Implementation of Slant-Path Radiative Transfer in Environment Canada's Global Deterministic Weather Prediction System

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ABSTRACT

The standard approach for assimilating satellite radiance observations is to interpolate all vertical levels of the background state and analysis increment to the same horizontal location for input to the radiative transfer model. This can add significant error for observations with large zenith angle. The impact of accounting for the true slanted satellite-viewing geometry was tested by modifying the horizontal interpolation routines in Environment and Climate Change Canada's Global Deterministic Weather Prediction System. Consequently, model variables are interpolated to a different horizontal position at each model level, for either just the innovation or both the innovation and increment calculation. When this slant-path operator is used for simulation of radiances, reductions in innovation standard deviation, up to 4.5%, for upper-tropospheric and stratospheric temperature and humidity channels of ATMS, AMSU-A, MHS, and CrIS instruments have similar magnitudes as reported in previous studies. In data assimilation experiments, statistically significant reductions in innovation standard deviation (up to 0.3%) for global GPSRO observations are obtained, due to an improved background state. Verification of short- and medium-range forecasts against ERA5, and our own analyses over the region poleward of 60°S show statistically significant reductions of error standard deviation by 2%–3% for wind and temperature in the upper troposphere and lower stratosphere. These positive impacts are mostly due to performing slant-path interpolation on the background state, while also using slant path on the analysis increment has little additional impact. This is expected since the analysis increment in this global configuration has lower spatial resolution, with grid spacing comparable with the maximum horizontal position error from not using the slant-path operator.

KEYWORDS: Radiative transfer; Satellite observations; Numerical weather prediction/forecasting

1. Introduction

Radiance observations are one of the most important categories of observations for numerical weather prediction (NWP) (Buehner et al. 2018). It is essential to optimize the use of radiance observations in operational data assimilation systems for NWP purposes. Any improvement to the observation operator used for assimilating satellite radiances contributes to this goal. The standard approach in NWP for assimilation of the radiances is to interpolate the three-dimensional (3D) background field to the horizontal location of the observation and use the resulting vertical profile as input to the radiative transfer model to obtain the simulated

observation. This approach neglects that the instrument line-of-sight is slanted through the atmosphere for off-nadir observations. For high peaking channels, the standard approach extracts the model information at the wrong horizontal location. For example, for a channel that has sensitivity around an altitude of 15 km and a satellite observation with 60° zenith angle, the horizontal distance between interpolated vertical profile and the instrument line-of-sight at this altitude is 26 km, which is nearly a distance of two grid points at the current resolution of the Canadian global model. The errors in the simulated observation could be avoided by considering the slanted profile.

The impact of slant-path radiative transfer has been the subject of previous studies. Joiner and Poli (2005) and Poli et al. (2005) studied Atmospheric Infrared Sounder (AIRS) and Advanced Microwave Sounding Unit-A (AMSU-A). They discuss that the effect of slant-path radiative transfer on these sounders' data is generally small, and below the instrument noise level for

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most of the channels. They indicated that the impact is limited to high peaking channels at large zenith angles.

Bormann (2017) used a two-dimensional (2D) interpolator, within the observation operator, to construct a series of vertical profiles along the observation azimuthal plane, and used the satellite zenith angle to horizontally interpolate the sampled profiles to the viewing path. Improved simulations of radiances were reported for high-peaking temperature-sounding channels at mid- and high latitudes, and for high-peaking humidity-sounding channels at midlatitudes. The assimilation experiments showed improvements lasting up to 3 days in forecasts in the upper troposphere and stratosphere, especially at high latitudes, when compared against own analyses.

In our recent attempt to perform slant-path radiative transfer at Environment and Climate Change Canada (ECCC), Shahabadi et al. (2018, hereafter BS18) used coarse-resolution background horizontal gradients, offline, to approximate the model's local variability, and to construct slant profiles for the assimilation of radiance observations. For the simulation of Advanced Technology Microwave Sounder (ATMS) channel 9 radiances, sensitive to the upper troposphere and lower stratosphere, they showed up to 6% reduction in standard deviation (stddev) of innovations for observations with high zenith angles in mid- and high latitudes. For their assimilation experiment, only the innovations were computed with the approximate slanted profiles, while the tangent linear and adjoint operators used the vertical profiles (i.e., the radiative transfer model Jacobians were computed using the interpolated background state vertical profiles, the gradient of the cost function was calculated with respect to vertical profiles, and the analysis increments were interpolated as vertical profiles). They reported improvements in forecasts with lead times up to three days in the stratosphere, linked to slant-path modifications of the observation operator, when the own analyses were used as reference.

This study presents the results of a new implementation of slant-path radiative transfer in ECCC's weather forecast system (Buehner et al. 2015; McTaggart-Cowan et al. 2019). Contrary to the offline approximate method used in BS18, slant-path calculation is fully accounted for and is now performed for nonlinear, tangent linear, and adjoint observation operators for the assimilation of the radiances within ECCC's 4D-EnVar system, facilitated by a new strategy for horizontal interpolation. In addition, the approach was implemented with the flexibility to be able to perform slant-path calculations only for background state or for both background state and analysis increments. These two flavors

of slant-path calculation will be explained in more details in the following sections.

This paper is organized as follows. Section 2 describes the details of the ECCC's global 4D-EnVar assimilation component. The methodology is presented in section 3. The results for the impact of slant-path calculations for simulation of observations are presented in section 4. In this section, innovation statistics when performing slant-path calculation using the new approach and the method presented in BS18 are compared. Results of using slant-path calculation during assimilation experiments are analyzed in section 5. Section 6 summarizes the findings and concludes this study.

2. Description of 4D-EnVar system

The global 4D-EnVar assimilation component (Buehner et al. 2015) provides the initial condition for the ECCC global deterministic forecasts. In this system, the background error covariances are calculated from the combination of flow-dependent estimates based on an ensemble of short-term forecasts produced by the operational ensemble Kalman filter (Houtekamer et al. 2019) and static climatological estimates. The length of the assimilation window is 6 h, and it is discretized in 15 min time slots for calculating the innovations of the assimilated observations. The operationally assimilated observations include those from radiosondes, aircrafts, land stations, ships and buoys, scatterometers, atmospheric motion vectors, satellite-based radio occultation, ground-based GPS instruments, and microwave and infrared satellite sounders and imagers. The analyzed variables are the horizontal winds, temperature, humidity, surface pressure, and surface skin temperature. About 13 million observations per day are currently assimilated in the operational global system.

ECCC's global 4D-EnVar is implemented in a completely independent software from the forecast model and therefore the parallelization of the forecast model is independent of the parallelization in the data assimilation system. The data assimilation system uses input files containing the global background state from the forecast model.

There is no outer loop in ECCC's 4D-EnVar assimilation system. The incremental approach is used such that the background state and analysis increment are treated separately when minimizing the following cost function:

$$J(\delta\mathbf{x}) = 1/2\delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x} + 1/2(H\mathbf{x}_b + \mathbf{H}\delta\mathbf{x}-\mathbf{y})^T\mathbf{R}^{-1}(H\mathbf{x}_b + \mathbf{H}\delta\mathbf{x}-\mathbf{y}), \quad (1)$$

FIG. 1. New approach for horizontal interpolation to the observation location, where P_i , T_i , HU_i , UU_i , and VV_i are the pressure, temperature, specific humidity, and horizontal winds in x (longitude) and y (latitude) directions at a grid point on model level i (for the purpose of this schematic figure only 4 levels are shown, though the real system has 80 levels). For further explanation, see main text.

where $\delta \mathbf{x}$ is the analysis increment at each iteration; $\mathbf{x}_b$ is the background state; $\mathbf{B}$ and $\mathbf{R}$ are the background and observation error covariance matrices, respectively; H and $\mathbf{H}$ are the nonlinear and linearized operators applied on the background state ($\mathbf{x}_b$) and analysis increment ($\delta \mathbf{x}$), respectively; and $\mathbf{y}$ is the observation vector.

In the current horizontal interpolation within 4D-EnVar, the gridded 3D fields at all model levels, times and variables are stored on each message passing interface (MPI) task for only a subset of latitudes and longitudes (i.e., a horizontal tile). To facilitate the horizontal interpolation of these fields to the observation locations, a single gridpoint halo is first constructed around each latitude–longitude tile by performing MPI communications among neighboring tiles. Each MPI task then interpolates directly from its latitude–longitude tile to the vertical profiles at different observation locations within the tile. In this approach observations must be distributed across the MPI tasks according to their geographical location within the latitude–longitude tiles that correspond with each MPI task.

3. Methodology

Performing slant path on the background state refers to applying slant path in the nonlinear operator [H in Eq. (1)], meaning the slanted profiles were used only for

calculation of the Jacobians and the innovations. Slant-path calculation for analysis increment is applying slant path in linearized operator [$\mathbf{H}$ in Eq. (1)] during minimization of cost function.

The observation operator used in this study for radiance observations includes version 12.1 of the RTTOV radiative transfer model (Saunders et al. 2018). Slanted profiles on model levels, constructed by interpolating the 3D gridded fields to the observation times and vertically varying horizontal observation locations (i.e., the intersection of the slanted geometry with each model level), were used to represent the slanted viewing geometry for the simulation of each complete set of radiance channels measured simultaneously. For this purpose, a new approach for performing horizontal and temporal interpolation to observation location and time is implemented at ECCO and shown in Fig. 1. As input, each MPI task (represented by different colors) has the gridded 3D field at all model levels, times and variables but for only a subset of latitudes and longitudes. A global all-to-all MPI communication is performed to change the MPI distribution such that each MPI task has the global 2D field for all times, but only a subset of model levels and variables. For the model levels and variables that reside on each MPI task, the horizontal and time interpolation to all observation times and locations are performed at this stage. Because complete global 2D

fields are present on each MPI task when performing the horizontal interpolation, there is no restriction on the observation location used for the interpolation. For each observation, the horizontal interpolation is done with respect to a different horizontal position (the location of the intersection of the slant-path and the model level) at each model level. This distinguishes our approach from that of [Bormann \(2017\)](#) in which only 6 or 3 (for the outer and inner loops, respectively) distinct horizontal positions are used in the interpolation for each set of radiance observations. A second global all-to-all MPI communication is then performed to construct the complete interpolated slanted profiles for all model levels and variables for each set of radiance observations. After this communication, each complete slanted profile (still on model levels) is located on the MPI task that is responsible for carrying out the remainder of the forward simulation for that set of radiance observations. The slanted profile (which also includes pressure at each model level) is then interpolated to the RTTOV pressure levels and is used as input to RTTOV. This vertical interpolation is performed in a separate part of the code that takes the complete profile on model levels as input and therefore did not require modification as part of this work. To minimize the imbalance of the computations, the observations are randomly distributed as evenly as possible for each observation type over all MPI tasks.

Since the MPI communications are performed on terrain-following model levels, Earth's curvature is accounted for in the calculation of the slanted geometry. Computation of the intersection between each model level and the slanted line-of-sight for each radiance observations is accomplished, following these steps: 1) constructing a unit vector from location of observation on the ground toward the satellite in global spatial coordinates; 2) calculating the distance along the line of sight, using the geometric height of the model level and the observation's zenith angle; and 3) computing the latitude and longitude of the intersection from observation's location and the distance along line of sight. The refraction at the zenith angles characteristic of satellite radiances is small, and hence is not considered in this calculation.

The cost of the two additional global all-to-all MPI communications represents a modest overall increase in currently used configurations of 4D-EnVar. Using 27 nodes on a Cray-XC40 supercomputer, there is an increase of about 100 s to the original total of 850 s for each 4D-EnVar analysis, when the slant-path radiative transfer is activated for both background state and analysis increments. The introduced changes to horizontal interpolation for the slant-path calculation are flexible and the same code will be used in both the high-resolution

regional deterministic assimilation system and an experimental ensemble data assimilation system based on the local ensemble transform Kalman filter, described by [Buehner \(2020\)](#). In addition to the ability to perform slant-path radiative transfer, performing horizontal interpolation on complete global 2D fields facilitates the use of a footprint observation operator, which becomes important when the model resolution is much finer than the observation footprint size. Instead of simple bilinear interpolation to the horizontal observation location, the footprint operator averages values at all model grid points that are located within the footprint of the observation. For some types of radiance observations and especially for high-resolution models, this could involve a large number of grid points. Such a footprint operator is already used for sea ice data assimilation at ECCC ([Buehner et al. 2013](#)) and is planned to be tested for the assimilation of radiance observations in high-resolution NWP assimilation systems at ECCC. Furthermore, the slant-path calculation is being applied to weather radar data, to simplify the data structure used for the storage and processing of radar data, toward radar data assimilation at ECCC.

4. Simulation of observations

In this section, the impact of slant-path calculation on the simulation of satellite radiance observations is investigated. The background fields are the 3–9 h short-range global forecasts with 15 km grid spacing and discretized in 15-min time slots. For each set of radiance observations, the vertical and slanted profiles were extracted at the observation location and provided as input to RTTOV to obtain the vertical and slant profile simulated brightness temperatures and their corresponding innovation (OMB). The variation of stddev of OMB as a function of scan position is shown in [Fig. 2](#) for channels 9–12 of ATMS instrument for three different cases: when using vertical profiles (blue), when using the slant profiles created with the horizontal gradient approximation (as introduced in [BS18](#); green), and when using the slant profiles obtained with the new interpolation method described in [section 3](#) (red). Overall, the stddev of OMB is reduced using the slant-path calculation, with the largest impact at the edges of the swath, where the zenith angle is highest.

ATMS channel 9 is a temperature sensitive channel, peaking around the altitude of the midlatitude jet stream (for the list of the peak weighting functions of different ATMS channels see [Tian and Zou \(2019\)](#), their Table 1). In mid- and high latitudes, where the horizontal temperature gradient is large, the difference for this channel between vertical and slanted profiles

FIG. 2. Comparison of stddev of ATMS channel 9–12 innovations as a function of scan position, using vertical profiles (blue), slant profiles from gradient approximation (green), and slant profile from current approach (red). The statistics are calculated based on global, bias-corrected, and thinned observations for the period 8–10 Jun 2016.

(and hence the difference in the simulated observations) is largest, especially for observations at high zenith angle (BS18, their Fig. 3). The reduction in stddev of OMB due to the slant-path calculation that uses the gradient approximation of BS18 and the new approach are similar. In other words, at the altitudes where the channel has sensitivity, the slanted profile approximated by using the large-scale horizontal gradients and the slanted profile obtained from direct interpolation of the background state to the vertically varying horizontal positions along the slant path are very similar.

For ATMS channels 10–12, which have sensitivities that peak at higher altitudes, the horizontal background temperature fields are smoother and the differences between the vertical and slanted profiles are small, even for observations at high zenith angle. Consequently, the use of slant path has less impact on the stddev OMB for these channels.

The number of data used to compute the innovation statistics in Fig. 2 are shown in Fig. 3, in which the increased filtering of nadir observations is visible. The steps between scan positions are constant in viewing angle, which results in finer horizontal distance between neighboring scan positions near nadir than at higher zenith angles. Therefore, the spatial thinning of radiance observations removes more observations at nadir, compared to observation with higher zenith angles.

The stddev of innovation from slanted profiles normalized by the stddev of innovation from vertical profiles for observations from ATMS on board the *Suomi National Polar-Orbiting Partnership* (SNPP), AMSU-A on board *NOAA-18*, MHS on board *MetOp-1*, and CrIS on board *SNPP* as a function of channel number, for all the scan positions, are shown in Fig. 4. It is shown that the slant-path calculation reduces the stddev of OMB of temperature sounding channels of AMSU-A, ATMS, and CrIS instruments by a maximum of 1.5%, 4.5%, and

FIG. 3. The number of data at each scan position used to compute the statistics in Fig. 2. Spatial thinning program filters more observations at nadir compared to high zenith angle observations.

2.5%, respectively. The large improvements in ATMS and CrIS are the results of lower instrument noise levels, combined with large zenith angle observations. The lower instrument noise levels mean the background and observation operator errors make up a larger part of the stddev OMB so the stddev OMB is more sensitive to improvements to the observation operator for these channels and instruments. The improvements are less for humidity channels of ATMS (channels 18–22, maximum 0.5%), and MHS (maximum 0.4%), as the humidity channels peak lower in the atmosphere, where the differences between vertical and slanted profiles are small. The slant path from gradient approximation in BS18 could not improve the OMB statistics for the humidity sounding channels, as the methodology relies on large-scale horizontal gradients and therefore could not resolve the small-scale humidity variations. For AIRS and IASI, the instrument noise are larger than ATMS and CrIS, and there is smaller sensitivity of stddev OMB to improvements in observation

operator. The slant-path calculation for AIRS and IASI instruments do not indicate a significant change in OMB statistics and therefore the results are not shown. The magnitude of maximum reduction of stddev of OMB for AMSU-A, ATMS, and CrIS are in line with those (1%, 8%, and 2%, respectively) reported in Bormann (2017). BS18 reported 1.7% and 2% reduction of stddev of OMB for channel 9 of ATMS and AMSU-A on board NOAA-18. Slant-path calculation with the new approach further improves the OMB statistics compared to BS18 gradient method.

5. Assimilation experiments

Three global 4D-EnVar assimilation tests, using a forecast model with 15 km grid spacing (for the background state) and 39 km grid spacing for analysis increments, were designed to examine the impact of performing slant-path radiative transfer for assimilating the radiance observations. The control experiment uses

FIG. 4. Stddev of innovation from slanted profiles, normalized by the stddev of innovation from vertical profiles for (a) AMSU-A on board *NOAA-18*, (b) ATMS on board *SNPP*, (c) MHS on board *MetOp-1*, and (d) CrIS on board *SNPP*. Filled dots indicate channels where the differences in stddev are statistically significant (F test with 90% confidence level). The statistics are calculated based on global, bias-corrected, and thinned observations for the period 8 Jun–8 Jul 2016.

vertical profiles for radiative transfer calculation (noSlant), as in the currently operational configuration. In the second experiment, the slant-path interpolation is performed only on the background state (Slant_nl). In this experiment, only the nonlinear operator [H in Eq. (1)] use slant profiles. In the final test, slant-path interpolation is performed on both the background state as well as for calculating analysis increments (Slant_nltlad). In this experiment, both nonlinear and linearized operators [H and $\mathbf{H}$ in Eq. (1)] use slant profiles. In all these experiments, the slant-path calculation is only done on radiances from the microwave sounder instruments AMSU-A, AMSU-B, MHS, and ATMS and the hyperspectral infrared sounder instruments AIRS, IASI, and CrIS. These instruments have high peaking channels at the levels with horizontal gradient in atmospheric fields and performing

slant-path radiative transfer could have an impact. Radiances from instruments on board geostationary platforms and SSMIS are not considered for slant-path calculation. The experiments cover the 8 June 2016–31 August 2016 period.

Within the Slant_nl and Slant_nltlad assimilation experiments, the slant-path calculation was applied in all procedures that involve the application of the observation operator for radiances. This includes the observation quality control, the calculation of bias correction coefficients, and the assimilation of the radiance observations. In addition to removing the cloud-affected, and over land surface-sensitive radiance observations, the observation quality control procedures include a background check that rejects observations with large OMB values. As part of the satellite radiance bias correction procedure, a reference state is obtained by performing a

FIG. 5. Stddev of OMB with respect to scan position for common set of assimilated observations between noSlant (blue) and Slant_nl (red) assimilation cycles. OMB are recomputed, using either (a),(c) vertical or (b),(d) slant profile as input to observation operator for channels (top) 9 and (bottom) 22 of ATMS on board *SNPP*. When slant (vertical) operator is used, observed values are taken from Slant_nl (noSlant) experiment (for explanation see main text). Red filled dots indicate scan positions where stddev of OMB of Slant_nl are significantly different than noSlant (F test at 90% confidence level). The statistics are calculated based on global observations for the period 15 Jun–26 Jul 2016.

3DVar analysis in which only the nonradiance observations are assimilated. From this analysis state, the observation-minus-analysis departures for all radiance observations are computed and used for estimating the coefficients of a bias model with linear regression. The bias model predictors for satellite radiance observations are 1000–300, 200–50, and 50–5 hPa geopotential height thicknesses, which are independent of scan positions, and a scan-dependent bias. The biases are calculated and applied for each instrument of a given satellite separately.

It is important to mention that we did not change the observation error variances used in these experiments even though, as seen in the previous section, using the slant-path interpolation results in smaller error (Figs. 2 and 4), which implies that the specified observation error variances in Slant_nl and Slant_nltlad

experiments could be reduced for the affected observations, as shown in BS18. This aspect is not investigated here and may be the subject of a future study. To evaluate the impact of slant-path interpolation during assimilation, the changes to the fit of the background state to the observations between different experiments are compared. Additionally, the upper-air forecasts are evaluated against radiosonde and GPSRO observations and analyses.

a. Fit of background state to observations

To evaluate the impact of using the slant-path interpolation when assimilating radiance observations on the quality of the background state, the fit of the background state to the observations are compared between noSlant and Slant_nl experiments. The stddev of OMB for the common subset of assimilated observations between the two experiments are shown in Fig. 5 as a

function of scan position for channels 9 and 22 of ATMS observations. Red filled dots indicate scan positions where stddev of OMB of Slant_n1 are significantly different than noSlant, at 90% confidence level. OMB are recomputed using both the vertical and slant-path profiles as part of the observation operator. The goal here is to evaluate the quality of the background state itself within the assimilation experiments and therefore the same observation operator must be applied to the background states from the different experiments in the comparisons. In addition, the bias correction applied to the observations was found to depend on the choice of observation operator used. To isolate the impact of only the background state on the OMB, when slant-path (vertical) profile is used, the bias-corrected observed values are taken from the Slant_n1 (noSlant) experiment. This ensures consistency between the observation operator and bias correction applied to the observations and also removes any differences in the bias correction from the comparisons in Fig. 5. For the temperature-sensitive channel 9, when the vertical profile is used to recompute the OMB in the Slant_n1 experiment (Fig. 5a), the stddev OMB is reduced by a small amount ($\sim 0.1\%$) for smaller scan positions and increased by the same magnitude for scan positions at the edge of swath, when comparing against the noSlant experiment. Figure 5b shows a small statistically significant improvement ($\sim 0.1\%$) of the global fit to the observations at high zenith angles due to better background state in the Slant_n1 experiment when slant-path interpolation is used to recompute the OMB. The differences in stddev OMB of humidity-sensitive channel 22 between the noSlant and Slant_n1 experiments are not statistically significant, when the vertical (Fig. 5c) or slant-path (Fig. 5d) profiles were used. The changes of OMB statistics for all ATMS channels between the Slant_n1 and Slant_n1tlad experiments are very small and not statistically significant (not shown). This indicates that the majority of the improvement in the fit of the background state to the global observations from using a slant-path interpolation in the data assimilation experiments is from applying the slant-path interpolation to the background state and not to the analysis increments. This could have been expected, since the analysis increment is at a much lower resolution than the background state (i.e., grid spacing of 39 versus 15 km). Also, the impact from using slant-path interpolation varies greatly among the different channels.

Figure 6 shows the fit (in terms of stddev) of the background state to GPSRO refractivity observations for the Slant_n1, and Slant_n1tlad experiments, normalized by the stddev of OMB in the noSlant experiment.

The statistics are calculated with observations grouped in 1-km-thick layers between 0 and 60 km altitude above MSL. The improvement of the global fit to the GPSRO observations in the Slant_n1 experiment relative to the noSlant experiment is small ($\sim 0.2\%$ – 0.3%), but statistically significant between 18 and 30 km altitude. Similarly, small ($\sim 0.2\%$ – 0.4%), but statistically significant improvements are seen for the Slant_n1tlad experiment between 15 and 37 km altitude. Larger improvements are seen over the region near the South Pole (poleward of 60°S), where applying the slant-path interpolation only to the background state for radiance observations (Slant_n1) lowers the stddev of OMB by a maximum 0.5% – 1% between 10 and 40 km altitude. Using the slant-path interpolation for radiance observations for both the background state and analysis increments (Slant_n1tlad) has the same magnitude of improvements, with a maximum of 1% around 30 km altitude, when compared against the noSlant experiment. The results imply the Slant_n1 experiment has a slightly better performance than Slant_n1tlad between 20 and 35 km altitudes. This improvement, however, is not statistically significant when Slant_n1 and Slant_n1tlad are compared against each other (not shown).

The use of slant-path interpolation can also have an impact on the mean of OMB and the mean of the computed bias correction values. This is shown as a function of scan position for the common set of assimilated observations between of noSlant and Slant_n1 assimilation experiments in Fig. 7, for ATMS channels 9 and 22 observations. It is seen that the mean of OMB is similar between the noSlant and Slant_n1 experiments, with Slant_n1 having slightly larger mean OMB for channel 9 nadir observations (Fig. 7a). For channel 9 observations, the mean of bias correction values from the Slant_n1 experiment have slightly less variation with respect to the scan position, as compared to the noSlant experiment (Fig. 7b). This indicates that the scan angle dependent biases are partially removed in the Slant_n1 experiment. This feature is not seen for humidity-sensitive ATMS channel 22 observations (Fig. 7d).

The changes to fit of background state to radiosonde observations are not statistically significant and the results are not shown.

b. Upper-air forecast verification

For upper-air forecast verification, medium-range forecasts launched at 0000 and 1200 UTC were evaluated against radiosondes and analyses. Comparing the noSlant and Slant_n1 experiments, the verification against radiosondes did not show statistically significant differences between the experiments. Similarly, comparing the Slant_n1 and Slant_n1tlad experiments

FIG. 6. Stddev of OMB of assimilated GPSRO refractivity observations in (left) global and (right) 60°–90°S domains for Slant_nl (green) and Slant_nltlad (red) experiments, normalized by the stddev of OMB for noSlant experiment. Filled dots indicate altitudes where stddev are significantly different (F test at 90% confidence level) from noSlant experiment. The statistics are calculated for the period 15 Jun–31 Aug 2016.

forecasts against radiosonde observations did not show statistically significant differences.

Medium-range forecasts were also evaluated against both ERA5 analyses and the analyses from each of the experiments. It is important to mention that verification of forecasts against the analyses produced by the same data assimilation experiment for very short forecast lead times cannot be interpreted as a measure of improvement in the forecasts. Instead, results from such an evaluation can only give an indication of changes in the consistency between the data assimilation system and the forecast model. When using such an evaluation against “own analysis” for short-range forecast verification, the resulting forecast scores are sensitive to changes in correlation between the forecast errors and the errors in the verifying analysis. This correlation can be arbitrarily increased, thereby seeming to improve the resulting forecasts, by simply reducing the influence of the assimilated observations in the data assimilation system. The verification of forecasts against observations can alleviate this limitation, but the radiosonde

observations normally used for forecast verification have a very limited geographical distribution. Figure 8 shows the verification of 24 and 48 h forecasts against the GPSRO refractivity observations for Slant_nl, and Slant_nltlad experiments in global and 60°–90°S domains. The stddev of the observation minus forecasts (OMF) from these experiments are normalized by the OMF stddev from the noSlant experiment. To accumulate enough samples to perform F test for statistical significance, the observations are grouped in 4-km-thick layers between 0 and 40 km altitude. Over the global domain, the Slant_nltlad performs better than the noSlant experiment with statistical significance for 24 h forecasts. At 24 h forecast lead time, the Slant_nltlad has smaller stddev of OMF than Slant_nl, with differences that are statistically significant at some levels (not shown). The two experiments are more neutral for 48 h forecast, compared against the noSlant experiment. The impacts are larger over 60°–90°S region. The Slant_nltlad perform better than Slant_nl for the 24 h forecasts. Over this region for 48 h forecasts, Slant_nl shows to have

FIG. 7. Mean of (a),(c) OMB and (b),(d) bias correction values with respect to scan position for common set of assimilated observations between of noSlant (blue) and Slant_nl (red) assimilation cycles. The results are shown for channels (top) 9 and (bottom) 22 of ATMS on board *SNPP*. The statistics are calculated based on global observations for the period 15 Jun–26 Jul 2016.

smaller stddev of OMF than Slant_nltlad. The comparison between Slant_nltlad and Slant_nl shows more neutral performance, when Slant_nl is used as control experiment (not shown). Overall both Slant_nl and Slant_nltlad perform better than noSlant experiment for 24 and 48 h forecasts when verified against GPSRO observations.

For the rest of this section the forecasts are verified against analyses. Only the statistically significant differences between the two experiments are highlighted. Using the own analyses of each experiment, there is a small reduction in stddev of error of 0–48 h horizontal wind forecasts in the Slant_nl experiment in the lower stratosphere of the southern extratropical region, compared to the noSlant experiment (not shown). The normalized difference in the error stddev of horizontal wind between the Slant_nl and noSlant experiments $[(\sigma_{\text{noSlant}} - \sigma_{\text{Slant_nl}})/\sigma_{\text{noSlant}}]$ over 60° – 90° S domain as a function of forecast lead time is shown in Fig. 9. Red contours show reductions in error stddev for Slant_nl

and blue contours show reduction in noSlant, as compared to the reference analyses.

When ERA5 analyses are used as reference, the stddev of errors of horizontal wind in Slant_nl experiment at the analysis time is reduced by 3% in lower stratosphere, compared to the noSlant experiment. The maximum reduction in error stddev at 12 h forecast lead time is 2%. When the own analyses produced by each experiment are used as the reference for evaluating the forecasts, the results show an improved agreement for the wind forecast in the lower stratosphere in Slant_nl experiment extending up to 2 days. There is statistically significant reduction of stddev of error for horizontal wind in Slant_nl experiment in upper troposphere and lower stratosphere by 2.7%–3.5% for 2 days (Fig. 9b). The normalized difference in stddev of errors of temperature between Slant_nl and noSlant experiments $[(\sigma_{\text{noSlant}} - \sigma_{\text{Slant_nl}})/\sigma_{\text{noSlant}}]$ as function of forecast lead time over 60° – 90° S domain is shown in Fig. 10. Similar to Fig. 9 for horizontal wind, there is a 3% reduction of

FIG. 8. Verification of 24 and 48 h forecasts against GPSRO observations over (top) global and (bottom) 60°–90°S domains for Slant_nl (green) and Slant_nltlad (red) experiments, normalized by the stddev of OMF for noSlant experiment. Filled dots indicate altitudes where stddev are significantly different (F test at 90% confidence level) from noSlant experiment. The statistics are calculated for the period 15 Jun–31 Aug 2016.

stddev of errors of temperature at 0–12-h forecast over 60°–90°S domain in lower stratosphere in Slant_nl experiment, when ERA5 is used as reference analyses. There is a reduction of stddev of errors in temperature forecasts in Slant_nl experiment by 3% in upper troposphere and lower stratosphere up to 3 days when own analysis is used as the reference (Fig. 10b).

Similar to forecast verification of Slant_nl and Slant_nltlad experiment against radiosonde and GPSRO observations, the comparison between these experiments using either ERA5 or own analysis as the reference analysis does not show any statistically significant change to the forecast scores in the short and medium range. This indicates that positive impact to the forecast scores is largely due to performing slant-path interpolation on the background state, while slant-path interpolation on the analysis increment has no significant impact on the forecasts (single observation experiments in Slant_nl and Slant_nltlad showed horizontal shift in the analysis increment in the stratosphere of approximately 1 grid point, results not shown). Considering the lower spatial resolution of the analysis increment,

this lack of significant impact from applying the slant-path interpolation to the increment should be expected.

6. Discussion and conclusions

In this paper we present the results of implementing slant-path radiative transfer in an experimental version of ECCC's global deterministic weather prediction system. The goal is to perform slant-path interpolation for nonlinear, tangent linear, and adjoint observation operators for the assimilation of the radiances within ECCC's 4D-EnVar system. A new technical strategy for horizontal interpolation has been implemented to facilitate the slant-path calculation. In this approach, 1) the slant-path calculation is fully accounted for such that the model variables are interpolated to a different horizontal position at each model level (unlike Bormann (2017) or the offline approximate method of BS18), and 2) the slant-path interpolation can be included in either just the innovation or both the innovation and increment calculation. This involves two extra global MPI communications so that on each MPI task a complete global

FIG. 9. The difference in stddev of errors of horizontal wind between Slant_nI and noSlant experiments normalized by stddev of errors of horizontal wind of noSlant experiment $[(\sigma_{\text{noSlant}} - \sigma_{\text{Slant_nI}})/\sigma_{\text{noSlant}}]$ over 60° – 90° S domain as a function of forecast lead time, when (a) ERA5 and (b) own analyses is used as reference. Red (blue) contours show better Slant_nI (noSlant), compared to the reference analyses. The number on the plot show the statistically significant results above 90% confidence level from F test.

2D field for all times but only a subset of levels and variables is accessible for the horizontal interpolation. The additional cost due to these additional MPI communications represents a modest overall increase in the context of the currently used configurations of 4D-EnVar. Using 27 nodes on a Cray XC40 supercomputer, the timing is increased by about 100 s, when the slant-path radiative transfer is activated for both background state and analysis increments.

Taking into account the observation slanted geometry reduces radiative transfer error for the simulation of observations. The slant-path effect is most noticeable for observations at mid- and high latitudes with large zenith angles, especially for observations sensitive to jet stream and polar vortex, where the horizontal gradients

are large. The magnitude of error reduction due to slant path is larger for high peaking temperature channels than for humidity channels. It is shown that the slanted profile approximated by using the large-scale horizontal gradients (as examined by BS18) and the slanted profile from direct interpolation of background state to the vertically varying horizontal positions along the slant path are very similar and yield similar OMB statistics for high peaking temperature channels (when using the same background states for each). Using the slant operator, the maximum reductions in stddev of OMB for different temperature sounding channels of AMSU-A, ATMS, and CrIS instruments are 1.5%, 4.5%, and 2.5%, respectively. The improvements are less for humidity channels of ATMS (channels 18–22, maximum 0.5%),

FIG. 10. As in Fig. 9, but for normalized difference in stddev of errors of temperature.

and MHS (maximum 0.4%), as the humidity channels peak lower in the atmosphere. The slant-path calculation for AIRS and IASI instruments do not indicate a significant change in OMB statistics. The magnitude of maximum reduction of stddev of OMB for AMSU-A, ATMS, and CrIS are in line with 1%, 8%, and 2% reported in Bormann (2017).

Three global 4D-EnVar assimilation experiments were conducted to examine the impact of performing slant-path interpolation for radiance observations: control experiment without slant path (noSlant, vertical profiles in both nonlinear and linearized operators), slant path only on the background state (Slant_nl, with slant profiles only in nonlinear operator), and slant path on background state and analysis increments (Slant_nltlad, with slant profile in both nonlinear and linearized operators). For these tests, the slant-path calculation is only done on the radiances from the microwave sounder instruments AMSU-A, AMSU-B, MHS, and ATMS and the hyperspectral

infrared sounder instruments AIRS, IASI, and CrIS. The experiments cover the 8 June–31 August 2016 period. Compared with the noSlant experiment, the fit, defined as reduction in stddev of OMB, of the background state from the Slant_nl experiment to ATMS channel 9 observations shows a small improvement ($\sim 0.1\%$) of the global fit to the observations (when measured by reapplying the same observation operator to the background states from each experiment), conforming with what was reported in Bormann (2017). Using the slant operator in the assimilation experiment does not change the fit of the resulting background state to the humidity-sensitive ATMS channel 22 observations. For ATMS channel 9 observations, the mean of bias correction values in Slant_nl experiment has less variation with scan angle, when compared to the noSlant experiment, implying that the scan angle dependent biases are reduced in the Slant_nl experiment, a feature not seen for humidity-sensitive channel 22 ATMS observations.

A 0.2%–0.3% statistically significant improvement was seen in the global fit of the background state to GPSRO observations when the slant operator was used for radiance observations. In the comparisons with GPSRO refractivity observations, a similar 0.2%–0.4% improvement was obtained when using the slant-path interpolation for both the background state and the analysis increment (Slant_nltlad) between 15 and 37 km altitude. Larger improvements are seen over the region near the South Pole (poleward of 60°S), where applying the slant-path interpolation only to the background state (Slant_nl) lowers the stddev of OMB by a maximum 0.5%–1% between 10 and 40 km altitude. Using the slant-path interpolation for both the background state and analysis increments (Slant_nltlad) over the region near the South Pole has the same magnitude of improvements, with a maximum of 1% around 30 km altitude.

Verification of upper-air forecasts against radiosondes do not show statistically significant differences between the Slant_nl and noSlant experiments. Verification of 24 and 48 h forecasts against GPSRO observations over global and 60°–90°S domains show Slant_nl and Slant_nltlad experiments have smaller stddev of OMF compared to the noSlant experiment, with Slant_nltlad performing slightly better than Slant_nl. The short- and medium-range forecast verification against ERA5 and own analyses over Southern extratropics and 60°–90°S domains show reduction of stddev of errors by 2%–3% for both horizontal wind and temperature forecasts in upper troposphere and lower stratosphere in the Slant_nl experiment, up to 48 h. The comparison between Slant_nl and Slant_nltlad experiments evaluated against either radiosondes, ERA5 or own analyses does not show any statistically significant change to the short- and medium-range forecast scores. Considering the lower spatial resolution of the analysis increment, this lack of significant impact from applying the slant-path interpolation to the increment should be expected.

It is important to note that we did not change the observation errors used during assimilation experiments. Use of the slant path instead of vertical profile results in smaller innovations, which implies that the observation error in Slant_nl and Slant_nltlad experiments could be reduced for the affected observations. This aspect is not tested here and may be the subject of a future study.

Overall, the improvements from performing slant-path interpolation for radiance observations is small and limited to the high latitudes and high peaking observations. While the main intention for implementing the new horizontal interpolation procedure was to allow the slant-path functionality, there are additional motivations. The new horizontal interpolation facilitates using footprint observation operator, which may become important

when the model resolution is much finer than observation footprint size. Additionally, slant-path interpolation is also being applied to weather radar data to simplify the data structure used for the storage and processing of radar data. Finally, the impact of slant-path interpolation for radiance observations will be evaluated for higher-resolution regional NWP configurations.

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