Assessing Sensitivity of MERRA-2 to AMSU-A in the Upper Stratosphere

MOHAR CHATTOPADHYAY,a,b WILL MCCARTY,a AND ISAAC MORADId,c

a Global Modeling and Assimilation Office, NASA GSFC, Greenbelt, Maryland
b Science System and Application Inc., Beltsville, Maryland
c Earth System Sciences Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland

ABSTRACT: Microwave temperature sounders provide key observations in data assimilation, both in the current and historical global observing systems, as they provide the largest amount of horizontal and vertical temperature information due to their insensitivity to clouds. In the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), microwave sounder radiances from the Advanced Microwave Sounding Unit-A (AMSU-A) are assimilated beginning with NOAA-15 and continuing through the current period. The time series of observation minus background statistics for AMSU-A channels sensitive to the upper stratosphere and lower mesosphere show variabilities due to changes in the AMSU-A constellation in the early AMSU-A period. Noted discrepancies are seen at the onset and exit of AMSU-A observations on the NOAA-15, NOAA-16, NOAA-17, and NASA EOS Aqua satellites. This effort characterizes the sensitivity, both in terms of the observations and the MERRA-2 data. Furthermore, it explores the use of reprocessed and intercalibrated datasets to evaluate whether these homogenized observations can reduce the disparity due to change in instrumental biases against the model background. The results indicate that the AMSU-A radiances used in MERRA-2 are the fundamental cause of this interplatform sensitivity, which can be mitigated by using reprocessed data. The results explore the importance of the reprocessing of the AMSU-A radiances as well as their intercalibration.

KEYWORDS: Data assimilation; Reanalysis data

1. Introduction

Microwave temperature sounders provide key information on global temperature to the initial conditions of numerical weather prediction models via the assimilation of their radiance measurements. These observations are core to the global observing system, as they fill in key observing gaps that would otherwise exist. They are complementary to conventional observations of temperature, which are spatially sparse over much of the globe—particularly over oceans. The bulk of conventional observations come from sondes, ships, buoys, and aircraft. Ships and buoys are concentrated at the surface. Aircraft data are deficient and lack in vertical resolution away from airports, and are otherwise clustered along flight tracks. Sonde data have excellent vertical resolution but are spatially sparse and typically launched twice per day (Tradowsky et al. 2018). In addition, the quality of the sondes highly depends on the instrument manufacturers, which causes spatial and temporal disparity. The intermittency in the data can be mitigated by homogenization process that is used in production of long-term continuous sonde data. The data can range from multiple years to multiple decades from a particular instrument, which is affected by artificial shifts. The homogenization process provides spatiotemporal consistency for radiosonde data. The Radiosonde Observation Correction Using Reanalyses (RAOBCORE) and Radiosonde Innovation Composite Homogenization (RICH) software package (Haimberger et al. 2012) use the difference between observation and model background (background departures) from reanalysis systems and have successfully removed temporal disparity in radiosonde observations from both pre and post satellite era. As explained above, the purpose of data reprocessing is to create a long-term consistent record of observations by applying corrections to the data. The corrections are applied to mitigate sudden changes caused by various factors including changes in instruments, changes to the instrument calibration, changes in the position of the instruments, as well as human error in collecting observations from instruments such as radiosondes. These reprocessing techniques have largely improved the quality of sonde data. Additionally, there are microwave data from scanning instruments that are reliable in their vertical coverage (due to uniform spectral resolution) and horizontal coverage (due to uniform orbital and scan geometry).

The microwave (MW) temperature sounders are complementary to the modern infrared (IR) sounders. Due to their longer wavelengths, compared to IR sounders, observations from MW sounders are only sensitive to precipitation and nonprecipitating hydrometeor contents in the atmosphere (Bennartz and Bauer 2003).
Since the launch of NOAA-15 on 13 May 1998, the core of the MW temperature sounding observing system has been the Advanced Microwave Sounder Unit-A (AMSU-A; Kidwell et al. 2014; Mo 1996), which measures radiances at frequencies sensitive to the surface, troposphere, and stratosphere. These instruments represent a generational step beyond the Microwave Sounding Unit (MSU), which primarily have measured the troposphere. Prior to NOAA-15, the stratosphere has been measured via the Stratospheric Sounding Unit (SSU), which have operated in the infrared spectrum via a pressure modulating approach (Nash and Saunders 2015).

The role of the observations in reanalysis has been illustrated in Bosilovich et al. (2017), Zhang et al. (2012), and Dee et al. (2011). Furthermore, the impact of assimilating AMSU-A radiances into numerical weather prediction (NWP) models have been discussed in English et al. (2000) and Baker et al. (2005). These data are one of the main contributors that have stabilized the climatology of troposphere and lower stratosphere (Pawson 2012) in both the Modern-Era Retrospective Analysis for Research and Applications (MERRA), (Rienecker et al. 2011) and its second version (MERRA-2) (Gelaro et al. 2017).

It is not uncommon to reprocess raw data to adjust for systematic errors or uncertainties in reanalysis. For sondes measurements, the RAOBCORE data developed by Haimberger (2007) have already been used in many reanalysis systems, including MERRA, MERRA-2, ERA-Interim, ERA5, and JRA-55 to name a few. The datasets are further enhanced by creating reference series from neighboring radiosonde stations for breakpoint adjustment as stated in Haimberger et al. (2012).

Reprocessing of conventional data is not unique. Poli et al. (2015) state that the reprocessed and rescued historical satellite data also complement the modern satellite observations by creating a continuous database that plays a crucial role in the reanalysis. In addition to reprocessing, satellite data are also subjected to intercalibration to create consistent continuous records. Intercalibration of satellite instruments involves relating the measurements of one instrument to those of another with a stated uncertainty (Goldberg et al. 2011). The intercalibrated satellite data use corrections and new calibration coefficients to yield well-merged multisatellite data for instruments aboard multiple platforms. The purpose of intercalibration is like reprocessing, which is to create a long-term consistent data record. The intercalibration technique is, however, applied to the data acquired from similar instruments across various platforms such as satellite observations.

The efforts of intercalibration of satellite data have been undertaken in EUMETSAT, NCEP and Japan Meteorological Agency (JMA). EUMETSAT has undertaken the exercise of intercalibrating infrared channels of SEVIRI with IASI on board MetOp-A and MODIS on board Aqua (EUMETSAT 2019). EUMETSAT is also undertaking efforts to intercalibrate Meteosat First Generation Satellites and HIRS instruments on board NOAA-16 and NOAA-17 (Holmlund et al. 2010). National Climate Data Center at NOAA has reprocessed data from MSUs and Advanced Microwave Sounding Unit (AMSU) data on board various platforms (Zou et al. 2013). JMA (Abe et al. 2018) and Cooperative Institute for Meteorological Satellite Studies (CIMSS) (Wanzong et al. 2014) have also undertaken efforts to reprocess historical atmospheric motion vectors (AMV) data.

In addition to the usage of MSU intercalibrated data in MERRA and MERRA-2, intercalibrated and reprocessed satellite datasets are also used in many reanalysis products. Brönnimann et al. (2018) and Hersbach et al. (2018) mention using reprocessed AMV datasets in their global reanalysis product from GOES (GOES-8 to GOES-13) for the time period 1995 to 2013. ERA5 assimilates reprocessed all-sky radiances from Meteosat Second Generation satellites, which replace the earlier clear-sky radiance. ERA5 also assimilates reprocessed SSMI Fundamental Climate Data Records (FCDR) produced by EUMETSAT’s Climate Monitoring-Satellite Application Facility (CM-SAF). Furthermore, reprocessed COSMIC GNSS-RO data and ASCAT scatterometer data from MetOp-A are also used in ERA5. Similar to MERRA and MERRA-2, the NCEP Climate System Forecast Reanalysis (CFSR) (Saha et al. 2010) also uses intercalibrated MSU radiance.

In MERRA and MERRA-2, both uncorrected (no correction due to reprocessing or intercalibration is applied) and intercalibrated MSU radiances are assimilated. Prior to 1 November 1986, the uncorrected data are assimilated as uncorrected antenna temperatures where antenna pattern corrections to remove sidelobe contaminations are not applied. From that date onward, intercalibrated MSU radiances (Zou et al. 2006) are assimilated. The necessity of the corrections applied to the intercalibrated data, however, is uncertain. This is because the assimilation methods in both reanalyses use a variational bias correction (VarBC) scheme (Wu et al. 2002; Derber and Wu 1998). As Harris and Kelly (2001) explain, VarBC removes systematic observation errors before observations are assimilated into the system, based on observations minus background (typically the model) statistics, also called background departure statistics. In many ways, VarBC (henceforth bias correction) and intercalibration procedures act to achieve the same goal—ensuring consistency in similar measurements across different platforms. McCarty et al. (2016) show that when the uncorrected data are used, the bias corrections differ greatly among the various MSU instruments. However, when the intercalibrated observations are used, the bias corrections are more consistent from sensor to sensor. In both cases, however, the departures between the observations and the background are consistent, showing that both procedures produce similar results.

While intercalibrated MSU data are used in both MERRA and MERRA-2, it is necessary to assess the potential advantages and drawbacks on other observations. This is particularly true for the AMSU-A record as there is a desire of consistency across more than 40 years of microwave temperature sounding record, which also includes MSU, and the Advanced Technology Microwave Sounder (ATMS). This paper investigates these observations during the early AMSU-A period—specifically from 2 July to 31 December 2002. This period is of interest because the observing system has been changing rather frequently with the addition of observations from NOAA-17 and Earth Observing System (EOS) Aqua while
the data from *NOAA-15* and *NOAA-16* are already being assimilated.

The current study illustrates the specific problem seen in MERRA-2 during this period and investigates the utility of alternate datasets where two new AMSU-A datasets are studied. The first is the level 1A antenna temperature data (reprocessed data), which are different from the MERRA-2 input stream. This is because the provenance of the MERRA-2 data stream has some underlying uncertainties due to the lack of any official documentation of the source and the processing of the data at the GMAO. The reprocessed data are processed differently compared to MERRA-2 input AMSU-A and no antenna corrections are applied (C.-Z. Zhu 2019, personal communications). Second, input AMSU-A data are the intercalibrated brightness temperatures where systematic corrections (including the antenna correction) are applied to achieve consistency in measurements across different satellites. Specifically, data from NOAA NESDIS (Zou et al. 2013; Ferraro et al. 2016) are investigated, as they are available not only for the test period but also for the entire data record. Data assimilation experiments are performed using methods similar to MERRA-2 to assess their viability in a future reanalysis system. The justification of the configuration and results from these experiments will be shown below.

2. Background

In MERRA and MERRA-2, AMSU-A plays an important role in the analysis of temperature in the upper stratosphere and lower mesosphere with the introduction of *NOAA-15* on 1 November 1998. Specifically, this region is observed by the highest peaking AMSU-A channel, channel 14 (hereafter CH14), which measures at $57.290 \pm 0.3222 \pm 0.0045$ GHz via multiple passbands with a nominal bandwidth of 3 MHz and a 3.3° nominal beamwidth (Kidwell et al. 2014).

AMSU-A CH14 is most sensitive in the upper stratosphere and lower mesosphere, and there is a lack of complementary observations in both MERRA and MERRA-2 until 2004, when other satellite data became available as described below. Although retrieved temperature data from SABER (Mertens et al. 2001) are available from January 2002, they have not been used in this study and will be considered for assimilation at a later stage. Typically, conventional observations from radiosondes do not reach that altitude. The intercalibrated radiances from MSU have been used in both MERRA and MERRA-2 from 1 January 1980 to 4 May 2006. In MERRA-2, the decision was made to discontinue using the observations from the highest peaking SSU channels when AMSU-A data became available (McCarty et al. 2016), thus resulting in a discontinuity in upper-stratospheric and lower-mesospheric temperature with the onset of *NOAA-15*. Additionally, in MERRA-2 this region was further constrained after 13 August 2004 with the assimilation of observations from the Microwave Limb Sounder (MLS) on NASA’s EOS Aura satellite. Temperature retrievals from this instrument are assimilated above 5 hPa (McCarty et al. 2016). It has been shown that the usage of these temperature retrievals improves the representation of stratospheric zonal winds and the structure of stratopause in MERRA-2 compared to MERRA (Coy et al. 2016; Pawson et al. 2014). Additionally, latitude-dependent, nonorographic gravity wave drag (GWD) source is increased in the tropics by nearly a factor of 8, producing a realistic quasi-biennial oscillation (QBO) in model runs (Molod et al. 2015). The turning on GWD parameterization has enabled MERRA-2 to generate QBO, which has led to more consistent mean meridional circulations and improved stratospheric transport compared to MERRA (Coy et al. 2016). Despite these changes, there are strong model variabilities (Fig. 22 in Gelaro et al. 2017) in this region interacting with the observations, especially before the assimilation of MLS data in 2004. In particular, MERRA-2 also has a bias in the representation of the height and gradient of stratopause (Gelaro et al. 2017; McCarty et al. 2016). It is an important issue because if data from AMSU-A CH14 are to be assimilated with a bias correction procedure, the correction will drift toward the model’s incorrect climatology (Dee 2005; Eyre 2016), as the correction is a function of the departure of the observations from the background model. Due to this issue, CH14 has traditionally been assimilated without applying any bias correction. In this case, CH14 serves as the anchor to observations in this region, as there are no other observations to serve as the anchor, particularly prior to the beginning of MLS. Although data from SABER (Mertens et al. 2001) can be used for assimilation at these heights, it is beyond the scope of this study to introduce a new observing system.

Experiments in this study are conducted for a period from 2 July to 31 December 2002. Prior to this study period, AMSU-A antenna temperatures from *NOAA-15* and *NOAA-16* are being assimilated in MERRA-2, which serve as the starting point for these experiments. Observations from CH14 of AMSU-A on board *NOAA-15* are not assimilated prior to this period due to channel degradation. The assimilation of AMSU-A data starts at 1800 UTC 10 August 2002 from *NOAA-17* and at 0000 UTC 13 October 2002 from NASA EOS *Aqua*. Furthermore, there is a loss of *NOAA-16* AMSU-A measurements from 19 to 28 November 2002. This intermittency in the data volume result in sudden changes in the mean background departure for CH14 in MERRA-2 (Fig. 1a), where background departure is defined as the difference between model background and observation in observation space. This is reflected in the temporal discontinuities in the global analysis fields in MERRA-2 and is illustrated by plotting the latitude average of zonal mean temperature at 2 hPa between 50° and 20°S (Fig. 1b) where the largest discontinuity is noted. The vertical lines in Fig. 1 represent the onset of *NOAA-17* AMSU-A assimilation (Fig. 1, green), the onset of *Aqua* AMSU-A assimilation (Fig. 1, blue), and the onset and end of the *NOAA-16* AMSU-A data dropout (Fig. 1, black).

To investigate if these discontinuities can be addressed by using intercalibrated AMSU-A radiances, a detailed assessment of their impact on a MERRA-2-like system is undertaken. MERRA-2 is based on version 5.12.4 of Goddard Earth Observing Systems (GEOS) atmospheric and data assimilation system. The atmospheric model (Rienecker et al. 2008; Molod et al. 2015) uses a cubed-sphere horizontal discretization at an approximate resolution of $0.5° \times 0.625°$ and 72 hybrid-eta levels from the surface to 0.01 hPa, and an assimilation scheme based on Wu et al. (2002) and Kleist et al. (2009). A detailed
A description of MERRA-2 can be found in Gelaro et al. (2017). This study uses similar data assimilation and model framework as MERRA-2 but at a coarser resolution of approximately 100 km horizontal grid resolution. A description of the data and experiment design are described in detail in the next section.

3. Experimentation

a. Data

The general practice in current operational NWP and reanalysis systems is to use AMSU-A radiances as measured by the satellite (Köpken et al. 2004; Zhu et al. 2014). These radiances are assimilated either in the form of antenna or brightness temperatures, with the main difference being that the latter has an antenna pattern correction performed at each field of view (FOV) (Mo 1999; Mo and Liu 2008). These observations are not intercalibrated among instruments. In other words, no attempt is made to correct for cross-instrument differences as seen in observation space.

AMSU-A data play an important role in globally constraining atmospheric temperature. In the absence of a realistic GWD parameterization in a model, the intercalibrated AMSU-A brightness temperature can significantly improve the temperature of the middle atmosphere (Polavarapu et al. 2005). There have been many efforts to intercalibrate the AMSU-A data record among the differing platforms. The intercalibration procedure aims to remove cross-platform differences, but the absolute value of the intercalibrated AMSU-A brightness temperature is not adjusted to an absolute truth. Instead, a reference instrument is selected based on analysis of observations from different platforms. The reference satellite is selected such that the reference and the other satellites have a minimum overlap period of one year. This helps in determining temperature variability and avoid calibration uncertainties. Observations from all other instruments (also known as target instruments) are intercalibrated with respect to this reference instrument to minimize difference between the reference and the target instruments (Zou and Wang 2011). For this reason, the variational bias correction (Wu et al. 2002) procedure is still applied to the intercalibrated data as they are not absolute ground truth.

The data used in this study are obtained from several different sources and converted into BUFR format, as shown in Table 1. The MERRA-2 data stream (M2) is the BUFR stream used in MERRA-2, which consists of antenna temperature from NOAA-15 to MetOp-A (Edwards and Pawlak 2000). This dataset originates from two locations:

- November 1998–20 May 2007: the same BUFR stream used in MERRA; and
- May 2008 onward: data processed from NOAA CLASS to BUFR.

There is a lack of documentation on the conversion of the radiance data to antenna temperature and brightness temperature at NASA GMAO for the early MERRA stream.

The FERRARO dataset, described in Ferraro et al. (2016), is a NOAA-developed Climate Data Record (CDR) for AMSU-A. It intercalibrates the brightness temperatures for the surface sensitive channels—channels 1, 2, 3, and 15 at 23.8, 31.4, 50.3, and 89.0 GHz, respectively. Within the MERRA-2 methodology, these channels are not actively assimilated and only used for bias correction terms and screening due to the presence of cloud and precipitation. The window channels are also corrected for the antenna pattern and possible scan biases, in addition to interplatform calibration (Ferraro et al. 2016).

The Z&W dataset, described in Zou et al. (2013), is also a NOAA-developed CDR. It consists of AMSU-A antenna temperatures for channels 4 to 14 with frequencies ranging from 52.8 and 57.6 GHz and like FERRARO dataset, also applies antenna pattern correction. Z&W data for AMSU-A channels 4 to 14 are created by using a technique called sequential simultaneous nadir overpass (SNO) described in Zou et al. (2006).

SNO is a sequential regression method where a reference satellite is selected such that its calibration-offset and nonlinear coefficient are known temporarily. Subsequent calibration offsets and nonlinear coefficients of all other satellites are determined sequentially from regressions of the SNO matchups between satellite pairs, starting from the satellite closest to the reference satellite. For AMSU-A observations, NOAA-I8 is the reference satellite for channel 6 and NOAA-I5 for all other channels. In order for the regression and sequential procedure...
to be complete, a satellite should overlap with another satellite for a time period of at least 1 year, which is considered long enough to avoid calibration uncertainties (Zou and Wang 2011). FERRARO and Z&W data both use same sequential SNO technique to intercalibrate the channels 1, 2, 3, and 15 and the process is described in Ferraro et al. (2016).

The SNO technique is used in the integrated microwave intercalibration approach (IMICA) (Zou et al. 2006; Zou and Wang 2011) method to obtain a long-term data product. These data are then applied in climate studies (Zou et al. 2006; Zou and Wang 2011; Wang and Zou 2014) by minimizing or removing the biases found in the operational calibration. Along with the IMICA calibrated radiances, the Z&W data files also contain the operational data used in NWP. In contrast, the FERRARO data files, containing the window channels, only include data for the intercalibrated window channels but no operational data.

The dataset called NOAA that are used in this study are the operational data available in NOAA CLASS website (Zou et al. 2016). Although the same AMSU-A data can be accessed from CLS, this study uses the same operational AMSU-A data from Z&W data files (for channels 4 to 14) instead of directly acquiring from CLS for the ease of processing. The observations for the window channels for NOAA data are obtained from the CLASS website and processed using NOAA operational calibration methodology presented in NOAA KLM user’s guide (Kidwell et al. 2014). To summarize, the NOAA data are operational data directly available from NOAA, which have not gone through any intercalibration or antenna correction and it encompasses channels 1 to 15 for AMSU-A instrument on board various platforms. NOAA data are also referred to as reprocessed data in this study (Table 3) as their processing is different from the AMSU-A data used in M2.

None of the three datasets mentioned here (Z&W, FERRARO, and NOAA) have gone through prior correction of the mean background departures when used in the experiments. It should be noted here that a complete intercalibration technique is not applied to Aqua as the raw data are not available for it (Zou and Wang 2011). Several experiments are performed using various versions of these datasets, which are described below.

b. Data assimilation experiments

One control and three experiments are performed using different sets of AMSU-A radiances, as shown in Table 2. The control, CTL, is a lower-resolution representation of MERRA-2 and uses the same observations (McCarty et al. 2016) including the M2 AMSU-A dataset. The first experiment, EXP_TANT, uses NOAA for all AMSU-A channels. The second experiment, EXP_IC, uses intercalibrated AMSU-A measurements from both FERRARO and Z&W. The final experiment, EXP_IC14 assimilates the NOAA data stream for all bands except CH14, which is obtained from the Z&W stream. MERRA-2 is listed in Table 2 for completeness and corresponds to the MERRA-2 products as described in Gelaro et al. (2017).

All functioning AMSU-A channels from 4 to 14 are assimilated in these experiments. It is notable that CH14 from NOAA-15 started degrading on 31 March 2002 and is absent in these experiments. Bias correction (VarBC) is applied to all assimilated channels except CH14.

As already mentioned, modeling and assimilation used in the control and experimentation is set up to mimic MERRA-2 at a reduced horizontal resolution of 100 km. This is done primarily to conserve computational resources and to allow longer-term experimentation. Otherwise, the configuration is the same as MERRA-2 as described in Gelaro et al. (2017).

4. Results

a. Validation of CTL as a MERRA-2 proxy

The experiments conducted in this study are performed at half the horizontal resolution of MERRA-2. To show that sensitivities seen relative to CTL are comparable to MERRA-2, it

### Table 1. Description of the data used in this study.

<table>
<thead>
<tr>
<th>Data source</th>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>—</td>
<td>Antenna temperature BUFR stream used in MERRA-2</td>
</tr>
<tr>
<td>FERRARO</td>
<td>Ferraro et al. (2016)</td>
<td>Intercalibrated AMSU-A measurements for channels 1–3 and 15</td>
</tr>
<tr>
<td>Z&amp;W</td>
<td>Zou et al. (2013)</td>
<td>Intercalibrated AMSU-A measurements for channels 4–14</td>
</tr>
<tr>
<td>NOAA (reprocessed)</td>
<td>Kidwell et al. (2014)</td>
<td>Antenna temperature acquired from Z&amp;W based on NOAA CLASS for channels 4–14 and from FERRARO for channels 1–3 and 15</td>
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</tbody>
</table>

### Table 2. Description of experiments and AMSU-A observations used. MERRA-2 is listed for completeness and as directly described in Gelaro et al. (2017). Data sources described above are illustrated in Table 1.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channels 1–3, 15</th>
<th>Channels 4–13</th>
<th>Channel 14</th>
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<td>M2</td>
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<tr>
<td>EXP_TANT</td>
<td>NOAA (reference in Table 1)</td>
<td>NOAA (reference in Table 1)</td>
<td>NOAA (reference in Table 1)</td>
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<tr>
<td>MERRA-2</td>
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</table>
is important to justify that the CTL shows similar responses to MERRA-2, particularly during the transitions between data and data gaps. Figure 2 shows the zonal mean temperature (Fig. 2a) and the zonal mean wind (Fig. 2b) for CTL during the focal period from 2 July to 31 December 2002. The low temperature of 200 K over the tropics at 100 hPa indicates the tropical tropopause. The position of the stratopause at 1 hPa is also resolved by CTL in Fig. 2a. The positions of the tropospheric and stratospheric jets are also represented correctly in CTL as seen in Fig. 2b. The differences between CTL and MERRA-2 for the same fields are shown in Fig. 3 during the same period.

The difference in temperature for the two systems is less than 2 K between the surface and 1 hPa (Fig. 3a). It is slightly larger in the mesosphere, where the difference exceeds 2 K in a few regions—specifically poleward of 30°S, between 50° and 60°N and poleward of 65°N above 1 hPa. The zonal mean wind difference between CTL and MERRA-2 (Fig. 3b) is also less than 2 m s⁻¹ from surface to 1 hPa. At 30°S and poleward of 30°N, the difference in wind field exceeds 2 m s⁻¹ above 1 hPa. The differences in the zonal mean climatologies of temperature and zonal mean wind of the two systems, due to their difference in resolution, are determined as not statistically significant using the Student’s t test. Figure 4 shows time series of the latitude average of zonal mean temperature at 2 hPa between 20° and 50°S for MERRA-2 and CTL. Similar discontinuities are seen in the upper stratosphere in both MERRA-2 and CTL due to the change in AMSU-A data. These results reflect that the time averages (Figs. 2 and 3) and the latitude average (Fig. 4) of CTL show the same sensitivities as MERRA-2 and is a suitable baseline for this study.

b. Results from data assimilation experiments

Time series of observation statistics from CTL for channels 13 are shown in Fig. 5. Mean background departure values (Fig. 5a) for NOAA-15, NOAA-16, NOAA-17, and Aqua are −0.04, −0.04, −0.07, and −0.052 K, respectively, which are in good agreement relative to each other across the platforms. This is an expected result due to the bias correction procedure applied to AMSU-A CH13. The mean CH13 bias correction values (Fig. 5b) applied for the period of simulation for NOAA-15, NOAA-16, NOAA-17, and Aqua are −0.25, 0.21, 0.6, and −0.35 K, respectively. There is a difference of almost 1.0 K between NOAA-16 and NOAA-17 illustrating the absence of cross-platform consistency in the data. NOAA-17 CH13 bias correction values for CTL show largest bias. Figure 5c shows that the values of difference between observation and analysis (analysis departure) are less than mean background departure as the analysis is informed by these observations. Evidently, the magnitude of the analysis departures is a function of the prescribed observation errors. The mean analysis departure is between 0.001 and 0.004 K across the platforms.

Similar observation statistics for CH14 of the CTL are shown in Fig. 6. With the onset of NOAA-17, the NOAA-16 mean background departures (Fig. 6a) increase by 0.4 K. Both NOAA-17 and Aqua sharply increase by 0.4 K with the onset of the missing NOAA-16 on 21 November 2002 and return to similar values upon the return on 28 November 2002. The mean background departure values are 0.45, −0.88, and −0.38 K for NOAA-16, NOAA-17, and Aqua, respectively. These features are also noted in the same channels for the same instruments for MERRA-2 (McCarty et al. 2016). As with the CH13, CH14 in NOAA-17 has the largest background departure values followed by NOAA-16. Furthermore, the mean background departure in NOAA-16 increases by 0.4 K at the onset of NOAA-17 data. This may indicate a lower quality of AMSU-A data used in the CTL. The analysis departure values for NOAA-16, NOAA-17, and Aqua are 0.24, −0.19, and −0.15 K, respectively, and show similar jumps to the mean background departures. Due to the absence of variational bias correction in CH14, these jumps are not compensated in the solution and contribute to the drop in temperature at 2 hPa level as seen in Fig. 4.
The observation statistics of CH13 and CH14 for EXP_TANT are shown in Figs. 7 and 8, respectively. There is an agreement in the mean background departure values of CH13 across the platforms, where the mean background departures over the period for NOAA-15, NOAA-16, NOAA-17, and Aqua are $-0.04$, $-0.06$, $-0.05$, and $-0.06$ K, respectively (Fig. 7a). These values are lower than the mean background departure values in CTL (Fig. 5). The bias correction values for CH13 are more consistent across platforms with values varying from $-0.07$ to $-0.08$ K between NOAA-16 and Aqua. The analysis departure also shows similarity across NOAA-15, NOAA-16, NOAA-17, and Aqua with the absolute value of the means being less than $0.01$ K for all platforms.

Figure 8 shows the background and analysis departures of CH14 for EXP_TANT, which uses NOAA data (Table 1) in assimilation. The abrupt changes noted before in CTL (Fig. 6) with the introduction of new datasets or during the absence of an existing dataset are not seen for this experiment anymore. The mean background departure values for NOAA-16, NOAA-17, and Aqua are $-0.14$, $-0.18$, and $-0.00$ K, respectively, which are much lower than the background departure values of CTL (Fig. 6). There is a marked improvement in the quality of NOAA-17 data that is reflected in the CH14 background departure values compared to CTL. Furthermore, the mean analysis departure values are also lower than CTL, where NOAA-16 and NOAA-17 have values $-0.013$ and $-0.027$ K. The mean analysis departure for Aqua, $0.12$ K, has also changed compared to CTL, which is $-0.13$ K for CH14. During the interval of loss of NOAA-16, both Aqua and NOAA-17 shows a relatively lower change in analysis departure of $-0.1$ K in EXP_TANT (Fig. 8) compared to CTL (Fig. 6) where analysis departure shows an increase of $0.5$ K during the same period. Although there is a slight change in the values of background and analysis departure for both NOAA-17 and Aqua during the absence of NOAA-16 (19 to 28 November 2002), the value of the change ($0.06$ K) is a fraction of that in CTL ($0.4$ K).

To assess the consistency of the AMSU-A data among the three different experimental datasets, the average bias correction per cycle is shown for EXP_TANT, EXP_IC, and EXP_IC14 for CH12 (Fig. 9) and CH13 (Fig. 10), and the mean bias corrections for the period are shown in Table 3. For both channels, the difference between EXP_TANT and EXP_IC14 in the mean bias correction values for the period is within $0.1$ K. This similarity is due to both experiments assimilating the same observations for these channels. However, no downward propagation of bias from CH14 is readily seen. This is contrary to the effects seen using the M2 data in CTL, where the changes in bias correction magnitude vary from $0.33$ to $0.9$ K across the platforms relative to EXP_TANT (Table 4). Therefore, the impacts of assimilating
CH14 from NOAA or Z&W are an order of magnitude smaller relative to each other compared to that of assimilating the M2 observations.

The magnitude of the mean bias correction values for EXP_IC is larger for both CH12 and CH13 compared to EXP_TANT, with the absolute differences ranging from 0.27 to 0.59 K for CH12 and 0.44 to 0.87 K for CH13. EXP_IC also shows the largest difference among the platforms in terms of bias correction. There is an absolute difference of 0.56 K between the mean bias corrections for NOAA-15 and Aqua in EXP_IC. In contrast, the absolute differences in bias correction between these platforms in EXP_TANT and EXP_IC14 are 0.34 and 0.29 K, respectively. This result is somewhat surprising, though it is noted that further disaggregation of the biases would be necessary before making a qualitative statement about these numbers. The intercalibrated data obtained from SNO method, used in EXP_IC, increase the magnitude of bias correction for CH12 and CH13 across all the platforms. The values are less consistent than that in EXP_TANT and EXP_IC14 as shown in Table 3. The bias correction values for Aqua are more pronounced probably because a complete SNO calibration scheme has not been applied to the data.
The range of bias correction values across the different platforms for CTL is much higher than any of the three datasets as shown in Table 3.

The average background departures per cycle for CH14 are shown in Fig. 11, and the mean background departure values for CH14 over the study period are shown in Table 4. It is noted that due to a misconfiguration, NOAA-17 CH14 is assimilated prior to the onset of the other channels for this instrument, but this is consistent across all experiments. The mean background departure values for EXP_IC and EXP_IC14 are similar to each other, as both assimilate the same observations for this band. Among the three experiments, the cross-platform absolute mean background departure difference does not exceed 0.1 K for CH14. It is noted that for the intercalibrated data (EXP_IC and EXP_IC14), NOAA-17 differs the most among the three instruments, which implies that the channels in NOAA-17 are unable to reap the full benefit of intercalibration due to a shorter overlap time (less than one year) with its reference satellite NOAA-15 (Zou and Wang 2011) compared to the other satellites. The mean background departure for CTL CH14 is the largest when compared with the other experiments.
The sudden changes in the observation departures are also reflected in the upper-stratospheric temperature. Zonal mean time series of the latitude average of zonal mean temperature between 50° and 20°S latitude at 2 hPa is shown in Fig. 12. The average temperature of CTL is 5 K warmer than EXP_TANT, illustrating the difference between using M2 and NOAA data streams. The upper-stratospheric channels, CH13 and CH14, in AMSU-A are crucial in determining the temperature between 5 and 1 hPa when they are assimilated. It is already seen in Fig. 5 that M2 data stream used in CTL has a large and inconsistent bias in AMSU-A CH13 across all platforms (Table 3). CH14 mean background departure values in Table 4 (depicted in Fig. 6) also show higher and inconsistent values of background departure compared to Fig. 11a. The reprocessed/intercalibrated observations assimilated in EXP_TANT, EXP_IC and EXP_IC14 are more consistent in their bias correction and background departure values, which offers more confidence in the quality of the data compared to M2 used in CTL. This also provides more confidence in the upper-stratospheric temperature as seen in Fig. 12 when the reprocessed data are assimilated.

The introduction of NOAA-17 data, however, has a mixed impact on the temperature response of CTL in the upper stratosphere, where a 3 K drop in temperature can be seen. In CTL, there is also a change in the background and the analysis departure in NOAA-16 coincident with the introduction of NOAA_17 (Fig. 6). EXP_TANT, EXP_IC and EXP_IC14 also
show a drop in temperature of 1 K at the same time (Fig. 12); however, the analysis and background departure of NOAA-16 does not show any abrupt changes for these experiments (Fig. 11) implying that the change in temperature might have a dynamic origin. It is therefore hard to attribute the sudden drop in temperature entirely to the introduction of a new dataset. With the beginning of Aqua, no discernable change in the mean background departure fields can be noticed in CTL, EXP_TANT, EXP_IC, and EXP_IC14 and hence, upper-stratospheric temperature fields also remain unaffected.

CTL shows a sudden 3.8 K drop in temperature from 0000 to 1800 UTC 19 November 2002, coinciding with the missing NOAA-16 data. The sudden change in the CTL background and analysis departures for CH14 (as seen in Fig. 6) also shows the impact of the loss of data. It is important to note here that the experiments using the NOAA and Z&W data do not show this response in temperature during the absence of NOAA-16 radiance. The mean background departure fields for these experiments (Fig. 11) also do not show sudden changes. To quantify, the mean temperature for this region over the entire period is 262.8, 257.03, 257.05, and 257.1 K for CTL, EXP_TANT, EXP_IC, and EXP_IC14, respectively. In other words, temperatures in CTL are higher than those in the other experiments.

Disregarding the CTL, the largest difference among EXP_TANT, EXP_IC, and EXP_IC14 is seen during the period of 1–15 November 2002, as emphasized in Fig. 13. A mean temperature difference of 0.8 K from 1 to 15 November 2002 in EXP_IC is visible compared to EXP_TANT. Following that difference, there is a much smaller difference during the NOAA-16 data gap, equating to a mean difference of 0.01 K between EXP_IC and EXP_TANT between 19 and 28 November 2002. The bias correction quantities for EXP_IC in CH12 and CH13 shown in Figs. 9b and 10b demonstrate a steady decline in the mean background departure values across all platforms, especially with the introduction of Aqua in the assimilation. The lowest values are from NOAA-16 and Aqua. It is also reflected in the low background departure values of EXP_IC compared to EXP_TANT and EXP_IC14, shown in Tables 2 and 3. This low background departure values from 1 to 15 November 2002 are reflected in the increase in upper-stratospheric temperature in EXP_IC. The mean background departures from CH12 and CH13 start to improve from 16 November 2002 after which the upper-stratospheric temperature from all three experiments are seen to have similar values. It should be mentioned here that the zonal mean temperature averaged over multiple upper-stratospheric levels smooth out the differences across all levels and the response in the temperature is not noticeable. Also, there is no apparent corresponding response in the zonal-mean zonal wind fields as there can be latitudinally uniform error in zonal mean temperature without introducing error in zonal mean wind.

The lack of sudden drops in temperature when observations from new platforms are introduced and during the loss of NOAA-16 show that the upper-stratospheric temperature has improved by using the reprocessed AMSU-A observation. It is also necessary to verify if this change has been translated in the improvement of the model background. As these experiments are performed in a reanalysis framework, no forecast is available for a forecast sensitivity test. Additionally, independent observations in the upper-stratospheric levels are also rare except for very few radiosonde observations up to 5 hPa. The improvement in the background can therefore be assessed by studying the mean background departure of radiosonde temperature observations for all simulations. An improvement in the model background can be measured by the reduction in the values of mean background departure of radiosonde temperature. These values are calculated for October 2002 between 7 and 5 hPa, where the strongest impact of the varying observations is seen. As the number of radiosonde observations are very low at these altitudes, global observations available between 7 and 5 hPa are used for all four experiments, and mean background departures are compared with each other. The mean background departure of CTL and EXP_TANT is shown in Fig. 14a and the difference between them is shown in Fig. 14b. It can be seen from Fig. 14b that the mean background departure of CTL is higher than EXP_TANT. This indicates that the quality of the background in EXP_TANT has improved compared to the background of the CTL. The mean background departure of radiosonde temperature for CTL, EXP_IC, and EXP_IC14 are 0.056, 0.022, and 0.016 K, respectively, higher than EXP_TANT, which shows that for this period of study, the observations used in EXP_TANT have resulted in better background than the other three experiments.

### Table 3. Mean bias correction values for CH12 and CH13 for EXP_TANT, EXP_IC, and EXP_IC14 for NOAA-15, NOAA-16, NOAA-17, and Aqua.

<table>
<thead>
<tr>
<th></th>
<th>NOAA-15</th>
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<th>NOAA-17</th>
<th>Aqua</th>
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<td>CH12</td>
<td>CH13</td>
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<td>CH13</td>
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<td>-1.38</td>
</tr>
<tr>
<td>EXP_IC14</td>
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<td>-0.82</td>
<td>-0.57</td>
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</tr>
<tr>
<td>CTL</td>
<td>-0.22</td>
<td>-0.33</td>
<td>0.40</td>
<td>0.675</td>
</tr>
</tbody>
</table>

### Table 4. Mean background departure for CH14 for EXP_TANT, EXP_IC, and EXP_IC14 for NOAA-16, NOAA-17, and Aqua.

<table>
<thead>
<tr>
<th></th>
<th>NOAA-16</th>
<th>NOAA-17</th>
<th>Aqua</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH14</td>
<td>CH14</td>
<td>CH14</td>
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<tr>
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<tr>
<td>CTL</td>
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<td>-0.89</td>
<td>-0.38</td>
</tr>
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</table>
AMSU-A radiances are an essential part of global observing system used in numerical weather prediction and in reanalysis. Particularly, the highest peaking bands provide valuable information as there is a dearth of conventional and radiance observations above 7 hPa from other platforms. Therefore, observations from channels 12, 13, and 14 are crucial in constraining the model predicted temperature in the upper stratosphere and lower mesosphere.

During 2002, the AMSU-A constellation went through a number of changes, with the onset of NOAA-17 at 1800 UTC 10 August, the onset of EOS Aqua at 0000 UTC 13 October, and a gap in data for NOAA-16 on 19–28 November 2002.

Although most of the channels assimilated in MERRA-2 do not respond to these changes in their background departure statistics, channel 14 is sensitive to these abrupt changes in the observation stream. As channel 14 is not bias corrected, these discontinuities are then projected onto the physical domain.

This study explores the GEOS system’s response to reprocessed and intercalibrated AMSU-A observations for mitigating the discrepancies in the observation statistics in AMSU-A. The reprocessed data used in this study do not apply antenna pattern correction whereas the intercalibrated data do. The antenna pattern correction factor depends on the antenna sidelobes and the efficiency of handling polarization by a particular microwave radiometer, but it is expected to be smaller than intercalibration corrections. Antenna pattern corrections are one of the many corrections that are applied to the intercalibrated data; hence, it is smaller in magnitude than the overall correction value as described in Zou et al. (2006).

This study further explores if the bias in the upper-stratospheric temperature in MERRA-2 can be mitigated by using these alternate data sources. The initial hypothesis is that the use of intercalibrated data can help mitigate the interplatform adjustments seen in MERRA-2. It is observed that both reprocessed and intercalibrated AMSU-A data are useful in mitigating such discrepancies. Indeed, the variational bias correction (VarBC) can be made more effective 1) if the model uncertainty is expected to be small with respect to the observations and is slowly varying and 2) if the anchoring observations are plentiful (Eyre 2016). This study, however, focuses on the upper stratosphere and lower mesosphere, where the models are known to have uncertainties due to insufficient GWD and a lack of in situ observations (Polavarapu et al. 2005). The biases in the upper-stratospheric channels observed in MERRA and MERRA-2 remain even after bias correction, which give rise to sudden temperature changes in the analysis. This feature is corrected by not changing the VarBC scheme but by using the reprocessed and the intercalibrated data. The analysis here shows that AMSU-A reprocessed data (which are processed according to the operational methodology without applying any further
corrections or calibrations) are able to mitigate the intermittent temperature changes in the upper stratosphere for this current study. There is an improvement in the background of the experiments where reprocessed and intercalibrated data are assimilated compared to the experiment where MERRA-2 data are assimilated. This leads to the conclusion that these adjustments are due to inconsistencies in the AMSU-A dataset that are used as input in MERRA and MERRA-2, as the data from these periods have not been reprocessed since the initial production of MERRA. The primary conclusion of this paper is that by assimilating either of these two datasets the inconsistencies in the mean background departures can be mitigated.

The results from this study also show that assimilation of the reprocessed radiances can resolve the unstable mean background departures and sudden drops in the upper-stratospheric and lower-mesospheric temperature when AMSU-A data sources are intermittently changed. It is also revealed, in this case, that by using the intercalibrated data there is no significant improvement in the background error statistics when compared against the reprocessed data. Independent assessments of mean background departures of radiosonde temperature from the upper stratosphere also show that the assimilation of reprocessed AMSU-A data have slightly improved the background, more than the intercalibrated data in this particular study. The temperature in the upper stratosphere and lower mesosphere also do not improve significantly when the intercalibrated data are used instead of reprocessed AMSU-A data in the assimilation.

When comparing the three experiments, it must first be pointed out that any difference seen among the three experiments are dwarfed by their difference against the CTL. However, when compared among themselves, the first-order assessment of the background error statistics is that there are no obvious drawbacks or advantages to using the intercalibrated data in this limited study. A more exhaustive study considering the utility and impact of these observations—not only in the stratosphere but also throughout the troposphere and for a longer period—would be necessary to make a more conclusive statement. It is worth noting that on these short time scales, the intercalibration signals are not readily apparent. It is reasonable to expect as the observations are handled in a different manner in a data assimilation system than in their typical use in climate studies and applications. While no conclusive statement is given in terms of the benefit or disadvantages of the assimilating intercalibrated data, it is noted that there are observed differences, particularly during the early November 2002 period, illustrated in the results.

Finally, this effort demonstrates the sensitivity of an atmospheric data assimilation system in the upper stratosphere and lower mesosphere to AMSU-A. In terms of MERRA and MERRA-2, the input observations have inconsistency across platforms and the model climate, also has bias in the middle atmosphere. This feature is reflected through the observation error statistics of channel 14, shown both in this effort and in McCarty et al. (2016). This is true in MERRA-2 prior to the assimilation of MLS temperature retrievals (Coy et al. 2016) and GNSS radio occultation (McCarty et al. 2016) measurements, which when they are assimilated, provide additional information in this region. This study documents the impact of intercalibration and reprocessing of AMSU-A observations on data assimilation statistics. It shows how possible inconsistencies in instrument calibration can have large impacts on the analysis. Although we only investigate AMSU-A observations, it is expected that the same conclusions apply to observations from other instruments. Therefore, it is necessary to ensure that the observations are properly reprocessed before being assimilated into data assimilation systems.

Acknowledgments. The development of MERRA-2 and the GEOS atmospheric data assimilation system are funded by NASA’s Modeling, Analysis, and Prediction program. This effort benefits from years of heritage development of the GMAO. Explicitly, the authors thank Dr. Meta Sienkiewicz, whose previous developments to the system are directly leveraged in this work. Authors are also obliged to Dr. Cheng-Zhi Zou for many helpful comments and clarification of the data and also express their gratitude to Dr. Lawrence Coy and Ms. Heather Weir for their helpful advice on the various aspects of the paper. Last but

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**Fig. 13.** Latitude average of zonal mean temperature (K) between 50° and 20°S and 2 hPa from 1 Oct to 31 Dec 2002 for four simulations: EXP_TANT (red), EXP_IC (blue), and EXP_IC14 (yellow).  

**Fig. 14.** (a) Mean background departure of CTL and EXP_TANT, (b) difference between mean background departure of CTL and EXP_TANT for October 2002.
not least, the authors thank the reviewers, whose comments have vastly improved the quality of this article.

APPENDIX

Acronyms and Their Definitions

AMSU  Advanced Microwave Sounding Unit  
AMV  Atmospheric motion vector  
Aqua  Earth Observing System satellite  
ASCAT  Advanced Scatterometer  
EUMETSAT  European Organisation for the Exploitation of Meteorological Satellites  
GMAO  Global Modeling and Assimilation Office  
GMASS  Comprehensive Large Array-Data Stewardship System  
GOES  Goddard Earth Observing System  
IASI  Infrared Atmospheric Sounding Interferometer  
IMICA  Integrated microwave intercalibration approach  
JMA  Japan Meteorological Agency  
MERRA  Modern-Era Retrospective Analysis for Research and Applications (MERRA-2)  
MODIS  Moderate Resolution Imaging Spectroradiometer  
MSU  Microwave Sounding Unit  
NCEP  National Centers for Environmental Prediction  
NOAA  National Oceanic and Atmospheric Administration  
QBO  Quasi-biennial oscillation  
RAOB  Radiosonde Observation Correction Using Reanalyses  
RICH  Radiosonde Innovation Composite Homogenization  
SBM  Soundin of the Atmosphere using Broadband Emission Radiometry  
SEVIRI  Spinning Enhanced Visible and Infrared Imager  
SNO  Simultaneous nadir overpass  
SU  Stratospheric Sounding Unit

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