been demonstrated by Vila *et al.* (2008) for the MCS over Atlantic region for the same nowcast model.

Figure 8. Average direct position error based on (a) location of minimum CTBT and (b) location of center of cloud cluster for the lead period of 30–180 min.

Table 4. Mean latitudinal and longitudinal errors in the prediction of track of convective cluster based on minimum CTBT.

Lead period (min)	Latitude error		Longitude error	
	Mean error (km)	Absolute mean error (km)	Mean error (km)	Absolute mean error (km)
30	−3.3	41.8	8.8	42.9
60	0.5	39.6	−5.5	56.1
90	6.6	47.3	−18.7	60.5
120	6.6	52.8	−35.2	79.2
150	1.1	46.2	−41.8	118.8
180	11.0	42.9	−28.6	134.2

Latitude error = forecast latitude–actual latitude. Longitude error = forecast longitude–actual longitude.

3.4 Track forecast error

The track forecast error has been calculated in two different ways. It is defined as Direct Position Error (DPE) between the actual position of minimum CTBT and the forecast position of the minimum CTBT. In a second approach, it is defined as the DPE between the center of

actual and forecast MCS. The error is calculated for every half hourly forecast. The average DPE on the basis of location of minimum CTBT are shown in figure 8(a). It clearly shows that the error is increasing with the increase in lead period. The error ranges from 70 to 144 km for 30–180 min forecast. It is <100 km up to 90 min forecasts.

Table 5. Mean latitudinal and longitudinal errors in the prediction of track of convective cluster based on centroid.

Lead period (min)	Latitude error		Longitude error	
	Actual error (km)	Absolute error (km)	Actual error (km)	Absolute error (km)
30	5.5	23.1	14.3	34.1
60	2.2	23.1	11.0	42.9
90	−8.8	19.8	−4.4	62.7
120	−9.9	37.4	−14.3	83.6
150	−14.3	53.9	−27.5	78.4
180	−8.8	48.4	−14.3	90.2

Latitude error = forecast latitude−actual latitude. Longitude error = forecast longitude−actual longitude.

The average DPE based on location of center of cloud cluster is shown in figure 8(b). It shows less error than the DPE calculated for the location of minimum CTBT. The DPE ranges from 49 to 113 km. The error is less than 100 km up to 120 min forecasts. It may be due to fact that due to vertical wind shear and interaction with mid-latitude westerlies, the distribution of CTBT may be asymmetric and hence away from geographical center.

The mean latitudinal and longitudinal error in prediction of track of MCS are presented in tables 4 and 5 based on location of minimum CTBT and location of centroid of MCS, respectively. It is found that the latitude error based on minimum CTBT varies from 41.8 km for 30 min to 52.8 km for 60 min forecast. The longitude error varies from 42.9 km for 30 min forecast to 79.2 km for 120 min forecast. It is significantly higher for 180 min. The latitude error based on centroid (table 5) varies from 23.1 to 37.4 km for 30–120 min forecast and longitudinal error varies from 34.1 to 90.2 km for 30–120 min forecast. Hence there is longitudinal bias in the forecast track of the MCS.

4. Conclusions

The satellite based nowcast technique developed by Vila *et al.* (2008) has been installed and tested based on 11 representative cases of convective activity over Indian region during March–June.

The model could predict reasonably the minimum CTBT of the convective cell with AAE of <7 K for different lead periods. The AAE for 30, 60, 90, 120, 150 and 180 min are 3.6, 4.8, 5.6, 6.0, 6.3 and 6.6 K, receptively. The RMSE of minimum CTBT for 30, 60, 90, 120, 150 180 min

are 4.4, 6.0, 6.9, 7.1, 7.8, and 8.3 K, respectively. There is a negative bias is the forecast of minimum CTBT, i.e., the minimum CTBT is underestimated for all the lead periods of forecasts from 30–180 min.

The error in the forecast of size of the cluster varies from about $3 \times 10^4 \text{ km}^2$ for 30 min forecasts to $7 \times 10^4 \text{ km}^2$ for 120 min forecast in terms of AAE and from 4×10^4 to $11 \times 10^4 \text{ km}^2$ in terms of RMSE. The mean absolute error in prediction of size is above 31–38% of actual size for different lead periods of forecasts from 30 to 180 min. There is positive bias or over estimation in prediction of size for 30 and 60 min forecasts, i.e., 17% and 2.6% of actual size of the cluster respectively and there as negative bias or underestimation in 90–180 min forecasts, i.e., −2.4% to −28% respectively.

The DPE based on the location of minimum CTBT ranges from 70 to 144 km for 30–180 min respectively. It is < 100 km up to 90 min forecasts. There is a longitudinal bias in the prediction of track of the MCS.

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