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SENSITIVITY OF TROPICAL CYCLONE TRACK FORECASTS TO CONVECTIVE MOMENTUM TRANSPORT IN THE NOGAPS EMANUEL CUMULUS PARAMETERIZATION

Timothy F. Hogan
Naval Research Laboratory
Monterey, CA 93943

Randal L. Pauley
Fleet Numerical Meteorology and Oceanography Center
Monterey, CA 93943

1. INTRODUCTION

The Navy Operational Global Atmospheric Prediction System (NOGAPS) is the U. S. Department of Defense (DoD) high-resolution (T239L30) global weather prediction system. Its development and operation is a joint activity of the Naval Research Laboratory (NRL) and the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC). NOGAPS forecasts provide high-resolution six-day forecasts every six hours and a daily-extended ten-day guidance using the FNMOC ensemble (T119L30), to numerous defense and civilian users. NOGAPS products are used as boundary conditions and forcing for a large number of DoD environmental and application systems. Prominent among these applications are the U.S. Navy's Coupled Ocean-Atmosphere Mesoscale Prediction System and the FNMOC version of NOAA's Geophysical Fluid Dynamics Lab tropical cyclone model, which is called GFDN. The tropical forecasts are used as guidance by both the DoD Joint Typhoon Warning Center and the NOAA National Hurricane Center and are part of the Florida State University super-ensemble (Kumar et al. 2003**)** and the consensus ensemble (Goerss 2000). NOGAPS is also used as the principal tool in the U.S. Navy's extensive global numerical weather prediction (NWP) research programs.

The introduction of the Emanuel cumulus convective scheme (Emanuel 1991 and Emanuel and Zivkovic-Rothman 1999) in May 2000 marked a significant improvement in the tropical cyclone (TC) track performance of NOGAPS. Subsequent additions to the parameterization scheme have further improved both the TC performance and the mid-latitude skill of NOGAPS (Peng et al. 2004). One of the key features of the Emanuel cumulus scheme is the treatment of momentum mixing by the convection through a sophisticated algorithm for convective momentum transport (CMT).

The purpose of this paper is to demonstrate through data assimilation tests the influence of the current CMT algorithm in NOGAPS and contrast the results with those using no CMT algorithm and with the results of an alternative algorithm proposed by Robe and Emanuel (2001). It will be shown that without a CMT algorithm the 72-120 h TC track performance of NOGAPS is degraded. The results using the CMT algorithm in Robe and Emanuel (2001) are nearly equivalent to the current scheme but show a slightly higher TC track error at 120 hours.

Section 2 provides a brief description of the CMT formulation in the current NOGAPS Emanuel cumulus parameterization and the CMT calculation of Robe and Emanuel (2001). Section 3 consists of a brief description of the data assimilation/medium range tests, which were conducted for the period August – September 2004. In Section 4 we present the TC track results of the three forecast tests: (1) with the current CMT algorithm, (2) with no CMT, and (3) with the CMT algorithm in Robe and Emanuel (2001). We end in Section 5 with a brief summary and a mention of the current operational NOGAPS CMT.

2. CMT ALGORITHMS

In parameterizations of CMT (Gregory et al. 1997) the change in the momentum of the mean flow $\bar{u}$ due to convective transport can be written as the derivative of a convective momentum flux as

$$\left(\frac{\partial \bar{u}}{\partial t}\right) = -g\,\frac{\partial F_u}{\partial p}\,, \qquad (1)$$

where the flux is given by the product of the cumulus mass flux and the difference of the in-cloud velocity and the mean flow:

$$F_u = M\,(u_c - \bar{u})\,. \qquad (2)$$

Typically the fluxes are computed separately for the convective updrafts and downdrafts. In the Emanuel cumulus parameterization the total updraft is the sum of the undiluted cloud-base mass flux and all upward buoyancy-sorting fluxes ending at level $i-1$ or lower:

$$M_i^u = \sum_{j=i}^{INB} \delta M_j + \sum_{j=1}^{i-1} \sum_{k=i}^{INB} MENT_{jk}\,, \qquad (3)$$

and the total downdraft is the sum of the mass flux of the unsaturated downdrafts and all downward buoyancy-sorting fluxes detraining at levels $i-1$ or lower:

$$M_i^d = M_i^p - \sum_{j=i}^{INB}\sum_{k=1}^{i-1} MENT_{jk} \,. \qquad (4)$$

The undiluted mass flux is given by Equation (1) in Peng et al. (2004), the unsaturated downdrafts is given by Equation (13) of Emanuel (1991) and the buoyancy sorting mass fluxes $MENT_{jk}$ are given by Equation (7) of Emanuel (1991).

In the Emanuel and Zivkovic-Rothman (1999) scheme the computation of cloud velocities is performed in a manner similar to the computation of the mixing ratio, with an in-cloud updraft between levels i and j

$$u_{ij}^{ent} = \sigma_{ij}\overline{u_i} + (1-\sigma_{ij})\overline{u}_K \,, \qquad (5)$$

where K is the level of maximum moist static energy in the lower atmosphere where σ_{ij} is the mixing fraction of the environmental air, given by Equation (6) in Emanuel (1991).

The downdraft zonal wind u_i^d is computed from a conservation equation similar to the mixing ratios:

$$M_i^d \left(\frac{\partial u^d}{\partial p}\right)_i = \begin{cases} (\overline{u_i} - u_i^d)\left(\dfrac{\partial M^d}{\partial p}\right)_i, & \left(\dfrac{\partial M^d}{\partial p}\right)_i > 0 \\ 0, & \left(\dfrac{\partial M^d}{\partial p}\right)_i \le 0 \end{cases} \qquad (6)$$

The numerical integration starts from the top of the convection and integrates downward.

In Robe and Emanuel (2001) the upward and downward cloud velocities are computed from a aerodynamic drag law of the form

$$gM\frac{\partial u_c}{\partial p} = -\lambda(u_c - \overline{u})\left|u_c - \overline{u}\right| \qquad (7)$$

with $\lambda = 4.0\times10^{-6}m^{-1}$. Equations (3) and (4) are used separately for the upward and downward velocities.

The TC track results for these two different methods of computing the cloud velocities are examined in Section 4 and compared with results that had no CMT.

3. DATA ASSIMILATION AND MEDIUM RANGE FORECAST TEST DESCRIPTION

The data assimilation and medium range forecast tests were conducted with the operational version of the NOGAPS, except for the different CMT algorithms tested. The resolution was the operational 239 triangular wave truncation with 30 levels. The period was the two summer months of August – September 2004.

The data assimilation component is the Navy Atmospheric Variational Data Assimilation System (NAVDAS) (Daley and Barker 2001). Through a variational principle NAVDAS combines the six-hour forecast of NOGAPS with data to create increments (changes) to the six-hour forecast. The assimilation data includes radiosondes, pibals, dropsondes, buoy and ship winds, surface pressures, SSMI windspeed and precipitable water, aircraft winds and temperatures, scatterometer winds, satellite feature-track winds, AMSU-A radiances (Baker and Campbell 2005), and synthetic wind soundings generated around a tropical cyclone warning position (Goerss and Jeffries 1994). Following the NAVDAS analysis, a normal mode initialization is performed on the analysis increments and these increments are then interpolated to the NOGAPS Gaussian grid to produce the initial fields. The sea surface temperature and ice fields are obtained from the FNMOC sea surface temperature and ice analysis (Cummings 2005). The snowfields are obtained from the United States Air Force (USAF) as part of the USAF's operational World Wide Merged Cloud Analysis.

The data assimilation and medium-range forecast tests conducted in this study were run in a mode nearly identical to the operational data assimilation run in that a six-hour assimilation cycle was performed at 00 UTC, 06 UTC, 12 UTC, and 18 UTC comprising wind synthetic sounding about a warned tropical cyclone, three-dimensional variational wind, temperature, and moisture analysis of conventional and satellite data, sea-surface temperature and sea-ice concentrations from U.S. Navy analyses, and snow amounts from the U.S. Air Force analysis. The data window is ±3 hours about the analysis time. However, unlike operations, where six-day forecasts are run every six hours, five-day (120 h) forecasts were run twice a day from the 00 UTC and 12 UTC initial (analysis) conditions.

4. TC TRACK RESULTS AND DISCUSSION

The period for the data assimilation and medium-range forecast testing in this study is 1 August 2004 – 30 September 2004. This was a period of high TC activity with a total of 35 tropical cyclones that were warned in the various basins of the Atlantic, Eastern Pacific, Western Pacific, and Indian Ocean. Each test consisted of data assimilation runs (short term forecasts) performed at 00 UTC, 06 UTC, 12 UTC, and 18 UTC and 120-hour forecasts performed from the 00 UTC and 12 UTC analysis fields. Throughout this paper these three tests will be designated as: EZR1999 for the CMT formulation described above in Equations (1) - (6), RE2001 for the CMT in described in by Equation (1), (2), and (7), (Robe and Emanuel 2001), and NOCMT for no computation of CMT. All the tests started from the NOGAPS operational analysis of 20 July 2004, which allowed a spin-up period of 11 days. All the tests were conducted at the current operational resolution of T239L30.

Fig. 1 is a comparison the TC track errors, using the sea-level pressure tracker described, for the three CMT experiments. The number of forecast tracks that were used as verification at each forecast time is listed below the forecast hour on the bar chart. In the medium range (72-120 h) the TC tracks for the EZR1999 and the RE2001 runs show considerable improvement over the NOCMT results. For the 0 – 96 h forecasts the average TC track results of EZR1999 and RE2001 are nearly the same, but there is a slight advantage of the EZR1991 results for the 120 h forecasts.

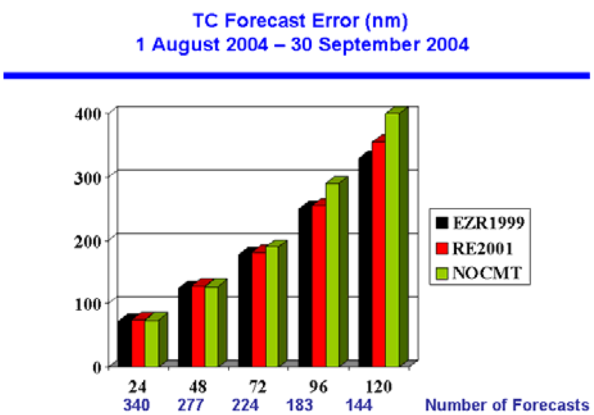

FIG. 1. A bar chart showing the comparison of the TC tracks errors in nautical mile for the three different CMT experiments. The number of forecast tracks, which were used as verification at each forecast time, is listed below the forecast hour.

Large TC track errors are often associated with poorly timed recurvature. Many of the tracks from the NOCMT experiment had a tendency to recurve too early. An example of this is shown in Fig. 2a for the forecast tracks for Chaba (19 W), where the early forecasts showed the storm erroneously recurving. Both the results from the test EZR1999 (Fig 2b) and RE2001 (Fig 2c) are considerably better, even though there is still a tendency for both of these results to be right of the warning track in the early forecasts.

An interesting feature of the results of the NOGAPS CMT experiments is that TC forecasts with a CMT algorithm had on average a tendency to have a forecasted central pressure less than the analysis, while the NOCMT forecasted deeper central pressures (Fig. 5). The central pressure forecasts for Chaba, whose tracks are shown in Figs. 2a – 2c, are a good example of this, with the EZR1991 and RE2001 average central pressures under forecast (too high) relative to the NOGAPS analysis by 5 hPa while the 120-hr forecasts for NOCMT were over-forecast (too deep) by 2 hPa. It is not suggested here that NOGAPS can accurately resolve the deep surface pressure wells (NOGAPS analysis values of central pressures for tropical cyclones typically run between 1000 hPa and 990 hPa, but can be as deep as 970 hPa for larger storms) or the maximum wind speeds of intense tropical cyclones. It appears that with the present horizontal resolution, the TC track forecasts of NOGAPS will be less skillful if it tries too strongly to resolve mesoscale features best left to higher resolution models. It should be noted that while there were minor differences in the analyzed central TC pressures for the different experiments, overall the values were all within 1 hPa of each other.

5. SUMMARY

This study presented TC track results from data assimilation/medium range forecast test for two different formulations of CMT in the Emanuel cumulus convective scheme with results obtained from a test with no CMT algorithm. The results show that the inclusion of either CMT algorithm dramatically improves the TC track for NOGAPS. Without a CMT formulation the NOGAPS also tends to forecast deeper tropical cyclones than that initialized by the analysis. As a final note the current NOGAPS uses a slight variation of the EZR 1999 CMT algorithm. The Emanuel cumulus parameterization contains a tunable parameter to control the amount of CMT tendency applied to the wind fields. Through extensive testing it has been determined that setting this parameter so that 75% of the “full CMT” is applied leads to the same TC track performance, but better Northern Hemisphere height anomaly corrections and smaller root mean square height errors.

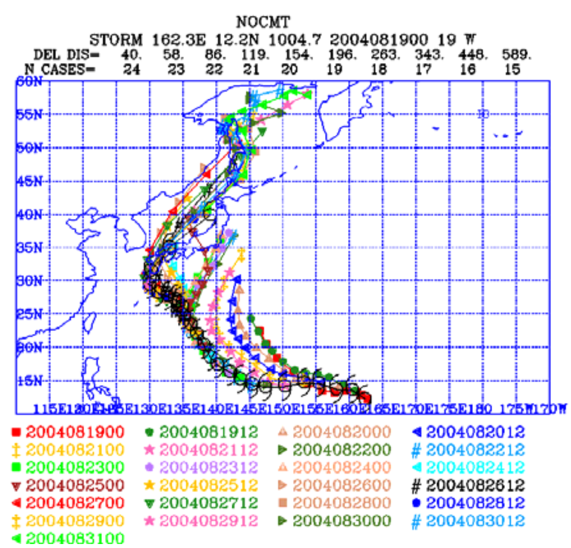

Fig 2a. The TC track forecast for the Western Pacific tropical storm Chaba (19 W) for the test NOCMT. The hurricane symbol marks the warning position and each colored symbol marks out the 120-h forecast track at each 12-h interval. The

headings above the figure indicate the number of forecasts at each 12-h interval (N CASES) and the mean track error in nautical miles (DEL DIS).

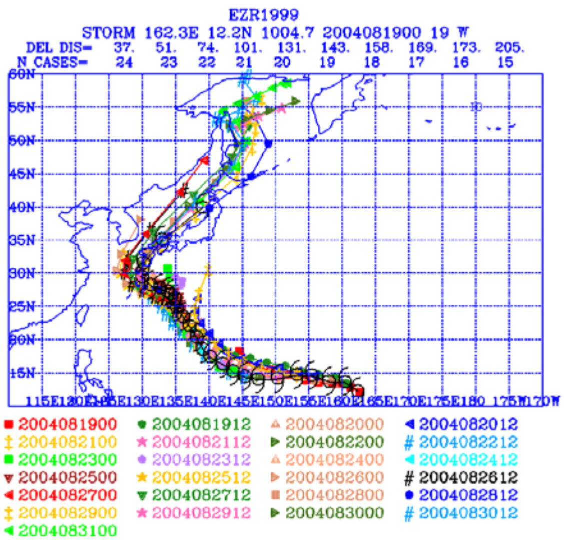

Fig 2b. The TC track forecast for the Western Pacific tropical storm Chaba (19 W) for the test EZR1999.

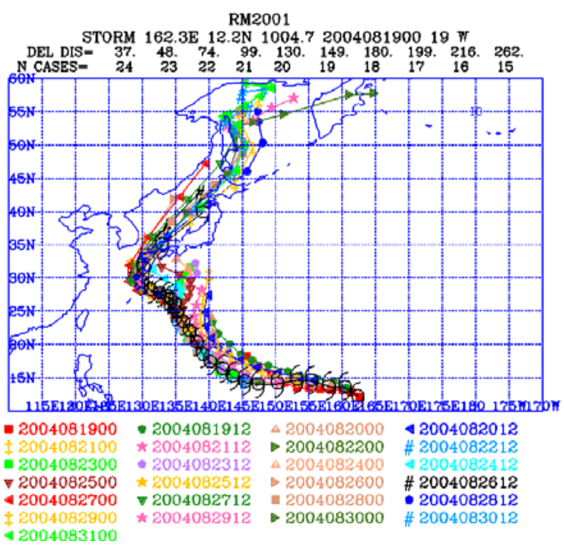

Fig 2c. The TC track forecast for the Western Pacific tropical storm Chaba (19 W) for the test RE2001.

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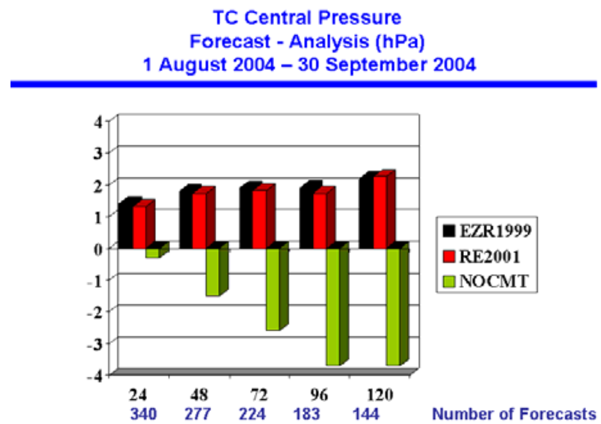

FIG. 5. A bar chart showing the comparison of the difference in the NOGAPS forecast minus analysis TC central pressure in hPa for the three different CMT experiments. The number of forecast tracks is listed below the forecast hour.

REFERENCES

Cummings, J. A., 2005: Operational multivariate ocean data assimilation. *Q.J.R.M.S.* In press.

Daley, R., and E. Barker, 2001: NAVDAS Source Book 2001: The NRL Atmospheric Variational Data Assimilation System. NRL Publication. Available from NRL, Atmospheric Dynamics and Prediction Branch, Marine Meteorology Division, Monterey CA 93943-5502, 160 pp.

Emanuel, K. A., and M. Zivkovic-Rothman, 1999: Development and evaluation of a convection scheme for use in climate models. *J. Atmos. Sci.*, **56**, 1766-1782.

Goerss, J., 2000: Tropical cyclone track forecasts using an ensemble of dynamical models. *Mon. Wea. Rev.,* **128,** 1187–1193.

Gregory, D., R. Kershaw, and P. M. Inness, 1997: Parameterization of momentum transport by convection: II Tests in single-column and general circulation models. *Q.J.R.M.S.,* **123**, 1153-1183.

Kumar, T. S. V. V., T. N. Krishnamurti, M. Michael Fiorino, and M. Nagata, 2003: Multimodel Superensemble Forecasting of Tropical Cyclones in the Pacific. *Mon. Wea. Rev.,* **131**, 574–583.

Peng M.S., J.A. Ridout, and T.F. Hogan, 2004**:** Recent modifications of the Emanuel convective scheme in the Navy Operational Global Atmosphere Prediction System. *Mon. Wea. Rev.,* **132**, 1254-1268.

Robe, F.R, and K. A. Emanuel, 2001: The effect of vertical wind shear on radiative-convective equilibrium states. *J. Atmos. Sci.***,** **58**, 1427-1445