Radio Occultation Observations as Anchor Observations in Numerical Weather Prediction Models and Associated Reduction of Bias Corrections in Microwave and Infrared Satellite Observations

L. CUCURULL
NOAA/NWS/NCEP/Environmental Modeling Center, College Park, Maryland, and University Corporation for Atmospheric Research, Boulder, Colorado

R. A. ANTHES
University Corporation for Atmospheric Research, Boulder, Colorado

L.-L. TSAO
Central Weather Bureau, Taipei, Taiwan, and NOAA/NWS/NCEP/Environmental Modeling Center, College Park, Maryland

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ABSTRACT

Satellite radiance measurements are used daily at numerical weather prediction (NWP) centers around the world, providing a significant positive impact on weather forecast skill. Owing to the existence of systematic errors, either in the observations, instruments, and/or forward models, which can be larger than the signal, the use of infrared or microwave radiances in data assimilation systems requires significant bias corrections. As most bias-correction schemes do not correct for biases that exist in the model forecasts, the model needs to be grounded by an unbiased observing system. These reference measurements, also known as “anchor observations,” prevent a drift of the model to its own climatology and associated biases, thus avoiding a spurious drift of the observation bias corrections.

This paper shows that the assimilation of global positioning system (GPS) radio occultation (RO) observations over a 3-month period in an operational NWP system results in smaller, more accurate bias corrections in infrared and microwave observations, resulting in an overall more effective use of satellite radiances and a larger number of radiance observations that pass quality control. A full version of the NCEP data assimilation system is used to evaluate the results on the bias corrections for the High Resolution Infrared Radiation Sounder-3 (HIRS-3) on NOAA-17 and the Advanced Microwave Sounding Unit-A (AMSU-A) on NOAA-15 in an operational environment.

1. Introduction

In recent years, the large increase in the number of satellite observations and the improvements in the assimilation of the data in numerical weather prediction (NWP) models have been major factors in improving the skill of numerical weather forecasts, particularly in the Southern Hemisphere, where the number of non-satellite observations is limited (Kelly and Pailleux 1988).

Infrared and microwave nadir sounders are the most commonly used satellite instruments for operational NWP, with over eight million radiance observations assimilated daily at the operational centers. Although the literature on data assimilation is mainly concerned with nonsystematic errors, model and observation errors are often systematic as well as random. Statistics of the differences between the observations and their model simulation counterpart reveal the existence of systematic errors (biases), either in the observations, the model, or both (Dee and Todling 2000; McNally 2004; Haimberger 2005). Although by examining the mean values of these differences one cannot identify the source of the biases (i.e., observations vs model), developing
patterns of these differences for specific components of the observing system can provide useful information about the nature of the biases (see, for instance, Dee 2005). To optimally combine model and observations to get accurate analyses and forecasts, biases in the observations and models need to be removed or mitigated in the data assimilation process.

Although satellite radiance observations are major contributors to the accuracy of NWP initial conditions and subsequent forecasts, they contain calibration- and instrument-dependent biases. Inaccuracies in the forward models or the characterization of the instruments used to simulate the observations can cause biases as well. These biases can be quite significant and can exceed the information content of the observations themselves (Dee 2005). Approximations in the radiative transfer calculations in the forward model can introduce state-dependent biases in the analysis. Therefore, the assimilation of radiances in operational NWP requires correcting for these biases (e.g., Eyre 1992; Susskind et al. 1983). It is important to note that these corrections should not account for biases that might exist in the model or the analysis, which implies that the assimilation of radiances requires some independent, unbiased observations to be assimilated in the system that can act as “anchor” points, and thus prevent a drift of the analysis and forecasts to the model climatology. Otherwise, it is possible for biases in the model to result in an inaccurate correction of radiance biases (either over- or undercorrection), resulting in a suboptimal use of the observations. The nearly unbiased nature of radio occultation (RO) observations makes them suitable for anchor points (Dee and Uppala 2008; Healy 2008b). [Although raw RO measurements (phase and amplitude) are unbiased, their retrievals might contain biases. However, these biases are so small in comparison with the biases associated with other observations that RO soundings do not need to be bias corrected in a data assimilation system.] The only other upper-air observations that serve as anchor observations are radiosonde data, which are assimilated without bias corrections. However, the radiosonde data are not as effective as RO because they have much less spatial and temporal coverage and they are bias corrected before they are assimilated. Radiosonde temperature biases are mainly caused by radiative effects, typically a warm daytime bias from sunlight heating the sensor and a cold bias at night as the sensor emits longwave radiation. Most radiosonde soundings contain corrections applied to each site to compensate for these biases. In addition, the National Centers for Environmental Prediction (NCEP) applies additional corrections for each radiosonde type to compensate for the remaining biases. Improved bias corrections are needed for the assimilation of radiosondes, and it has been recently suggested that RO can be directly used to improve the radiation-induced bias correction for the radiosonde data (Sun et al. 2013).

Radio occultation measurements are obtained when a low-Earth-orbiting (LEO) satellite carrying an RO receiver rises or sets behind Earth relative to a global navigation satellite system. The radio waves are slowed and refracted (bent) by Earth’s atmosphere. The resulting Doppler shift can be measured very accurately and used to retrieve the bending angle and refractivity as a function of height in the stratosphere and troposphere. The RO technique is described by Kursinski et al. (1997, 2000), and its applications to weather prediction, climate monitoring, and space weather are reviewed by Anthes (2011) and Steiner et al. (2011). These papers note that the accuracy, precision, and unbiased nature of the measurements, the lack of instrument drift, and the self-calibration characteristics make them ideal as climate benchmark observations and for assimilation as anchor observations in NWP models.

Poli et al. (2010) showed that the assimilation of RO observations in the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) reduced temperature biases with respect to radiosondes in the upper troposphere and lower stratosphere by about 0.1–0.2 K in both hemispheres. They also showed that the RO observations acted as references via variational bias correction to correct satellite radiances, and that removing the RO observations leaves the analysis system more prone to fitting the warm-biased aircraft data.

RO soundings are assimilated at most worldwide NWP centers on a routine basis. Typically, profiles of refractivity or bending angle are used, and their assimilation makes use of forward operators that neglect horizontal gradients of atmospheric refractivity (e.g., Healy and Thépaut 2006; Cucurull and Derber 2008; Poli et al. 2009; Rennie 2010; Anlauf et al. 2011). In all known cases, the significant positive impact in terms of weather forecast skill has been found, regardless of the type of RO retrieval used. In fact, RO observations typically rank in the top five of all observational systems in terms of positive impact on forecasts (Cardinali 2009a,b; Anthes 2011; A. Thorpe 2013, personal communication; Cardinali and Prates 2011), in spite of their relatively small number, and have the largest impact of all satellite observational systems on a per-observation basis (WMO 2012). It is expected that more accurate forward operators for RO that incorporate deviations from spherical symmetry of the atmosphere could further improve forecast skill, particularly in the lower troposphere (Eyre 1994; Zou...
Unlike microwave and infrared sounder radiances, RO retrievals are almost insensitive to clouds and are unbiased—or at least their bias is small enough so they do not need to be bias corrected. RO data are not being bias corrected at any operational NWP center. RO data reduce the model drift and the resulting spurious drift in the bias corrections applied to other observations, thus improving the assimilation of other observations, including radiances. In addition, since RO is a limb sounding technique, it has high vertical resolution, complementing the lower vertical resolution of the nadir sounders. In contrast, nadir sounders provide higher horizontal resolution than limb sounders. In a simulation study, Collard and Healy (2003) analyzed the nature of temperature information provided from infrared and RO observations. Their results confirmed that both data types provide useful and complementary information in NWP. The importance of RO observations as anchor observations and the complementarity of RO and radiance observations are summarized by WMO (2012).

The potential value of using RO to improve the bias correction of satellite radiance measurements was first noted by Working Group 3 at the ECMWF/European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) NWP Satellite Application Facility (SAF) Workshop on Bias Estimation and Correction in Data Assimilation in 2005. Specific applications of Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) data for the Advanced Microwave Sounding Unit-A (AMSU-A) instrument were investigated by Healy (2008a) with a simplified NWP system. This study, which used only radiance data from AMSU-A and the Microwave Humidity Sounder (MHS) on Meteorological Operation-A (MetOp-A), demonstrated that COSMIC data modified the temporal evolution of midstratospheric AMSU-A channels and thus the assimilation of COSMIC data resulted in a better fit to radiosonde observations.

In this paper we demonstrate the impact of assimilating RO observations on the bias corrections of infrared and microwave radiances with a full operational version of the NCEP Global Data Assimilation System when using all operational observations. The paper is organized as follows. First, the methodology to assimilate radiances and RO at NCEP is outlined in section 2. The impact of the assimilation of RO soundings on the temporal evolution of the satellite radiance bias corrections over a 3-month period is described in section 3. Finally, a discussion and summary are given in section 4.

2. Methodology

Data assimilation techniques that attempt to estimate and correct biases incorporate assumptions on the source of the biases and on their representation in terms of a set of parameters. A correct identification of the source of the bias (model and/or observations) is important in order to prevent the assimilation process from forcing the model toward the source of the bias. The estimation of these biases is based on the formulation of a model for the bias and an unbiased reference dataset to estimate the parameters of this bias model (Dee 2005).

Characterization of the bias associated with the model is complex and several approaches have been proposed (Derber 1989; Dee and da Silva 1998; Dee and Todling 2000; Bell et al. 2004; Balmaseda et al. 2007; Chepurin et al. 2005; Tsyrulnikov 2005). NCEP’s system does not correct for biases that might exist in the model. However, the assimilation of observations affects the bias in the analysis and consequently the model.

Satellite radiances are bias corrected at NCEP using a variational bias-correction approach in its three-dimensional variational data assimilation (3DVAR) system (Derber and Wu 1998; Dee 2004; Dee and Uppala 2008). In this approach, the model variables and the parameters that are used to characterize the bias model are estimated simultaneously. NCEP’s system uses a two-step process. First, an airmass correction based on a series of predictors is applied followed by a slowly evolving scan-angle bias correction. Although the assimilation algorithms include the scan angle plus the airmass-dependent components of the bias correction, only the airmass bias-correction parameters are allowed to change during the minimization. The updating of the scan-angle component of the bias correction is done outside the minimization algorithms, after the coefficients for the airmass component have been estimated.

The standard cost function used in 3DVAR can be modified to correct for biases in satellite radiances. Following the notation by Dee (2005), the modified penalty function is given by

\[ J(z) = (z - b)^T \mathbf{Z}^{-1} (z - b) + [y - H(z)]^T \mathbf{R}^{-1} [y - H(z)], \]

where

\[ z^T = [x^T \beta^T], \]

and it includes the model state vector \( x \) and the parameters \( \beta \) of the model for the bias. The forward operator
H maps the augmented control vector z to the radiance space and in principle it could depend on both the state variables and the bias parameters. The vector $z^b$ is the background estimate for the augmented control vector and $y$ is the observation vector. The matrices $Z$ and $R$ are the background and observation error covariances, respectively.

The model bias $b$ for the airmass component of the total bias uses a linear model based on a set of predictors $p_i$, defined as

$$b(\beta, x) = \sum_{i=0}^{N_p} \beta_i p_i(x),$$

where $N_p$ is the number of predictors. The forward operator $H$ is given by the contribution of the standard forward operator $h$ operating on the model state variables (a radiative transfer model) plus the bias term, written as

$$H(z) = h(x) + b(\beta, x).$$

By convention, the first predictor $p_0$ is a constant. The rest of the predictors typically depend on the instrument itself or the atmospheric state at the location of the observation. At NCEP these are the pathlength, the integrated lapse rate, the square of the integrated lapse rate, and the cloud liquid water. In practice, some of these predictors slightly differ or are set to zero for some channels. The predictor coefficients $\beta_i$ vary for each satellite sensor and channel. The background vector for the predictor coefficients $\beta^b$ is the value estimated in the previous analysis cycle. When a new sensor is introduced in the assimilation system, the parameters for that sensor are initialized to zero and quickly spun up. Assuming uncorrelated errors between the bias-correction parameters and the model state vector, Eq. (1) becomes

$$J(x, \beta) = (x^b - x)^T B^{-1}_x (x^b - x) + (\beta^b - \beta)^T B^{-1}_\beta (\beta^b - \beta) + [y - h(x) - b(x, \beta)]^T R^{-1} [y - h(x) - b(x, \beta)],$$

where $B^{-1}_x$ and $B^{-1}_\beta$ are the inverse of the model and parameter background error covariances, respectively. The first term in Eq. (5) is the standard background term in 3DVAR. The second term controls how much the estimated parameters are allowed to change. Finally, the third term is the bias-corrected term for the radiance satellite data. The advantage of this type of assimilation process is that the system maintains consistency with all the available information so it can quickly handle new satellite observations and adjust to changes in the characterization of an instrument/channel by modifying the bias accordingly. Note, however, that this bias-correction scheme does not distinguish whether the bias originates in the observations $y$ (either in the instrument or processing of the data) or the forward model $h$. Both situations are bias corrected the same way.

A more serious concern is that the variational bias-correction scheme assumes that the model itself is unbiased. However, biases in the model can introduce spurious bias corrections in the observations, resulting in a less-than-optimal use of the observations—for example, radiances—being corrected. The reason for this is that the variational assimilation will adjust the satellite radiance observations in order to reduce their differences with the model-simulated equivalents, regardless of whether the bias comes from the observation or the model. In the situation where the source of the bias is the model, the observations will be incorrectly bias corrected to compensate for the model bias (bias in model forecasts), resulting in an analysis that will drift toward the model climatology. Assimilation of unbiased observations, such as RO, can mitigate this problem by reducing the biases in the model background field.

Two different forward operators may be used to evaluate the assimilation of RO profiles. For assimilation of refractivity soundings, we use

$$N = k_1 \left( \frac{P_d}{T} \right) + k_2 \left( \frac{P_w}{T} \right) + k_3 \left( \frac{P_u}{T^2} \right),$$

where $N$ is the refractivity of moist air in the neutral atmosphere at microwave wavelengths, $P_d$ is the pressure of the dry air in hektopascals, $P_w$ is the pressure of the water vapor in hektopascals, and $T$ is the absolute temperature in kelvins. The $k_1$, $k_2$, and $k_3$ are the atmospheric refractivity constants, provided by Bevis et al. (1994). The assimilation of refractivities has an altitude range of zero to 30 km. Cucurull (2010) provides further details on the implementation of this forward operator at NCEP. The use of Eq. (6) assumes local spherical symmetry of the atmosphere in the retrieval of the RO observations. Horizontal variations over scales $\lesssim 300$ km around the tangent point of the ray are ignored.

Also under the assumption of local spherical symmetry, the assimilation of bending angles makes use of the following forward operator:

$$\alpha(a) = -2a \int_0^\infty \frac{d \ln n}{dx} \frac{dx}{(x^2 - a^2)^{1/2}}$$

and

$$\alpha(a) = n r,$$

where $\alpha(a)$ is the bending angle as a function of the impact parameter $a$, $n$ is the index of refraction, and $r$ is
the distance between the center of symmetry and a point on the ray path. Cucurull et al. (2013) describe the implementation of Eq. (7) at NCEP in detail. When soundings of bending angle are used, observations are assimilated with an altitude range of zero to 50 km. The top of the profiles is higher than with the assimilation of refractivities because bending angles are not calculated using climatology, so they can be used up to a higher altitude than refractivities.

When assimilating bending angles, Rüeger (2002) rather than Bevis (Bevis et al. 1994) coefficients are used to calculate $n$ in Eq. (7) and the compressibility factors are taken into account when localizing an RO value within the model vertical grid (Aparicio et al. 2009). It was found that the use of compressibility factors and the Bevis coefficients resulted in larger systematic differences between RO data and their model-simulation counterpart (Cucurull 2010). This was the case for both the refractivities and bending angles. On the other hand, the use of the compressibility factors along with the more accurate Rüeger (2002) refractivity coefficients solved this bias problem. When we implemented the forward operator for bending angles, the latest configuration was chosen for being more accurate. Both radiances and RO observations are assimilated with their own quality control systems.

NCEP began assimilating RO soundings of refractivity in May 2007. On 22 May 2012, NCEP switched to assimilating soundings of bending angle because the retrieval of bending angles from the raw RO data requires fewer assumptions and steps than for refractivity retrievals. Also, bending angle profiles could be assimilated up to 50 km in impact height, defined as the difference between the impact parameter of the ray path and the height of the radius of curvature of Earth around the tangent point of the ray. Soundings of refractivity were assimilated only up to 30 km, since above this height refractivity profiles are typically affected by weighting with climatology information (Kuo et al. 2004). The differences between the assimilation of the soundings of the bending angle and refractivity were described in detail by Cucurull et al. (2013) in terms of impact in weather forecast skill. Their study found a slight improvement in all fields and pressure levels when bending angle observations were used.

In this study, two forward operators for the assimilation of RO data were first considered: one for the assimilation of refractivity soundings and another that assimilates soundings of a bending angle. Because the results were nearly the same below 30 km using either operator, we show results using profiles of refractivity, which was the variable being assimilated at NCEP during the main period of this study (2007–08 and 2011).

Although the increments to the water vapor and temperature analyses associated with assimilating bending angles and refractivities were similar, in agreement with the results from Cucurull et al. (2013), they were much smaller than the increments associated with the assimilation of infrared or microwave radiances, probably because of the much smaller number of RO observations compared to the radiances observations. In addition, the RO increments and the radiance increments showed surprisingly small correlations (less than 0.1 for water vapor and approximately 0.5 for temperature). The reasons for these low correlations are being investigated in a separate study.

3. Impact of GPS RO on satellite radiance bias correction

This section addresses the effect of assimilation of RO observations on the assimilation of radiances through reducing biases in the model background fields and thus changing the radiance bias corrections, as described in section 2. As representative examples of how RO interacts with microwave and infrared sensors, we will consider two different satellite instruments: AMSU-A on NOAA-15 and the High Resolution Infrared Radiation Sounder-3 (HIRS-3) on NOAA-17. Stratospheric channels for these two sensors showed the largest impact when using RO. However, the impact of combining RO with satellite radiances was also evident for other satellite instruments, particularly for stratospheric channels. Observations used in the different experiments are listed in Table 1.

Figure 1a shows the 500-hPa geopotential height anomaly correlation (AC) score for the Southern Hemisphere at day 5 for forecasts with “gps” and without “nogps” assimilation of refractivity. The experiments run from 1 December 2007 to 1 March 2008. Verification of the two parallel runs showed an improvement in forecast skill when sounding of refractivity was assimilated into the system, with an increase in the mean AC score from 0.833 to 0.844. Similar positive impacts were found at other levels and model variables in the Southern Hemisphere. A slightly lower positive impact was found in the Northern Hemisphere. Figure 1b shows the stratospheric (above 100 hPa) global temperature biases and root-mean-square errors (RMSEs) fit against radiosonde. In both experiments, the analysis field is plotted in black and the background field in gray. The use of RO refractivities improves the fit to radiosondes throughout most of the stratosphere. As summarized in the introduction, the improvement in forecast skill with the use of RO
observations has been widely demonstrated in previous studies. The intent of Fig. 1 is to show that the assimilation of RO observations improves the forecast skill of this model configuration, as they do in other configurations and model systems.

The temporal evolution from 1 December 2007 to 1 March 2008 of the brightness temperature background departures is displayed in Fig. 2a for AMSU-A, channel 12 on NOAA-15. The channel 12 weighting function peaks at \(10\) hPa \((30\) km). The departures of Fig. 2a are not bias corrected yet, so these departures are the term \(y - h(x)\) in Eq. (5). From Fig. 2a, when RO observations are not assimilated (nogps), the differences \(y - h(x)\) between the observed brightness temperatures and their background simulations increase slowly with time, reaching a maximum value of \(1\) K at the middle of the experiment, and then decrease slightly toward the end of the experiment. Assuming there is no drift in the temperature derived from this channel occurring during this 3-month period, this indicates that the bias in the model grows with time, requiring a larger bias correction in the radiance observations. In contrast, there is less drift when RO observations are assimilated. The initial difference of \(0.5\) K decreases slowly with time and at the end of the experiment the difference is almost zero. This indicates that for this 3-month period the RO observations are causing the model analyses and forecasts biases to decrease with time, thereby requiring smaller bias corrections in the radiances. The assumption that there is no drift in temperature for this particular channel for this 3-month period is supported by the fact that the difference \(y - h(x)\) does not drift when RO data are assimilated.

The results shown in Fig. 2 indicate that the effect of RO observations on the microwave brightness temperature background departures and the bias corrections are similar in both hemispheres and the tropics. As seen below, this latitudinal similarity also occurs for the infrared sensors.

Larger and less accurate differences between observed and model brightness temperatures caused by model biases will result in a larger bias correction \(b(x, \beta)\) [see Eq. (5)] to the satellite radiances in order to reduce the differences between the observations and their model equivalents \(y - h(x)\). This is seen in Fig. 2b, where the temporal evolution of the total bias correction (TBC) for gps and nogps is depicted. The globally averaged bias correction needed in nogps is \(0.942\) versus \(0.496\) K in gps. After the bias correction is applied, the final background residuals \(y - h(x) - b(x, \beta)\) are similar in both cases, as shown by the nearly indistinguishable lines near zero in Fig. 2b.

The behavior of the bias corrections for infrared sensors is similar to that for microwave sensors. As an example, the temporal evolution from 1 December 2007 to 1 March 2008 of the background departures prior to the bias correction for HIRS-3, channel 2 on NOAA-17, is shown in Fig. 3a. The channel 2 weighting function peaks at \(50\) hPa \((20\) km). As in the previous example, larger differences (by \(0.2\) K) are found when RO

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**Table 1. List of conventional and satellite data assimilated in the experiments.**

<table>
<thead>
<tr>
<th>Conventional data</th>
<th>Satellite data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raob (ship, mobile land, and fixed land)</td>
<td>All experiments</td>
</tr>
<tr>
<td>Dropsonde</td>
<td>Atmospheric Infrared Sounder (AIRS)</td>
</tr>
<tr>
<td>Pibal</td>
<td>MHS</td>
</tr>
<tr>
<td>Profiler</td>
<td>AMSU-B</td>
</tr>
<tr>
<td>Next Generation Weather Radar (NEXRAD) wind reports</td>
<td>AMSU-A</td>
</tr>
<tr>
<td>Aircraft reports (AIREP)</td>
<td>HIRS-4</td>
</tr>
<tr>
<td>Pilot reports (PIREP)</td>
<td>HIRS-3</td>
</tr>
<tr>
<td>Aircraft Meteorological Data Relay (AMDA)</td>
<td>National Aeronautics and Space Administration (NASA)</td>
</tr>
<tr>
<td>Aircraft Communications Addressing and Reporting System (ACARS)</td>
<td>Tropical Rainfall Measuring Mission (TRMM) data</td>
</tr>
<tr>
<td>Reconnaissance reports (RECCO)</td>
<td>GPS RO</td>
</tr>
<tr>
<td>Ship</td>
<td>Satellite-based winds (SATWND)</td>
</tr>
<tr>
<td>Buoys (drifting and moored)</td>
<td>OZONE</td>
</tr>
<tr>
<td>Coastal-Marine Automated Network (C-MAN)</td>
<td>Geostationary Operational Environmental Satellite (GOES)</td>
</tr>
<tr>
<td>Tide gauge</td>
<td>2007–08 experiments only</td>
</tr>
<tr>
<td>Aviation routine weather report (METAR)</td>
<td>Quick Scatterometer (QuikSCAT)</td>
</tr>
<tr>
<td>Synoptic</td>
<td>Special Sensor Microwave Imager (SSMI) rainfall rates</td>
</tr>
<tr>
<td></td>
<td>2011 experiments only</td>
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<tr>
<td></td>
<td>Ozone Monitoring Instrument (OMI)</td>
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<tr>
<td></td>
<td>Global Ozone Monitoring Experiment (GOME)</td>
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<tr>
<td></td>
<td>Infrared Atmospheric Sounding Interferometer (IASI)</td>
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</tbody>
</table>
observations are not assimilated into the system. As a consequence, a larger bias correction is needed to reduce this discrepancy (Fig. 3b).

If an unphysical bias correction is applied to the data, then less information content will be obtained from the observations, as they will be trusted less, meaning that the data will be used suboptimally. If the magnitudes of the required bias corrections are too large, then the data may be rejected from the assimilation system. In fact, a less biased background field, which produces smaller and more accurate bias corrections in the radiances, led to a slight increase in the number of radiance observations that passed the quality controls in gps, as compared to nogps, by a maximum of 4% (Fig. 4). The counts are shown for HIRS-4 on MetOp-A because the overall differences were largest for this instrument/platform. Also, if the observations are erroneously bias corrected to compensate for biases associated with the model or analysis, then the observations have less influence on the analysis and there is the potential for the assimilation process to drift toward the climatology of the model.

The large difference in the magnitude of the bias corrections required between the forecasts with and without the assimilation of RO data indicates that even the small number of RO observations compared to the radiance observations has a significant positive effect on the forecasts—more than the comparatively small analysis increments would indicate. The relatively small number of RO observations is effective in anchoring the model analyses and forecasts, reducing model drift, and therefore requiring smaller bias corrections to the radiance observations, making them more effective in reducing model errors.

**FIG. 1.** (a) Scores for 500-hPa geopotential height AC for the SH at day 5. Forecasts without using RO data are indicated by the solid dark line; those with the assimilation of RO data are indicated by the light gray line and triangle data points. (b) Stratospheric (above 100 hPa) global fit to radiosonde observations (obs) for nogps experiment (continuous lines) and gps experiment (dotted lines). For each set of forecasts, verification for the model analysis (black) and model background (gray) is shown. Biases are depicted by the four profiles on the left and RMSEs by the four profiles on the right. Both the biases and RMS errors are generally smaller when RO data are used.
FIG. 2. (a) Temporal evolution from 1 Dec 2007 to 1 Mar 2008 of the differences between brightness temperatures and model forecasts prior to the bias correction for AMSU-A on NOAA-15, channel 12 for forecasts with (light gray line) and without (dark black line) RO observations. Plots are given for global, Northern Hemisphere, Southern Hemisphere, and tropics. An 8-point moving average using the 3 points prior and the 4 points after has been used to create the fitting curves. The differences are significantly less when RO data are assimilated.

(b) Temporal evolution from 1 Dec 2007 to 1 Mar 2008 of the TBC applied to the differences in (a), and the mean value (mean) of the differences after applying the bias correction. The TBC in the forecasts with RO data assimilated is significantly closer to zero compared to forecasts without RO (mean of −0.496 vs −0.942 K globally). The mean differences for both sets of forecasts after the bias corrections are applied are close to zero.
FIG. 3. (a) Temporal evolution from 1 Dec 2007 to 1 Mar 2008 of the differences between brightness temperatures and model forecasts prior to the bias correction for HIRS-3, channel 2 on NOAA-17, for forecasts with (light gray line) and without (dark black line) RO observations. Plots are given for global, Northern Hemisphere, Southern Hemisphere, and tropics. An 8-point moving average using the 3 points prior and the 4 points after has been used to create the fitting curves. The differences are significantly less when RO data are assimilated. (b) Temporal evolution from 1 Dec 2007 to 1 Mar 2008 of the TBC applied to the differences in (a), and the mean value (mean) of the differences after applying the bias correction. The TBC in the forecasts with RO data assimilated is closer to zero (−1.98 K globally) compared to forecasts without RO (−2.18 K globally). The mean differences for both sets of forecasts after the bias corrections are applied are close to zero.
Because bending angles are assimilated up to 50 km, while refractivities are assimilated only up to 30 km, smaller differences of \( [y - h(x)] \) and smaller bias corrections may be expected above 30 km when bending angles are assimilated, assuming the instrument/channel is functioning well. This difference is illustrated in Fig. 5, where the assimilation of refractivities (experiment “ref”) and bending angles (experiment “bndc”) is examined in terms of the amount of bias correction applied to the radiance observations. The period covered by this experiment is 1 February–21 March 2011. The temporal evolution of the increments without bias correction (Fig. 5a) and the corresponding bias corrections applied to the observations (Fig. 5b) are shown for AMSU-A, channel 13 on NOAA-15. The channel 13 weighting function peaks at \(-5\) hPa, which is approximately 37 km in altitude. Differences in bias corrections are reduced from approximately 1.0 to approximately 0.5 K when bending angles are assimilated. The assimilation of bending angles has a significant impact on the temporal evolution of the amount of applied bias correction by anchoring the model at the higher altitudes, thus resulting in smaller and more appropriate bias corrections of channels with weights that peak at high levels. There are no other unbiased observations at these high altitudes that can anchor the model and improve the accuracy of the bias corrections in these stratospheric channels.

**Fig. 4.** Monthly (December 2007, January and February 2008) differences (%) of the number of HIRS-4 on METOP-A observations that passed the quality controls between gps and nogps experiments as a function of the channel number. Plots are (top to bottom) for global, Northern Hemisphere, Southern Hemisphere, and tropics. For most channels, more HIRS-4 observations pass the quality control criteria and are assimilated when RO observations are also assimilated.
FIG. 5. (a) Temporal evolution from 1 Feb to 21 Mar 2011 of the differences between brightness temperatures and model forecasts prior to the bias correction for AMSU-A, channel 13 on NOAA-15, for forecasts assimilation RO bending angle (bnde, blue line) and RO refractivity (ref, red line) observations. Plots are given for global, Northern Hemisphere, Southern Hemisphere, and tropics. An 8-point moving average using the 3 points prior and the 4 points after has been used to create the fitting curves. The differences are closer to zero when bending angles are assimilated \((-0.593 vs -1.080 \text{ globally})\). (b) Temporal evolution of the TBC applied to the differences in (a), and the mean value (mean) of the differences after applying the bias correction. The bias corrections are closer to zero when bending angles (blue line) are assimilated compared to when refractivities (red line) are assimilated \((-0.487 vs -0.990 \text{ globally})\).
4. Summary and conclusions

The largest contribution to improving NWP forecast skill over the last decade has come from the assimilation of microwave and infrared radiances from passive nadir sounders. However, these observations contain biases that need to be corrected, and thus require the assimilation of additional unbiased measurements, such as RO, to prevent a drift in the bias corrections applied to the radiance measurements. Thus, the benefits of RO observations come from two different sources: first, from the direct effect of the observations by providing accurate, precise, and independent information on the thermodynamic state of the atmosphere; and second, from the indirect effects on the assimilation of satellite radiances through improving their bias corrections. The former has been extensively analyzed in previous studies. The latter has been investigated here.

We have shown that the assimilation of RO observations reduces the bias in the model analyses and background fields, thereby resulting in more accurate bias corrections to the radiances, with an associated higher impact of the radiance data. With more appropriate bias corrections applied to all of the radiance data, their collective positive impact on the analysis is greater than without assimilation of the much smaller number of “anchor” RO observations.

We have evaluated the reduction in the bias corrections of two specific sensors, one infrared and the other microwave, after the assimilation of RO observations. Given high-quality satellite radiances and a less biased forecast model—due to the assimilation of unbiased RO observations—the magnitude of the bias corrections applied to radiance observations over time was found to be significantly lower. This indicates that more atmospheric information is extracted from radiances when combined with RO soundings, which results in an overall better use of these observations in the data assimilation system and an improvement in weather prediction skill. Correcting for biases in the model also prevents the analysis and forecasts to drift toward the model climatology, which is different from the actual climate.

Assimilation of refractivities and bending angles produced similar results in this study, confirming that the information is embedded within the characteristics of the RO observations, rather than in the specific RO variable being used.

In summary, satellite radiances and RO soundings are complementary, and both provide independent and useful information on the state of the atmosphere. Since the number of RO soundings is negligible compared to the number of satellite radiances used operationally at most NWP centers, it is expected that an increase in RO soundings would result in a further direct improvement in forecast skill and an enhancement of the benefits obtained from the satellite radiances.

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