Impact of 4DVAR Assimilation of AIRS Total Column Ozone Observations on the Simulation of Hurricane Earl

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) provides twice-daily global observations of brightness temperature, which can be used to retrieve the total column ozone with high spatial and temporal resolution. In order to apply the AIRS ozone data to numerical prediction of tropical cyclones, a four-dimensional variational (4DVAR) assimilation scheme on selected model levels is adopted and implemented in the mesoscale non-hydrostatic model MM5. Based on the correlation between total column ozone and potential vorticity (PV), the observation operator of each level is established and five levels with highest correlation coefficients are selected for the 4DVAR assimilation of the AIRS total column ozone observations. The results from the numerical experiments using the proposed assimilation scheme for Hurricane Earl show that the ozone data assimilation affects the PV distributions with more mesoscale information at high levels first and then influences those at middle and low levels through the so-called asymmetric penetration of PV anomalies. With the AIRS ozone data being assimilated, the warm core of Hurricane Earl is intensified, resulting in the improvement of other fields near the hurricane center. The track prediction is improved mainly due to adjustment of the steering flows in the assimilation experiment.

Key words: numerical prediction of tropical cyclones, AIRS total column ozone, data assimilation

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1. Introduction

Due to imperfect parameterization of the air-sea interaction and convection, and a lack of observations over the ocean, the large-scale environmental fields and initial conditions of a tropical cyclone (TC) cannot be accurately described in a numerical weather prediction (NWP) model. This leads to serious errors in numerical prediction of TCs. However, satellite remote sensing data contain valuable meteorological information and have wide coverage (especially in areas with limited conventional observations, such as oceans and remote plateaus) and high spatial and temporal resolution. Satellite observation is therefore a major observational source used to improve prediction of TCs (Li and Fang, 2012).

In general, satellite data assimilations are divided into two categories: indirect assimilation of atmospheric temperature and moisture data retrieved from satellite observations in an NWP model, and direct assimilation through a radiative transfer model, linking satellite observations and model variables to obtain temperature and moisture variables close to the actual state of the atmosphere (Xue, 2009). Previous studies have demonstrated that these two methods are efficient in improving the numerical prediction of TC

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track and intensity (Le et al., 2002; Ding et al., 2010; Wang et al., 2013; Wu et al., 2014). However, there are still a number of satellite observations that cannot be in any way incorporated into an NWP model, resulting from lack of an observation operator. Among them are the ozone data measured by the Atmospheric Infrared Sounder (AIRS) on board the Aqua satellite of the Earth Observing System (EOS).

AIRS is presently the most advanced hyperspectral infrared atmospheric sounding instrument, covering 2378 spectral channels from 3.74 to 15.4 μm. The cross-track dimension of AIRS is 1650 km and the spatial resolution at nadir is 13.5 km with twice-daily observations. With the Advanced Microwave Sounding Unit (AMSU) and Humidity Sounder for Brazil (HSB), AIRS can provide ozone profiles and total column ozone with high spatial and temporal resolution (Aumann et al., 2003). Since ozone concentration varies at different altitudes and latitudes due to inhomogeneous transport of atmospheric flow, total column ozone is a passive tracer on synoptic scale. Therefore, ozone is highly correlated with many atmospheric variables (Tian et al., 2007).

In the early days, Normand (1953) and Ohring and Muench (1960) noted that the temporal variations of station ozone data were inherently related to those of temperature, geopotential height, and meridional wind at 100 hPa. Danielsen (1968) and Shapiro et al. (1982) found that ozone distributions at the tropopause could be treated as a surrogate for potential vorticity (PV) in the stratosphere and contained information on both synoptic-scale and mesoscale flow regimes. Davis et al. (1999) noted that the distribution character of vertically integrated ozone was linked to the positions of upper-level troughs and ridges. Jang et al. (2003) made the first efforts to assimilate Total Ozone Mapping Spectrometer (TOMS) data. Their results indicated that the spatial distribution of total ozone within a TC reflected the cyclone circulation evolution, so the total ozone distribution could be used to predict winter storms.

Attempts have been made to apply ozone data to the study of hurricanes. Using TOMS ozone data from 1979 to 1982, Stout and Rodgers (1992) concluded that a TC changed direction when its distance from the ozone-rich upper tropospheric trough was approximately 15-degree latitude. Carsey and Willoughby (2005) reported that the minimum and maximum ozone concentrations during intensification of hurricanes measured by the NOAA P-3 hurricane research aircraft were observed in the eyewall and eye respectively, while low ozone concentrations during weakening of hurricanes were found throughout the eyewall and eye regions. After a careful examination of TOMS observations of many hurricanes from 1996 to 2003, Zou and Wu (2005) confirmed Carsey and Willoughby's findings. Moreover, Zou and Wu (2005) found that the spatial distribution of total ozone within TCs was correlated with that of mean PV and upper-level geopotential height. Wu and Zou (2008) subsequently assimilated TOMS ozone data into an NWP model to better describe the large-scale environment of Hurricane Erin (2001), based on the relationship between total ozone and mean PV. Their results suggested that the assimilation of total ozone data produced a significant improvement in hurricane track prediction. More recently, a quality control (QC) scheme for assimilating AIRS ozone data in an NWP model was developed by Wang et al. (2012). The numerical simulation results of hurricane cases implemented by the QC scheme showed that the main information provided by the ozone data was retained, while the data quality was significantly improved.

Previous studies have concerned primarily on improving TC simulations by adjusting the large-scale environment field with TOMS ozone data assimilation. In contrast to TOMS data, AIRS ozone data have higher temporal and spatial resolution and contain more meteorological information in the upper troposphere. This study aims to examine if it is possible to improve the prediction of TC track and intensity by assimilating the AIRS ozone data into the initial fields of a mesoscale NWP model. For this purpose, application of a four-dimensional variational (4DVAR) assimilation scheme on selected model levels is developed to assimilate AIRS ozone data and to verify the assimilation effects on numerical prediction of Hurricane Earl (2010).

2. Synoptic overview of Hurricane Earl (2010)

Hurricane Earl (2010) is chosen for initialization and hindcast experiments in this study. Figure 1 depicts its observed track based on Unisys data (http://weather.unisys.com/hurricane/). Hurricane Earl began as a tropical depression on 25 August 2010, and strengthened into a tropical storm around 1200 UTC 25 August. Under the influence of a subtropical ridge over the western Atlantic, the storm moved quickly westward in the next two days. It was expected to slow and turn northwestward due to the Fujiwhara effect of the nearby Hurricane Danielle (2010). At about 0000 UTC 30 August, Hurricane Earl intensified into a category-3 hurricane, and reached category-4 strength on the same day. At 0000 UTC 1 September, Earl weakened to a category-3 hurricane, due to increased southwest shear. However, data from NOAA indicate that Earl re-strengthened to a category-4 hurricane at 1800 UTC 1 September, with a minimum sea level pressure (SLP) of 927 hPa and 230 km h^{-1} maximum sustained winds. Earl remained at this intensity until 1500 UTC 2 September 2010, then it began to weaken on 3 September 2010. Earl turned northeastward and further weakened to a tropical storm at 0000 UTC 4 September, before making landfall in Nova Scotia as a category-1 hurricane around 1400 UTC 4 September. After landfall, Earl transformed into an extratropical cyclone, and merged with another low pressure system over the Labrador Sea by 0600 UTC 6 September. This study focuses on the period when Earl regained its peak intensity prior to its landfall from 1800 UTC 1 to 1800 UTC 4 September 2010.

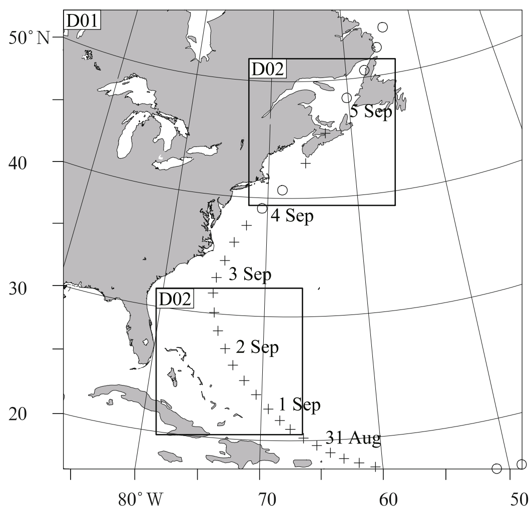

Fig. 1. Observed track of Hurricane Earl from 0000 UTC 30 August to 1800 UTC 5 September 2010, with open circles indicating storm or depression status, and plus symbols indicating hurricane status. The dates are indicated along the track. Also indicated in this figure are the outermost hindcast domain, D01 (45-km resolution), and two moving inner domains, D02 (15-km resolution), one at the beginning (1800 UTC 1 September 2010) and one at the end (1800 UTC 4 September 2010) of the Hurricane Earl simulation with a start time of 1800 UTC 1 September.

3. Numerical model, observational data, and assimilation scheme

3.1 Numerical model

The Penn State/NCAR non-hydrostatic mesoscale model version 5 (MM5) (Grell et al., 1994) and its 4DVAR system (Zou et al., 1997) are used in this study. All experiments are carried out on two nested model domains (Fig. 1). The outer domain (D01), with 95 × 95 grid points, is fixed, and simulates the large-scale environment with a horizontal resolution of 45 km. The inner domain (D02) has 91 × 91 grid points and moves with Hurricane Earl, simulating the storm-scale flows with a horizontal resolution of 15 km. There are 27 σ layers in the vertical direction, and the pressure at model top is 50 hPa. The physical parameterizations used for the forecast model are the same as those for the data assimilation system, including the Grell cumulus scheme, the medium-range forecast (MRF) planetary boundary layer (PBL) scheme, and the Reisner explicit moisture scheme (Grell et al., 1994). The initial and lateral boundary conditions are obtained from the NCEP Global Forecast System (GFS) Final (FNL) data with a spatial resolution of 1°× 1°.

3.2 AIRS ozone data and quality control

AIRS ozone data are retrieved from 41 channels, covering a spectral range from 9.354 to 10.029 μm (including the peak of the P-branch of the strong ozone absorption close to 10 μm). These ozone data can be found in both AIRS level-2 and level-3 standard products. AIRS level-2 datasets, which are produced twice daily, contain the ozone mixing ratio at 28 standard pressure levels and the total column ozone on a resolution of 45 km at nadir. Many studies on the evaluation of AIRS-retrieved ozone have shown that AIRS ozone data are credible and appropriate for further applications (Bian et al., 2007; Monahan et al., 2007; Pan et al., 2007; Pittman et al., 2009). The AIRS level-2 standard ozone data are chosen for this study.

The spatial distribution of AIRS total ozone is highly correlated with the corresponding Geostationary Operational Environmental Satellite (GOES)-13 visible cloud image (http://www.nrlmry.navy.mil/) for Hurricane Earl (Fig. 2). It is shown that AIRS total ozone may be a good source of information reflecting the structure of hurricane near the tropopause, with high total ozone in downdraft areas and low total ozone in updraft areas. The intrusion of stratospheric air into the hurricane core usually causes ozone-rich areas, defined as tropopause folding (Rodgers et al., 1990; Bosart, 2003). AIRS provided good data coverage for Hurricane Earl at 1800 UTC 1 September 2010, which was chosen as the model initial time.

Before applying AIRS total ozone to data assimilation, erroneous data were removed by a QC scheme. The QC scheme also ensures that the observation errors are consistent with the errors assumed in the data assimilation model. Wang et al. (2012) found that almost all AIRS ozone data around the center of a hurricane are flagged as poor by the original QC scheme, even though the data might be informative. They developed a new QC scheme that improved the quality of AIRS ozone data for the assimilation requirement, while retaining more observations than the original QC scheme near the hurricane center. The QC scheme developed by Wang et al. (2012) is used to improve the quality of AIRS ozone data in this study. The significant improvement of the correlation between mean PV and AIRS total ozone after QC, as well as lower mean error and standard deviation in the data as seen in Table 1, lends credibility to the assimilation applications of AIRS ozone data.

3.3 Assimilation scheme

It is difficult to directly apply total ozone data in the NWP model, because total ozone is not a model variable or an explicit function of model variables. Jang et al. (2003) found that TOMS total ozone observations (Ω) were highly correlated with mean PV ($\overline{q}$) in midlatitudes at both 30- and 90-km resolutions.

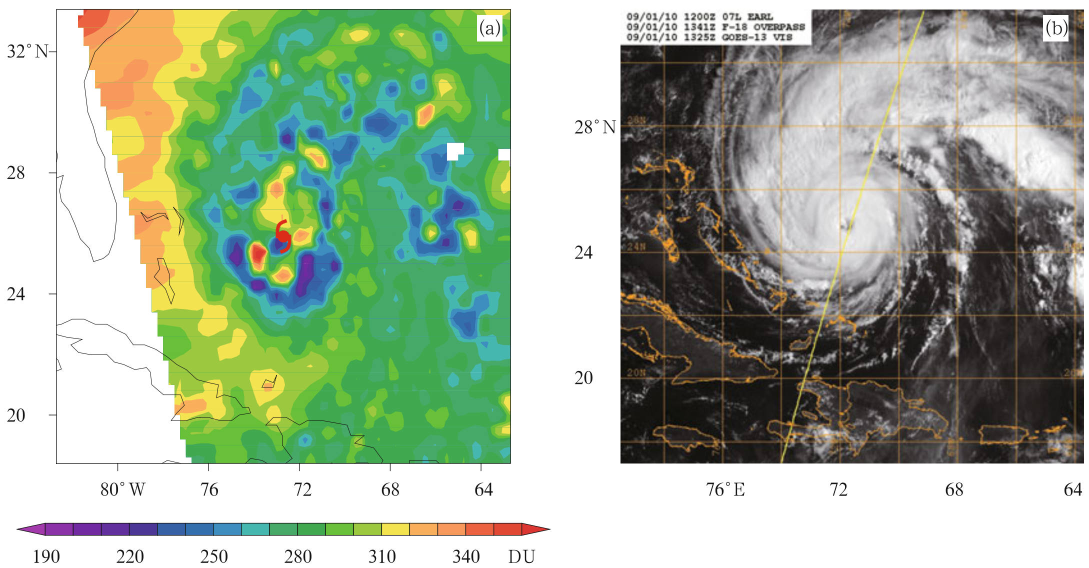

Fig. 2. (a) AIRS total ozone distribution for Hurricane Earl at 1800 UTC 1 September 2010 and (b) the corresponding GOES-13 visible cloud image (http://www.nrlmry.navy.mil) for Hurricane Earl at 1325 UTC 1 September 2010.

Table 1. Characteristics of AIRS ozone data before and after QC

	Mean error (DU)	Standard deviation (DU)	Correlation between mean PV and AIRS total ozone
Before QC	–2.3243	23.3862	0.5428
After QC	1.2473	14.2231	0.8801

A linear regression model between total ozone and mean PV was used as a simple observation operator for assimilating TOMS ozone in a 4DVAR procedure:

$$\Omega = \alpha \cdot \overline{q} + \beta, \tag{1}$$

where α and β are constants determined by the statistics of total ozone and mean PV. The mean PV is calculated by using

$$\overline{q} = \frac{1}{p_2 - p_1}\int_{p_1}^{p_2} \frac{1}{\rho}\eta \cdot \nabla\theta \mathrm{d}p, \tag{2}$$

where p is pressure, p_1 is 400 hPa, p_2 is 50 hPa, ρ is atmospheric density, η is absolute vorticity, and θ is potential temperature. The unit of mean PV is PVU, where 1 PVU = 10^{-6} m^2 K kg^{-1} s^{-1}. Thus, total ozone is associated with the model variables by Eqs. (1) and (2). Using TOMS ozone data, Zou and Wu (2005) found that high correlations between total ozone and mean PV could still be obtained if storm- and synoptic-scale features were separated. They developed a procedure to apply Eq. (1) in two different regimes, making it possible to assimilate total ozone data within and around a TC. In the later large-scale assimilation experiments conducted by Wu and Zou (2008), they took a simple regime-dependent linear regression model as the observation operator, and demonstrated the capability of TOMS ozone data in hurricane track prediction.

The relationship of Eq. (1) is applicable throughout the whole development process of a TC (Liu, 2014). Therefore, ozone data assimilation based on Eq. (1) can be used to efficiently adjust the large-scale environment field (Wu and Zou, 2008). However, a known problem in the total ozone assimilation is the incorrect vertical data distribution, which results in a difficulty of TC initialization based on ozone data assimilation (Durnford et al., 2009). Compared with TOMS ozone data used in Jang et al. (2003), Zou and Wu (2005), and Wu and Zou (2008), AIRS ozone data have a higher spatial and temporal resolution and contain more meteorological information that can be incorporated into mesoscale data assimilation. Thus, Eq. (1) requires modification before it is used to assimilate AIRS ozone data. Moreover, the total ozone is highly correlated with PV at some levels (Hood et al., 2005), indicating that different linear relations between total ozone and mean PV at different levels may need to be applied in the ozone data assimilation (Durnford et al., 2009). Based on the above discussion, this study seeks a proper initialization scheme to incorporate AIRS ozone data into the meso- and micro-scale initial field over D02 to improve TC prediction.

First, we calculate the correlation between the AIRS total ozone and mean PV in D02 at 1800 UTC 1 September 2010, and obtain a correlation value of 0.88, which is consistent with the result of Zou and Wu (2005). Second, we calculate the correlation between AIRS total ozone and PV at each model level from 400 to 50 hPa. The correlation values range from –0.51 to –0.76, indicating the existence of high correlation between total ozone and PV at some model levels. Third, we select five model sigma levels ($\sigma = 0.15$, 0.19, 0.23, 0.27, and 0.31) with the highest correlation coefficients and establish the observation operator of each level for the 4DVAR assimilation of AIRS ozone data. The observation operator can be linearly expressed as

$$\Omega = \alpha \cdot q + \beta, \tag{3}$$

where α and β are constants.

For Hurricane Earl, specific steps for AIRS ozone data preparation are as follows. First, we improve the quality of AIRS ozone data with the QC scheme developed by Wang et al. (2012). After QC, 1672 ozone data were collected at 1800 UTC 1 September 2010. Second, we use the Cressman interpolation method to obtain the PV value at the corresponding location of ozone data at each level. At 1800 UTC 1 September 2010, 1672 PV data were collected at each level. Third, we perform a statistical analysis on the ozone data and the PV data to obtain α and β at each level.

The values of α and β at the five selected levels are shown in Table 2.

Table 2. Values of α and β at the five selected levels in the simulation of Hurricane Earl beginning at 1800 UTC 1 September 2010

Model level (σ)	α	β
0.15	–1.98322	275.53690
0.19	–3.62480	276.21295
0.23	–3.38182	276.31168
0.27	–3.21336	276.46906
0.31	–3.32674	276.70087

The assimilation module of the AIRS ozone data is then designed and added in the MM5 4DVAR system. In 4DVAR experiments, the cost function to be minimized is written as

$$J(\boldsymbol{x}_0) = \frac{1}{2}(\boldsymbol{x}_0 - \boldsymbol{x}_\mathrm{b})^\mathrm{T}\boldsymbol{B}^{-1}(\boldsymbol{x}_0 - \boldsymbol{x}_\mathrm{b}) + \frac{1}{2}\sum_{t_i}\{\boldsymbol{d} - H[M(\boldsymbol{x}_0)]\}^\mathrm{T} \times \boldsymbol{R}^{-1}\{\boldsymbol{d} - H[M(\boldsymbol{x}_0)]\}, \quad (4)$$

where $\boldsymbol{x}_0$ is the model state at t_0 (the beginning of the assimilation window); $\boldsymbol{x}_\mathrm{b}$ is a background or prior estimate of $\boldsymbol{x}_0$; $\boldsymbol{B}$ is the background error covariance matrix; $\boldsymbol{R}$ is the observation error covariance matrix; $\boldsymbol{d}$ is the AIRS ozone observation, M is the nonlinear operator representing the NWP model from initial time t_0 to time t_i; and H is the observation operator that converts model space to observation space. The 4DVAR method seeks the optimal initial conditions under the constraint of an NWP model, so the initial model fields are dynamically and physically consistent. It is also worth noting that the observation operator in this study, established directly at a model level, avoids the conversion process between the p-coordinate and σ-coordinate systems in Eq. (1). Therefore, the assimilation efficiency with Eq. (3) is significantly greater than that with Eq. (1).

A group of experiments (denoted as Earl0118) are conducted to assess the impact of AIRS ozone data on the 72-h hindcast of Hurricane Earl. Hindcasts without data assimilation (i.e., initialized with $\boldsymbol{x}_\mathrm{b}$) are referred to as "control." Experiments labeled "ozone" use the initial conditions obtained after AIRS ozone data assimilation. In Earl0118, AIRS ozone data at 1800 UTC 1 September 2010 are assimilated at 3-min intervals in a half-hour 4DVAR assimilation window from 1800 to 1830 UTC.

4. Numerical results

4.1 TC track

Figure 3a shows the predicted tracks of Hurricane Earl from both the control and ozone experiments, from 1800 UTC 1 September 2010. The Unisys observed best track (OBS) is also plotted for comparison. Earl initially moved northwestward, experienced a sharp turn, and then moved northeastward 24 h later. Without any data assimilated into the NWP model, the TC track predicted by the control experiment is on the east side of the observed track and the track error increases rapidly after the simulation start time (Fig. 3b), resulting in delayed landfall with a position error of about 250 km. Compared with the control experiment, the ozone experiment improves the track simulation significantly during the entire 72-h hindcast period, with the track error below 150 km and the landfall position closer to that observed. The track differences between the control and ozone experiments are very small during the first 18 h and become much larger afterwards.

4.2 TC intensity

Figure 4 depicts the time variation of the central SLP (Fig. 4a) and the central SLP error (Fig. 4b) from the control and ozone experiments. The observed central SLP from Unisys is also shown as a reference in the figure. The OBS shows that the central SLP of Earl during the first 15 hours rapidly reduces from 940 to 930 hPa, prior to the gradual weakening. Without the assimilation of AIRS ozone data, variations of TC central SLP predicted by the control experiment show a steady trend that fails to capture the intensity change of Earl. In contrast, the central SLP in the ozone experiment reduces significantly during the first 18 hours and is almost the same as the observation between 1800 and 2100 UTC. This indicates that the central SLP is adjusted by the numerical model gradually after the assimilation of ozone data.

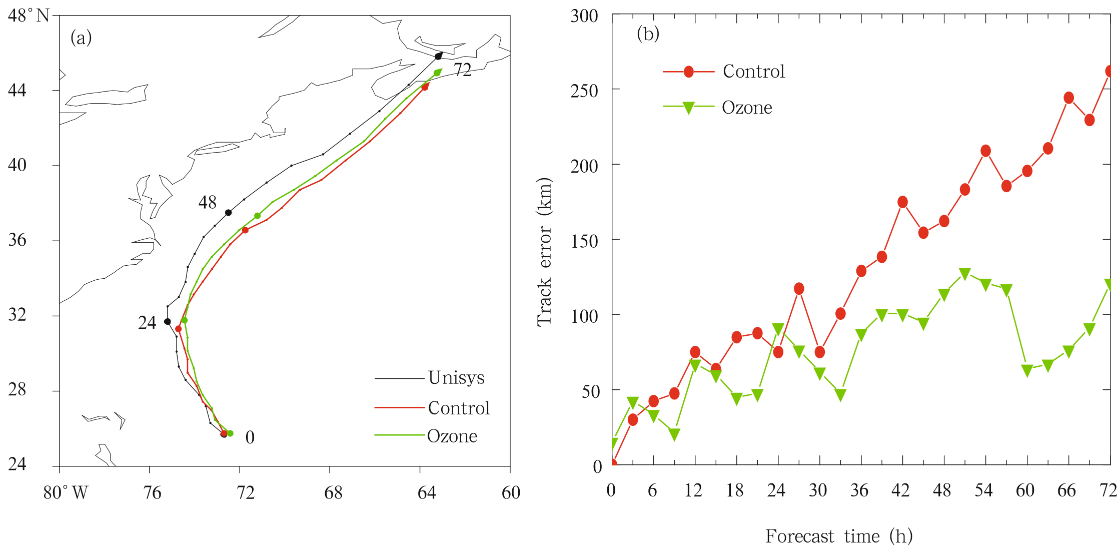

Fig. 3. (a) Tracks of Hurricane Earl from control and ozone experiments of Earl0118 and the best track provided by Unisys (http://weather.unisys.com), and (b) track errors of the control and ozone experiments of Earl0118 during the 72-h hindcast period. The hindcast model is initialized at 1800 UTC 1 September 2010, and the numbers along the tracks in (a) indicate the hindcast hour.

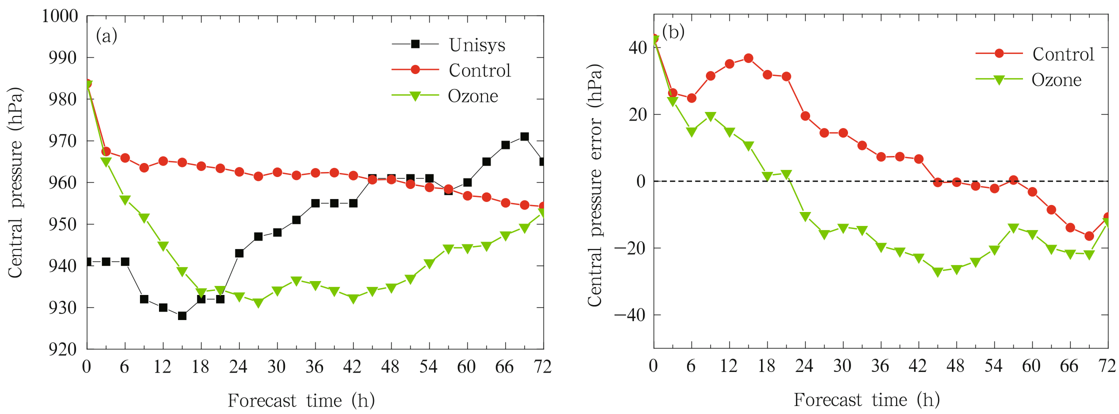

Fig. 4. (a) Sea level pressure (SLP) of the center of Hurricane Earl from control and ozone experiments of Earl0118 and Unisys (http://weather.unisys.com), and (b) SLP error of control and ozone experiments of Earl0118 during the 72-h hindcast period.

From the SLP error of control and ozone experiments of Earl0118 during the 72-h hindcast period (Fig. 4b), it can be seen more clearly that the ozone experiment during the first 18 hours improves the intensity simulation constantly, but tends to overpredict the intensity during the following simulation.

4.3 Batch experiments

To investigate the effectiveness of the 4DVAR assimilation scheme using AIRS ozone data in improving the prediction of Hurricane Earl, comparison experiments are conducted for five more cases (see Table 3). Because AIRS provides twice-daily global observations, the overpass time of the chosen areas is within ±3 h of 0600 and 1800 UTC every day. Thus, the initial time in this study is chosen to be either 0600 or 1800 UTC, corresponding to the observation time of AIRS ozone data. Moreover, only the AIRS ozone data with good coverage of Earl are selected. Similar to Earl0118, the QC scheme developed by Wang et al. (2012) is applied in the five added cases (Earl2918, Earl3006, Earl3106, Earl0306, and Earl0318). In addition, the physical options in the five cases are the same as those in Earl0118, with only different time settings as shown in Table 3. The statistical results show that the mean track error is reduced significantly after the assimilation of AIRS ozone data, especially after assimilating the ozone data during the strong intensity period. Compared with the control experiment, the simulated central SLP is reduced significantly after the assimilation of AIRS ozone data, and is even lower than the observation. On the whole, the batch experiments indicate that the 4DVAR assimilation scheme on the selected levels (as indicated in Table 1 for Earl0118, table omitted for other groups of experiments) improves the track prediction of Hurricane Earl effectively, in addition to having some capability in reproducing the intensity and intensity changes of Hurricane Earl as the time of integration increases.

Table 3. Time settings, mean track errors, and central sea level pressure (SLP) errors from the six groups of experiments

Name	Initialization time/simulation start time	Assimilation time window/simulation time window	OBS storm scale	Mean track errors (km)		Mean central SLP errors (hPa)	
				Control	Ozone	Control	Ozone
Earl2918	1800 UTC 29 Aug 2010	30 min/72 h	1	128.76	98.78	7.26	–1.48
Earl3006	0600 UTC 30 Aug 2010	30 min/72 h	2	120.67	88.64	10.35	–5.83
Earl3106	0600 UTC 31 Aug 2010	30 min/72 h	4	142.87	78.60	13.60	–9.47
Earl0118	1800 UTC 1 Sep 2010	30 min/72 h	3	131.07	75.69	11.38	–7.50
Earl0306	0600 UTC 3 Sep 2010	30 min/48 h	2	105.38	83.61	15.81	–3.48
Earl0318	1800 UTC 3 Sep 2010	30 min/36 h	1	101.37	90.59	9.68	–1.07

4.4 Potential vorticity increments

PV is a physical quantity containing thermodynamic and dynamic information, which can be applied to the comprehensive diagnosis of TCs (Wu and Wang, 2000). In order to assess the impact of incorporating AIRS ozone data into the initial field in simulating Hurricane Earl, Fig. 5 shows PV at 400 hPa, the zonal cross-section of PV through the hurricane center from the control experiment of Earl0118, and PV increments from ozone experiment of Earl0118 at 1800 UTC 1 September 2010. Mesoscale information is incorporated into the PV field after the assimilation of AIRS ozone data (Figs. 5a and 5b). From Figs. 5c and 5d, the assimilation of AIRS ozone data is seen to modify the PV field most above 400 hPa, consistent with the selected levels in the assimilation scheme. PV above 400 hPa is increased in the ozone experiment. To assess the impact of the initial PV adjustments on the development of Earl, Fig. 6 shows PV at 400 hPa, a zonal cross-section of PV through the hurricane center from the control experiment, and PV increments from the ozone experiment of Earl0118 at 1200 UTC 2 September 2010. This last panel corresponds to the timing of the significant improvement of Earl as observed in Figs. 3 and 4. This result shows that the PV increments from the ozone experiment of Earl0118 are stronger after an 18-h integration, compared with the control experiment (Figs. 6a and 6b). Meanwhile, vertical differences are found below 300 hPa, especially below 500 hPa (Figs. 6c and 6d). The results from the other five groups of experiments (figures omitted) also indicate that the PV differences in the ozone experiment propagate into the lower layers as the integration time increases, although the assimilation of AIRS ozone data at the initial time is found to mainly change the PV distribution close to the tropopause. According to the conclusion of Wu and Wang (2000), low-level vortex motion can be affected through the so-called asymmetric penetration flows associated with the upper-level PV anomaly. Thus, the modification of the PV field in the ozone experiment improves the simulation of Hurricane Earl.

4.5 Warm core

Around the TC center, release of huge latent heat associated with vigorous updrafts and abundant moisture occurs, while in the TC eye area, adiabatic warming occurs with strong downdrafts. They are combined to generate the TC warm core (Yan et al., 2013). Figure 7 shows zonal and meridional cross-sections of tem-

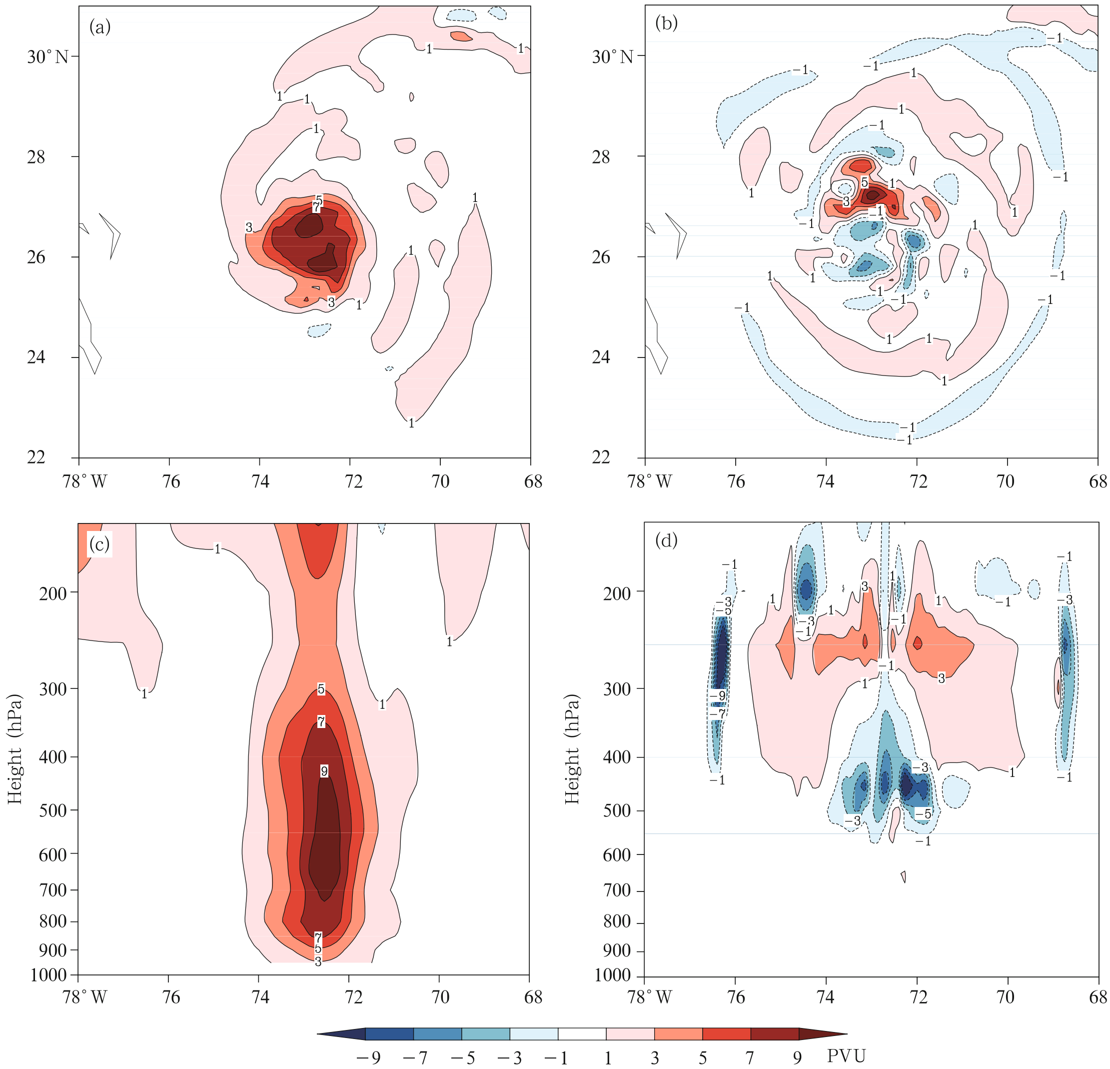

Fig. 5. Horizontal distributions of (a) PV at 400 hPa from the control experiment and (b) PV increments at 400 hPa from the ozone experiment. Zonal sections across the hurricane center of (c) PV from the control experiment and (d) PV increments from the ozone experiment. All panels are for Earl0118 at 1800 UTC 1 September 2010.

perature departure in the control and ozone experiments at 1800 UTC 1 September 2010. Temperature departure is calculated as the temperature at each grid point minus the mean temperature averaged over the area centered at the hurricane eye and with a radius of 500 km to the hurricane center at each model level. At the model intial time, the warm core in the ozone experiment is stronger, with a maximum temperature departure of 12°C (while it is about 7°C in the control experiment) and a narrower cylindrical area from 600 to 150 hPa (Fig. 7). The stronger warm core in the ozone experiment indicates that the intensity of the hurricane is increased at some model levels with the assimilation of AIRS ozone data. The wind field in the ozone experiment displays no much difference at this time. Figure 8 shows zonal and meridional cross-sections of temperature departure in control and ozone experiments after an 18-h integration. The maximum wind speed surrounding the hurricane center is significantly enhanced after 18 h, and the warm core is stronger at all the levels above 700 hPa with a more uniform vertical structure, indicating that the effect of ozone data assimilation has penetrated to a larger vertical extent. The results from the other five groups of experiments (figures omitted) reveal that the warm core of Hurricane Earl is significantly intensified in all the cases after the assimilation of AIRS ozone data, which leads to improvement in simulation of other fields (such as wind) near the hurricane center. A detailed diagnosis of the impact of ozone data assimilation on wind field is provided next.

4.6 Steering flows

TC motion can be approximated by a mass-weighted deep layer-mean flow field, which is generally better than single level steering (Dong and Neumann, 1983; Velden and Leslie, 1991). The environmental steering flows can be approximated by the mean flows near the TC center (Holland, 1984; Wang et al., 1998). Therefore, the steering flows in this study are calculated between 850 and 300 hPa in the hurricane center area with a radius of 500 km. Figure 9 shows the zonal and meridional components of the steering flows from the control and ozone experiments of Earl0118 during the 72-h hindcast period. It is found that the zonal component of the steering flows from the control and ozone experiments first decreased, and then increased during the simulation (Fig. 9a), consistent with the simulated motion feature as shown in Fig. 3a. Moreover, the zonal component of the steering flows from the ozone experiment during 12–51 h is smaller than that from the control experiment, resulting in a west-

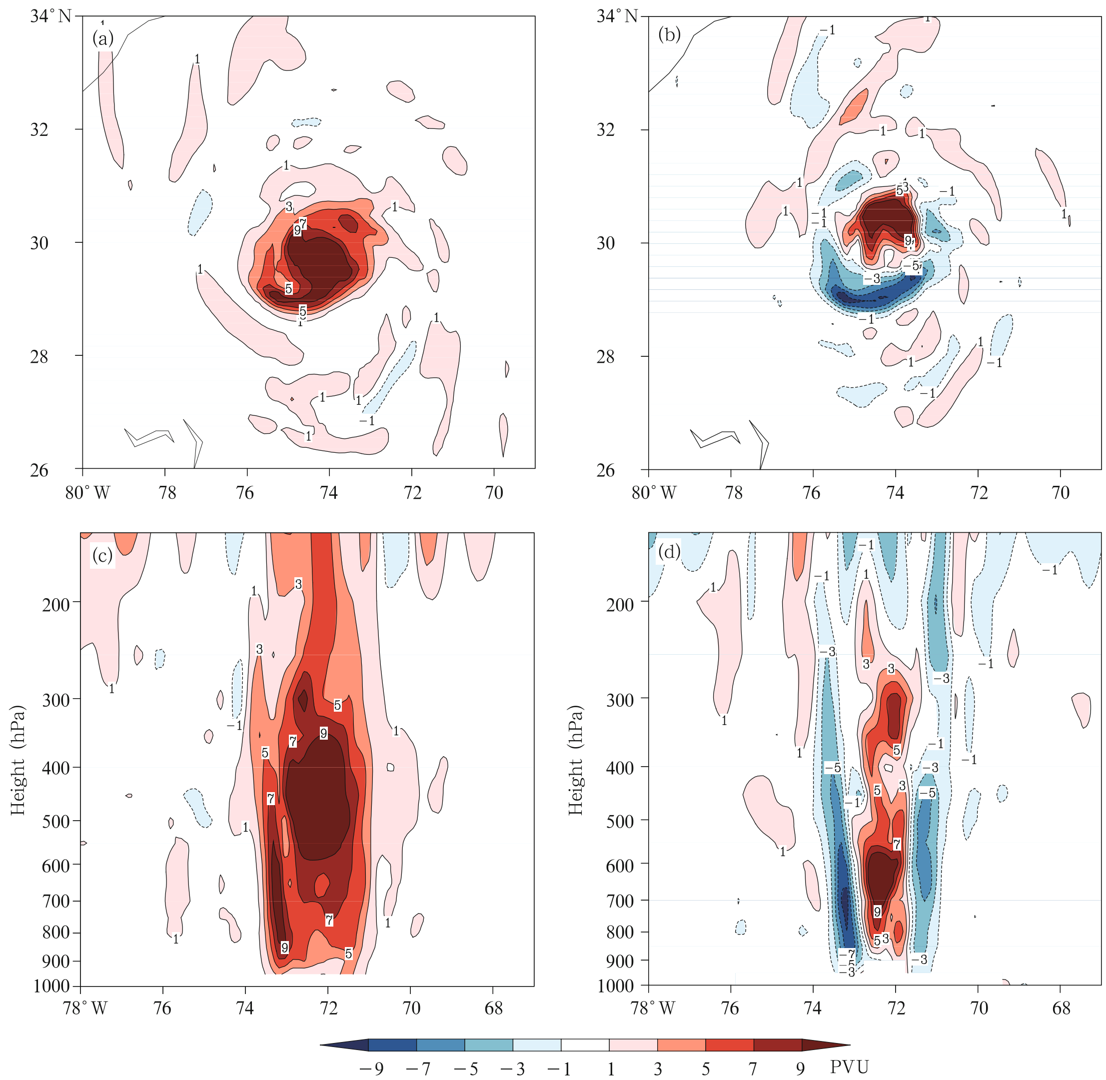

Fig. 6. As in Fig. 5, but at 1200 UTC 2 September 2010.

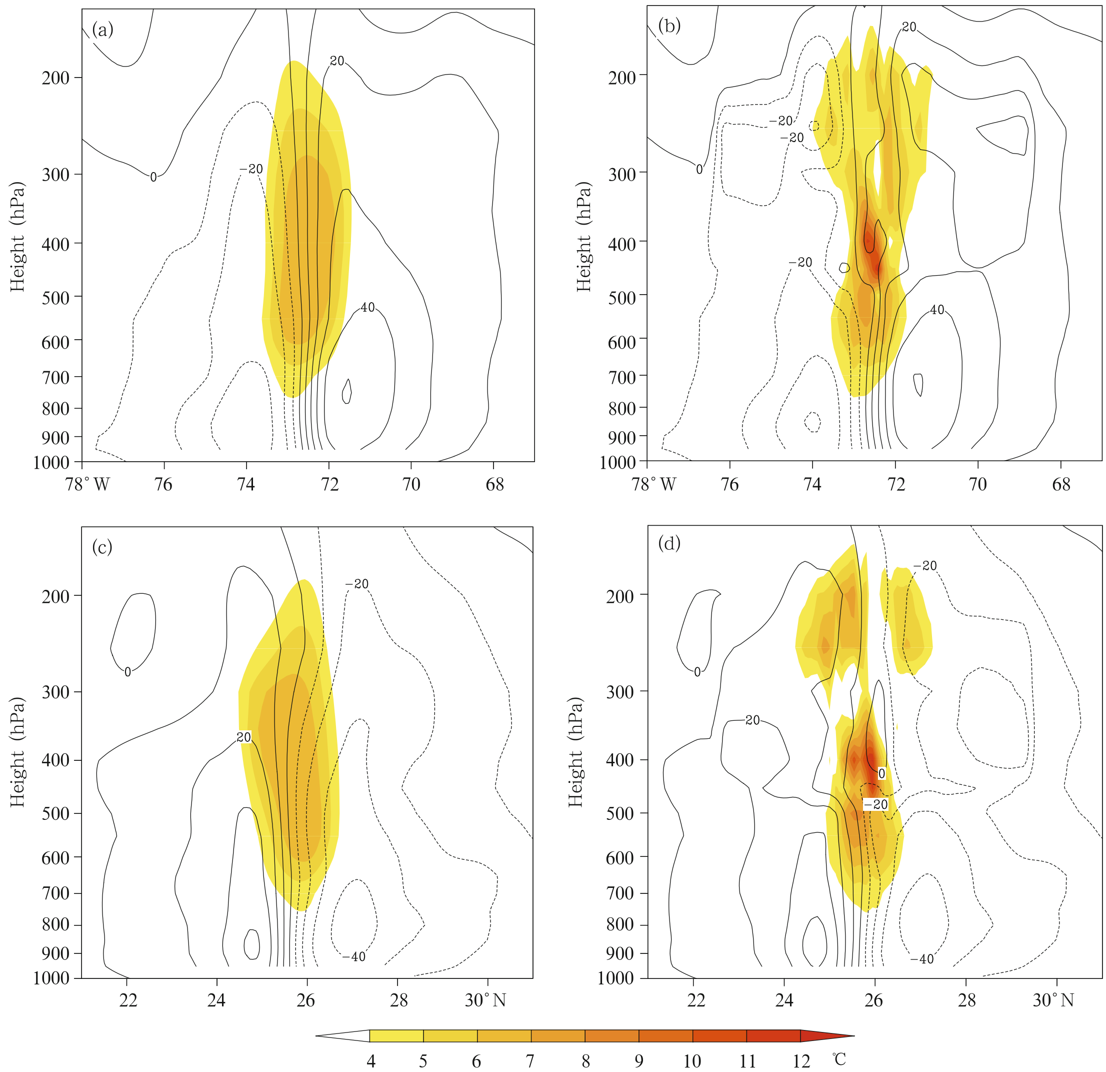

Fig. 7. (a, b) Longitude-height sections and (c, d) latitude-height sections of the temperature departure (shaded) and horizontal wind field (contour) across the hurricane center from (a, c) the control experiment of Earl0118 and (b, d) the ozone experiment of Earl0118 at 1800 UTC 1 September 2010.

ward track during the simulation. Figure 9b indicates that the difference in the meridional component of the steering flows between the control and ozone experiments is obvious after 54 h. In particular, the meridional component of the steering flows from the ozone experiment is greater than that from the control experiment during 12–54 h, while less than that from the control experiment after 54 h, resulting in the meridional difference of the track. The results from the other five groups of experiments (figures omitted) also confirm that the improvement in the track prediction of Hurricane Earl is mainly due to the adjustment of the steering flows after the assimilation of AIRS ozone data.

5. Summary

Defining the initial conditions for numerical prediction of a TC with few observations is challenging. This study applies the AIRS ozone data for numerical prediction of Hurricane Earl (2010). Based on the relationship between total column ozone and mean PV as found in previous studies (Jang et al., 2003; Zou and Wu, 2005; Wu and Zou, 2008; Wang et al., 2012;

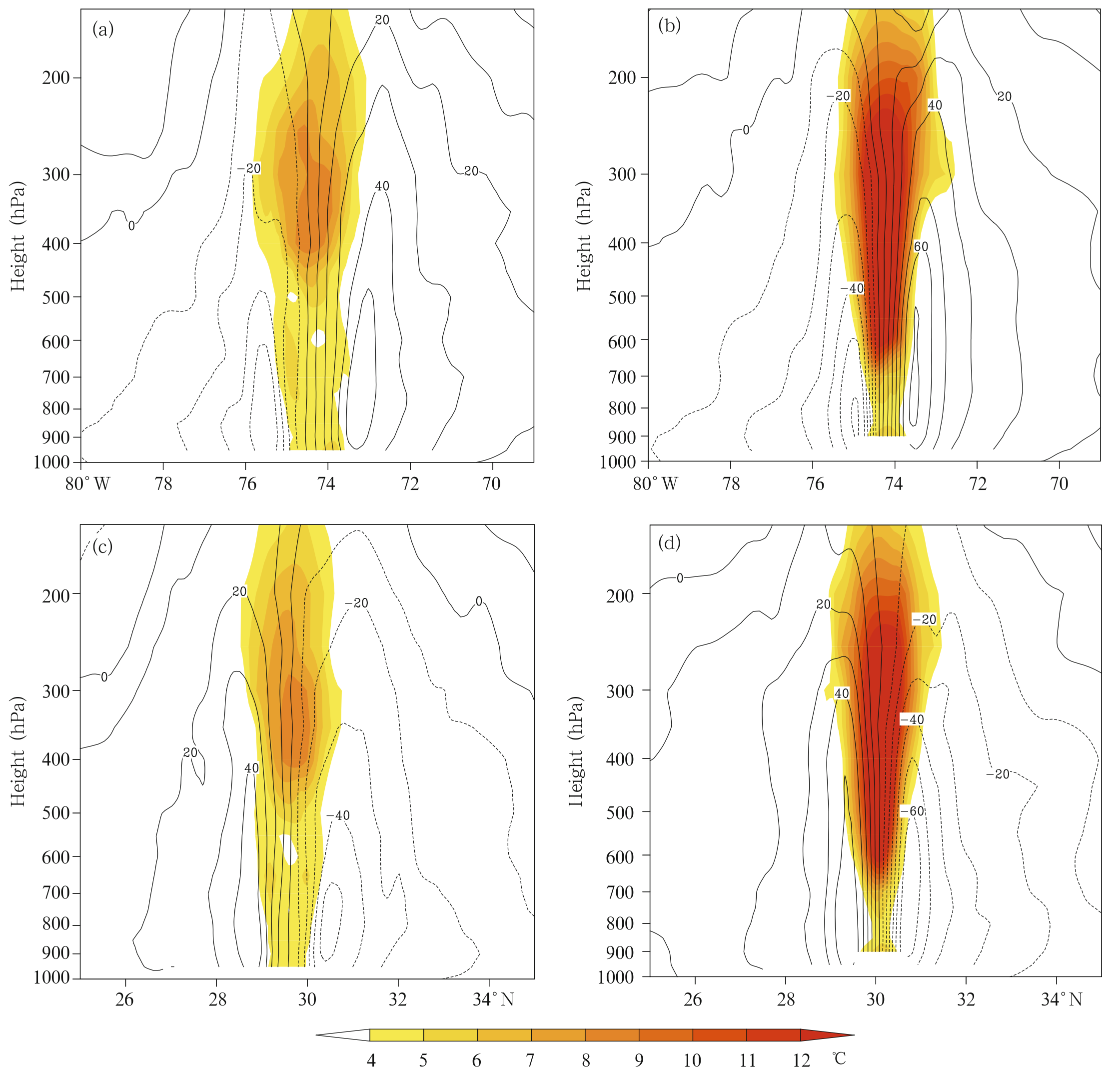

Fig. 8. As in Fig. 7, but at 1200 UTC 2 September 2010.

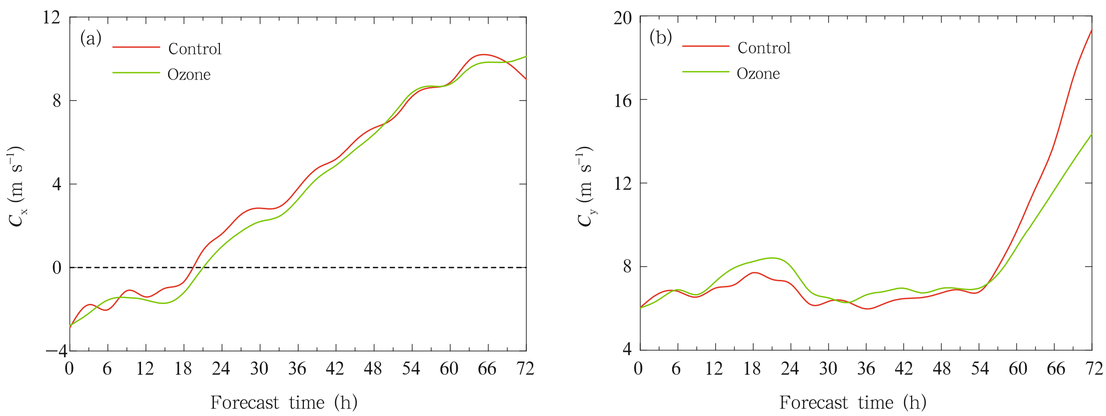

Fig. 9. (a) Zonal and (b) meridional components of the steering flows from the control and ozone experiments of Earl0118 during the 72-h hindcast period.

Liu, 2014), a 4DVAR assimilation scheme at selected model levels is adopted and implemented in MM5 to simulate Hurricane Earl. Meanwhile, batch experiments are conducted to show that this scheme could be useful for improved hurricane prediction. The results are summarized as follows.

(1) In order to assimilate AIRS ozone data, the observation operator is established at the levels with high correlation coefficients between total column ozone and PV. Five levels with the highest correlation coefficients between total column ozone and PV are selected from the model levels between 400 and 50 hPa.

(2) Assimilation of AIRS ozone data improves prediction of the hurricane track, and has some capability in reproducing the intensity and intensity changes of the hurricane as the integration time increases.

(3) Ozone data assimilation affects PV first at high level, and then the effect propogates to both middle and low levels. Due to high spatial and temporal resolution of ozone data, mesoscale information in the upper-level PV field is incorporated into the model initial condition. Through the so-called asymmetric penetration flows associated with the upper-level PV anomaly, mesoscale disturbances occur at lower levels. The overall improved PV simulation leads to better track and intensity prediction of Hurricane Earl.

(4) With the assimilation of AIRS ozone data, the warm core of Hurricane Earl is significantly intensified, resulting in improvement of other fields (such as wind) near the hurricane center.

(5) The improvement in the track prediction of Hurricane Earl is mainly due to the adjustment of the steering flows after the assimilation of AIRS ozone data.

This study suggests that AIRS ozone data contain valuable meteorological information about the upper troposphere and could therefore be useful for numerical prediction of TCs such as Hurricane Earl (2010). However, we realize that more case studies are needed before drawing any general conclusion on the performance of the ozone assimilation scheme. Additionally, there is room for further improvement of the ozone assimilation scheme. For example, the combined assimilation of AIRS ozone data and bogus data (Zou and Xiao, 2000; Park and Zou, 2004) may further improve the initialization and forecast of TCs.

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