J14.1 THE NAVY OPERATIONAL GLOBAL ATMOSPHERIC PREDICTION SYATEM: CURRENT STATUS AND TESTING OF CONVECTIVE MOMEMTUM TRANSPORT IN THE EMANUEL CUMULUS PARAMETERIZATION

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ABSTRACT

The Navy Operational Global Atmospheric Prediction System (NOGAPS) is the U. S. Department of Defense's high-resolution global weather prediction system, which is used for operational medium range weather prediction, forcing for operational mesoscale and oceanographic models, and numerical weather prediction research. Recent changes to the forecast model component of the system include an increase in horizontal resolution to a triangular truncation of 239 waves, an increase in vertical resolution to 30 levels, a new cloud scheme, and modifications to the Emanuel cumulus parameterization, which increase parcel buoyancy, include effects of ice, and increase the convective momentum transport. Data assimilation results will be presented which document the increase in forecast skill of the various changes, especially in the tropics. In particular, results will be presented that demonstrate that the increase in convective momentum transport resulted in (1) improved tropical lower level winds, (2) improved tropical cyclone track forecasts, (3) reduction in the number of false alarms for tropical cyclones, and (4) a reduction in the central pressure deficits for tropical cyclones.

1. INTRODUCTION

The purpose of this paper is to give a brief account of the current status of the Navy Operational Global Atmospheric Prediction System (NOGAPS). NOGAPS is the U. S. Department of Defense's (DoD) high-resolution global weather prediction system. Its development and operation is a joint activity of the Naval Research Laboratory (NRL) and the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC). NOGAPS forecasts provide high-resolution six-day forecasts every 6 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 Navy's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS™), FNMOC's ocean wave model, sea ice model, ocean thermodynamics model, tropical cyclone model, and aircraft and ship-routing programs. In addition to serving as the backbone of the Navy's end-to-end weather prediction ability, NOGAPS is a backup global system for the National Weather Service. NOGAPS is also used as the principal tool in the Navy's extensive global numerical weather prediction (NWP) research programs.

Since May 2000 several significant upgrades have been implemented in NOGAPS. These include:

(1) The introduction of the Emanuel cumulus convective scheme (Emanuel and Zivkovic-Rothman, 1999) in May 2000,
(2) A new boundary layer cloud scheme (Teixeira and Hogan, 2002) in December 2000,
(3) New mass flux scheme for the Emanuel cumulus parameterization and corrected specific heat of ice/water (Peng, et al., 2004) in June 2002,

(4) An increase in horizontal resolution from T159 (horizontal resolution of 0.75^o) to T239 (horizontal resolution of 0.5^o) and an increase in vertical resolution from 24 levels to 30 levels in September 2002,
(5) Increased convective momentum transport in the Emanuel convective scheme (Hogan, 2003) in December 2002,
(6) Conversion of the executable from 64-bit precision to 32-bit precision in June 2003,
(7) Replacement of the multi-variant optimum interpolation analysis (MVOI) of heights and winds and the Cressman analysis of moisture with the three-dimensional variational analysis of temperature, winds, and moisture (Daley and Barker, 2001) in October 2003,
(8) A new gravity wave drag parameterization (Webster et al., 2003) in November 2003,
(9) Enhanced cloud top mixing of temperature, winds, and moisture due to longwave cooling off cloud tops (, Hogan and Teixeira 2003) in November 2003, and
(10) Replacement of the silhouette orography with mean orography (Hogan and Teixeira, 2003 and Kim and Hogan 2004) in November 2003.

The current configuration of NOGAPS is given in Table 1.

NOGAPS 2004

Horizontal resolution: spectral T239 (720 x 360 grid),
Vertical resolution: 30 vertical levels,
Model top: 1 mb.
Three-dimensional variational analysis of temperature, winds, and moisture
Normal mode initialization of analysis increments,
Time differencing: Central time differencing with Robert filtering,
32-bit precision calculation,
Mean orography,
Gravity wave drag: Webster et al. (2003),
Vertical mixing: Louis (1979),
Surface flux: Louis (1979),
Enhanced cloud top mixing Hogan and Teixeira (2003),
Emanuel cumulus convection : Emanuel et. al (1999), Peng. et al. (2004),
Solar and Longwave radiation: Harshvardhan et al. (1987),
Cloud scheme: Teixeira's and Hogan (2002),
Large-scale precipitation,
Bucket hydrology,
Fully implicit skin temperature calculation.

Table 1. Summary of NOGAPS configuration

Taken together, these changes have resulted in improvements in the medium range forecast ability of the U. S. Navy. Figures 1 - 4 are, respectively, the annual means of the Northern Hemisphere (NH) 500 mb height anomaly correlation, the annual means of the Southern Hemisphere (SH) 500 mb height anomaly correlation, the annual means of the NH 1000 mb height anomaly correlation, and the SH 1000 mb height anomaly correlation for the years 1998 - 2003, with 2003 representing the year up through October 2003. Figure 5 is the tropical cyclone (TC) track error in nautical miles for the years 1998 – 2003. While there is some spread in the results it is believed that the results for 2000 – 2003 represent a general trend of increasing skill in NOGAPS over the previous years. Also, while the conversion of the forecast model from one performing 64-bit calculations to one performing 32-bit calculations resulted in no noticeable changes in the results, the efficiency of the forecast model was increased by 35%.

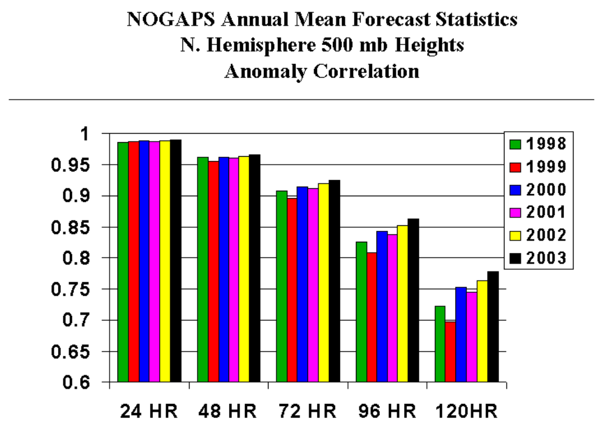

FIG. 1. The annual mean Northern Hemisphere 500 mb anomaly correlation for the years 1998 - 2003, with 2003 representing the year up through October 2003

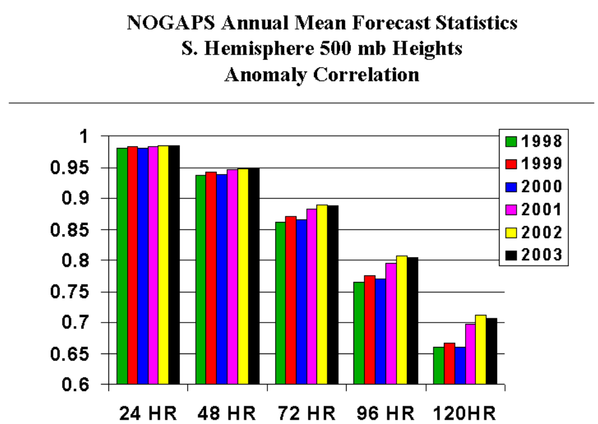

FIG. 2. The annual mean Southern Hemisphere 500 mb anomaly correlation for the years 1998 - 2003, with 2003 representing the year up through October 2003

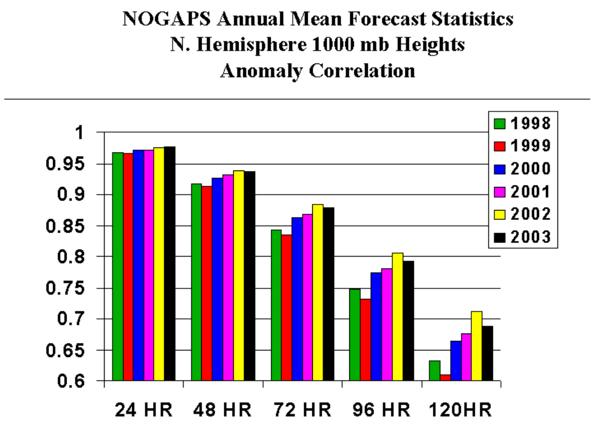

FIG. 3. The annual mean Northern Hemisphere 1000 mb anomaly correlation for the years 1998 - 2003, with 2003 representing the year up through October 2003.

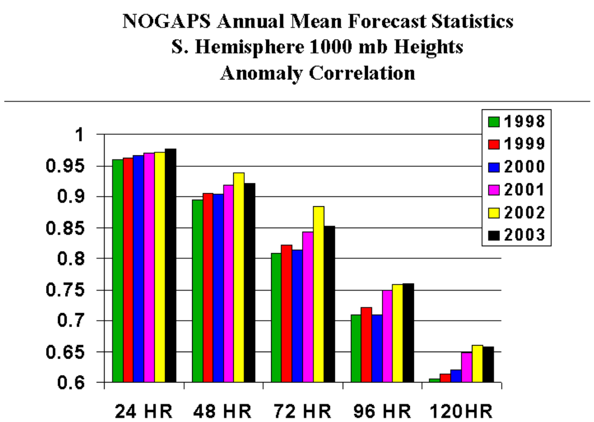

FIG. 4. The annual mean Southern Hemisphere 1000 mb anomaly correlation for the years 1998 - 2003, with 2003 representing the year up through October 2003.

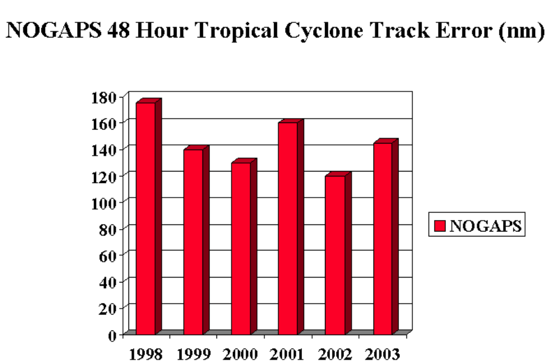

FIG. 5. The NOGAPS 48-hour mean tropical cyclone track error for the years 1998-2003, with 2003 representing the year up through October 2003.

The increase in skill in the Tropics is primarily due to the introduction of the Emanuel cumulus convective parameterization and its upgrades. Figure 6 shows the results of the data assimilation runs for the months of August and September 1999 conducted at T159L24 with the MVOI. The graph shows the 24, 48, 72, 96, and 120 hour forecast TC track error of the then operational NRL Relaxed Arakawa Scheme (RAS) versus the original Emanuel convective scheme. Figure 7 is a comparison of the mean TC track error using the Emanuel convective scheme with a new mass flux scheme and a corrected specific heat of ice/water (TEST_CON) and the May 2002 operational Emanuel cumulus parameterization scheme (CONTROL) for all tropical storms verifying in the month of September 2001.

The increase in horizontal and vertical resolution in September 2002 resulted in an increase in skill as measured by most (but not all) forecast statistics. Figure 8 is the NH 500-mb height AC vs. forecast hour of the T239L30 with the T159L24 for the month of September 2001. This result (a small positive impact) is typical of what was observed in the data assimilation experiments that were performed for a NH summer month (September 2001) and a NH winter month (January 2002).

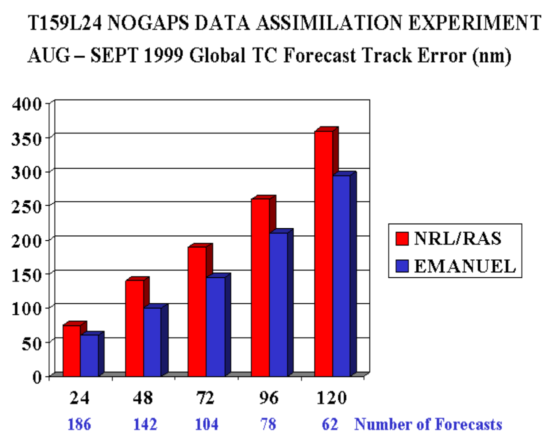

FIG. 6. The 24, 48, 72, 96, and 120 hour forecast TC track error of the NRL Relaxed Arakawa Scheme (RAS) versus the original Emanuel convective scheme.

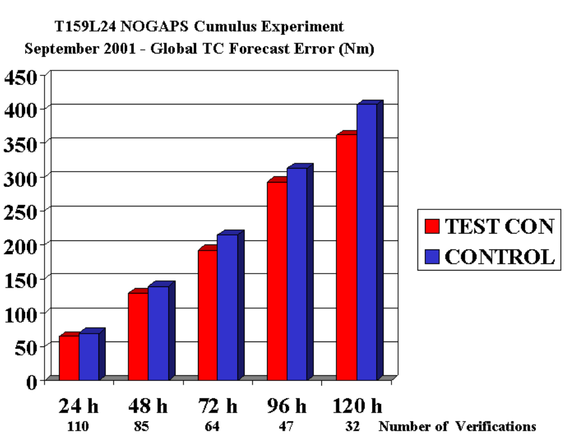

FIG. 7. A comparison of the mean tropical cyclone track error using the improved Emanuel convective scheme (TEST_CON) and the May 2002 operational convective scheme (CONTROL) for all tropical storms verifying in the month of September 2001.

2. THE CONVECTIVE MOMEMTUM TRANSPORT CHANGE

After the transition of the T239L30 to operations, two problems were noted with the operational forecasts, (1) an increase in the number of TC false alarms (i.e. the model spinning up storms that did not verify) and (2) a positive lower-level wind speed bias over the oceans. These tendencies were most evident in the Indian Ocean and Western Pacific. These observations led to an investigation of the causes and possible remedies of the over-forecasting in the Tropics. After testing several different mechanisms, it was found that increasing the momentum transport in the Emanuel convective parameterization (from the previous operational value of 30% of the maximum transport to 100%) reduced the false alarm rate, reduced the lower level tropical winds, and reduced the forecast central pressure deficit of tropical storms which tended to be too deep compared to the global MVOI analysis.

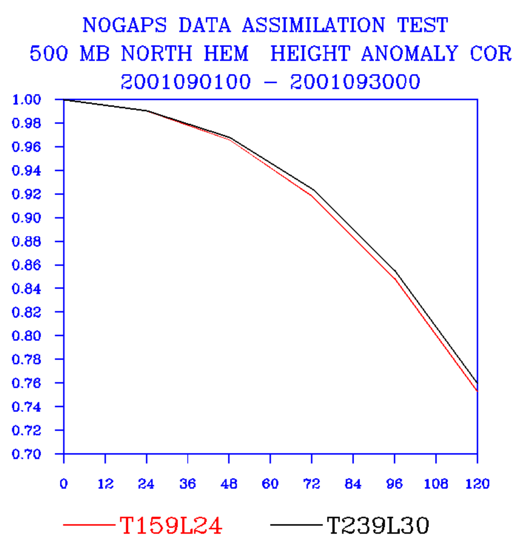

FIG. 8. The Northern Hemisphere's 500-mb height AC vs. forecast hour for the month of September 2001. The T159L24 is the operational model (August 2002) and T239L30 is the higher horizontal and vertical resolution version.

The Emanuel convective parameterization scheme includes the convective momentum transport (CMT) by convective systems. The formulation is based on the work of Gregory et al. (1997) with the tendency given by

$$\frac{\partial \overline{V}}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[(1-C_u)M_c(V_c-\overline{V})\right] \qquad (1)$$

where M_c is the cloud mass flux, $\overline{V}$ is mean/environmental horizontal wind vector, V_c is the cloud horizontal wind, and C_u is an empirical constant. The constant C_u was set at 0.7, which was based on tests using the TOGA-COARE data by Emanuel and Zivkovic-Rothman (1999). As is evident the value of C_u at 0.7 means that the CMT is reduced to 30% of its "full potential value". It is probably true that a value of C_u greater than 0 is appropriate since the internal cloud pressure gradient would modulate the convective momentum transport, however our comparisons will be with C_u=0. Figs. 9 and 10 show the 120-hour averaged tendencies for all momentum terms in the Tropics for a forecast with initial conditions of September 1, 2002 with increased CMT (C_u=0) and with transport at 30% of the total. In the figures U-VFL is the turbulent mixing, U-CUM is the convective momentum transport tendency, U-GWD is the gravity wave drag tendency, U-ADIAB is the adiabatic tendency, and U-TOT is the total (sum) of all the tendencies. As seen from the figures the increased CMT brings down more easterly momentum, but this is countered by increased vertical turbulent mixing by the planetary boundary layer parameterization. The total impact of the increase in CMT is not readily apparent and it turns out that the net effect in NOGAPS is to reduce the lower level winds.

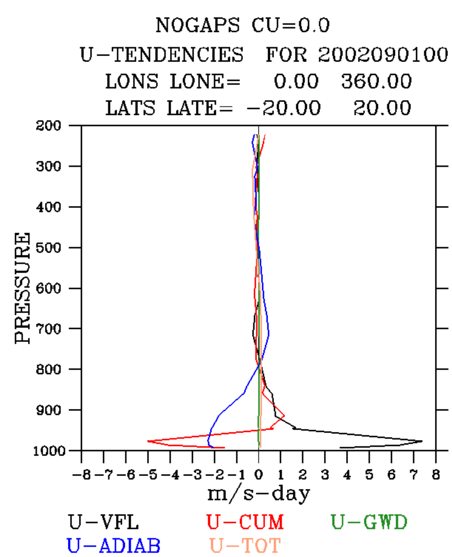

FIG. 9. The 120-hour average tendencies for the T159L30 forecast with initial conditions of September 1, 2002 for the u-component of the wind over the tropical band from 20S to 20N with the full convective momentum transport.

Fig. 9 shows the mean over the entire Tropical band, showing primarily the impact in the lower atmosphere. However, for cases of deep convection the momentum tendencies for CMT extend into the upper atmosphere. Fig. 11 shows the u-tendencies for the case of the genesis of TC Erika. The CMT has a large positive tendency in the upper troposphere, countering the adiabatic tendency to increase the upper easterly flow.

The impacts for weather prediction of increased CMT were assessed using standard data assimilation/medium-range-forecast intercomparison tests. The control version was the November 2002 operational NOGAPS (identified by CONTROL in the graphics) and the test version was NOGAPS (identified by FULL_MT) with the changes described above.

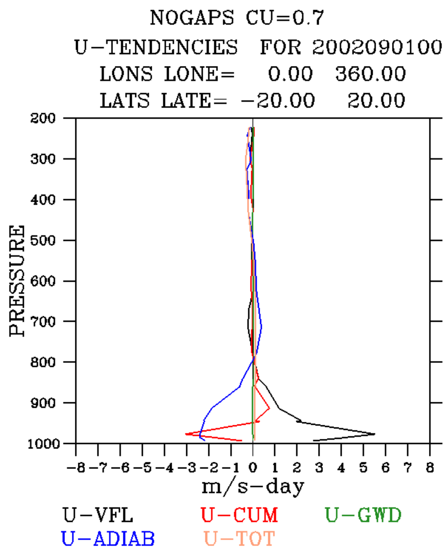

FIG. 10. The 120-hour average tendencies for the T159L30 forecast with initial conditions of September 1, 2002 for the u-component of the wind over the tropical band from 20S to 20N with partial (30%) convective momentum transport.

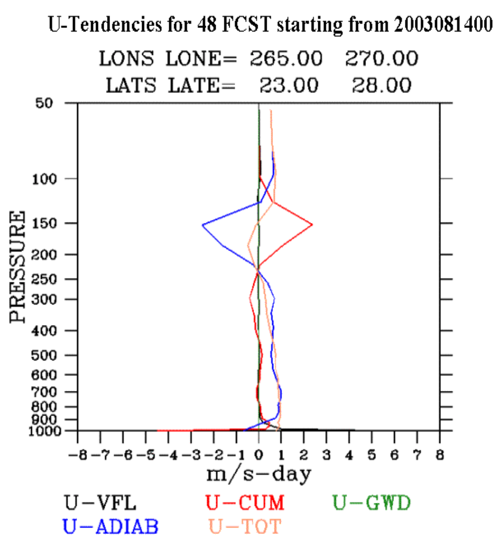

FIG. 11. The 48-hour average tendencies for the T239L30 forecast with initial conditions of September 14, 2003 for the u-component of the wind over the Gulf of Mexico area band from 20S to 20N with C_u =0.0.

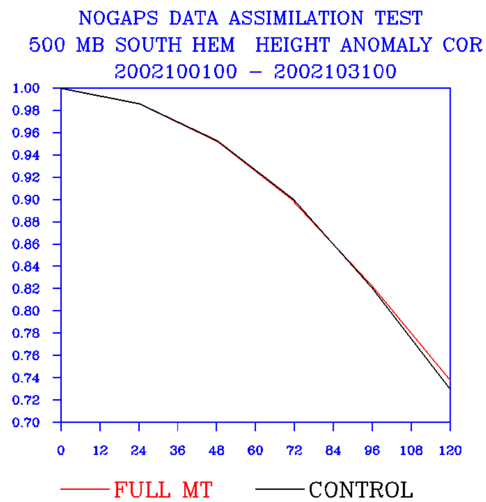

FIG. 12. The Southern Hemisphere's 500-mb height AC vs. forecast hour for the month of October 2002. FULL_MT is convection changes described in Section 2 and the CONTROL is the operational NOGAPS (May 2002). All results are for the T239L30 NOGAPS.

The 500-mb heights AC for the Southern Hemisphere (80S-20S) and Northern Hemisphere (20N- 80N) for the month of October 2002 are given in Fig. 12 and 13, respectively. The figures demonstrate a neutral impact of the changes in the Southern Hemisphere and Northern Hemisphere for the month. These neutral results were also seen for almost every mid-latitude field statistics from 1000-mb to 100-mb and in the statistical comparisons using radiosonde data only.

In the Tropics the wind and tropical cyclone track forecasts are deemed to be the two most critical forecast fields. Fig. 14 and Fig. 15 are the 850-mb and the 250-mb RMS vector wind error for the tropical region 20S to 20N. The key result is a reduction in the tropical wind error (as measured by the RMS) in the lower levels. This is a consistent result for both the T159L30 and the T239L30 tests. The tropical cyclone track errors are plotted in Fig. 16. It should be noted that the runs were extended into early November to include the tropical cyclone that began in late October and extended into early November 2002. Overall the

24 – 48 hour track errors are the same, but there is a reduction in the track error at the longer ranges (however only 8 forecasts verify at 120 hours so the results may not be significant). Similar improvements were also seen in the T159L30 run for September 2002.

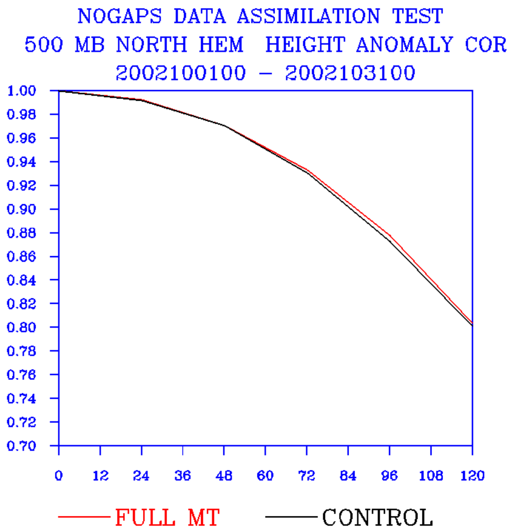

FIG. 13. The Northern Hemisphere's 500-hPa height AC vs. forecast hour for the month of October 2002.

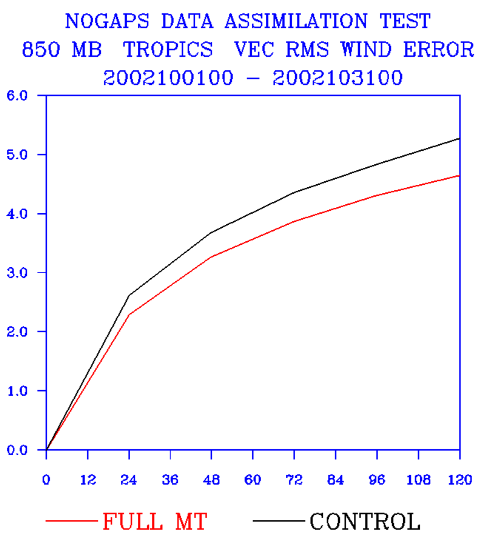

FIG. 14. The Tropics 850-mb vector wind RMS error (m s^{-1}) vs. forecast hour for the month of October 2002.

With the increased CMT the marine surface wind forecasts have a smaller mean speed error relative to the analysis. Fig. 17 and Fig. 18 show the mean 1000-mb wind speed errors over the Atlantic and Western Pacific Oceans, respectively. In both ocean basins NOGAPS has a positive wind speed bias, but this mean bias is reduced using the increased CMT. A comparison of the 10-meter winds at fixed buoys locations in the Northern Hemisphere shows a slight reduction in the wind speed (Fig. 19). The overall low wind speed bias at the buoy locations is partially due to the interpolation of the one-degree fields to the buoy location.

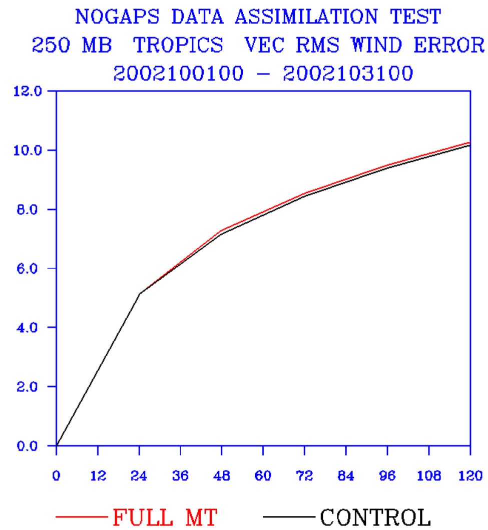

FIG. 15. The Tropics 250-mb vector wind RMS error (m s^{-1}) vs. forecast hour for the month of October 2002.

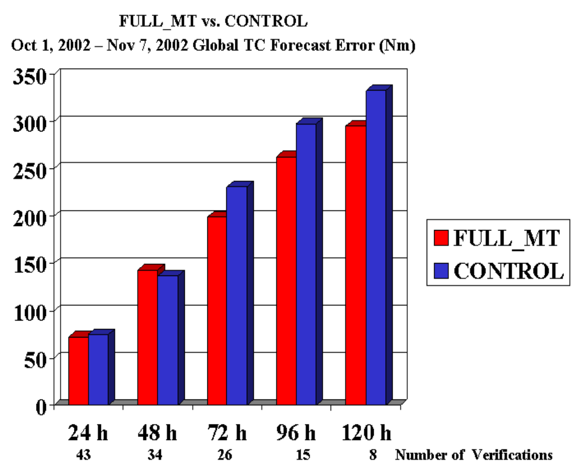

FIG. 16. A comparison of the mean tropical cyclone track error using the improved Emanuel convective scheme (FULL_MT) and the May 2002 operational convective scheme (CONTROL) for all tropical storms verifying in the month of September 2001.

An evaluation of forecast maps for the Indian and Western Pacific Ocean region indicated the tendency of the forecast model to spin up storms that did not verify was greatly reduced. In general, the over-forecast of the central pressure deficit of tropical cyclones (too deep by an average of 5 mb) was eliminated with the higher convective transport. These two results were particularly evident at the higher resolution of T239L30.

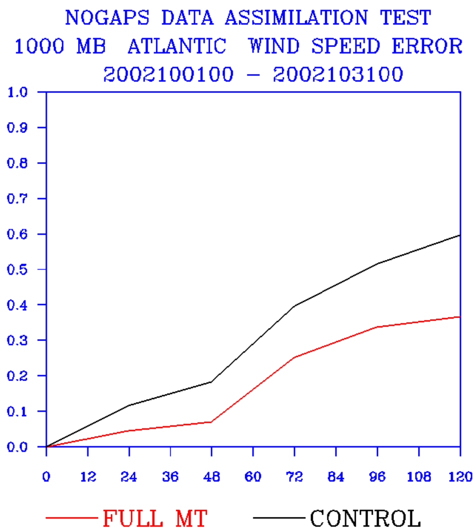

FIG. 17. The Northern Hemisphere's Atlantic mean 1000-mb wind speed error (m s^{-1}) vs. forecast hour for October 2002.

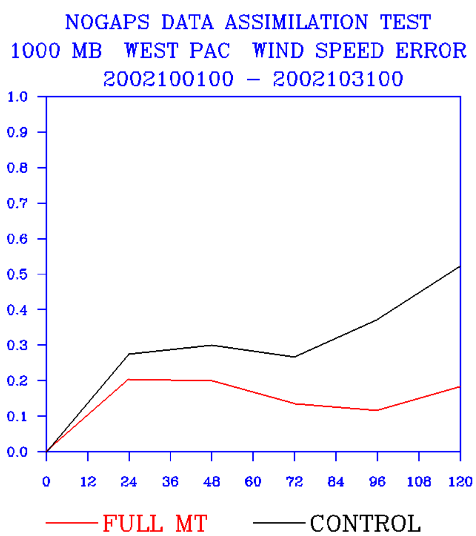

FIG. 18. The Northern Hemisphere's Western Pacific mean 1000-mb wind speed error (m s^{-1}) vs. forecast hour for the month of October 2002.

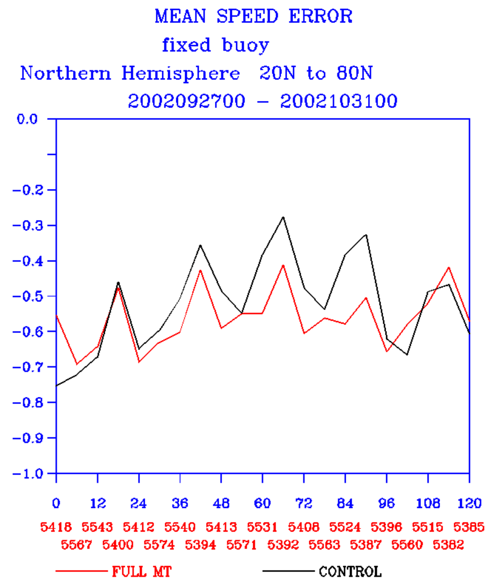

FIG. 19. The mean speed errors (m s^{-1}) for fixed buoys vs. forecast hour for the month of October 2002. The numbers indicate the number of reports for the month.

3. SUMMARY

Significant changes have been implemented in NOGAPS that have increased its forecast skill in both the Tropics and mid-latitudes. In particular, the introduction of increased convective momentum transport into the Emanuel convective parameterization (Emanuel and Zivkovic-Rothman 1999) shows a significant positive impact on the prediction of winds and tropical cyclone tracks in the Tropics. The overall effect is lower tropical wind speeds, which reduces the mean wind speed and the RMS error and reduces the false alarm rate of tropical cyclones in NOGAPS.

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