Sensitivity of Hurricane Intensity Forecast to Convective Momentum Transport Parameterization

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ABSTRACT

A parameterization of the convection-induced pressure gradient force (PGF) in convective momentum transport (CMT) is tested for hurricane intensity forecasting using NCEP's operational Global Forecast System (GFS) and its nested Regional Spectral Model (RSM). In the parameterization the PGF is assumed to be proportional to the product of the cloud mass flux and vertical wind shear. Compared to control forecasts using the present operational GFS and RSM where the PGF effect in CMT is taken into account empirically, the new PGF parameterization helps increase hurricane intensity by reducing the vertical momentum exchange, giving rise to a closer comparison to the observations. In addition, the new PGF parameterization forecasts not only show more realistically organized precipitation patterns with enhanced hurricane intensity but also reduce the forecast track error. Nevertheless, the model forecasts with the new PGF parameterization still largely underpredict the observed intensity. One of the many possible reasons for the large underprediction may be the absence of hurricane initialization in the models.

1. Introduction

To suppress spurious tropical storm development from initially weak tropical disturbances (known as the false alarm problem in hurricane forecasting), the National Centers for Environmental Prediction's (NCEP) operational Global Forecast System (GFS) and its nested Regional Spectral Model (RSM) have recently included convective momentum transport (CMT) in their simplified Arakawa–Shubert (SAS; Pan and Wu 1995) cumulus scheme by allowing mass fluxes induced in the updraft and the downdraft to transport momentum as well as heat and moisture (Moorthi et al. 2001). In the upgrade, the momentum exchange is calculated through the mass flux formulation in a manner similar to that for heat and moisture. An evaluation has indicated that while inclusion of the convective momentum transport helps suppress spurious hurricane development, it produces weaker hurricanes when compared to observations, implying that the CMT parameterization leads to too much vertical mixing in the environmental flows.

Unlike the exchange for heat and moisture, it has been demonstrated (LeMone 1983; LeMone et al. 1984) that cumulus convection can induce significant perturbations in a pressure field in and around the convective area, and that such a convection-induced pressure gradient can strongly affect convective momentum transport. The convection-induced pressure gradient effect in the updated GFS has been taken into account, somewhat empirically, by increasing the entrainment for momentum in the updraft and thus enhancing mass exchange between the cloud and environment. However, initial tests have indicated that the empirical parameterization for the convection-induced pressure gradient force has a negligible effect on the hurricane intensity forecast.

In this study, we test the parameterization of cloud pressure gradients proposed by Wu and Yanai (1994) and Gregory et al. (1997). In the parameterization the pressure gradient force is assumed to be proportional to the product of the cloud mass flux and the vertical wind

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shear. This parameterization has a theoretical basis from Rotunno and Klemp's (1982) linear analysis in which the pressure perturbation across an isolated updraft is shown to be related to the mean shear of the cloud environment and the updraft vertical velocity, as demonstrated from an observational study (LeMone et al. 1988a,b). Zhang and Cho (1991a,b) also developed a similar scheme that parameterizes the perturbation pressure gradients in terms of cloud-scale circulation and the interaction between convective updrafts/downdrafts and the vertical wind shear. Using the Zhang and Cho scheme in their 20-yr general circulation model simulation, Wu et al. (2003) showed that the CMT-induced secondary meridional circulation played a central role in producing the observed seasonal migration of the intertropical convergence zone (ITCZ) across the equator.

The rate of change in the environmental flows due to momentum transport by the convective updraft (denoted as subscript u) can be expressed as (Wu and Yanai 1994; Zhang and Wu 2003)

$$\frac{\partial \overline{V}}{\partial t} = M_u \frac{1}{\rho} \frac{\partial \overline{V}}{\partial z} + \delta(V_u - \overline{V}) + \sigma_u \frac{1}{\rho} (\nabla p)_u, \qquad (1)$$

where $\overline{V}$ represents the domain-averaged wind vector, t the time, M_u the updraft mass flux, ρ the air density, V_u the mean horizontal wind vector of the updrafts, δ the mass detrainment at the cloud boundaries, σ_u the fractional area of updrafts, and p the pressure perturbation. The above equation is obtained from the budgets of mass and horizontal momentum for steady-state clouds; that is,

$$\delta - \varepsilon - \frac{\partial M_u}{\rho \partial z} = 0, \qquad (2)$$

$$\delta V_u - \varepsilon \overline{V} + \frac{\partial (M_u V_u)}{\rho \partial z} = -\frac{1}{\rho} \sigma_u (\nabla p)_u, \qquad (3)$$

where ε is the mass entrainment at the cloud boundaries. On the right-hand side of Eq. (1), the first term is interpreted as the vertical advection from the compensating subsidence in the cloud environment; the second represents the horizontal detrainment from the updrafts into their environment; the last term represents the pressure gradient across the updrafts. A similar form can also be obtained for the downdrafts.

According to studies by Wu and Yanai (1994) and Gregory et al. (1997), the convection-induced pressure gradient force (PGF) term in Eqs. (1) and (3) is parameterized as

$$\sigma_u \frac{1}{\rho} (\nabla P)_u = -c M_u \frac{1}{\rho} \frac{\partial \overline{V}}{\partial z}, \qquad (4)$$

where c is a positive empirical constant. Using Eq. (4) in Eq. (1), we obtain

$$\frac{\partial \overline{V}}{\partial t} = (1 - c) M_u \frac{1}{\rho} \frac{\partial \overline{V}}{\partial z} + \delta(V_u - \overline{V}). \qquad (5)$$

Equation (5) implies that the convection-induced PGF directly counteracts environmental subsidence by the cloud and makes momentum mixing less effective than that of heat or moisture. This is similar to turbulence mixing behavior in the convective boundary layer in which eddy diffusivity for momentum is observed to be less (by about 3 times) than that for heat and/or moisture (e.g., Deardorff 1972). Gregory et al. (1997) demonstrate validity of this PGF parameterization compared to their cloud-resolving model (CRM) results and find that $c = 0.7$ is an optimal value. From a theoretical examination of the dynamic forcing of the pressure field, Zhang and Wu (2003) show that the above PGF parameterization scheme is the dominant linear forcing term and the nonlinear forcing term is of secondary importance. They find that $c = 0.55$ is the best optimal value from their CRM results, and this is used in the present study.

Section 2 provides a brief description of NCEP's GFS and RSM and the experiment setup. In section 3, sensitivity test results from the convection-induced PGF parameterization on hurricane intensity forecasts are presented. Finally, in section 5 we summarize our results and draw some conclusions.

2. Models and experiment setup

The NCEP GFS is a global spectral model for weather and climate prediction, until recently named the NCEP Medium-Range Forecast (MRF) model. The RSM developed by Juang and Kanamitsu (1994) is a limited-area spectral model for regional weather and climate prediction and is being used operationally as a member of the short-range ensemble forecast system at NCEP. The RSM was designed to have the same model structure, dynamics, and physics as the GFS. In the GFS, total fields are predicted using spherical harmonic functions for spectral computation, while in the RSM perturbation fields from coarse-resolution base fields (usually global analysis or forecast fields) are represented by double Fourier trigonometric functions, which are relaxed to zero at the lateral boundaries.

Recently, RSM model physics have been updated following update of the GFS model physics. In the upgrade, the diagnostic large-scale cloud scheme has been replaced by a prognostic cloud scheme. The radiation parameterization uses predicted cloud condensate in

TABLE 1. Hurricanes for model experiments: EP and AL stand for eastern Pacific and western Atlantic, respectively, P_{min} minimum central mean sea level pressure, V_{max} peak maximum 1-min surface wind speed, and R mean radius of V_{max} during model forecasts.

Case	Place and year	P_{min} (hPa)	V_{max} (m s^{-1})	R (km)	RSM grid size (km)
Elida	EP2002	921	72	19	15
Hernan	EP2002	921	72	56	20
Isabel	AL2003	921	72	37	20
Isidore	AL2002	934	57	19	15
Kate	AL2003	962	51	37	20
Kenna	EP2002	915	72	9	10
Lili	AL2002	940	64	9	10
Marty	EP2003	973	44	28	20
Nicholas	AL2003	990	31	56	20
Patricia	EP2003	981	39	37	20

TABLE 2. Experimental setup.

GFS-CTL	GFS control forecast
GFS-PGF	GFS forecast with new PGF parameterization
RSM-CTL	RSM control forecast using GFS-CTL forecast as boundary condition every 3 h
RSM-PGF	RSM run with new PGF parameterization using GFS-PGF forecast as boundary condition every 3 h

the cloud–radiation interaction. The rapid radiative transfer model (Mlawer et al. 1997) is now used for the longwave radiation. A new prognostic variable ozone is introduced, which is predicted using temporally and spatially varying climatological ozone production and destruction rate. The updated cumulus convection parameterization was described in the introduction. The gravity wave drag parameterization includes the effects of subgrid orographic asymmetry and fractional area of subgrid orography larger than grid orographic height for four different wind directions, in addition to the subgrid orographic variance used in old version. The U.S. Navy 10-min topography data have been replaced by high-resolution topography data (Hong 1999) in which 2-, 4-, and 8-min-resolution data are available. The surface soil and vegetation types have been changed to allow heterogeneous types with 9 and 13 different kinds, respectively. Surface albedo now has four components. More details of the updated model physics can be found in Moorthi et al. (2001) and Hou et al. (2002).

Ten cases of hurricanes that occurred during the 2003–04 period over the western Atlantic and eastern Pacific were selected for this study (Table 1). The selection was somewhat arbitrary and had no specific preference. The GFS and RSM models each had 64 vertical sigma layers. While the GFS had a constant horizontal resolution of T254 (triangular truncation at wavenumber 254; about 52 km at equator), the RSM horizontal resolution was set at 20, 15, and 10 km (based on the size of the storm) as shown in Table 1.

Four 5-day forecasts for each case were conducted with and without the new convection-induced PGF parameterization in the CMT parameterization, using both the GFS and RSM (Table 2). As shown in Table 2, the RSM forecasts were run using the GFS forecasts every 3 h as boundary conditions. Initial times for model experiments were determined so as to include rapid intensity changes in observed hurricanes during the 5-day forecasts. Initial sea surface temperatures were kept unchanged during the forecasts. NCEP analysis data were used as initial conditions, and no special initialization for the hurricane was conducted.

3. Results

Before discussing experimental results of the 10 cases of Table 1, we present some sensitivity test results for the effect of the PGF parameterization. Examples of spurious hurricane forecasts and the effect of the CMT parameterization are shown in Fig. 1. Compared to the verifying analysis (Fig. 1a), the 132-h GFS forecast without the CMT parameterization (Fig. 1b) generates a spurious storm over the north-central Pacific. On the other hand, the control forecast (Fig. 1c; the forecast with empirical PGF parameterization in the CMT parameterization, used in the operational GFS) suppresses even the real storm [Hurricane Isaac (2000)] over the western Atlantic as well as the spurious hurricane. With the new PGF parameterization (Fig. 1d), the real storm is retained while the spurious storm is largely suppressed. Note that the analysis data largely underestimate the actual intensity (minimum central pressure of 970 hPa) although it represents an accurate hurricane position.

Figure 2 shows vertical cross sections of azimuthally averaged horizontal velocity at 84 forecast hours from the RSM forecast for Hurricane Hernan of Table 1. The control forecast (Fig. 2a) displays a weaker velocity profile compared to the forecast with the new PGF parameterization (Fig. 2b), indicating that the PGF in cumulus clouds plays a role in reducing vertical momentum exchange, and consequently, enhancing hurricane intensity. Figure 3 shows variation in the minimum central mean sea level pressure (MSLP) of the RSM forecast at 72 h for Hurricane Hernan as the value of the coefficient c in Eq. (5) varies. As expected, the minimum MSLP decreases as the coefficient increases because of less vertical momentum exchange; the change is not linear. When c is in the range of 0.4–0.6,

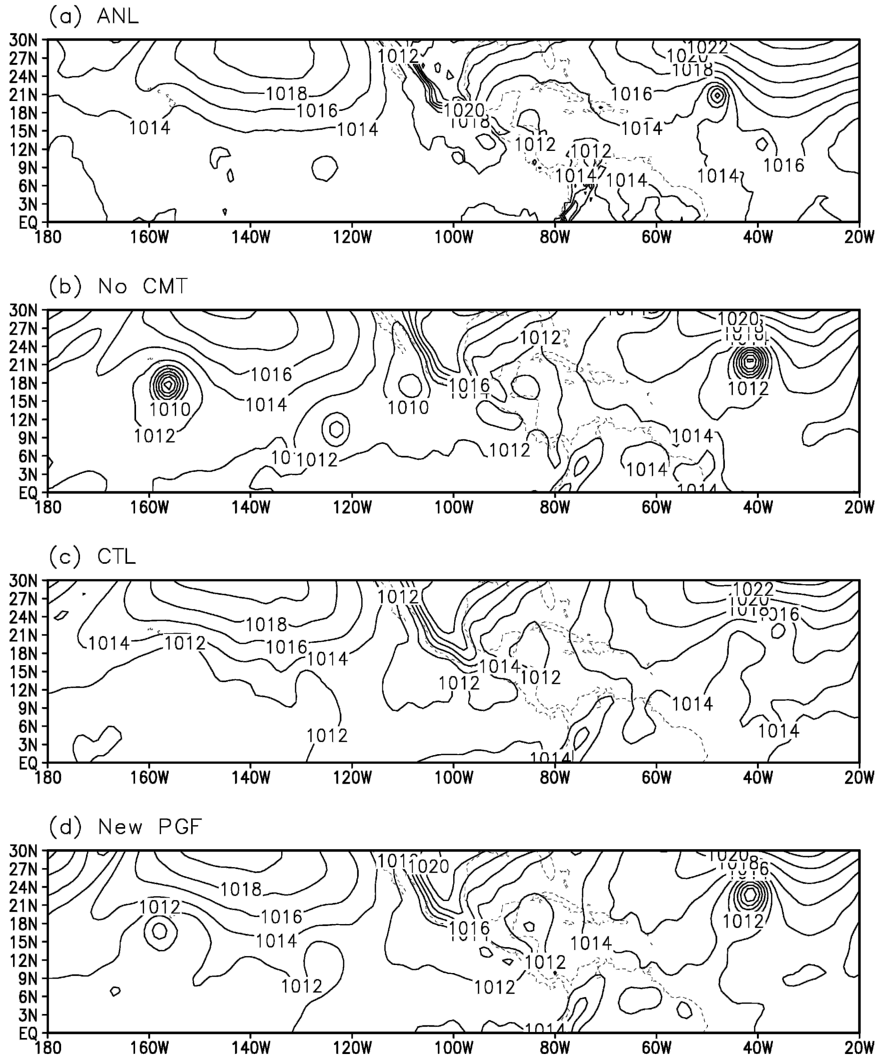

FIG. 1. Mean sea level pressure fields from (a) the verifying analysis and 132-h GFS forecasts with a horizontal resolution of T170 (about 78.5 km at equator) and 42 vertical sigma layers [(b) without CMT parameterization; (c) with the empirical PGF parameterization in the CMT parameterization (control forecast); and (d) with the new PGF parameterization in the CMT parameterization] for Hurricane Isaac (2000). The GFS forecasts were initialized at 0000 UTC 22 Sep 2000.

the rate of decrease in minimum MSLP is reduced. Note that it would be better not to use a c value of 1.0 (or close to it) for hurricane forecasts, as it often results in spurious tropical storm development, as shown in Fig. 1b.

Figures 4 and 5 present the time evolution of intensity forecasts for the 10 cases of hurricanes (Table 1) from the four experiments shown in Table 2 compared to observations produced by the National Hurricane Center (Jarvinen et al. 1984). The time evolutions of 200–850-hPa mean wind shear (the difference between horizontal wind velocities averaged over a 500-km radius along the hurricane track at 200 and 850 hPa) are also presented in Fig. 6 for the RSM forecasts, because the wind shear is known to have a strong impact on hurricane intensity change (e.g., Frank and Ritchie 2001).

As seen in Figs. 4 and 5, the new PGF parameterization does increase hurricane intensity compared to the control forecasts, giving rise to a closer comparison to the observations. The increase rate is different for different cases. Compared to coarse-resolution GFS forecasts, finer-resolution RSM forecasts also tend to increase intensity but with an increase smaller than that with the new PGF parameterization. However, model forecasts largely underpredict the observed intensity

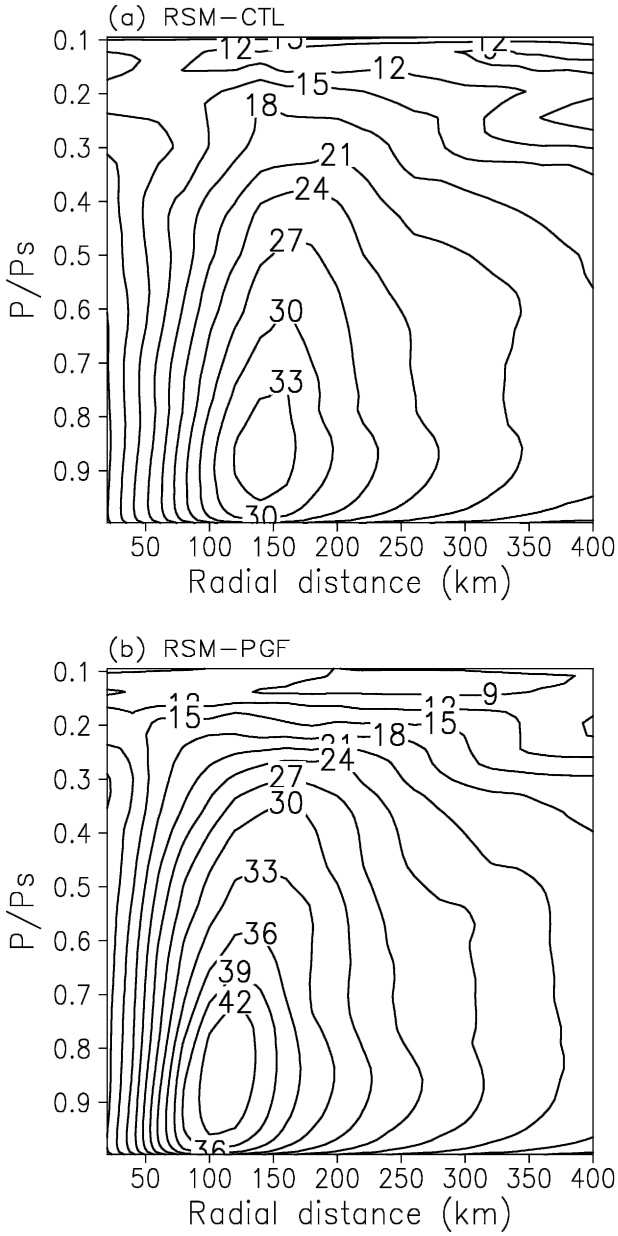

FIG. 2. Vertical cross sections of azimuthally averaged horizontal velocity (m s^{-1}) at 84 RSM forecast hours for Hurricane Hernan from (a) control forecast and (b) forecast with the new PGF parameterization.

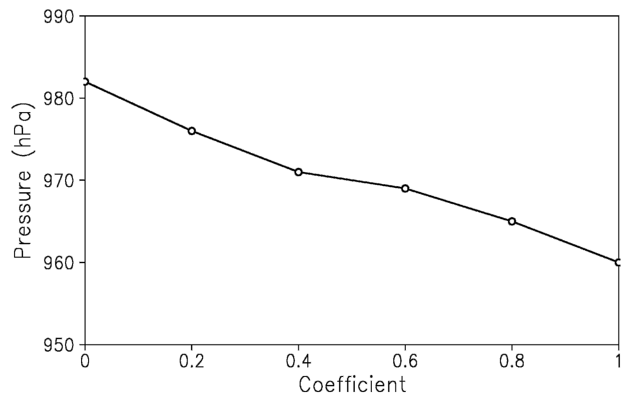

FIG. 3. Minimum central mean sea level pressure with varying value of the coefficient, *c*, in Eq. (5) at 72 RSM forecast hours for Hurricane Hernan with the observed minimum central pressure value of 956 hPa.

even with the new PGF parameterization and higher-resolution RSM. In addition, the intensity changes in the model forecasts are slower, giving rise to a delay in the time when intensity reaches its maximum. It appears that weakening in the observed intensity is associated with strong environmental wind shear (Fig. 6) for some hurricanes (e.g., Hurricanes Kate, Nicholas, and Patricia). Unlike observation, however, weakening in the model forecasts does not show a strong relationship with environmental wind shear. On the other hand, weakening in intensity in the observations of Hurricanes Isidore, Kenna, Lili, and Marty could be caused mainly by landfall or proximity to the land. For Hurricane Lili, however, Krishnamurti et al. (2005) have shown that the advection of earth's angular momentum into the storm was a major contributor for the intensity weakening prior to landfall.

Figures 7 and 8 display the time evolution of mean intensity forecast errors for the 10 cases of hurricanes. As expected from Figs. 4 and 5, the higher-resolution forecasts with the new PGF parameterization give rise to the best performance. The new PGF parameterization appears to be more effective in improving intensity forecasts than the resolution increase. The intensity forecast errors become smaller as the observed hurricanes weaken rapidly after maximum intensification while the forecasted hurricanes are still intensifying slowly. The smaller bias errors (Fig. 7) especially for the RSM-PGF experiments compared to the absolute errors (Fig. 8) in later time periods are due to the compensation of a very large underintensification of Hurricane Isabel with a smaller overintensification of Hurricanes Elida, Hernan, and Nicholas, as shown in Figs. 4 and 5.

The absence of a hurricane initialization process may be one of reasons for the slower and weaker intensification in the model forecasts. The much larger radius (Fig. 9) and weaker intensity (Figs. 4 and 5) at initial time compared to the observation would have made it difficult for the models to develop hurricanes rapidly. In addition, the grid sizes used in the present model forecasts (9–50 km) may not be fine enough to simulate inner-core dynamics that contributes to hurricane intensification. Exploration of many other contributors to

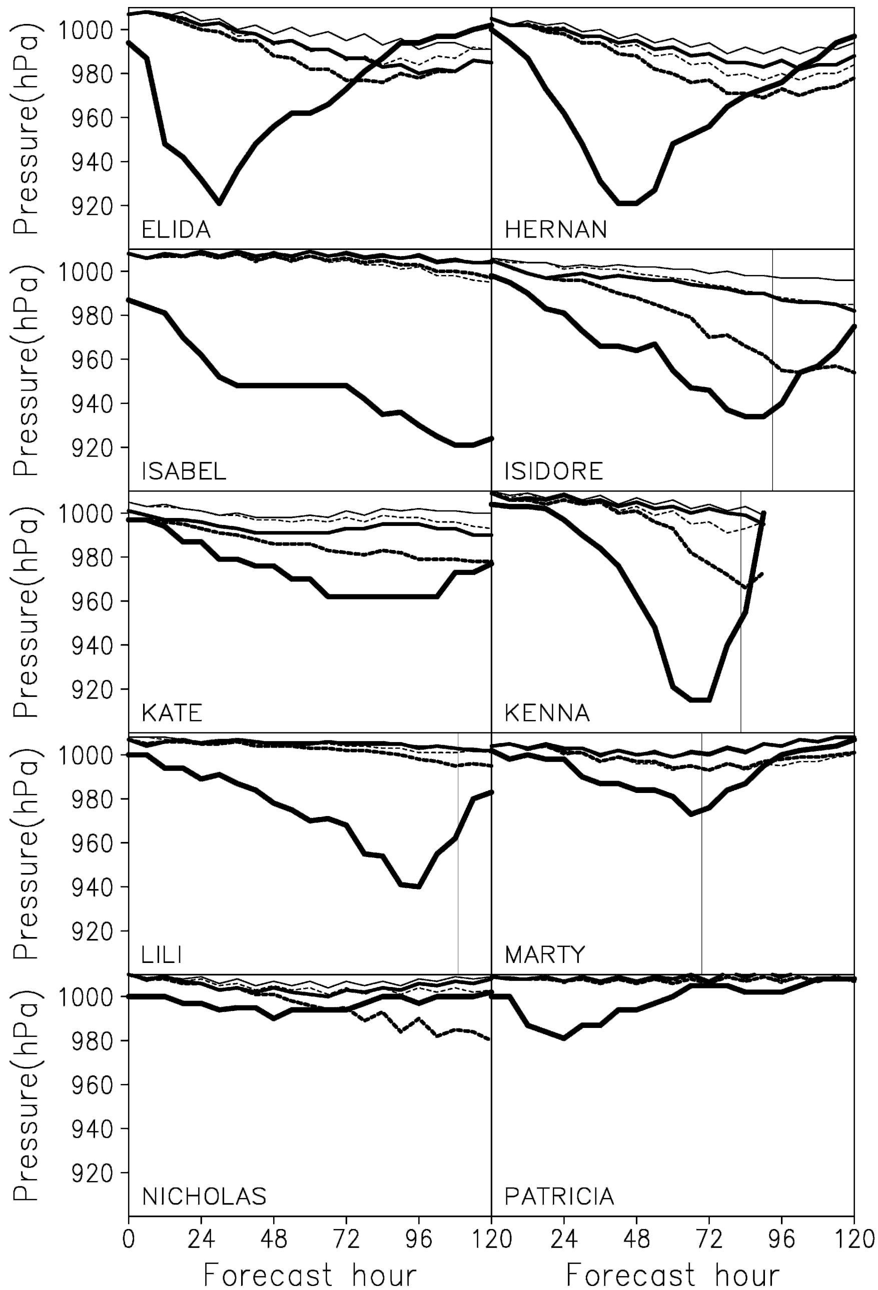

FIG. 4. Time evolution of minimum central MSLP from observations and model forecasts: the thickest solid line represents observation, the thinnest solid and dashed lines GFS-CTL and GFS-PGF, respectively, and the thicker solid and dashed lines RSM-CTL and RSM-PGF, respectively. Vertical lines for Hurricanes Isidore, Kenna, Lili, and Marty represent the times of landfall.

model's underprediction of the observed intensity may need a different sensitivity experiment and diagnosis approach for each hurricane, which will be pursued in future studies.

Figure 10 displays 6-h accumulated precipitation at 72 forecast hours from the RSM forecast for cases of relatively stronger Hurricanes Isidore, Kenna, and Elida, which show more pronounced differences between control forecasts and forecasts with the new PGF parameterization. Although not shown, the GFS forecasts also show differences between the two experiments similar to the RSM, while displaying a broader

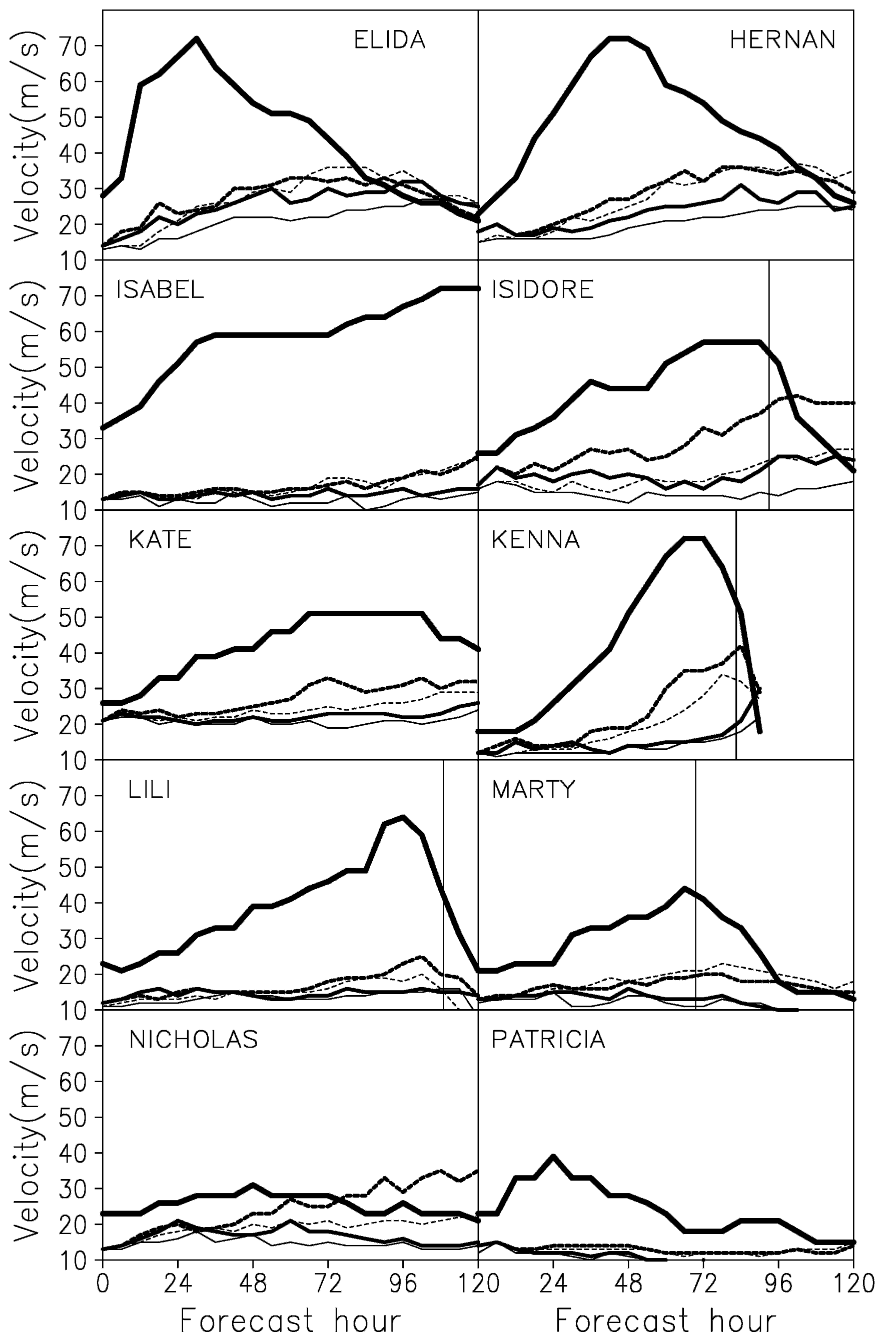

FIG. 5. Same as Fig. 4 but for maximum surface wind speed.

precipitation pattern around the hurricane core due to coarse resolution (about 50 km). Compared to control forecasts, forecasts with the new PGF parameterization not only produce more precipitation but also show more realistically organized precipitation patterns.

While a detailed exploration of each hurricane track forecast is beyond the scope of this study, a mean track forecast error is presented in Fig. 11. A significant error at initial time reflects an error associated with the coarse resolution of the global analysis data and the interpolation method seeking the hurricane center. With improved hurricane intensity forecasts, the new PGF parameterization helps reduce the track forecast error especially during 72–96-h forecasts. This implies that improvement in forecasting both the driving steer-

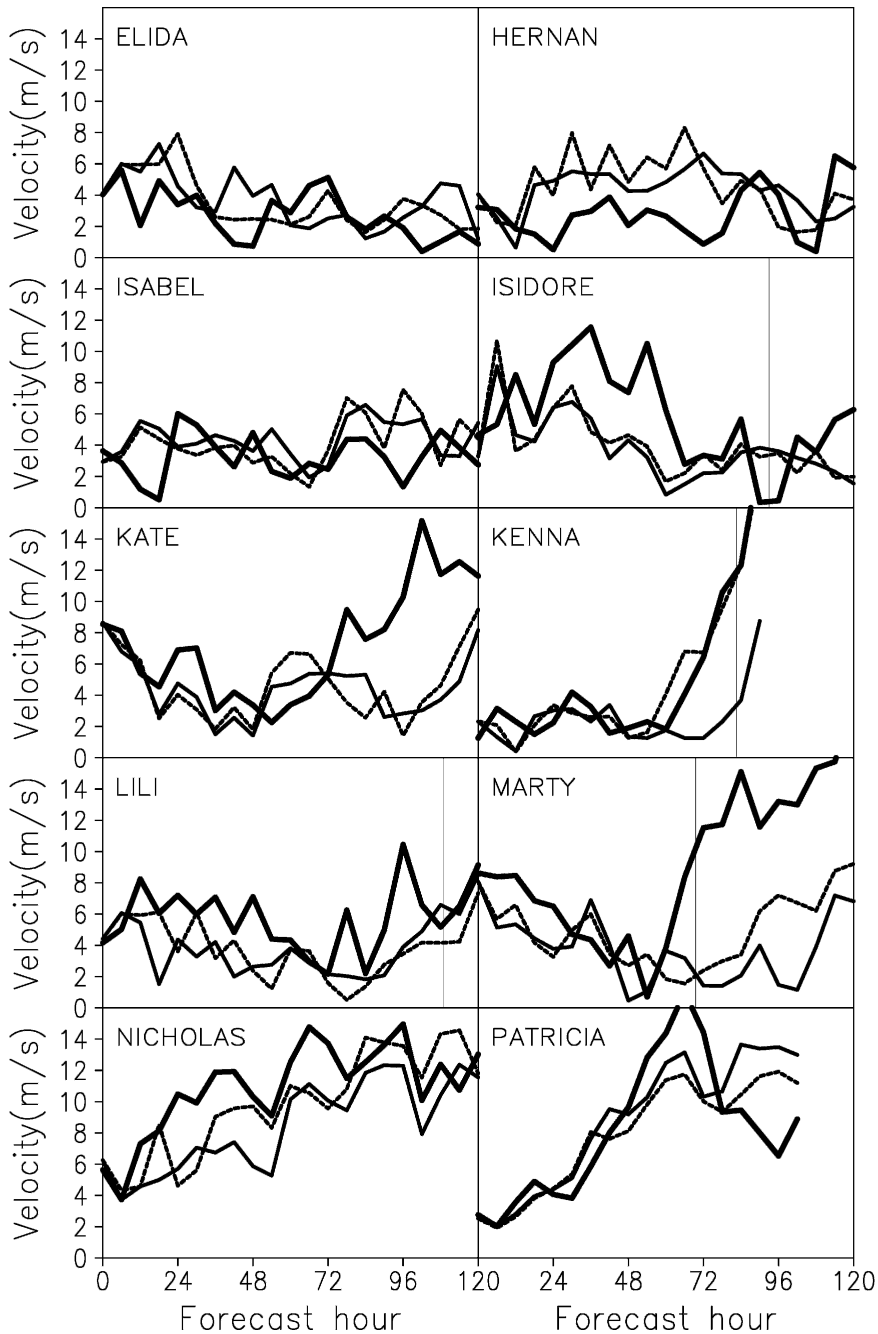

FIG. 6. Same as Fig. 4 but for 200–850-hPa mean wind shear averaged over 500-km radius along hurricane track: the thicker solid line represents observation, the thinner solid line RSM-CTL, and the dashed line RSM-PGF.

ing flow and intensity of a hurricane imbedded in the steering flow is important for improving the track forecast. The higher-resolution RSM run also appears to improve the track forecast compared to the lower-resolution GFS forecast. Although not shown in the figures, underprediction of intensity in forecasts from the control experiments tends to yield slower hurricane movements compared to the observed track, and the new PGF parameterization tends to reduce both along-track and cross-track biases by improving intensity forecasts except for the observed cases that show complex, stagnant track behavior. However, more experiments would be needed to have more confidence in the results from the track forecast statistics.

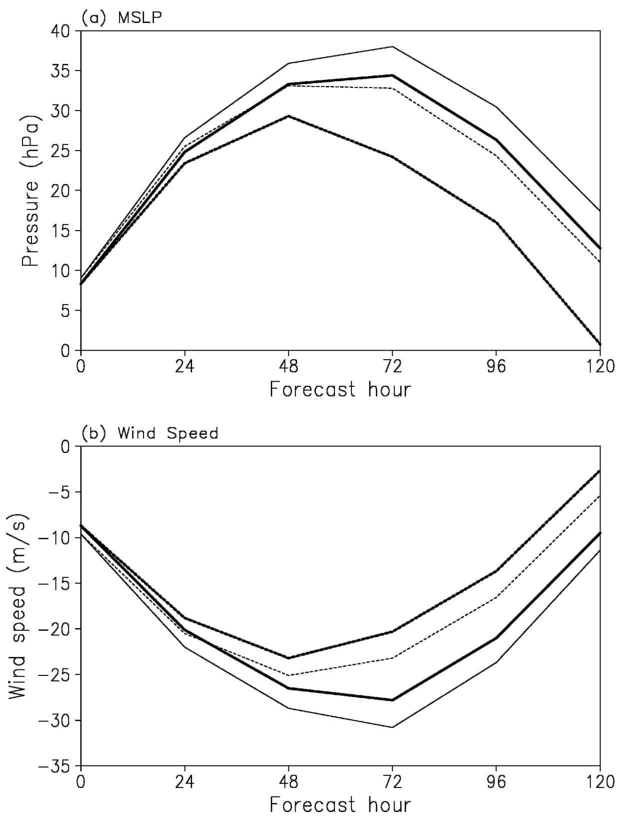

FIG. 7. Time evolution of the mean differences of (a) minimum central MSLP and (b) maximum surface wind speed between model forecasts and observations for the 10 cases of hurricanes: thin solid and dashed lines represent GFS-CTL and GFS-PGF, respectively, and thick solid and dashed lines RSM-CTL and RSM-PGF, respectively.

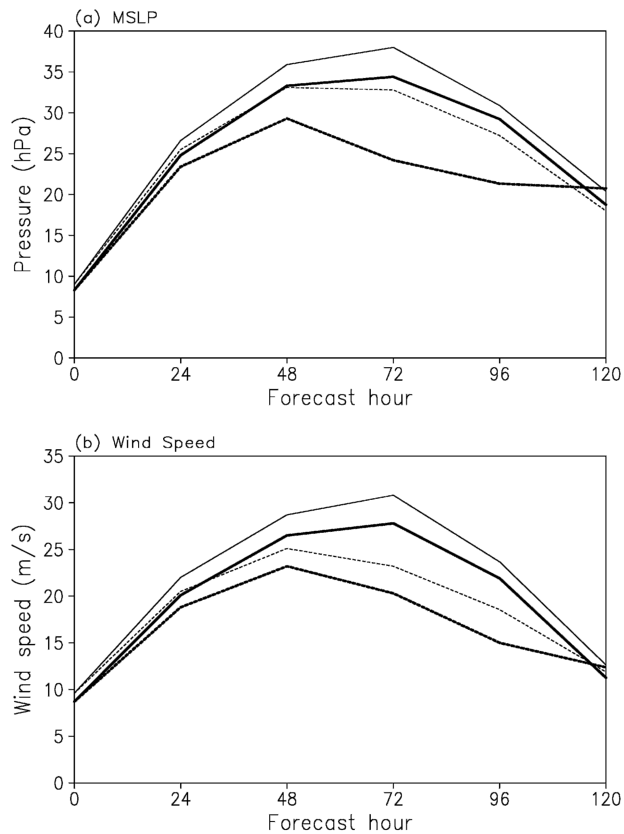

FIG. 8. Same as Fig. 7 but for the mean absolute differences.

4. Summary and conclusions

While the importance of convective momentum transport has been recognized, progress in incorporating it into numerical weather models has been slow. Recently, the National Centers for Environmental Prediction's (NCEP) operational global forecast system (GFS) and its nested Regional Spectral Model (RSM) have included convective momentum transport (CMT) in their simplified Arakawa–Shubert (SAS) cumulus scheme by allowing mass fluxes induced in the updraft and downdraft to transport momentum as well as heat and moisture. The convection-induced pressure gradient force (PGF) has been taken into account, somewhat empirically, by increasing the entrainment of momentum in the updraft, implying enhanced mixing between the cloud and environment. An evaluation has indicated that while inclusion of the CMT helps suppress spurious hurricane development, it produces a weaker hurricane compared to observations even in the higher-resolution RSM forecast, implying that there is too much vertical mixing in the environmental flows. In addition, the simple empirical parameterization of the convection-induced PGF had a negligible effect on the hurricane intensity forecast.

In this study, we have investigated the sensitivity of hurricane intensity forecast to the parameterization of

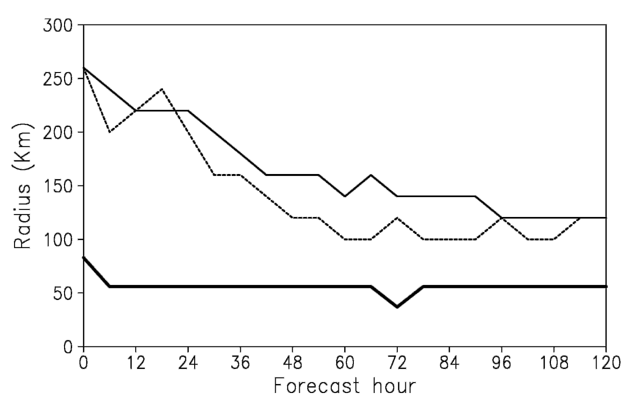

FIG. 9. Time evolution of the radius of maximum surface wind speed from observation and model forecasts for Hurricane Hernan: thick solid line represents observation and thin solid and dashed lines RSM-CTL and RSM-PGF, respectively.

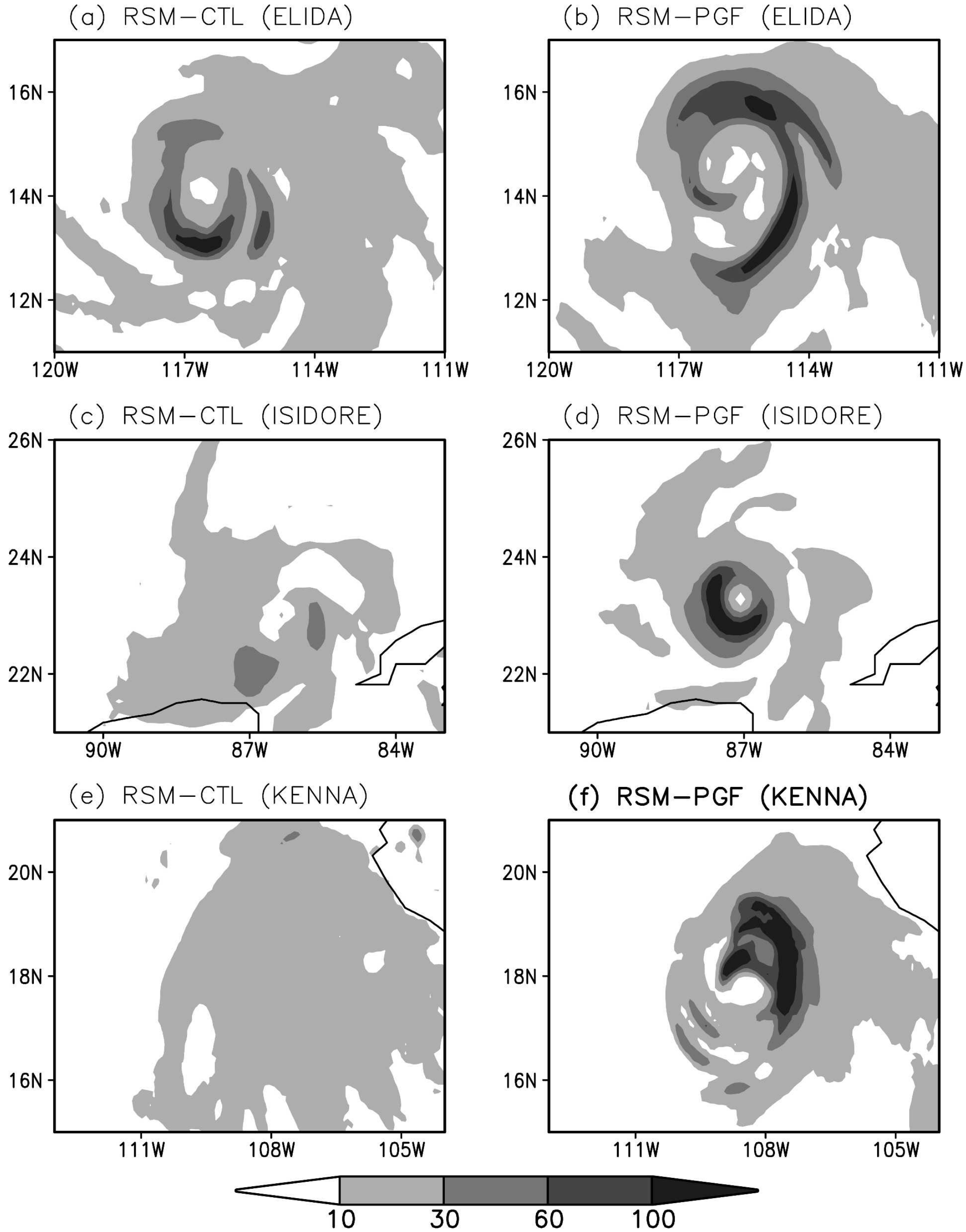

FIG. 10. Six-hour accumulated precipitation (mm) at 72 RSM forecast hours for Hurricanes (a),(b) Elida, (c),(d) Isidore, and (e),(f) Kenna: (left) RSM − CTL, and (right) RSM − PGF.

the convection-induced PGF with a more theoretical basis proposed by Wu and Yanai (1994) and Gregory et al. (1997), which assumes that the PGF is proportional to the product of the cloud mass flux and vertical wind shear. Compared to control forecasts using the present operational GFS and RSM where the PGF effect in CMT is taken into account empirically, the new PGF parameterization helps increase hurricane intensity by reducing the vertical momentum exchange, giving rise to a closer comparison to the observations. Finer-resolution forecasts with the RSM also yield a better intensity forecast than the lower-resolution GFS forecast, although the improvement is less than with the new PGF parameterization. In addition to the improve-

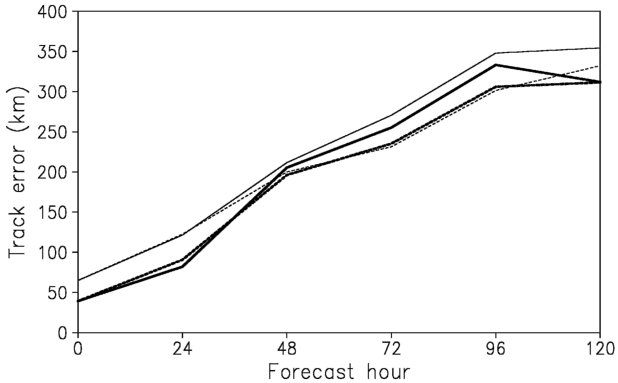

FIG. 11. Same as Fig. 7 but for hurricane track forecast error.

ment in intensity forecasts, the forecasts with the new PGF parameterization not only show more realistically organized precipitation patterns but also reduce the track forecast error. The forecasts with both the new PGF parameterization and higher resolution give rise to the best performance.

Nevertheless, model forecasts still largely underpredict the observed intensity even with the new PGF parameterization. In addition, the intensity changes in the model forecasts are slower, giving rise to a delay in the time when intensity reaches its maximum. The absence of a hurricane initialization process may be one of reasons for the slower and weaker intensification in the model forecasts. Many other contributors to model's underprediction of the observed intensity warrant further study.

The CMT parameterization with the convection-induced PGF effect studied in this paper will be tested in the next-generation Hurricane Weather Research and Forecasting (WRF) model for possible implementation, which will use the GFS SAS cumulus scheme and is being developed at NCEP. The present study will be applicable not only to a hurricane model but also global climate or mesoscale weather models that need a parameterization for subgrid-scale cumulus convection.

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