Forecast Impact of FORMOSAT-7/COSMIC-2 GNSS Radio Occultation Measurements

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Abstract
The FORMOSAT-7/COSMIC-2 GNSS-RO mission was launched on June 25, 2019, and it has provided a large increase in the number of GNSS-RO observations available for operational numerical weather prediction (NWP) in the latitude band between ±40°. A key aim of this mission has been to improve the GNSS-RO measurement quality in the lower and middle troposphere. In this study, we summarize the impact of the FORMOSAT-7/COSMIC-2 measurements in two independent NWP systems, which are now assimilating these measurements operationally. These are the United States Navy Global Environmental Model (NAVGEM) and the European Center for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). Both systems employ a 4-dimensional variational system (4D-Var), and assimilate GNSS-RO bending angles. The experiments cover the period January to March 2020. The impact of the FORMOSAT-7/COSMIC-2 measurements is assessed using improvements in short-range forecast departures to other observations such as radiosonde and radiances, forecast error statistics against a verifying analysis, and adjoint based Forecast Sensitivity to Observation Impact (FSOI) estimates. The FORMOSAT-7/COSMIC-2 measurement has a clear impact on stratospheric temperatures and winds in the tropics. A novel finding is that the measurements also improve the tropical tropospheric humidity fit to radiosondes, and the fit to tropospheric radiances sensitive to humidity. To date, the impact of GNSS-RO on humidity has been difficult to demonstrate in well constrained, operational NWP systems assimilating the full suite of observations. The results are achieved with a conservative assimilation approach which extended the quality control and observation error assignments used for the previous COSMIC receivers; further, possible improvements to the assimilation strategy are noted.

KEYWORDS
Data assimilation, numerical methods and NWP, remote sensing, remote sensing
1 | INTRODUCTION

Global Navigation Satellite Systems - Radio Occultation (GNSS-RO) measurements have become a trusted observation type, and they are now routinely assimilated in operational numerical weather prediction (NWP) systems (e.g., Cucurull et al., 2007; Bauer et al., 2014). The GNSS-RO observations complement satellite radiances in the Microwave and Infrared due to their good vertical resolution, and the fact that they are assimilated without bias correction estimated from the forecast model. Because of the lack of bias correction, the GNSS-RO observation are often considered as anchor observations, and help to constrain the bias corrections applied to the radiance measurements (Healy and Thépaut, 2006; Cucurull et al., 2014). This characteristic also makes them useful for climate reanalysis applications (e.g., Poli et al., 2010).

Many modern global NWP systems assimilate profiles of bending angle (BA) up to heights between 50–60 km (e.g., Met Office, Meteo-France, NCEP, DWD). The GNSS-RO measurements have a large impact in the upper troposphere and lower/middle stratosphere (Cardinali and Healy, 2014), which is sometimes called the “core region”. The recent launch of the joint Taiwan-United States (U.S.) FORMOSAT-7/COSMIC-2 (COSMIC-2 hereafter) constellation of six satellites (Schreiner et al., 2020) has increased the number of GNSS-RO profiles by 5,000 per day, from around 3,000 profiles to 8,000. The COSMIC-2 profiles are distributed in a band between ±40° latitude. This mission has both ionospheric and neutral atmosphere applications, and operational NWP is a key example of the latter. COSMIC-2 provides measurements made with GPS and GLONASS signals for the first time. Schreiner et al. (2020) have presented the first estimates for the precision and accuracy of the GPS and GLONASS COSMIC-2 data, by computing differences of nearby COSMIC-2 profiles, and comparing them with both NWP short-range forecasts and reanalyses. They emphasize that an important aim of this mission is to improve the GNSS-RO measurement quality in the troposphere, with the use of an advanced Tri-GNSS Radio Occultation System (TGRS) instrument.

In this work we summarize the forecast impact of COSMIC-2 measurements in two independent NWP systems that are both now using this data operationally. These are the U.S. Navy Global Environmental Model (NAVGEM) and the European Center for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). The GNSS-RO assimilation approach used at both centers will be described. The approach is conservative in both systems, meaning the quality control and observation errors used for the previous generation of COSMIC receivers will be used. However, it will be shown that the COSMIC-2 measurements have a significant impact on tropical stratospheric temperatures and winds. Perhaps more significantly, we will also demonstrate that these measurements are also providing tropospheric humidity information.

2 | OBSERVING SYSTEM EXPERIMENT SET-UP

2.1 | Atmospheric Modeling and Data Assimilation System

The study uses two independent NWP systems at the US Naval Research Laboratory (NRL) and ECMWF. The NRL system uses the global model NAVGEM and an associated hybrid 4D-Var system the NRL Atmospheric Variational Data Assimilation System – Accelerated Resresenter (NAVDAS-AR). The NRL system will be running the forecast model at the previous spatial resolution (T425, approximately 31 km at equator), with the solver adjoint at operational resolution and using the operational 6-hr assimilation window. The ECMWF 4D-Var experiments use IFS CYCLE 46R1, with a forecast model grid spacing of 18 km at the equator (TC0639).

In these Observing System Experiments (OSE), the full suite of observations used in the operational systems are included in the control experiments. The COSMIC-2 experiments add the COSMIC-2 data to the control. These experiments cover the period from January 1 to March 31, 2020.

2.2 | GNSS-RO and provisional COSMIC-2 observations

The COSMIC-2 observations used in this paper are the provisional level-2 bending angles provided by the University Corporation for Atmospheric Research (UCAR) COSMIC Data Analysis and Archive Center (CDAAC) available since October 1, 2019. The bending angle observations are provided on 247 vertical levels (von Engeln et al., 2009), matching the levels used by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Radio Occultation Meteorology Satellite Application Facility (ROM SAF) processing of the GNSS Receiver for Atmospheric Sounding (GRAS) receiver onboard the Meteorological Operational (Metop) Satellites.

3 | COSMIC-2 ASSIMILATION

3.1 | Simulation of GNSS-RO Bending Angle

At NRL the COSMIC-2 observations are assimilated using the one-dimensional (1D) bending angle operator
from the Radio Occultation Processing Package (ROPP), developed under the EUMETSAT ROM-SAF (Burrows et al., 2014; Culverwell et al., 2015). This operator uses the impact parameter, time of the observation, location, Earth radius of curvature and an undulation correction provided with the observation. It simulates bending angles as a function of impact parameter using the geopotential height of the model surface, and the vertical profiles of temperature and humidity, and the model level pressures from the NWP state estimate. Tangent point drift is included for each bending angle (e.g., Cucurull, 2012), meaning that different NWP profile information is used for each bending angle in a given occultation.

ECMWF uses a two-dimensional (2D) operator to assimilate the bending angles, similar to that described in Healy et al. (2007). A 2D slice of vertical profiles are extracted from the NWP state, where the slice is determined using the observation location and bearing/azimuth angle, pointing from the GNSS to the LEO satellite. The 2D slice is composed of 31 NWP profiles separated by 40 km in the horizontal, thereby spanning 1,200 km. However, when computing the increments in the inner loop of the 4D-Var, only 7 profiles separated by 200 km in the horizontal are used to span the 1,200 km. In addition, to reduce the number of profiles required for a given occultation, the tangent point drift is approximated when compared to the NRL approach. The bending angles are batched into groups of 11 in the vertical, and the same 2D slice is used for all 11 bending angles in the batch.

We note that neither operator computes bending angles below a ducting layer, where the vertical gradient of refractivity exceeds a critical value (−0.157 refractivity units/km).

### 3.2 Quality Control of Bending Angle Observation

The level-2 bending angle product before assimilation is checked for various quality indicators. Both NRL and ECMWF perform simple physical reality checks on the location, time, Earth radius of curvature and an undulation correction. This is followed by a check of quality bits defined in the World Meteorological Organization (WMO) Binary Universal Form for the Representation of meteorological data (BUFR) level-2 bending angle product as processed by the UCAR CDAAC team. The quality bits checked include the non-nominal quality of the occultation, excess phase non-nominal, and bending angle non-nominal. At the provisional release, rising COSMIC-2 occultations which use GPS transmitters and the L2P carrier frequency are rejected by NRL due to a bias in the processing (personal communication Jan Peter Weiss), but this was not done at ECMWF.

The NRL system examines each occultation profile through sets of bending angles grouped into 1 km bins in the vertical. This check begins with the first occultation point below 12 km and steps downward through each occultation point. Within the 1 km vertical grouping of point, if the minimum and maximum value differ by more than 0.045 rad the bending angle profile from the top of the bin to the surface is rejected. ECMWF performs a “first guess check” on the observed minus bending angles computed from the short-range forecast, followed by variational quality control during the 4D-Var (Anderson and Järvinen, 1999). The combined impact of these is effectively to remove bending angles with departures greater than 5 times the assumed observation uncertainty.

### 3.3 Assumed Bending Angle Uncertainty

The assumed bending angle uncertainty model is a critical element of the assimilation. In the NRL system, these estimates were derived largely from the performance of the bending angle fits to the model simulations. The uncertainty is defined as a percentage of the observed bending angle values and the error model is the same for all receivers and GNSS signals, meaning that GPS and GLONASS measurements are given the same weight. The error model is tailored to match a zonal mean of the bending angle fit. The variation of the assumed uncertainty in the vertical uses impact height, which we define as impact parameter minus the local radius of curvature.

At a value of zero impact height (Note that the actual minimum height is around 2 km, but we use 0 km for convenience when specifying the uncertainty model.), NRL use a maximum percentage uncertainty of 25% at 0° latitude, but this is damped away from the equator by cosine of the latitude, cos(lat), falling to 16.5% at the Poles as given by in Equation 1. The percentage uncertainty also falls linearly with impact height to 1.5% at a “minimum error height”. This varies from 12 km at 0° latitude, decreasing by cosine of latitude to 5,333.33 km at the Poles shown in (Equation 2).

\[
\text{Maximum error at zero impact height} = 0.25 \times \left( 0.66 + \frac{\cos(lat)}{3} \right)
\]

(Eq.1)

\[
\text{Minimum error height} = 8666.66 + 3333.33 \times \cos(2 \times \text{lat})
\]

(Eq.2)

The minimum uncertainty value of 1.5% of the observation is used vertically upwards until this drops below a threshold of 6 microradians.
The ECMWF uncertainty estimate is a cruder global model, which only includes a variation in the vertical as function of impact height. The uncertainty is assumed to be 20% of the observed bending angle value at an impact height of 0 km, with the percentage falling linearly with impact height to 1.25% at 10 km. Above 10 km, 1.25% is used until this reaches the 3 microradian lower limit, meaning ECMWF gives the data more weight than NRL in the middle and upper stratosphere.

We note that neither NRL nor ECMWF currently account for vertical error correlations, but these are difficult to introduce when tangent point drift is included in the forward model. In addition, recent work has suggested that the forecast impact of GNSS-RO measurements can be improved with more sophisticated GNSS-RO uncertainty models (**Bowler, 2020), but these have not been tried here.

### EVALUATION OF COSMIC-2 IMPACTS ON NWP

Schreiner et al. (2020) have already demonstrated the quality of the COSMIC-2 bending angle profiles by comparing with NWP analyses and reanalyzes. We obtain similar results in these kind of comparisons, but they will not be reproduced here. Instead, the main focus is the COSMIC-2 impact on NWP forecasts. This has been investigated in three ways. Firstly, we show that assimilating the COSMIC-2 measurements improves the short-range departures for other in situ and satellite observations, such as radiosonde humidity profiles and ATMS radiances. We then demonstrate the quality of medium-range forecasts by verifying against operational analyses.

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**FIGURE 1** Change in standard deviations of the first guess departures fit of radiosonde for temperature, pseudo relative humidity, and zonal and meridional wind from January 1–April 1, 2020 for a region from 20 S to 20 N for the NRL system. Number of observations are shown on the right hand vertical axis, and the horizontal bars correspond to a 95% significance level.
Finally, the 24 hr forecasts are assessed by computing the adjoint-based forecast sensitivity to observation impact (FSOI) metric (Langland and Baker, 2004).

4.1 | Change in observation fits for radiosonde

The radiosonde measurements of temperature, humidity and wind in the tropics are of critical importance for verification. Although there are fewer radiosondes in the tropics, over the 3 month experimental period an adequate sample of observations are gathered in the Tropical region between 20S and 20 N. Shown in Figure 1 is the percentage change in the standard deviations of the radiosonde fits for the NRL system normalized by the control. The four panels show temperature, pseudo relative humidity (a relative humidity dependent on background temperature, see Dee and da Silva, 2003), and the zonal and meridional components of the wind. The reduction due to the introduction of COSMIC-2 is indicated by values less than 100, and a 95% confidence interval is shown at each level. All four variables show reduced standard deviations, with statistical significance.

FIGURE 2 Change in the standard deviations for the fit of radiosonde temperature, humidity and zonal and meridional winds in the tropics due to the introduction of COSMIC-2 for the ECMWF system. The horizontal bars correspond to a 95% significance level.
in temperature at and above 300 hPa and zonal wind at and above 50 hPa. A strong signal is also seen in the tropospheric humidity between 700 hPa and 300 hPa.

A similar change in the standard deviation of first guess departures for radiosondes in the ECMWF system is shown in Figure 2. As with NRL, for all four variables the standard deviations of short-range forecast departures are reduced. The ECMWF results show a statistically significant improvement in the fit of temperature throughout the column in the tropics, and for the winds at and above 300 hPa. The temperature improvements above 200 hPa are around 5%, which is a very large signal. Biases with respect to radiosondes are also reduced in this vertical interval. A similar improvement to NRL is seen for the fit of tropospheric humidity variable, with the ECMWF improvement peaking near 500 hPa. This result represents a significant step forward in the assimilation of GNSS-RO, because demonstrating an impact on tropospheric humidity in operational NWP systems has been difficult prior to COSMIC-2.

4.2 Change in observation fits for microwave radiances

The microwave sounding radiometers provide significant benefits to global NWP. Here we examine the impact of COSMIC-2 on the first guess departure statistics on radiances from the Advanced Technology Microwave Sounder (ATMS), which contains both temperature and humidity sounding channels and currently flies on Suomi National Polar-orbiting Partnership (SNPP) and the National Oceanic and Atmospheric Administration (NOAA) - 20 satellites. Figure 3 is the change in the standard deviation for a combination of SNPP and NOAA-20 ATMS first guess departures from tropical latitudes (+/−20°) resulting from the addition of COSMIC-2 data in the ECMWF system. The standard deviations of the ATMS first guess departure is reduced for every assimilated channel. Figure 4 is a similar plot from the NRL system, showing the change of the standard deviation of the first guess departure fits for the ATMS sensor separately for SNPP and NOAA20. This shows a more modest change in the standard deviations for the majority of channels from each satellite. Some of the most consistent improvement at NRL is for the higher peaking temperature channels 13–15, with a 1.5% reduction in the standard deviations. The humidity channels for the ATMS channels 18–22 do not realize the benefit seen by ECMWF, with the highest peaking humidity channels 21 and 22 showing slightly increased standard deviations. However, the NRL system did see a small but statistically significant reduction in the mean of the first guess departure for channels 18–20 (not shown) for both ATMS sensors. Overall, from the aggregate of the two systems, a positive impact on the fits to both the temperature and humidity sounding channels is found with the introduction of COSMIC-2 data.

4.3 Traditional NWP Forecast Verification

To assess the impact of the COSMIC-2 data in the OSE, both of these runs are compared with a verifying analysis. For the NRL system the verification uses both a self-analysis and an ECMWF analysis at the verifying forecast time. A traditional scorecard was computed for the NRL OSE (not shown). It considers a limited set of metrics decided between NRL and the operational partner Fleet Numerical Meteorology and Oceanography Center (FNMC). These are not a comprehensive set and also contain a threshold of significant change for each metric, for this traditional scorecard the COSMIC-2 OSE showed a neutral scoring of +0, which is sufficient to justify use of the data operationally. A more comprehensive set of metrics also exhibited predominantly neutral impacts. However, the most consistent impact was made to the
vector RMS of wind error, when compared to radiosonde, self-analysis and ECMWF analysis which all consistently showed an improvement. This occurred for levels at and above 500 hPa, and for all forecast times, though not statistically significant.

For the ECMWF system, the change in the standard deviation of the geopotential forecast errors as a function of latitude and pressure is shown in Figure 5. The hatching indicates significance at the 95% confidence level. As expected, the largest impact is in the latitude band between ±40° where the COSMIC-2 have been added, and this impact is statistically significant out to day-5 in the troposphere. Similar to NRL, the COSMIC-2 data also have positive impact on lower to middle stratospheric vector winds in the tropics in the ECMWF system statistically significant to day-10 at 30 hPa and 10 hPa when verified against observations (not shown). Overall, both systems showed either neutral impact or improvement of the forecasts from the introduction of COSMIC-2 data.

4.4 | Forecast Sensitivity to Observation Impact

The Forecast Sensitivity to Observation Impact (FSOI) is a metric which can be used to indicate an observation benefit to the resulting analysis by examining the reduction of a 24-hr error norm due to the assimilation of the observation. The method has been implemented in the NAVGEM system (Langland and Baker, 2004). Note that the due to the total energy being larger in the tropics, observations which are beneficial in this region tend to have larger FSOI impacts. Figure 6 shows the FSOI for the NAVGEM system per observation for the various GNSS-RO receivers over the January 1 to April 1, 2020 time period. The COSMIC-2 receivers have been noted to provide a consistent reduction of the 24-hr forecast error norm over this period, with an impact similar to that of the GRAS receivers from the Metop series. There are many caveats which should be noted in interpreting this result, as the local sampling time and number of other competing observations also impact the result. This global FSOI value does provide a statistically robust answer and can be interpreted that the GRAS and COSMIC-2 receivers provide consistent positive impact. Note that FSOI estimates were not produced in the ECMWF research experiments shown here, but we find that the operational ECMWF FSOI values produced since COSMIC-2 went operational on March 25, 2020 are qualitatively consistent with the NRL values.

5 | SUMMARY AND CONCLUSIONS

The COSMIC-2 GNSS-RO observations have been introduced into two independent NWP systems and the forecast impact has been assessed over a three month period
FIGURE 5  The change in the standard deviation of the forecast error as a function of latitude and pressure for the ECMWF system. Blue indicates that the standard deviation of the forecast errors is reduced when COSMIC-2 is assimilated. The hatching indicates significance at the 95% confidence level.
from January 1 to March 31, 2020. We have presented how the COSMIC-2 data are forward modeled, weighted in the assimilation, and quality controlled in the two systems. As expected, the COSMIC-2 measurements have a large impact on upper tropospheric and stratospheric temperatures and winds, which is consistent with previous work showing good impact in the GNSS-RO “core region”. More specifically, both systems show a good improvement in the short-range forecast fit to radiosonde temperature, wind and humidity measurements. A key new result is the impact on tropical tropospheric humidity forecasts. We have found that the COSMIC-2 improves the fit to both radiosonde humidity measurements and the ATMS radiances sensitive to tropospheric humidity. This is encouraging because a central aim of the COSMIC-2 mission has been to improve the GNSS-RO measurement quality and penetration depth in the troposphere. Information content studies suggest that GNSS-RO observations should provide useful tropospheric humidity information, but this has been difficult to demonstrate prior to COSMIC-2.

The impact of COSMIC-2 in both systems has been achieved with a relatively conservative assimilation approach, where the COSMIC-2 measurements have been assimilated as if they were COSMIC-1 measurements. In the future examinations are likely to include giving the COSMIC-2 measurements more weight when they are assimilated, and to distinguish between the measurements by transmitter (e.g., GPS or GLONASS). NRL have assimilated COSMIC-2 operationally since December 18, 2019, and ECMWF since March 25, 2020.

ACKNOWLEDGEMENTS
We would like to thank our sponsors from the United States Office of Naval Research; the Taiwan National Space Organization (NSPO) and the COSMIC team at the University Center for Atmospheric Research for providing the data and details on the processing.

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How to cite this article: Ruston B, Healy S. Forecast Impact of FORMOSAT-7/COSMIC-2 GNSS Radio Occultation Measurements. Atmos Sci Lett. 2021;22:e1019. https://doi.org/10.1002/asl.1019