THE IMPACT OF SATELLITE-DERIVED WINDS ON HURRICANE ANALYSIS AND TRACK FORECASTING

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ABSTRACT

While qualitative information from meteorological satellites has long been recognized as critical for monitoring tropical cyclone activity, quantitative data are required to improve the objective analysis and numerical weather prediction of these events. In this paper, results are presented which show that the inclusion of high-density, multispectral satellite-derived information into the analysis of tropical cyclone environmental wind fields can effectively reduce the error of objective track forecasts.

1. Introduction

Analysis uncertainties are often cited as a major source of forecast errors in numerical models. This is especially true in hurricane track prediction, where lack of conventional tropospheric observations over the oceanic regions can lead to erroneous depictions of the environmental flow that accounts for much of the storm motion. Operational meteorological satellites (particularly geostationary) have the ability to frequently sample the large scale oceanic environment, making them prime tools for monitoring tropical cyclones. At the University of Wisconsin-Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS), an effort has been underway to develop and incorporate high density, high quality satellite-derived wind observations into analyses of tropical cyclone environmental wind fields in hopes of reducing track forecast errors. This program is a cooperative effort with the NOAA National Hurricane Center (NHC), the Atlantic Oceanographic and Meteorological Laboratory-Hurricane Research Division (AOML-HRD), the National Environmental Satellite Data and Information Service (NESDIS), and the National Meteorological Center (NMC). The impact of these satellite data on barotropic model hurricane track forecasts is examined here.

2. Methodology

Efforts at UW-CIMSS have focussed on improving the depiction of the wind fields in the tropical cyclone environment by enhancing the operationally-derived cloud-motion winds with high-density vectors from several different sources of GOES satellite data. The enhanced satellite wind sets include: 1) high-density cloud-motion vectors produced by automated methods using sequences of high-resolution infrared-window imagery, 2) automatically-derived vectors from animated imagery of two VAS (VISSR Atmospheric Sounder) water vapor channels (6.7 and 7.3 micron), and 3) gradient winds derived from multispectral VAS-retrieved height fields. These enhanced satellite winds are combined with operationally-derived cloud-motion winds produced at NESDIS (full-disk, low density) and rawinsonde upper-air reports. The data set is quality controlled by both automated and manual techniques, and then objectively analyzed at the mandatory levels from 850 to 200 mb. The final step is the creation of a tropospheric (850-200 mb), mass-weighted deep layer-mean (DLM) wind analysis from these fields. The DLM analysis is a good approximation of the environmental steering flow in most cases, and can be used qualitatively by NHC, or to initialize objective hurricane track forecast models. The foregoing procedures were developed on the Man-computer Interactive Data Access System (McIDAS) at UW-CIMSS, and have been implemented into operations on the VDUC (VAS Data Utilization Center) system at NESDIS in Washington, DC. Routine processing has been conducted by NESDIS since 1988. Through a telecommunications link to NHC, the winds and DLM have been transmitted during hurricane season in a quasi-operational mode for evaluation by NHC forecasters.

3. Satellite Data Impact Results

In this section, cases from 1989 Atlantic Hurricanes Hugo, Gabrielle and Jerry are used to examine the specific impact of the quantitative satellite data on model mean forecast errors (MFE). Two independent analysis and forecast schemes are utilized to determine the consistency of the impact. In addition, the relative contributions of two satellite data components (cloud-motion and VAS gradient) towards the reduction in model MFE are examined.

a. UW-CIMSS analysis and forecast system

The enhanced satellite wind sets were produced in an operational mode by NESDIS during North Atlantic and East Pacific tropical cyclone events in 1989. 18 data sets (cases) produced during Hurricanes Hugo and Gabrielle are investigated for their impact on model track forecasts. The forecast procedure consists of two components: a nondivergent barotropic forecast of the environmental flow field, and a point (storm center) trajectory forecast based on the barotropic forecast of the environmental flow. The trajectory begins at the specified storm center location, and is calculated after each barotropic forecast time step (30 min). 72-hour forecasts from the 18 cases initialized with the satellite data-enhanced DLM fields are compared with forecasts initialized with DLM fields that do not include the enhanced satellite winds (only conventional data and operational satellite winds). The results of the track forecasts are tabulated in Table 1. A 9-17% reduction in middle to longer range MFE is found when the model is initialized with the satellite wind-enhanced analyses. In the context of simple barotropic model track forecasting, this represents a notable improvement.

Table 1. Mean track forecast errors (km) from the UW-CIMSS analysis and forecast system initialized on DLM analyses with (SATWINDS) and without (NOSAT) satellite-enhanced winds, for a sample of cases from 1989.

Forecast Interval	12 h	24 h	36 h	48 h	60 h	72 h
NOSAT	53	95	160	250	375	510
SATWINDS	51	88	133	207	321	457
# of Cases	14	14	14	13	12	11
% Difference	2	7	16	17	14	9

Given the positive impact of the enhanced satellite winds on the overall reduction of MFE, it is of interest to examine the contributions by the individual wind components, or types. 72-hr track forecasts from the 18 cases were produced using DLM analyses containing the entire wind set, and with individual types (cloud-motion and VAS gradient) taken out. The results are shown in Table 2. The cloud-motion vectors are located mainly near 850 and near 200 mb, which are levels that are not as well correlated with storm motion as the middle tropospheric levels, and do not typically make a strong contribution to the mass-weighted DLM flow. Therefore, their impact on forecasts from this relatively simple analysis and barotropic forecast system is minimal.

Table 2. Mean track forecast errors (km) from the UW-CIMSS analysis and forecast system, which includes a control containing all enhanced satellite wind vectors (SATWINDS), control minus enhanced cloud-motion vectors (NOCLDMOT), and control minus VAS gradient vectors (NOGRAD) for a sample of cases from 1989.

Forecast Interval	12 h	24 h	36 h	48 h	60 h	72 h
SATWINDS	51	88	133	207	321	457
NOCLDMOT	52	90	137	211	325	470
NOGRAD	55	100	156	246	373	530
# of Cases	14	14	14	13	12	11

VAS gradient winds at 850, 500 and 200 mb were included in the enhanced satellite data sets processed in 1989. A somewhat surprising result from Table 2 is the magnitude of the impact of the gradient winds. It is rather unexpected that gradient winds would have such an impact in tropical applications. An examination of the individual satellite wind sets, however, reveals that very few gradient wind vectors south of 20N passed through the quality control procedures at NESDIS. In addition, Hurricane Hugo tracked into the sub-tropics late in it's trek, and Hurricane Gabrielle moved northward into a mid-latitude regime for much of it's lifetime. Thus, cases from these two storms provided an opportunity for the gradient winds to show an impact.

Table 3. Mean track forecast errors (km) from the UW-CIMSS analysis and forecast system initialized on DLM analyses which include all enhanced satellite wind vectors (SATWINDS), and SATWINDS minus the VAS gradient wind vectors (NOGRAD), for a sample of cases from 1989. The cases are stratified by those with initial storm position south of 25N latitude (top), and those north of 25N (bottom).

South of 25N

Forecast Interval	12 h	24 h	36 h	48 h	60 h	72 h
SATWINDS	54	98	149	241	368	516
NOGRAD	57	103	157	249	378	523
# of Cases	10	10	10	10	10	9
% Difference	------------ less than 5 % -----------					

North of 25N

Forecast Interval	12 h	24 h	36 h	48 h	60 h	72 h
SATWINDS	45	76	124	169	208	338
NOGRAD	54	96	163	242	356	531
# of Cases	6	6	6	5	4	3
% Difference	18	21	24	30	41	36

This impact is further examined by stratifying the results in Table 2 into those cases north and south of 25 N. This latitude was picked somewhat arbitrarily to separate tropical cases from sub-tropical or mid-latitude cases. The results are presented in Table 3. It is evident that the gradient winds have a major impact on track forecasts north of 25N. In fact, up to a 41% degradation in the MFE (at 60-h) results with the exclusion of these winds from the data set.

b. AOML-HRD analysis and forecast system

In this section, the VICBAR track forecast model is used to evaluate the impact of the satellite data. The VICBAR forecasting system consists of a multilevel analysis and a barotropic prediction model. This forecasting system is more sophisticated than the relatively simple UW-CIMSS system, with the likelihood of increased sensitivity to enhanced data. Control forecasts using only the NMC operational data base were made for 21 cases from 1989 Atlantic hurricanes Hugo, Gabrielle and Jerry. The enhanced high-density cloud-motion winds were then added to the data base and the forecasts re-run (enhanced cloud-motion winds were available in 18 of the 21 cases). Figure 1 illustrates the impact of the enhanced cloud-motion winds on the VICBAR track forecasts relative to the control. A positive impact is found in the 24-72 h forecast intervals, peaking near 14% at 48 h. The maximum impact at the middle and longer forecast intervals is consistent with the UW-CIMSS results. Table 4 summarizes the impact of the cloud-motion winds on the VICBAR forecasts. The reduction in forecast errors at 48 h was found to be significant (paired t-test) at the 95% confidence level. The consistency of the reduction in forecast errors is shown by the fact that the track predictions are improved 64-81% of the time at the later forecast periods.

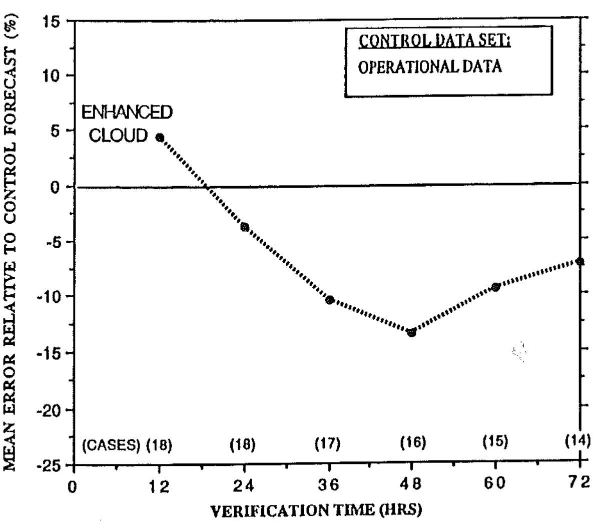

Figure 1. Impact on mean VICBAR track forecast errors by adding enhanced cloud-motion vectors to a control data set. Errors are shown relative to the mean forecast error of the control.

Table 4. Impact of enhanced cloud-motion vectors on VICBAR forecasts. Verification statistics are valid for forecasts from the NMC operational data base plus the enhanced cloud-motion vectors: number of forecasts (N), effective number of independent forecasts (N^*), and mean forecast error (MFE). Also given are comparisons with forecasts from the operational data base only: the mean forecast improvement (MFI), expressed both in km and as a % relative to the operational data-only forecast error, the standard deviation of the improvements (SDI), the frequency of improved forecasts (FIF), and whether the improvements are statistically significant at the 95% confidence level (SIG).

Forecast Interval (h)	N	N^*	MFE (km)	MFI (km)	SDI (km)	MFI (%)	FIF (%)	SIG (y/n)
12	18	11.2	42	-2	13	-4.5	39	n
24	18	11.2	74	3	21	3.8	44	n
36	17	10.4	116	14	32	10.5	65	n
48	16	9.4	181	28	42	13.5	81	y
60	15	9.0	296	31	57	9.5	67	n
72	14	8.6	424	34	79	7.3	64	n

The next experiment involves the inclusion of the VAS gradient winds to the operational data base. Figure 2 illustrates the impact of the gradient winds on the VICBAR forecasts, relative to the control runs. As was the case with the cloud-motion winds, the greatest forecast impact occurs in the 36-72 h time period. This is not surprising, since gradient wind information is not available in cloudy regions near the storm. Positive impact results mainly from an improved definition of the synoptic-scale environmental flow features away from the storm circulation, especially north of 25 N as shown earlier. Table 5 presents a summary of the impact of the gradient winds on the VICBAR forecasts. The MFE are reduced by 6-9% in the 36-72 h forecast period, and are statistically significant at the 95% confidence level. In addition, nearly 3/4 of the cases are improved over this period by the inclusion of the winds, indicating a good degree of consistency in the reduction of forecast error. In agreement with the UW-CIMSS results presented earlier, the most improved forecasts were associated with cases out of the deep tropics.

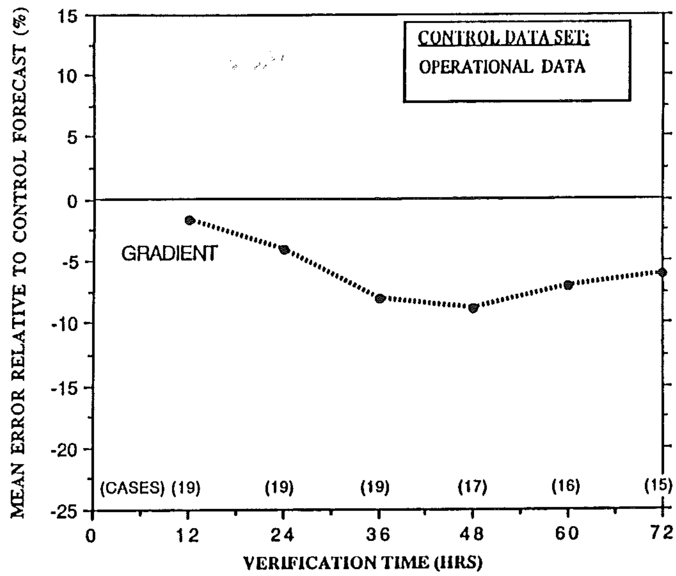

Figure 2. Impact on mean VICBAR track forecasts errors by adding VAS gradient vectors to a control data set. Errors are shown relative to the mean forecast error of the control.

Table 5. As in Table 4, except the statistics reflect the inclusion of the VAS gradient winds only.

Forecast Interval (h)	N	N^*	MFE (km)	MFI (km)	SDI (km)	MFI (%)	FIF (%)	SIG (y/n)
12	19	10.4	39.3	0.6	4.5	1.6	66	n
24	19	10.4	71.1	3.0	8.7	4.1	58	n
36	19	10.4	121.3	10.6	13.1	8.1	76	y
48	17	9.0	180.8	17.4	20.9	8.8	82	y
60	16	8.6	291.2	22.2	27.9	7.1	75	y
72	15	8.2	415.8	27.1	39.1	6.1	73	y

Verifications for the combined satellite data set (enhanced cloud-motion plus gradient winds) against the control are shown in Fig. 3 and Table 6. The forecast errors are reduced at nearly all forecast periods, with the 23% reduction in MFE at 48 h significant at the 99% level of confidence. High levels of confidence (> 95%) are also found at 36 and 60 h. An example of the combined impact of the enhanced cloud-motion plus gradient winds on an individual forecast from Hurricane Gabrielle is shown in Fig. 4.

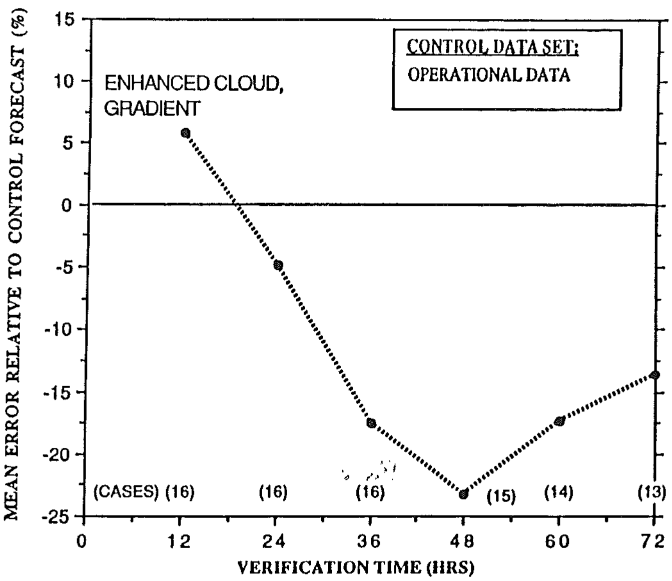

Figure 3. Impact on mean VICBAR track forecast errors by adding enhanced cloud-motion plus VAS gradient vectors to a control data set. Errors are shown relative to the mean forecast error of the control.

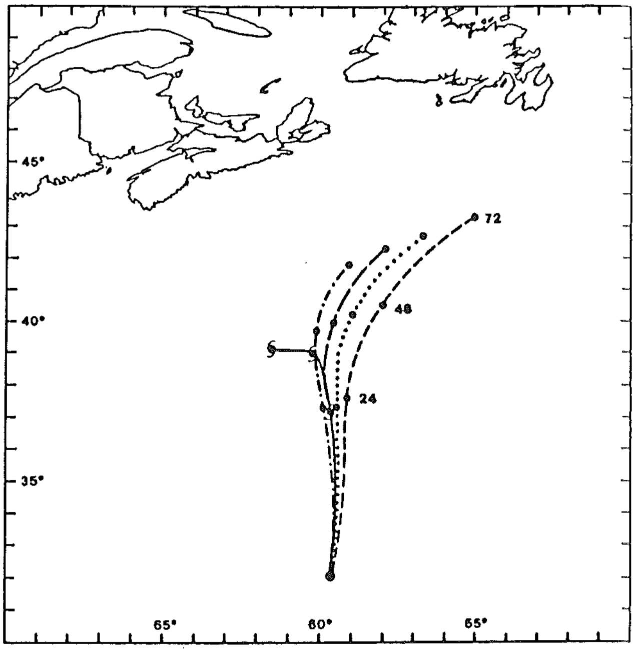

Figure 4. 72-h VICBAR forecast tracks from Hurricane Gabrielle at 00 UT 8 September 1989, including the control run (--), control plus enhanced cloud-motion vectors (– –), control plus VAS gradient vectors (• • •), and control plus enhanced cloud-motion and VAS gradient vectors (-•-). Verifying track is also shown (——).

Table 6. As in Table 4, except the statistics reflect the inclusion of the enhanced cloud-motion plus gradient winds.

Forecast Interval (h)	N	N*	MFE (km)	MFI (km)	SDI (km)	MFI (%)	FIF (%)	SIG (y/n)
12	16	10.0	42	-2	15	-5.8	38	n
24	16	10.0	67	3	24	4.8	50	n
36	16	10.0	104	22	35	17.5	75	y
48	15	9.0	160	48	49	23.2	87	y
60	14	8.6	274	58	71	17.4	86	y
72	13	8.2	402	64	104	13.6	69	n

4. Summary

The results presented in this study show a consistent positive impact by the satellite-derived winds on the reduction of barotropic track forecast errors, especially notable at longer ranges (36-72 h). The reduction in MFE is as high as 23% in 48 h VICBAR forecasts for a sample of 1989 cases. The improvement results from a complementary distribution of the high-density cloud-motion winds, and the "clear-air" VAS gradient winds. The positive impact of the gradient winds is mainly limited to storms in, or moving into, higher latitude regimes (i.e. north of 25 N). The fact that the VICBAR forecast model is quasi-operational, and that these enhanced satellite data sets were produced under operational constraints, demonstrates the potential for real-time applications to NHC forecast guidance.