Impact of Loss of U.S. Microwave and Radio Occultation Observations in Operational Numerical Weather Prediction in Support of the U.S. Data Gap Mitigation Activities

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ABSTRACT

As the U.S. polar-orbiting satellites *NOAA-15*, *-18*, and *-19* and NASA's *Aqua* satellite reach the ends of their lives, there may be a loss in redundancy between their microwave (MW) soundings, and the Advanced Technology Microwave Sounder (ATMS) on the *Suomi–National Polar-Orbiting Partnership* (*NPP*) satellite. With the expected delay in the launch of the next generation of U.S. polar-orbiting satellites, there may be a loss in at least some of the U.S. MW data. There may also be a significant decrease in the number of radio occultation (RO) observations. The mainstay of the global RO system, the COSMIC constellation of six satellites is already past the end of its nominal lifetime. A replacement of RO soundings in the tropics is planned with the launch of COSMIC-2 satellites in 2016. However, the polar constellation of COSMIC-2 will not be launched until 2018 or 2019, and complete funding for this constellation is not assured. Using the NCEP operational forecast system, forecasts for March–April 2013 are carried out in which various combinations of the U.S. MW and all RO soundings are removed. The main results are that the forecasts are only slightly degraded in the Northern Hemisphere, even with all of these observations removed. The decrease in accuracy is considerably greater in the Southern Hemisphere, where the greatest forecast degradation occurs when the RO observations are removed. Overall, these results indicate that the possible gap in RO observations is potentially more significant than the possible gap in the U.S. MW data.

1. Introduction

Satellite radiances from the Advanced Technology Microwave Sounder (ATMS) on the *Suomi–National Polar-Orbiting Partnership* (*NPP*) satellite were assimilated into the operational National Centers for Environmental Prediction (NCEP) Global Data Assimilation System starting in May 2012, just 7 months after its launch in October 2011. *Suomi-NPP* is the preparatory mission for the Joint Polar Satellite System (JPSS), the U.S. next-generation polar-orbiting operational environmental satellite system. JPSS is the NOAA–NASA component of the former National Polar-orbiting Operational Environmental Satellite System (NPOESS). Subsequent JPSS missions (JPSS-1 and JPSS-2) will follow. The ATMS instrument on *Suomi-NPP* represents an advanced follow-on capability to the Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) temperature–moisture sounding suite combined. Some of the ATMS enhancements over AMSU-A are reduced size and power, improved spatial coverage, and improved information content (one additional temperature channel and two additional moisture channels). *Suomi-NPP* was placed in the early afternoon orbit, providing similar information to the existing polar-orbiting satellites with microwave (MW) sounders (AMSU-A and MHS on *NOAA-18* and *-19*, AMSU-A on *Aqua*, and AMSU-A on *NOAA-15*). As a consequence of this redundancy in information content, previous studies evaluating the benefits from assimilating ATMS at NCEP with the current satellite

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TABLE 1. Sounders on polar-orbiting satellites used operationally at NCEP as of March–April 2013. In the IR column, the asterisk indicates not assimilated. In the Launch date/nominal lifetime column, italics indicate missions that are past their nominal lifetimes.

Satellite	Orbit	IR	MW	RO	Launch date/nominal lifetime
NOAA-15	A.M.	None	AMSU-A		*13 May 1998/2*
NOAA-18	P.M.	None	AMSU-A, MHS		*20 May 2005/2*
NOAA-19	P.M.	HIRS/4	AMSU-A, MHS		*6 Feb 2009/2*
Suomi-NPP	P.M.	CrIS*	ATMS		28 Oct 2011/5
MetOp-A	A.M.	HIRS/4, IASI	AMSU-A, MH	GRAS	*19 Oct 2006/5*
Aqua	P.M.	AIRS	AMSU-A		*4 May 2002/6*
COSMIC (five satellites)				JPL Blackjack	*15 May 2006/5*
TerraSAR-X				JPL Blackjack	*15 Jun 2003/5*
GRACE-A				JPL Blackjack	*17 Mar 2002/5*
C/NOFS				C/NOFS Occultation Receiver for Ionospheric Sensing and Specification (CORISS)	*16 Apr 2008/2*

configuration showed a neutral impact (Garrett et al. 2012; K. Garrett 2013, meeting presentation; Collard et al. 2013). However, Zou et al. (2013) found a positive impact of ATMS on four hurricane forecasts in 2012. These somewhat mixed results using different models and metrics are common in studies of the impact of individual observational systems on numerical weather prediction (NWP) accuracy, and are also indicative of the difficulty in showing a significant impact on NWP in a system that already is tuned to many different observational systems (English et al. 2013).

Since the expected end of the lifetime of *Suomi-NPP* is 2016, and the launch of the first JPSS satellite has been delayed from 2016 to at least early 2017, a gap or significant reduction in the U.S. microwave satellite data stream is possible. However, because there are other MW observations besides the ones on the NOAA satellites, as well as a number of infrared (IR) sensors on various satellites and radio occultation (RO) soundings (Table 1), it is uncertain how much the NWP forecast skill would decrease because of this gap. To address this question, Garrett (2013) conducted a forecast impact experiment in which ATMS was removed from the observing system in one experiment, and MW soundings from *NOAA-18* and *-19* were removed in a second experiment. Both experiments showed similar skill in terms of the anomaly correlation (AC) score for the 500-mb geopotential heights in the Northern Hemisphere (NH) extratropics (20°–80°N), indicating that the use of ATMS (and other sounding systems) would mitigate the loss of the older early afternoon microwave sounders. However, no information on other variables or latitude ranges was provided in the study and it was not shown how much the absence of either ATMS or *NOAA-18* and *-19* degraded the forecast.

In addition to the possible loss of the NOAA MW sounders, there may be a significant loss of RO observations. RO observations complement the microwave (and infrared) sounders by providing information on the temperature, water vapor, and pressure with high accuracy and precision, and in all weather (Kursinski et al. 2000; Collard and Healy 2003; Kuo et al. 2004; Anthes 2011; WMO 2012; Cucurull et al. 2014). RO observations have, since 2006, shown a significant positive impact on global NWP forecasts (Healy 2008, 2013; Aparicio and Deblonde 2008; Poli et al. 2009; Cucurull 2010; Radnóti et al. 2010; Rennie 2010; Bonavita 2014; Bauer et al. 2014). The mainstay of the global RO system since its launch in 2006, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) with six satellites (Rocken et al. 2000; Anthes et al. 2008), is already past the end of its nominal lifetime, and only four satellites are still operating. A replacement of RO soundings in the tropics is planned with the launch of COSMIC-2 satellites into equatorial orbit in 2016. However, the polar constellation of COSMIC-2 will not be launched until 2018 or 2019 at the earliest, and this launch is uncertain because complete funding for this constellation is not assured.

This study investigates the impacts on the skill of NCEP global forecasts as a result of a loss of the NOAA and *Aqua* MW and all RO soundings. These gaps are potentially important because atmospheric sounders from satellites form the backbone of the global observing system (English et al. 2013). Furthermore, MW soundings (particularly AMSU-A) are consistently the number one observing system contributing to NWP forecast accuracy, and, as shown by adjoint-based observation sensitivity techniques, RO soundings are typically among the top five observing systems contributing to short-range forecast accuracy (Cardinali and Prates 2011; Anthes 2011; Gelaro et al. 2011; Cardinali and Healy 2014; English et al. 2013). We only consider the MW sounder on *Suomi-NPP* because the Cross-track

Infrared Sounder (CrIS) instrument was not yet being assimilated at NCEP at the time of the study.[1]

We consider two extreme scenarios. First, we assume that the MW instruments from *NOAA-15*, *-18*, and *-19*, as well as *Aqua*, have not reached the end of their life before JPSS-1 is launched, and, second, we assume the loss of all of these instruments. Despite the fact that *NOAA-15* has now drifted into an early morning orbit, we have included it in this study because it is the oldest of the currently operating NOAA satellites (launched in May 1998). Furthermore, we consider the impact of losing all RO observations, which occur throughout the day. Although COSMIC provides most of the RO data, there are other satellites that provide some RO data. However, to simplify the interpretation of results, we remove all RO data [*MetOp-A*, *GRACE-A*, Communications/Navigation Outage Forecast System (C/NOFS), and *Terra synthetic aperture radar (SAR)-X*], as well as COSMIC in the RO data-denial experiments.

Because all of the MW and RO systems in our study are not likely to fail before there are at least some replacements, these results may be considered pessimistic (worst case). But as pointed out by English et al. (2013), it is often difficult to obtain a statistically significant result from a single satellite system; therefore, we consider the extreme scenario of losing all of these MW and RO observations rather than just some of them in order to get a significant signal indicating the relative importance of these losses. Finally, the impact of the possible loss of RO observations on the MW satellite bias corrections is analyzed.

In a recent, closely related but even more extreme study, Bonavita (2014) used the European Centre for Medium-Range Weather Forecasts (ECMWF) model to study the impacts of IR, MW, and RO observations in the ECMWF system for two periods (January–February and July–September 2011). A control (CTL) experiment used all the observations in the operational ECMWF model at this time. In a baseline experiment, the study removed the Advanced Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (ATOVS); the AMSU-A, AMSU-B/MHS, and High Resolution Infrared Radiation Sounder (HIRS) package on *NOAA-15*, *-18*, and *-19*, as well as *Aqua* and *MetOp-A*; the two hyperspectral IR sounders [Infrared Atmospheric Sounding Interferometer (IASI) on *MetOp-A* and Atmospheric Infrared Sounder (AIRS) on *Aqua*]; and all RO observations (COSMIC and *MetOp-A* for the winter experiment; and COSMIC, *MetOp-A*, *GRACE-A*, and *TerraSAR-X* for the summer experiment). Subsequent experiments added back ATOVs, the hyperspectral sounders, and RO one at a time. Their results showed that ATOVS and the hyperspectral sounders had similar impacts, recovering approximately 80%–90% of the temperature forecast accuracy using all observations (CTL) with respect to the baseline system. RO observations alone, even though only 0.8% of the number of ATOVS profiles and 3.3% of the hyperspectral IR profiles, recovered 30%–70% of the forecast accuracy in the total system.

McNally (2012) conducted observing system experiments with the ECMWF modeling system in which he tested the impact of a future satellite system consisting of only two polar orbiters: one from the United States and one from Europe. Each satellite contained a microwave sounder (AMSU-A) and a hyperspectral IR sounder (AIRS or IASI). The European satellite also carried an RO receiver [Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS)]. His results showed a serious degradation of forecast skill when both satellites were lost [10% for Europe and North America, equivalent to about 12 h of lost skill and 30% for the Southern Hemisphere (SH), equivalent to about 24 h of lost skill]. McNally's experiments also showed that losing just one polar satellite resulted in marginally reduced forecast skill compared to the two-satellite baseline.

McNally's results as well as other data-denial experiments using modern model and data assimilation systems offer a number of important lessons for the interpretation of the results of the present study. Many of these are discussed in the comprehensive overview of the impact of satellites by English et al. (2013). First, with modern data assimilation techniques and the wealth of observations now used by the major modeling centers (e.g., observations from more than 50 instruments are actively assimilated at ECMWF), the different observing systems compensate to a large extent for each other, and the loss of any one system often makes little noticeable impact. Conversely, it is difficult to show the gain in forecast accuracy by the addition of a new observing system (such as RO or ATMS). Impact studies often show small changes in measures of forecast accuracy, and these changes can differ from one study to another and in any one study depending on the variable selected for verification, the measure of accuracy, the level in the atmosphere, the period of study, the hemisphere, and the range of the forecast. However, even seemingly small changes in forecast accuracy as

[1] The U.S. Defense Meteorological Satellite Program (DMSP) satellites, currently *DMSP-16*, *-17*, *-18*, and *-19*, also carry microwave sensors [Special Sensor Microwave Imager/Sounder (SSM/IS)] but these data were not yet assimilated by NCEP at the time of the study and therefore cannot be included in these data-denial experiments.

TABLE 2. Summary of the different experiments conducted in this study.

Expt name (No.)	Description
CTL (1)	Control experiment, March–April 2013 operational NCEP GDAS
noRO (2)	CTL without RO observations
noATMS (3)	CTL without ATMS observations
noUSAMSU (4)	CTL without AMSU-A/MHS on *NOAA-18* and *-19*, AMSU-A on *Aqua*, and AMSU-A on *NOAA-15*
ATMS Only (5)	CTL without AMSU-A/MHS on *NOAA-18* and *-19*, AMSU-A on *Aqua*, AMSU-A on *NOAA-15*, and RO
RO Only (6)	CTL without AMSU-A/MHS on *NOAA-18* and *-19*, AMSU-A on *Aqua*, AMSU-A on *NOAA-15*, and ATMS

measured by common metrics such as AC score can be considered important by experienced scientists who work in the field of numerical weather prediction and data assimilation (J. Eyre et al. 2014, personal communication). Furthermore, small changes in global skill scores over long periods of time may mask the impact of an observing system on a few high-impact weather systems; over much of the world on many days the impact of any one system is quite small. Finally, progress in increasing forecast accuracy has been slow but steady and due to several factors; the combination of enhanced observing systems, improved models, and increased computer power has led to an average gain of one day of useful forecast skill per decade over the past three decades, which is equivalent to an improvement of ~1.5% yr^{-1} in the AC score at 500 mb (English et al. 2013).

The paper is organized as follows. Section 2 describes the different experiments and observations being used. Results for the mass and wind fields are presented in sections 3 and 4, respectively. The sensitivity of the satellite bias correction to the assimilation of RO in the data assimilation system is investigated in section 5. Finally, the main conclusions are summarized in section 6.

2. Experiment design

We conducted two sets of data-denial experiments; the first set includes three parallel runs CTL, noRO, and noATMS. CTL is the operational configuration at the time of the study (March–April 2013) and it includes all the observations used operationally at NCEP. In noRO, all RO observations were removed from CTL, while in experiment noATMS, MW satellite radiances from ATMS were removed from CTL. This set of experiments provides a measure of the value of ATMS or RO with all the other observations present, or a degradation in global forecasts if we lose ATMS or RO before losing the U.S. microwave soundings (AMSU-A and MHS from *NOAA-18* and *-19*, and AMSU-A from *Aqua* and *NOAA-15*).

Another scenario is that the earlier-launched U.S. satellites will reach the end of their life before ATMS or RO are lost. To evaluate this scenario, we repeated the experiments above (CTL, noRO, and noATMS), but assuming that there are no longer other NOAA satellite MW radiances nor AMSU-A from *Aqua*, leaving no U.S. AMSU sounders in the early afternoon orbit and a reduction of MW sounders in the morning orbit. In this second set of experiments, noUSAMSU is identical to CTL except that AMSU-A and MHS from *NOAA-18* and *-19*, and AMSU-A from *Aqua* and *NOAA-15*, were removed from the assimilation system. Experiment ATMS Only removes RO data from noUSAMSU, and experiment RO Only removes ATMS data from noUSAMSU. A summary of the different experiments conducted in this study is provided in Table 2. All the experimental forecasts began at 0000 UTC and ran for 8 days (192 h) from 21 February to 30 April 2013. The first 7 days are used for model spinup and the forecast comparisons cover the period from 28 February to 30 April 2013. The horizontal resolution of NCEP's operational Global Data Assimilation System at the time of this study is T574 (~27 km) with 64 levels in the vertical. All the experiments used the hybrid version of the Global Data Assimilation System.

Observations from COSMIC, *MetOp-A*, *TerraSAR-X*, *GRACE-A*, and C/NOFS are used in the experiments that assimilate RO data. These are the RO missions used in the NCEP operational configuration at the time of the study. A typical number of assimilated RO soundings at the time of the study is about 2000 per day, and yields about 0.4 M individual observations per day after applying the quality control procedures. Retrievals of bending angles computed with NCEP's bending angle method [see Cucurull et al. (2013) for details on the forward operator used at NCEP] are assimilated up to 50 km in impact height. RO observations were first assimilated operationally at NCEP in 2007 (Cucurull and Derber 2008; Cucurull 2010).

ATMS observations are assimilated using the fast Community Radiative Transfer Model (CRTM), which was developed and is maintained by the Joint Center for Satellite Data Assimilation. CRTM (Han et al. 2006) is used to assimilate microwave and infrared satellite radiances from nadir-scanning radiometers in NCEP's data assimilation system. It is a modular code, and it has a wide range of applications. The code is publicly available for download online [ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/REL-2.0.5/]. The total number of microwave radiance observations assimilated each day in March–April 2013 was ~3.5 M, from which ~2.1 M came from AMSU-A, ~0.7 M from ATMS, and ~0.7 M from *MetOp-A*. Thus, in experiment 6 (RO Only), approximately 80% of the daily global MW soundings were removed.

3. Analysis and forecast accuracy of geopotential heights and temperatures

a. Anomaly correlation score

Verification of the experiments is done against a consensus analysis between NCEP, ECMWF, and the Met Office (UKMO). We computed the AC skill scores for each of the experiments and tested the statistical significance of the mean difference in scores between them. Overall, for the NH extratropics (20°–80°N), we find that the loss of ATMS or AMSU-A (experiments 3 and 4) generally degrades the forecasts slightly compared to CTL, but the differences in the accuracy of the forecasts at most times are not statistically significant at the 95% confidence level as measured by the 500-mb geopotential height AC score (Figs. 1a and 2a). Loss of the RO observations (experiments 2 and 5) is neutral or slightly positive, but the impact is also not statistically significant. This is not a surprise as it is becoming more and more difficult to detect statistically significant improvements in AC scores in medium-range forecasts with the limited number of forecasts. Increasing the period of the testing is computationally unaffordable at most operational weather centers. This presents a serious problem as we are trying to detect small, but potentially important, impacts in the current system.

The AC scores as a function of the forecast lead time for the first set of experiments (CTL, noRO, and noATMS) are shown in Figs. 1a (NH extratropics) and 1c (SH extratropics; 20°–80°S). Differences in AC compared to the CTL for experiments noRO and noATMS are shown below. In the NH extratropics, removing RO and ATMS does not result in any noticeable change in forecast skill up to day 3. Removing either set of observations slightly increases the skill at day 4, and a degradation in skill does not occur until day 6 after removing RO and day 5 after removing ATMS. The loss of ATMS produces a larger degradation than the loss of RO in the NH extratropics. However, these results are not statistically significant at the 95% confidence level. On the contrary, in the SH extratropics the loss of ATMS produces a small improvement in forecast skill (Fig. 1c), although again the results are not statistically significant.

Removing RO observations in noRO in the SH extratropics causes a degradation of the system as compared to CTL at all forecast times, with results being statistically significant up to day 3 (Fig. 1c). At day 3, the degradation of noRO compared with CTL with respect to a mean variation from perfect skill, defined as (difference in AC scores)/(1.0 − current AC score), is ~10.2%. Although not shown here, the degradation is larger for the smaller scales (wavenumbers 10–20).

The AC scores as a function of the forecast length for the second set of experiments (noUSAMSU, ATMS Only, and RO Only) are shown in Figs. 1b (NH extratropics) and 1d (SH extratropics). Differences are now shown below against noUSAMSU. In the NH extratropics (Fig. 1b), there is a small loss in skill by removing ATMS in RO Only after day 3, while removing RO in ATMS Only is neutral up to day 4, with slight improvement for days 5–8. However, these results are not statistically significant at most forecast times. This indicates that the impact of ATMS and RO in the NH extratropics with respect to the two baselines evaluated here (CTL and noUSAMSU) for this measure of skill (500-mb AC) is neutral from a statistical point of view. This is likely due to the large amount of conventional observations already available in the NH. Results are quite different in the SH extratropics (Fig. 1d). Opposite to the results found for the first set of experiments (Fig. 1c), removing ATMS from the system in RO Only degrades the skill as compared to noUSAMSU, although the results are not statistically significant. Removing RO in ATMS Only yields a larger degradation that is statistically significant up to day 4. At day 3, removal of RO observations in ATMS Only results in a 9.7% degradation compared to noUSAMSU with respect to a mean variation from perfect skill.

We next compare all the degraded forecasts to the 2013 operational configuration (CTL). Figure 2 compares the impacts of losing the RO, ATMS, and the AMSU-A/MHS observations individually (experiments 2–4) as well as the impact of ATMS and RO alone in the absence of the MW sounders [experiment 5 (ATMS Only) and experiment 6 (RO Only)]. As discussed above, removing only the RO observations makes the least difference and removing both AMSU-A and ATMS makes the largest difference in the NH extratropics (Fig. 2a), causing loss of skill at all forecast ranges. The relative impact of ATMS and AMSU-A varies with forecast time and the impact of each system is positive compared to experiment 6 (RO Only), which contains neither. These results suggest that ATMS may mitigate to some extent the loss of other U.S. MW sounders in the NH. However, none of these differences is significantly different at the 95% confidence level

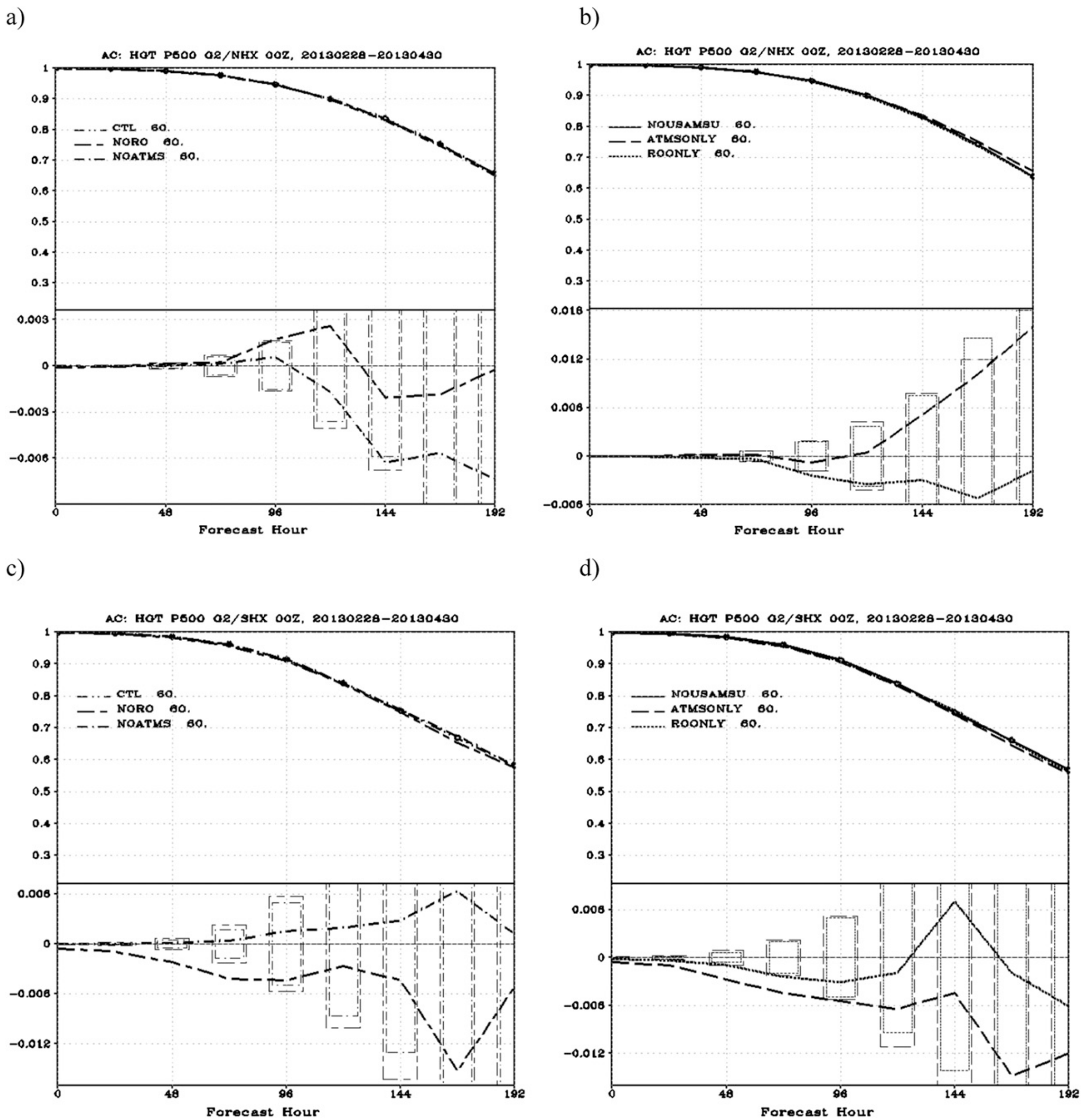

FIG. 1. AC score as a function of the forecast length for the 500-mb geopotential heights in the (a),(b) NH and (c),(d) SH. The results are filtered to represent the structures with total wavenumbers 1–20. The analyses used for verification are a consensus among the NCEP, UKMO, and ECMWF analyses. The difference in AC scores with respect to CTL for experiments noRO and noATMS, and with respect to noUSAMSU for experiments ATMS Only and RO Only are given below. Vertical bars indicate limits of statistical significance at the 95% confidence levels; curves within the corresponding bars are not statistically significant.

from the CTL in the NH extratropics where there are relatively abundant conventional observations, particularly radiosondes and aircraft observations.

The situation is different in the SH extratropics (Fig. 2b). The worst two scenarios in the SH extratropics include the loss of the RO observations [experiment 2 (noRO) and experiment 5 (ATMS Only)] out to 7 days, and these results are statistically significant out to 3 days, but not beyond. The impact of losing AMSU-A in ATMS Only at day 3 in the current operational configuration accounts for an additional ~5.2% of skill degradation on top of the 10.2% due to the loss of RO. It is

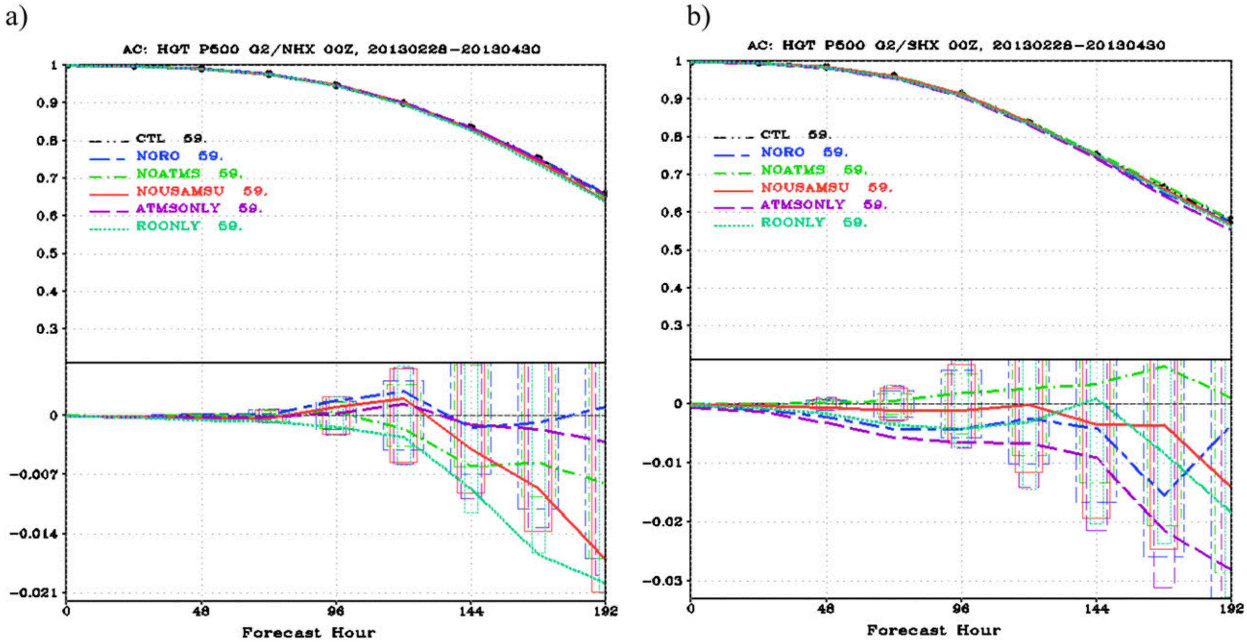

FIG. 2. AC score as a function of the forecast length for the 500-mb geopotential heights in the (a) NH and (b) SH. The results are filtered to represent the structures with total wavenumbers 1–20. The analyses used for verification are a consensus among the NCEP, UKMO, and ECMWF analyses. The differences in AC scores with respect to CTL in the NH and SH are given below. Vertical bars indicate limits of statistical significance at the 95% confidence levels; curves within the corresponding bars are not statistically significant.

remarkable that the loss of RO observations (~0.4 M per day) as compared to the number of U.S microwave observations (~2.1 M AMSU-A observations per day) makes the largest impact in forecast skill in the SH extratropics. Experiment 5 (ATMS Only) shows the lowest AC score in the SH extratropics, and in fact, removing ATMS in the current operational configuration [experiment 3 (noATMS)] actually improves the forecasts slightly, although the results are not statistically significant. (This was already seen in Fig. 1c.) Also, the fact that noUSAMSU (experiment 4), which contains ATMS, shows nearly the same skill as RO Only, which does not contain ATMS (experiment 6), seems to indicate that use of ATMS is not improving the forecast in the absence of U.S. AMSU-A observations in the SH extratropics. These results indicate that ATMS does not mitigate for the loss of the other MW soundings in the SH extratropics. This is not surprising since despite the theoretical superiority of ATMS over the older microwave instruments (AMSU-A), the temperature and water vapor sounding channels on ATMS exhibit a clear striping noise pattern in the along-track direction (Bormann et al. 2013). The striping noise is undetectable for AMSU-A, but present in AMSU-B and MHS data (Qin et al. 2013). This noise feature requires ATMS radiances to be assimilated with larger errors in the Global Data Assimilation System than the AMSU-A observations.

Results for the geopotential heights are similar at other pressure levels; that is, there are few differences that are statistically significant. However, we find significant differences in the temperature forecasts at upper levels, as shown by the AC scores for the temperature forecasts at 250 mb in the SH extratropics in Fig. 3. Figures 3a and 3b show the results for experiments 1–3 and 4–6, respectively. Note the statistically significant degradation in accuracy when RO is removed in both sets of experiments (noRO and ATMS Only). The impact of removing only ATMS is neutral (noATMS in Fig. 3a). For the experiments without RO (noRO and ATMS Only), the degradation in skill is largest for the midrange forecast (day 4). The negative impact of removing RO is largest in ATMS Only, which contains no AMSU-A observations (Fig. 3b). At day 5, the degradation in skill with respect to a mean variation from a perfect skill and verified against its own baseline is 9.0% in noRO and 11.1% in ATMS Only, which indicates that the negative impact of losing RO will be slightly greater if the U.S. MW sounders are lost. Thus, the value of RO in these forecasts increases as the number of microwave observations decreases. In this second set of experiments (Fig. 3b), the ATMS observations provide some positive benefit up to day 5, and these are statistically significant through day 3. These results corroborate the value of RO in improving the

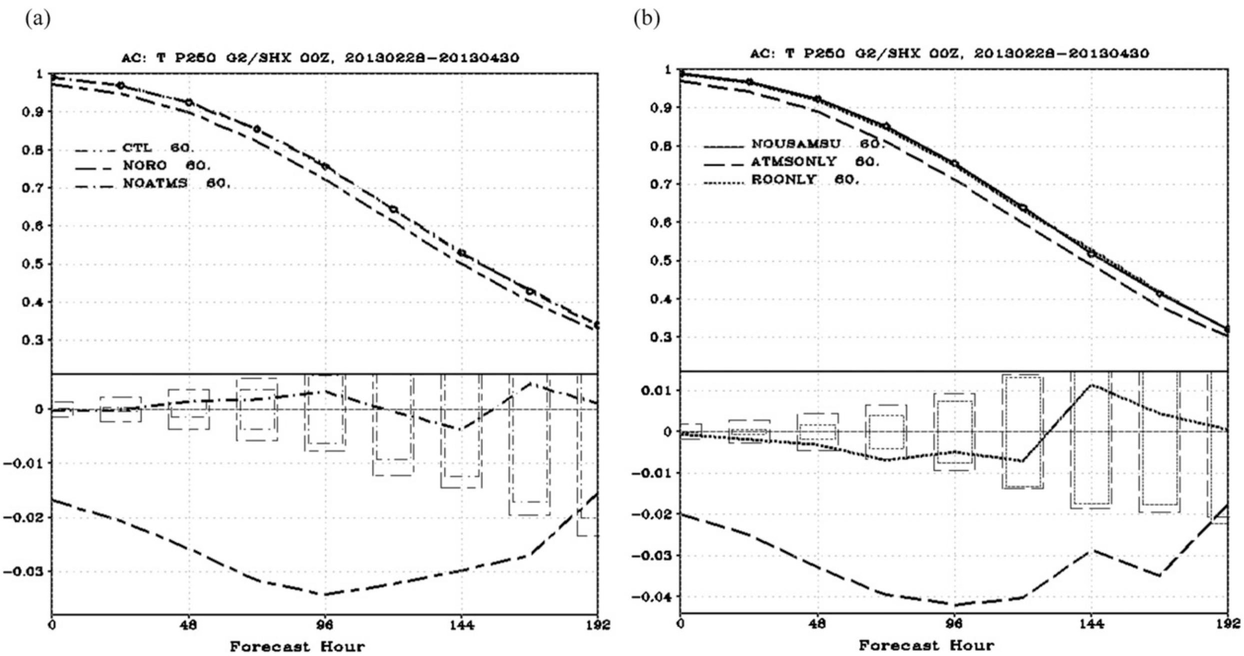

FIG. 3. AC score as a function of the forecast length for the 250-mb temperature field in the SH for (a) first and (b) second sets of experiments (see text). The analyses used for verification are a consensus among the NCEP, UKMO, and ECMWF analyses. The differences in AC scores with respect to CTL and noUSAMSU are given below. Vertical bars indicate limits of statistical significance at the 95% confidence levels; curves within the corresponding bars are not statistically significant.

temperature field in the upper troposphere and lower stratosphere (e.g., Buontempo et al. 2008; Poli et al. 2010; Rennie 2010; Cardinali and Healy 2014; Cucurull et al. 2014; Bauer et al. 2014). In the NH (not shown), there is a small but statistically significant loss in skill compared to CTL when RO is removed in noRO during the first 48 h. A slight benefit from both ATMS and RO observations is found in the second set of experiments in the NH extratropics.

All the 250-mb temperature forecasts are evaluated together against CTL in Fig. 4. Figures 4a and 4b show results for the NH extratropics and SH extratropics, respectively. As found for the 500-mb geopotential heights, the largest benefits in the NH extratropics (Fig. 4a) come from the MW soundings, since the largest degradation occurs when all the AMSU-A and ATMS data are removed from the system in RO Only, and these results are statistically significant out to 3 days. Results are quite different in the SH extratropics (Fig. 4b). The greatest degradation in weather forecast skill is found in the two experiments in which RO data are not used (noRO and ATMS Only). The differences between these two experiments and CTL are larger in the SH extratropics than the difference between any of the experiments and CTL in the NH extratropics by an order of magnitude in anomaly correlation score. There is some slight degradation in the SH extratropics when losing the microwave sounders in RO Only and noUSAMSU, but these results are not statistically significant beyond day 3. The worst-case scenario is losing RO in addition to the U.S. AMSU-A microwave soundings (ATMS Only), with a loss in forecast skill of 12% with respect to a mean deviation from perfect skill. For the RO experiments, results are statistically significant for all forecast times through 7 days in noRO and 8 days in ATMS Only.

b. *Temperature fit of analyses and forecasts to radiosondes*

The temperature fit of the analyses to radiosondes is shown in Fig. 5 for all six experiments. In the stratosphere, there is an overall cold bias for all of the experiments. The fit is best when AMSU-A observations are not used (noUSAMSU) and all MW observations are removed (RO Only) and it is worst when RO observations are removed from the assimilation system (noRO and ATMS Only). Removing RO data increases the cold bias to ~0.4 K in the upper stratosphere; without the early afternoon AMSU-A and ATMS data, the cold bias is reduced to ~0.1 K. Thus, the MW observations tend to increase the stratospheric cold bias, while RO tends to reduce it, as found by Cucurull and Anthes (2014). As a consequence, when all the MW and RO soundings are included in CTL, the bias is somewhere in

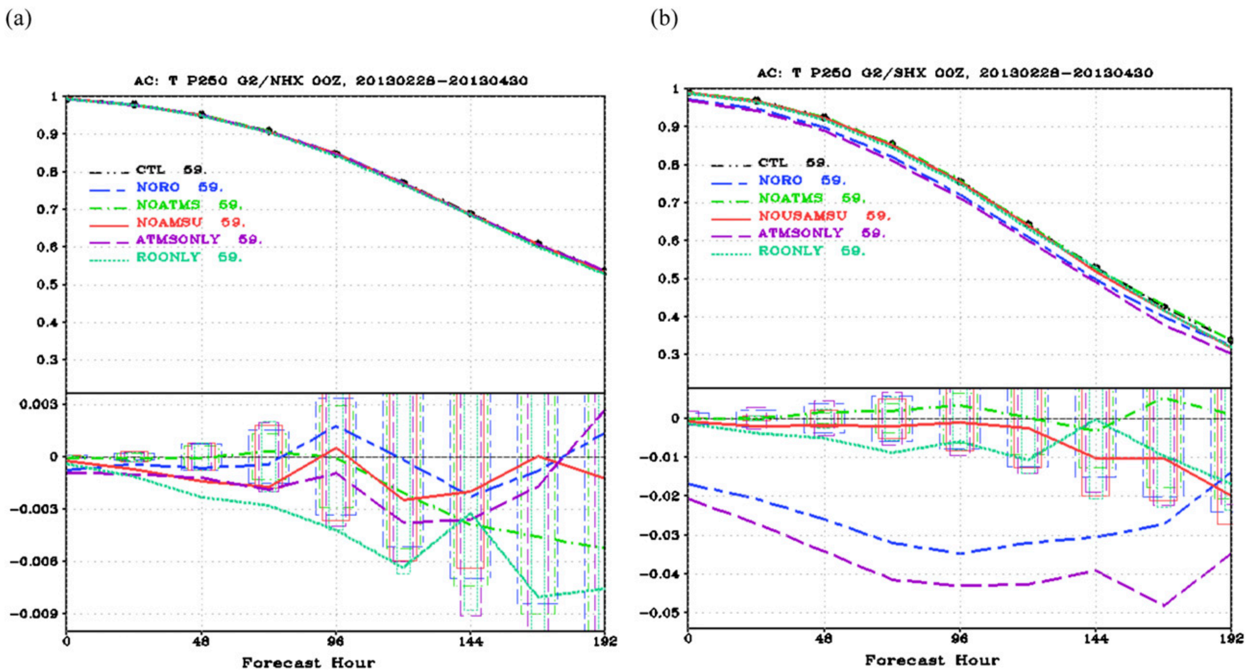

FIG. 4. AC score as a function of the forecast length for the 250-mb temperature field in the (a) NH and (b) SH for all six experiments. The differences in AC scores with respect to CTL in the NH and SH are given below. Vertical bars indicate limits of statistical significance at the 95% confidence levels; curves within the corresponding bars are not statistically significant.

between. This seems to indicate that the assimilation of microwave observations in NCEP's system is not optimal and/or the number of RO observations is too small to anchor the system, resulting in an inaccurate bias correction of the MW observations.

As described in Cucurull and Anthes (2014), the sharp warm bias of 0.3–0.4 K around ~250 mb is likely due to an induced warm bias as a result of the assimilation of aircraft data (Ballish and Kumar 2008; Cardinali et al. 2003). The vertical smoothing of the tropopause by the model and interpolation inaccuracies may also play a role. This warm bias is seen in all the experiments. However, the bias is largest when RO observations are not used, which indicates that the unbiased RO observations compensate for some of the warm-biased aircraft data. In the middle and lower troposphere, the worst fit (greatest biases) is also found when RO observations are removed. The best fit in the troposphere occurs when all microwave observations are removed in RO Only. The impact of ATMS is neutral along the whole vertical range of the atmosphere for the first set of experiments (the structure of the bias between CTL and noATMS is almost identical). The impact is also mostly neutral for the second set of experiments, although in this case a slightly better fit is achieved by removing ATMS in RO Only.

The impact on the temperature biases of removing RO observations is found in the forecasts and well as the analysis. The temporal evolution of the global temperature biases and the differences from CTL are plotted against the forecast time at 300 and 20 mb in Figs. 6a and 6b, respectively. Note that the largest biases occur when RO data are removed from the system for all forecast ranges, while the smallest biases occur when the AMSU-A and ATMS data are not used in RO Only. All results are statistically significant at the 95% level except noATMS.

4. Accuracy of forecast winds

The root-mean-square error (RMSE) wind speeds at day 3 (computed against radiosondes) as a function of the pressure vertical level in the tropics (20°S–20°N) and SH extratropics are shown in Figs. 7a and 7b, respectively. The greatest difference between the experiments in the tropics is found between ~100 and 200 mb. For this vertical pressure range, CTL provides the best fit. There is almost no impact when ATMS is removed from the system in noATMS. There is an increase in RMSE by ~0.2 m s^{-1} when RO observations are not assimilated in noRO, and these differences are statistically significant. There are slightly greater differences when AMSU-A observations are eliminated. RMSE values are greatest when both AMSU-A and RO observations are not assimilated in ATMS Only.

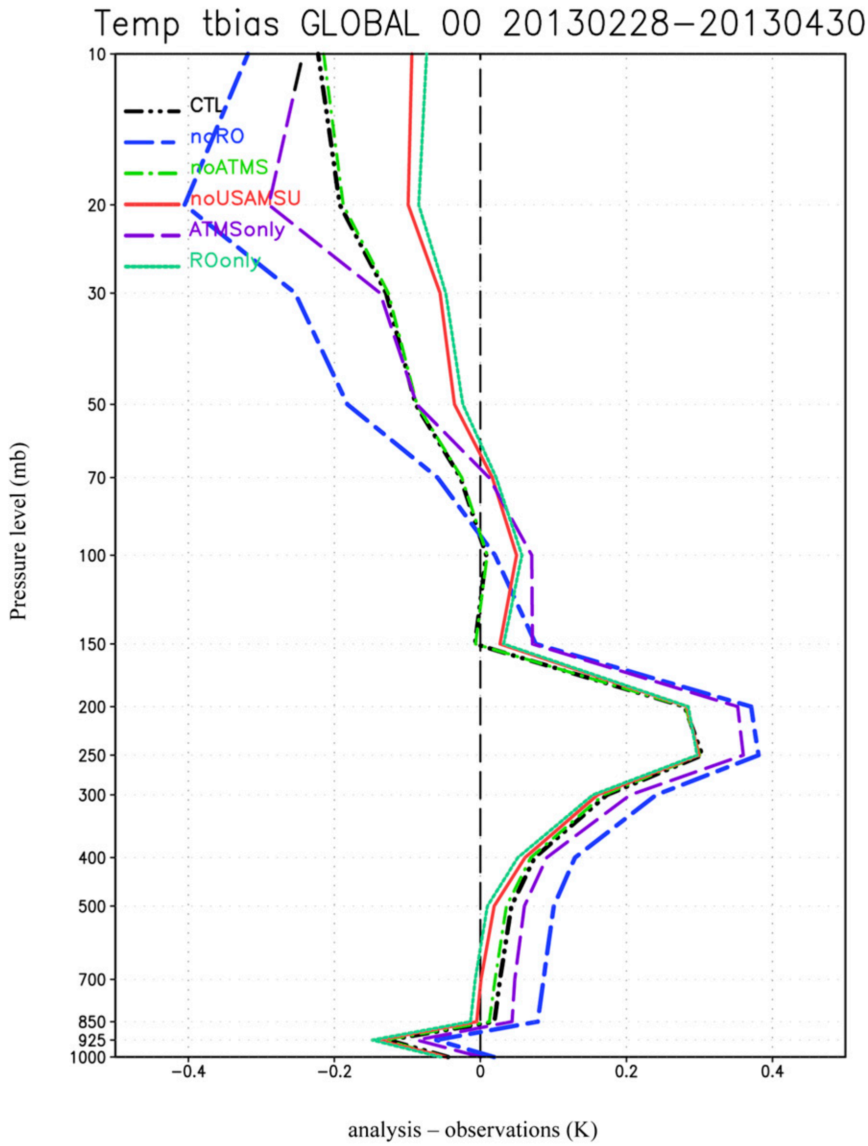

FIG. 5. Global temperature biases of analyses relative to radiosondes in all six experiments.

Similar results are found in the SH extratropics (Fig. 7b), although differences here peak between 200 and 400 mb. As in the tropical latitudes, CTL and noATMS show similar RMSE values and the worst-case scenario is when both AMSU-A and RO are excluded from the assimilation system in ATMS Only, followed by the loss of all the MW in RO Only. All the experiments show similar statistics in the NH.

The RMSE as a function of the forecast length is shown in Figs. 8a and 8b for the 100-mb level in the tropics and 250-mb level in the SH extratropics, respectively. In both regions the lowest RMSE compared to the CTL occurs in noATMS (with AMSU-A and RO) while the forecasts with the largest RMSEs occur with ATMS Only and RO Only (no AMSU-A). Thus, the U.S. AMSU-A observations have the greatest positive impact on the wind forecasts in these regions.

5. Role of RO on the bias correction of satellite radiances

The nearly unbiased nature of RO observations makes them suitable to serve as ‘‘anchor’’ points in NWP models, preventing the model from drifting toward its own biased climate (Dee 2005; Healy et al. 2005; Healy and Thépaut 2006; Healy 2008; Poli et al. 2010; Bauer et al. 2014; Cucurull et al. 2014; Bonavita 2014). Cucurull et al. (2014) looked at the sensitivity of the

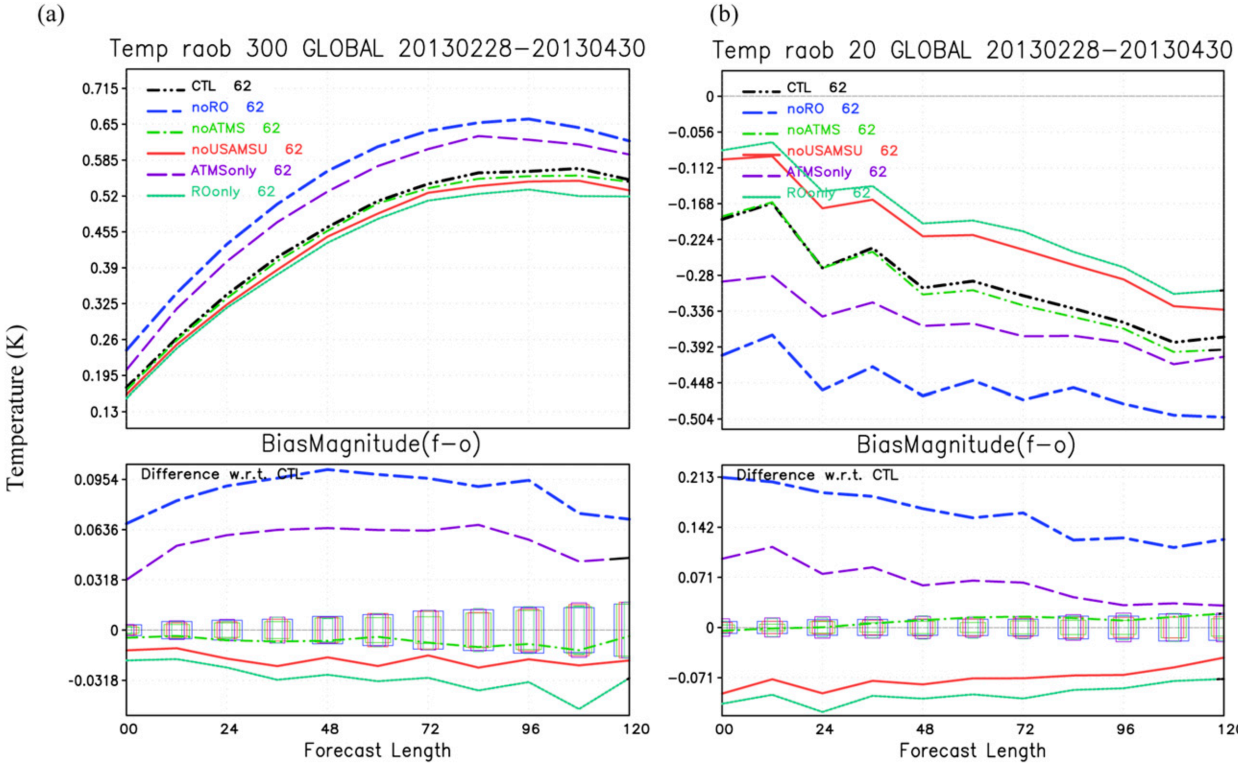

FIG. 6. Evolution of the magnitude of the global temperature fit to radiosondes at (a) 300 and (b) 20 mb. Difference in biases with respect to CTL are given below. Vertical bars indicate limits of statistical significance at the 95% confidence levels; curves within the corresponding bars are not statistically significant.

satellite bias corrections to the use of RO data. The study covered a 3-month period and used an older version of NCEP's data assimilation system. The largest impacts were found for the stratospheric channels, for both the MW and IR sensors. Newer instruments (e.g., *Suomi-NPP*) became operational since that study was done for the 2007–08 period. To evaluate whether the newer observing system, along with an improved version of the assimilation system, are still sensitive to the assimilation of anchoring observations such as RO, we looked at the total bias correction applied to the satellite radiances in experiments CTL and noRO. In interpreting these results, it is important to note that anchor observations such as RO do not necessarily reduce the bias corrections. Without anchor observations, the bias corrections for IR or MW radiances may increase or decrease with time because the model may drift toward its own climatology, either toward or away from the radiances, thus requiring smaller or larger bias corrections. Instead, anchor observations improve the impact of the bias corrections and make them more stable with time because the bias in the model is better controlled.

To better understand the differences in bias correction between the AMSU-A and ATMS instruments, the temporal evolution of the total amount of bias correction applied to ATMS and AMSU-A is presented for two different stratospheric channels in Fig. 9. The total amount of bias correction on ATMS channel 14 in noRO shows a decrease over the last month of the time series, whereas the bias correction in channel 12 shows an increase over the last month (Figs. 9e,f). In contrast, CTL shows a more stable time series for these channels (Figs. 9a,b). A similar behavior is seen for AMSU-A channel 13 (which is equivalent to channel 14 in ATMS) and channel 11 (which is equivalent to channel 12 in ATMS). Thus, stratospheric channels in noRO tend to drift, while the CTL experiment, which contains RO observations, exhibits a more stable time series of the total bias correction. Although Fig. 9 shows ATMS and AMSU-A on *NOAA-18*, results are similar for the other platforms. Similar results are found for some moisture channels.

6. Conclusions

There is a risk of losing some of the microwave observations on the U.S. polar orbiters and radio occultation observations beginning in 2015 and continuing for

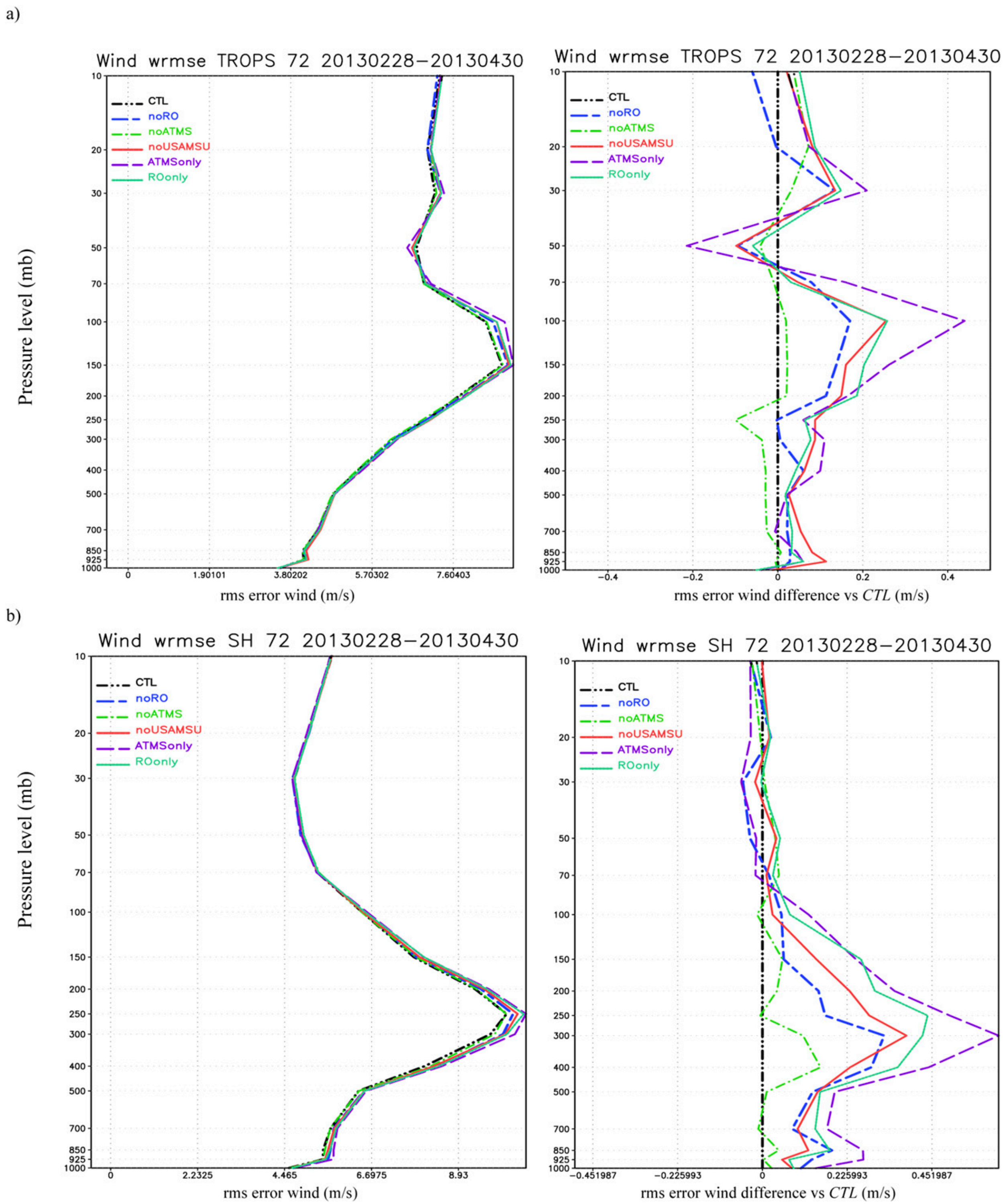

FIG. 7. RMSE winds ($m\,s^{-1}$) fit to radiosonde data and differences with respect to CTL for (a) tropical and (b) SH latitudinal ranges at forecast day 3.

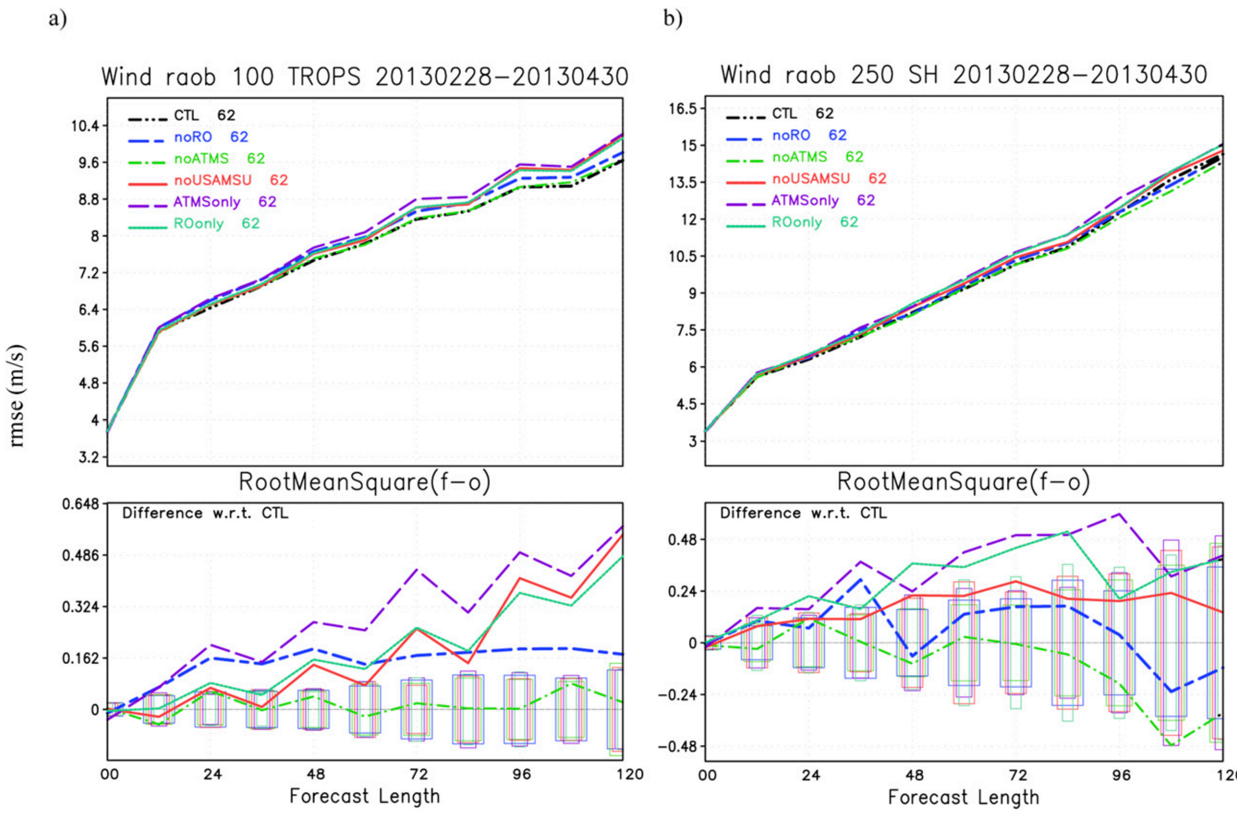

FIG. 8. RMSE winds (m s^{-1}) and differences with respect to CTL for (a) tropics at 100 mb and (b) SH at 250 mb as a function of the forecast length.

one or more years. In support of the U.S. data gap mitigation activities, we have considered the loss in global forecasting accuracy associated with the complete loss of these MW and RO data using the NCEP global forecast model system in March–April 2013.

A slight, statistically insignificant loss of forecast accuracy in the NH extratropics occurs with the loss of all U.S. MW data (which is about 80% of all MW soundings globally), and this loss in skill is not mitigated with the RO observations at that time. However, the situation is quite different in the SH extratropics, where the loss of RO data produces a much larger (and statistically significant) negative impact on the forecasts than does the loss of the U.S. MW observations. The role of ATMS in mitigating the loss of the other MW sounders is mixed, but generally neutral. Thus, the potential gap in RO may be a more serious risk to global forecast accuracy than potential gaps in the U.S. microwave observations. These results are generally consistent with the results from Bonavita (2014) using the ECMWF system in showing that RO observations are effective in partially mitigating against the loss of MW observations and contribute significantly to the accuracy of forecasts, with or without other sounding systems.

Like previous studies, our results confirm the significant anchoring effect of RO observations and the associated reduction in analysis and forecast biases in temperature and water vapor at nearly all levels. They also suggest that some limitations exist in the current way of assimilating the AMSU-A and ATMS microwave observations in the NCEP system, as the global biases in analyses and forecasts increase as the number of MW observations increases, particularly in the stratosphere. The modest amount of unbiased RO observations only partially reduces these biases, which suggests that an increase in RO observations should further anchor the model, resulting in improved bias corrections of the satellite radiances.

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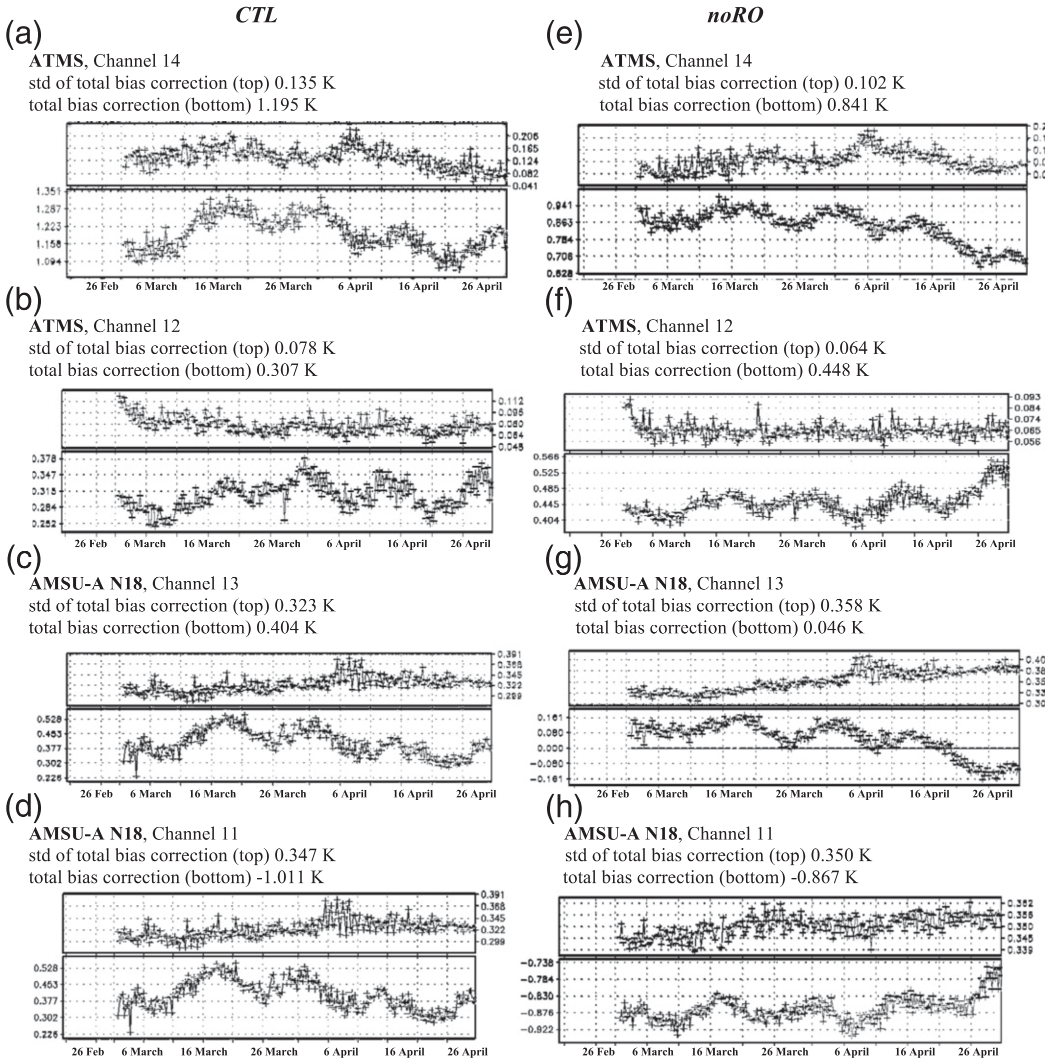

FIG. 9. Time series of the total amount of bias correction. Channel 14 on ATMS corresponds to channel 13 on AMSU-A (the weighting functions peak at ~38 km) and these are the highest stratospheric channels being assimilated; channel 12 on ATMS corresponds to channel 11 on AMSU-A (the weighting functions peak at ~25 km).

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