Impact of Infrared, Microwave, and Radio Occultation Satellite Observations on Operational Numerical Weather Prediction

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ABSTRACT

A comparison of the impact of infrared (IR), microwave (MW), and radio occultation (RO) observations on NCEP’s operational global forecast model over the month of March 2013 is presented. Analyses and forecasts with only IR, MW, and RO observations are compared with analyses and forecasts with no satellite data and with each other. Overall, the patterns of the impact of the different satellite systems are similar, with the MW observations producing the largest impact on the analyses and RO producing the smallest. Without RO observations, satellite radiances are over- or under-bias corrected and RO acts as an anchor observation, reducing the forecast biases globally. Positive correlation coefficients of temperature impacts are generally found between the different satellite observation analyses, indicating that the three satellite systems are affecting the global temperatures in a similar way. However, the correlation in the lower troposphere among all three systems is surprisingly small. Correlations for the moisture field tend to be small in the lower troposphere between the different satellite analyses. The impact of the satellite observations on the 500-hPa geopotential height forecasts is much different in the Northern and Southern Hemispheres. In the Northern Hemisphere, all the satellite observations together make a small positive impact compared to the base (no satellite) forecasts. The IR and MW, but not the RO, make a small positive impact when assimilated alone. The situation is considerably different in the Southern Hemisphere, where all the satellite observations together make a much larger positive impact, and all three observation types (IR, MW, and RO) make similar and significant impacts.

1. Introduction

Radio occultation (RO) observations have recently (since late 2006) been shown to have a positive impact on global numerical weather prediction, complementing infrared (IR) and microwave (MW) observations from satellites (Cardinali 2009; Anthes 2011; Bonavita 2014; Healy 2008, 2013; Poli et al. 2009; Cucurull 2010; Radnóti et al. 2010; Rennie 2010; Aparicio and Deblonde 2008; Bauer et al. 2014). A radio occultation occurs when a receiver on a low-Earth-orbiting (LEO) satellite tracks a global positioning system (GPS) satellite that is observed to rise or set relative to Earth. The arrival time of the received radio signal is retarded because of the refractive bending and slowing of the signal as it traverses the atmosphere. By measuring the change in phase measurements during the occultation event, profiles of bending angle, atmospheric refractivity, pressure, temperature, and water vapor can be retrieved as a function of altitude (Hajj et al. 1994, 2002; Rocken et al. 1997; Kursinski et al. 2000; Kuo et al. 2004). GPS operates at very long wavelengths compared to other remote sensing instruments, and its frequencies are below any absorption lines. In addition, particle scattering is negligible. Thus, the RO technology does not suffer from scattering and absorption effects as other instruments operating at shorter wavelengths do (Melbourne et al. 1994).

Observations made by radiometry of absorption and emission spectra from natural sources usually are
obtained from amplitude measurements that are more vulnerable to long-term stability errors in their calibration systems. As a result, most atmospheric remote sensing instruments require calibration on orbit. In contrast, the RO technology uses very precise phase measurements of artificial signals. Because the RO technique is free of instrumental biases, it can serve as a calibration system for other instruments. For example, Zou et al. (2014) used precise and accurate RO observations to calibrate upper temperature channels from the Advanced Technology Microwave Sounder (ATMS) on board the Suomi National Polar-Orbiting Partnership (Suomi-NPP) satellite.

Nadir-viewing instruments provide information associated with a weighted average over atmospheric layers of different thicknesses, which limits the vertical resolution of these observations. Increasing the number of channels improves the vertical resolution, but radiance emitted over a scale height ultimately limits the resolution that can be achieved. In contrast, RO provides high-vertical-resolution profiles. However, the horizontal footprint associated with the nadir geometry is smaller than the one associated with a limb-viewing technology (Kursinski et al. 1997), which enables the nadir-viewing radiance sounders to have higher horizontal resolution than RO. Thus, the two systems are highly complementary [e.g., Collard and Healy (2003) and as summarized by WMO (2012)].

The assimilation of satellite radiances in operational weather forecasting benefits from the assimilation of unbiased observations that reduce the drift of a weather model toward its own climatology (Derber and Wu 1998; Dee 2004, 2005; Dee and Uppala 2008). The role of RO observations as “anchor observations” in NWP models and the resulting improvements in the bias correction of the satellite radiances has been shown in a number of studies (Healy et al. 2005; Healy and Thépaut 2006; Healy 2008; Poli et al. 2010; Bauer et al. 2014; Cucurull et al. 2014; Bonavita 2014).

Active RO limb soundings and passive MW and IR nadir-viewing instrument systems on satellites produce information on the three-dimensional temperature and water vapor structure in the atmosphere and are together the most effective space-based observational systems in reducing forecast errors (Anthes 2011; Cardinali and Prates 2011; Cardinali and Healy 2014). Several studies have shown the contribution of the different systems to short-range (24 h) forecast accuracy using the Forecast Sensitivity to Observations (FSO) method (Baker and Daley 2000; Langland and Baker 2004; Errico 2007; Gelaro et al. 2007; WMO 2012). The FSO technique uses the adjoint of a data assimilation system. In addition, observing system experiments (OSEs) are frequently run at the operational numerical weather prediction centers (e.g., Radnótí et al. 2010; McNally et al. 2014). Comparison between OSEs and FSO results has been investigated by Gelaro and Zhu (2009), Todling (2013) suggests a new approach to evaluate the impact of current observations in weather forecasting based on the “observation space” approach rather than the “state space” approach used in the tangent linear methods. However, detailed studies of the differences in how the three satellite systems (MW, IR, and RO) affect the analyses and subsequent forecasts have not been done. The goal of this paper is to investigate the differences and similarities between the impacts on global temperature and moisture analyses and forecasts associated with the separate assimilation of RO, MW, and IR observations in the National Centers for Environmental Prediction (NCEP) operational global data assimilation system. Where these analyses and forecasts differ significantly from each other or from the model analysis without the satellite observations can indicate possible issues with the satellite systems and/or the model.

A description of the different experiments is presented in section 2. The methodology used to evaluate the results is presented in section 3. Section 4 analyzes the results of the experiments, and the main conclusions are summarized in section 5.

2. Experiments

We conducted six experimental sets of 39 forecasts over the period 21 February–31 March 2013. The control experiment CTL assimilated all the observations used in the operational suite of the NCEP’s global data assimilation system, including RO and satellite radiance observations. A second experiment, BASE, removed all satellite sounding systems (IR, MW, and RO) while retaining all other observations. Experiments 3–5 (designated IR, MW, and RO) selectively added back to the BASE the IR, MW, and RO observations. A summary of the five experiments is provided in Table 1. All the experimental forecasts begin at 0000 UTC and run for 8 days (192 h) from 21 February to 31 March 2013. The first 7 days are used for model spinup, and the comparisons cover the period 28 February–31 March 2013. The horizontal resolution of the operational NCEP’s global data assimilation at the time of this study is T574 (~27 km) with 64 levels in the vertical. The model top is located at 0.266 hPa (~60 km). Satellite radiances are thinned to 145 km and bias corrected at NCEP using a variational bias correction approach in its hybrid three-dimensional variational data assimilation (3DVAR) system (Derber and Wu 1998; Dee 2004; Dee and Uppala 2008). The variational bias correction is active in all the
3. Analysis of the forecasts

We make five types of analyses of the differences in temperature ($T$) and water vapor ($q$, specific humidity) among the five experiments (see appendix for mathematical definitions).

First, vertical profiles of the fit to radiosondes of the $CTL$, BASE, $IR$, $MW$, and $RO$ analyses of $T$ and $q$ are analyzed. The $T$ or $q$ analyses are interpolated to the time and location of all available, high-quality (as estimated by the NCEP quality-control system) radiosondes globally. The global and temporal (32 days) means of the differences are calculated for each vertical level. These profiles show where, on average, the different sounding systems improve or degrade the BASE analysis compared to radiosondes. They are biased toward land areas of the Northern Hemisphere where most of the radiosonde observations are.

Second, horizontal maps at different levels of the mean differences between the $IR$, $MW$, and $RO$ temperature and specific humidity analyses compared to the BASE analysis are analyzed. These differences are called the analysis impacts of $IR$, $MW$, and $RO$ observations. They show horizontal patterns of a month’s average of the difference between analyses using the different satellite observations and the BASE analysis. These bias differences may be caused by either biases in the sounding systems or the BASE, or a combination of both.

Third, we analyze horizontal maps at different levels of the root-mean-square (RMS) differences between the $IR$, $MW$, and $RO$ analyses compared to the BASE analysis. These charts are a measure of the temporal and spatial variability of the impacts on the analysis from the three sounding systems compared to the BASE analysis. Where the RMS values are small, the sounding system produces little impact on the BASE analysis during the 32-day period. Where the RMS values are large, the analyses from the BASE and the sounding systems show greater differences from day to day.

Fourth, we analyze vertical profiles of global and temporal averages of

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TABLE 1. Summary of the different experiments conducted in this study.

<table>
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<tr>
<th>Expt name</th>
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<tr>
<td>$CTL$</td>
<td>Control experiment. Assimilates all the observations used operationally in the NCEP’s global data assimilation system. The satellite radiances include (IR) High Resolution Infrared Radiation Sounder 4 (HIRS/4) on Meteorological Operational A (MetOp-A) and National Oceanic and Atmospheric Administration-19 (NOAA-19), Infrared Atmospheric Sounding Interferometer (IASI) on MetOp-A, Atmospheric Infrared Sounder (AIRS) on Aqua, and the sounders from the GOES-I5 geostationary satellite (for IR) and Advanced Microwave Sounding Unit A (AMSU-A) on NOAA-15, NOAA-18, NOAA-19, MetOp-A, and Aqua; Microwave Humidity Sounder (MHS) on NOAA-18, NOAA-19, and MetOp-A; and ATMS on Suomi-NPP (for MW). The assimilation of RO includes data from Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS) on MetOp-A, Gravity Recovery and Climate Experiment–A (GRACE-A), Terra synthetic aperture radar operating in X band (TerraSAR-X), and Communications/Navigation Outage Forecasting System (C/NOFS).</td>
</tr>
<tr>
<td>$BASE$</td>
<td>Baseline experiment. As in $CTL$, but removing all the RO and satellite radiances (both the IR and MW).</td>
</tr>
<tr>
<td>$IR$</td>
<td>As in $BASE$, but with the infrared satellite radiances.</td>
</tr>
<tr>
<td>$MW$</td>
<td>As in $BASE$, but with the microwave satellite radiances.</td>
</tr>
<tr>
<td>$RO$</td>
<td>As in $BASE$, but with the radio occultation data.</td>
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experiments that assimilate satellite radiances. The background error statistics are computed online through an ensemble Kalman filter for all the experiments. Experiment $RO$ assimilates ~400 000 bending angles daily. RO profiles are assimilated up to 50 km in impact height [see Cucurull et al. (2013) for details on the forward operator used at NCEP]. On average, there are ~8 million IR and ~3.5 million MW radiance observations assimilated daily. (Statistics for satellite radiances and RO data used operationally at NCEP can be found at www.emc.ncep.noaa.gov/gmb/gdas, and details on the use of satellite radiances in the $CTL$ experiment that include the sensors and channels being used can be found at www.emc.ncep.noaa.gov/gmb/wx20cl/radiances/OSSE/OSE/prctl/.)

We chose the strategy of adding the satellite systems of observations to the $BASE$ experiment that does not contain the three systems one at a time, rather than an alternative strategy of omitting each system one at a time from a base that contained all three systems (data denial experiments). Both strategies provide useful information. The strategy followed here, which was also followed by Bonavita (2014), allows for an enhanced and clearer impact of each individual system because the complex interactions with the other systems do not occur.
2) RMS differences of temperature and specific humidity for IR–MW, IR–RO, and MW–RO; and
3) global mean correlations of the mean monthly analysis impacts (differences from BASE) as a function of vertical level among IR–MW, IR–RO, and MW–RO.

These profiles show quantitatively where the three sounding systems agree most closely on their impact on the BASE analyses and where they differ.

Finally, standard forecast skill verification, including anomaly correlation (AC) score and bias, is evaluated against a consensus analysis from NCEP, the European Centre for Medium-Range Weather Forecasts (ECMWF), and Met Office analyses.

4. Results

a. Fit of analyses to radiosondes

We first look at the fit of the five analyses to radiosondes. Figure 1 shows the mean over all analyses at $r = 0$ tropopause height and pressure level for the CTL experiment. The mean tropopause height varies from more than 17 km [less than 90 mb (1 mb = 1 hPa)] in the tropics to less than 8 km (more than 240 mb) in the polar regions.

Figure 2 shows the fit of $T$ and $q$ to the radiosondes of the five analyses (analysis observations). All the analyses except RO are cold compared to the radiosondes in the stratosphere (above 100 mb). The cold bias in the NCEP stratospheric analyses and forecasts is well known (Yang 2013). The ability of the unbiased RO observations to reduce or eliminate biases in the stratosphere is also well known (Healy et al. 2005; Healy and Thépaut 2006; Healy 2008; Poli et al. 2010; Cucurull et al. 2014). It is interesting that the MW and IR observations increase the cold bias, while the BASE (no satellite observations) actually has a smaller bias. RO observations act as “anchor” measurements, reducing a drift of the model to its own climatology. As a consequence, the bias correction of radiance observations is improved, which results in better analyses.

The warm bias in the upper troposphere that peaks around 200 mb in all experiments is very likely due to the assimilation of aircraft observations, which have a warm bias of up to 0.5 K (Cardinali et al. 2003; Ballish and Kumar 2008; B. Ballish 2012, meeting presentation). In addition, the model does not represent the tropopause well, smoothing the cold tropopause. The tropopause level varies considerably over the globe (Fig. 1), and so the net bias introduced by smoothing the temperature minimum at the tropopause over the entire Earth would be a relatively thick layer of warm bias. All the experiments show this warm bias, indicating that it is not caused by satellite data.

The MW and IR experiments show the greatest warm bias at 200 mb. This might be due to the fact that the lack of unbiased observations in these two experiments enhances the effects of the warm-biased aircraft data around this level. The RO experiment shows a smaller peak bias at 200 mb, but the bias is still 0.25 K.

From 300 to 800 mb the biases are all under 0.1 K, but the larger warm bias in the MW stands out from the other experiments. It is noticeable that MW produces the largest cold bias in the stratosphere and the warmest bias in the troposphere.

At 925 mb, all analyses show a noticeable cold bias of about −0.1 K, possibly related to model errors in resolving the location and structure of the atmospheric boundary layer (ABL). Different topographies and surface effects make it difficult to compare model analyses and observations at these lower heights.

The fit of the $q$ analyses to radiosondes (Fig. 2b) shows a drier stratosphere (above 200 mb) and a moister troposphere, with moisture impact maxima at 700 and 925 mb, with a relative minimum at 850 and 1000 mb. All these analyses show the same shape, indicating that some other factor in the model analyses is causing this pattern (there is no reason to think that the IR, MW, and RO observation errors are correlated in the vertical).

The cold and moist bias at 925 mb compared to radiosondes in this study is consistent with what is seen in the NCEP’s forecast system verification (S. Saha 2014, personal communication).

b. Global distribution of mean differences between satellite analysis and BASE

Figure 3 shows the global distribution of the monthly mean differences of temperature at 850 mb from the IR, MW, and RO analyses and the BASE analysis. Most of the impacts of the three satellite systems are within ±0.5 K in the monthly mean. As expected, the greatest differences are in the Southern Hemisphere, where there are fewer radiosondes and other nonsatellite observations. The MW analysis stands out in its much warmer Arctic region;1 its strong region of warming over northern Africa; and its warmer analysis over the

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1 The unphysical extended warmer area in MW at the very high latitudes, which are probably related to difficulties in estimating the surface emissivity over sea ice, has been recently improved at NCEP with the use of an enhanced satellite bias correction (Zhu et al. 2013) and some quality-control fixes.
North Atlantic, the Southern Ocean, and western Antarctica. Both the IR and RO analyses show cooler patterns over the Southern Ocean. All three analyses show a cooler region off the western coast of South America, where the marine ABL is especially well defined. The uncertainty in the model of the exact location of this layer in this poorly observed region could lead to sharp maxima in the background error profiles. This would result in similar large analysis increments for all three observing systems, justifying the similar cooling pattern found in the IR, MW, and RO experiments.

Figure 4 shows the global distribution of the mean differences between the specific humidity at 850 mb from the IR, MW, and RO analyses and the BASE. The IR and MW water vapor impacts (Figs. 4a,b) show similar patterns: wetter over Africa, off the west coasts of North and South America, and over the tropical Atlantic, and drier over Australia and off the eastern coast of South America. The RO impacts are significantly less,
although there are similarities in patterns to the IR and MW, particularly the IR.

Figure 5 shows the global distribution of the mean differences between the temperature at 700 mb from the IR, MW, and RO analyses and the BASE analysis. All three satellite sounding systems show warm impacts over eastern Antarctica and cooling over the ocean surrounding Antarctica, 50°–70°S and centered at 60°S. The cooling impacts are greatest for MW (over −2 K) and least for RO (≈−1 K). MW shows large warm impacts over the Arctic, while IR shows weak warming and RO shows little change. In general, RO shows the least change compared to the BASE, probably because of the relatively small number of RO observations.

Figure 6 shows the global distribution of the mean differences between the specific humidity at 700 mb from the IR, MW, and RO analyses and the BASE analysis. All three satellite systems slightly moisten the air at 700 mb over Antarctica, IR, MW, and to some extent RO show an elongated band of moistening extending east-southeastward from Africa, across the Indian Ocean and Indonesia and into the South Pacific. The three sounding systems also provide a drying impact over the equatorial Pacific and off the west coast of Australia. Again, the RO impacts are generally smaller than the IR or MW.

At 500 mb (figures not shown) the dominant feature in the temperature impacts for all three satellite systems is a strong cooling in the ocean surrounding Antarctica, between 50° and 70°S. The pattern is similar to that shown in Fig. 5, but the magnitude of the cooling is larger, exceeding −2.5 K in MW. The magnitude of the cooling is least in RO, with a maximum of about −1.5 K.

The main feature in the specific humidity impacts at 500 mb for all three satellite systems is a large region of drying from the equator southward to 30°S in the Indian Ocean, from 10°N to 30°S in the Pacific Ocean, and from the equator to 20°S in the Atlantic Ocean. Maximum values of drying are about 1.5 g kg⁻¹ in MW and IR and about 0.5–1.0 g kg⁻¹ in RO. The patterns are similar. Outside these regions moisture impact is small, less than ±0.5 g kg⁻¹.

To illustrate the impacts at high levels, we show the temperature impacts at 100 mb in Fig. 7. The dominant temperature impact at 100 mb is a warming of over 1 K in the subtropical Pacific. The magnitude and shape is similar in all three satellite systems. There are also weak cooling impacts noted over east Antarctica (30°–150°E) in all three systems and weak cooling off the Antarctica coast between 120° and 60°W in the IR and RO experiments, but not the MW.

The preceding discussion has shown where biases exist over the month of March 2013 between the
analyses from the three satellite observing systems and the BASE analyses. Only a few regions show bias differences greater than ±0.5 K. Of course, the satellite systems are expected to have much greater impacts from day to day, especially in the Southern Hemisphere. This is indeed what we find, and we illustrate the results at two levels, 500 and 850 mb.

c. Global distribution of RMS differences between satellite analysis and BASE

Figure 8 shows the RMS differences between the IR, MW, and RO analyses compared to the BASE analysis for temperature at 500 mb. The striking features of Fig. 8 are the small RMS impacts over the continents...
(except Africa) where radiosonde and other data are plentiful and the band of large RMS impacts extending around the globe between $40^\circ$ and $70^\circ$S, where the day-to-day variability of weather associated with this strong baroclinic zone and storm tracks together with lack of other data make the satellite data especially impactful. RMS differences associated with $MW$ are the greatest, exceeding 3 K, while the RMS differences associated with $RO$ are the smallest (maximum of 2.5 K). Smaller regions of impacts between 1.0 and 1.5 K exist over the Indian Ocean from the equator to $40^\circ$S and over the North Pacific in all three satellite systems.

Figure 9 shows the RMS differences between the $IR$, $MW$, and $RO$ specific humidity analyses compared to the $BASE$ analysis at 500 mb. In contrast to the temperature
impacts shown in Fig. 8, the specific humidity impacts from the three satellite systems are greatest over the tropics and subtropics (30°N–30°S), with typical values 1.0–1.5 g kg⁻¹, but reaching as high as 2.0 g kg⁻¹ in the MW analysis over the equatorial Pacific and Atlantic Oceans. As with temperature impacts, the magnitude of the RO water vapor impacts are slightly less those for the IR or MW impacts.

Figure 10 shows the RMS differences between the IR, MW, and RO temperature analyses compared to the BASE analysis.
BASE analysis at 850 mb. At 850 mb, the maximum impacts are generally in the Southern Hemisphere, with maxima over Antarctica, the Southern Ocean, and the South Pacific. A region of exceptionally large impacts is off the coast of South America, where the RMS differences exceed 3 K. This is the region of a well-defined marine boundary layer where there are extremely sharp vertical gradients in temperature and water vapor as well as a persistent marine stratocumulus deck, which present challenges for the model physics and the satellite observations. All three analyses show large RMS differences over the tropical North Pacific. The MW analysis shows a strong maximum over the Arctic, which occurs to a lesser degree in the IR analysis and is only barely discernable in RO.

Figure 6 shows the global distribution of the specific humidity differences (g kg⁻¹) at 700 mb from the (a) IR, (b) MW, and (c) RO analyses compared to the BASE analysis.
(Fig. 11) show similar patterns in IR, MW, and RO. High values extend across the globe north and south of the equator to about 40°N and 40°S, respectively. There is a weak relative minimum in impacts over the equator itself. Strongest maxima of over 2 g kg⁻¹ exist over equatorial Africa, the Indian Ocean, tropical North Pacific, and Caribbean and off both the east and west coasts of South America.
The results of these comparisons show that, in general, the patterns of the impacts of IR, MW, and RO are similar. The MW impacts are usually largest and the RO impacts are the smallest, with IR in between. The reason for the relatively small RO impacts is almost certainly due to the fact that there are far fewer RO observations than either IR or MW satellite radiances. However, it is encouraging that these comparisons show impacts from

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**FIG. 8.** RMS differences between the (a) IR, (b) MW, and (c) RO temperature analyses (K) compared to the BASE analysis at 500 mb.
all three satellite systems that generally agree in pattern and in magnitude.

d. Vertical profiles of global and temporal averages of mean and RMS differences and correlations between the different analyses

The preceding discussion has illustrated differences between the analysis impacts and the BASE for the three satellite systems, IR, MW, and RO. To see how the global means of these impacts vary in the vertical, as well as how the global mean impacts among the three systems vary among themselves, we plot the vertical profiles of 1) global mean analysis minus BASE temperatures; 2) global mean IR–MW, IR–RO, and MW–RO temperature impacts; and 3) correlation coefficients among IR–MW, IR–RO, and MW–RO temperature impacts in Fig. 12.
The vertical profiles of the global mean impacts of IR and RO are similar, showing a cooling of $-0.1$ to $-0.2$ K from the surface to about 300 mb. From 300 to 100 mb they show a warming of up to 0.2 K. Above 100 mb, where the cold bias exists in the NCEP analysis, IR shows a slight cooling while RO shows a warming, which is offsetting the cold bias, by up to 0.4 K. The vertical profile of MW impacts is quite different from the IR and RO impacts, showing a warming of up to 0.2 K from the surface to 800 mb, cooling up to $-0.2$ K from 700 to 400 mb, warming between 300 and 200 mb, and then cooling above 200 mb. The more pronounced vertical structure correction from MW in the lower troposphere seems to be associated with the larger analysis.
differences in the high latitudes, particular the polar regions (Figs. 3b, 5b).

Another way of looking at the difference in impacts is to compare the vertical profiles of impacts from the three satellite systems with each other (Fig. 12b). This chart shows the relative similarity of IR and RO except above 100 mb, where IR and RO impacts in the stratosphere are of opposite sign. The oscillating profiles of IR–MW and MW–RO in Fig. 12b highlight the differences shown in Fig. 12a. In terms of RMS differences (Fig. 12c), the largest variability exists between the MW and RO analyses. In all three cases, the largest RMS differences are found in a layer between 800 and 900 mb.

Finally, we consider the correlation of the global mean impacts among the three satellite systems in Fig. 12d. Globally averaged correlation coefficients of pairs of time-averaged analysis impacts are computed. Here we
see positive correlations exceeding 0.6 from 700 to 200 mb between pairs of all three systems (except for a layer between 350 and 300 mb for MW–RO). These relatively high correlations indicate that the three satellite systems are affecting the global temperatures in generally the same way. However, the correlation in the lower troposphere (surface to 800 mb) among all three systems is surprisingly low (less than 0.5), and in the case of MW and RO, the correlation is even negative below 900 mb. The correlation between MW and IR is also negative near 200 mb. That IR observations cannot penetrate through clouds, that both IR and MW data are affected by errors in surface emissivity and skin temperature, and that RO data are limited in number and may experience superrefraction in the tropics may explain the low correlations between the three systems in the lower troposphere.

Figure 13 shows the corresponding vertical profiles of global mean and impact differences and their correlations for specific humidity. Overall, all three satellite
systems produce drier analyses than the BASE (Fig. 13a). However, MW tends to moisten the analyses below 750 mb, and to a small extent, so does IR below 850 mb. Both IR and MW analyses are drier than RO analyses between 650 and 350 mb. This is also reflected in Fig. 13b, where the differences between the mean analyses impacts for pairs of satellite systems are shown. Below 700 mb, MW is wetter than RO and IR, and IR is wetter than RO below 800 mb. The largest RMS differences (Fig. 13c) between the analyses impacts are found at ~800 mb, which is generally above the ABL height. This seems to indicate that the ABL structure is dominated by the assimilation of conventional observations and/or model physics. Overall, the differences in RMS between the experiments are small. The RMS differences between IR and MW are the smallest, which is expected since we have seen that RO analyses do not impact the moisture field as much as the IR and MW analyses (Figs. 4, 6). Because the magnitude of the impacts of RO is small compared to the magnitude of the
and IR impacts, the RMS differences between the RO and MW and IR impacts will be larger than the RMS differences between MW and IR, even if the impacts are highly correlated. Correlations between the different monthly mean impacts are shown in Fig. 13d. IR and MW are highly correlated above ~700 mb. However, their correlation is surprisingly low (<0.6) in the lower troposphere. The lower vertical resolution associated with the IR and MW observations might not be good enough to resolve the boundary layer structures and to correct for the large model errors present in this region. Also, surface emissivity and skin temperature errors and the presence of clouds affect the IR and MW differently in the lower troposphere.

The vertical profiles of the correlation coefficients shown in Figs. 12 and 13 are profiles of the correlations among the monthly mean impact fields at each vertical level; they help quantify the similarities among the patterns shown in the horizontal maps of monthly mean impacts shown in Figs. 3–7. Another way of showing how closely the three different satellite systems impact the BASE analysis is to compute the monthly average of the daily correlation coefficients of pairs of the impacts. Vertical profiles of these correlation coefficients are shown in Fig. 14. The vertical profiles of the mean daily temperature impact correlations (Fig. 14a) are similar in shape to the corresponding profiles of the monthly mean impacts (Fig. 12d), but they are somewhat smoother and do not show any levels of negative correlations. The correlations between IR and MW are larger than those between IR and RO and MW and RO, which may be due to the greater independence of the active limb-scanning RO observations compared to the passive, nadir-viewing radiance observations. The correlations between all the pairs are least below 800 and above 400 mb.

The vertical profiles of the correlations of the mean daily specific humidity impacts (Fig. 14b) are also smoother than the corresponding profiles of the monthly mean correlations (Fig. 13d) and show higher values in the lower troposphere. As with temperature, the specific humidity correlations are higher for IR and MW than for IR–RO or MW–RO.

e. AC score and biases of extended forecasts

The preceding results have considered the differences and similarities of the five analyses. This section compares the accuracy of the forecasts made from these analyses.

Figure 15 shows the 500-mb geopotential heights AC score for the five experiments out to 192 h (8 days) for the Northern (NH) and Southern Hemispheres (SH). The satellite observations have a relatively small effect in the NH. The CTL (all satellite observations) shows the greatest effect, as expected, and these impacts are statistically significant at all forecast times. The next largest effect is MW, followed by IR, and both of these experiments show differences that are statistically significant out to 120 h (5 days). RO shows no significant differences compared to BASE. In the SH the situation is quite different. The CTL again shows the greatest impact, but MW, IR, and RO all show significant impacts and all three are similar in magnitude. The impact of satellite observations in the SH is much more significant.
than in the NH because of the limited number of conventional observations in the SH (Kelly and Pailleux 1988).

Figure 16 shows the temperature biases, as compared to radiosondes, as a function of the forecast length for the different experiments. At 50 mb (upper left), MW shows the largest biases for all the forecast times, while RO has the smallest bias. IR and CTL show similar biases, and these are larger than in BASE and RO. This indicates that the assimilation of IR and MW increases the bias of the analyses and forecasts over BASE. Since CTL has a higher bias than RO, the number of RO observations is not enough to anchor the model and completely correct the biases in the IR and MW satellite radiances.

Results are similar at 250 mb (upper right), although at this level IR, BASE, and CTL show similar biases, significantly larger than RO. As at 50 mb, the MW bias is the largest. At 500 mb (lower left), as the forecast time increases, the BASE experiment produces the worst fit, followed by MW. At this level, IR, RO, and CTL show the least biases. At 850 mb (lower right), BASE, IR, CTL, and RO show a negative (cold) bias while the MW biases are smaller and positive (warmer). This result is consistent with Fig. 2a.

The zigzag structure seen in the biases at 50 and 850 mb indicates a small diurnal variation in the global radiosondes. It may be related to the fact that the 0–24–48–72–96–120-h forecasts only used 0000 UTC radiosonde data for verification, while the 12–36–60–84–108-h forecasts only used 1200 UTC radiosonde data for verification. However, it is surprising that the global mean of all radiosondes shows a variation between 0000 and 1200 UTC.

5. Conclusions

This study has investigated the individual impacts of limb-viewing RO and nadir-viewing IR and MW observations on analyses and forecasts for March 2013 in the operational NCEP global model. We carried out five experiments; the control uses all observations in the NCEP operational forecasts for March 2013. A BASE experiment removes all satellite IR, MW, and RO observations. The next three experiments successively add back the IR, MW, and RO observations separately.
When compared to radiosondes, all the analyses except RO are too cold in the stratosphere (above 100 mb), and this cold bias is mostly caused by the IR and MW observations. All experiments are warm compared to radiosondes at 200 mb, likely a result of warmly biased aircraft observations. RO is only a little less biased than the other experiments at this level. From 300 to 800 mb, the biases of all experiments are under 0.1 K. In the lower troposphere, around 925 mb, all analyses show a cold bias of about –0.1 K, possibly due to model errors in resolving the location and structure of the atmospheric boundary layer. The MW experiment shows the largest biases in these comparisons. The fit of the specific humidity analyses to radiosondes shows a drier
stratosphere and a moister troposphere for all experiments, suggesting that the model is slightly biased.

We analyzed the similarities and differences between the impacts of IR, MW, and RO observations with respect to the BASE experiment. The benefits of RO in anchoring the model were demonstrated, as the experiments only assimilating satellite radiances show larger biases throughout the whole vertical range of the atmosphere. These biases are found to be larger in the stratosphere, where the impact of RO is the greatest. Overall, the three satellite systems produce similar impacts. The impacts are larger in the SH and over the oceans, where the number of nonsatellite observations is much lower. RO produces the smallest impacts because of the lower number of observations being assimilated compared to the number of IR and MW observations. RMS differences between the different experiment impacts show the greatest differences in the tropics and the SH.

Although correlations between the analysis impacts from the IR, MW, and RO experiments tend to be relatively high and positive, they are surprisingly low in the lower troposphere for both the temperature and moisture fields. There are even negative correlations in the monthly mean impacts at some levels. However, monthly means of the daily impacts are positively correlated at all levels. The IR and MW impacts are more highly correlated than the IR and RO or MW and RO impacts, suggesting the greater independence of RO observations from the other two systems.

Forecasts made from the five different analyses show that the satellite observations make the largest positive impact in the Southern Hemisphere and that IR, MW, and RO observations produce similar positive impacts. In the Northern Hemisphere, the satellite observations make a relatively small but statistically significant positive impact. IR and MW observations alone also make a small but significant positive impact, but only out to 5 days. The forecasts confirm previous studies that show RO acts as an anchor observing system, reducing the forecast biases in both the NH and SH.

In summary, this study emphasizes again the complementary nature of IR, MW, and RO observations in increasing the forecast skill and producing forecasts with minimum biases.

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APPENDIX

Calculation of Means, RMS Differences, and Correlation Coefficients

a. Mean differences

The variable $A$ is a global field (analysis or forecast) of some variable (e.g., $T$ or $q$) and is a function of latitude $\lambda$, longitude $\phi$, time $t$, and height $z$: $A(\lambda, \phi, t, z)$.

For each experiment we have 32 eight-day forecasts at $t = 0$ (one per day, starting at 0000 UTC). From this set of 32 analyses available for each experiment, we compute the following horizontal and temporal average:

$$A(z) = \frac{1}{N_{\text{lat}}} \frac{1}{N_{\text{lon}}} \frac{1}{N_{\text{time}}} \sum_{\text{lat,lon,}t} A(\lambda, \phi, t, z).$$

Then, the mean difference between the analyses of experiment 1 and the analyses of experiment 2 is computed as $A_1 - A_2$. This gives us a value of the mean difference for each vertical level.

b. RMS differences

Given the analyses of two experiments, $A_1(\lambda, \phi, t, z)$ and $A_2(\lambda, \phi, t, z)$, the RMS different between $A_1$ and $A_2$ is computed as follows:

$$\text{rms}(A_1 \text{ and } A_2) = \sqrt{\frac{1}{N_{\text{lat}}} \frac{1}{N_{\text{lon}}} \frac{1}{N_{\text{time}}} \sum_{\text{lat,lon,}t} (A_1 - A_2)^2}}.$$  

This gives us an RMS value for each vertical level.

c. Correlation coefficient

Given the analysis $A(\lambda, \phi, t, z)$, we compute the following temporal average:

$$A'(\lambda, \phi, z) = \frac{1}{N_{\text{time}}} \sum_{\text{time}} A(\lambda, \phi, t, z).$$

The global spatial correlation between the temporally averaged analyses of two experiments $A_1'$ and $A_2'$ is computed as follows:
where $A_1$ and $A_2$ are the horizontal and temporal averages of the analyses of experiment 1 and the analyses of experiment 2, respectively. This gives us correlation coefficient value for each vertical level.

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