Characteristics of Himawari-8 Rapid Scan Atmospheric Motion Vectors Utilized in Mesoscale Data Assimilation

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Abstract

Rapid scan atmospheric motion vectors (RS-AMVs) were derived using an algorithm developed by the Meteorological Satellite Center of the Japan Meteorological Agency (JMA) from Himawari-8 rapid scan imagery over the area around Japan. They were computed every 10 min for seven different channels, namely, the visible channel (VIS), near infrared and infrared channels (IR), three water vapor absorption channels (WV), and CO$_2$ absorption channel (CO$_2$), from image triplets with time intervals of 2.5 min for VIS and 5 min for the other six channels. In June 2016, the amount of data was increased by more than 20 times compared to the number of routinely used AMVs. To exploit these high-resolution data in mesoscale data assimilation for the improvement of short-range forecasts, data verification, and assimilation experiments were conducted. The RS-AMVs were of sufficiently good quality for assimilation and consistent overall with winds from JMA's mesoscale analyses, radiosonde, and wind profiler observations. Errors were slightly larger in WV than in VIS and IR channels. Significant negative biases relative to sonde winds were seen at high levels in VIS, IR, and CO$_2$, whereas slightly positive biases were noticeable in WV at mid- to high levels. Data assimilation experiments with the JMA's non-hydrostatic model based Variational Data Assimilation System (JNoVA) on a cold vortex event in June 2016 were conducted using RS-AMVs from seven channels. The wind forecasts improved slightly in early forecast hours before 12 hours in northern Japan, over which the vortex passed during the assimilation period. They also showed small improvements at low levels when averaged over the whole forecast period. The results varied slightly depending on the channels used for assimilation, which might be caused by different error characteristics of RS-AMVs in different channels.

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1. Introduction

Atmospheric motion vectors (AMVs) are wind vectors derived by tracking the spatial distributions of clouds and water vapor in consecutive satellite images. They have been used in operational numerical weather prediction (NWP) systems around the world since as early as the 1970s (Menzel 2001). With their good coverage, AMVs have been proven useful for identifying synoptic air flows, including over the ocean where other observational data are comparatively scarce. The Meteorological Satellite Center (MSC) of the Japan Meteorological Agency (JMA) began routinely computing AMVs using imagery from their first geostationary meteorological satellite in 1978, and the JMA started to use them in their NWP system the next year. Advances in both satellites and NWP systems over the years have made more highly spatial and temporal AMV datasets available for assimilation into operational NWP systems with finer model resolutions. AMVs are considered to be useful for representing local-scale flow in mesoscale systems as well as synoptic winds in global systems (Bedka and Mecikalski 2005; Velden et al. 2005; Bedka et al. 2009). Now that recent satellites such as Himawari and the Geostationary Operational Environment Satellite (GOES) series are operated in rapid scan (RS) mode, the possibility of producing even higher resolution AMVs is expanding.

The benefits of reducing the time interval between images for computing AMVs have been discussed in earlier studies (Rodgers 1979; Johnson and Suchman 1980; Saito and Takano 1986; Uchida et al. 1991; Velden et al. 2005). The major advantages of RS-AMVs found in these studies include an increase in the number of data points, especially at low levels, and the possibility of depicting wind fields near targeted tropical cyclones (TCs) or front systems in greater detail; thus, they have been considered favorably for dealing with such mesoscale phenomena. Among recent studies that use RS imagery from multi-functional transport satellites (MTSAT-1R and 2R), Oyama et al. (2016) showed that upper tropospheric AMVs can be used to detect TC intensification, and Hamada and Takayabu (2016) estimated vertical velocities at the convective cloud top.

Furthermore, attempts to assimilate high-resolution RS-AMVs into NWP systems to improve forecasts of tropical cyclones have been getting more attention. Some studies using GOES RS-AMVs for assimilation showed improvements in forecasts of TC track or intensity (Langland et al. 2009; Velden et al. 2017; Wu et al. 2015). Berger et al. (2011) and Wu et al. (2014; 2015) investigated the impact of assimilating enhanced AMVs processed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS, University of Wisconsin–Madison) from MTSAT RS imagery obtained for the THORPEX Pacific Asian Regional Campaign in 2008 (Nakazawa et al. 2010).

MTSATs, the former geostationary satellite series before Himawari-8 and Himawari-9, conducted RS operations during the THORPEX campaign, daytime during the summers of 2011–2014, and during some other periods, and RS-AMVs were produced accordingly by MSC. Yamashita (2010) performed assimilation experiments for typhoon cases with MTSAT RS-AMVs during the THORPEX campaign using the global and mesoscale operational NWP systems of the JMA and found positive impacts on track forecasts. MTSAT RS-AMVs derived from three images at 5-min intervals proved to be useful in global and mesoscale assimilation and typhoon analyses in some studies: Yamashita (2012) reported some improvements in rainfall and typhoon intensity forecasts by assimilating such RS-AMVs into JMA’s operational mesoscale NWP system. Otsuka et al. (2015) conducted assimilation experiments of a heavy rainfall event associated with a stationary front and found a slight positive impact on precipitation forecasts.

Since July 2015, with additional varieties of channels and improved sensor performance, Himawari-8 has been able to produce higher resolution AMVs such as hourly computed AMVs from 10 min full disk scans for routinely operated NWP systems (RTN-AMV) and RS-AMVs from 2.5 min rapid scans. Assimilation of Himawari-8 RTN-AMVs into the JMA’s operational global and mesoscale NWP systems positively impacted analyses and improved typhoon and rainfall forecasts (Yamashita 2016). The assimilation of Himawari-8 RS-AMVs by an ensemble Kalman filter implemented with a mesoscale regional model improved precipitation forecast scores for a heavy rainfall event (Kunii et al. 2016) and wind forecasts in another case study (Otsuka et al. 2016). Although these results suggest that the impacts of Himawari-8 RS-AMVs on mesoscale forecasts are positive and
promising, they still seem to be case dependent since there is no established method for making better use of such a large amount of high-resolution RS-AMV data and their data representativeness and error characteristics are not sufficiently taken into account. It is necessary to understand more about the features and qualities of RS-AMV data before developing optimal methods for data selection, data thinning, quality control, and other pre-processing procedures to utilize them more efficiently in a mesoscale NWP system. In addition to the increase in resolution and frequency, Himawari-8 RS-AMVs are available in more channels than MTSAT RS-AMVs, including the two new water vapor channels (WV) and the CO$_2$ absorption channel (CO$_2$). The data characteristics of RS-AMVs in each channel had not yet been fully examined in the previous studies. We also need to study the characteristics of different channels and provide useful information so as to better handle these multi-channel RS-AMVs in the assimilation system.

The purpose of this study was to clarify the data characteristics of RS-AMVs in terms of their use in mesoscale data assimilation for the improvement of short-range forecasts. First, their data quality and observation error characteristics were examined based on the statistics of the differences from JMA mesoscale analyses, radiosonde, and wind profiler observations, and JMA non-hydrostatic model (JMA-NHM; Saito et al. 2006) forecasts. Next, assimilation experiments were conducted for a mesoscale cold vortex event to investigate the impacts of RS-AMVs on the analyses and forecasts and to see how the data characteristics were reflected in the results of the assimilation.

The rest of the paper is structured as follows. Section 2 describes the data verification and error characteristics of RS-AMVs, Section 3 describes the assimilation experiments, and Section 4 provides the discussion. Finally, we present our conclusions in Section 5.

2. Verification and error characteristics of RS-AMVs

2.1 Data verification

a. Data and methods

Himawari-8 RS-AMVs were derived from image triplets at 2.5-min intervals for the visible (VIS) channel and at 5-min intervals for the near-infrared and infrared (IR) channels, three WV channels, and the CO$_2$ channel, extracted from 2.5 min rapid scan observations over two rectangular areas around Japan (Fig. 1). They were computed every 10 min for each of the seven channels of the Advanced Himawari Imager (AHI) using the same AMV software used for RTN-AMVs, which was developed to adapt to the high spectral, spatial, and temporal resolutions of the AHI (Shimoji 2014). Figure 2 shows the number of RS-AMVs by pressure level for the month of June 2016. Black, dark gray, gray hatched with black lines, gray, white hatched with light gray lines, white hatched with black lines, and white bars show the number of B03, B07, B08, B09, B10, B13, and B16 observations, respectively.
improvements in cloud feature tracking and cloud height assignment methods in the software and the increased number of channels enabled Himawari-8 to produce many more low- and middle-level winds as well as additional high-level winds than previous satellites. It should be noted that low-level winds over land finally became available because the high resolution of the AHI made it possible to distinguish cloud movements from land features. The horizontal resolution of the RS-AMV dataset was about 0.04° in latitude and longitude, and the target box size used for cloud tracking in the computation was 5 pixels × 5 pixels. The total number of data for the month was more than 20 times the number of RTN-AMVs, owing to the higher space and time resolution of the RS-AMV data.

Because each channel of the AHI has a unique specification and sensitivity to atmospheric conditions as described in Bessho et al. (2016), RS-AMVs of different channels are expected to represent wind fields with different horizontal scales and at different heights. For example, high clouds such as cirrus or water vapor features with relatively large horizontal scale are tracked in mid- to upper air in IR or WV for the retrieval of AMVs, while local cumulus clouds are targeted in VIS and IR at low levels. It is necessary to understand their data characteristics before putting them to use for assimilation. As shown in Table 1, RS-AMVs were computed in seven channels: VIS with the highest spatial resolution of 0.5 km (B03), IR included in the short-wave infrared band (B07) and the infrared band (B13), WV in the water vapor absorption bands (B08, B09, and B10), and CO₂ in the CO₂ absorption band (B16). AMVs have been computed in almost the same bands as B03, B07, B08, and B13 since the MTSAT series, while B09, B10, and B16 are entirely new for AMV retrieval. WV AMVs were obtained only in cloudy conditions, so they were supposed to track cloud tops similarly to high-level IR winds (Velden et al. 1997). CO₂ AMVs also track clouds since CO₂ is normally well mixed in the troposphere. Though the CO₂ band is often used in height assignment as auxiliary information, it seems convenient for tracking because land features are not so apparent at low levels in its imagery and tracking features are more recognizable at high levels than in those of WVs.

The RS-AMV datasets were compared with the JMA’s Mesoscale Analysis (MA) and upper-air observational data for the month of June 2016. Figure 3 maps out the GPS radiosonde and wind profiler (WPR) stations in the JMA’s upper-air observation network used for the comparisons. The distance between a pair of compared observations was within 150 km hori-

Table 1. Seven channels of the AHI used for computing RS-AMVs.

| Channel | Wavelength (μm) | Category | Spatial resolution (km) | Time resolution (min) | AMV height level |
|---------|----------------|----------|------------------------|----------------------|-----------------|
| B03     | 0.64           | VIS      | 0.5                    | 2.5                  | Low, Mid, High  |
| B07     | 3.9            | IR       | 2                      | 5                    | Low, Mid, High  |
| B08     | 6.2            | WV       | 2                      | 5                    | High            |
| B09     | 6.9            | WV       | 2                      | 5                    | Mid, High       |
| B10     | 7.3            | WV       | 2                      | 5                    | Mid, High       |
| B13     | 10.4           | IR       | 2                      | 5                    | Low, Mid, High  |
| B16     | 13.3           | CO₂      | 2                      | 5                    | Low, Mid, High  |

Fig. 3. Upper-air observation stations of the JMA used for the comparison with RS-AMVs. Circles and crosses represent sonde and WPR stations, respectively.
zontally, 25 hPa vertically, and 1.5 hours in time for sonde observations following the recommendation of the Coordination Group for Meteorological Satellites (Schmetz et al. 1999). Moreover, WPR observations used for comparison were within 50 km, 10 hPa, and 10 min, respectively. The statistical analysis for the verification was separately made for each group of three different height classes: low (below the 700 hPa pressure level), middle (700–400 hPa), and high (above 400 hPa) levels.

b. Results of verification

First, RS-AMVs were compared with MA at the nearest grids. Table 2 shows the differences (RS-AMV minus MA) averaged over the entire month of June 2016. The root mean square vector differences (RMSVDs) in the VIS and IR (B03, B07, and B13) channels were around 3.4–4.6 m s\(^{-1}\) at low levels, 4.5–4.8 m s\(^{-1}\) at mid-levels, and 5.4–5.6 m s\(^{-1}\) at high levels. They were somewhat smaller compared to those in the WV channels (B08, B09, and B10) at mid- or high levels. The root mean square differences (RMSDs) for the u- and v-components and wind speed were also slightly larger in WV than in the VIS and IR channels, and slight positive biases were noticeable in the mean differences (MD) for wind speed in B08 and B09. B10 showed the smallest differences among the three WV channels. As for the CO\(_2\) channel, its low-level winds had larger RMSVDs and RMSDs compared to VIS and IR, while its errors for mid- and high-level winds were comparable to VIS and IR and smaller than the WV channels.

The comparisons with sonde observations (Table 3) showed similar results, with slightly larger RMSVDs and RMSDs in the WV channels than in the VIS, IR, and CO\(_2\) channels. In contrast to the results of the comparison with MA, MDs of the u-component and wind speed suggested that RS-AMVs in VIS and IR had significant negative biases above mid-level. High-level winds in CO\(_2\) also showed a slight negative bias. Furthermore, in the WV channels, slight positive biases were seen at high levels in B08 and at mid-level in B09 and B10. Low-level winds in VIS and IR showed slight positive biases, which were not distinctly seen in the comparison with MA.

With their higher spatial and temporal data resolutions than sonde observations, WPR observations could validate many more local winds at low level. Table 4 shows the differences of low-level RS-AMVs in the VIS, IR, and CO\(_2\) channels from WPR observations. Overall, they appear consistent, except for a slight negative bias in the u-component and wind speed of B16. RMSVD, RMSDs, and MDs were smallest in the VIS channel, as expected, because it
has the highest spatial and temporal resolutions of all of the channels. The positive wind speed biases that were seen in the comparison with sonde low-level winds in VIS and IR were not recognized in the comparison with WPR observations.

In summary, the quality of Himawari-8 RS-AMVs is sufficient for assimilation. The VIS and IR channels that were inherited from the MTSAT series proved to produce better RS-AMVs than the WV channels, including the two new channels (B09 and B10), in terms of consistency with MA, sonde, and WPR observations; however, negative biases against sonde observations above mid-level were significant. In fact, this negative trend has been a well-known issue in AMV communities for many years (Schmetz et al. 1993; Velden and Bedka 2009); it has been considered because of either height assignment errors or target tracking errors, especially in and near jet streams, and was recognized in MTSAT-1 RS-AMV as well (Otsuka et al. 2015). Although Shimoji and Nonaka (2016) reported that the negative biases against sonde were somehow alleviated in Himawari-8 RTN-AMVs compared to MTSAT RTN-AMVs, the same trend was still found. The reason why they were not conspicuous in the comparison with the MA may be that RTN-AMVs were already assimilated during the construction of the MA. Velden and Bedka (2009) showed that errors associated with height assignment contributed an important part of AMV data uncertainties by comparing with collocated rawinsonde profiles. It was found that many AMVs in the location of the jet stream were assigned to higher than the level of best fit determined with the rawinsonde collocation. Similar issues of the height assignment uncertainties and

Table 3. RMSVD, RMSD, and MD values of RS-AMVs relative to sonde observations.

| Channel | Level | RMSVD (m s$^{-1}$) | RMSD (m s$^{-1}$) | MD (m s$^{-1}$) | Number of data |
|---------|-------|-------------------|------------------|----------------|----------------|
| B03     | Low   | 6.38              | 4.92             | 0.03           | 2,803          |
|         | Mid   | 6.84              | 5.28             | -1.14          | 3,673          |
|         | High  | 9.13              | 7.17             | -0.88          | 6,464          |
| B07     | Low   | 7.14              | 5.18             | 0.77           | 5,407          |
|         | Mid   | 7.24              | 5.54             | -0.89          | 7,853          |
|         | High  | 9.21              | 7.06             | -1.36          | 13,789         |
| B08     | High  | 10.42             | 8.03             | 0.12           | 17,479         |
| B09     | Mid   | 8.42              | 6.04             | 0.86           | 3,577          |
|         | High  | 9.89              | 7.62             | -0.28          | 17,375         |
| B10     | Mid   | 8.08              | 6.08             | 0.43           | 5,993          |
|         | High  | 9.77              | 7.56             | -0.39          | 17,190         |
| B13     | Low   | 7.24              | 5.23             | 0.77           | 4,861          |
|         | Mid   | 7.35              | 5.51             | -0.45          | 7,747          |
|         | High  | 9.19              | 7.01             | -0.96          | 15,230         |
| B16     | Low   | 7.18              | 5.15             | -0.02          | 1,488          |
|         | Mid   | 7.60              | 5.78             | -0.04          | 7,054          |
|         | High  | 9.39              | 7.15             | -0.50          | 15,695         |

Table 4. RMSVD, RMSD, and MD values of low-level RS-AMVs in VIS, IR, and CO$_2$ channels relative to wind profiler observations.

| Channel | RMSVD (m s$^{-1}$) | RMSD (m s$^{-1}$) | MD (m s$^{-1}$) | Number of data |
|---------|--------------------|-------------------|----------------|----------------|
| B03     | 5.30               | 3.96              | -0.07          | 72,952         |
| B07     | 6.73               | 4.89              | 0.26           | 70,892         |
| B13     | 7.01               | 5.10              | 0.22           | 68,948         |
| B16     | 6.60               | 4.88              | -0.46          | 23,269         |
the vertical representativeness were addressed in other studies as well using space-borne lidar observations (Weissmann et al. 2013; Folger and Weissmann 2014; Folger and Weissmann 2016) or simulated AMVs (Hernandez-Carrascal and Bormann 2014; Lean et al. 2015). In contrast to IR channels, WV channels, B08 in particular, tended to show a positive bias above mid-level. Velden et al. (1997) reported that WV high-level winds were similar to those of IR but exhibit slightly lower heights because of the spectral response functions. This may partly explain the bias difference between IR and WV. Another new channel, CO₂, also seemed to produce winds of good quality comparable to those of VIS and IR, except at low level. Low-level winds in VIS and IR, including those over land areas, were in good agreement with WPR, so that they could possibly capture characteristic wind features near the surface that are useful for mesoscale prediction. It should be noted that low-level winds in B03 were of better quality than other winds, probably because that channel has the highest resolution in both space and time.

We estimated the same kind of statistical analysis to RTN-AMVs and found that the tendency and magnitude of the differences from MA and upper-air observations for each channel were similar to those of RS-AMVs regardless of their differences in temporal resolution (not shown). This result means that the characteristics of AMVs found in the data originated from the AHI specifications as well as from the new retrieval algorithm (Shimoji 2014). The advantages of using a 2.5 min rapid scan over the routine 10-min scan for AMV retrieval seemed to be in the increased number of data and higher density and frequency rather than the data quality.

2.2 Inter-channel observation error correlation

a. Data and method

We estimated the inter-channel correlation of observation errors of RS-AMV based on first-guess departure (RS-AMVs minus NHM first-guess winds) statistics using the so-called Hollingsworth–Lönnberg method (Bormann and Bauer 2010; Waller et al. 2016). This method is limited in its ability to estimate accurately observation error correlation between observations because first-guess departures may also be influenced by correlated first guesses between the two observations. However, it may serve our purpose in this paper for obtaining an overall view of the relationships of the error characteristics among the multi-channel RS-AMVs. The first-guess samples were taken every 10 min from the 15-hour NHM forecasts, which were run every day at an initial time of 00:00 UTC from 1 to 10 June 2016 with a horizontal resolution of 5 km (721 × 577 grid points) and 50 vertical levels. Among the 15-hour forecasts, those in the first six hours were discarded as spin up and not used for the computation. First-guess departures were obtained as RS-AMVs minus NHM forecast winds (first guess) at the time of RS-AMV observations every 10 min from the 6 hour Forecast Time (FT06) to FT15. Correlations of first-guess departures between pairs of observations within the same 3-hour window and within a distance of 50 km in the horizontal and 25 hPa in the vertical were calculated and averaged for the 10-day period.

b. Estimated observation error correlations

Table 5 shows the estimated inter-channel observation error correlations for the u- and v-components. It is generally considered that an error correlation between two adjacent observations greater than around 0.2 degrades the analysis and forecast (Liu and Rabier 2003). The values were around 0.20 to 0.35, indicating moderately high correlations between the channels. The two IR channels, B07 and B13, were most strongly related, with values of 0.35 for both u and v. The three WV channels also showed relatively high correlation with each other and were well correlated with B13, with values above 0.25. B16 showed the strongest correlation with B13 and rather high
correlations with WV and B07 as well. B03 showed the highest correlation value with B13 compared with the other channels. These relationships among the channels seem reasonable, assuming similar error characteristics for channels of the same category as we saw in the data verification results in Section 2.2. The differences or similarities of data distribution by layers (Fig. 2) between the channels could also be a factor to decide their relationships.

3. Assimilation experiments

The features of the RS-AMV observation errors were presented in the previous sections. For the next step, this section shows how their data characteristics are reflected in their assimilation behavior, which is one of our major interests in this paper.

3.1 The data assimilation system and experimental design

Assimilation experiments were conducted using the JNoVA data assimilation system (Honda et al. 2005). JNoVA is an incremental 4D-Var system for mesoscale analysis based on the formulations of Courtier et al. (1994). Because details of the system are described in JMA (2013), here we only explain the modifications that were made for the purpose of assimilating RS-AMVs in this study. First, 10-min RS-AMV observations were collected into 10-min time slots within a 3-hour time window instead of the ordinary interval of 1 hour used for the other observation data, including surface, upper air, radar, satellite, and ground-based Global Navigation Satellite System data. Thus, data for each slot were compared with the NHM first guess and quality controlled every 10 min in the case of RS-AMV. Second, RTN-AMVs around Japan were excluded when RS-AMVs were assimilated to avoid the redundancy that might be caused using two AMV datasets obtained from the same Himawari-8. It should be noted that the domain of excluded RTN-AMVs was almost the same as the MA area (Fig. 4a) and much broader than the rapid scan area in Fig. 1. Finally, the horizontal scale of RS-AMV thinning was reduced to 0.5° or 1.0° from the operational setting of 2.0° to exploit these high-density data. Two different thinning scales were used to examine the impact on the analysis and forecast by the length of data thinning. A thinning distance of 0.5° may be slightly too short, considering possible observation error correlations in space. However, its use can be justified because we intended to distinguish the expected impact using as many RS-AMV data as possible and to demonstrate their effects in a case study on mesoscale disturbance.

The vertical thinning scale was 100 hPa, the same as that for RTN-AMVs. The data thinning was done once during a 3-hour window in the same way as RTN-AMVs to avoid observation error correlations in time space. Through the thinning procedure, a representative RS-AMV vector was chosen from all of the RS-AMVs of all of the channels in a three-dimensional thinning box space of 0.5° × 0.5° × 100 hPa (1° × 1° × 100 hPa) collected in 10-min timeslots in a 3-h assimilation window. It was determined based

![Fig. 4](image-url)
on combining three factors with weights, the time difference from the analysis time, distance from the center of the thinning box, and the value of the quality indicator flag (QI; Holmlund 1998). A vector that is closer to the analysis time and the box center and has a higher QI value was prioritized. In this way, we could usually avoid inter-channel observation error correlations. The possible nearest distance between adjacent observations was approximately 50 (100) km and 100 hPa in space and 10 min in time.

RS-AMVs were selected based on QI, which was attached to individual data in the first phase of quality control, before going through the thinning process and other quality checks such as for gross errors. The QI value is based on consistency checks with the first-guess field of a global spectral model, neighboring wind vectors, and previous observations. A higher QI value means better data quality. The QI thresholds used in the experiments were determined depending on the channel categories and height classes, taking into account the results of data verification (Table 6). The observation errors were the same as those used operationally during the time of the MTSAT series (Table 7). The magnitudes of the observation errors were determined according to pressure height levels, regardless of the differences among channels.

Table 6. Quality Index threshold values for each channel.

| Channel | Threshold of QI number
|---------|------------------------|
|         | Low | Mid | High |
| B03     | 0.60 | -   | -    |
| B07     | 0.60 | 0.60 | 0.75 |
| B08     | -   | -   | 0.90 |
| B09     | -   | 0.90 | 0.90 |
| B10     | -   | 0.90 | 0.90 |
| B13     | 0.60 | 0.60 | 0.75 |
| B16     | -   | 0.90 | 0.90 |

Table 7. Observation error values for RS-AMVs used in JNoVA.

| Pressure level (hPa) | Observation error (m s⁻¹) |
|---------------------|---------------------------|
|                     | u  | v  |
| 10                  | 6.2 | 7.2 |
| 30                  | 5.1 | 6.2 |
| 50                  | 3.5 | 5.1 |
| 100                 | 4.4 | 6.0 |
| 200                 | 3.8 | 4.9 |
| 300                 | 4.6 | 3.7 |
| 500                 | 3.7 | 3.0 |
| 700                 | 3.2 | 2.6 |
| 850                 | 2.9 | 2.3 |
| 1000                | 4.1 | 3.3 |
| 1100                | 4.1 | 3.3 |

Table 8. Summary of the assimilation experiments.

| Experiment | Level of RS-AMVs assimilated |
|------------|------------------------------|
| B03        | Low                          |
| B07        | Low, Mid, High               |
| B08        | High                         |
| B09        | Mid, High                    |
| B10        | Mid, High                    |
| B13        | Low, Mid, High               |
| B16        | Mid, High                    |
| ALL        | Low, Mid, High               |

The domains of assimilation and forecasts are shown in Fig. 4. The assimilation experiments described in Table 8 were conducted during 12 hours in the daytime when VIS AMVs were available (21:00 UTC 19 to 09:00 UTC 20 June 2016), i.e., four forecast-analysis cycles of JNoVA, during which a cold vortex, described in the next section, passed over the north Tohoku region from the Japan Sea to the Pacific side of Japan. In each experiment, the analysis results at 09:00 UTC 20 were used as the initial conditions, and a 24-h forecast was obtained.

3.2 The selected event

Assimilation experiments with RS-AMVs were performed for a cold vortex event that occurred on 20 June 2016. On that day and the next, a Baiu stationary front extended across from China to the southern coast.
of the main island of Honshu (Figs. 5a, b, c), and a low appeared in the Japan Sea off the coast of northern Japan, Hokkaido and Tohoku. At 500 hPa, there was an upper level low over the Japan Sea accompanied with a cold vortex of −15°C (Fig. 5d) that moved eastward during the day, passed across the northern part of Tohoku and out on to the Pacific at night (Figs. 5e, f).

Figures 6a, 6b, 6c, and 6d show the distributions of the Himawari-8 AMVs that were assimilated in the experiments of CNTL, ALL, CNTL0.5, and ALL1.0 during the fourth cycle, 06:00−09:00 UTC 20 June. RS-AMVs in ALL (Fig. 6b) distinctly represent the wind field near the cold vortex over northern Japan with much denser data than RTN-AMVs in CNTL (Fig. 6a), which also indicated the location of the vortex but less clearly with many fewer data. CNTL 0.5 (Fig. 6c) assimilated a larger amount of RTN-AMVs than CNTL but still failed to capture wind vectors near the vortex in detail compared to ALL or ALL1.0 (Fig. 6d). It seemed that RS-AMVs had the advantage of detecting mesoscale flow fields near the vortex with higher temporal resolution than RTN-AMVs. Figures 6e and f show the first-guess departures of wind vectors in the ALL experiment during the same period. The low-level winds around the low over the Japan Sea seemed to have changed to strengthen cyclonic flow, and weakening of westward winds was significant above 400 hPa. Hereafter, we focus on the changes that occurred only in the vicinity of the cold vortex in northern Japan because our strongest interest was in those local winds near the vortex that were expressed well with RS-AMVs but not with RTN-AMVs.

Fig. 5. JMA-produced weather analysis at 00:00 UTC (a), 12:00 UTC (b) on 20, and 00:00 UTC on 21 (c) June 2016 for the surface. Geopotential heights in meters (color shades) and contours of temperatures in degrees Celsius using a contour interval of 3.0 degrees at 500 hPa height obtained from JMA’s meso analyses at 00:00 UTC (d), 12:00 UTC (e) on 20, and 00:00 UTC on 21 (f) June 2016.
3.3 Results of assimilation experiments

a. Analysis

The differences in the analyses at the end of the four cycles at 09:00 UTC on 20 June 2016 between ALL and CNTL experiments are shown in Fig. 7. The cold vortex was over northern Tohoku at that time and moving eastward. Differences in the wind vector and wind speed fields at 500 and 300 hPa (Figs. 7a, b) corresponded well with the wind field of the first-guess departures in the last assimilation circle (Figs. 6e, f) described in the previous section. Westward winds near the cold vortex were weaker at 300 hPa in ALL, which might affect the eastward moving speed of the cold vortex. In ALL, geopotential heights of 500 hPa were higher to the north of the vortex and lower to its south (Fig. 7c), and temperatures at 500 hPa were slightly lower around the cold vortex than in CNTL (Fig. 7d).

b. Forecast

Next, the forecasts in ALL and CNTL were compared at 12:00 UTC on 20 June (FT03). The maps
in Figs. 5b and 5e show that the center of the cold vortex was off the Pacific coast of northern Tohoku, a low at 500 hPa was over the strait between Tohoku and Hokkaido, and surface lows appeared on both the Japan Sea and Pacific sides of the upper low. The ALL experiment simulated the positions and scales of the cold core and upper low (Fig. 8a) nearly as well as CNTL (not shown). Although the temperatures at 500 hPa did not show significant differences around the vortex (Fig. 8c), geopotential heights at 500 hPa (Fig. 8b) and surface pressures (Fig. 8d) in ALL were lower than those in CNTL in that area. These changes seem to agree with the changes in wind field analyses where cyclonic flows at low or mid-levels were enhanced by RS-AMVs. It is probable that assimilation of RS-AMVs caused the slight change in the intensity of the vortex.

The mesoscale cold vortex had weakened and lost its circular structure as it moved to the northeast over the Pacific in later hours. By 00:00 UTC on 21 June (FT15), circulation of the cold vortex was no longer identifiable, the intensity of the low had weakened (Fig. 8e), and two small cold-core lows appeared side by side in the area between Hokkaido and Tohoku (Fig. 5f). The geopotential heights of 500 hPa near the lows were lower in ALL than in CNTL (Fig. 8f), indicating...

Fig. 7. Differences in the analysis results between ALL and CNTL (ALL minus CNTL) at 09:00 UTC on 20 June 2016 after the four assimilation cycles. (a) Wind vectors and wind speeds at 500 hPa, (b) wind vectors and wind speeds at 300 hPa, (c) geopotential heights at 500 hPa, and (d) temperatures at 500 hPa. Arrows represent wind direction in (a) and (b). Color shades represent wind speed (m s\(^{-1}\)) in (a) and (b), geopotential heights in (c), and temperatures in (d). Crosses indicate the position of the center of the cold vortex.
their slight intensification.

The forecast winds and temperatures at FT03 and FT15 were validated using sonde data at the observational sites over northern Japan (Fig. 9). At FT03, the RMSVDs were smaller overall in ALL than CNTL from 850 to 300 hPa levels, except at around 600 hPa (Fig. 9a), indicating a positive impact on the wind fields near the cold vortex. Furthermore, the temperature errors improved slightly at mid- to high levels (300–600 hPa) but degraded at the lowest and uppermost levels (below 800 hPa and above 250 hPa; Fig. 9b). The RMSVDs at FT15 showed better agreement in ALL than CNTL from 700 to 300 hPa (Fig. 9c). The temperatures at 500 and 600 hPa were worse than CNTL, but improvement was seen at some levels, especially above 400 hPa (Fig. 9d).

As described in Section 3.2, two additional experiments, CNTL0.5 and ALL1.0 besides CNTL and ALL in which the scales of data thinning were changed, were also conducted. CNTL0.5 exhibited similar results to CNTL besides the winds at FT15. It also outperformed ALL at low levels at that time, which might be because its dense coverage in much broader area than ALL had some advantages in later hour forecasts. As for ALL1.0, the results showed no or little improvement compared to ALL, except for the temperatures at FT03. More RS-AMVs with a shorter length thinning scale might cause a more positive impact; however, we do not further discuss about the reason for it. We can deduce that we could safely use the thinning scale of 0.5° in assimilating RS-AMVs for the purpose of this paper without fear of degradation originated from observation error correlations among neighboring
observations. Hereinafter, we refer to the ALL experiment with the data-thinning scale of 0.5° only. In the comparison with ALL, CNTL with the operational thinning scale of 2.0° was used because our main purpose was to distinguish the impact of RS-AMV and investigate their characteristics in the current operational system.

3.4 Impact by channel

The analyses and forecasts for the seven experiments where the RS-AMVs of each individual channel were assimilated were examined in the same way as ALL in the previous section. Because the RS-AMVs of the seven channels were assimilated in ALL, the contribution from each channel mixed with the others so it was not easy to track it to its source. As we saw in Section 2.1, the different characteristics of winds in different channels might affect the results of the assimilation in ALL differently. We compared the assimilation results of individual channel experiments to those of ALL.

Figure 10 shows the analysis and forecast differences of 500 hPa geopotential heights in each experiment at FT00 (Figs. 10b–h), FT03 (Figs. 10j–p), and FT15 (Figs. 10r–x). We can tell whether analyses and forecasts obtained in each experiment contradicted those in ALL (Figs. 10a, i, q) by the appearance of the color patterns in the figures. At FT00 and FT03, the analysis and forecast differences from CNTL around northern Japan in ALL corresponded well overall to those in the seven experiments, with the exceptions of B03 and B08. It may be reasonable that B03 or B08 showed patterns dissimilar to ALL and the others because their RS-AMVs covered only low or high levels. IR (B07 and, in particular, B13) was in fairly good agreement with ALL, as expected. This agreement is probably because a sufficient number of RS-AMVs were assimilated to cover all of the layers from lower to upper. B10 and B16 also had results similar to ALL, with a good amount of wind at mid- and high levels, although the negative region over the central part of Honshu was shifted eastward in both B10 and B16 at FT00. B09 showed a few contradictions, but still some similarities were found. The negative region in B09 seemed smaller compared to the negative regions in other experiments at FT00 and FT03, except for B03 and B08. At FT15, when the differences from CNTL became much smaller than those in previous hours as the cold vortex disappeared, only IR showed results similar to ALL. The three WV channels (B08, B09, and B10) and B16 sometimes showed more similarity to each other than to ALL or IR. In addition to the differences of layers covered by the data, the channel categories might have such different patterns because of their different data characteristics.

The differences of RMSVDs against sonde winds from those of CNTL (RMSVDs with RS-AMV minus RMSVDs without RS-AMV) for each experiment at FT03 and FT15 are shown in Fig. 11. Negative (positive) values mean improvement (degradation) compared with CNTL. At FT03 (Figs. 11a–d), B03, B13, and B10 slightly improved at low levels below 700 hPa. B07, B08, B09, and B16 showed no or little improvement at low levels but improved at 500–400 hPa. B13, B09, B10, and B16 showed slight improvements at 300–200 hPa. Because ALL improved below
Fig. 10. Differences in the analysis and forecast results of geopotential heights at 500 hPa from CNTL. Analysis differences in (a) ALL and (b) B03, (c) B07, (d) B08, (e) B09, (f) B10, (g) B13, and (h) B16. Forecast differences at 12:00 UTC 20 June (FT03) in (i) ALL and (j) B03, (k) B07, (l) B08, (m) B09, (n) B10, (o) B13, and (p) B16. Forecast differences at 00:00 UTC 21 June (FT15) in (q) ALL and (r) B03, (s) B07, (t) B08, (u) B09, (v) B10, (w) B13, and (x) B16.
700 hPa and at 500–300 hPa as mentioned in the previous section, the results of individual channel experiments partly contradicted and were partly consistent with ALL. B13 showed the most similarity to ALL in the RMSVD profiles. At FT15 (Figs. 11e–h), VIS, IR, B10, and CO2 improved from CNTL around 700 hPa, but B08 and B09 showed no or little improvement at that level. Moreover, WV (B08, B09, and B10) showed some improvements at 400–200 hPa, whereas the other channels showed overall degradation.

3.5 Validation of forecast winds against wind profiler observations

Wind profiler observations enabled more frequent and closer comparison for low- to mid-level winds than sonde observations. The forecast winds below the 400 hPa level were compared with WPR winds in northern Japan at each forecast hour up to 24 hours. The RMSVDs for ALL and CNTL experiments showed little difference (Fig. 12a); however, the values were slightly smaller in ALL in the early hours before FT12. This result seems to be consistent with the fact that the winds below 700 hPa and at 500–300 hPa in ALL at FT03 were in better agreement with
sonde winds than CNTL, as we saw in Section 3.3. The same statistical analysis was also applied to the other seven experiments (B03–B16), in which the RS-AMVs of an individual channel were assimilated. A tendency to show slight improvement from CNTL in the earlier hours and no or little improvement in the later hours was commonly found among all of the channels, with the exception of B03 (not shown in the figures).

Figure 12b shows the profiles of RMSVDs averaged over the entire forecast period of 24 hours. In ALL, RMSVDs were somewhat smaller in nearly all of the layers, especially at 900 to 800 hPa, indicating a slight improvement from CNTL. The RMSVD profiles for individual channel experiments are shown in Fig. 13 as the differences from CNTL. They were nearly the same pattern as CNTL, although slight differences were seen in wind height levels where improvement or degradation occurred according to the channels. B03 also showed a slight improvement at 900 to 800 hPa (Fig. 13a), and in addition, B13 excelled at that level and also at 600 to 400 hPa (Fig. 13b). B07 improved above 700 hPa at mid-levels (Fig. 13b). Overall, WV channels and B16 showed degradation below 700 hPa without any low RS-AMVs assimilated, but slight improvements were seen at some levels in mid-layers (Figs. 13c, d). When averaged over entire layers, RMSVDs were smallest in ALL compared with the other experiments. These results of the comparisons with WPR are roughly consistent with those with sonde data as described in the previous section.

4. Discussion

The results of both the data verification and assimilation experiments suggest some ideas for building a future strategy for dealing with such high-density data as Himawari-8 RS-AMVs in a mesoscale data assimilation system. The process of data selection should be refined to pick up the most beneficial information from an enormous amount of data without causing possible degradation of the analysis due to observation error correlations. As the number of channels available for AMV retrieval has increased from four to seven by the change from MTSAT to Himawari-8, it is necessary to optimize the use of data from all of these channels. We found that channels of the same category shared similar error characteristics, which, as a consequence, could have similar impacts on the assimilation experiments. For example, in Section 2.1, negative biases were observed in upper air in IR channels, while in some WV channels, positive biases were seen at the same levels. When these negative IR winds and positive WV winds are assimilated together, their effects might be somehow mixed and produce an unexpected impact. It can be said that the ALL experiment in Sections 3.3 to 3.5 provided fairly reasonable assimilation results, with overall consistency with the individual channel experiments despite a few exceptions. We need to develop a method to prioritize data of better quality to make better use of multi-channel RS-AMVs.

In the experiments described in this paper, the data selection relied on QI number thresholds and other basic QCs such as gross error checks that are embedded in the pre-processing procedures of JNoVA. Because QI can sometimes assign a low number to a mesoscale AMV (Bedka and Mecikalski 2005), we may need to lower the thresholds or disable the forecast check test and develop an additional quality check tailored to high-resolution RS-AMVs. Concern-
The negative wind speed biases in upper layers that are also recognized in RTN-AMVs, Yamashita (2016) introduced a new QC procedure in the JMA global NWP system to reject u-components with negative bias around the jet stream. Shimoji and Nonaka (2016) reported that estimated heights of Himawari-8 showed some improvement in accuracy compared to those of MTSAT-2 in terms of collocation with backscatter plots of Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), which is probably due to the new height assignment method (Shimoji 2014) with more variety of channels. However, the available samples for collocation were limited, and the accuracy of the CALIPSO product as reference was not exactly known. Future work should include estimation of height assignment uncertainties and representative errors of Himawari-8 AMVs based on best-fit statistics (Salonen et al. 2015). It is necessary to consider these error characteristics in QC or other pre-processing procedures to better utilize RS-AMVs in data assimilation.

The data-thinning procedure is another important issue in dealing with high-density RS-AMVs. Judging from the results of the assimilation and their comparison with CNTL, data thinning on a scale of 50 km once within a 3-hour time window for RS-AMVs for all of the channels seems to have been adequate for the purpose of this study. It is necessary to find an optimal scale and time interval for data thinning by trying other cases in different settings. A super observation approach is another option if the data representative scale can be properly taken (Wu et al. 2014; Yamashita 2016; Kunii et al. 2016). In dealing with multiple channels, it may be worthwhile to try to assimilate RS-AMVs for each channel separately as different kinds of observation. In this study, RS-AMVs of all channels were formed into one box observation through the data thinning process to avoid possible inter-channel correlations.

5. Conclusion

Himawari-8 RS-AMVs obtained in June 2016 were more than 20 times the number of RTN-AMVs obtained in the same month, and they had much higher density and frequency. Their data quality proved to be sufficiently good for assimilation when compared...
with MA and upper-air observations. Different error characteristics were observed in different channels, which can be classified by the categories VIS, IR, WV, and CO$_2$. The channels in the same categories showed characteristics similar to each other in terms of data quality. Among the categories, VIS and IR showed a relatively high degree of similarity, and CO$_2$ fell in between these two and WV. Such tendencies in the relationships between channels and categories were also recognized in the estimated inter-channel observation error correlations.

Assimilation experiments for a cold vortex event were conducted with JNoVA using RS-AMVs from the seven channels. Although the differences in analysis and forecast results between the experiments with and without RS-AMVs were subtle, some interesting changes were found. First, RS-AMVs seemed to slightly intensify the upper low at 500 hPa. Second, the verifications against sonde and WPR observations indicated small improvements in low- to mid-level winds over northern Japan in the vicinity of the cold vortex, especially in the early forecast hours before FT12. In addition, the results from the experiments that used each individual channel might reflect similarities in the error characteristics among channels. The experiment in which all seven channels were assimilated performed better than the individual channel experiments in terms of the agreement of wind forecasts with upper air observations. The better coverage of RS-AMVs from low to high levels may be the reason for the better forecast results. Although the spatial and temporal resolutions of the RS-AMV data set were improved over that of RTN-AMVs, the domain of rapid scan observations was limited, which might be a reason of the subtle impact of RS-AMVs particularly in later hours.

To exploit these high-density and high-frequency data, we need to further investigate optimal methods for data selection and QCs before assimilation, based on what we found in this work.

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