



TAMDAR Observation Assimilation in WRF 3D-Var and its Impact on Hurricane Ike (2008) Forecast

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4 **TAMDAR Observation Assimilation in WRF 3D-Var and its Impact on**
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7 **Hurricane Ike (2008) Forecast**
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ABSTRACT

This study evaluates the impact of atmospheric observations from Tropospheric Airborne Meteorological Data Reporting (TAMDAR) observing system on numerical weather prediction of the hurricane Ike (2008) using Weather Research and Forecast model (WRF) 3-dimensional data assimilation system (WRF 3D-Var). TAMDAR data assimilation capability is firstly expended in WRF 3D-Var by incorporating TAMDAR observation operator and corresponding observation processing procedure. Two 6 hourly cycling data assimilation and forecast experiments are conducted. The track and intensity forecast are verified against the best track data.

The results show that, on average, assimilating TAMDAR observations has a positive impact on the forecast of the hurricane Ike (2008). The TAMDAR data assimilation reduces the track forecast errors of about 30 km for 72-h forecasts. The improvements in intensity forecast are also seen after 24-h data assimilation. The diagnosis shows that assimilation of the TAMDA data improves subtropical ridge and steer flow analysis in regions along hurricane track, which results in improvements of hurricane forecasting.

Key words: Data assimilation, TAMDAR, Numerical weather prediction, Hurricane, WRF

1. Introduction

Since the quality of initial condition plays an important role in numerical weather prediction (NWP), data assimilation schemes aim at producing accurate analyses by making the best possible use of the information provided by a background state and available observations (Raynaud et al., 2011). Observations with high spatial and temporal resolution are expected to improve the analysis and subsequent forecast skill. Automated aircraft reports (AIREP) observations have been shown to improve both short- and long-term weather forecasts, and have become increasingly important for regional and global NWP (e.g., Smith and Benjamin, 1994; Zapotocny et al., 2002; Moninger, et al. 2003; Benjamin et al., 2010). However, the deficiency of the AIREP observations is the absence of humidity measurement. In recent years, a new Tropospheric Airborne Meteorological Data Reporting (TAMDAR) observing system has been developed by AirDat LLC (<http://www.airdat.com/>) of Raleigh, NC and Evergreen, CO, USA. The TAMDA multi-function atmospheric sensor, deployed on commercial aircrafts, is designed to measure atmospheric pressure, temperature, wind, humidity, icing, and turbulence (Daniels et al., 2006). Unlike AIREP data, humidity is also available in TAMDAR observing system. The temporal resolution of TAMDAR observations is 2 minutes (about 10-25 km). The vertical resolution on ascent and descent is 10 hPa.

Recent works have shown promising positive impacts of TAMDAR data on severe weather forecasts over the continental United States (e.g., Jacobs et al., 2006; Liu et al., 2007; Moninger et al., 2004, 2007, and 2010). These works were conducted

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4 in contexts of the Rapid Update Cycle (RUC) data assimilation and forecast system
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6 (Benjamin et al., 2004), and a four dimensional nudging data assimilation system (Liu
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8 et al., 2007). Considering the Weather Research and Forecast model (WRF)
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10 3-dimensional data assimilation system (WRF 3D-Var) (Barker et al., 2004, Huang et
11
12 al., 2009) developed at National Center for Atmosphere Research (NCAR) has been
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14 extensively used in research and operational centers, the TAMDAR assimilation
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16 capability is expended in WRF 3D-Var in this study. The added value of TAMDAR
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18 data on NWP is demonstrated by the hurricane Ike (2008) case study through
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20 assimilating TAMDAR observations along with other conventional observations.
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28 This paper is organized as follows: section 2 introduces the variational data
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30 assimilation system WRF 3D-Var and TAMDAR data assimilation scheme. A
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32 description of hurricane Ike and experiment design are presented in section 3.
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34 Results are discussed in section 4, and section 5 gives a brief summary.
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38 **2. Assimilating TAMDAR in WRF 3D-Var**

39 **2.1 WRF 3D-Var**

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42 The WRF 3D-Var (Barker et al., 2004, Huang et al., 2009) developed at NCAR
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44 is employed as data assimilation system. In general, a variational data assimilation
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46 system is designed to provide an analysis \mathbf{x}_0^a of the initial atmosphere state \mathbf{x}_0 by
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48 minimizing a prescribed cost function:
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$$54 \quad J(\mathbf{x}_0) = \frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_0^b)^T \mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}_0^b) + \frac{1}{2}[\mathbf{y}^o - \mathbf{H}(\mathbf{x}_0)]^T \mathbf{R}^{-1}[\mathbf{y}^o - \mathbf{H}(\mathbf{x}_0)] \quad (1)$$

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60 \mathbf{x}_0 present the atmosphere state vector, and \mathbf{x}_0^b is the background, which may be

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4 provided by a previous forecast. \mathbf{y}^o is the observation, and \mathbf{H} is the observation
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6 operator. \mathbf{B} and \mathbf{R} are the background and observation error covariance matrices,
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8 respectively.
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11 The analysis \mathbf{x}_0^a represents a posteriori maximum likelihood (minimum
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13 variance) estimate of the true state of the atmosphere (Barker et al., 2004). The
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15 analysis fit to background \mathbf{x}_0^b and observations \mathbf{y}^o is weighted by estimates of
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17 their errors. The control variables used in this study are streamfunction, "pseudo"
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19 relative humidity, and the unbalanced components of velocity potential, temperature,
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21 and surface pressure. The "unbalanced" control variables are defined as the
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23 difference between full and "balanced" (i.e., correlated with streamfunction)
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25 components of the field.
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33 **2.2 TAMDAR observation assimilation**

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35 For the TAMDA data above surface, observation operator is a bilinear
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37 interpolation function since the observed temperature, wind and humidity in
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39 TAMDAR are analysis variables. This observation operator maps the analysis
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41 variables from analysis grid to the observation space. For the TAMDAR surface
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43 observation, there are two options to assimilate them. The first is that the
44
45 atmosphere state of the lowest model level in first guess is assumed to be the surface
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47 atmosphere state, thus only the bilinear interpolation operator is needed. For the
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49 second option, a similarity theory for planetary boundary layer is used as the
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51 observation operator.
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60 The observation processing procedure for TAMDAR includes: 1) converting

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4 observation to the format that WRF 3D-Var required; 2) quality control by a
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6 maximum error check; 3) assigning observation errors. The observation error
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8 statistics of wind and temperature for TAMDA is the same as those of the AIREP in
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10 WRF 3D-Var. The observation error of relative humidity is set to 10%, which is
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12 comparable to the optimal error 12 % used in the study by Moninger et al. (2007).
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17 **3. Experiment design**

18 **3.1 Hurricane Ike**

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23 Ike was a long-lived Cape Verde hurricane that caused extensive damage along
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25 the coasts of Texas and Louisiana (berg, 2009). Ike originated from a well-defined
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27 tropical wave that moved off the west coast of Africa on 28 August 2008. It
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29 designated as a tropical depression by 0600 UTC 1 September. The depression
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31 quickly strengthened to a tropical storm by 1200 UTC that day and then gradually
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33 intensified over the next two days as it moved west-northwestward over the tropical
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35 Atlantic, steered by a strong subtropical ridge to the north. The storm responded
36
37 with deep convection redeveloping over the northern semicircle and quickly
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39 returned to Category 4 status by 1800 UTC 6 September. The subtropical ridge
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41 re-strengthened by late on 10 September and caused Ike to turn back to the
42
43 west-northwest. Ike reached the western periphery of the subtropical ridge and
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45 turned to the northwest towards the upper Texas coast late on 12 September. So the
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47 subtropical ridge has important influence on its motion.
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57 **3.2 Experiment setup**

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60 The Advanced Research WRF model is used as the forecast model. The WRF is

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4 the next generation mesoscale model designed for cloud and mesoscale applications
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6 over a limited area, as well as for global numerical weather prediction (Skamarock
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8 et al., 2005). The model uses a third order Runge-Kutta time integration, third to
9
10 fifth order advection operators, and split-explicit fast wave integration conserving
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12 both mass and energy. One domain a grid spacing of 18 km is configured for all the
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14 simulations. The domain has 400×255×42 grid points, and is big enough for this
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16 study. The physics packages chosen for this study include the WSM5 microphysics
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18 scheme (Hong et al., 2004) and the Kain-Fritsch scheme (Kain, 2004) for cumulus
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20 parameterization.
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28 Two 6-hourly cycling data assimilation and forecast experiments are carried out.
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30 In the first experiment (CNTR), conventional observations are assimilated. In the
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32 second experiment (TAMDAR), TAMDAR observations are assimilated in addition
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34 to observations used in CNTR. The 3.5 day data assimilation and forecast cycles
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36 start from 1200 UTC 7 to 0000 UTC 11 September. The analysis at 0000 UTC and
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38 1200 UTC everyday is used to initialize a 96-h (72-h for the last day) forecast. The
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40 initial conditions and boundary conditions are generated from National Centers for
41
42 Environmental Prediction (NCEP) Global Final Analysis (FNL) analysis. The first
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44 guess is a 12-h forecast initialized from 0000 UTC 7 September. Verifications
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46 against best track data from the U.S National Hurricane Center (NHC) (center
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48 location, minimum sea level pressure, and maximum wind speed) are performed.
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57 **4. Results**

58 **4.1 Assimilated observations**

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4 We find that the data used during the assimilation and forecast cycling with the
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6 largest numbers are SATOB, AIREP and TAMDAR data. Fig. 1 shows the
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8 observation counts of these three observation types at the assimilation time. The
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10 numbers of upper air observations vary from cycle to cycle, more at 0000, 1200,
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12 1800, and less at 0600 UTC. The TAMDAR data has the least amount among these
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14 three types since it is available only over the continent of United States.
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19 20 **4.2 Impact on forecast** 21

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23 The 96-h or 72-h track forecasts of hurricane Ike at four different times are
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25 shown in Fig. 2. The control forecast has a persistent northward bias. This bias is
26
27 reduced significantly in TAMDAR experiment. The improvement only becomes
28
29 obvious after 24-hour cycling. It is because that TAMDAR data are over continental
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31 United States and far away from the Ike to influence it immediately. After 24 hours,
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33 Ike starts to respond to the upstream analysis difference caused by adding
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35 TAMDAR observations as shown in Fig. 2b, c and d.
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42 The center location errors in the analysis and 72-h track forecast errors in two
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44 experiments are compared in Fig. 3. Although TAMDAR shows the positive effect
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46 on track forecast after 24-h cycling, it is until 48-h cycling that there is clear impact
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48 on Ike initial location specification.
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52 Error statistics of track, minimum sea level pressure (SLP) and maximum wind
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54 speed (MWS) is given in Table.1. On average, TAMDAR data has a positive impact
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56 on hurricane initial location specification, but a neutral impact on the intensity
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58 analysis. TAMDAR data improves the track forecast with an average value of 30 km
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4 at 72-h. The forecasts of SLP and maximum wind speed are improved as well after
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7 24-h cycling period.

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10 The reason leading to improvement of forecast using the TAMDAR data is
11 explored. The track forecast in CTRL experiment has a northeastward bias
12 compared with the real track. Since the key synoptic system which influences Ike
13 motion is the subtropical high over the North Atlantic, the differences in the wind
14 fields between two experiments (TAMDAR - CTRL) are shown in Fig. 4a-b. For
15 comparison, the differences between GFS analysis and CTRL are also given in Fig.
16 4c-d. The differences are time averaged over 8 examples from 1200 UTC 07 to 0000
17 UTC 11 Sep 2008. The vertical average is also carried out from Eta level 0.8435
18 (about 850 hPa) to 0.3825 (about 350 hPa).
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33 From Fig. 4 we can see that a considerable westward and southward flow
34 component is found when assimilating TAMDAR. The southwest quart of
35 subtropical high is also strengthened. These will drive the Ike move southward and
36 westward. Comparison Fig. 4a-b with Fig. 4c-d, it is clear that assimilation
37 TAMDAR improves the analysis over continent U.S., along the east coast and along
38 the Ike track also. However, there is room to improve the analyses in TAMDAR
39 since the amplitude is not as large as the GFS analysis.
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51 52 **5. Summary**

53 Automated aircraft reports are one of the important observation resources in
54 regional and global weather analysis and forecast systems. In this study, the
55 assimilation capability of data from the TAMDA observation system was expended
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4 in WRF 3D-Var. The TAMDAR observation operator and preprocess code were
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6 developed. Two 6 hourly 3D-Var cycling experiments for hurricane Ike (2008) had
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8 been conducted. The data assimilation period was 3.5 day starting from 1200 UTC
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10 07 September to 0000 UTC 11 September 2008. The track and intensity analysis and
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12 forecast were verified against the best track estimates.
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17 The results from data assimilation and forecast experiment showed that WRF
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19 3D-Var system worked well with the TAMDAR data. On average, the quality of
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21 analyses and forecast skills on hurricane Ike were improved. At the analysis time,
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23 the TAMDAR data had a positive impact on hurricane initial location specification
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25 but neutral impact on the intensity analysis. The TAMDAR data improved the track
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27 forecast by 30 km at 72 h. After 24-h cycling period, intensity forecasts were
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29 improved as well. More case studies are planed to evaluate the performance of
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31 updated WRF 3D-Var and the added values of TAMDAR observations.
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For Review Only

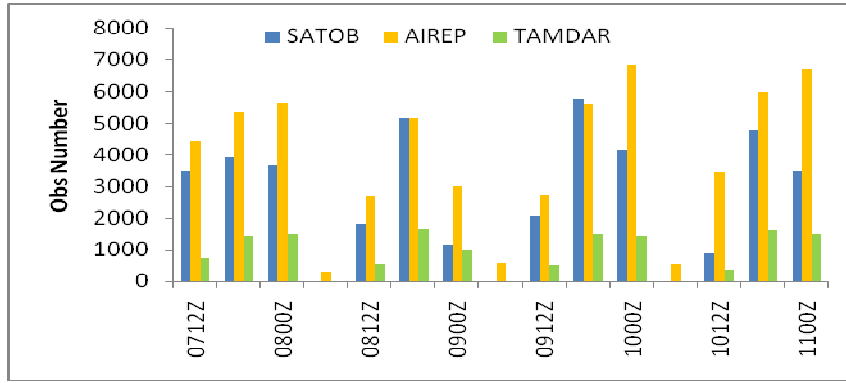


Fig. 1 Observation used during 1200 UTC 7 to 0000 UTC 10 September 2008.

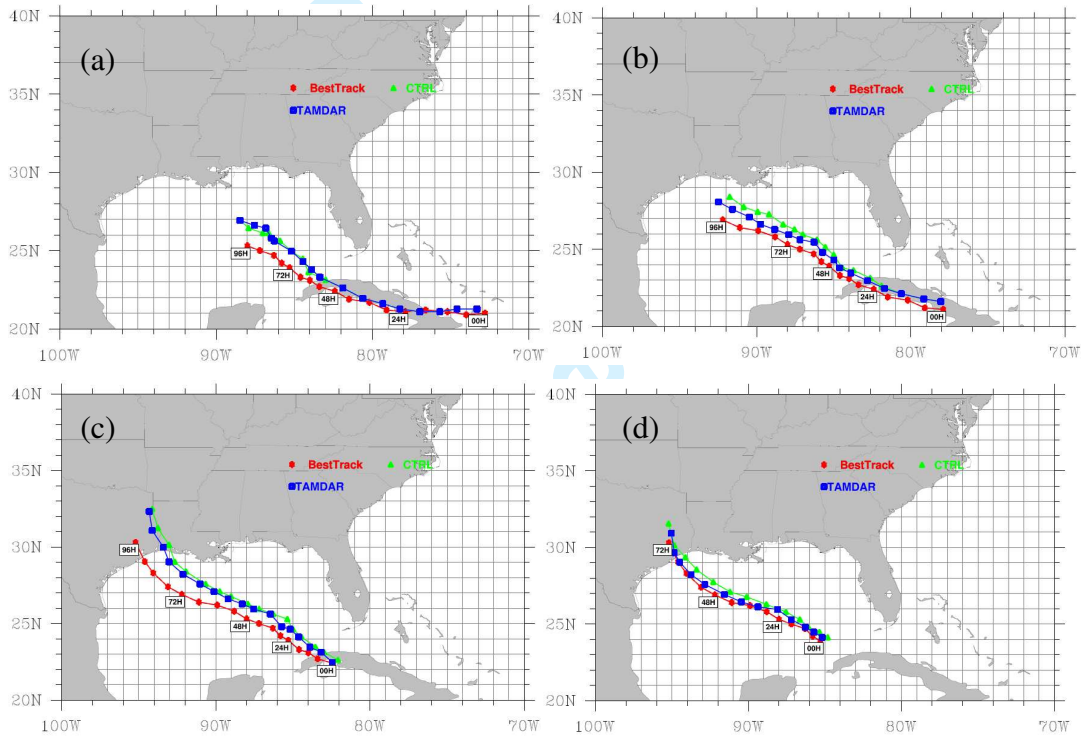


Fig. 2 96-hTracks of best estimation and forecast of experiment CTRL and TAMDAR initiated (a) at 1200 UTC 7, (b) 1200 UTC 8, (c) 1200 UTC 9 and (d) 1200 UTC 10 September 2008. Only 72-h forecasts were made after 0000 UTC 10 Sep.

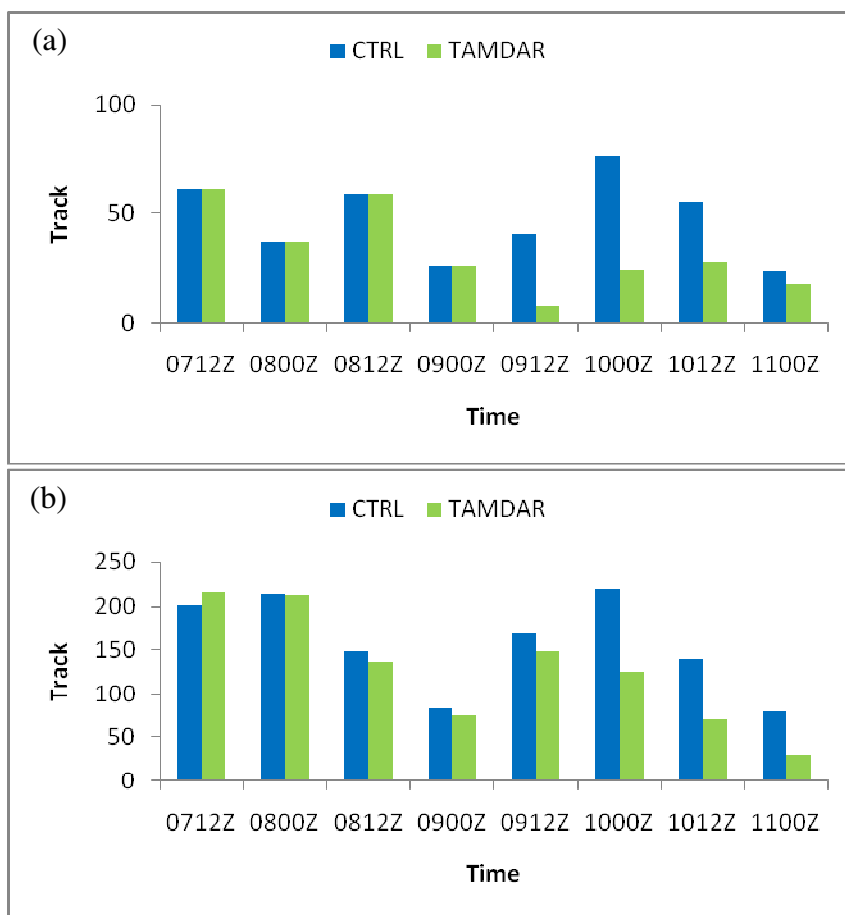


Fig. 3 (a) Ike location error at analysis time, and (b) Ike track forecast error at 72-h

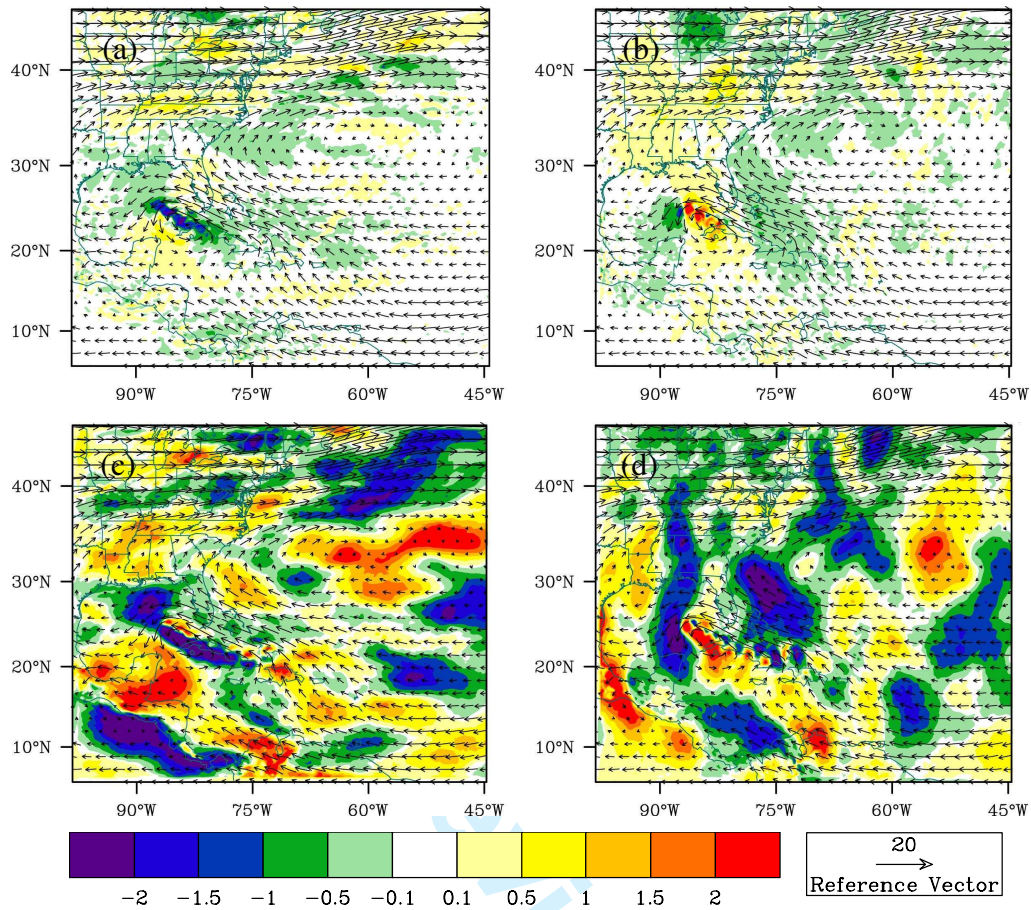


Fig. 4 The averaged difference between experiments TAMDAR and CTRL (a) u , (b) v , and the averaged difference between GFS analysis and experiment CTRL (c) u , and (d) v . The averaged stream in CTRL is overlaid. The average is carried out over 8 examples and from Eta level 0.8435 (about 850 hPa) to 0.3825 (about 350 hPa). Only the plots in the sub-domain are shown.

Table 1. Statistics of Ike forecast at analysis and different forecasting time

Index	EXP	Analysis time		24-h		48-h		72-h	
		Average	RMSE	Average	RMSE	Average	RMSE	Average	RMSE
Track	CTRL	47.629	50.67	76.016	78.637	114.717	118.797	156.506	164.712
	TAMDAR	32.876	37.364	67.276	68.704	98.777	107.413	126.67	141.112
SLP	CTRL	10.824	16.093	3.751	7.213	-2.933	8.387	3.58	8.645
	TAMDAR	10.958	16.277	3.448	7.997	-1.937	7.929	2.074	8.008
MWS	CTRL	-10.576	20.675	0.393	7.017	2.776	4.435	-5.763	15.009
	TAMDAR	-10.658	20.835	0.595	7.029	1.075	3.364	-3.829	11.046