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# Impact of cyclone bogusing and regional assimilation on tropical cyclone track and intensity predictions

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**सार** – इस अध्ययन का उद्देश्य अल्प अवधि पूर्वानुमान में चक्रवात के पथ और उसकी तीव्रता का पूर्वानुमान लगाने के लिए डब्ल्यू.आर.एफ. समीकरण और पूर्वानुमान प्रणाली में उष्णकटिबंधीय काल्पनिक चक्रवात के आधार पर उसके प्रभाव का निर्धारण करना है। इस प्रभाव को चक्रवात के प्रभाव की त्रुटि, केन्द्रीय दाब और अधिकतम सतत पवन गति के रूप में बताया गया है।

यह अध्ययन वर्ष 2010 में बने तीन चक्रवातों नामतः 'लैला' (बंगाल की खाड़ी), 'गिरी' (बंगाल की खाड़ी) और 'फेट' (अरब सागर) पर आधारित है। डब्ल्यू. आर. एफ. मॉडल प्रचालनात्मक एन.सी.एम. आर.डब्ल्यू.एफ. टी. 382 एल 64 के विश्लेषण और पूर्वानुमानों का उपयोग करता है और इस मॉडल को चक्रवात के पथ और इसकी तीव्रता का पूर्वानुमान लगाने के लिए 72 घंटे तक समाकलित किया गया है। इस परीक्षण के चार सैटों की जाँच की गई (*i*) नियंत्रण परीक्षण (सी.एन.टी.एल.) जिसमें ना तो समीकरण और ना ही काल्पनिक चक्रवात को आधार माना गया है। इस मॉडल का आरंभ अंतर्वेशित भूमंडलीय मॉडल विश्लेषण का उपयोग करते हुए किया गया। (*ii*) समीकरण परीक्षण (वी.ए.आर.) में डब्ल्यू. आर. एफ. वी. ए. आर. आँकड़ा समीकरण प्रणाली (बिना काल्पनिक आधार पर माना गया चक्रवात) का उपयोग करते हुए मॉडल की आरंभिक स्थितियाँ तैयार की गईं। (*iii*) चक्रवात के परीक्षण (बी.ओ.जी.) समीकरण के बिना केवल काल्पनिक चक्रवात को मानते हुए काल्पनिक आधार पर चक्रवात के प्रयोग किए गए हैं। इस मामले में काल्पनिक आघार पर चक्रवात का उपयोग करते हुए मॉडल के प्रथम अनुमान को संशोधित किया गया और इसका आरंभिक स्थितियों के रूप में उपयोग किया गया है। (*iv*) चौथे परीक्षण में काल्पनिक आधार पर चक्रवात के बाद डब्ल्यू. आर. एफ. आँकड़ा समीकरण (बी. ओ. जी. वी. ए. आर.) दोनों का उपयोग करते हुए मॉडल की आरंभिक स्थितियाँ तैयार की गई।

इनसे प्राप्त हुए परीणामों से आरंभिक स्थितियों में काल्पनिक चक्रवात के उल्लेखनीय प्रभाव का पता चला है। ये तीनों ही चक्रवात काल्पनिक (बी.ओ.जी. और वी.ए.आर.) प्रयोगों की आरंभिक स्थितियों (0000 यू. टी. सी.) में पाए गए जा सकते हैं जो अन्यथा काल्पनिक आधार पर तैयार किए गए चक्रवातों के अभाव में (वी. ए.आर. और सी. एन. टी. एल.) प्रयोग में नहीं होती है। बी. ओ. जी. वी. ए. आर. परीक्षण के पथ त्रुटियों में उल्लेखनीय कमी देखी गई है। वी. ए. आर. की तुलना में बी. ओ. जी. वी. ए. आर. में पथ त्रुटि में अधिकतम कमी क्रमशः 'लैला' में 76.8 प्रतिशत, 'गिरी' में 87.3 प्रतिशत और 'फेट' में 51.5 प्रतिशत रही। 'लैला' और 'गिरी' के लिए वी.ए.आर. की तुलना में बी.ओ.जी.वी.ए.आर. में लिए गए प्रेक्षण अधिकतम सतत/क्रमिक पवन गति और अधिकतम केन्द्रीय दाब के निकट हैं।

**ABSTRACT.** The aim of this study is to assess the impact of tropical cyclone bogusing in WRF assimilation and forecast system for cyclone track and intensity prediction in short range forecast. The impact is demonstrated in terms of track error, central pressure, and maximum sustained wind speed.

The study is based on the three cyclones; namely 'LAILA' (Bay of Bengal), 'GIRI' (Bay of Bengal) and 'PHET' (Arabian Sea), formed in the year 2010. The WRF model makes use of the operational NCMRWF T382L64 analysis and forecasts and the model is integrated upto 72 hrs for producing the cyclone track and intensity forecast. Four sets of experiments were performed: (*i*) The control experiment (CNTL) in which neither assimilation nor cyclone bogusing is done. The model is initialized using interpolated global model analysis. (*ii*) In assimilation experiment (VAR), model initial condition is prepared using WRF VAR data assimilation system (without cyclone bogusing). (*iii*) The cyclone bogusing experiment (BOG) featuring cyclone bogusing alone without assimilation. In this case the model first guess is modified using cyclone bogusing and used as the initial condition. (*iv*) In the forth experiment, the initial condition of the model is prepared with both cyclone bogusing followed with WRF data assimilation (BOGVAR).

Results indicate remarkable impact of cyclone bogusing on the initial condition. All three cyclones can be located in the initial conditions (0000 UTC) of bogus (BOG and BOGVAR) experiments which were otherwise absent in no-bogus (VAR and CNTL) experiments. Significant reductions in track errors occurred in BOGVAR experiment. The maximum reduction in track error in BOGVAR compare to VAR is 76.8 % in 'LAILA', 87.3 % in 'GIRI' and 51.5 % in 'PHET' respectively. Maximum sustained wind speed and minimum central pressure are close to observations in BOGVAR compared to VAR for 'LAILA' and 'GIRI'.

**Key words** – TC (Tropical Cyclone), Vortex relocation, Rankine vortex, Tc-bogusing, Forecast track errors, WRF-VAR.

## 1. Introduction

Tropical cyclones (TC) spend most of their lifetime over oceans where meteorological observations are few compared to land region. This leads to inaccurate representation of location and intensity of tropical cyclones in the initial condition (IC). It is essential to reduce this error for improving the forecast of TC. Special effort must be taken to properly initialize the numerical prediction models for this purpose. To improve the storm representation, the use of bogus vortices is often adopted (Trinh and Krishnamurti 1992; Kurihara *et al.,* 1993; Leslie and Holland 1995). Kurihara *et al.,* (1993) proposed a scheme to improve the representation of a TC in the IC of a high-resolution hurricane model. Satellite data coverage over the ocean along with high resolution data assimilation tools (3DVAR or 4DVAR) also provides an opportunity to improve the IC. This study concentrates on the impact of bogus vortex in WRF model on track and intensity predictions of the TC's formed over Indian Seas during year 2010.

The TC bogus initialization method available in pre-processing system of WRF is designed for cold start using interpolated IC and boundary conditions from global models (Davis and Low-Nam 2001). There are two key components for numerical TC forecasting—an accurate forecast model and a proper method to initialize TC. The global model analysis forecast is used (T382L64) is of relatively coarse resolution (approximately 32 km horizontal resolution) and hence in its analysis (which is used as IC for WRF in this study) the vortex is often broad, weak and misplaced, particularly when the system is located over the data sparse oceanic regions.

A brief description of the three tropical cyclones of 2010 is given in Table 1. Details of the WRF model used to run different experiments, the cyclone bogusing technique adopted for bogus experiments and different sets of experiments performed are discussed in the next section.

Section 3 describes the results from the model experiments. Firstly the impact of cyclone bogusing is assessed on the initial analysis, followed by the impact on the forecast track errors. The impact of bogusing on the forecast and intensity (wind and SLP) is also discussed. Section 4 gives the summary and section 5 gives the conclusion.

## 2. Model description, cyclone bogusing and experiments

Table 2 lists the WRF model specifications in brief, used in the present study. Fig. 1 show the geographic model domain used in different set of experiments. The shading in the Fig. 1 shows the model terrain height (km) above Sea level. Model has single domain at 27 km resolution with 301 E -W grid points and 275 N-S grid points covering both Bay of Bengal and Arabian Sea. The T382L64 forecasts are used as lateral boundary conditions (updated at 6 hrs interval). The IC's are prepared as described in Table 3.

An efficient and dynamically consistent TC vortex bogusing scheme for WRF (Davis and Low-Nam, 2001) is used to initialize the TC in this study. A crudely resolved tropical cyclone in the large-scale analysis is replaced by a synthetic vortex in the IC of the model. In this technique large scale analysis is decomposed into environment flow and vortex circulation. The TC circulation is removed from the background, and then an axis-symmetric vortex is inserted at observed TC location. Appropriate filters are used to remove the vortex from the large-scale analysis so that a smooth environmental field remains. The new specified bogus vortex takes the form of a deviation from this environmental field so that it can be easily merged with the latter field at the correct position.

Since the observed parameters of the TC are limited, the observation input to the bogusing scheme is also kept minimum, consisting mainly of storm location and estimated maximum wind, the specification of a three-dimensional vortex structure is arbitrary. The vortex wind profile is given by the simple Rankine vortex which is derived from reported maximum wind from best track data (Low-nam and Davis, 2001).

The NCEP 'TCVITALS' cyclone data is used as observed data to bogus vortex generation experiments. In early 1990's the WMO recommended a 1-line text format for sharing critical observed TC information. NCEP refers to this format as "TC vital statistics". The 'TCVITALS' provides real time cyclone formatted text message of 149

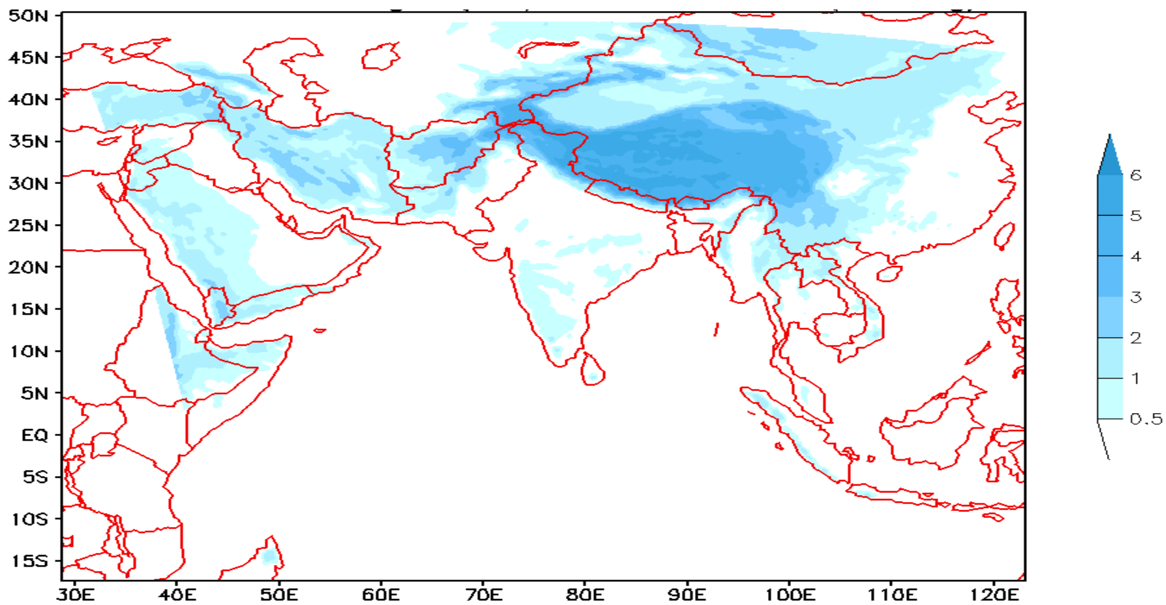



**Fig. 1.** Geographical domain used in WRF forecasting system. Model terrain height (km) above sea level (shading)

**TABLE 1**

**Cyclonic Storm 'LAILA', 'GIRI' and 'PHET' summary**

| Name | 'LAILA' | 'GIRI' | 'PHET' |
|---|---|---|---|
| Basin | Bay of Bengal | Bay of Bengal | Arabian Sea |
| Category | Severe Cyclonic Storm (SCS) | Very Severe Cyclonic Storm (VSCS) | Very Severe Cyclonic Storm (VSCS) |
| Date, Time and place of genesis (Lat °N, Long °E) | 17 May, 0600 UTC near 10.5/88.5 | 20 October, 1200 UTC near 17.5/ 91.5 | 31 May, 0600 UTC near 15.0/64.0 |
| Estimated Maximum wind speed (kt), time date and Lat °N/Long °E | 55 kt at 0600 UTC of 19 May near 13.5/81.5 | 105 kt at 0900 UTC of 22 October near 19.5/93.5 | 85 kt at 1200 UTC of 02 June near 18.0/60.5 |
| Estimated Lowest central pressure, time date and Lat °N / Long °E | 986 hPa at 0600 UTC of 19 May near 13.5/81.5 | 950 hPa at 0900 UTC of 22 October near 19.5/93.5 | 964 hPa at 1200 UTC of 02 June near 18.0/60.5 |
| Areas affected | Srilanka and India | Myanmar and Bangladesh | Oman, Pakistan and India |
| Landfall (Lat °N / Long °E) | Crossed Andhra Pradesh Coast near 16.0/80.5 between 1100 & 1200 UTC of 20 May. | Crossed Myanmar coast near 20/93.5 about 70 km east-southeast of Sittwe around 1400 UTC of 22 October. | Crossed Oman coast near 21.5 °N between 0000 & 0200 UTC of 4 June and again crossed Pakistan coast, close to south of Karachi near 24.7/67.2 between 1230 and 1330 UTC of 6 June |

character length. It includes storm center latitude, storm center longitude, estimated maximum wind speed and estimated radius of maximum wind etc. Based on TCVITAL information TC vortex bogusing scheme prepares the synthetic vortex for all the three TC studied here.

To study the impact of TC bogusing four sets of forecast experiments were carried out for three cyclones 'LAILA', 'GIRI' and 'PHET'. All four experiments are summarized in Table 3. With each of the experiments mentioned in Table 3, forecasted TC track is extracted using RIP4 (WRF model graphic tool).

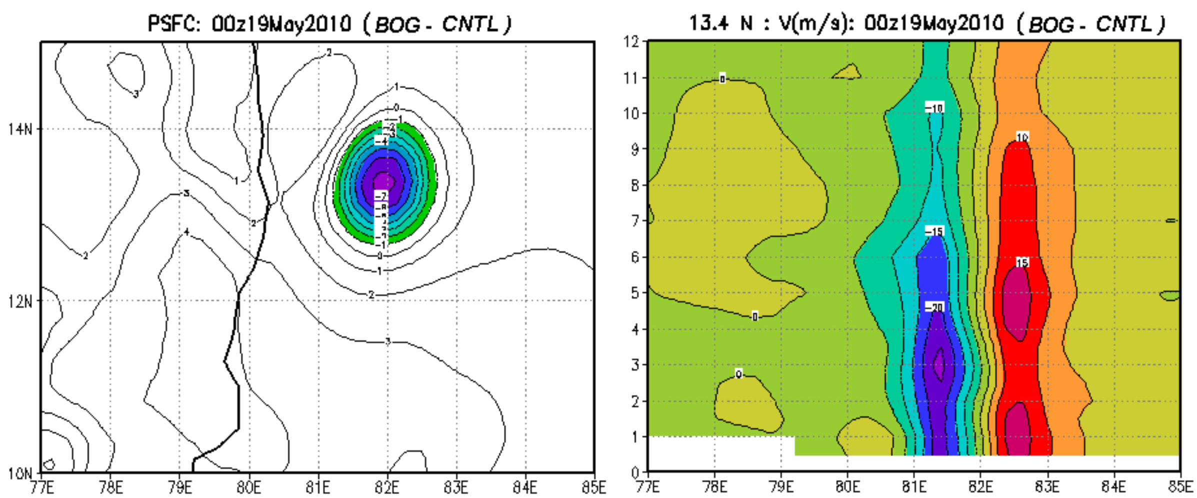



**Fig. 2(a).** 'LAILA': Difference between the IC before and after bogusing for 19 May, 2010

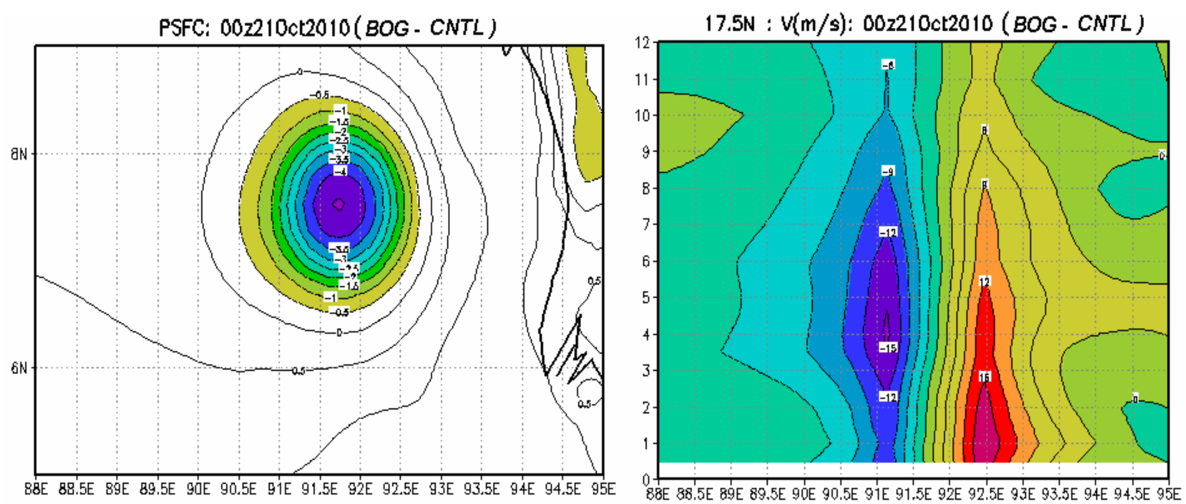



**Fig. 2(b).** 'GIRI': Difference between the IC before and after bogusing for 21 Oct, 2010

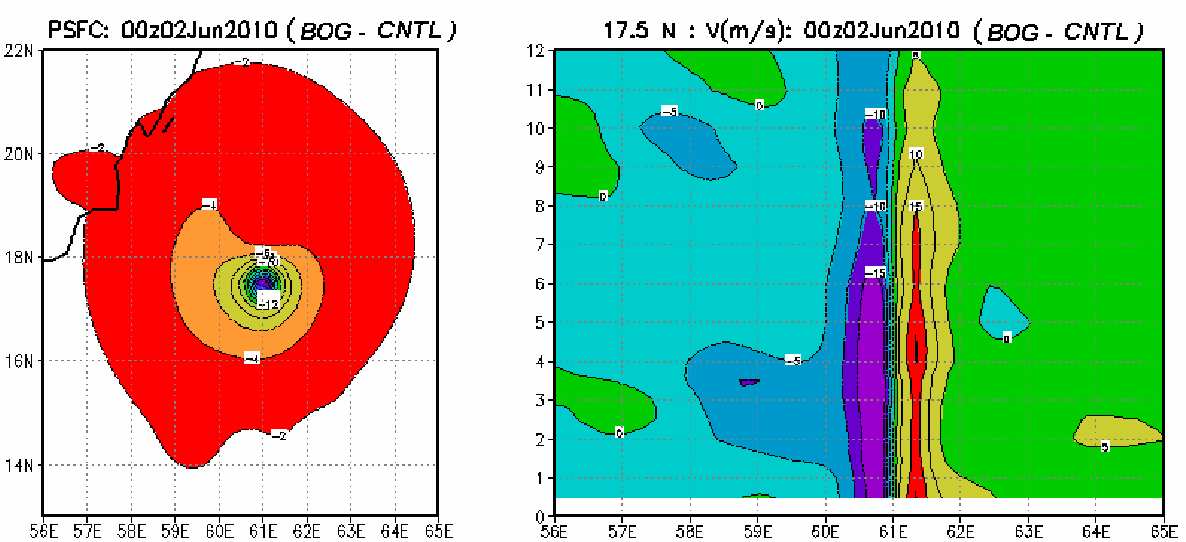



**Fig. 2(c).** 'PHET': Difference between the IC before and after bogusing for 02 Jun, 2010

**TABLE 2**

**WRF model configuration details**

| Model | WRF |
|---|---|
| Horizontal Resolution | 27 km-Arakawa-C Grid |
| Vertical Levels | 38 |
| Topography | USGS |
| Time Integration | Semi Implicit |
| Time Steps | 90 s |
| Vertical Differencing | Arakawa's Energy Conserving Scheme |
| Time Filtering | Robert's Method |
| Horizontal Diffusion | 2nd order over Quasi-pressure surface, scale selective |
| Convection | Kain-Fritsch |
| PBL | YSU Scheme |
| Cloud Microphysics | WSM3-Class Simple Ice |
| Radiation | RRTM (LW) |
| | Dudhia (SW) |
| Gravity Wave Drag | No |
| Land Surface Processes | Thermal Diffusion |

**TABLE 3**

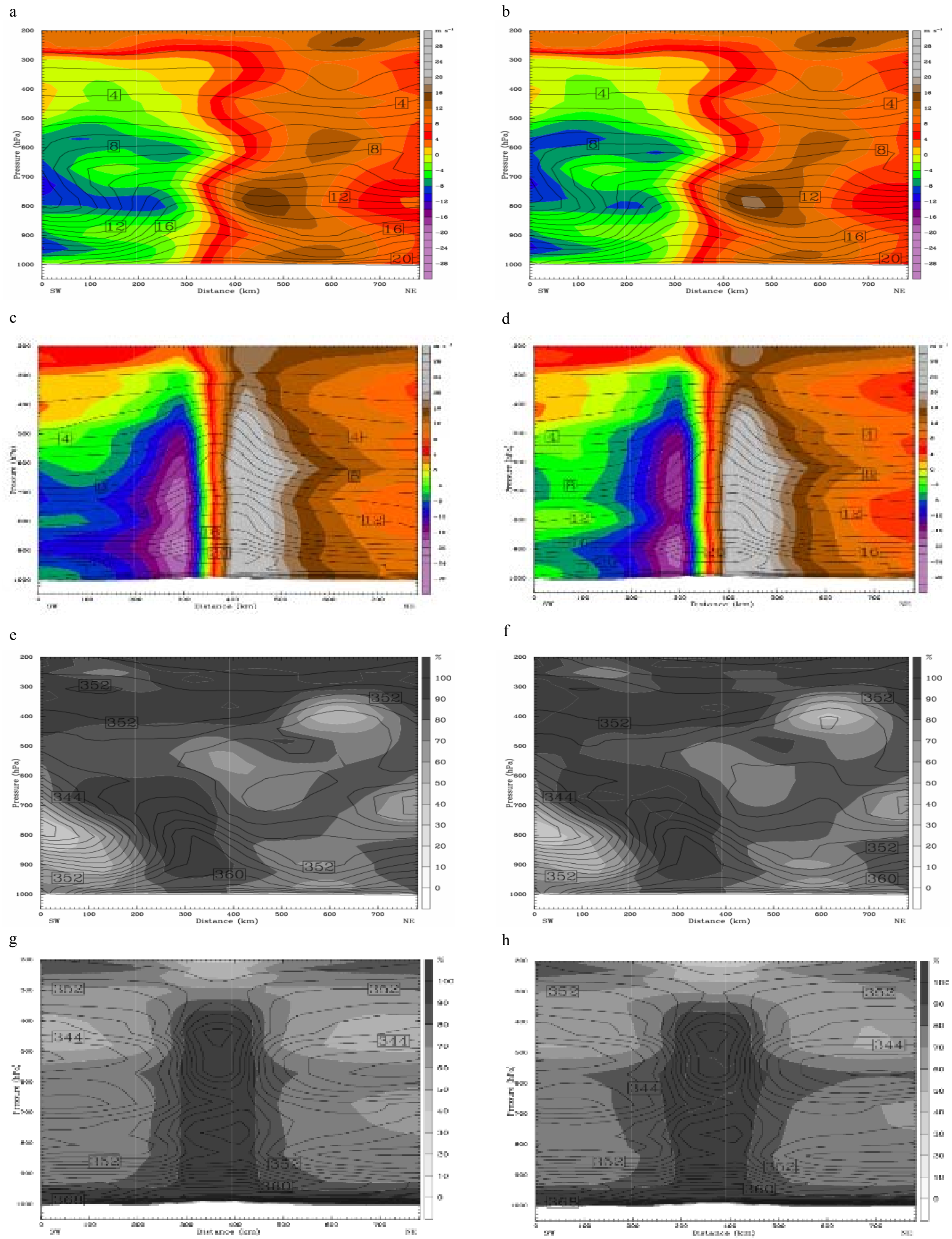
**Experiments (*in all cases cold start is used*)**

| Experiment Name | Abbreviation | Details |
|---|---|---|
| Control | CNTL | Cold start run with interpolated global T382L64 model analysis IC without performing any bogusing or assimilation. |
| Assimilation | VAR | No cyclone bogusing. IC is prepared by regional assimilation system (WRF 3DVAR). |
| Bogus | BOG | Model is run with T382L64 global model interpolated output initialized with bogusing. No assimilation is performed. |
| Bogus+ assimilation | BOGVAR | IC is prepared with cyclone bogusing followed by regional data assimilation (WRF 3DVAR). |

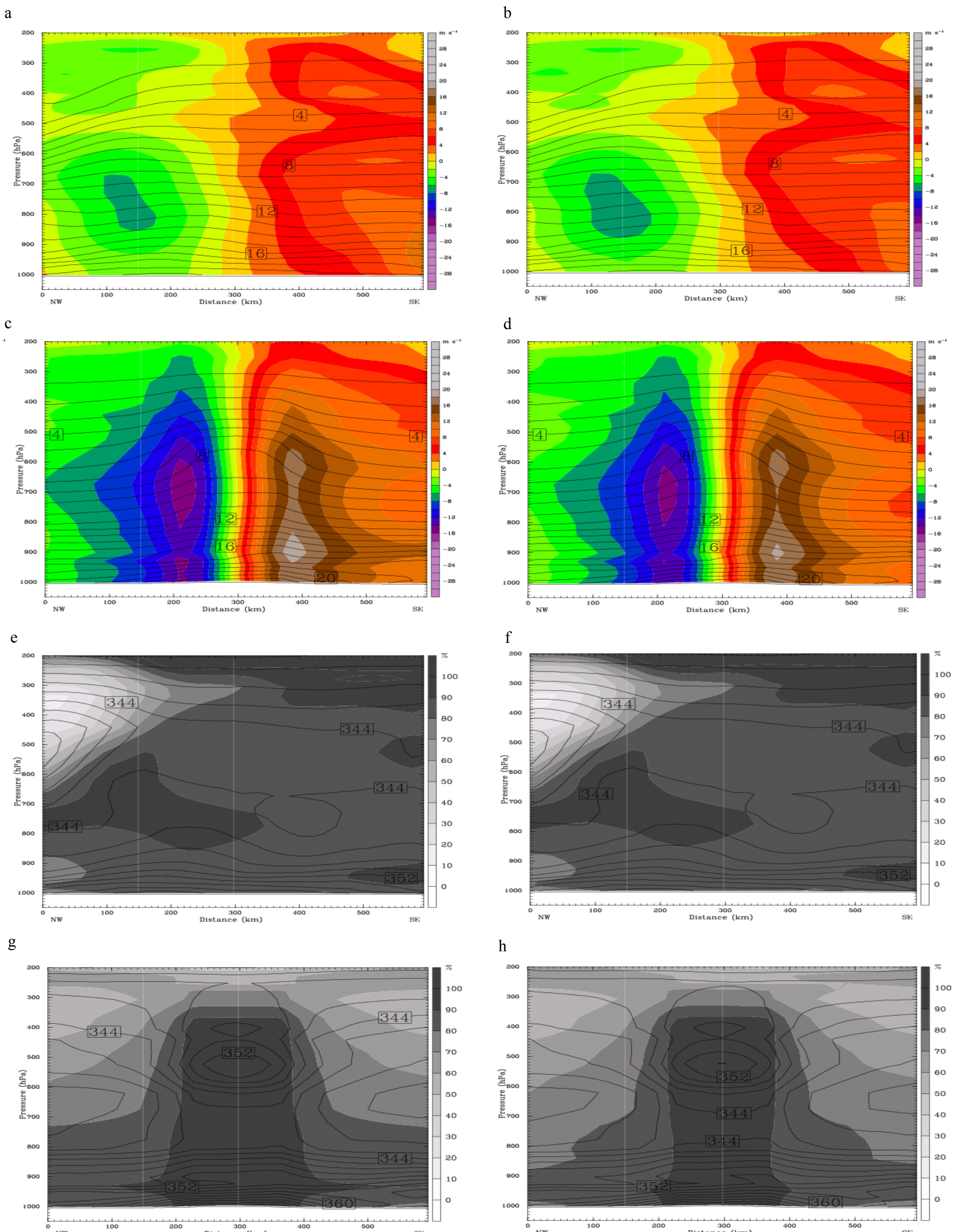
## 3. Results and discussion

Difference in BOG and CNTL with respect to the model analysis near surface (PSFC) and vertical structure (meridional wind) are examined to understand the impact of bogusing. Fig. 2(a), Fig. 2(b) and Fig. 2(c) show the difference (BOG - CNTL) in the IC for 'LAILA', 'GIRI' and 'PHET' respectively. Left panels show the difference (BOG - CNTL) of surface pressure which varies from -8 hPa to -1 hPa for 'LAILA' (19 May), -4 hPa to -0.5 hPa for 'GIRI' (21 Oct) and -6 hPa to -1 hPa for 'PHET' (02 Jun). In all the three cases it is evident that the difference is negative indicating that near the centre of cyclone, surface pressure is reduced due to bogusing. Right panels show difference (BOG - CNTL) in vertical cross-section of meridional wind (m/s) where the latitude is fixed at the observed location of the cyclone. For all the three cases the difference in wind have positive values towards east indicating more pronounced southerly wind component and negative values towards west indicating more pronounced northerly wind component after bogusing, larger differences are seen in the lower and middle tropospheric levels. TC bogusing reduces surface pressure near the centre of the cyclone and enhance the cyclonic circulation for all the cases. Similar analysis is carried out to study the impact of WRF VAR against CNTL in improving the IC for the same dates. However, the impact was rather poor. Both CNTL and VAR experiments failed to show the genesis of cyclones.

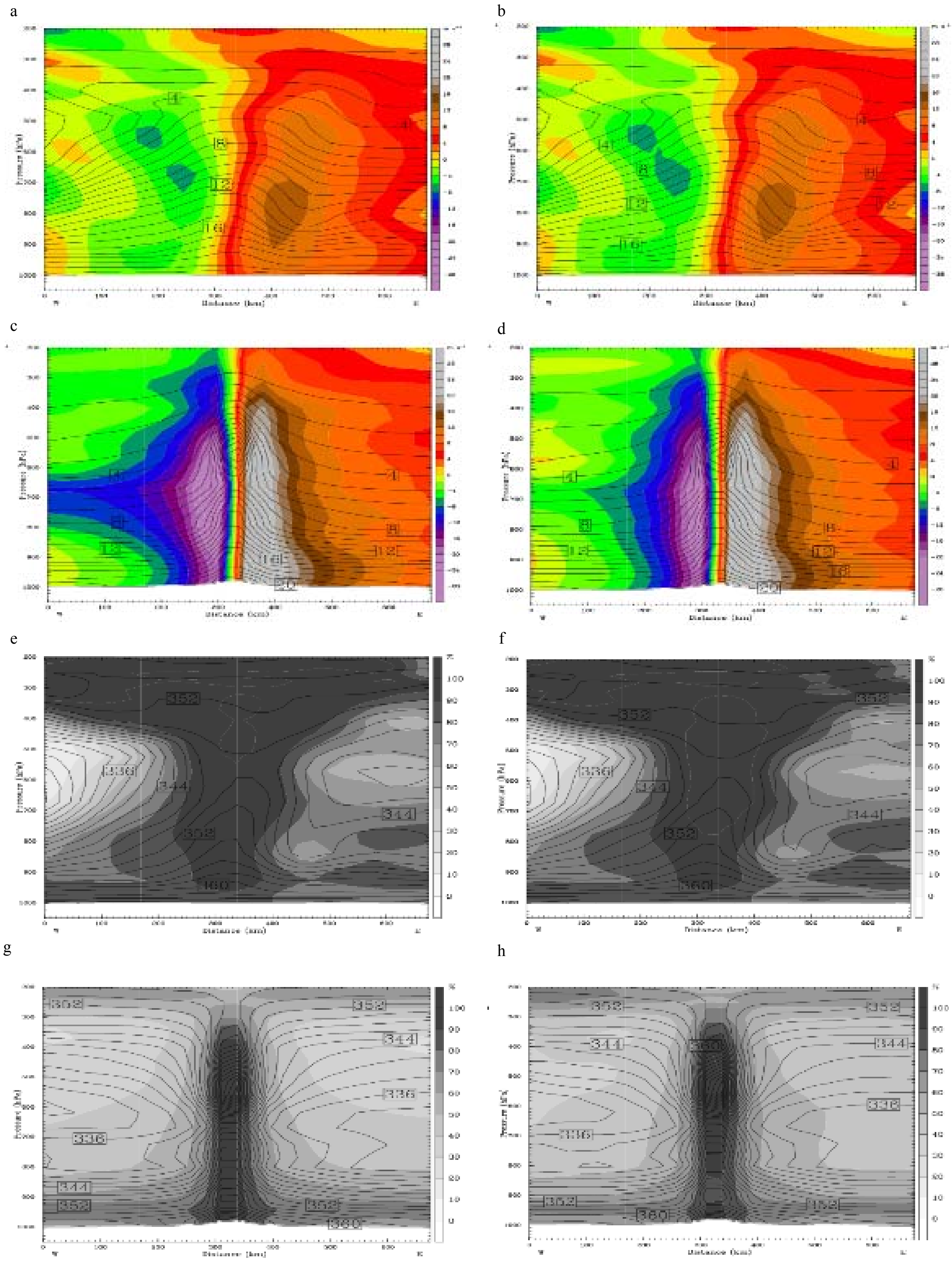
To further assess the impact of the TC initialization on the dynamic and thermodynamic structure of the TC, vertical cross section of different fields, cutting across the TC centre are presented. For the case of TC 'Laila', cross section of tangential wind (m/s) and water vapor mixing ratio (g/kg) are shown in Figs. 3 (a-d) in the four experiments. The cross section of tangential winds in the BOG and BOGVAR show well developed deep vortex, which is completely missing in the CNTL and VAR runs. The water vapor mixing ratio contours in the BOG and BOGVAR runs show well organized distribution of water vapor with high concentrations in the lower levels near the TC centre. The cross section of equivalent potential temperature ($\theta_e$) and relative humidity (RH) are shown in the bottom panels of Figs. 3 (e-h). In the BOG and BOGVAR runs $\theta_e$ contours show warm core and unstable characteristics of the vortex. High relative humidity tower in the centre of the vortex, relative to the surroundings is also remarkable. Similar cross section plots for the case of TC 'Giri' and 'Phet' are shown in Figs. 4(a-h) and



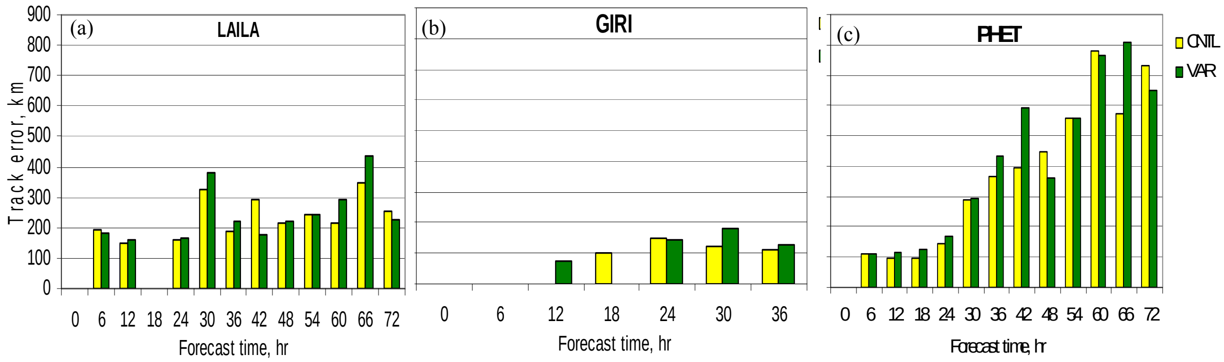

**Figs. 3(a-h)**. Vertical Cross of tangential wind (shaded) and water vapor mixing ratio for case of cyclone 'Laila' in (a) CNTL (b) VAR (c) BOG and (d) BOGVAR runs. Panels e, f, g and h are same as a, b, c and d respectively for RH (shaded) and $\theta_e$ (contour)



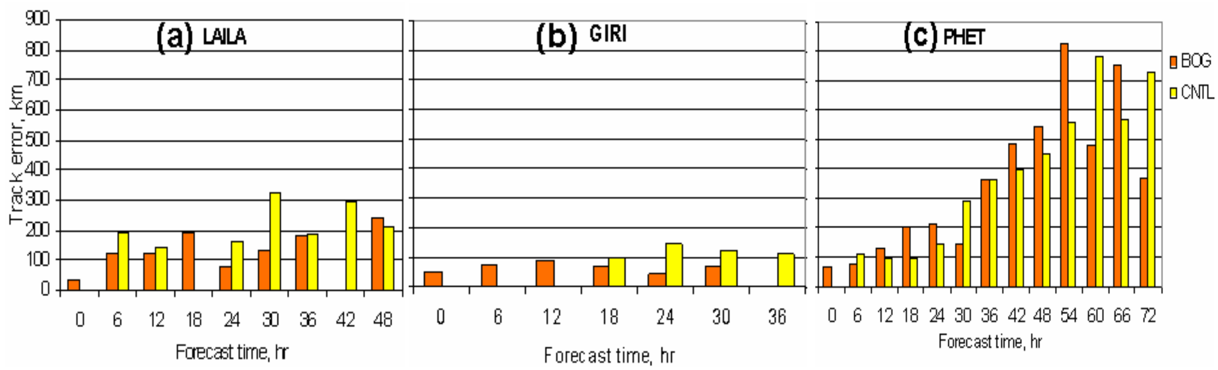
**Figs. 4(a-h).** Vertical Cross of tangential wind (shaded) and water vapor mixing ratio for case of cyclone 'Giri' in (a) CNTL (b) VAR (c) BOG and (d) BOGVAR runs. Panels e, f, g and h are same as a, b, c and d respectively for RH (shaded) and $\theta_e$ (contour)



**Figs. 5(a-h).** Vertical Cross of tangential wind (shaded) and water vapor mixing ratio for cyclone 'Phet' in (a) CNTL (b) VAR (c) BOG and (d) BOGVAR runs. Panels e, f, g and h are same as a, b, c and d respectively for RH (shaded) and $\theta_e$ (contour)




**Figs. 6(a-c).** (a) 'LAILA' (b) 'GIRI' (c) 'PHET' track errors for VAR and CNTL experiments (It may be noted that for some hours bars are missing because TC did not exist in model output during those hours)




**Figs. 7(a-c).** (a) 'LAILA' (b) 'GIRI' (c) 'PHET' track errors for BOG and CNTL experiments

Figs. 5(a-h) respectively. In the case of TC 'Giri' with a weak intensity in the initialization (prescribed SLP 1002 hPa) as well as in the case of TC 'Phet' with strong intensity in the initialization (prescribed SLP 986 hPa), BOG and BOGVAR runs show remarkable improvement over the CNTL and VAR runs.

To study the impact of bogus (BOG) against WRF VAR, assimilation IC are prepared without bogusing (VAR). Additionally, another set of IC were prepared using bogusing followed by WRF VAR to feature the combined impact of both methods (BOGVAR) [Table 3].

Based on model runs with multiple IC's, forecast track errors are computed for each model run. Figs. 6(a-c) show the average track error for each of the three cyclones 'LAILA', 'GIRI' and 'PHET' in non bogus experiments *i.e.*, VAR and CNTL. 'GIRI' was a short lived cyclone and can be seen only up to 36 hr in the forecast. Since there was no signature of cyclone in T382L64 global model analysis which is used as IC for WRF in CTNL experiment, the TC/Depression is not seen in the IC for all the three cyclone cases in the CNTL experiments. The forecast in the CTNL experiments show large track errors. The forecast based on the IC prepared by regional assimilation (VAR experiments) also produced large track errors. It can be noted that the assimilation is deteriorating results by increasing the mean track errors. This suggests that there is a need to modify the TC/Depression in the IC of the model. Based on the method discussed in earlier section, bogusing is carried out to insert TC in the IC of the model. In the forecast with this IC, in case of 'LAILA' the track errors show maximum reduction at 30 hr of the forecast, and in case of 'GIRI' maximum reduction is seen at 24 hrs of the forecast as shown in Fig.7 (a) and Fig.7 (b) respectively. In case of 'PHET' no clear conclusion can be

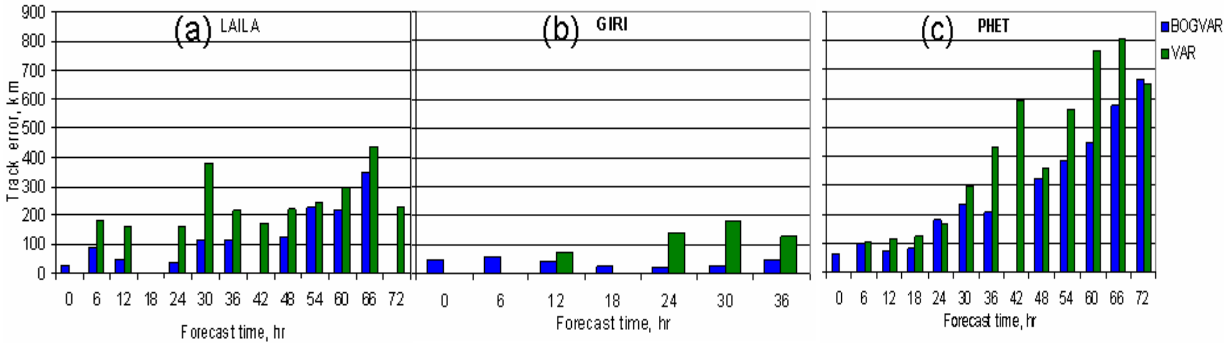
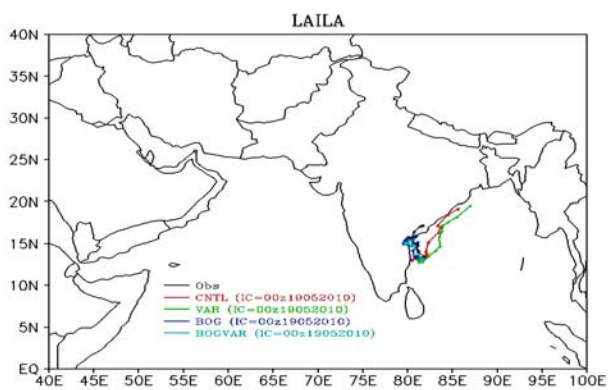
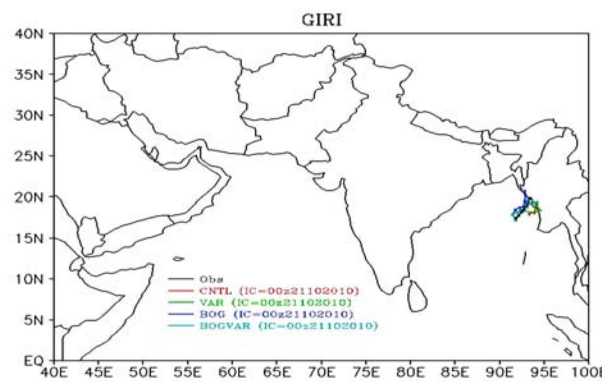



**Fig. 8(a-c).** (a) 'LAILA' (b) 'GIRI' (c) 'PHET' track errors for BOGVAR and VAR experiments

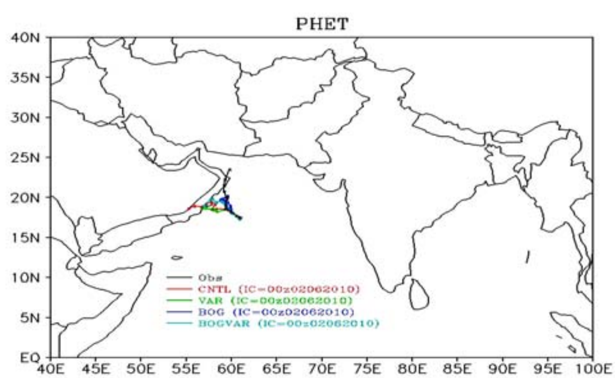
(a)




(b)



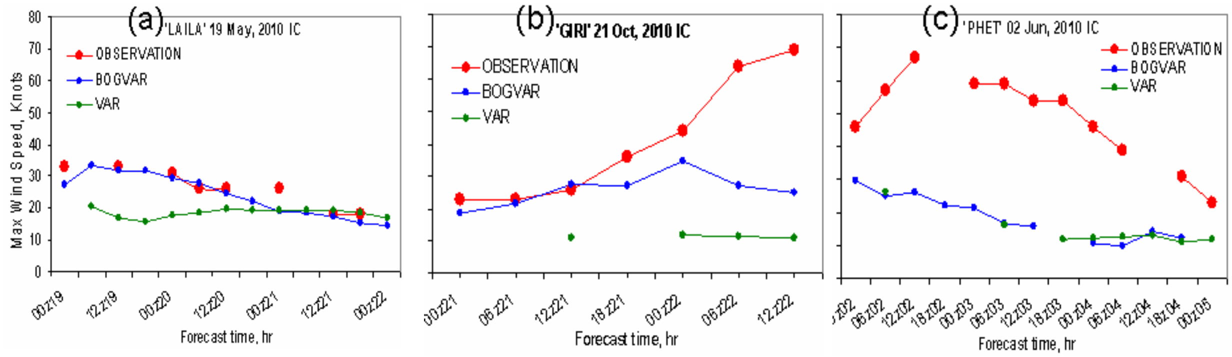

(c)



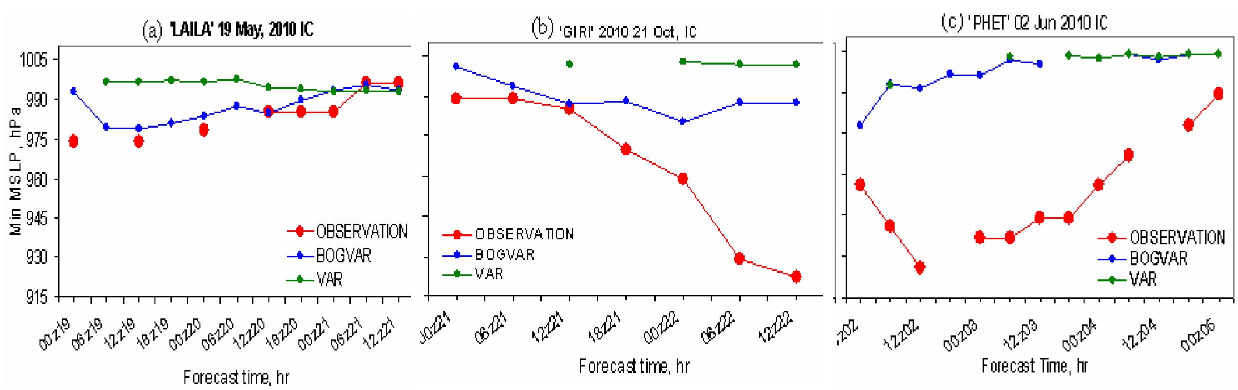

**Figs. 9(a-c).** Observed and forecast tracks for cyclones (a) 'Laila' (b) 'Giri' and (c)'Phet'

drawn as track errors are not consistent for either BOG or CNTL experiments throughout the forecast period as evident from Fig. 7(c).

Although, bogusing seems to improve the IC by relocating the system close to the observed position, the forecasted position errors are not reduced in all cases,




**Figs. 10(a-c).** (a) 'LAILA' (b) 'GIRI' (c) 'PHET' maximum wind speed for BOGVAR and VAR experiments compared with observations




**Figs. 11(a-c).** (a) 'LAILA' (b) 'GIRI' (c) 'PHET' minimum sea level pressure for BOGVAR and VAR experiments compared with observations

when compared to CNTL. It is likely that the modified initial analysis and the lateral boundary conditions create some discontinuity in the absence of updated boundary conditions. Therefore bogusing and assimilation are carried out together to include the improved location and updated boundary conditions (BOGVAR).

Figs. 8(a-c) show the comparisons in track errors between BOGVAR and VAR experiments. The results suggest that the cyclonic vortex which was not prominent in CNTL and VAR experiments is well developed in the IC after performing TC-bogusing (BOG and BOGVAR experiments). However, in the BOG experiment the cyclonic vortex introduced through bogusing technique is not sustained always in the forecast period. The BOGVAR experiment suggests that this problem can be overcome by using BOG along with VAR, because the fields are more dynamically consistent after assimilation in VAR experiment. Fig. 8 shows that BOGVAR, *i.e.*, bogusing followed by assimilation, gave significant reductions in track errors. The percentage reduction in track errors in BOGVAR experiment over VAR experiment is given in Table 4.

Except for 'PHET' at 24 hrs all other values implies that the track error are less in BOGVAR compared to VAR. It can be seen that in case of cyclone 'LAILA', and 'GIRI', the reduction in track error is as high as 70 to 90 % at the 24 hrs forecast. The official track forecast errors (km) provided by IMD for 'GIRI' cyclone with lead time

**TABLE 4**

**Percentage reduction in track error of BOGVAR experiments over VAR experiments**

| Cyclone name | % reduction in track error of BOGVAR experiments over VAR experiments | | | |
|---|---|---|---|---|
| | 12 hr | 24 hr | 36 hr | 48 hr |
| 'LAILA' | 71.7 | 76.8 | 46.7 | 44.5 |
| 'GIRI' | 41.7 | 87.3 | 61.7 | - |
| 'PHET' | 35.4 | -7.8 | 51.5 | 9.9 |

at 12 hourly intervals are 45 km (12 hrs), 73 km (24 hrs) and 68 km (36 hrs) (Mohapatra *et al*. 2010) while the respective track errors for 'GIRI' from BOGVAR experiment are found to be 43.64 km (12 hrs), 17.96 km (24 hrs) and 48.51 km (36 hrs). Therefore, results from BOGVAR experiment in case of 'GIRI' show remarkable improvement compared to official forecast of IMD.

Observed and forecast (CNTL, VAR, BOG and BOGVAR runs) tracks of the three TCs are shown in Figs. 9(a-c). Fig. 9(a) show observed track during 19 - 21 May, 2010 for the case of cyclone ‘Laila’ and predicted track with 19 May, 2010 IC for CNTL,VAR, BOG and BOGVAR runs. The forecast tracks indicate that the BOGVAR (cyan) track is very close to observed (black) track. However, the VAR (green) track shows movement in a totally different direction, *i.e.*, North-East. In case of TC ‘Giri’ [Fig. 9(b)], the predicted tracks with 21 May, 2010 IC of CNTL, VAR, BOG and BOGVAR are shown along with the observed track (21 – 22 Oct, 2010). The BOGVAR predicted track is close to the observation and the movement is in the same direction as observations. In Fig. 9(c) observed track (02 - 06 June, 2010) and CNTL,VAR, BOG and BOGVAR predicted tracks with 2 Jun, 2010 IC are shown. In this case direction of TC motion compares well with the observation in all the forecast experiments still BOGVAR track is much closer to the observations. From the three panels in Figs. 9(a-c) it is evident that the initial position and track are significantly improved in the BOGVAR experiment compared to CNTL, BOG and VAR experiments in terms of direction of TC movement.

Fig. 10(a) show the maximum wind speed for VAR and BOGVAR experiments for 'LAILA' on 19 May, 2010. The maximum wind speed in BOGVAR forecast is close to the observations in comparison to VAR forecast, except at 0000 UTC of 19 and 21 May. Similarly, Fig. 10(b) show maximum wind speed for VAR and BOGVAR experiments for 'GIRI' on 21 Oct, 2010. Initially, cyclone was not present in VAR experiment for several forecast hours, whereas it was present in the analysis of BOGVAR experiment and sustained for longer period in the forecast. For the first 24 hours after bogus (BOGVAR) wind speeds are close to observations, but after 24 hour since the landfall has occurred the wind values are far from the observations. The BOGVAR experiments forecasted wind fields after landfall is better than that of VAR experiments. For the first 24 hrs, BOGVAR wind variations are same as that of observation which is not the case in the VAR experiments. In case of cyclone 'PHET' [Fig. 10(c)], predicted winds do not show improvement in VAR and BOGVAR experiments. The case of ‘PHET’ is challenging with peculiar movement in which the cyclone made landfall in Oman desert on 04 Jun, 2010 and then again entered to Arabian Sea.

Fig. 11(a) and Fig. 11(b) show minimum sea level pressure of VAR and BOGVAR experiments for cyclone 'LAILA' on 19 May, and cyclone 'GIRI' on 21 Oct, 2010. The minimum sea level pressure in BOGVAR forecast is close to the observations as compared to VAR forecast for TC 'LAILA'. The trend in pressure drop and increase in wind speed are consistent with the observation. Similarly, in the case of 'GIRI', BOGVAR experiment show intensification similar to observation. However, the improvement of BOGVAR over VAR in case of 'GIRI' is not as significant as in the case of 'LAILA'. Same is true for wind forecast also. While in case of 'PHET' [Fig. 11(c)] improvement is not seen in the BOGVAR experiment compare to VAR experiment. However, the cyclone is sustained for longer duration in BOGVAR experiment. Cyclone bogusing is generally not expected to improve intensity forecast. The intensity forecast is found to be a bigger challenge as compared to track forecast.

## 4. Summary

The aim of this study was to understand the impact of tropical cyclone bogusing in the WRF regional assimilation and forecast system. Different sets of experiments were carried out using WRF model. The three cyclones of the year 2010 in the Indian Seas were chosen for the present study.

The interpolated initial analysis based CNTL experiments results in a poor representation of cyclone in all the three cases. Regional assimilation in the VAR experiments did not bring any definite dramatic improvement. However, bogusing experiments (BOG) successfully introduced the vortex at observed location and also allowed for development of a well defined vertical structure in the initial condition.

The impact of the IC produced by the regional assimilation (VAR experiments) in predicted track is not positive with respect to the cyclone forecast. Difference in track errors is marginal in the VAR and CNTL experiments. The study indicates that assimilation alone do not play significant role in reducing track errors in the case of no additional data over TC region.

With the introduction of bogus vortex (BOG experiments) the track errors show improvement in line with the improvement in the initial analysis of BOG runs. Track errors show reduction in both 'GIRI' and 'LAILA' for BOG compared to CNTL, though reduction is marginal; still the results are encouraging with bogusing. Results with BOG followed by assimilation gives significant reductions in track errors. The highest reduction in track error in BOGVAR experiment is 76.8 % in 'LAILA', 87.3 % in 'GIRI' and 51.5 % in 'PHET' respectively compared to VAR experiment. The predicted track is significantly improved in terms of direction of motion as well as cyclone location in the BOGVAR in comparison to VAR experiments.

A detailed analysis of the impact on intensity showed that the maximum sustained wind speed and minimum central pressure are closer to observations in BOGVAR compared to VAR, particularly from the case of 'LAILA' and 'GIRI'. The trend in the predicted drop in minimum central pressure and increasing wind speed closely match with the observations. For the first 24 hrs BOGVAR wind variations are same as observation which is not captured in the VAR experiments. The case of 'PHET' cyclone was an exception. The impact of BOGVAR seen in the other two cases of cyclones is completely missing in case of 'PHET'. Cyclones are sustained for longer period in the BOGVAR experiments compared to VAR experiments, and the predicted intensity is closer to observations.

## 5. Conclusions

The study is based on just three cyclones in the year 2010. Two of these cyclones, namely 'LAILA' and 'GIRI' can be considered as well behaved cyclones in terms of track and evolution. The model seems to have successfully captured the track and evolution in BOGVAR experiments and reduced the errors in comparison to the forecasts without bogusing. On the contrary, the only case of Arabian Sea cyclone 'PHET' was rather erratic in movement and evolution, suggesting that the model (almost all four experiments) failed to capture the track and intensity evolution of TC 'PHET'. However the experiments show that the location and intensities of the cyclone in the initial conditions are significantly improved by the inclusion of synthetic vortex.

The results and conclusions are based on WRF model at 27 km grid spacing which is rather too coarse to resolve some of the key processes of tropical cyclones intensification. Since the main aim was to study the impact of cyclone bogusing *vis-à-vis* regional data assimilation high resolution nested experiments which are computationally expensive, were not attempted. These results could further improve if high resolution nested experiments are carried out as shown in similar study by Hasio *et al*. (2010). This study also suggests that BOG with VAR produced good results with 70 – 90 % error reduction. Though, even after introduction of bogus vortex, there was an error of 50-70 km in the initial field. These errors can be further reduced if 'Nudging' is performed while introducing the vortex in the initial field. This may improve results even further. Thus within the specified scope of the study the effectiveness of the cyclone bogusing is demonstrated using WRF model for predicting the tropical cyclone in the Indian region.

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