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Short communication

Tropical cyclone intensity prediction over the North Indian Ocean – An NWP based objective approach

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A Numerical Weather Prediction (NWP) based objective intensity prediction approach has been explored for prediction of tropical cyclone intensity over the North Indian Ocean (NIO) using ECMWF model outputs. The intensity of a tropical cyclone is classified by the maximum sustained wind (10-min mean) according to World Meteorological Organization (WMO). An empirical relationship between the difference of the model's maximum mean sea level pressure (*MSLP*) inside a 6° × 6° grid box around the centre of the system and the lowest mean sea level pressure at the centre of the system (ΔP) with the observed intensity is developed using over 100 analyses during 2010–2012. The same is used to predict intensity of very severe cyclonic storm Hudhud and a Deep Depression observed over the Bay of Bengal during 2014. The results show that the empirical equation is skillful in prediction of intensity as compared to predictions computed using the relationship $V_{max} = K\sqrt{\Delta P}$ with different constant values of K. The error analyses show that the relative error in intensity prediction using the empirical equation derived in the present study is 34% less than the same using $K = 14.2\,\text{kt}/\sqrt{\text{hPa}}$ in $V_{max} = K\sqrt{\Delta P}$ with an improvement which is significant at the level of 0.95.

Keywords: Numerical Weather Prediction (NWP), North Indian Ocean (NIO), intensity, mean sea level pressure, pressure defect, average absolute error, standard deviation

1. Introduction

From the operational perspective it is always desirable to apply all corrections to the direct model outputs that help to improve the result. Therefore, several post-processing based prediction methods have been adopted at different Numerical Weather Prediction (NWP) centres across the globe. In the NWP Division of the India Meteorological Department (IMD) a comprehensive post processing based objective Cyclone Prediction System (CPS) has been implemented for forecasting of Tropical Cyclones (TC) over the North Indian Ocean (NIO). Intensity prediction is one important aspect of the CPS and a Statistical Cyclone Intensity Prediction (SCIP) (Kotal et al., 2008) model has been used to provide guidance to the operational forecasters in IMD up to 72 hours lead time. Multi Model Ensemble (MME) technique is another component of the CPS used for TC track prediction. Prior to 2013 the MME was used up to 72 hours forecast lead time and presently the MME track forecast has been extended to 120 hours lead time. While development of modified SCIP model is under way, in this paper an attempt has been made to develop an alternative NWP based objective approach for TC intensity prediction, at 12 hourly intervals, up to 120 hours lead time. A relationship between the pressure drop at the centre of the system (ΔP) with the observed intensity has been explored. By the time of the model runs are available in all practical cases the initial error in prediction of intensity is known from the difference of the observed and the models' analysis outputs. The prospect of minimization of forecast errors through initial bias correction is also examined in this paper.

2. Data sources

The observed data for the cyclones' intensity and other variables have been taken from the data base of the Cyclone Division of the Regional Specialized Meteorological Centre (RSMC), New Delhi. The RSMC, New Delhi is entrusted by the World Meteorological Organization for analysis of the intensity of tropical cyclones over the NIO. The RSMC TC intensity determination technique is mainly based on subjective methods as described by Dvorak (1975). When the systems come within the range of RADAR installed at different observatories along the coasts, such observations are also considered for estimation of intensity of the systems. The European Centre for Medium-range Weather Forecasting (ECMWF) model output with $0.25° \times 0.25°$ latitude-longitude horizontal resolution (obtained under special arrangement) are used as training period data during 2010–2012. NCEP (National Center for Environmental Prediction) data available at $1° \times 1°$ grid, IMD-GFS model data available at $0.5° \times 0.5°$ grid and ECMWF model data at $0.5° \times 0.5°$ resolution available through GTS (Global Telecommunication System) are also used in this study. The ECMWF GTS data are available in 24-hour forecast intervals. The 12 hourly forecasts for the same are obtained by interpolation method. In this study, knot (kt) is used instead of standard unit meter per second as winds are expressed in knots ($1\,\text{kt} = 0.5144\,\text{m}\,\text{s}^{-1}$).

3. Choice of model

Choosing a suitable model for operational use is an essential component of forecasting decisions. In this Section, before undertaking the development

Table 1. The Average Absolute Error (AAE) and the Standard Deviation (SD) for MSLP (at centre of cyclonic storms) of the ECMWF, NCEP-GFS, IMD-GFS.

No. of samples = 91	ECMWF	NCEP-GFS	IMD-GFS
AAE (hPa)	4.9	9.1	13.8
SD (hPa)	6.9	13.7	19.1

scheme, a performance verification for the Very Severe Cyclonic Storm (VSCS) Hudhud (8–14 October 2014) and Deep Depression (DD) (6–8 November 2014) observed over the NIO has been taken up. The NCEP-GFS, IMD-GFS and ECMWF models' mean sea level pressure (MSLP) prediction skills at the centre of the system have been compared for 91 cases of analyses and 12 hourly forecasts for the above mentioned systems. The Average Absolute Error (*AAE*) and the Standard Deviation (*SD*) of the NCEP-GFS were 9.1 hPa and 13.7 hPa, respectively. The same for the IMD-GFS model were 13.8 hPa and 19.1 hPa, while for ECMWF they were 4.9 hPa and 6.9 hPa respectively. Being the lowest error for the *MSLP* forecasts (Tab. 1), ECMWF data are used in in this study.

4. Choice of equation

The cyclostrophic balance equation is given by $(V^2 / \mathrm{r}) – (1 / \mathrm{r})(\partial P / \partial r) = 0$.

Hence, the condition for maximum wind (V_{max}) may be written as $\partial^2 P / \partial r^2 = 0$ which leads to a well known relationship between TC intensity and pressure defect (ΔP) as

$$V_{max} = K\sqrt{\Delta P} \tag{1}$$

This equation is also known as *Fletcher's formula* (Fletcher, 1955).

The same has been used widely for prediction of TC intensity. Mishra and Gupta (1976) determined the value of K as 14.2 $\mathrm{kt}/\sqrt{\mathrm{hPa}}$ for the NIO. Raj (2010) theoretically derived that the value of K should be 11.0 $\mathrm{kt}/\sqrt{\mathrm{hPa}}$. Pradhan et al. (2012) used an average value of $K = 13.637$ $\mathrm{kt}/\sqrt{\mathrm{hPa}}$ to estimate the TC intensity. In all these studies, the value of K was kept fixed as per the respective findings of the studies. RSMC New Delhi adopted the relation $K = 14.2$ $\mathrm{kt}/\sqrt{\mathrm{hPa}}$ for estimation of observed TC intensity (Tab. 2). In this study pressure defect ΔP has been defined as the difference of the maximum *MSLP* inside a 6° × 6° grid box around the centre of the system and central *MSLP*. The ΔP for 110 cases for the period of 2010–2012 and 91 cases for VSCS *Hudhud* and DD (6–8 November 2014) of analyses and forecasts using ECMWF data have been evaluated.

The corresponding values of K have been calculated using the relation $K = V_{obs}/\sqrt{\Delta P}$ where V_{obs} is the observed intensity in each of the cases. Figs. 1 and 2 show the variation of K for the cases considered for 2010–2012 and 2014 respectively, clearly indicating that the value of model derived K for estimation of

Table 2. Value of K adopted by RSMC New Delhi for estimation of observed TC intensity.

ΔP (hPa)	Wind speed (V_{max}, knots)	C.I. Number	K (= $V_{max}/\sqrt{\Delta P}$)
4.5	30	2.0	14.1
6.1	35	2.5	14.2
10	45	3.0	14.2
15	55	3.5	14.2
20.9	65	4.0	14.2
29.4	77	4.5	14.2
40.2	90	5.0	14.2
51.6	102	5.5	14.2
65.6	115	6.0	14.2
80	127	6.5	14.2
97.2	140	7.0	14.2
119.1	155	7.5	14.2
143.3	170	8.0	14.2

the maximum peripheral pressure, varies considerably from case to case. This finding led to need for a new representation of the relationship between TC intensity and model derived ΔP to be used in the present study. Figure 3 shows intensity plotted against model derived K leading to a modified equation for relationship between tropical cyclone intensity and pressure defect as

$$V_{max} = 23.0 \cdot e^{0.031 \cdot \Delta P} \tag{2}$$

Here we choose exponential fitting, although some other, like second order potential fitting, would also do it well. The relationship that intensity of TC increases exponentially is in good agreement with the findings of Bhowmik et al. (2006) and also Kaplan and DeMaria (1995; 2001).

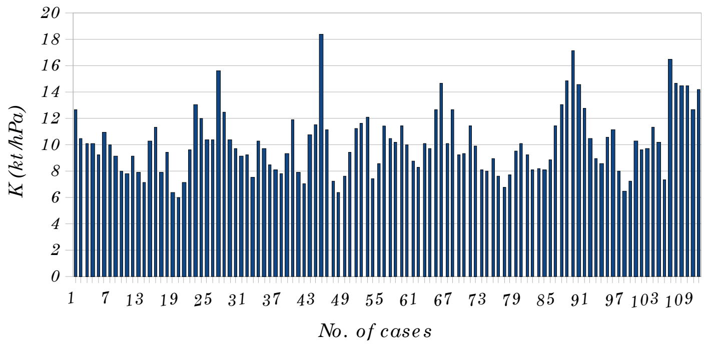

Figure 1. Variation of K for the training period 2010–2012 calculated from model derived ΔP and corresponding observed intensity.

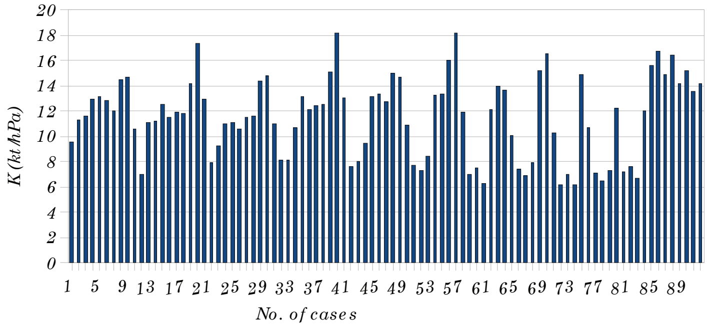

Figure 2. Variation of K for the verification period 2014 calculated from model derived ΔP and corresponding observed intensity for cyclone Hudhud (8–14 October 2014) and DD (6–8 November 2014).

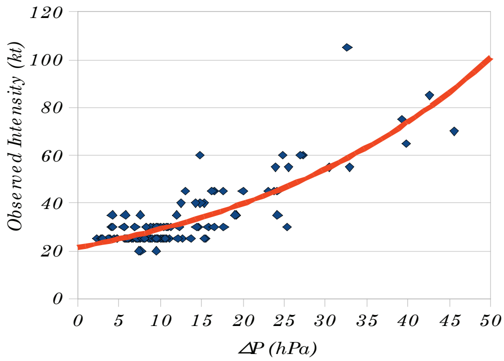

Figure 3. Observed intensity *vs.* ΔP curve used for determination of equation used for intensity prediction.

5. Results of training period (2010–2012)

Table 3 shows *AAE* and *SD* in the intensity estimation for 110 cases for the training period (2010–2012) calculated from model derived ΔP using equation (1) with $K = 14.2$, 13.637, 11.0 kt/$\sqrt{\text{hPa}}$ and also using equation (2). The *AAE* and *SD* in prediction of intensity using $K = 14.2$ kt/$\sqrt{\text{hPa}}$ in equation (1) were the highest 15.1 kts and 17.3 kts. In the same equation using $K = 13.367$ kt/$\sqrt{\text{hPa}}$ yielded *AAE* and *SD* 13.5 kts and 15.5 kts respectively and using $K = 11.0$ kt/$\sqrt{\text{hPa}}$ the same are 7.1 kts and 9.3 kts respectively. The results show that, among all the 4 techniques, the derived one using equation (2) with *AAE* and *SD* being 5.0 kts and 7.5 kts respectively, has been most skillful.

6. Verification for independent cases

The performance of the equation for TC intensity prediction derived in this paper has been verified with the observed intensity of 91 cases during VSCS

Table 3. Results for training period (2010–2012) Average Absolute Error (AAE) and the Standard Deviation (SD) in estimation of intensity using various options.

No. of samples = 110	Eq. (2)	$K = 14.2$ (kt/$\sqrt{\text{hPa}}$)	$K = 13.637$ (kt/$\sqrt{\text{hPa}}$)	$K = 11.0$ (kt/$\sqrt{\text{hPa}}$)
AAE (kts)	5.0	15.1	13.5	7.1
SD (kts)	7.5	17.3	15.5	9.3

Hudhud and Deep Depression (6–8 November 2014). The nomenclatures and corresponding of intensities of tropical cyclone for the NIO is given in Tab. 4. The VSCS Hudhud experienced Rapid Intensification (RI) in its life span when the intensity shoot up from 60 kts to 90 kts between 0600 UTC of 10 October 2014 and 0600 UTC of 11 October 2014 matching the criterion of an increase of intensity 30 kts (15.4 ms $^{-1}$) during 24 h. There was also a rapid decay of the system after the landfall around 0700 UTC of the 12 October 2014 and the intensity sharply fell after the landfall from 90 kts at 0900 UTC to 60 kts at 1200 UTC with 3 hours. The DD showed a converse characteristic and despite being over the sea surface it did not intensify into a cyclonic storm and decayed before making any landfall. This two systems covered a good range of stages of intensity varying from 25 kts to 100 kts and a significant landfall providing a wide scope for verification of intensity prediction model.

6.1. Results for verification for VSCS Hudhud (8–14 October 2014) and Deep Depression (6–8 November 2014)

ECMWF data are used for evaluating ΔP for 91 analyses and forecast cases inclusive of pre and post landfall phases. The equation (1), used with $K = 14.2$, 13.637 kt/$\sqrt{\text{hPa}}$, and also equation (2) have been applied for intensity prediction using ECMWF data. The results (Tab. 5) show that the *AAE* and *SD* have been lowest for intensity derived using equation (2) at 9.1 kts and 12.1 kts respectively. The error analyses show that the relative error using equation (2) is 34% less than the same using $K = 14.2$ kt/$\sqrt{\text{hPa}}$ in equation (1). The Student's t-test

Table 4. Nomenclatures and corresponding of intensities of tropical cyclone.

System	Associated wind speed (kts)
Low pressure area	<17
Depression	17–27
Deep Depression (DD)	28–33
Cyclonic Storm (CS)	34–47
Severe Cyclonic Storm (SCS)	48–63
Very Severe Cyclonic Storm (VSCS)	64–89
Extremely Severe Cyclonic Storm (ESCS)	90–119
Super Cyclonic Storm (SUCS)	>119

Table 5. Results for verification VSCS Hudhud (8–14 October 2014) and DD (6–8 November 2014).

No. of samples = 91	Eq. (2)	K=14.2 (kt/$\sqrt{\text{hPa}}$)	K=13.637 (kt/$\sqrt{\text{hPa}}$)	K=11.0 (kt/$\sqrt{\text{hPa}}$)
AAE (kts)	9.1	13.8	12.6	11.9
SD (kts)	12.1	16.7	15.3	15.0

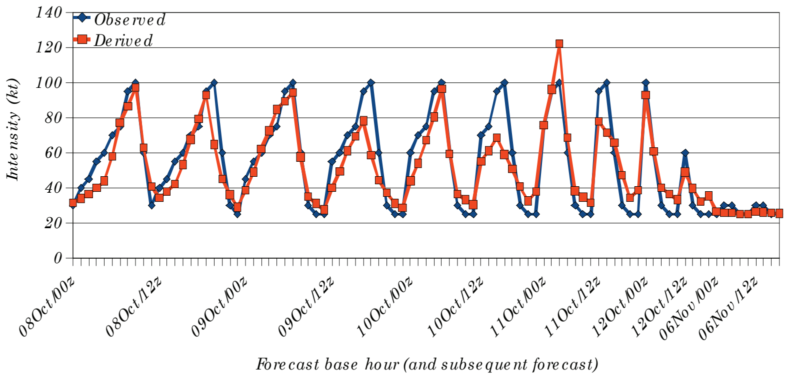

Figure 4. Plot for observed intensity and equation derived intensity.

(Welch, 1947) shows that this improvement is significant at the level of 0.95. Figure 4 shows a plot of derived intensity using the equation (2) along with the observed intensity for the verification cases.

6.2. Stage wise verification

Tropical cyclones are categorized on the basis of intensity (Tab. 6). In this section of the study the life span of the systems has been split into two phases viz. pre-landfall and post-landfall and when both are considered in a single group they are termed as ALL. The *AAE* and *SD* in prediction of intensity for different stages of intensities derived using equation (2) as compared to the corresponding observed intensities have been shown in Tab. 6. It is found that in the pre-landfall stages the errors increased with intensification of the systems and was maximum in prediction of intensities when the systems were in their VSCS stage. The *AAE* and *SD* was 7.9 kts and 8.8 kts respectively for the post-landfall phases which are lower than the average *AAE* and *SD* for both the pre-landfall and post-landfall phases combined together.

6.3. Verification of 12 hourly forecast

Table 7 shows the verification results of 12 hourly intensity prediction for VSCS Hudhud (8–14 October 2014) and DD (6–8 November 2014) using equation

Table 6. Stage wise verification result for VSCS Hudhud (8–14 Oct. 2014) and DD (6–8 Nov 2014) using equation (Numbers in parenthesis show the number of cases verified)

	ALL	Pre-landfall					Post-landfall
		All	<SCS	SCS	VSCS	SCS+VSCS	
AAE (kts)	9.1 (91)	10.0	3.6 (15)	11.3 (9)	12.8 (30)	12.4 (39)	7.9 (37)
SD (kts)	12.1	14.0	4.5	12.3	17.2	16.2	8.8

Table 7. Verification of 12 hourly intensity prediction result for VSCS Hudhud (8–14 October 2014) and DD (6–8 November 2014) using equation (2) (Numbers in parenthesis show the number of cases verified).

Lead time (hr)	00	12	24	36	48	60	72	84	96	108	120
AAE (kts)	8.5 (12)	9.0 (12)	9.7 (12)	11.1 (12)	8.4 (10)	12.2 (8)	6.5 (7)	12.4 (6)	6.9 (5)	4.5 (4)	5.6 (3)

(2). The results show that the average absolute error was limited within 13 kts for all the lead times.

6.4. Initial bias correction

By the time the model simulation data for any date and time are available to the forecasters the satellite based observed intensity of the cyclonic system gets already known. Therefore, an initial bias correction (IBC) may be applied to the forecast intensities based on the difference of model analysis intensity and observed intensity at that time and the IBC may be represented as ΔV_{anl}. The intensity after IBC may then be written as

$$V_{IBC} = V_{max} - \Delta V_{anl} \tag{3}$$

Table 8 shows the V_{IBC} for the pre-landfall phases (pre-landfall is referred to the time period when the system was over the sea before landfall) of the 2014 verification cases. It shows that IBC causes a reduction in relative error by 37% in intensity prediction using the equation (3). Figure 5 shows the observed intensity and equation derived pre-landfall intensities without and with initial bias correction. The figure shows the reduction of error in intensity prediction in the pre-landfall phases irrespective of the stage of intensification. *AAE* for 12 hourly equation (2) derived pre-landfall intensities without and with initial bias correction have been plotted in Fig. 6. The figure shows that the IBC reduced the intensity prediction error for almost all forecast lead time.

7. Summary and conclusions

ECMWF model is found to be more skillful in prediction of mean sea level pressure at the centre of the tropical systems over the NIO as compared to the

Table 8. Stage wise verification result for VSCS Hudhud (8–14 October 2014) and DD (6–8 November 2014) after initial bias correction (IBC).

	Pre-landfall									
	All		<SCS		SCS		VSCS		SCS+VSCS	
	without IBC	with IBC	without IBC	with IBC	without IBC	with IBC	without IBC	with IBC	without IBC	with IBC
AAE (kts)	10.0	6.3	3.6	2.8	11.3	6.3	12.8	8.0	12.4	7.6
SD (kts)	14.0	9.7	4.5	4.0	12.3	9.0	17.2	11.6	16.2	11.1

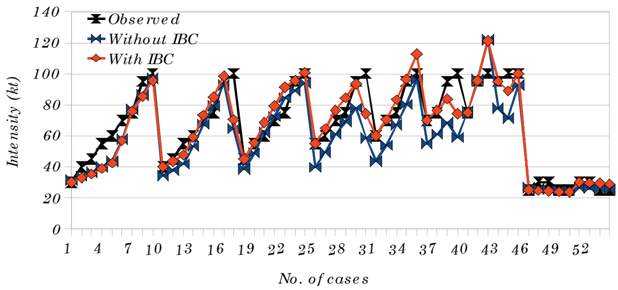

Figure 5. Plot for observed intensity and equation derived pre-landfall intensities without and with initial bias correction (IBC).

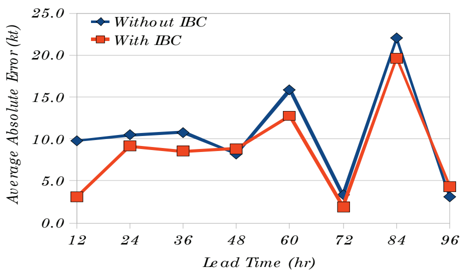

Figure 6. Plot for *AAE* of 12 hourly equation derived pre-landfall intensities without and with initial bias correction (IBC).

performance of the NCEP-GFS and IMD-GFS models. In this study pressure defect ΔP has been defined as the difference of the maximum *MSLP* inside a 6° × 6° grid box around the centre of the system and central *MSLP*. It is found that K derived from the equation $K = V_{obs}/\sqrt{\Delta P}$ where V_{obs} is the observed intensity varies from case to case and as such it is concluded that the value of K if kept fixed in obtaining intensity using the equation $V_{max} = K\sqrt{\Delta P}$ may yield more error.

A mathematical equation $V_{max} = 23.0 \cdot e^{0.031 \cdot \Delta P}$ derived using relationship between analysis ΔP obtained from ECMWF model outputs and observed intensity for tropical cyclones observed over the North Indian Ocean during the period of 2010–2012 is found to be skilful in prediction of cyclone intensity. The verification using ΔP, obtained from 91 ECMWF analyses and forecasts also show that the *AAE* and *SD* of the intensities obtained using the equation derived in this paper are less as compared to the same computed by using the relationship $V_{max} = K\sqrt{\Delta P}$ with various fixed values of K estimated in previous studies including the one adapted by the RSMC New Delhi. Initial bias correction has been found to add skill to the performance of the intensity forecast using the mathematical equation derived in this paper. The equation may provide useful guidance for intensity forecasting extended up to 120 hours forecast lead time covering both pre-landfall and post-landfall cases and has scope to indicate impending decay over the seas.

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SAŽETAK

Prognoza intenziteta tropskih ciklona nad Sjeverno-indijskim oceanom – Objektivni pristup temeljen na numeričkoj prognozi vremena

Sumit Kumar Bhattacharya, Shyam Das Kotal, Sankar Nath, Swapan Kumar Roy Bhowmik i Prabir Kumar Kundu

U radu je istražena metoda objektivne prognoze intenziteta tropskih ciklona nad Sjeverno-indijskim oceanom (NIO) temeljm numeričke prognoze vremena (NWP) modelom Europskog centra za srednjoročnu prognozu vremena (ECMWF). Intenzitet tropskog ciklona klasificira se prema prema Svjetskoj meteorološkoj organizaciji (WMO) na temelju maksimalnog vjetra (10-minutni srednjak). Upotrebom preko 100 analiza tijekom 2010.–2012. izvedena je empirijska relacija koja povezuje razliku između najvećeg srednjeg tlaka zraka na razini mora (*MSLP*) unutar kvadrata mreže 6° × 6° oko središta sustava i najnižeg srednjeg tlaka na razini mora u središtu sustava (ΔP) s opaženim intenzitetom ciklona. Dobivena relacija primjenjena je na prognozu intenziteta olujnih ciklona Hudhud i Deep Depression (Duboka depresija) koji su opaženi u Bengalskom zaljevu tijekom 2014. godine. Rezultati pokazuju da empirijska jednadžba prognozira intenzitet ciklona uspješnije od prognoza izračunatih pomoću relacije $V_{max} = K\sqrt{\Delta P}$ s različitim konstantnim vrijednostima *K*. Analize pogrešaka pokazuju da je relativna pogreška u prognozi intenziteta primjenom dobivene empirijske jednadžbe 34% manja od pogreške pri korištenju relacije $K = 14{,}2\ \mathrm{kt}/\sqrt{\mathrm{hPa}}$ u $V_{max} = K\sqrt{\Delta P}$, a poboljšanje je značajno na razini signifikantnosti od 0,95.

Ključne riječi: numerička prognoza vremena (NWP), Sjeverno-indijski ocean (NIO), intenzitet, srednji tlak zraka na razini mora, deficit tlaka zraka, srednja apsolutna pogreška, standardna devijacija

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