GEOFIZIKA VOL. 28 2011

Original scientific paper
UDC 551.509.32

A multimodel ensemble (MME) technique for cyclone track prediction over the North Indian Sea

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Received 7 January 2011, in final form 18 October 2011

A multimodel ensemble (MME) technique for predicting track of tropical cyclones over the North Indian Sea has been proposed. The technique is developed applying multiple linear regression procedure. Parameters of the ensemble technique are determined from the forecast datasets on the tracks of tropical cyclones over the North Indian Sea during the year 2008-2009. The parameters selected as predictors are: forecast latitude and longitude positions at 12-hour interval up to 72-hours forecast of five operational numerical weather prediction models. The dynamical models included for development of the ensemble technique are: (i) forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF), (ii) the National Centers for Environmental Prediction Global Forecast System (NCEP), (iii) the MM5 model, (iv) the Quasi-Lagrangian model (QLM) and (v) the model of Japan Meteorological Agency (JMA). A collective bias correction is included in the ensemble technique in which a multiple linear regression based minimization principle for the model forecast position against to the observed position is applied. These bias factors are described by separate weights at every 12-hours interval up to the 72-hour forecasts for each of the member model. When the technique is tested with the independent samples, forecast skill of the MME technique is found to be reasonably good. The average error ranges from of the order of 74 km to 290 km for forecasts up to 72-hour. Performance of the MME technique shows that there are skill improvements up to 30 km for the position errors over the best model at 72-hour forecast. The forecast skill of the MME technique for forecasts up to 72-hour also shows an improvement as compared to the forecasts from member models and the simple ensemble mean (ENM).

Keywords: tropical cyclone, track prediction, multiple linear regression, regression coefficient, ensemble mean and multimodel ensemble technique

1. Introduction

Tropical Cyclones are well known for their destructive character and impact on human activities. Operational forecasting of track of tropical cyclone remains a challenging task to the Meteorologists.

During the last two decades, weather forecasting all over the world has greatly benefited from the guidance provided by the Numerical Weather Prediction (NWP). Significant improvement in accuracy and reliability of NWP products has been driven by sophisticated numerical techniques. However, limitations remain, particularly under the circumstances of wide variation of forecasts of different NWP models.

In this context, many studies (Krishnamurti et al., 1999, 2000a, 2000b, 2001, 2003; Goerss, 2000; Mackey and Krishnamurti, 2001; Weber, 2003; Vijaya Kumar et al., 2003; Williford et al., 2003) have shown that the application of the ensemble approach is very promising to address the problem of operational forecasting of weather and tropical cyclone.

The motivation for this study was based on the success of the ensemble technique for forecasting of tropical cyclone in the Atlantic region and Pacific basins. Due to non-availability of such objective methods, in the operational scenario a subjective approach combining the inputs of persistency, climatology, and NWP models is the primary aid for the forecast of tropical cyclone track over the North Indian Sea.

Towards this direction, herein, an ensemble based track forecast technique is developed for the tropical cyclones over the North Indian Sea (at 12-hour interval up to 72-hour) using the cyclone data of year 2008 and pre-monsoon season (March, April, May) of 2009. The technique is tested for forecasting of tropical cyclones over the North Indian Sea during 2010 and post-monsoon season (October, November, December) of 2009.

The source of data sample is described in Section 2. The ensemble methodology is presented in Section 3. Development of the method is described in Section 4. Performance and limitations of the technique is discussed in Section 5 and concluding remarks are given in Section 6.

2. Data sources

In this study, the model forecast positions (latitude and longitude) are obtained from five operational models along with best (observed) track. The models selected for the ensemble are: (i) European Centre for Medium-Range Weather Forecasts (ECMWF), (ii) the National Centers for Environmental Prediction Global Forecast System (NCEP), (iii) the MM5 model, (iv) the Quasi-Langrangian model (QLM) and (v) the model of Japan Meteorological Agency (JMA). The QLM and MM5 models are operational at India Meteorological Department (IMD), New Delhi. Observed track data are taken from the records of the Cyclone Warning Division of the Regional Specialized Meteorological Centre (RSMC), New Delhi operating in Head Quarters office of the India Meteorological Department (IMD). World Meteorological Organization (WMO) recognizes this office as the Regional Specialized Meteorological Centre (RSMC) for providing cyclone warning advisories over the region. The best (observed) track is estimated based on the post storm analysis of cloud patterns in visible and infrared imagery from geostationary satellites (INSAT Kalpana-I). The forecast positions (based on 0000 UTC and 1200 UTC) of tropical cyclones during 2008–2010 (at 12-hour interval up to 72-hour) are determined by locating the lowest central sea level pressure from the model datasets.

The MM5 model is run at the horizontal resolution of 45 km. The Quasi--Lagrangian Model (QLM) is run at a horizontal resolution of 40 km for tropical cyclone track prediction.

For the day-to-day weather forecasting, IMD also makes use of NWP products prepared by some other operational NWP Centres like, European center for medium range weather forecast (ECMWF), National Centers for Environmental Prediction Global Forecast System (NCEP), and Japan Meteorological Agency (JMA). The NCEP is freely available on the Internet on real time at the resolution of 1° × 1° latitude/longitude. ECMWF and JMA model data are received on real time through a special arrangement. The resolution of the ECMWF model is 0.25° × 0.25° latitude/longitude. JMA data is available at the resolution 1.25° × 1.25° latitude/longitude. The resolution of three member models (ECMWF, QLM and MM5) varies from 25 to 45 km and for other two models (NCEP and JMA) it varies from 100 to 125 km. As bilinear interpolation is used to locate the centre of the storms, the error of representativeness does not vary significantly from one model to another.

The life period, year, maximum intensity (maximum sustained wind) and coast of landfall of the 7 dependent sample cyclonic systems during 2008 and pre-monsoon season (March, April, May) of 2009 are shown in the Table 1. In this study, knots is used instead of standard unit metres per second as winds are expressed in knots (1 kt = 0.5144 m s^{-1}). The technique is tested for recently occurred 6 tropical cyclones over the North Indian Sea during 2010 and post-monsoon season of 2009. These cyclones are presented in Table 2. The coastal states referred in the Table 1 and Table 2 are shown in Figure 1. All data samples of the tropical cyclones during the three years (2008–2010) are placed in two groups (dependent and independent), such that each group contains nearly equal number of sample data. The 7 dependent sample cyclonic

Table 1. The seven dependent cyclonic systems.

S.No.	Cyclonic systems (period)	Year	Max. wind speed (kt)	Coast of landfall
1	NARGIS (27 April to 4 May)	2008	90	Myanmar
2	RASHMI (25–27 October)	2008	45	Bangladesh
3	KHAIMUK (13–16 November)	2008	40	Andhra Pradesh
4	NISHA (25–27 November)	2008	45	Tamilnadu
5	Deep Depression (4–7 December)	2008	30	Sri Lanka
6	BIJLI (14–17 April)	2009	40	Bangladesh
7	AILA (23–26 May)	2009	60	West Bengal

Table 2. The six independent cyclones.

S.No.	Cyclonic systems (period)	Year	Max. wind speed (kt)	Coast of landfall
1	PHYAN (9–12 November)	2009	45	Maharastra
2	WARD (10–15 December)	2009	45	North Sri Lanka
3	LAILA (17–21 May)	2010	55	Andhra Pradesh
4	PHET (31 May–7 June)	2010	85	Pakistan
5	GIRI (20–23 October)	2010	105	Myanmar
6	JAL (4–8 November)	2010	60	Tamilnadu

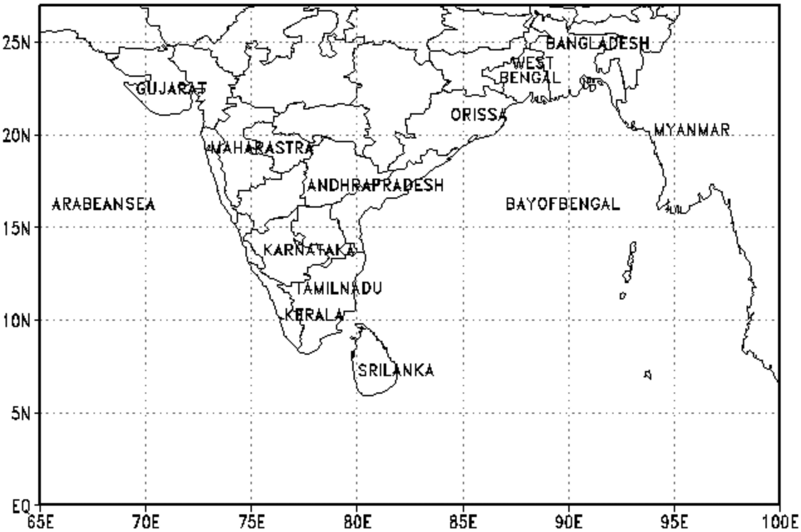

Figure 1. North Indian Sea and adjoining coastal states.

systems contributed 47 cases at 12-hour, 46 cases at 24-hour, 45 cases at 36-hour; 38 cases at 48-hour, 31 cases at 60-hour, and 24 cases at 72-hour during their life period for regression analysis. The 6 independent cyclonic storms contributed 53 cases at 12-hour, 45 cases at 24-hour, and 39 cases at 36-hour; 33 cases at 48-hour, 27 cases at 60-hour, and 21 cases at 72-hour during their life period for testing the skill score of the MME technique.

3. The multimodel ensemble (MME) and ensemble mean (ENM) methodology for cyclone track prediction

The multimodel ensemble (MME) technique is based on a linear statistical model. The predictors (Table 3) selected for the ensemble technique are forecasts latitude and longitude position at 12-hour interval up to 72-hour of five

Table 3. Model parameters.

S.No.	Member models	Symbol of predictors	
		Latitude position	Longitude position
1	European Centre for Medium-Range Weather Forecasts (ECMWF)	$ECMWF^{lat}$	$ECMWF^{lon}$
2	National Centers for Environmental Prediction (NCEP)	$NCEP^{lat}$	$NCEP^{lon}$
3	Japan Meteorological Agency (JMA)	JMA^{lat}	JMA^{lon}
4	MM5 Model	$MM5^{lat}$	$MM5^{lon}$
5	Quasi-Lagrangian model (QLM)	QLM^{lat}	QLM^{lon}

operational models. In the MME forecasts, model-forecast latitude position and longitude position of the member models are linearly regressed against the observed latitude position and longitude position respectively for each forecast time at 12-hour intervals for the forecast up to 72-hour. Multiple linear regression technique is used to generate weights (regression coefficients) for each model for each forecast hour (12-h, 24-h, 36-h, 48-h, 60-h, and 72-h). These coefficients are then used as weights for ensemble forecasts.

Ensemble mean (ENM) forecast positions are determined by taking the simple mean of forecast latitude position and mean of forecast longitude position of member models for each forecast positions.

4. Multimodel ensemble (MME) technique

The MME method is developed using multiple linear regression technique

$$y = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n$$

where y is the dependent variable (predictant) and $x_1, x_2, \ldots, x_n$ are independent variables (predictors). The regression coefficients $a_1, a_2, \ldots, a_n$ are determined using cyclone data set over the North Indian Sea during 2008 and pre-monsoon season of 2009.

The ensemble (MME) technique estimates positions at 12, 24, 36, 48, 60 and 72 hours. Six separate regression analyses for latitude and longitude are carried out for forecast interval 12, 24, 36, 48, 60 and 72 hours.

The 12-hourly forecast latitude (LAT^f) and longitude (LON^f) positions by multiple linear regression technique is defined as:

$$LAT^f{}_t = a_0 + a_1 ECMWF_t^{lat} + a_2 NCEP_t^{lat} + a_3 JMA_t^{lat} + a_4 MM5_t^{lat} + a_5 QLM_t^{lat}$$

$$LON^f{}_t = a'_0 + a'_1 ECMWF_t^{lon} + a'_2 NCEP_t^{lon} + a'_3 JMA_t^{lon} + a'_4 MM5_t^{lon} + a'_5 QLM_t^{lon}$$

for t = forecast hour 12, 24, 36, 48, 60 and 72 hours.

Table 4. Regression coefficients for latitude position for different forecasts hours; N= number of dependent samples.

Forecast hours	a_0	a_1	a_2	a_3	a_4	a_5	N
12 hr	0.74456	0.38331	0.20073	–0.12914	0.01762	0.47580	47
24 hr	–0.04004	0.60605	–0.29157	0.07128	0.10610	0.48553	46
36 hr	0.50786	0.99796	–0.01564	–0.16945	0.04084	0.12818	45
48 hr	0.52079	0.97890	0.05614	–0.12841	0.02156	0.05646	38
60 hr	–0.52159	1.08971	–0.26299	0.00813	0.02717	0.19980	31
72 hr	0.49694	1.37249	–0.41667	0.61152	–0.23442	–0.20898	24

Table 5. Regression coefficients for longitude position for different forecasts hours, N= number of dependent samples.

Forecast hours	a'_0	a'_1	a'_2	a'_3	a'_4	a'_5	N
12 hr	–0.75443	0.73609	–0.06040	0.04108	0.25979	0.25979	47
24 hr	0.5404	0.65633	–0.34397	0.08676	0.32993	0.25677	46
36 hr	5.3802	0.06696	–0.09126	0.48339	0.14787	0.14787	45
48 hr	3.06001	0.55688	–0.23017	0.02481	0.40224	0.20862	38
60 hr	–1.1903	0.95819	0.05603	–0.18819	0.08314	0.10306	31
72 hr	7.56335	0.32499	0.38245	0.16653	0.01254	0.01902	24

The dependent variable latitude (LAT^f) in °N and longitude (LON^f) in °E.

The constant term a_0 and coefficients a_1, a_2, …, a_5 for 12 hourly forecast intervals for latitude and a'_0 and coefficients a'_1, a'_2, …, a'_5 for longitude along with the number of samples at each forecast hour are given in Table 4 and Table 5 respectively. The positive regression coefficients as shown in Table 4 and Table 5 indicate that the relationship of this variable with the dependent variable is positive and the negative regression coefficients indicate the relationship is negative.

5. Performance and limitations of the MME technique

The performance of the model is tested using independent samples.

5.1. Skill score for independent samples

Figure 2 shows the error statistics of the member models, ensemble mean (ENM) and multimodel ensemble (MME) technique at 12-hour, 24-hour, 36--hour, 48-hour, 60-hour and 72-hour forecasts. The forecast errors of member

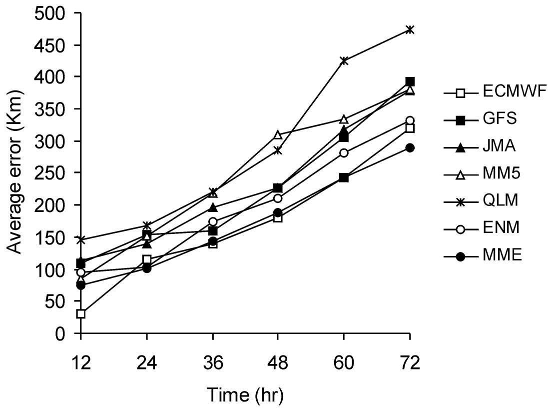

Figure 2 Average error (AE) of member models, ensemble mean (ENM) and ensemble (MME) technique for independent sample.

models and the corresponding ensemble forecasts (MME) along with the number of samples at each forecast hour are summarized in Table 6. The Average Error (AE) of the member models ranges from 31 km to 146 km for forecasts up to 12-hour. The AE of the member models increases with the forecast period and it ranges from of the order of 116 km to 168 km, 139 km to 220 km, 181 km to 310 km, 243 km to 426 km and 320 km to 474 km for 24, 36, 48, 60 and 72 hour forecast respectively. ECMWF model is found to be the best among the member models. The AE of the ensemble mean (ENM) ranges from 95 km to 332 km and it ranges from of the order of 74 km to 290 km for multimodel ensemble (MME) technique for forecast up to 72-hour. The ensemble mean (ENM) technique is found to be better than most of the member models but not than the best model (ECMWF). Whereas, performance of

Table 6. Skill scores (average error in km) of 12 hourly forecasts made for the independent samples; N= number of independent samples.

	Forecast hours →					
MODEL	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
ECMWF	31	116	139	181	243	320
NCEP	110	153	160	226	305	392
JMA	113	139	196	227	317	378
MM5	86	151	219	310	333	381
QLM	146	168	220	286	426	474
ENM	95	104	175	211	282	332
MME	74	101	143	189	242	290
N	53	45	39	33	27	21

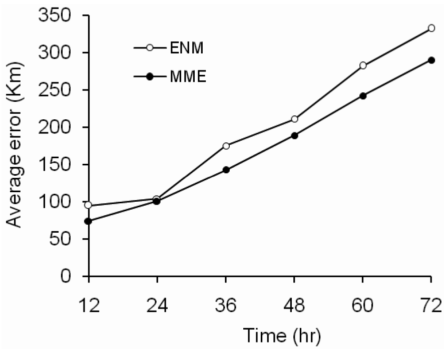

Figure 3. Average errors for MME and ENM for independent sample.

multimodel ensemble (MME) technique shows that there are skill improvements of the order of 30 km over the best model and 42 km over the ENM at 72-hour forecast.

5.2. ENM versus MME technique

Figure 3 shows an inter-comparison of the average errors (*AE*) between MME and the ENM at 12, 24, 48, 60 and 72-hour forecasts. Inter-comparison reveals that there is an improvement in MME than ENM at all forecast hours. The maximum error is reduced by 42 km at 72-hour forecast and minimum at 24-hour. For the comparison purpose, we also compute relative errors (*RE*) index. The RE is defined as:

$$RE = 100 \frac{AE_{MME} - AE_{ENM}}{AE_{ENM}}$$

Figure 4 shows that the RE is negative for all forecast hours except for 24 hour. The average errors of MME technique are reduced by 3% to 22% for all

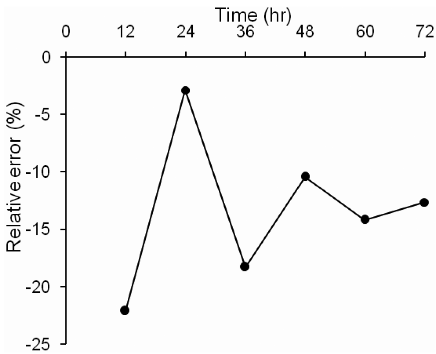

Figure 4. Relative errors for MME and ENM for independent sample.

forecast hours. Maximum improvement of error (22%) occurred at the 12-hour forecast and minimum (3%) at 24-hour. 18% improvement occurred at 36-hour forecast, 10% improvement at 48-hour forecast, 14% improvement at 60-hour forecast and 13% improvement at 72-hour forecast. These results have distinctly established that the MME technique is superior to the ENM.

5.3. Official forecast versus model and MME forecast for cyclones in 2010

The forecast errors of member models and the corresponding ENM and ensemble forecasts (MME) along with the IMD official forecasts for cyclones in 2010 are presented in Table 7. The table shows that errors of ECMWF model

Table 7. Track forecast error (km) of multi-model ensemble and its member models along with official forecasts for cyclones in 2010.

	Forecast hours →					
MODEL	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
ECMWF	54	71	102	170	202	246
NCEP	158	178	177	236	253	334
JMA	195	96	176	203	232	268
MM5	118	141	241	350	363	356
QLM	103	144	167	181	256	311
ENM	101	107	175	226	292	335
MME	72	97	153	223	256	283
Official	66	131	167	249	330	465

are found to be lower than other member models at all forecast hours from 12-hour to 72-hour, which ranges from 54 km to 246 km. The errors of MM5 model are found to be greater than other member models, which range form 118 km to 356 km. The MME forecast position errors are found to be less than ENM and Official forecasts at all forecast hours except for 12-hour. Similarly, ENM forecast position errors are found to be less than Official forecast at all forecast hours except for 12-hour and 36-hour.

5.4. Case study for the Independent samples

As averaging of a parameter for many events smoothens its internal variation, it is worthwhile to compare the composite characteristics with individual cases to verify consistency. In this section, we examine the performance of the individual models and MME forecast for two independent cyclones of 2009 and 2010. Two cyclones, “PHYAN” and “LAILA”, were formed during the cyclone season of 2009 and 2010 respectively.

Case 1: Cyclonic storm "PHYAN" of (9–12) November 2009

Figure 5 and Figure 6 display the observed track and forecast track of the cyclone PHYAN by various NWP models (ECMWF, NCEP, JMA, MM5, QLM) and multimodel ensemble (MME) based on initial conditions of 0000 UTC of

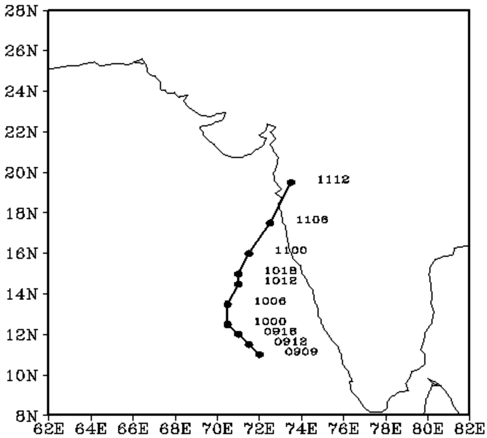

Figure 5. Observed track of cyclone PHYAN.

10 November 2009 respectively. All the NWP models indicated that the cyclonic storm PHYAN was going to move northerly direction and crossed the Gujarat coast except the NCEP model, which showed northeasterly direction and crossed Maharastra coast.

The forecast error of member models and the corresponding ensemble forecasts (MME) is presented in Table 8. The 36-hour forecasts shows that forecast position error varies from around 115 km to 406 km. Corresponding

Table 8. Track forecast error (km) of multi-model ensemble and its member models based on 0000 UTC of 10 November 2009 for cyclone PHYAN.

	Forecast hours →		
MODEL	12 hr	24 hr	36 hr
ECMWF	55	85	115
NCEP	362	346	123
JMA	62	38	325
MM5	322	248	339
QLM	144	223	406
ENM	128	154	277
MME	78	144	250

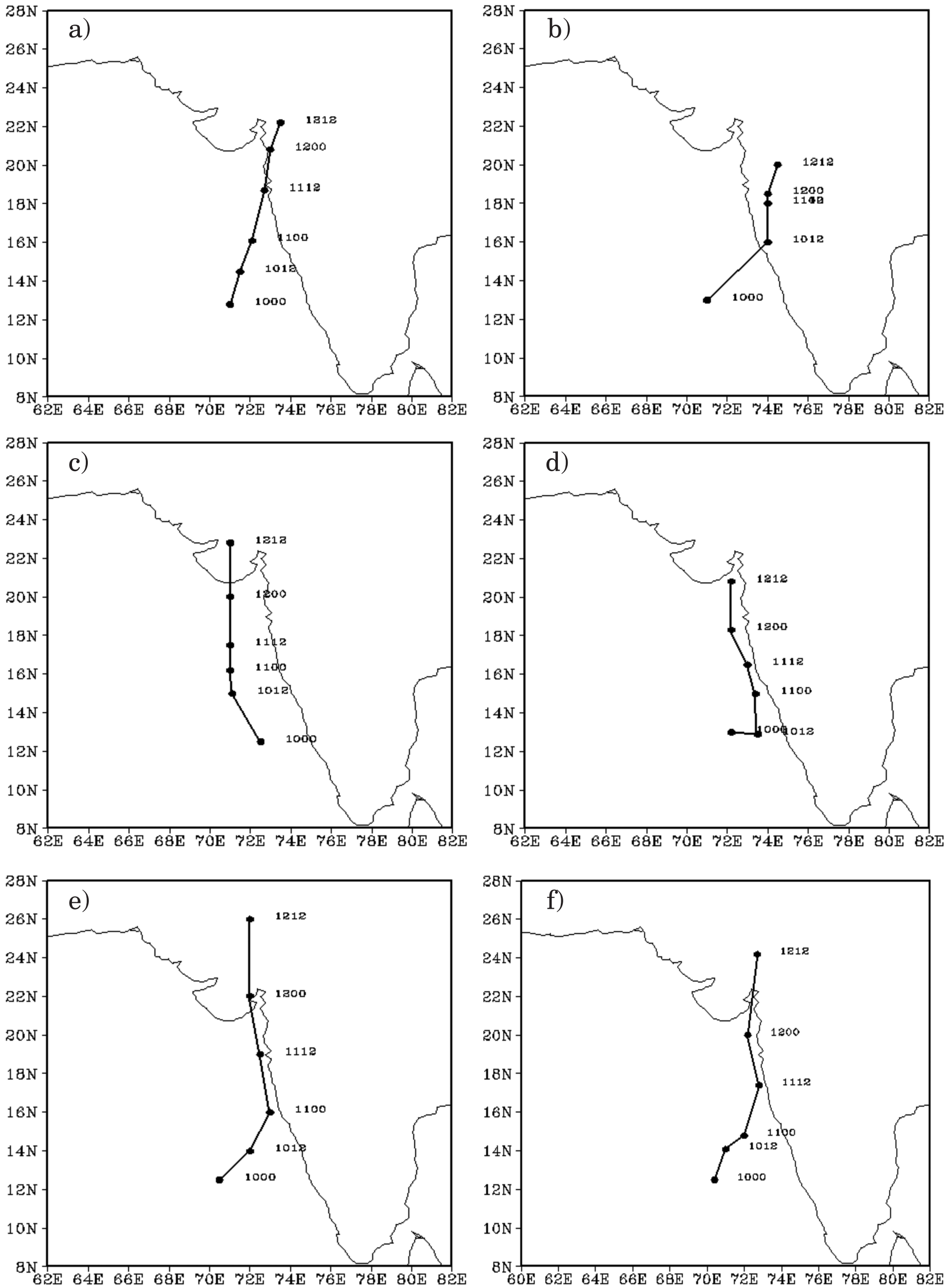

Figure 6. Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 10 November 2009 of cyclone PHYAN: (a) ECMWF (b) NCEP (c) JMA (d) MM5 (e) QLM and (f) MME

ENM and MME forecast position errors are 277 km and 250 km respectively. The 24-hour forecasts position error varies from 38 km to 346 km with lowest error by JMA and largest error by NCEP model. Corresponding ENM and MME forecast position errors are 154 km and 144 km respectively. The 12-hour forecast position error varies from 55 km to 362 km with lowest error by ECMWF and largest error by NCEP model, whereas, ENM and MME errors are 128 km and 78 km respectively.

Case 2: Severe cyclonic storm "LAILA" of (17–21) May 2010

Figure 7 and Figure 8 display the observed track and forecast track of the cyclone LAILA by various NWP models (ECMWF, NCEP, JMA, MM5, QLM) and multimodel ensemble (MME) based on initial conditions of 0000 UTC of 18 May 2010 respectively. It is encouraging to note that all the NWP models indicated that the cyclonic storm LAILA was going to move in the northwest direction. Although the NCEP and MM5 model both predicted movement in the northwesterly direction but not going to landfall during the next 72-hour. The MME showed northwesterly movement and also landfall at Andhra Pradesh coast during next 72-hour.

The forecast errors of member models and the corresponding ensemble forecasts (MME) are summarized in Table 9. The 72-hour forecasts show that error ranges from 20 km to 222 km. Corresponding ENM and MME forecast position errors are 164 km and 148 km respectively. The 60-hour forecast position error varies from 154 km to 202 km with ENM and MME errors are 182 km and 107 km respectively. The 48-hour forecasts position error varies from 86 km to 253 km with lowest error by JMA and largest error by QLM model. Corresponding ENM and MME forecast position errors are 167 km and 112 km respectively. The 36-hour forecasts error varies from 63 km to 191 km

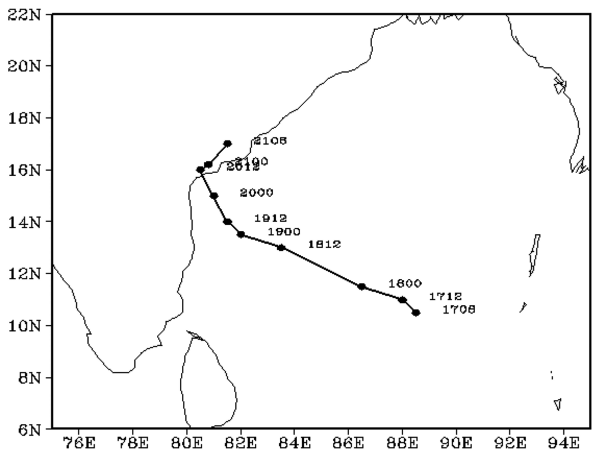

Figure 7. Observed track of cyclone LAILA.

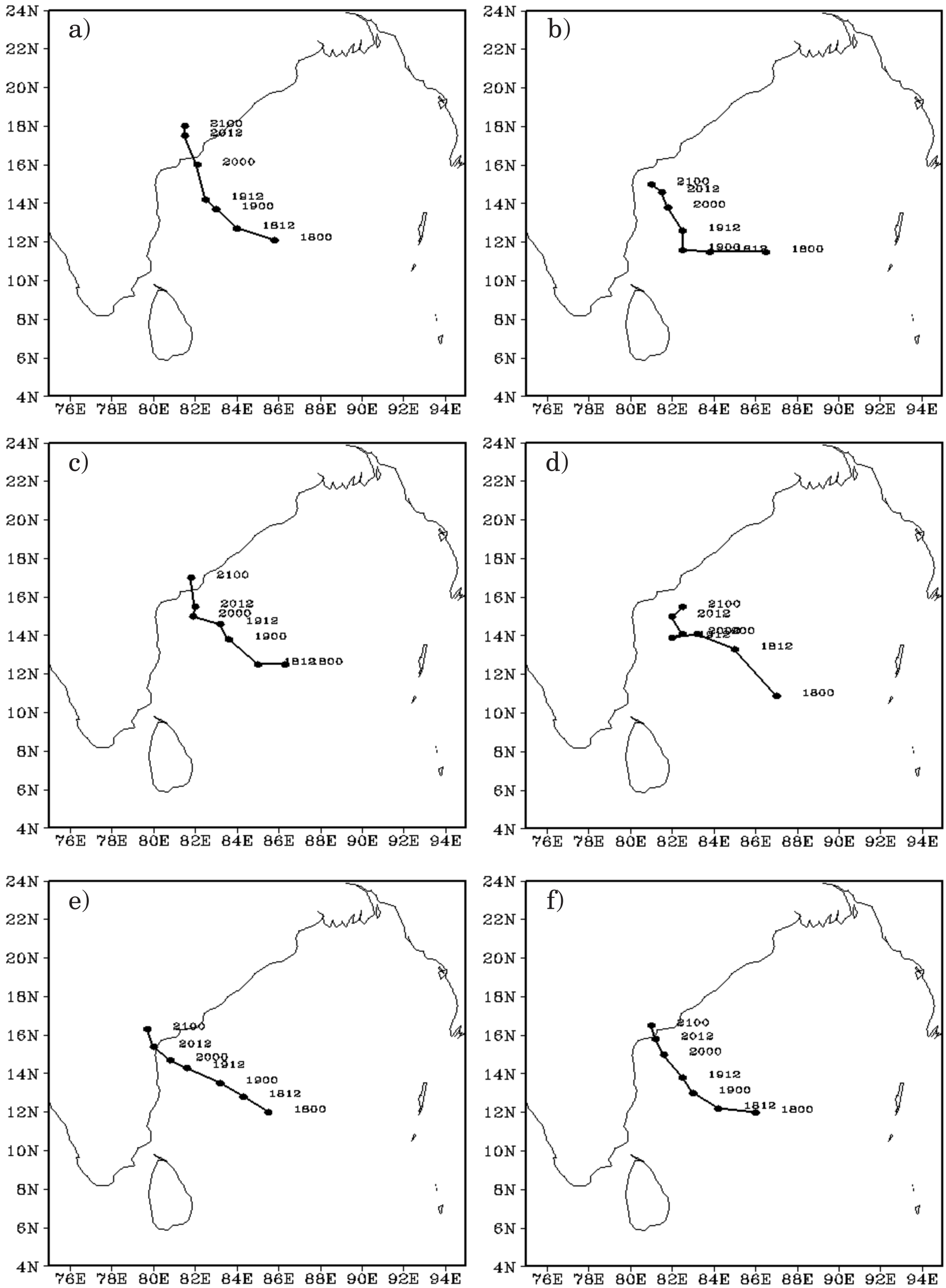

Figure 8. Track forecasts of multimodel ensemble and its member models based on 0000 UTC of 18 May 2010 of cyclone LAILA: (a) ECMWF (b) NCEP (c) JMA (d) MM5 (e) QLM and (f) MME.

Table 9. Track forecast error (km) of multi-model ensemble and its member models based on 0000 UTC of 18 May 2010 for cyclone LAILA.

	Forecast hours →					
MODEL	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
ECMWF	64	130	110	170	198	138
NCEP	170	218	189	159	189	216
JMA	172	185	191	86	166	20
MM5	155	146	63	181	202	198
QLM	144	121	149	253	154	222
ENM	138	119	108	167	182	164
MME	117	103	141	112	107	148

with lowest error by MM5 and largest error by JMA model. Corresponding ENM forecasts (108 km) showed less error than MME (141 km). The 24-hour forecasts position error varies from 121 km to 218 km with lowest error by QLM and largest error by NCEP model. Corresponding ENM and MME forecast position errors are 119 km and 103 km respectively. The 12-hour forecast position error varies from 64 km to 172 km with lowest error by ECMWF and largest error by JMA model, whereas, ENM and MME errors are 138 km and 117 km respectively.

The above case study shows that consensus forecasts could provide useful guidance under the circumstances of wide variations of individual model forecasts.

5.5 Limitations of the multimodel ensemble (MME) technique

The consistency of performance of the multimodel ensemble technique largely depends on the consistency of configuration and consistency of performance of the member models. Regular changes of model configuration could be a difficult proposition for the application of ensemble technique. Short training period to construct the ensemble technique could be an option to avoid this problem. Thus, herein, cyclonic systems in 2008 and pre-monsoon season of 2009 were considered as the training period and cyclones of 2010 and post-monsoon of 2009 were used for the evaluation of skill of the MME.

In case of changes of configuration of member models during the training and the forecast period the ensemble mean technique (ENM) could also be useful to operational forecasters.

6. Concluding remarks

For the operational practices, there is a growing demand for accurate prediction of tropical cyclone track. During the last two decades, weather forecasting all over the world has greatly benefited from the guidance provided by the Numerical Weather Prediction (NWP) model. Significant improvement in accuracy and reliability of NWP products has been driven by sophisticated numerical techniques. However, limitations remain, particularly under the circumstances of wide variation of forecasts position of different NWP models. The present paper describes a multimodel ensemble (MME) cyclone track prediction technique for the North Indian Sea for the forecast at 12-hour interval valid up to 72-hour. The method is developed using multiple linear regression technique with five member models, namely ECMWF, NCEP, MM5, QLM and JMA. The model parameters are selected based on the sample database of cyclonic systems that occurred in 2008 and pre-monsoon season in 2009. The performance of the model is tested using the independent samples that occurred during 2010 and post-monsoon season in 2009. ECMWF model is found to be the best among member models. The ensemble mean (ENM) technique is found to be better than the most of the member models but not than the best model. The average track forecast error of the ENM ranges from 95 km to 332 km and it ranges from of the order of 74 km to 290 km for MME technique for forecast up to 72-hour. The maximum error is reduced by around 40 km at 60-hour and 72-hour forecasts of MME than ENM. The performance of ensemble technique (MME) shows that there are skill improvements of the order of 30 km over the best model at 72-hour forecast. The case studies also show that under the circumstances of wide variation of forecasts position of different NWP models, the proposed MME technique based on individual numerical models could provide useful guidance to the operational forecasters. The results of this study using the data of 2008 to 2009 are very promising. We intend to include the all data of cyclones during 2008 to 2010 for regression of MME technique for forecasting the cyclone track of 2011. A collective bias correction is included in the ensemble technique as a multiple linear regression based minimization principle for the model forecast position against to the observed position is applied in this study. We also intend to extend the work of individual bias removal of member models in our future study.

Acknowledgements – The Authors are grateful to the Director General of Meteorology, India Meteorological Department, New Delhi for providing all the facilities to carry out this research work. Authors acknowledge the use of ECMWF, JMA and NCEP data in this research work. Authors are grateful to the anonymous reviewers for their valuable comments to improve the quality of the paper.

References

Goerss, J. S. (2000): Tropical cyclone track forecasts using an ensemble of dynamical models, *Mon. Weather Rev.,* **128**, 1187–1193.

Krishnamurti, T. N., Kishtawal, C. M., LaRow, T., Bachiochi, D., Zhang, Z., Williford, C. E., Gadgil, S. and Surendran, S. (1999): Improved skills for weather and seasonal climate forecasts from multimodel superensemble, *Science,* **285**, 1548–1550.

Krishnamurti, T. N., Kishtawal, C. M., Zhang, Z., Larow, T., Bachiochi, D., Williford, E., Gadgil, S. and Surendran, S. (2000a): Multimodel superensemble forecasts for weather and seasonal climate, *J. Climate,* **13**, 4196–4216.

Krishnamurti, T. N., Kishtawal, C. M., Shin, D. W. and Williford, C. E. (2000b): Improving tropical precipitation forecasts from a multianalysis superensemble, *J. Climate,* **13**, 4217–4227.

Krishnamurti, T. N., Sajani Surendran, Shin, D. W., Correa-Torres, R. J., Vijaya Kumar, T. S. V., Williford, E., Kummerow, C., Adler, R. F., Simpson, J., Kakar, R., Olson, W. S. and Turk, F. J. (2001): Real-time multianalysis-multimodel super-ensemble forecasts of precipitation using TRMM and SSM/I products, *Mon. Weather Rev.,* **129**, 2861–2883.

Krishnamurti, T. N., Rajendran, K., Vijaya Kumar, T. S. V., Lord, S., Toth, Z. Zou, X., Ahlquist, J. and Navon, I. M. (2003): Improved skills for the anomaly correlation of geopotential heights at 500 hPa, *Mon. Weather Rev.,* **131**, 1082–1102.

Mackey, B. P. and Krishnamurti, T. N. (2001): Ensemble forecast of a typhoon flood event, *Weather Forecast.*, **16**, 399–415.

Vijaya Kumar, T. S. V., Krishnamurti, T. N., Fiorino, M. and Nagata, M. (2003): Multimodel superensemble forecasting of tropical cyclones in the Pacific**,** *Mon. Weather Rev.,* **131**, 574–583.

Weber, H. C. (2003): Hurricane track prediction using a statistical ensemble of numerical models, *Mon. Weather Rev.,* **131**, 749–770.

Williford, C. E., Krishnamurti, T. N., Correa-Torres, R. J., Cocke, S., Christidis, Z. and Vijaya Kumar, T. S. (2003): Real-time multimodel superensemble forecasts of Atlantic tropical systems of 1999, *Mon. Weather Rev.,* **131**, 1878–1894.

SAŽETAK

Višemodelna ansambl metoda (MME) za prognozu putanja ciklona preko Sjevernoindijskog mora

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U ovom radu predlaže se metoda za višemodelnu ansambl prognozu (MME) putanja tropskih ciklona nad sjevernim dijelom Indijskog oceana korištenjem prognoza nekoliko različitih modela. Metoda je razvijena na temelju višestruke linearne regresije. Parametri MME metode određuju se pomoću prognoziranih podataka putanja tropskih ciklona nad sjevernim dijelom Indijskog oceana u razdoblju 2008.–2009. Odabrani parametri su: prognozirana zemljopisna širina i dužina položaja ciklona u 12-satnom intervalu u 72-satnoj prognozi za pet operativnih numeričkih prognostičkih modela. Korišteni članovi ansambla u MME metodi su: (i) prognoze Europskog centra za srednjoročne prognoze vremena (ECMWF), (ii) prognoze Nacionalnog centra za zaštitu okoliša prognostičkog globalnog sustava (NCEP), (iii) MM5 model, (iv) kvazi-Lagrangian model (QLM) i (v) model Japanske meteorološke agencije (JMA). Koristeći višestruku linearnu regresiju između opaženih i modelima prognoziranih putanja, predložena metoda uključuje i smanjenje sveukupne srednje pogreške. Odgovarajući čimbenici odstupanja opisuju se odvojenim težinama u svakom 12-satnom intervalu u cijeloj 72-satnoj prognozi za svaki pojedini model. Nakon testiranja metode na nezavisnim uzorcima pokazalo se da je uspješnost prognoze MME metodom zadovoljavajuća. Srednja pogreška je za 72-h prognoze unutar intervala od 74 km do 290 km. Performanse MME metode pokazuju da je poboljšanje uspješnosti do 30 km prilikom određivanja pogreške pozicije ciklone za najbolji model unutar 72-satne prognoze. Uspješnost prognoze pomoću MME metode za prognoze do 72-sata također pokazuju poboljšanje u usporedbi s prognozama kako svakog pojedinačnog modela, tako i s prognozom temeljenom na jednostavnom srednjaku ansambla.

Ključne riječi: tropski ciklon, prognoza putanje, višestruka linearna regresija, koeficijent regresije, srednjak ansambla i metoda višemodelne ansambl prognoze

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