The Impact of Multispectral *GOES-8* Wind Information on Atlantic Tropical Cyclone Track Forecasts in 1995. Part II: NOGAPS Forecasts

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ABSTRACT

Experimental wind datasets were derived for two time periods (13–20 July and 24 August–10 September 1995) from *GOES-8* observations processed at the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW CIMSS). The first dataset was focused on Tropical Storm Chantal, and the second dataset was focused on the multiple-storm environment that included Hurricanes Humberto, Iris, and Luis. Both datasets feature a processing and quality control strategy designed to optimize the quantity and content of geostationary satellite-derived winds in the vicinity of tropical cyclones. Specifically, the winds were extracted from high-density targets obtained from multispectral imagery, which included three water vapor bands (6.7, 7.0, and 7.3 μm), infrared, and visible. The Navy Operational Global Atmospheric Prediction System (NOGAPS) was used as the vehicle to determine the impact of these winds upon tropical cyclone track forecasts. During the 1995 Atlantic hurricane season the NOGAPS forecasts were found to be quite skillful, displaying relative improvement of tropical cyclone position error with respect to CLIPER (climate and persistence) of 20% at 24 h, 35% at 48 h, and 33% at 72 h. The NOGAPS data assimilation system was run with and without the high-density *GOES-8* winds for the two aforementioned time periods. The assimilation of these winds resulted in significant improvements in the NOGAPS forecasts for Tropical Storm Chantal and Hurricane Iris and mixed results for Hurricanes Humberto and Luis. Overall, for all four cyclones, the NOGAPS forecasts made with the use of the UW CIMSS winds displayed relative improvement of forecast position error with respect to those made without the use of the UW CIMSS winds of 14% at 24 h, and 12% at both 48 and 72 h.

1. Introduction

The tropical ocean areas of the globe, in which tropical cyclones (TCs) form and spend the majority of their lifetime, are typically regions sparsely covered by conventional meteorological observations. Rawinsonde observations are taken on a relatively small number of islands scattered throughout the Tropics. The coverage provided by surface observations (land stations, fixed and drifting buoys, and ships) is considerably better but would still be considered sparse by midlatitude standards. Furthermore, for obvious reasons, ships try to steer clear of areas inhabited by active TCs. The lion's share of observational data for the tropical ocean areas is provided by satellite sensors. Temperature profiles (of limited use in the Tropics) and surface wind observations are produced at high spatial density from measurements taken by polar-orbiting satellites. Wind observations, primarily covering the lower and upper troposphere, are derived at moderate density from tracking clouds in sequential geostationary satellite imagery. To supplement the data available to their forecast models, most of the global forecast centers generate synthetic observations in the vicinity of TCs (Ueno 1989; Ueno and Ohnogi 1992; Lord 1991; Fiorino et al. 1993; Goerss and Jeffries 1994; Heming et al. 1995). These synthetic observations, for the most part, are used to describe the cyclonic low-level portions of the TC.

In this paper, we focus on the potential of a new source of data for the Tropics, namely, the high-density multispectral *GOES-8* winds described in Part I (Velden et al. 1998). While these winds can provide broad large-scale coverage of the TC environment, they especially complement the synthetic observations in the vicinity

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TABLE 1. Relationship between TC separation and the number of synthetic observations generated for each TC in a multiple-storm environment.

Separation (km)	Stronger TC	Weaker TC
1100–1320	13	9
880–1100	9	9
660–880	9	5
440–660	5	5
<440	5	0

of TCs since the majority of these winds are upper tropospheric (150–400 mb).

The extremely busy 1995 Atlantic hurricane season proved to be a fertile test bed for determining the impact of the *GOES-8* winds on TC track forecasts. Experimental wind datasets were derived for two time periods (13–20 July and 24 August–10 September 1995) from *GOES-8* observations processed at the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW CIMSS). These datasets feature a processing and quality control strategy designed to optimize the quantity and content of geostationary satellite–derived winds in the vicinity of TCs. The first dataset focused on Tropical Storm Chantal, while the second focused on the multiple storm environment that included Hurricanes Humberto, Iris, and Luis. To determine the utility of these experimental winds, the Navy Operational Global Atmospheric Prediction System (NOGAPS) was run over the two time periods with and without their assimilation. The data impact upon NOGAPS tropical cyclone forecasts is the focus of this paper.

In the next section the NOGAPS data assimilation system utilized in this study is described and its operational performance during the 1995 Atlantic hurricane season is briefly summarized. The datasets used in this study are discussed in section 3, and the results of the data assimilation experiments are presented in section 4. In the final section the results of this study are summarized.

2. Data assimilation system

The data assimilation system used in this experiment closely matched the operational global data assimilation system run at Fleet Numerical Meteorology and Oceanography Center (FNMOC). The key components of this system are 1) the quality control of observational data; 2) the generation of synthetic TC observations; 3) the global multivariate optimum interpolation (MVOI) analysis; and 4) the global spectral forecast model. Like those run at the other major forecast centers, the navy's global data assimilation system is constantly evolving. As we describe the experimental data assimilation system in this section, we will briefly outline the significant changes that have been made to its key components since they were last documented in the open literature.

At each analysis time (every 6 h) the raw meteorological observations are processed using the operational quality control procedures described by Baker (1992). These procedures were upgraded in May 1994 and now

TABLE 2. Homogeneous comparison of NOGAPS, the GFDL model, and CLIPER forecast position errors (km) for the 1995 Atlantic hurricane season, where *N* denotes the number of positions. Relative forecast improvement with respect to CLIPER is displayed in parentheses.

	N	NOGAPS	GFDL	CLIPER
24 h	176	167 (20%)	155 (26%)	209
48 h	142	270 (35%)	245 (41%)	416
72 h	114	409 (33%)	371 (39%)	610

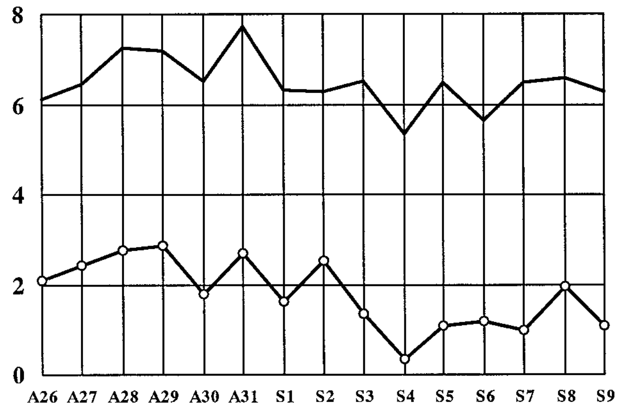

FIG. 1. Root-mean-square error (solid line) and wind speed bias (circles) in meters per second for *GOES-8* multispectral winds assigned to 300 mb with respect to the NOGAPS background from 0000 UTC August 26 to 0000 UTC September 9.

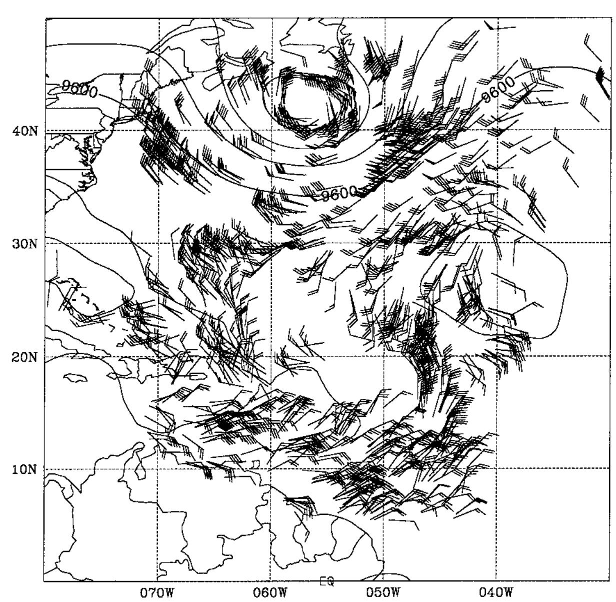

FIG. 2. NOGAPS 300-mb geopotential height analysis and high-density *GOES-8* multispectral winds assigned to 300 mb for 1200 UTC 31 August.

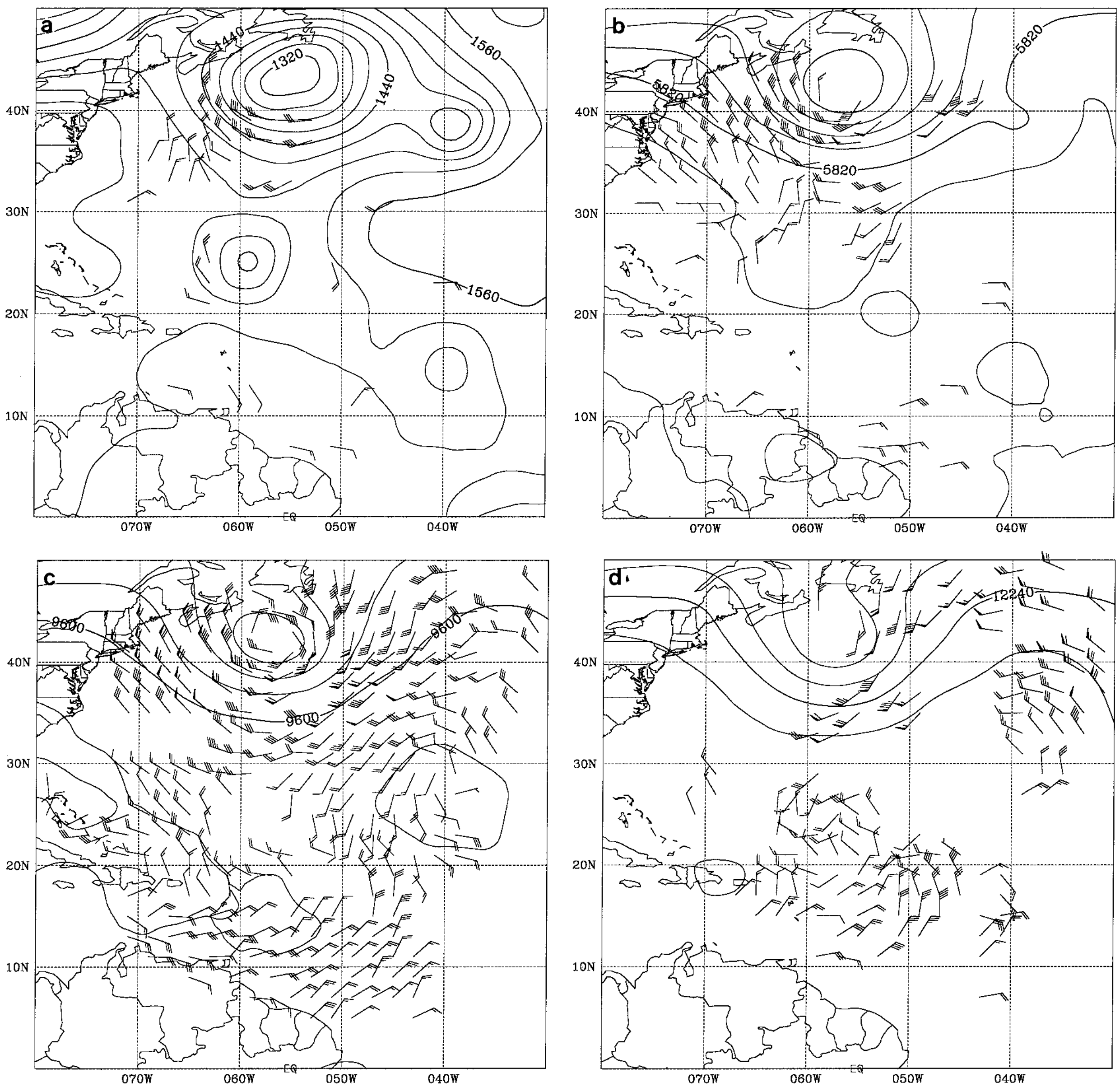

FIG. 3. NOGAPS geopotential height analysis and superobs produced from high-density *GOES-8* multispectral winds at (a) 850 mb, (b) 500 mb, (c) 300 mb, and (d) 200 mb for 1200 UTC August 31. The warning positions for Hurricanes Humberto, Iris, and Luis were 38.4°N, 39.1°W; 24.8°N, 59.0°W; and 14.6°N, 39.7°W; respectively.

include the complex quality control developed at the National Centers for Environmental Prediction Environmental Modeling Center (NCEP EMC) and described by Collins and Gandin (1990).

Synthetic observations are generated from the TC warning messages using the current operational procedure, which has evolved somewhat from the technique used operationally in 1991 and described in detail by Goerss and Jeffries (1994). The procedure has been modified to incorporate TC motion, and a strategy has been developed to eliminate the possiblility of overlapping synthetic observations in a multiple-storm environment.

The current procedure begins by deriving the synthetic wind observations for a TC using the old technique. Next, a TC motion vector is computed from the current and 12-h-old TC positions. Then, the mean wind vector for all of the synthetic wind observations at a specific pressure level is computed and subtracted from the TC motion vector to produce a correction vector for that level. This correction vector is then added to each of the synthetic wind observations at that level. As a

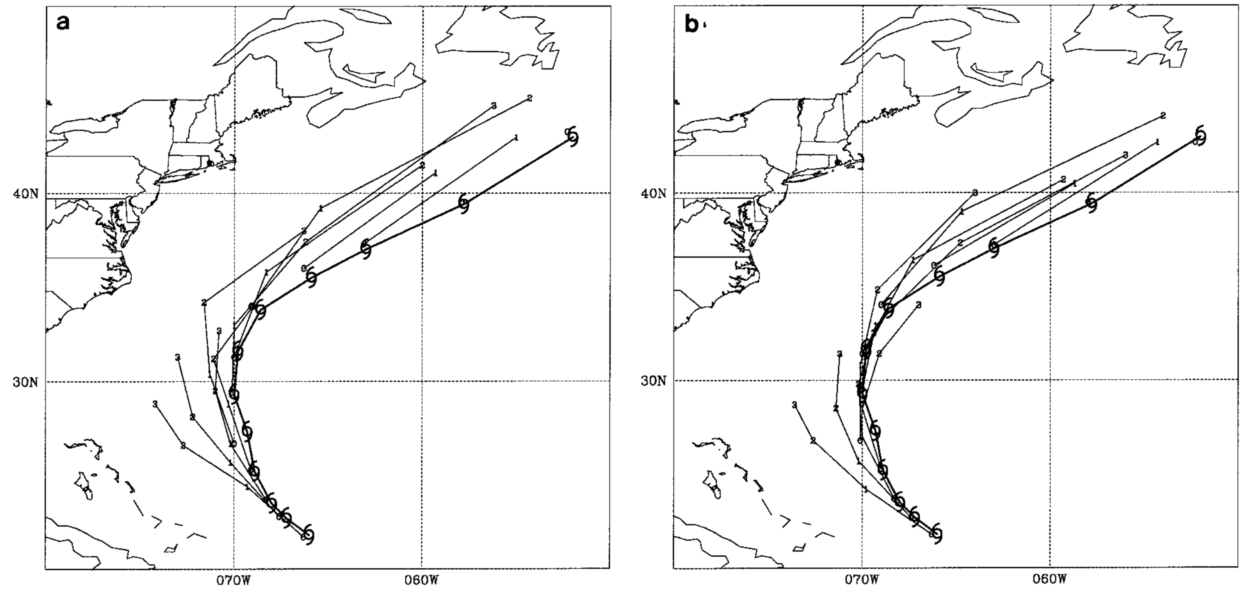

FIG. 4. A comparison of the warning positions with the NOGAPS (a) CNTL and (b) EXP analysis and forecast positions for Tropical Storm Chantal. The 12-h warning positions are denoted by the appropriate symbol along the track from 0000 UTC 15 July to 1200 UTC 20 July. The analysis and forecast positions (at 1-day intervals) are denoted by 0, 1, 2, and 3, respectively.

result, the mean wind vector for the synthetic observations at each level is equal to the TC motion vector.

Under normal circumstances the set of synthetic observations for a TC consists of 13 observations: one at the TC's center; four located 220 km north, south, east, and west of the center; four located 440 km northeast, southeast, southwest, and northwest of the center; and four located 660 km north, south, east, and west of the center. In a multiple-storm environment, if the distance between TCs becomes less than 1320 km, there is the possibility of overlapping synthetic observations. A simple strategy has been developed to prevent this problem. Based on the separation of the TCs and their respective intensities, the number of synthetic observations for each TC is reduced following the rules displayed in Table 1. For example, if two TCs are only 700 km apart, nine synthetic observations (the outer ring is dropped) are generated for the stronger TC, and five synthetic observations (the outer two rings are dropped) are generated for the weaker.

All observations are presented to the global MVOI analysis (Goerss and Phoebus 1992). The 6-h forecast fields from the NOGAPS global spectral model (Hogan and Rosmond 1991) serve as the first guess or background for the MVOI analysis. The NOGAPS forecast model is currently run with 159-wave, triangular truncation (T159) and 18 vertical levels. The horizontal grid of the MVOI analysis is the physical (or Gaussian) grid of the spectral model and has a resolution of approximately 80 km. The analysis employs the volume method developed by Lorenc (1981) with a maximum of 600 observations utilized in each volume. The synthetic TC observations are forced into the analysis between 35°S and 45°N for the Atlantic and between 35°S and 35°N, elsewhere.

TABLE 3. Homogeneous comparison of CNTL, EXP, and CLIPER forecast position errors (km) for Tropical Storm Chantal, where *N* denotes the number of positions. Relative forecast improvement with respect to CLIPER is displayed in parentheses.

	N	CNTL	EXP	CLIPER
24 h	10	185 (11%)	148 (29%)	207
48 h	8	331 (9%)	229 (37%)	363
72 h	6	557 (−9%)	448 (12%)	511

To assess the suitablility of NOGAPS as a vehicle for our tropical data assimilation experiment, a complete evaluation of its TC forecast performance was performed for the 1995 Atlantic hurricane season. As was done in an earlier study for the 1991 typhoon season in the western North Pacific (Goerss and Jeffries 1994), TC position errors were determined for all NOGAPS analyses produced when a TC was of tropical storm strength or greater, and for all NOGAPS forecasts initialized from such analyses and valid at times when the TC was of tropical storm strength or greater. The forecast performance was also evaluated in terms of detection percentage: the percent of time a TC could be detected in a NOGAPS analysis or forecast when the actual TC was of tropical storm strength or greater. Results of the evaluation showed that the NOGAPS analysis error was 56 km, and forecast errors were 161 km at 24 h, 270 km at 48 h, and 407 km at 72 h. The detection percentages were 98% (201 of 206) at 24 h, 94% (166 of 176) at 48 h, and 90% (132 of 146) at 72 h. By way of comparison, the respective analysis and forecast er-

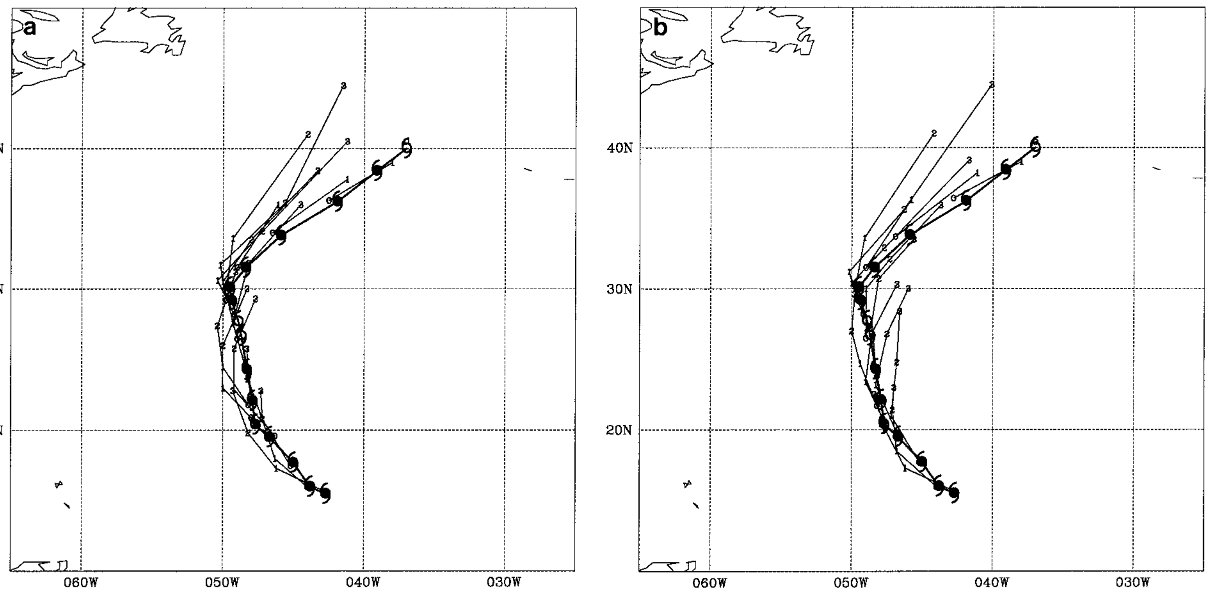

FIG. 5. As in Fig. 4 but for Hurricane Humberto from 1200 UTC 24 August to 0000 UTC 1 September.

rors for NOGAPS for the 1991 typhoon season were 76, 188, 299, and 434 km, and the respective detection percentages were 96% (288 of 300), 90% (221 of 246), and 87% (167 of 192). Thus, the NOGAPS forecast performance for the 1995 Atlantic hurricane season was consistently better in terms of both position error and detection percentage than its performance for the 1991 typhoon season, its best season to date.

During the 1995 Atlantic hurricane season, the NCEP Tropical Prediction Center (TPC) relied heavily on the hurricane prediction system developed at the Geophysical Fluid Dynamics Laboratory (GFDL) and run operationally at NCEP EMC (Kurihara et al. 1993, 1995; Bender et al. 1993). A homogeneous comparison of the forecast performance for NOGAPS, the GFDL model, and CLIPER (climate and persistence) for the 1995 season was conducted, and the results are displayed in Table 2. This comparison included all of the major storms except for large portions of Opal and Roxanne. While not quite as good, the quality of the NOGAPS forecasts is comparable to that of the GFDL model. The improvement with respect to CLIPER for NOGAPS was 20% at 24 h, 35% at 48 h, and 33% at 72 h, whereas the respective improvements for the GFDL model were 26%, 41%, and 39%. To put these numbers into perspective, the improvement with respect to CLIPER of VICBAR (DeMaria et al. 1992), whose performance was typical of the other track-forecasting aids used by NCEP TPC, was approximately 20% at 24 and 48 h and approximately 10% at 72 h.

TABLE 4. As in Table 3 but for Hurricane Humberto.

	N	CNTL	EXP	CLIPER
24 h	14	181 (5%)	154 (19%)	191
48 h	10	179 (48%)	166 (52%)	346
72 h	9	229 (49%)	242 (46%)	448

3. High-density *GOES-8* winds

In this section we give a brief description of the *GOES-8* imagery and the processing strategy utilized to create the wind datasets used in this study. Details are presented in Part I.

Wind vectors were generated by automated methods developed at CIMSS designed to track features in sequential multispectral imagery from *GOES-8.* This imagery includes five independent channels in the visible (VIS) and infrared (IR) spectra. High-resolution (1 km) VIS imagery at 15- or 30-min intervals is employed to track cumulus in the lower troposphere. IR-window imagery yields cloud-tracked wind vectors especially in the cirrus-laden outflow region in the upper troposphere. The final element is water vapor (WV) motion winds (Velden 1996; Velden et al. 1997). Features in the WV field in cloud-free regions can be tracked and processed into wind vector fields to complement the cloud-tracked winds. Three channels are utilized at 6.7, 7.0, and 7.3 μm. The 6.7-μm imager channel is an upper-tropospheric sensing channel. The latter two channels are contained on the *GOES-8* sounder and yield information in the middle troposphere.

The processing strategy is aimed at maximizing the quantitative informational content available from *GOES-8* to measure all scales of importance to TC motion. This strategy involves the following elements: 1) process vectors at high spatial density; 2) process vector fields at 6-h intervals to ensure input to the data assimilation cycle at all data integration times; 3) employ multiple channels that sense at different tropospheric

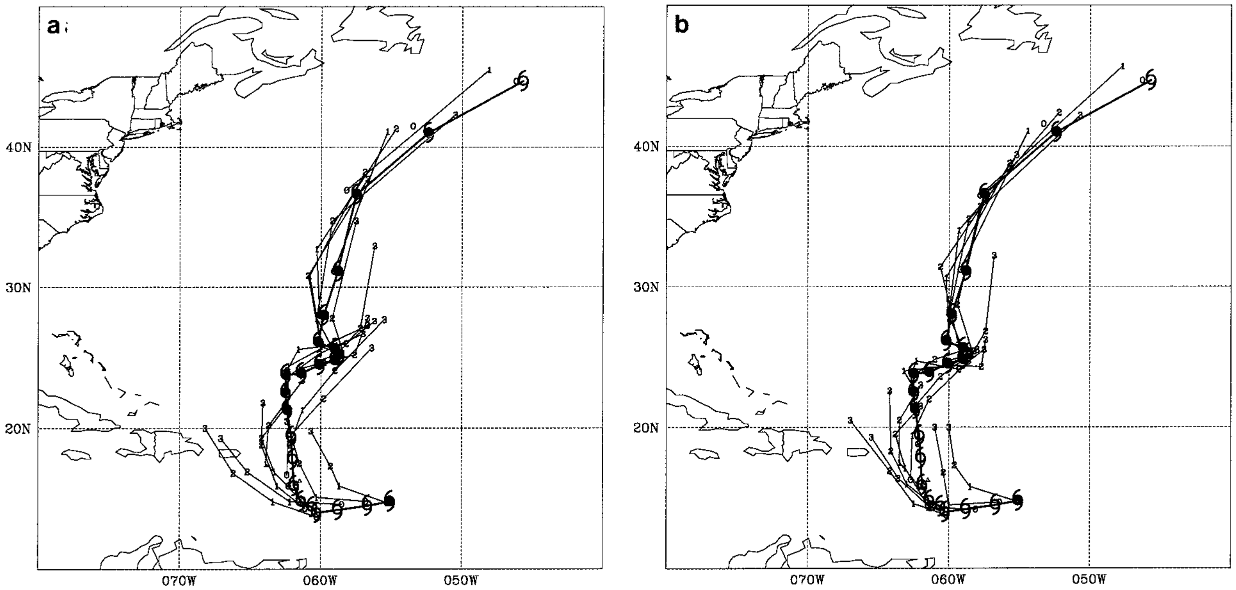

FIG. 6. As in Fig. 4 but for Hurricane Iris from 1200 UTC 24 August to 1200 UTC 4 September.

levels to attain vectors throughout the steering layer; and 4) tune the attendant quality control to retain information in the vector field that may be relevant to TC motion. The last element includes down weighting the dependence on the background (first guess) field when evaluating vector quality.

Using this processing strategy, two experimental datasets were produced. The first, from 13 to 20 July 1995, was focused on Tropical Storm Chantal. Typically, between 3000 and 4000 wind vectors were produced every 12 h for an area in the Atlantic extending from 10° to 50°N and from 40° to 80°W. The second dataset, from 24 August to 10 September 1995, was focused on the aforementioned multiple-storm environment. Between 4000 and 5000 wind vectors were produced every 6 h for a larger area extending from 0° to 50°N and from 20° to 90°W. For a given time about 10% of the wind vectors were derived from VIS imagery (lower-tropospheric cloud-tracked winds), 20%–25% were derived from IR-window imagery (primarily upper-tropospheric cloud-tracked winds), and 60%–65% were derived from the WV channels (primarily 150–400 mb).

To determine the observation error to be assigned to the experimental winds in the MVOI analysis, their root-mean-square error (rmse) with respect to the analysis background was computed. The rmse is displayed in Fig. 1 along with the wind speed bias (observation minus background) at the 300-mb level for 0000 UTC 26 August–9 September. For the entire time period at this level the rmse was approximately 6.5 m s^{-1}, and the wind speed bias was between 1 and 2 m s^{-1}. For the levels between 150 and 400 mb, inclusive, the rmse was typically between 5 to 8 m s^{-1}, compared with 8–10 m s^{-1} for operationally available satellite-derived winds. For the same levels this measure is about 5.5 m s^{-1} for North American rawinsondes and about 5 m s^{-1} for North American ACARS winds. Overall, for the levels between 150 and 400 mb, inclusive, we found that the wind speed bias was negligible.

Because of the limitations imposed within the MVOI analysis upon the number of observations that may be used within each analysis volume, we combined the high-density wind observations into superobs at approximately 200-km resolution. This is consistent with the treatment of other high-density data types (Special Sensor Microwave/Imager wind speeds and precipitable water) by the analysis. Typically, between three to five high-density observations are combined to create one superob. Based on the results of the error analysis and because of the superobbing process, the experimental wind superobs were given observation errors 40% smaller than those assigned to the conventional cloud-tracked winds: wind component error of 1.7 m s^{-1} at 1000, 925, and 850 mb; 2.3 m s^{-1} at 700 mb; 2.9 m s^{-1} at 500 mb; 3.5 m s^{-1} at 400 mb; and 3.9 m s^{-1} at levels at or above 300 mb. By way of comparison, the wind component error given to the synthetic TC observations is 2.2 m s^{-1} at 1000, 925, 850, and 700 mb; 2.8 m s^{-1} at 500 mb; and 3.0 m s^{-1} at 400 mb. The high-density wind observations that were assigned to the 300-mb level for 1200 UTC 31 August are displayed in Fig. 2.

TABLE 5. As in Table 3 but for Hurricane Iris.

	N	CNTL	EXP	CLIPER
24 h	21	163 (29%)	137 (41%)	231
48 h	19	290 (45%)	228 (57%)	527
72 h	17	355 (51%)	252 (65%)	723

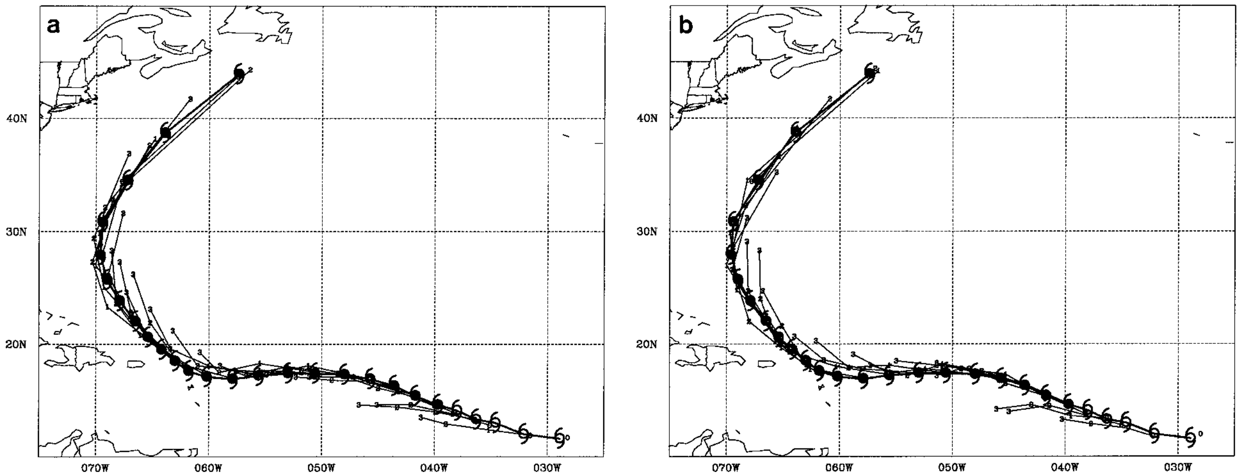

FIG. 7. As in Fig. 4 but for Hurricane Luis from 0000 UTC 29 August to 0000 UTC 11 September.

The superobs at four pressure levels for the same time are displayed in Fig. 3. Comparing Fig. 2 with Fig. 3c, we see that the spatial coverage provided by the superobs, whose density is commensurate with the requirements of the global analysis, is very close to that provided by the raw high-density *GOES-8* observations. One of the great strengths of the multispectral processing strategy is illustrated in Fig. 3 as well. There are several areas where wind observations have been produced at multiple levels in the atmosphere.

Finally, we found that the multispectral wind observations and the synthetic TC observations are highly complementary. The synthetic TC observations are confined to the lower levels (1000–400 mb) and provide uniform coverage within a 660-km radius of the TC position. Typically, about 70% of the multispectral winds are observed above 400 mb, about 15% at 400 mb, and about 15% below 400 mb. Due to the nature of the cloud patterns associated with TCs, the amount of overlap between these two types of data is minimal. When they do overlap, we have seen that their qualitative agreement is generally good, but that the multispectral winds can be derived only in certain sectors of the circle covered by the synthetic observations. Thus, the synthetic TC observations provide a more complete description of the lower-level flow in the vicinity of the TC, while the multispectral wind observations complete the picture for the upper levels not just in the vicinity of the TC but also for the large-scale environment surrounding it.

TABLE 6. As in Table 3 but for Hurricane Luis.

	N	CNTL	EXP	CLIPER
24 h	24	78 (48%)	81 (46%)	150
48 h	22	135 (62%)	161 (55%)	355
72 h	20	272 (52%)	287 (49%)	564

4. Experimental results

The NOGAPS data assimilation system was run with (EXP) and without (CNTL) the experimental wind datasets over the two aforementioned time periods. From each run 72-h forecasts were produced every 12 h. The TC position errors were determined for all NOGAPS forecasts that were initialized at a time when a TC was of tropical storm strength or greater, and that were valid at a time when the TC was of tropical storm strength or greater. All tests of statistical significance in this section were conducted using the modified *t* test described by DeMaria et al. (1992) in which the effective sample size was determined using a 30-h criterion for forecast independence. In Fig. 4 the NOGAPS CNTL and EXP forecast tracks are displayed along with the observed track for Tropical Storm Chantal. A close inspection of Figs. 4a and 4b indicates that the assimilation of the multispectral *GOES-8* winds has resulted in qualitative improvement in the NOGAPS forecast tracks. The quantitative impact of the winds upon the NOGAPS forecasts is illustrated in Table 3. Although the satellite-derived winds were available only every 12 h, their assimilation resulted in a 20%–30% improvement in the NOGAPS forecasts for Chantal. This improvement was found to be significant at the 97% level at 48 h and at the 92% level at 24 and 72 h. Without their assimilation, the NOGAPS forecasts showed little or no skill with respect to CLIPER.

Qualitatively, one would be hard pressed to find much difference between the CNTL and EXP tracks for Hurricane Humberto shown in Fig. 5. The quantitative results for Humberto are shown in Table 4. For this cyclone the NOGAPS CNTL run displayed little skill at 24 h (only 5% improvement with respect to CLIPER) and exceptional skill at 48 and 72 h (nearly 50% improvement with respect to CLIPER). The assimilation of the satellite-derived winds resulted in a 15% im-

TABLE 7. As in Table 3 but for all tropical cyclones considered in this study (Chantal, Humberto, Iris, and Luis).

	N	CNTL	EXP	CLIPER
24 h	69	141 (26%)	122 (36%)	191
48 h	59	218 (47%)	192 (53%)	411
72 h	52	326 (45%)	287 (51%)	590

provement with respect to the CNTL run at 24 h (significant at the 95% level) and statistically insignificant forecast impact at 48 and 72 h.

The forecast tracks for Hurricane Iris are shown in Fig. 6. As illustrated in Table 5, the NOGAPS CNTL run exhibited outstanding skill at all forecast lengths (30%–50% improvement with respect to CLIPER) for this cyclone. However, the EXP run resulted in further improvements of 16%, 21%, and 29% with respect to the CNTL run at 24, 48, and 72 h, respectively. The improvement at 24 h was significant at the 90% level, whereas those at 48 and 72 h were significant at the 96% level. The EXP forecasts showed improvement with respect to CLIPER of 41%, 57%, and 65% at 24, 48, and 72 h, respectively.

The NOGAPS CNTL forecasts for Hurricane Luis (Fig. 7) were even better than those for Humberto and Iris, displaying 50%–60% improvement with respect to CLIPER. The forecast impacts shown in Table 6 at 24 and 72 h were not found to be significant. However, the 19% degradation at 48 h was found to be significant at the 90% level.

Finally, the results for all four cyclones are summarized in Table 7. The CNTL forecasts showed 26%, 47%, and 45% improvement with respect to CLIPER at 24, 48, and 72 h, respectively. The assimilation of the satellite-derived winds resulted in further improvement with respect to the CNTL run of 14%, 12%, and 12%, respectively. The improvement at 24 h was found to be significant at the 98% level, whereas those at 48 and 72 h were significant at the 93% level. Overall, the EXP forecasts showed improvement with respect to CLIPER of 36% at 24 h, 53% at 48 h, and 51% at 72 h. In terms of detection percentage, the assimilation of the UW CIMSS winds had no apparent impact upon the NOGAPS forecasts. The detection percentages for both the CNTL and EXP forecasts were 100%, 97%, and 98% at 24, 48, and 72 h, respectively.

5. Summary

NOAA's newest generation of geostationary meteorological satellites became operational with the launch of *GOES-8* in 1994. This satellite was positioned to cover the western Atlantic Ocean and monitor TC activity. This generation represents a significant improvement in observing and sensing capabilities over previous GOES platforms. Combined with an automated data processing strategy developed at UW CIMSS aimed at maximizing the quantitative informational content pertinent to all scales important to TC motion, the resultant datasets consisting of high-density wind vector fields are to be considered the most complete achieved to date from geostationary sensing. Utilizing multiple spectral bands including three water vapor channels, wind information is derived throughout the depth of the troposphere. The quality of these data and their resultant impact on NOGAPS TC forecasts was the focus of this paper.

The 1995 Atlantic hurricane season was one of the most active of all time and permitted us, for the first time, to perform a thorough investigation of NOGAPS tropical cyclone forecast performance for that basin. We found that for the entire season the NOGAPS forecast performance was competitive with that of the GFDL model, the primary track-forecasting aid used by NCEP TPC. Based on the overall quality of the NOGAPS tropical cyclone forecasts, we concluded that it was a suitable vehicle for conducting experiments to determine the impact of the assimilation of the high-density winds derived from multispectral *GOES-8* observations.

Synthetic TC observations are an integral part of the NOGAPS data assimilation system in the Tropics. We found that the primarily upper-level coverage provided by the UW CIMSS wind observations complemented the lower-level coverage provided by the synthetic observations with very little overlap. While we did not run any experiments without the use of the synthetic TC observations, the distribution of the multispectral *GOES-8* wind observations does not suggest that they could effectively replace the synthetic observations in the NOGAPS data assimilation system.

Data assimilation experiments were performed for two time periods (13–20 July and 24 August–10 September 1995) using NOGAPS to determine the impact of high-density multispectral *GOES-8* winds. The first time period featured Tropical Storm Chantal while the second focused on the multiple storm environment, which included Hurricanes Humberto, Iris, and Luis. We found that the assimilation of the high-density *GOES-8* winds resulted in significant improvements in the NOGAPS forecasts for Tropical Storm Chantal and Hurricane Iris. While the results for Hurricanes Humberto and Luis were mixed, it is fair to say that the NOGAPS CNTL and EXP forecasts were both excellent for these two cyclones. Considering all four cyclones collectively, we found significant improvement in the NOGAPS forecasts due to the assimilation of the satellite-derived winds. Based on the results of this study and of a successful three-week parallel experiment performed in early July 1996, the routine assimilation of these winds into NOGAPS was initiated at FNMOC in late July 1996.

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