Impact of Enhanced Satellite-Derived Atmospheric Motion Vector Observations on Numerical Tropical Cyclone Track Forecasts in the Western North Pacific during TPARC/TCS-08

HOWARD BERGER
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

ROLF LANGLAND
Naval Research Laboratory, Monterey, California

CHRISTOPHER S. VELDEN
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

CAROLYN A. REYNOLDS AND PATRICIA M. PAULEY
Naval Research Laboratory, Monterey, California

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ABSTRACT
Enhanced atmospheric motion vectors (AMVs) produced from the geostationary Multifunctional Transport Satellite (MTSAT) are assimilated into the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) to evaluate the impact of these observations on tropical cyclone track forecasts during the simultaneous western North Pacific Ocean Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (TPARC) and the Tropical Cyclone Structure—2008 (TCS-08) field experiments. Four-dimensional data assimilation is employed to take advantage of experimental high-resolution (space and time) AMVs produced for the field campaigns by the Cooperative Institute for Meteorological Satellite Studies. Two enhanced AMV datasets are considered: 1) extended periods produced at hourly intervals over a large western North Pacific domain using routinely available MTSAT imagery and 2) limited periods over a smaller storm-centered domain produced using special MTSAT rapid-scan imagery. Most of the locally impacted forecast cases involve Typhoons Sinlaku and Hagupit, although other storms are also examined. On average, the continuous assimilation of the hourly AMVs reduces the NOGAPS tropical cyclone track forecast errors—in particular, for forecasts longer than 72 h. It is shown that the AMVs can improve the environmental flow analyses that may be influencing the tropical cyclone tracks. Adding rapid-scan AMV observations further reduces the NOGAPS forecast errors. In addition to their benefit in traditional data assimilation, the enhanced AMVs show promise as a potential resource for advanced objective data-targeting methods.

1. Introduction
The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (TPARC) was an international field program conducted in 2008 to investigate the development, intensification, and extratropical transition of tropical cyclones in the western North Pacific Ocean (Harr et al. 2011, unpublished manuscript). This innovative campaign was designed to deploy special in situ observations, including dropwindsondes, driftsondes, and buoys, to improve the near-environmental analyses of targeted storms during the experiment. Reconnaissance aircraft missions provided by the U.S. Air Force Reserve were able to penetrate into the core to provide valuable information on structure and intensity and to provide validation data for a suite of remotely sensed observations from both operational and research satellites (Hawkins and Velden 2011). The U.S. Office of Naval Research (ONR) sponsored
a coincident field campaign aimed at a more-detailed study of tropical cyclone structure [Tropical Cyclone Structure—2008 (TCS-08)] during genesis and intensity changes. The coincident satellite and in situ data in TPARC/TCS-08 provide a rare opportunity to test and validate new satellite-derived methods, products, and applications to improve numerical weather prediction (NWP) track and intensity forecasting in the western North Pacific basin.

A key component of tropical cyclone NWP is data assimilation. An active area of research involves the improved use of satellite observations through their evaluation in data sensitivity studies, including the concept of “targeted observations.” Improved use of satellite observations is particularly relevant in tropical genesis and development regions where satellites often provide the bulk of upper-air observations. This paper will focus on a series of satellite data assimilation experiments that measure the impact of enhanced atmospheric motion vectors (AMVs) in the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS). The AMVs are analyzed using four-dimensional variational data assimilation (4D-Var) in the Naval Research Laboratory Atmospheric Variational Data Assimilation System—Accelerated Representer (NAVDAS-AR).

Although AMVs have been assimilated using 3D-Var in NOGAPS for many years, TPARC/TCS-08 provides a chance to examine the use of higher-spatial-and-temporal-resolution AMVs that were produced during the field campaigns and to test the impact using NAVDAS-AR. A secondary objective is to compare the forecast impacts of AMVs assimilated continuously over large geographic regions with targeted dropwindsondes that were deployed by aircraft periodically and over limited regions. In section 2 we provide details on the generation and characteristics of the AMV observations produced during TPARC/TCS-08. We describe the observation impact experiments in section 3, describe the results in section 4, and provide a summary in section 5.

2. Enhanced AMVs

AMVs provide a major fraction of the global observation data for the operational NOGAPS initial conditions (Langland et al. 2009; Goerss et al. 1998; Goerss 2009). The datasets are routinely generated every 6 h at various national satellite data processing centers that operate geostationary meteorological satellites and are made available on the Global Telecommunications System (GTS). The vectors are obtained by automated tracking of cloud and water vapor motions in successive satellite images [normally from a set of three visible (VIS), infrared (IR), water vapor, or shortwave IR images]. The AMVs are then assigned heights (in pressure coordinates) and are quality controlled. For more information on AMVs, see Velden et al. (2005). The experiments in this study examine two specially processed and enhanced AMV datasets that were produced from Multifunctional Transport Satellite (MTSAT) images by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) for the TPARC/TCS-08 field campaign: 1) vector fields at hourly intervals and 2) AMVs produced from rapid-scan images.

The hourly AMVs (LeMarshall 1996) are derived using the routinely available MTSAT image triplets (30-min image frequency), but datasets are made available every hour rather than as the traditional 6-hourly datasets from operational processing. The continuous coverage is more ideal for capturing steering-flow tendencies and upper-level-flow interactions with adjacent environmental features that can have an impact on storm-track and intensity forecasts. In this regard 4D-Var is well suited to assimilate the hourly datasets.

Rapid-scan AMVs (Velden et al. 2005) for TPARC/TCS-08 are derived from postprocessed 15-min MTSAT-2 image triplets. The Japan Meteorological Agency (JMA) provided these special rapid-scan images only during selected high-impact TPARC/TCS-08 observing periods. Although availability of these rapid-scan AMVs is limited to certain time periods, the shorter time interval between the rapid-scan images allows for improved tracking of cloud motions and resultant flow details. As an example during Typhoon Sinlaku, Fig. 1 shows the 15-min upper-level rapid-scan AMVs plotted with the routine operational AMVs provided by JMA. It is evident that the rapid-scan AMVs provide more detailed coverage of

![Rapid-scan AMVs near Typhoon Sinlaku (blue dot = center) valid 0000 UTC 11 Sep 2008.](image-url)
the upper-level-flow structure. These higher-resolution AMVs have data assimilation applications as well. In a previous study, rapid-scan AMVs were shown to reduce medium-range track errors in NOGAPS forecasts of Hurricane Katrina (Langland et al. 2009). In that study, AMVs from rapid-scan Geostationary Operational Environmental Satellite (GOES) imagery (5-min intervals) replaced the operational AMVs and were assimilated over a large region around Katrina. The rapid-scan AMVs improved most of the NOGAPS 84–120-h track forecasts for Katrina, even though the original operational NOGAPS forecasts already had above-average skill.

3. Description of experiments

a. Model framework

All experiments in this study use NAVDAS-AR, a full 4D-Var approach solved in observation space (Chua et al. 2009), and a 239-harmonic triangular spectral truncation/42-level (T239L42) version of NOGAPS with the model top at 0.04 hPa (Hogan and Rosmond 1991; Peng et al. 2004). In operations, AMVs are treated by NAVDAS-AR using a “superob” technique in the assimilation process. A superob in NAVDAS-AR is an observation that is created by averaging all available AMVs.
discussed in a later section.

The potential ramifications of this are

son with that of AMVs and other observations (Goerss

diosondes. This results in relatively large initial analysis

operations, tropical cyclone bogus observations are

maximum wind speed of the storm. In NAVDAS-AR

gradient balance whose structure is determined by the

analyses are greatly enhanced with the addition of the hourly

AMVs. The experiments described in this study all use

the operational NAVDAS-AR “superobbing” scheme.

Superobbing, through averaging, also reduces random

error and can take better advantage of high-resolution

AMV data. Most NWP centers use some type of data

thinning to reduce the number of observations ingested

into their assimilation systems. Thinning is a simpler tech-

nique but does not have a corresponding error reduction,

and most current practices essentially ignore surrounding

data (Berger and Forsythe 2004). Even with superobbing,

it is acknowledged that correlated observation error can

still exist, both in space and time, and could be an issue with

these enhanced-AMV datasets in the 4D-Var framework.

This will be a subject of future work.

In operations, the NAVDAS-AR–NOGAPS system

assimilates synthetic wind and height observations be-

between 400 and 1000 hPa to represent the tropical

cyclone–scale vortex and near environment within

about 600 nm of the storm center. Commonly referred
to as a “bogus,” this cyclone-scale set of synthetic ob-

servations represents a symmetric Rankine vortex in

gradient balance whose structure is determined by the

maximum wind speed of the storm. In NAVDAS-AR

operations, tropical cyclone bogus observations are

assigned the same observational error variance as ra-

diosondes. This results in relatively large initial analysis

weights given to the synthetic observations in compar-

ison with that of AMVs and other observations (Goer-

ss and Jeffries 1994). The potential ramifications of this are
discussed in a later section.

b. AMV impact experiments

A control sequence and two data-impact experiments

are performed to test the influence of enhanced AMVs

(hourly and rapid scan) and are summarized in Table 1.

An additional experiment that tests the impact of drop-

windsondes is also included in the table and will be de-

scribed in a subsequent section. Each experiment is a

continuous global forecast and assimilation cycle in which

analyses are produced between 0000 UTC 1 August and

1200 UTC 30 September 2008. Thus in this cycling mode,

effects of previously assimilated observations influ-

ence future analyses and forecasts. Five-day forecasts

are started from each 0000 and 1200 UTC analysis. Model

tropical cyclone forecast positions are determined using

the tropical cyclone tracking software that is employed

operationally at the Fleet Numeric Meteorology and

Oceanography Center. This tracker is based on that de-

scribed in Marchok (2002).

The control analysis and forecast cycle (referred to as

“CONTROL”) uses all operationally available observa-

tions along with the special hourly MTSAT AMVs de-

scribed in the previous section. The “NO-CIMSS-AMV”

experiment includes all observations from CONTROL

except for the AMVs produced by CIMSS. The majority

of these AMVs are the hourly MTSAT AMVs (note that

the operationally produced AMVs that are routinely

available over the GTS nominally every 6 h are retained).

The second experiment (“RAPID-SCAN”) includes all

of the CONTROL observations but adds the special

rapid-scan AMVs produced by CIMSS during Typhoons

Slinlaku and Jangmi. The rapid-scan data were limited to

a few periods during these two storms, as listed in Table 2.

Thus, although only some of the analyses and forecasts are
directly impacted by the addition of the rapid-scan

data, the influence of the intermittently added observa-
tions can propagate through the 4D-Var cycle back-
ground into subsequent analyses/forecasts.

c. Comparison with dropwindsonde impacts

A final evaluation compares the NOGAPS analysis

and forecast impact of dropwindsondes (Franklin et al.

2003) with the impact of the AMVs. Dropwindsonde ob-
servations are often involved in data-targeting exercises
designed to ameliorate analysis deficiencies in potential

rapid-error-growth regimes as determined by objective

numerical methods. Because AMVs cover a larger do-

main than aircraft-deployed dropwindsondes do and are

<table>
<thead>
<tr>
<th>Expt</th>
<th>Description</th>
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<tbody>
<tr>
<td>CONTROL</td>
<td>All operational obs plus special hourly MTSAT AMV datasets (no aircraft dropwindsondes)</td>
</tr>
<tr>
<td>NO-CIMSS-AMV</td>
<td>Same as CONTROL, but hourly AMVs are removed</td>
</tr>
<tr>
<td>RAPID-SCAN</td>
<td>Same as CONTROL, but rapid-scan AMVs are added when available</td>
</tr>
<tr>
<td>CONTROL-DROP</td>
<td>Same as CONTROL, but dropwindsondes are added when available</td>
</tr>
</tbody>
</table>

TABLE 1. NOGAPS experiments designed to test the impact of specially enhanced hourly and rapid-scan AMVs and dropwindsondes produced during TPARC/TCS-08.
available more frequently, they could also be considered as potential candidates for data-targeting approaches if their forecast impact is comparable. The previously described CONTROL and NO-CIMSS-AMV experiments (both without dropwindsondes) are compared with the “CONTROL-DROP” experiment that also assimilates the TPARC/TCS-08 dropwindsondes. This set of experiments is also described in Table 1.

4. Results

a. Hourly AMVs

Figure 4 shows the mean track forecast error (n mi) as a function of forecast time (0–120 h) for the NOGAPS CONTROL and NO-CIMSS-AMV experiments. The statistics were generated for the 23 tropical cyclones in the western North Pacific during TPARC/TCS-08. The number of forecast cases for each forecast interval is plotted along with the respective track-error results. Note that these comparisons are homogeneous so that only times for which both experiments produced valid forecasts (e.g., the storm tracker could find a valid storm-center position) are included. Figure 4 shows the relatively small differences between mean track errors out to 72 h. Beyond that, CONTROL (with the enhanced hourly AMVs) consistently produces smaller track errors, although they are not statistically significant because of the relatively small number of forecasts. Additional information is provided in Table 3, which shows the percentage difference between the CONTROL and NO-CIMSS-AMV forecast results and the frequency of superior forecast performance (FSFP; the percentage of how often the corresponding forecast has the lowest error of the two). The FSFP reinforces the mixed but generally positive impact of the AMVs on this set of NOGAPS track forecasts. At the longer forecast lengths, the CONTROL FSFP values are generally slightly above 50% while the mean forecast errors are reduced by 6%–10%.

These results suggest that the enhanced AMVs primarily act to reduce the larger NOGAPS track-forecast-bust cases. This is further supported by Fig. 5, which shows box-and-whisker plots of the 120-h forecast track errors for the CONTROL and NO-CIMSS-AMV experiments. The top and bottom of the boxes represent the upper and lower quartiles of the error distributions, respectively. The whiskers represent the upper and lower 99th percentile of the error distributions, respectively. The solid

<table>
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<tr>
<th>Date</th>
<th>Rapid-scan AMVs (UTC)</th>
<th>Storm name</th>
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<td>10 Sep 2008</td>
<td>1300, 1600–2300</td>
<td>Sinlaku</td>
</tr>
<tr>
<td>11 Sep 2008</td>
<td>0000–1300, 1600–2300</td>
<td>Sinlaku</td>
</tr>
<tr>
<td>12 Sep 2008</td>
<td>0000–1300, 1600, 1800–2300</td>
<td>Sinlaku</td>
</tr>
<tr>
<td>13 Sep 2008</td>
<td>0000–0600</td>
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</tr>
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<td>17 Sep 2008</td>
<td>1300, 1600–2300</td>
<td>Sinlaku (ET)</td>
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<tr>
<td>18 Sep 2008</td>
<td>0000–1100</td>
<td>Sinlaku (ET)</td>
</tr>
<tr>
<td>27 Sep 2008</td>
<td>1300, 1600–2300</td>
<td>Jangmi</td>
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</table>

FIG. 4. Mean track forecast error (n mi) for the NOGAPS CONTROL and NO-CIMSS-AMV experiments. The number of homogeneous forecasts at each forecast interval is shown. These statistics include 23 western North Pacific tropical cyclones in August and September 2008.

Table 3. Comparison (homogeneous sample) of NOGAPS track forecasts between the CONTROL and NO-CIMSS-AMV experiments as described in Table 1. These statistics include all 23 western North Pacific tropical cyclones in August and September 2008.

<table>
<thead>
<tr>
<th>Forecast interval (h)</th>
<th>0</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>96</th>
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<tr>
<td>Mean track error (n mi)</td>
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<tr>
<td>CONTROL</td>
<td>33</td>
<td>48</td>
<td>80</td>
<td>104</td>
<td>132</td>
<td>168</td>
<td>220</td>
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<td>Frequency of superior forecast performance (%)</td>
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<td>51</td>
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<tr>
<td>No. of forecasts</td>
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<td>85</td>
<td>76</td>
<td>65</td>
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<td>46</td>
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<td>34</td>
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<td>21</td>
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</table>
lines near the middle of the box indicate the median track forecast errors, and the circles represent the mean forecast errors. Although the mean error values are relatively close, the median values and whisker spread indicate that the CONTROL has fewer large forecast errors as compared with the NO-CIMSS-AMV experiment.

b. Case study: Typhoon Sinlaku, 1200 UTC 11 September 2008

One of the most significant tropical cyclones in terms of intensity and duration during TPARC/TCS-08 was Sinlaku. In this section we examine the impact of the AMVs on NOGAPS track forecasts of Sinlaku in more detail. In particular, the forecast from 1200 UTC 11 September 2008 indicates a large positive impact from the AMVs, as shown in Fig. 6. Although all NOGAPS forecasts take Sinlaku to the northeast of the verifying track, the NO-CIMSS-AMV forecast takes Sinlaku much too far northeast and in 5 days has it just west of northern Japan. The CONTROL forecast, while still to the northeast, deviates much less from the observed track. Furthermore, the forecast that includes the rapid-scan AMVs (RAPID-SCAN; discussed in the next section) results in the best 120-h position of Sinlaku relative to the observations used for verification.

A closer examination of the forecast fields reveals a potential explanation for the improved track forecasts with the enhanced AMV data. Figure 7 shows the 48-, 60-, and 72-h forecasts of the 5850-m contours of 500-hPa geopotential height from the NOGAPS forecasts initialized at 1200 UTC 11 September, along with the CONTROL verifying analysis valid at the 72-h forecast time. The tracks of Sinlaku in the NOGAPS forecasts appear to be influenced by an approaching midlatitude trough crossing China to the northwest of the storm on 11–14 September (Komaromi et al. 2011). The observed track (Fig. 6)
suggests that this trough was not strong/deep enough to influence the steering of Sinlaku toward the north. This is not the case with the NOGAPS tracks, however, which respond to the approaching trough by lifting the storm to the north. All three forecasts develop the trough too far to the south toward Sinlaku during the forecast period. The forecast without the enhanced AMVs, however, indicates a much greater trough interaction, especially by 72 h. This interaction likely results in the forecast quickly accelerating Sinlaku to the northeast as shown in Fig. 6. The contours for the RAPID-SCAN and CONTROL forecasts (Fig. 7) are very close to each other, and both indicate a weaker forecast trough. The trough interaction for those forecasts has less influence on Sinlaku and is closer to the observed track. Despite the dense rawinsonde network over Asia, this case illustrates that the enhanced AMVs combined with a 4D-Var system can still influence the analysis of midlatitude synoptic features that play a key role in certain tropical cyclone track forecasts. This result is consistent with the findings for Atlantic Hurricane Katrina (2005) described in Langland et al. (2009).

Perhaps these findings should not be too surprising given the general positive impact of the enhanced AMVs on NOGAPS midlatitude analyses and forecasts. As shown in Fig. 8, the CONTROL forecasts (with CIMSS AMVs) are significantly more skillful than the NO-CIMSS-AMV experiment in terms of the 500-hPa midlatitude anomaly correlation for the western North Pacific region (20°–80°N, 130°–180°E) during the Sinlaku period. This result indicates that enhanced AMVs can effectively reduce
components of analysis error that contribute to the growth of NOGAPS medium-range forecast errors in midlatitudes, and provides strong evidence that the enhanced-AMV improvements to midlatitude analyses and resultant forecasts may partially explain the positive impact of these observations on recurring tropical cyclone tracks in the NOGAPS forecasts of Sinlaku.

c. Rapid-scan AMVs

In the above-described Sinlaku case-study example, the NOGAPS track forecast that assimilated rapid-scan AMVs (RAPID-SCAN) in addition to the hourly AMVs was shown to be superior. The rapid-scan AMVs are described in sections 2 and 3. In this section, NOGAPS track-forecast results for RAPID-SCAN are shown for the periods during which rapid-scan AMVs were available during TPARC/TCS-08.

Figure 9 compares the CONTROL, NO-CIMSS-AMV, and RAPID-SCAN experiments. The limited number of rapid-scan datasets reduces the number of forecasts that can be directly compared with the other experiments. It is curious that, for shorter forecast intervals, the RAPID-SCAN experiment has slightly higher forecast errors than the CONTROL. After 72 h, the RAPID-SCAN results are comparable. Table 4 shows the detailed statistics for all three experiments. The FSFP confirms that in this limited sample the rapid-scan wind observations appear not to produce superior NOGAPS track forecasts in the short range (less than 72 h), but do improve considerably on the NO-CIMSS-AMV forecasts at 72 h and beyond. These results are similar to those presented in Langland et al. (2009) for Atlantic Hurricane Katrina NOGAPS forecasts.

It is hypothesized that the negative impact of the rapid-scan AMVs at shorter forecast intervals may be linked to the use of synthetic observations by the NOGAPS system to help to define tropical cyclone vortex structures in the initial analyses. The plethora of lower-tropospheric rapid-scan AMVs normally achievable from VIS imagery on the outer periphery of the vortex (outside the central dense overcast) may disagree with the bogus values. This could set up erroneous gradients in the sensitive regions where the vortex interacts with the steering flow, thus creating negative short-term track forecast impacts. In addition, while the synthetic vortex observations only extend up to 400 hPa, the model analysis attempts to create a balanced condition above this, and these bogus observations may be at odds with the detailed upper-level structure defined by the enhanced rapid-scan AMVs in the tropical cyclone core and near environment. Therefore, it is possible the effects of the bogus observations may not only dampen the initial analysis information provided by the enhanced AMVs in the near-storm environment but may even contribute to negative influences on subsequent shorter-term forecasts. We recommend that a future study examine the effects of down weighting on the outer periphery of the vortex (outside the central dense overcast) may disagree with the bogus values. This could set up erroneous gradients in the sensitive regions where the vortex interacts with the steering flow, thus creating negative short-term track forecast impacts. In addition, while the synthetic vortex observations only extend up to 400 hPa, the model analysis attempts to create a balanced condition above this, and these bogus observations may be at odds with the detailed upper-level structure defined by the enhanced rapid-scan AMVs in the tropical cyclone core and near environment. Therefore, it is possible the effects of the bogus observations may not only dampen the initial analysis information provided by the enhanced AMVs in the near-storm environment but may even contribute to negative influences on subsequent shorter-term forecasts. We recommend that a future study examine the effects of down weighting.

**Table 4.** Comparison (homogeneous sample) of NOGAPS track forecasts among the CONTROL, NO-CIMSS-AMV, and RAPID-SCAN experiments as described in Table 1. These statistics include a limited set of cases from western North Pacific tropical cyclones in August and September 2008 for which rapid-scan datasets were available.

<table>
<thead>
<tr>
<th>Forecast interval (h)</th>
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<th>12</th>
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the bogus in the NOGAPS initial analysis in the presence of enhanced AMVs.

d. Forecast impacts relative to dropwindsondes

The aircraft missions flown during TPARC/TCS-08 afford an opportunity to assess the impact of dropwindsonde observations on NOGAPS track forecasts, relative to the enhanced AMVs. A set of experiments to compare these impacts is described in section 3c and Table 1. Only NOGAPS forecasts initialized within 24 h of an aircraft dropwindsonde mission are included in the comparison cases. The results of this comparison are shown in Fig. 10 and Table 5. At least for this small sample of cases, the dropsonde observations show a slightly negative impact relative to the CONTROL. The differences are small, and the dropsonde impact is highly variable. Note that in this experiment all dropwindsondes were assimilated, including those dropped in the core eyewall. Some studies have suggested that eyewall dropwindsondes can lead to negative model track forecasts (Aberson 2008; Harnisch and Weissmann 2010). These limited results suggest that enhanced AMV datasets could be candidates for objective data-targeting approaches to improve numerical tropical cyclone track forecasts, and more comprehensive studies with larger datasets are recommended.

5. Summary and discussion

This study has examined the assimilation of enhanced hourly and rapid-scan AMVs in a 4D-Var system to evaluate their impact on tropical cyclone track forecasts during TPARC/TCS-08. Observing-system experiments are performed using the NAVDAS-AR–NOGAPS global assimilation and forecast system. In general, the results here support the hypothesis that increasing the amount of assimilated AMV observations (hourly) can improve medium-range numerical forecasts of tropical cyclone tracks, especially in cases in which track forecasts have relatively large uncertainty. The reduction in NOGAPS mean track forecast errors is 6%–10% in the 3–5-day forecast period. Inclusion of rapid-scan AMVs with the hourly AMVs provides a slight additional improvement in the track forecast skill for the cases in which those data were available. The mean forecast errors are slightly degraded, however, at shorter intervals (1–3 days), suggesting that perhaps the operational NOGAPS bogus may receive too much weight in the analysis relative to enhanced-AMV observations in the near-cyclone environment.

Additional case studies are required to demonstrate the full impact of enhanced AMVs on tropical and midlatitude forecasts to achieve statistical significance. It would also be of interest to test the impact of these observations in other data assimilation and forecast systems and over different geographic regions to demonstrate the robustness of the results. Studies are currently under

![Figure 10. Mean track forecast error (n mi) for the NOGAPS CONTROL, CONTROL-DROP, and NO-CIMSS-AMV experiments as described in Table 3. The number of homogeneous forecasts at each forecast interval is shown. These statistics include only those western North Pacific tropical cyclones cases in August and September 2008 that had aircraft dropwindsondes.](http://journals.ametsoc.org/jamc/article-pdf/50/11/2309/3558503/jamc-d-11-019_1.pdf)

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way to test high-density AMVs (and other multiplatform satellite observations) in high-resolution hurricane mesoscale models [e.g., Hurricane Weather Research and Forecast System model (HWRF) and Coupled Ocean–Atmosphere Mesoscale Prediction System—Tropical Cyclone (COAMPS-TC)]. These experiments will also focus on improving tropical cyclone intensity and structure prediction—parameters that are not forecast well in current global models.

In terms of observation targeting, the addition of hourly and rapid-scan AMVs represents a viable complement to “traditional” targeting with aircraft dropwindsondes, provided that proper assimilation methods and strategies are employed. Because high-density AMVs can be derived at frequent intervals over regional-size domains, these observations are more likely than dropwindsondes to provide complete space–time flow coverage over objectively determined “target regions,” leading to an improvement in numerical tropical cyclone track forecasts.

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REFERENCES