Responses to the Comments of Referee 2

General Comments

The manuscript presents the results of Observing System Experiments (OSEs) that assimilate massive amounts of GNSSRO observations to assess their impact on forecasts over the Indian region. OSEs are carried out by employing the Weather Research and Forecasting (WRF) model with 2D bending-angle observation operator implemented in this study. The manuscript provides a detailed evaluation of the forecast impact by verifying model performance against both reanalysis fields and satellite-derived observations. These results demonstrate the potential of GNSS-RO observations to improved forecast skill of rainfall associated with mesoscale system. While most previous studies assimilating GNSS-RO to limited area model employ refractivity, this study assimilates bending angle using 2D operator. I feel that the results add valuable knowledge to the community and suggest publication after revision to address the following points.

Reply: We sincerely thank the reviewer for the positive and constructive comments, which have helped us improve the manuscript.

Major comments

Comment 1: Fig5/6. The quality and impact of GNSSRO observations on the NWP system vary with altitude. To help readers better interpret the results, it would be helpful to include the data distribution and OmB/OmA statistics as a function of altitude and relate these to the presented findings.

Reply 1: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have included a figure showing the O-B and O-A statistics as a function of altitude.

Comment 2: Line 205. The term "Impact Parameter" has a well defined meaning in GNSSRO. Using the same term for a forecast verification metric may confuse readers. Please revise the wording so as to make readers easy to follow.

Reply 2: We fully agree with the reviewer that the use of the term “impact parameter” created confusion. Therefore, in the revised manuscript, this term has been replaced with “Impact Metric (IM)” in the results section.

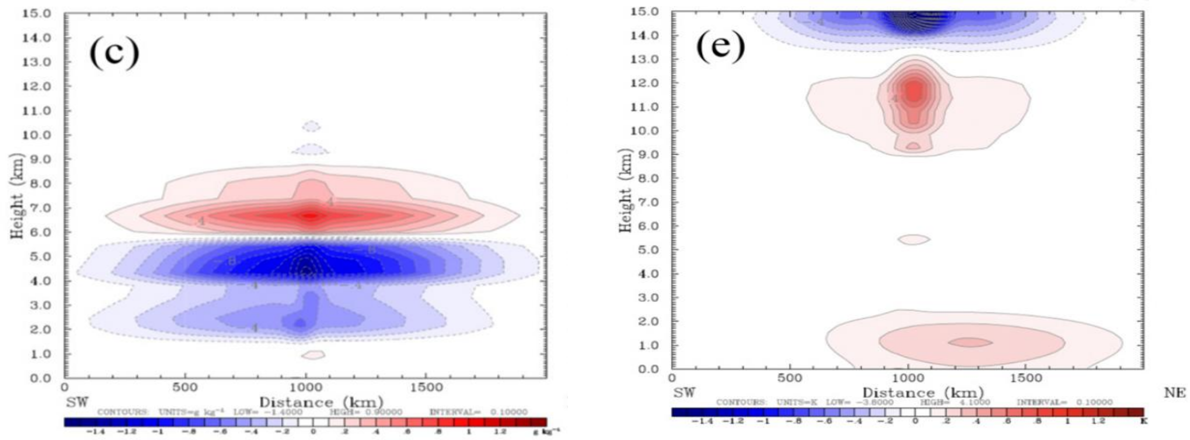
Comment 3: Line 324. Figure 10 shows that the improvement of temperature forecast remains longer than that of specific humidity. It is reasonable since lifetime of convection is shorter than that of large-scale flow. However, the current wording appears to imply that the improvement in specific humidity is primarily due to the water vapor information directly contained in the RO observations. If this is the authors’ intention, please provide clearer physical justification for this interpretation. If not, I suggest rephrasing the text to clarify that the longer-lived temperature improvement may be the main driver of the humidity improvement.

Reply 3: We agree that the lifetime of the specific humidity increments is shorter than that of temperature, as indicated by the reviewer and shown in Fig. 10. RO observations directly impact both the water vapor and the temperature analysis in the moist tropical tropopause. Fig. 10 shows that the impact of RO on specific humidity is immediate (affects the analysis and short-term forecasts) and has no relationship to the impact on temperature. This impact decreases with time during the first day, which is different from what would be expected if the temperature changes were the main driver of the specific humidity because the temperature changes increase over the first day and persist over the entire three days of the forecast.

Many studies have shown that the impact of RO data on the water vapor analysis is direct and immediate because bending angles and refractivity are sensitive to water vapor in the moist tropical troposphere. Increments in bending angle produce changes in model refractivity and increments in both water vapor and temperature. In moist tropical air, the largest changes often occur in the water vapor.

Fig. 3 in Chen et al. (2020) show an example of the increments in a model water vapor mixing ratio (c, in g/kg) and temperatures (d, in K) at 700 hPa due to the assimilation of RO observations. This illustrates that most of the impact of RO information at this level occurs in the water vapor rather than temperature.

Fig. 3 in Chen et al. (2020)



We have revised the paragraph beginning with line 324 to more specifically describe what is shown in Fig. 10:

"RO assimilation improves the specific humidity analysis and forecasts in the middle troposphere out to 3 days, with the largest improvement (10-15%) occurring in the first day. Specific humidity biases are reduced, especially over the oceans where conventional observations are sparse. The assimilation corrects both moist and dry biases, resulting in a more realistic representation of the water vapor distribution. Temperature and wind fields also show improvements (10 to 12%) over the three day forecasts, with the most noticeable impact on winds occurring in the upper troposphere."

Reference

Chen et al. 2020. The Impact of GPS RO Data on the Prediction of Tropical Cyclogenesis Using a Nonlocal Observation Operator: An Initial Assessment. Mon. Wea. Rev.
https://doi.org/10.1175/MWR-D-19-0286.1

Minor comments:

Comment 1: line 22. Please specify 'conventional observation' for the reader's understanding.

Reply 1: Thank you for the comment. The conventional meteorological observations used in the data assimilation include surface observations from synoptic and METAR stations, upper-air observations from radiosondes, pilot balloons, wind profilers, aircraft measurements, winds derived from geostationary satellites and scatterometers, and marine observations from ships and buoys.

This has been added to the abstract of the revised manuscript

Comment 2: line 53. Adding a reference here would help readers follow the discussion more smoothly.

Reply 2: We thank the reviewer for this suggestion. In the revised manuscript, the references (Healy and Thépaut, 2006; Cucurull et al., 2007) have been cited

Comment 3: line114. Please specify the dataset from which the 'observation errors' were obtained. Since raw conventional data usually does not include error estimates for assimilation, it would be helpful to clarify how these errors were prepared.

Reply 3: We thank the reviewer for pointing out this important aspect of the data assimilation system. The following statement has been included (in Section 2.3) in the revised manuscript:

"For conventional observations, the observation error information is included in the BUFR data itself. Therefore, the observation errors were taken directly from the BUFR data. However, for GNSS-RO observations, the bending-angle error is estimated using an approach similar to that adopted in the NCEP GFS (GSI data assimilation) operational system (Cucurull et al. 2007, Cucurull et al., 2013; Kleist et al., 2009).

Comment 4: line 116. Adding a reference here would help readers follow the manuscript more smoothly.

Reply 4: We thank the reviewer for this suggestion. In the revised manuscript, the references (Cucurull et al., 2007, 2013; Kleist et al., 2009) have been added.

Comment 5: line 245.The statement "with only minor degradation" does not seem match with the figure which show the magnitude of degradations is comparable to those of improvements. Please revise the wording so as to better reflect what is shown in figure.

Reply 5: We thank the reviewer for pointing this out. We agree with the reviewer that, near the surface during the initial hours, the degradation is comparable to the improvement. The discussion has been revised accordingly, and the word "minor" has been removed from the revised manuscript.