BAMS Article

Radio Occultation Modeling Experiment (ROMEX): Determining the Impact of Radio Occultation Observations on Numerical Weather Prediction

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Occultation;
Data assimilation;
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ABSTRACT: The international radio occultation (RO) community is conducting a collaborative effort to explore the impact of a large number of RO observations on numerical weather prediction (NWP). This effort, the Radio Occultation Modeling Experiment (ROMEX), has been endorsed by the International Radio Occultation Working Group, a scientific working group under the auspices of the Coordination Group for Meteorological Satellites (CGMS). ROMEX seeks to inform strategies for future RO missions and acquisitions. ROMEX is planned to consist of at least one 3-month period during which all available RO data are collected, processed, archived, and made available to the global community free of charge for research and testing. Although the primary purpose is to test the impact of varying numbers of RO observations on NWP, the 3 months of RO observations during the first ROMEX period (ROMEX-1, September–November 2022) will be a rich dataset for research on many atmospheric phenomena. The RO data providers have sent their data to EUMETSAT for processing. The total number of RO profiles averages between 30 000 and 40 000 per day for ROMEX-1. The processed data (phase, bending angle, refractivity, temperature, and water vapor) will be distributed to ROMEX participants by the Radio Occultation Meteorology Satellite Application Facility (ROM SAF). The data will also be processed independently by the UCAR COSMIC Data Analysis and Archive Center (CDAAC) and available via ROM SAF. The data are freely available to all participants who agree to the conditions that the providers be acknowledged, and the data are not used for commercial or operational purposes.

SIGNIFICANCE STATEMENT: The paper is significant because it informs the international community about a unique atmospheric dataset that is available for testing in numerical weather prediction models and other research projects, as well as being useful for planning for future RO observations.

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1. Introduction

Radio occultation (RO) is an active remote sensing technique that provides quasi-vertical profiles of density in planetary atmospheres by measuring the phase delay of radio waves emitted by a transmitter and received by a satellite orbiting the planet. Originally used to probe the atmosphere of Mars by Mariner 4 in 1964 (see review by Yunck et al. 2000), it was not until 1995 that the technique was demonstrated for Earth's atmosphere using global positioning system (GPS) for the transmitters and a receiver on a low-Earth-orbiting (LEO) satellite in the GPS/meteorology (GPS/MET) experiment (Ware et al. 1996; Kursinski et al. 1997; Rocken et al. 1997).

Eyre (2008) provides an introduction to RO. As radio waves from a Global Navigation Satellite System (GNSS) transmitting satellites pass through the atmosphere, they are slowed and bent slightly downward. When the waves are received by a LEO satellite, the delay in signal is measured by the excess phase compared to what would have been the case in a vacuum. The excess phase measurement can be related mathematically to the bending angle of the ray, which in turn can be used to calculate the refractivity. The refractivity provides information on the temperature, water vapor, and pressure in the stratosphere and troposphere and on the election density in the ionosphere. Either bending angles or refractivities can be assimilated in NWP models.

Many RO satellite missions have followed GPS/MET, including *CHAMP*, GRACE/GRACE-FO, *SAC-C/D*, *TerraSAR-X*, *TanDEM-X*, COSMIC and *COSMIC-2*, GRAS on *MetOp-A/MetOp-B/MetOp-C*, GNOS on *FengYun-3C/D/E*, C/NOFS, *KOMPSAT-5*, and *Paz* (for a list and brief description of these and other RO missions, please see https://space.oscar.wmo.int/spacecapabilities). Figure 1 shows the growth in the number of RO profiles per day processed by the UCAR COSMIC Data Analysis and Archive Center (CDAAC; https://cdaac-www.cosmic.ucar.edu/) and provided to the research and operational communities. Because of the positive impact of RO data on NWP model forecasts, and the relatively simple and inexpensive technology compared to other remote atmospheric sounding systems from space, the private sector has recently launched RO receivers on commercial satellites and obtained high-quality data for sale to the community. These companies include PlanetiQ, GeoOptics, Muon Space, and Spire in the United States and Aerospace Tianmu and Yunyao Aerospace in China. In 2021, commercial vendors began selling operational RO data to NOAA and EUMETSAT and now contribute a significant portion of the total number of RO observations being used by the international community.

A primary, but by no means only, application of RO is NWP. Other important applications include analysis of weather phenomena such as tropical cyclones, fronts, and atmospheric rivers; analysis of upper-troposphere/lower-stratosphere phenomena; and examination of the planetary boundary layer. Additional applications include climate studies and reanalyses. RO is unique among other sounding systems because it also provides ionospheric observations for space weather applications, including electron density profiles and scintillation events. The many applications of RO in the areas of weather, climate, and space weather are

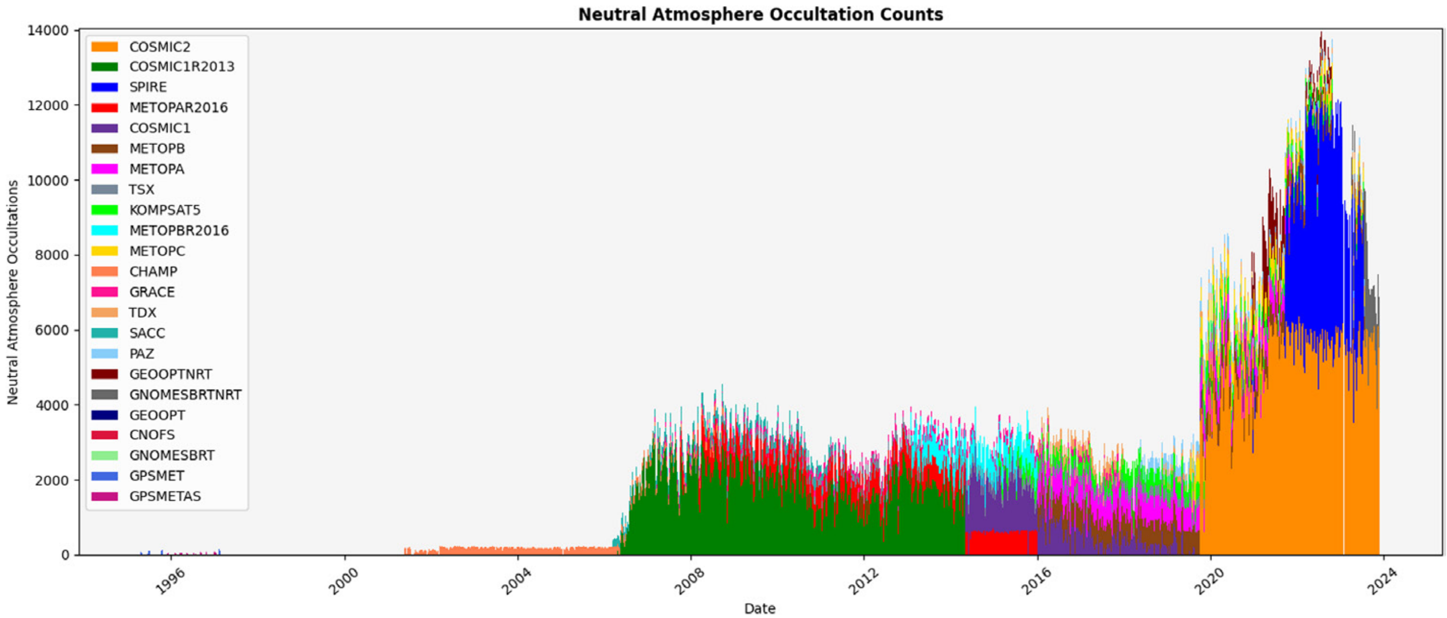

FIG. 1. Total number of RO profiles per day (in thousands) processed by UCAR CDAAC since the launch of GPS/MET in 1995. The dates on the abscissa range from 23 Aug 1994 to 18 Mar 2024 (source: J. Weiss, UCAR COSMIC program, 2024, personal communication. Figure produced by Mike Perotta, UCAR).

too numerous to list here and are reviewed by Anthes (2011), Yue et al. (2014), Bonafoni et al. (2019), and Ho et al. (2020).

This paper introduces the Radio Occultation Modeling Experiment (ROMEX), which is a special collection of RO observations available from all sources during a 3-month period (September–November 2022) called ROMEX-1. The overarching purpose of ROMEX-1 is to provide timely information that is relevant to planners of future global observing systems and to providers of RO data. An average of approximately 30 000–40 000 RO profiles per day has been obtained for this period, roughly 3 times the number used currently in operational models, and they are available to the community free of charge for evaluation and testing in regional and global NWP models. These data will also be available for other research purposes, such as case studies of atmospheric phenomena and validation of other datasets. A limitation of the ROMEX-1 data is that only neutral-atmosphere (troposphere, stratosphere, and lower mesosphere) profiles of bending angles and refractivity are available. If ROMEX-1 is successful, an additional period will be considered that may include space weather data as well.

The outline of the paper is summarized as follows: Section 2 reviews previous studies showing the impact of RO observation on NWP forecasts using limited numbers of real data and theoretical methods. Section 3 summarizes theoretical studies investigating the impact of future large numbers of RO observations using the ensemble of data assimilation (EDA) technique and observing system simulation experiments (OSSEs). Section 4 projects the number of future RO observations based on current plans by the Coordination Group for Meteorological Satellites (CGMS) and shows that a significant reduction in RO observations is expected to occur beginning before 2030, which indicates the need to begin plans now for a provision of global RO observations to support NWP and other applications. To assist in this planning, ROMEX, described in section 5, will provide valuable information for CGMS.

2. Impact of RO data on NWP

Numerous studies have shown a large positive impact of a relatively modest number (2500–5000) RO observations on global and regional NWP models, as well as reanalyses, which are widely used for climate studies. Early studies include Healy et al. (2005), Healy and Thépaut (2006), Cucurull et al. (2007), Aparicio and Deblonde (2008), Healy (2008), Poli et al. (2009, 2010), Rennie (2010), and Bonavita (2014). RO observations are important in NWP because of their accuracy and precision, high vertical resolution, and all-weather capability. They can be assimilated without bias corrections and therefore act as anchors to reduce model biases (Bauer et al. 2014; Cucurull et al. 2014). They have their greatest impact in the upper troposphere–lower stratosphere, the region of the jet stream that is weakly constrained by other observations.

a. Methods to evaluate the impact of different observations and their numbers. Several methods can be used to determine the impact of different types or quantities of observations. Observing system experiments (OSEs) assess the impacts of different observing systems in forecasts using real data (Boukabara et al. 2016) and provide the most reliable method to assess observational impact. Data denial experiments, in which certain real observations are withheld from the forecasts, are a common form of OSEs. The Forecast Sensitivity to Observations Impact (FSOI) quantifies the relative contributions of each of the assimilated observations to model forecasts using an adjoint or ensemble approach. Cardinali (2009) compares the FSOI and OSE approaches. The FSOI method measures the response of a single forecast to all perturbations of the observing system, while an OSE measures the effect of a single observation type on all aspects of the forecast. FSOI can be computed quickly on a daily basis, while OSEs require many forecasts and are time and computer intensive. The FSOI method has limitations; for example, it is based on a linearization approximation and is therefore valid for only short-range forecasts (1–3 days), it is affected by the use of a verification state that is correlated with the forecast state, and it depends on the optimality of the data assimilation system. Despite these limitations, the FSOI method is widely used, and studies show that the ranking of observation types in FSOI is similar to those obtained by OSEs (Cardinali 2009; Candy et al. 2021). FSOI studies consistently show that microwave (MW), infrared (IR), and RO soundings are among the top five observational systems contributing to short-range NWP forecast accuracy (e.g., Cardinali and Healy 2014).

A third technique to evaluate the impact of observations is the EDA. EDA combines different quantities of real or simulated observations, and the impact of an observing system is quantified by the reduction in uncertainty ("spread" of the forecasts) in the ensemble after adding additional observations (Harnisch et al. 2013). A positive impact of the additional observations is indicated by a reduction in spread. At least for RO, decreased EDA spread values provide a reliable tool to assess the observational impact of RO data in the higher troposphere and stratosphere (Lonitz et al. 2021b).

The above methods are useful in evaluating the impact of real observations. To estimate the potential value of future observations (observations that do not exist), OSSEs may be used (Atlas et al. 1985; Hoffman and Atlas 2016; Cucurull et al. 2018; Errico and Privé 2018; Zeng et al. 2020). In OSSE, a well-tested numerical model is used to simulate the atmosphere over a period of time. This simulation (called the nature run or truth) is used to simulate any number or type of observations, which are then assimilated into a different model to test their impact on the forecasts. Although OSSEs have provided valuable insights into the relative value of different future observing systems, they are computationally expensive and have limitations related to the realism of the simulated observations and their errors, and the accuracy of the nature run and the models used in the experiments.

b. Impact of RO observations on global models. The most reliable way of determining the impact of different types or numbers of observations on NWP forecasts is to use real data by adding or deleting observations from an existing set. Data denial experiments carried out by Poli et al. (2008), Bauer et al. (2014), and Boukabara et al. (2016) showed a clear negative impact of a decreased number of RO observations, but these studies were limited by the total number of observations available for testing (fewer than 3000 profiles per day). As the total number of RO observations increased due to the introduction of *COSMIC-2* (launched in 2019) and commercial RO datasets at about the same time (Fig. 1), it became possible to test the impact of varying numbers of RO profiles of 10 000 or more profiles per day.

In 2023, both NOAA and ECMWF assimilated between 10 000 and 14 000 RO profiles per day into their global forecast systems, with approximately a third coming from commercial sources. The acquisition of commercial RO data began with pilot studies in 2016 and progressed to a fully operational data program in 2021. EUMETSAT has also begun purchasing and distributing commercial RO data to augment the government-sponsored data sources by approximately 1500 profiles per day.

With the assimilation of approximately 10 000 RO global profiles today, RO is often estimated to be among the five most impactful datasets contributing to NWP accuracy. This estimate is derived from several FSOI studies, which determine the relative contributions to forecast accuracy from all datasets assimilated. Figure 2 shows an example from the NASA Goddard Earth Observing System, version 5 (GEOS-5), forecast model (NASA 2023) for 1 year (23 April 2023–21 April 2024). In this study, RO is ranked fifth, behind Geo winds, two microwave sounders, and radiosondes for the entire globe (Fig. 2), and second behind Geo winds in the tropics (not shown), where most of the RO observations were located in this year (the number of RO profiles varied between 4000 and 8000 day^{-1} during this period). Another study from ECMWF, using a similar distribution of global observations for April 2024, shows RO ranking third, behind microwave temperature (MWT) and microwave water vapor (MWWV) (Fig. 3).

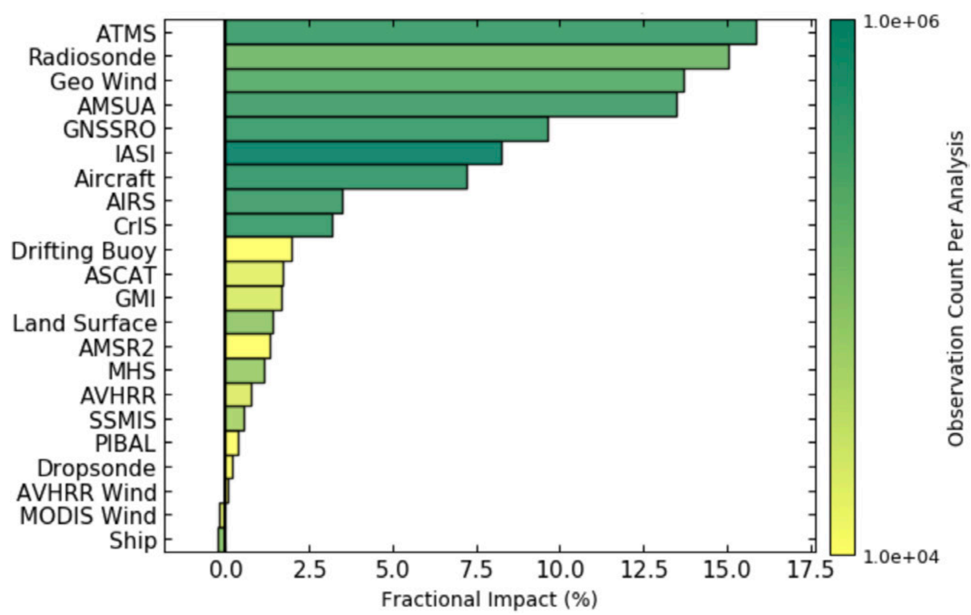

Fig. 2. Example of impact results of various observation types, from the NASA GEOS model for 1 year (23 Apr 2023–21 Apr 2024). This figure depicts FSOI, the fractional impact in %, a global measure of 24-h forecast error that combines errors in wind, temperature, specific humidity, and surface pressure with respect to the verifying analysis from the surface to 1 hPa in terms of moist total energy (J kg^{-1}). Observation impact is taken to be the difference in this error measure between 24-h forecasts initialized from the analysis and the corresponding background state, where this difference is due entirely to the assimilation of the observations. The observation counts for RO and the other observations per 6-h assimilation period are indicated by the color scale on the right side of the figure. Source: NASA GMAO: GMAO Observation Impact Monitoring.

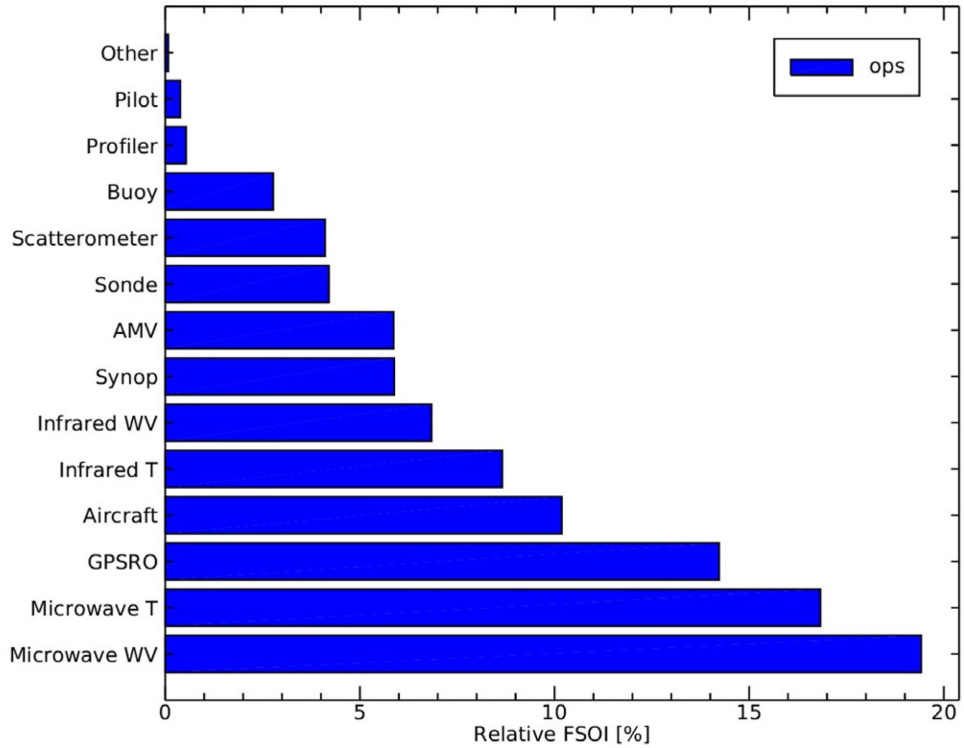

Fig. 3. Relative FSOI (%) from ECMWF for 1–31 Mar 2024 showing relative contributions to forecast accuracy. RO is third in impact (source: Katrin Lonitz, ECMWF).

A clear example of the impact of additional RO observations in the operational ECMWF forecast model was evident when about 5000 *COSMIC-2* profiles per day were first assimilated on 21 March 2020, followed a few weeks later by about 6000 Spire profiles per day on 10 May 2020. The global FSOI impact jumped from about 4%–10% with the introduction of *COSMIC-2* data and to about 14% with the introduction of Spire data (Fig. 4). A sudden decrease in RO FSOI in August 2020 occurred when the Spire data ended. After that, a slow, irregular increase occurred as EUMETSAT purchased various numbers of Spire data. Figures 5 and 6 show a strong relationship between the impact of RO by the FSOI metric and the number of RO observations, with a correlation coefficient of 0.96. The high correlation indicates that there is no saturation of impact versus number of RO profiles per day over this range of numbers. These real-data results show the value of varying the number of RO observations in an operational NWP model, which is the main goal of ROMEX, but with a much larger number of observations.

3. Future RO needs—Determining the optimal number of RO observations

As shown above, the current large impact of RO on NWP is directly related to the increase in the number of observations available for assimilation up to the number tested (∼12 000 profiles per day). Several studies have been made to estimate the effect of additional RO data well beyond the numbers currently available. Harnisch et al. (2013) used the EDA method to investigate the impact of increasing the number of RO profiles to 128 000 profiles per day and found no saturation of impact up to this very large number (Fig. 7).

Privé et al. (2022) investigated the potential impact of a large number of RO profiles on global NWP forecasts using OSSEs carried out with the GEOS model. The nature run was the GEOS-5 model with 72 vertical levels and 7-km horizontal resolution. The forecast model was a version of GEOS using the same 72 vertical levels and 25-km horizontal resolution (horizontal grid spacing). The analysis quality, forecast skill, and FSOI were analyzed and shown to improve with the addition of RO observations up to 100 000 profiles per day.

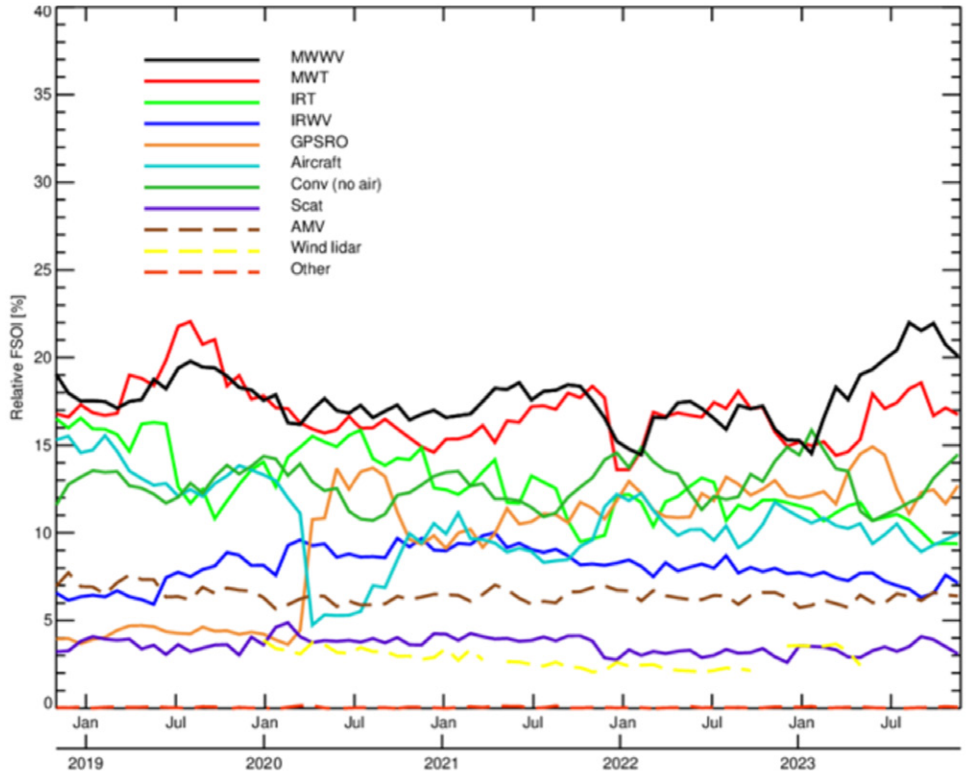

Fig. 4. Global FSOI for all the observations assimilated by ECMWF from November 2018 to 2023. The orange time series shows the percent contribution to the total error reduction by RO. Approximately 5000 *COSMIC-2* profiles were assimilated beginning on 21 Mar 2020 and another 6000 Spire profiles beginning on 10 May 2020. The Spire observations were discontinued on 10 Aug 2020. The other observations shown in the figure include MWWV, MWT, IR temperature (IRT), IR water vapor (IRWV), aircraft, conventional observations (nonsatellite, including radiosondes and surface data), scatterometer winds (Scat), atmospheric motion vectors (AMVs), wind lidar, and all other types (source: Sean Healy, ECMWF).

These OSSEs showed the impact of different numbers of RO profiles in maps of temperature, winds, and specific humidity, and these all showed improvements with increasing numbers of RO profiles. Figure 8 shows that with 50 000 and above, RO becomes the dominant satellite data source in reducing forecast errors, especially in the tropics. However, although saturation had not been reached at the maximum of 100 000 profiles per day, the improvement in model performance for each additional 25 000 increment in the number of profiles beyond the first 25 000 increment decreased, suggesting, similar to Harnisch et al., that there is a "knee" (maximum in curvature) in the benefit-versus-cost curve.

Although the Harnisch et al. (2013) and Privé et al. (2022) studies are independent studies using different methods and show the same results (increasing impact of RO profiles up to

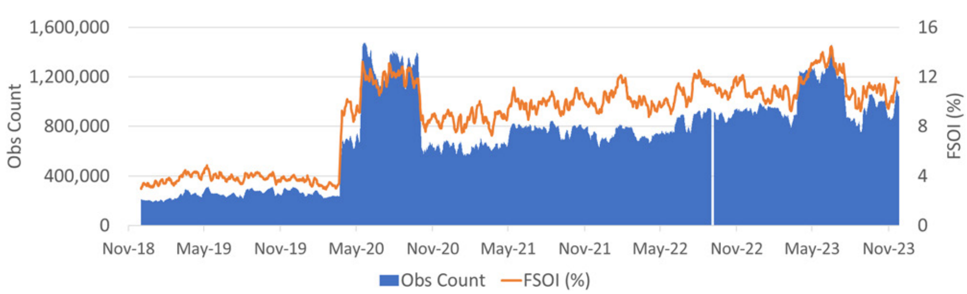

Fig. 5. Time series of the FSOI for all RO observations assimilated by ECMWF (orange) and total number of RO observations assimilated in each 12-h period (blue). Note that these are number of RO observations, not profiles, per 12-h period (produced by Jon Starr, UCAR, based on data provided by Sean Healy and Alan Geer, ECMWF).

100 000 per day), they are based on simulated data. Confirmation of these theoretical results is needed using OSEs with real data. Lonitz et al. (2021a) confirmed these results in part by using *COSMIC-2*, Spire, and other RO sources to show that increasingly large positive impacts were attained on nearly all forecast metrics for RO profiles up to at least 10 000 profiles per day. ROMEX will allow testing of the theoretical results up to an average of 35 000 profiles per day using real data.

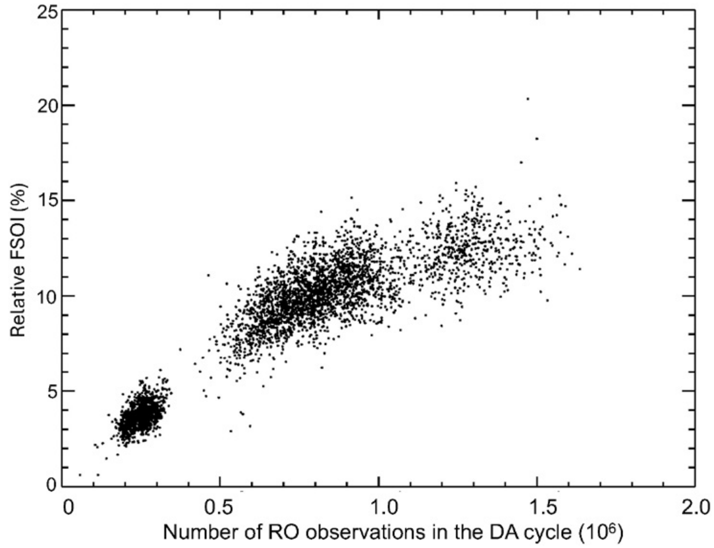

Fig. 6. Scatterplot of daily RO relative FSOI vs number of RO observations in millions assimilated per 12 h at ECMWF for time period shown in Figs. 4 and 5 (source: Sean Healy and Alan Geer, ECMWF).

The numerous positive results from the above impact studies and others prompted the International RO Working Group (IROWG) in 2015 to recommend acquiring a baseline of at least 20 000 RO profiles per day with complete global and local time coverage. Others have suggested that 30 000 profiles per day may be closer to an optimum number when considering benefit versus cost. The related cost–benefit curve will depend on the price per profile, as well as the impact per profile. While recognizing the potential for commercial RO companies to provide some of these data, the IROWG at its meeting in September 2022 recommended a government-sponsored backbone: "IROWG recommends operational Global Navigation Satellite System (GNSS) RO mission for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage" (IROWG 2022).

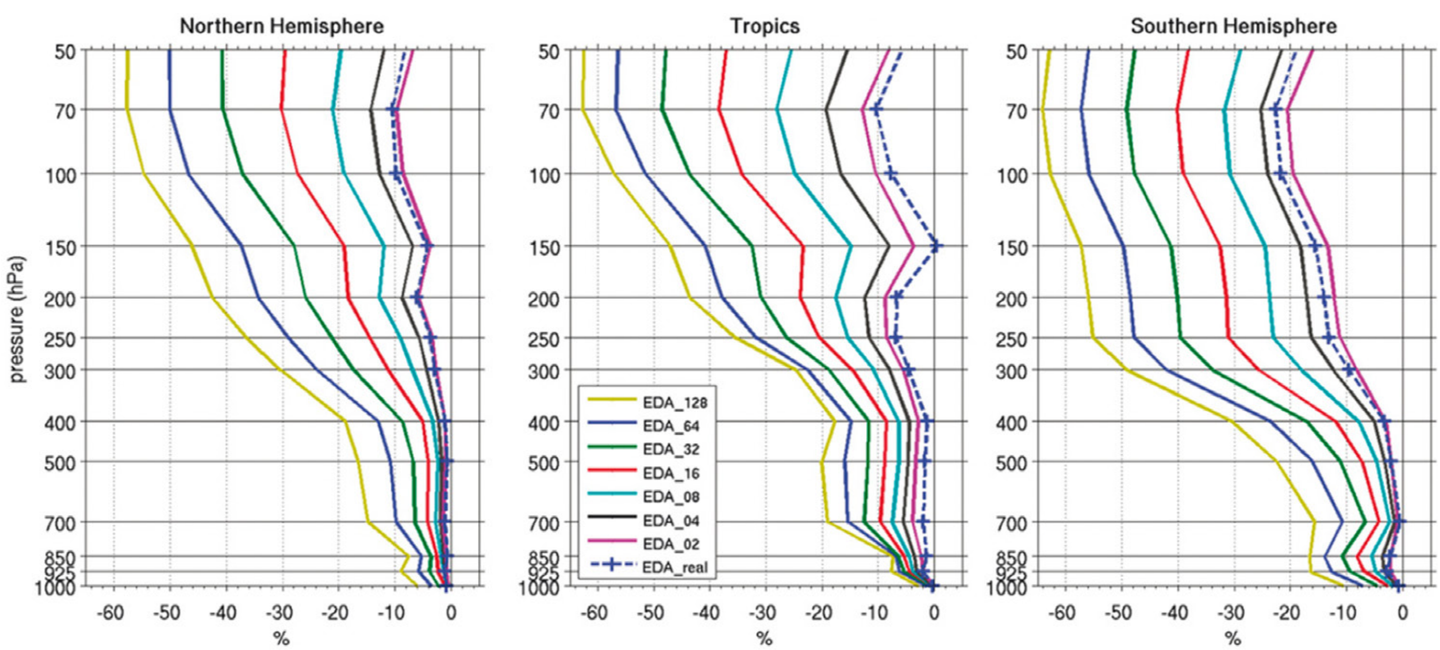

Fig. 7. Vertical profiles (*y* axis is pressure in hPa on a log scale) of normalized difference of EDA spread (%) for temperature averaged over the (left) NHEX, (center) tropics, and (right) Southern Hemisphere (SHEX) for the period 8–15 Aug 2008. Larger negative values indicate reduced uncertainty of the forecasts and a positive impact (Fig. 4 from Harnisch et al. 2013).

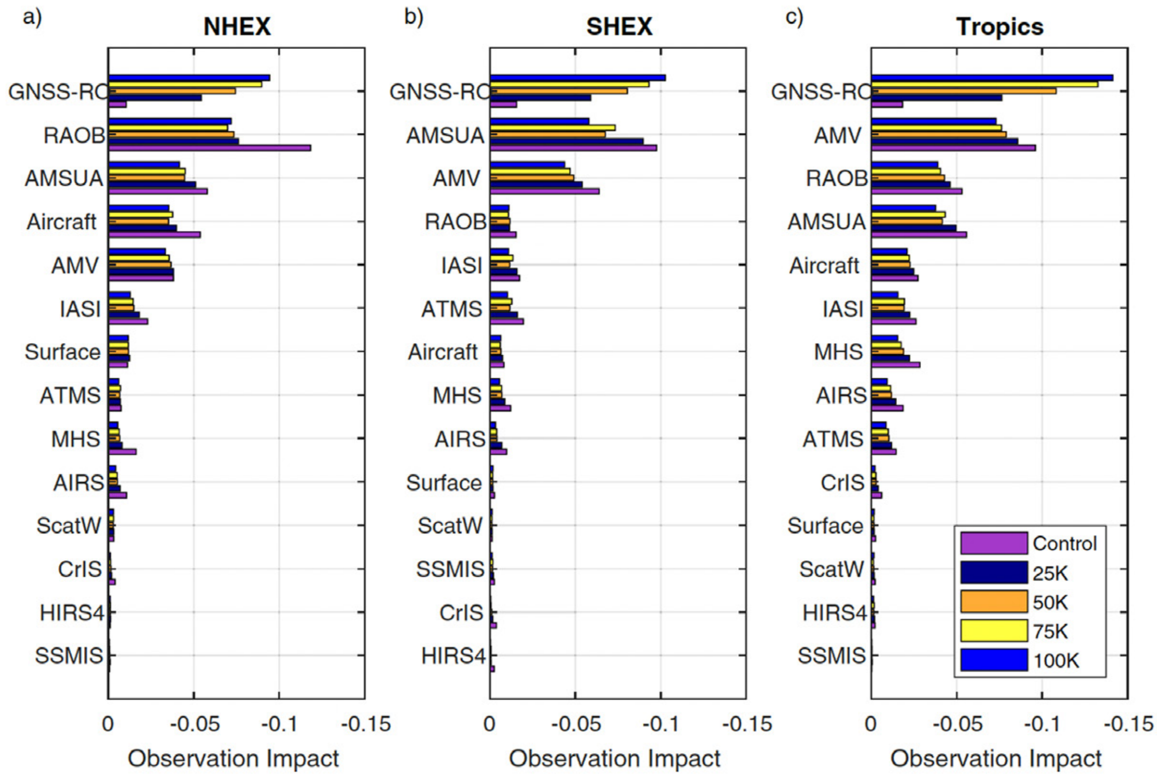

Fig. 8. FSOI impact (24-h wet energy norm in J kg^{-1}) for different numbers of RO profiles per day for NHEX, SHEX, and tropics (Fig. 22 from Privé et al. 2022).

An independent working group of the NOAA Science Advisory Board, the Environmental Information and Services Working Group (EISWG), supported the concept of a backbone in its first recommendation: "NOAA should employ a backbone approach to integrating alternative-source observations, with the nature of that backbone determined through a process involving a formal decision and implementation framework" (EISWG 2023).

4. Planning for the future

Over the past decade, NOAA has been planning for its future satellite observing systems, beginning with the NOAA Satellite Observing System Architecture (NSOSA) study (Volz et al. 2016; NOAA 2018; Maier et al. 2021). The Maier et al. (2021) study estimated the cost effectiveness of over 180 possible constellations on NWP, as well as many other user needs. Critical input to this study included the Environmental Data Record Value Model, which was developed by the Space Platform Requirements Working Group (Anthes et al. 2019). In this study, RO was the second highest priority (behind 3D winds) for improvement over the NOAA Program of Record 2025 in weather- and climate-related observations. The high priority of RO was based on two main factors—the large impact of RO on NWP and a projected future gap in RO observations.

Figure 9 shows the near-real-time monthly mean daily RO profiles available so far or as expected in the future as of January 2024 according to EUMETSAT; future numbers are based on mission requirements. The numbers plotted here represent data from publicly funded open-access data, i.e., the current backbone of publicly operated RO missions, as well as the current commercial data procured with a global license by either NOAA or EUMETSAT. Even though there is a significant amount of commercial data available for purchase and future acquisitions are now being planned, the number acquired from commercial vendors so far has been limited. Figure 9 shows a clear shortfall from the recommended 20 000 profile baseline. This discrepancy will become even larger in the next 10 years, since *COSMIC-2* is expected to end and the CGMS partners have no plans yet for government-sponsored follow-on

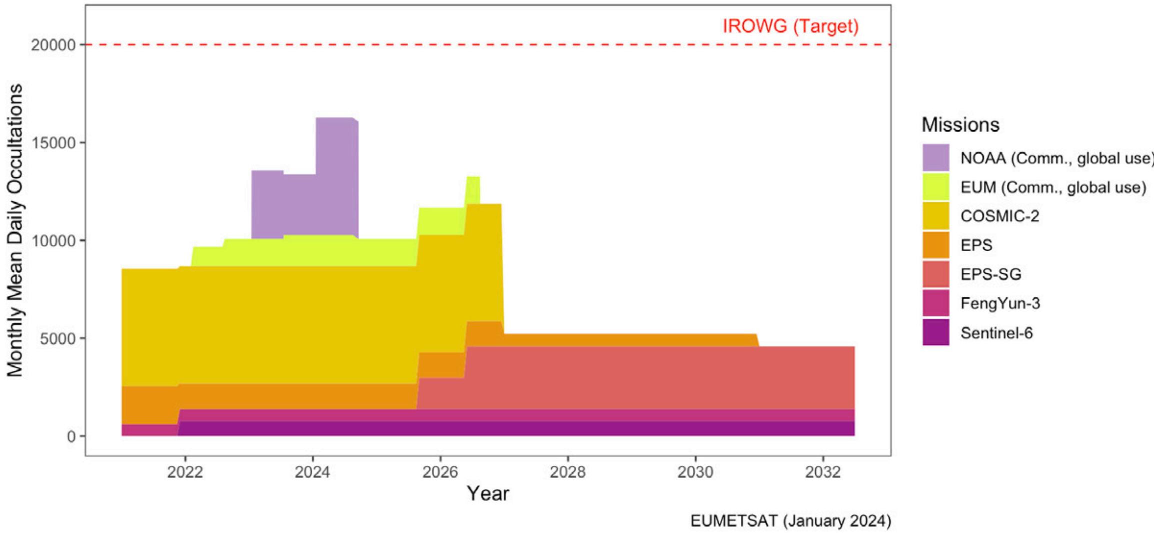

Fig. 9. Current and expected daily number or RO profiles provided in near–real time (NRT) based on the requirements for the listed set of ongoing and known upcoming public missions and their planned lifetimes. The figure also includes the current commercial data procured with a global license by either NOAA or EUMETSAT (source: EUMETSAT).

RO missions (Fig. 10). Meanwhile, the commercial data continue to pose uncertainties in terms of availability, open data access, full traceability, global and local time coverage, and long-term reliability.

Thus, despite numerous independent studies showing the large impact of RO observations on NWP, one of the most important applications of satellite meteorology, the number of RO observations is already below the base number recommended by the IROWG. There is a further risk of a decreasing number of RO observations in the future, and there are no plans yet for a stable provision of RO observations that are freely available to the community. The results from ROMEX, showing the value of up to 35 000 RO profiles per day, will test the theoretical estimates in previous studies and provide valuable information for members of the CGMS as they plan for the future.

Fig. 10. Top-level risk assessment of Earth observations. The risk is highest for RO observations (CGMS WGIII Report 2023).

5. The Radio Occultation Modeling Experiment

ROMEX-1 will make available the largest volume of RO data ever collected to the international community free of charge for testing in NWP models and other science and applications' research. The RO data from all known government and commercial providers have been collected for a 3-month period September–November 2022, which overlaps the Northern Hemisphere (NHEX) tropical cyclone season. A second ROMEX period during the Northern Hemisphere winter will be considered if the first period is successful.

The ROMEX concept was endorsed by the Ninth International Radio Occultation Workshop (IROWG-9) on 8–14 September 2022 in Leibnitz, Austria, and presented to the CGMS-51 Working Group II (WGII) meeting on 14 April 2023 and the CGMS-51 at its plenary meeting 26–28 June 2023. The IROWG NWP community has approval from their respective institutions to perform forecast experiments with the additional RO measurements over the ROMEX-1 period.

a. Questions to be addressed by ROMEX. High-level questions that can be addressed by ROMEX include the following:

What is the impact of increasing the number of RO observations in NWP models?

Is there an optimum number of RO profiles per day? With 30 000–40 000 profiles per day, the experiments can measure improvements up to these numbers in different operational NWP models.

How should RO observations be distributed around the globe and in local time?

Should the tropics or other specific latitudes receive relatively more focus? How important is uniform local time sampling to NWP and climate applications?

Are there systematic differences in the RO sources and their processing algorithms?

Issues include the value of higher signal-to-noise ratio, latency, differences between GNSS sources, and differences between processing algorithms.

How can we exploit the various aspects of RO quality such as penetration depth and detection of superrefraction?

How can these attributes be exploited in NWP and other applications? Quantifying these quality aspects into data requirements is an important topic, especially for commercial purchases.

How can the impact of RO data be increased, especially in the moist lower troposphere?

The greatest value of RO data has been in the upper troposphere/lower stratosphere, but RO observations provide much information on water vapor in the lower troposphere and numerous studies have shown a large impact of RO on tropical cyclone development and heavy precipitation events (Chen et al. 2020; Chang and Yang 2022). ROMEX can provide data to improve the impact of RO data in the moist lower troposphere.

How can RO data be most effectively used to observe the atmospheric boundary layer?

Observing and understanding the atmospheric boundary layer (ABL) was one of the highest priorities in the most recent NASA Decadal Survey (National Academies of Sciences, Engineering, and Medicine 2018). RO observations have been shown to be useful in determining the ABL height and the presence of superrefraction (Kalmus et al. 2022; Sokolovskiy et al. 2024). Three months of RO data with global and all local time coverage provide a unique dataset for global ABL studies.

b. ROMEX project details. A ROMEX website has been established under the auspices of the CGMS IROWG (https://irowg.org/ro-modeling-experiment-romex/). This site provides organizational details of ROMEX and how users may access and use the data. A ROMEX steering committee has been established (the authors of this paper), and questions or requests for information can be addressed to any of its members.

EUMETSAT and ROM SAF (https://rom-saf.eumetsat.int/) are taking the lead to collect, process, store, and redistribute the ROMEX data. EUMETSAT is managing an agreement with the data providers. As part of the data use agreement, users of ROMEX data are required to sign a data license with EUMETSAT for the terms and conditions of using the data. EUMETSAT has performed security checks and processed and reformatted the data in BUFR format, and the data are available through ROM SAF; variational retrievals of temperature and water vapor profiles will also be made available to the ROMEX participants. Individual data processing centers may also receive the lower-level data from EUMETSAT under mutual agreement.

The ROMEX excess phase data obtained by EUMETSAT will also be processed independently by the UCAR CDAAC (https://cdaac-www.cosmic.ucar.edu/) and made available to the research community via the ROM SAF. In addition to bending angles and refractivity, CDAAC will provide vertical profiles of temperature and specific humidity using a one-dimensional variational approach (Wee et al. 2022), as well as local spectral width, which is a measure of uncertainty of the RO observations in the troposphere (Liu et al. 2018; Zhang et al. 2023; Sjoberg et al. 2023).

All of the RO data for the ROMEX-1 period have been delivered to EUMETSAT. The daily numbers by the main data providers are shown in Fig. 11. A list of the providers and their contributions is presented in Table 1. The existing data providers were able to provide datasets to ROMEX beyond what have been available to real-time operations at NWP centers accessible either through the global telecommunication system (GTS) or under the commercial purchase contracts of NOAA, NASA, and/or EUMETSAT. For example, Spire Global Inc. provides nearly 17 000 profiles per day for the ROMEX studies.

It is noteworthy that two of the data providers are contributing data that are relatively new to the RO community. These are Yunyao Aerospace, a private company in Tianjin, China, and China Aerospace Science and Industry Corporation subsidiary Xiyong Microelectronics Park. The latter produces GNSS radio occultation profiles for research and operations

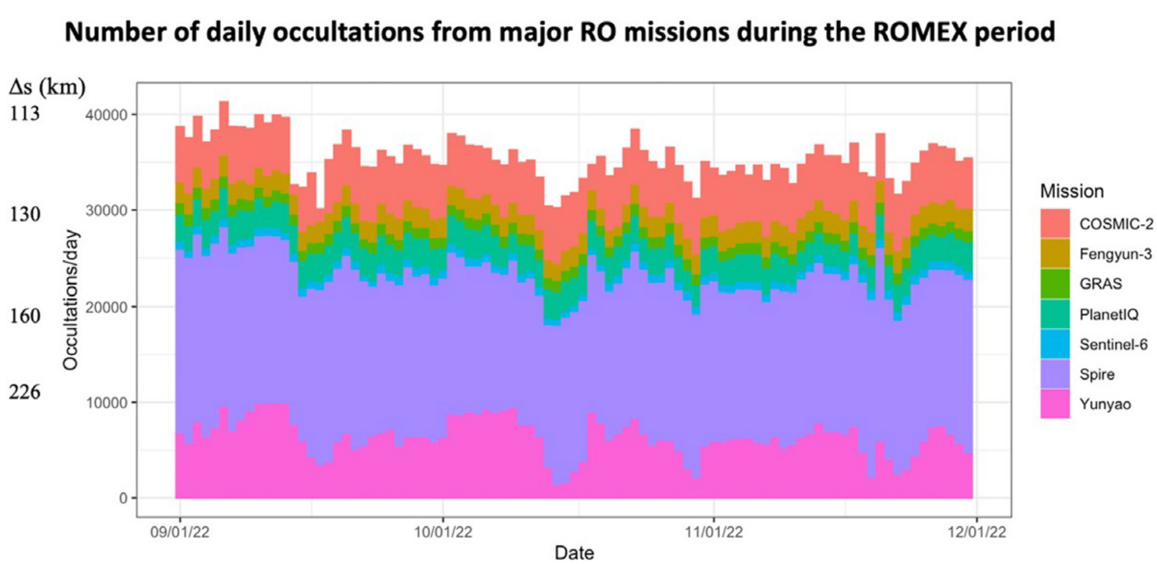

Fig. 11. Number of daily RO profiles from major RO missions during the ROMEX-1 period (1 Sep–30 Nov 2022). Approximate average horizontal spacing between observations indicated by Δ*s* on the left of the figure. Colors indicate the contribution by the various missions, stacked on top of each other. Additional missions not shown are GeoOptics, *TerraSAR-X*, *TanDEM-X*, *KOMPSAT-5*, and Tianmu (source: EUMETSAT).

with its Tianmu satellites. During the first ROMEX period, Yunyao is the second largest data provider, with up to 5400 profiles per day (Table 1). There are no published reports yet on the processing and evaluation of the Yunyao data, but the authors of this paper have discussed the processing with Yunyao scientists (C. Yan 2024, personal communication) and carried out a preliminary assessment; the data are comparable in quality to other well-evaluated missions such as *COSMIC-2* and MetOp. Data from the Tianmu satellites were limited to a few hundred profiles per day (not shown in Fig. 11) since the ROMEX period is during its prelaunch period with only one satellite available, but might provide a significantly larger number of occultations during a second ROMEX period.

Table 1. Average number of RO profiles per day acquired by EUMETSAT from the data providers and available for ROMEX-1 after quality control by the processing center (available at ROM SAF).

Mission	RO/day
Spire	16 750
Yunyao	5400
COSMIC-2	4900
PlanetiQ	2750
Fengyun-3 (GNOS)	1950
MetOp (GRAS)	1150
Sentinel-6	850
Tianmu	270
Other (GeoOptics, *KOMPSAT-5*, *Paz*, *TerraSAR-X*, *TanDEM-X*)	500
ROMEX-1 total	34 520

Figure 12 (top) shows the global distribution of RO profiles from the ROMEX-1 baseline case, consisting of *COSMIC-2*, MetOp, *KOMPSAT-5*, Sentinel-6, *Paz*, *TanDEM-X*, and *TerraSAR-X* on 1 September 2022 (about 7000 profiles). The middle panel of Fig. 12 shows the distribution of all RO profiles in ROMEX-1 on the same day (about 35 000 profiles). The bottom panels show all the ROMEX-1 profiles versus latitude and local time. The predominance of missions in the same polar orbit, which concentrates the observations near the same local time, is evident.

6. Summary

Numerous studies have shown a large impact of radio occultation in NWP model forecasts for real observations numbering approximately 10 000 profiles per day. With these numbers, RO consistently ranks in the top five of observations contributing to global NWP accuracy and even higher in the tropics. Theoretical studies have shown a significant additional impact up to at least 100 000 profiles per day. ROMEX-1 is providing approximately 35 000 RO profiles per day for a 3-month period (September–November 2022), and these are available free of charge to the community for testing in global and regional models. The data are also available for other scientific studies in weather and climate.

ROMEX-1 will provide additional guidance to NOAA, EUMETSAT, and other CGMS organizations for planning their future observational systems. Figures 9 and 10 clearly show this need, as a significant gap in RO observations is projected in less than 10 years. With an end of life of *COSMIC-2* and one of the EUMETSAT satellites as early as 2027, planning for follow-on missions and/or acquisitions must begin now.

The ROMEX-1 data have been collected and processed by EUMETSAT and are available to the community via the ROM SAF. The data are also being processed independently by UCAR CDAAC and are also available to the community. Early results were reported at the first IROWG ROMEX Workshop hosted by EUMETSAT 17–19 April 2024 in Darmstadt, Germany, with additional results reported at the next IROWG Workshop 12–18 September 2024 in Boulder, Colorado.

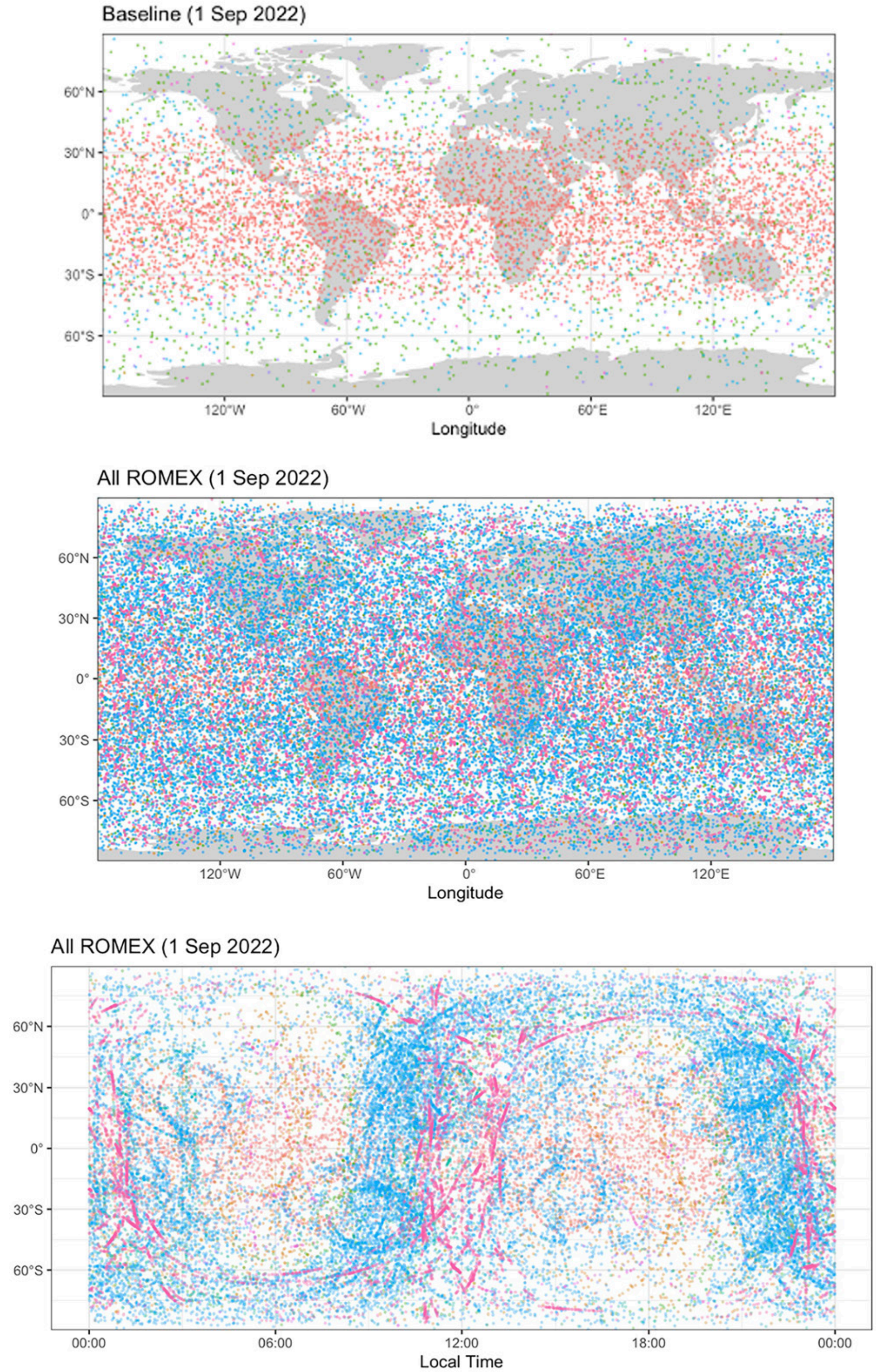

Fig. 12. Global distribution of ROMEX missions on 1 Sep 2022. Colors denote occultations from different missions; e.g., red dots indicate *COSMIC-2*; light blue and green dots denote occultations from MetOp, Sentinel-6, and smaller missions in the baseline data; and other colors denote Spire (blue), Yunyao (magenta), and other data. (top) Profiles in the baseline (~7 K) consisting of *COSMIC-2*, MetOp, *KOMPSAT-5*, Sentinel-6, *Paz*, *TanDEM-X*, and *TerraSAR-X* on 1 Sep 2022. (middle) All ROMEX-1 vs latitude and longitude on the same day. (bottom) All ROMEX-1 vs latitude and local time on the same day.

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Data availability statement. The EUMETSAT figures are based on global licensed data so they are available through the WMO GTS service and archives at various NWP centers. ROMEX data are available through ROM SAF under the ROMEX terms and conditions (see section 5b for details). The sources for the data used to create the figures are given in the figure captions.

References

Anthes, R. A., 2011: Exploring Earth's atmosphere with radio occultation: Contributions to weather, climate and space weather. *Atmos. Meas. Tech.*, **4**, 1077–1103, https://doi.org/10.5194/amt-4-1077-2011.

——, and Coauthors, 2019: Developing priority observational requirements from space using multi-attribute utility theory. *Bull. Amer. Meteor. Soc.*, **100**, 1753–1774, https://doi.org/10.1175/BAMS-D-18-0180.1.

Aparicio, J. M., and G. Deblonde, 2008: Impact of the assimilation of CHAMP refractivity profiles on Environment Canada global forecasts. *Mon. Wea. Rev.*, **136**, 257–275, https://doi.org/10.1175/2007MWR1951.1.

Atlas, R., E. Kalnay, and M. Halem, 1985: Impact of satellite temperature sounding and wind data on numerical weather prediction. *Opt. Eng.*, **24**, 242341, https://doi.org/10.1117/12.7973481.

Bauer, P., G. Radnóti, S. Healy, and C. Cardinali, 2014: GNSS radio occultation constellation observing system experiments. *Mon. Wea. Rev.*, **142**, 555–572, https://doi.org/10.1175/MWR-D-13-00130.1.

Bonafoni, S., R. Biondi, H. Brenot, and R. Anthes, 2019: Radio occultation and ground based GNSS products for observing, understanding and predicting extreme events: A review. *Atmos. Res.*, **230**, 104624, https://doi.org/10.1016/j.atmosres.2019.104624.

Bonavita, M., 2014: On some aspects of the impact of GPSRO observations in global numerical weather prediction. *Quart. J. Roy. Meteor. Soc.*, **140**, 2546–2562, https://doi.org/10.1002/qj.2320.

Boukabara, S.-A., K. Garrett, and V. Krishna-Kumar, 2016: Potential gaps in the satellite observing system coverage: Assessment of impact on NOAA's numerical weather prediction overall skills. *Mon. Wea. Rev.*, **144**, 2547–2563, https://doi.org/10.1175/MWR-D-16-0013.1.

Candy, B., J. Cotton, and J. Eyre, 2021: Recent results of observation data denial experiments. Weather Science Tech. Rep. 641, Met Office, 35 pp., https://digital.nmla.metoffice.gov.uk/IO_441cf4bf-3ca9-4f52-8e66-f640ac8eadd1/.

Cardinali, C., 2009: Monitoring the observation impact on the short-range forecast. *Quart. J. Roy. Meteor. Soc.*, **135**, 239–250, https://doi.org/10.1002/qj.366.

——, and S. Healy, 2014: Impact of GPS radio occultation measurements in the ECMWF system using adjoint-based diagnostics. *Quart. J. Roy. Meteor. Soc.*, **140**, 2315–2320, https://doi.org/10.1002/qj.2300.

CGMS WGIII, 2023: Coordination Group for Meteorological Satellites Working Group III report. 19 pp., https://www.cgms-info.org/Agendas/GetWpFile.ashx?wid=6b9c7bef-b49a-4077-95aa-2602d01fd780&aid=7c140ccd-b73e-4890-a84d-ee4e6841ad7b.

Chang, C.-C., and S. C. Yang, 2022: Impact of assimilating Formosat-7/COSMIC-II GNSS radio occultation data on heavy rainfall prediction in Taiwan. *Terr. Atmos. Oceanic Sci.*, **33**, 7, https://doi.org/10.1007/s44195-022-00004-4.

Chen, S.-Y., Y.-H. Kuo, and C. Y. Huang, 2020: The impact of GPS RO data on the prediction of tropical cyclogenesis using a nonlocal observation operator: An initial assessment. *Mon. Wea. Rev.*, **148**, 2701–2717, https://doi.org/10.1175/MWR-D-19-0286.1.

Cucurull, L., J. C. Derber, R. Treadon, and R. J. Purser, 2007: Assimilation of global positioning system radio occultation observations into NCEP's Global Data Assimilation System. *Mon. Wea. Rev.*, **135**, 3174–3193, https://doi.org/10.1175/MWR3461.1.

——, R. A. Anthes, and L.-L. Tsao, 2014: Radio occultation observations as anchor observations in numerical weather prediction models and associated reduction of bias corrections in microwave and infrared satellite observations. *J. Atmos. Oceanic Technol.*, **31**, 20–32, https://doi.org/10.1175/JTECH-D-13-00059.1.

——, R. Atlas, R. Li, M. J. Mueller, and R. N. Hoffman, 2018: An observing system simulation experiment with a constellation of radio occultation satellites. *Mon. Wea. Rev.*, **146**, 4247–4259, https://doi.org/10.1175/MWR-D-18-0089.1.

EISWG, 2023: A NESDIS observing system backbone framework. Report of the NOAA Science Advisory Board Environmental Information and Services Working Group, 10 pp., https://sab.noaa.gov/wp-content/uploads/EISWG-Backbone-Report-For-SAB-Review.pdf.

Errico, R., and N. C. Privé, 2018: Some general and fundamental requirements for designing Observing System Simulation Experiments (OSSEs). WMO WWRP Rep. 2018-8, 24 pp., https://ntrs.nasa.gov/api/citations/20190025338/downloads/20190025338.pdf.

Eyre, J., 2008: An introduction to GPS radio occultation and its use in numerical weather prediction. *GRAS SAF Workshop on Applications of GPS Radio Occultation Measurements*, Reading, United Kingdom, ECMWF, https://www.ecmwf.int/sites/default/files/elibrary/2008/9342-introduction-gps-radio-occultation-and-its-use-numerical-weather-prediction.pdf.

Harnisch, F., S. B. Healy, P. Bauer, and S. J. English, 2013: Scaling of GNSS radio occultation impact with observation number using an ensemble of data assimilations. *Mon. Wea. Rev.*, **141**, 4395–4413, https://doi.org/10.1175/MWR-D-13-00098.1.

Healy, S. B., 2008: Forecast impact experiment with a constellation of GPS radio occultation receivers. *Atmos. Sci. Lett.*, **9**, 111–118, https://doi.org/10.1002/asl.169.

——, and J.-N. Thépaut, 2006: Assimilation experiments with CHAMP GPS radio occultation measurements. *Quart. J. Roy. Meteor. Soc.*, **132**, 605–623, https://doi.org/10.1256/qj.04.182.

——, A. M. Jupp, and C. Marquardt, 2005: Forecast impact experiment with GPS radio occultation measurements. *Geophys. Res. Lett.*, **32**, L03804, https://doi.org/10.1029/2004GL020806.

Ho, S.-p., and Coauthors, 2020: The COSMIC-FORMOSAT-3 radio occultation mission after 12 years: Accomplishments, remaining challenges, and potential impacts of COSMIC-2. *Bull. Amer. Meteor. Soc.*, **101**, E1107–E1136, https://doi.org/10.1175/BAMS-D-18-0290.1.

Hoffman, R. N., and R. Atlas, 2016: Future observing system simulation experiments. *Bull. Amer. Meteor. Soc.*, **97**, 1601–1616, https://doi.org/10.1175/BAMS-D-15-00200.1.

IROWG, 2022: Summary of the Ninth International Radio Occultation Workshop. 25 pp., https://irowg.org/wpcms/wp-content/uploads/2023/04/IROWG9_Minutes_Summary.pdf.

Kalmus, P., C. O. Ao, K.-N. Wang, M. P. Manzi, and J. Teixeira, 2022: A high-resolution planetary boundary layer height seasonal climatology from GNSS radio occultations. *Remote Sens. Environ.*, **276**, 113037, https://doi.org/10.1016/j.rse.2022.113037.

Kursinski, E. R., G. A. Hajj, J. T. Schofield, R. P. Linfield, and K. R. Hardy, 1997: Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System. *J. Geophys. Res.*, **102**, 23 429–23 465, https://doi.org/10.1029/97JD01569.

Liu, H., Y.-H. Kuo, S. Sokolovskiy, X. Zou, Z. Zeng, L.-F. Hsiao, and B. C. Ruston, 2018: A quality control procedure based on bending angle measurement uncertainty for radio occultation data assimilation in the tropical lower troposphere. *J. Atmos. Oceanic Technol.*, **35**, 2117–2131, https://doi.org/10.1175/JTECH-D-17-0224.1.

Lonitz, K., N. Bowler, E. Holm, and S. Healy, 2021a: Assimilating Spire and COSMIC-2 data. *ECMWF Newsletter*, No. 169, ECMWF, Reading, United Kingdom, 25–32, https://www.ecmwf.int/en/newsletter/169/meteorology/assimilating-spire-and-cosmic-2-data-ifs.

——, C. Marquardt, N. Bowler, and S. Healy, 2021b: Final Technical Note of "Impact assessment of commercial GNSS-RO data". ESA Contract Rep. 4000131086/20/NL/FF/a, 74 pp., https://www.ecmwf.int/en/elibrary/81281-final-technical-note-impact-assessment-commercial-gnss-ro-data.

Maier, M. W., and Coauthors, 2021: Architecting the future of weather satellites. *Bull. Amer. Meteor. Soc.*, **102**, E589–E610, https://doi.org/10.1175/BAMS-D-19-0258.1.

NASA, 2023: GEOS-5: A high resolution global atmospheric model. Accessed 30 June 2024, https://earthobservatory.nasa.gov/images/44246/geos-5-a-high-resolution-global-atmospheric-model.

National Academies of Sciences, Engineering, and Medicine, 2018: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* The National Academies Press, 716 pp., https://doi.org/10.17226/24938.

NOAA, 2018: The NOAA Satellite Observing System Architecture study. Building a Plan for NOAA's 21st Century Satellite Observing System, 36 pp., https://www.regulations.gov/document/NOAA-NESDIS-2018-0053-0002.

Poli, P., S. B. Healy, F. Rabier, and J. Pailleux, 2008: Preliminary assessment of the scalability of GPS radio occultations impact in numerical weather prediction. *Geophys. Res. Lett.*, **35**, L23811, https://doi.org/10.1029/2008GL035873.

——, P. Moll, D. Puech, F. Rabier, and S. B. Healy, 2009: Quality control, error analysis, and impact assessment of FORMOSAT-3/COSMIC in numerical weather prediction. *Terr. Atmos. Oceanic Sci.*, **20**, 101–113, https://doi.org/10.3319/TAO.2008.01.21.02(F3C).

——, S. B. Healy, and D. P. Dee, 2010: Assimilation of global positioning system radio occultation data in the ECMWF ERA-Interim reanalysis. *Quart. J. Roy. Meteor. Soc.*, **136**, 1972–1990, https://doi.org/10.1002/qj.722.

Privé, N. C., R. M. Errico, and A. E. Akkraoui, 2022: Investigation of the potential saturation of information for the Global Navigation Satellite System radio occultation observations with an observing system simulation experiment. *Mon. Wea. Rev.*, **150**, 1293–1316, https://doi.org/10.1175/MWR-D-21-0230.1.

Rennie, M. P., 2010: The impact of GPS radio occultation assimilation at the Met Office. *Quart. J. Roy. Meteor. Soc.*, **136**, 116–131, https://doi.org/10.1002/qj.521.

Rocken, C., and Coauthors, 1997: Analysis and validation of GPS/MET data in the neutral atmosphere. *J. Geophys. Res.*, **102**, 29 849–29 866, https://doi.org/10.1029/97JD02400.

Sjoberg, J., R. Anthes, and H. Zhang, 2023: Estimating individual radio occultation uncertainties using the observations and environmental parameters. *J. Atmos. Oceanic Technol.*, **40**, 1461–1474, https://doi.org/10.1175/JTECH-D-23-0029.1.

Sokolovskiy, S., and Coauthors, 2024: Detection of super-refraction at the top of the atmospheric boundary layer from COSMIC-2 radio occultations. *J. Atmos. Oceanic Technol.*, **41**, 65–78, https://doi.org/10.1175/JTECH-D-22-0100.1.

Volz, S., M. W. Maier, and D. Di Pietro, 2016: The NOAA Satellite Observing System Architecture study. *2016 IEEE Int. Geoscience and Remote Sensing Symp. (IGARSS)*, Beijing, China, Institute of Electrical and Electronics Engineers, 1–4, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160008953.pdf.

Ware, R., and Coauthors, 1996: GPS sounding of the atmosphere from low Earth orbit: Preliminary results. *Bull. Amer. Meteor. Soc.*, **77**, 19–40, https://doi.org/10.1175/1520-0477(1996)077<0019:GSOTAF>2.0.CO;2.

Wee, T.-K., R. A. Anthes, D. C. Hunt, W. S. Schreiner, and Y.-H. Kuo, 2022: Atmospheric GNSS RO 1D-Var in use at UCAR: Description and validation. *Remote Sens.*, **14**, 5614, https://doi.org/10.3390/rs14215614.

Yue, X., W. S. Schreiner, N. Pedatella, R. A. Anthes, A. J. Mannucci, P. R. Straus, and J.-Y. Liu, 2014: Space weather observations by GNSS radio occultation: From FORMOSAT-3/COSMIC to FORMOSAT-7/COSMIC-2. *Space Wea.*, **12**, 616–621, https://doi.org/10.1002/2014SW001133.

Yunck, T. P., C.-H. Liu, and R. Ware, 2000: A history of GPS sounding. *Terr. Atmos. Oceanic Sci.*, **11** (1), 1–20, https://doi.org/10.3319/TAO.2000.11.1.1(COSMIC).

Zeng, X., and Coauthors, 2020: Use of observing system simulation experiments in the United States. *Bull. Amer. Meteor. Soc.*, **101**, E1427–E1438, https://doi.org/10.1175/BAMS-D-19-0155.1.

Zhang, H., Y.-H. Kuo, and S. Sokolovskiy, 2023: Assimilation of radio occultation data using measurement-based observation error specification: Preliminary results. *Mon. Wea. Rev.*, **151**, 589–601, https://doi.org/10.1175/MWR-D-22-0122.1.