An Analysis of Alternatives for the COSMIC-2 Constellation in the Context of Global Observing System Simulation Experiments

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ABSTRACT

Observing system simulation experiments (OSSEs) were conducted to evaluate the potential impact of the six Global Navigation Satellite System (GNSS) radio occultation (RO) receiver satellites in equatorial orbit from the initially proposed Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2) mission, known as COSMIC-2A. Furthermore, the added value of the high-inclination component of the proposed mission was investigated by considering a few alternative architecture designs, including the originally proposed polar constellation of six satellites (COSMIC-2B), a constellation with a reduced number of RO receiving satellites, and a constellation of six satellites but with fewer observations in the lower troposphere. The 2015 year version of the operational three-dimensional ensemble–variational data assimilation system of the National Centers for Environment Prediction (NCEP) was used to run the OSSEs. Observations were simulated and assimilated using the same methodology and their errors assumed uncorrelated. The largest benefit from the assimilation of COSMIC-2A, with denser equatorial coverage, was to improve tropical winds, and its impact was found to be overall neutral in the extratropics. When soundings from the high-inclination orbit were assimilated in addition to COSMIC-2A, positive benefits were found globally, confirming that a high-inclination orbit constellation of RO receiving satellites is necessary to improve weather forecast skill globally. The largest impact from reducing COSMIC-2B from six to four satellites was to slightly degrade weather forecast skill in the Northern Hemisphere extratropics. The impact of degrading COSMIC-2B to the COSMIC level of accuracy, in terms of penetration into the lower troposphere, was mostly neutral.

1. Introduction

Costs of developing, deploying, and maintaining new space-based architectures typically exceed \$100–\$500 million per instrument. As new satellite observing systems for weather applications are proposed, a rigorous evaluation of their potential impact in global and regional numerical weather prediction (NWP) systems is necessary, so a cost–benefit analysis should be developed for better planning and decision-making.

Although standard data denial experiments with operational weather models quantify the impact of current observations, these studies cannot evaluate the impact of observing platforms that have not yet been developed. In this context, observing system simulation experiments (OSSEs) can be used to quantitatively evaluate the impact of proposed satellite observing systems (Atlas 1997; Atlas et al. 2015a,b; Cucurull et al. 2018) before they are deployed in space. Briefly, an OSSE consists of a free-running numerical weather prediction forecast, typically from an operational model, which provides a complete record of the assumed true state of the atmosphere. This model integration, usually referred to as the *nature run* should reproduce the main characteristics of the real atmosphere. Synthetic observations from the current and proposed instruments, including their error characteristics, are simulated from the nature run and assimilated into a weather forecast model different from the model used to generate the nature run. Impact of current and proposed observations are validated against the nature run.

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In order for the results of an OSSE to be useful, there are a few criteria that need to be met: 1) OSSEs need to be completed on time to be useful; 2) the nature run used in the OSSE system and the differences between the nature run and forecast system used in the experiments should be realistic; 3) spatial and temporal coverage, as well as the error characteristics of the simulated observations, must represent those of the real atmosphere; and 4) forecast accuracy and the impact of existing observing systems in an OSSE should be comparable to the impacts in the real world. Finally, it is fundamental to understand the limitations of any OSSE and conclusions should not be drawn beyond these limitations. An excellent review of the OSSE methodology and its current status and anticipated progress is provided in Hoffman and Atlas (2016).

Information from OSSEs can lead to better planning and decision-making by providing quantitative information on the impact of new observing systems, evaluating the impact of alternative mix of current and/or proposed instruments, and optimizing data assimilation strategies. OSSEs can also significantly reduce the time lag between instrument deployment and operational use of new observations by evaluating and/or developing new methodologies to process and assimilate new types of data. Overall, information from OSSEs can lead to an optimization of the global observing system for weather and climate, as well as other applications.

The success of the six-satellite Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission (Rocken et al. 2000; Anthes et al. 2008) in improving global weather forecasts at NOAA (Cucurull 2010; Cucurull et al. 2013; Cucurull and Anthes 2014) motivated the United States to develop, in partnership with Taiwan, the follow-on COSMIC-2 mission, a 12-satellite constellation to be originally deployed in two launches. The first six satellites (COSMIC-2A) at 24° inclination were launched in June 2019 in a low-inclination orbit for dense equatorial coverage. The second six (COSMIC-2B) were to be deployed at a later time in a high inclination (polar) orbit to provide global coverage. However, the United States and Taiwan decided to not move forward with the second launch of COSMIC-2. The main payload of the COSMIC-2A mission is a radio occultation (RO) receiver (see, e.g., Melbourne et al. 1994; Rocken et al. 1997; and Kursinski et al. 1997 and references therein for a detailed description of the RO technique). COSMIC-2A is expected to provide $\sim$6000 RO profiles day^{-1}, with better instrument performance than COSMIC, particularly in the tropical latitudes. Most relevant to current operational NWP, RO soundings from COSMIC-2 are expected to penetrate deeper into the lower moist tropical troposphere due to an improved RO receiver and larger antennas with higher signal-to-noise-ratio (T. Meehan 2018, personal communication). The negative effects in NOAA's global weather forecasts if a gap in RO data would occur were investigated in Cucurull and Anthes (2015) with the use of real RO observations from the COSMIC mission.

In previous studies, Cucurull et al. (2017) provided a quantitative evaluation of the impact of COSMIC-2A and COSMIC-2B in improving global NWP forecasts. The study used a simplified OSSE system setup with perfect simulated observations, a low-resolution nature run, and an earlier version of the National Centers for Environmental Prediction (NCEP) data assimilation system. These authors found that the polar component of the COSMIC-2 mission (i.e., COSMIC-2B) was necessary to improve weather analyses and forecasts globally. More recently, the impact of COSMIC-2A and COSMIC-2B combined was investigated with a state-of-the-art OSSE system in Cucurull et al. (2018). However, this study did not consider the benefits in global NWP from the assimilation of COSMIC-2A alone. Since NOAA is not moving forward with the launch of COSMIC-2B, it was important to quantify the impact of assimilating COSMIC-2A without the added benefits of the assimilation of COSMIC-2B. Also, and before the decision to not move forward with the launch of the COSMIC-2B receiving satellites was made, NOAA conducted a series of trade-off studies in the design and configuration of COSMIC-2B to evaluate possible alternatives to the originally proposed polar component of the mission. Some of these are reported here as potentially useful for future instrument trade studies. In particular, the number of RO soundings and their accuracy and spatial coverage were investigated.

This paper describes the OSSEs conducted at NOAA to evaluate the impact of COSMIC-2A RO soundings in the context of global weather forecast skill with a state-of-the-art OSSE system. Furthermore, the added value of the polar component of the mission beyond the assimilation of COSMIC-2A is investigated by considering a few alternate architecture designs for the COSMIC-2B component, including the originally proposed constellation.

The paper is structured as follows: section 2 briefly reviews the OSSE system setup used in our experiments. Section 3 quantifies the impact of the COSMIC-2A and COSMIC-2B, as in its original proposed design, in global NWP. The gained value in weather prediction skill over the assimilation of COSMIC-2A soundings from alternatives to the originally planned COSMIC-2B is discussed in section 4. Finally, section 5 summarizes the main conclusions of our study.

2. OSSE system

To focus on the impact of the different RO satellite configurations on global NWP, including the impact on the mass, moisture, and wind fields, we used the existing state-of-the-art NOAA OSSE system. This system includes a nature run based on the 7-km-resolution, nonhydrostatic NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System Model, version 5 (GEOS-5; Putman et al. 2014, 2015). Conventional and clear-sky satellite radiance observations from the nature run were simulated for a 2-month period (August–September 2006) based on the real 2014 observing system configuration and following the methodology described in Boukabara et al. (2018a). Calibration of the RO component of the OSSE system is provided in Fig. 1, showing that the accuracy and impact of simulated COSMIC observations in the OSSE system are comparable to their values in the real world. Calibration of the overall system is summarized in Boukabara et al. (2018b).

COSMIC-2A and COSMIC-2B RO quasi-vertical profiles of refractivity were simulated using the forward operator described in Cucurull (2010), but with slightly modified assimilation algorithms to allow a larger percentage of COSMIC-2 soundings to penetrate in the lower troposphere, particularly in the tropics (Cucurull et al. 2018). Essentially, refractivity profiles are derived from interpolating pressure, water vapor and temperature values from the nature run to the location of the observations. As it is currently done for the other observing systems, the same methodology is used to simulate and assimilate the refractivity profiles. (As we continue to improve the global OSSE system, we plan to introduce differences between the operators used to simulate and assimilate observations in the near future.)

As in previous studies with COSMIC-2 receivers, transmitting satellites from both the U.S. Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS) constellations were included in the simulation of COSMIC-2 profiles. As an example, the relative distribution of the COSMIC-2A and COSMIC-2B soundings for a 6-h assimilation time window is shown in Fig. 2a. Notice that only the COSMIC-2B component provides global data coverage. Random errors were added to all the perfect simulated observations following the procedures described in Errico et al. (2013). This methodology uses an iterative process to tune the observation random errors in order to match the observation minus background statistics from the OSSE system to the corresponding statistics with real observations. When systematic errors exist in the real observations and these errors are accounted for in the data assimilation algorithms (i.e., for satellite radiances), these biases were also added in the simulated observations following the approach described in Boukabara et al. (2016). Although in reality errors are correlated, such correlations were not included in either the simulation or assimilation processes.

We ran a series of OSSEs to quantify the potential value of COSMIC-2 to improve global weather prediction. All the observations that were operationally assimilated in 2014, except for RO observations, were assimilated in a CONTROL experiment. A list of observations operationally assimilated at NCEP in 2014 is provided in Table 1. Simulated COSMIC-2A RO refractivity soundings were added to the CONTROL in the COSMIC2A experiment. Three different runs quantified the impact of a polar component of COSMIC-2 in addition to the assimilation of COSMIC-2A under different satellite configuration scenarios. First, the added value of COSMIC-2B as originally planned was investigated in COSMIC2. Second, the impact of decreasing the number of receiving satellites from six to four but maintaining the same level of accuracy as COSMIC-2, was investigated in COSMIC2_4PO ("4PO" for four polar satellites). Finally, the impact of decreasing the expected level of penetration into the lower troposphere of the six COSMIC-2B satellites to the level of COSMIC was investigated in COSMIC2_C1PO ("C1PO" for the COSMIC level of penetration into the lower atmosphere for the polar component). We should note that the differences between the instrument observation errors of COSMIC and COSMIC-2 were not considered in the experiments. This is because currently, model representativeness error is significantly larger than the impact of RO instrument errors (Cucurull et al. 2018). Although the benefits in global NWP skill from the assimilation of COSMIC-2 soundings were already investigated in Cucurull et al. (2018), we include the results of this experiment in our study to better quantify the relative impact of COSMIC-2 versus COSMIC-2A, as well as the relative impact of COSMIC-2 versus the use of alternatives approaches for the COSMIC-2B (polar) component of COSMIC-2.

Except for the RO forward operator, the NCEP's data assimilation system used in all the experiments was the Global Data Assimilation System (GDAS)/Global Forecast System (GFS) configuration that was operational in 2015 (Q1FY15 version), but at the lower horizontal forecast model research resolution of T670 (~27 km). The number of vertical levels was kept the same as in the operational configuration (64). For compatibility, all the experiments used the hybrid three-dimensional (3D) ensemble–variational (EnVar) version of the NCEP's Gridpoint Statistical Interpolation

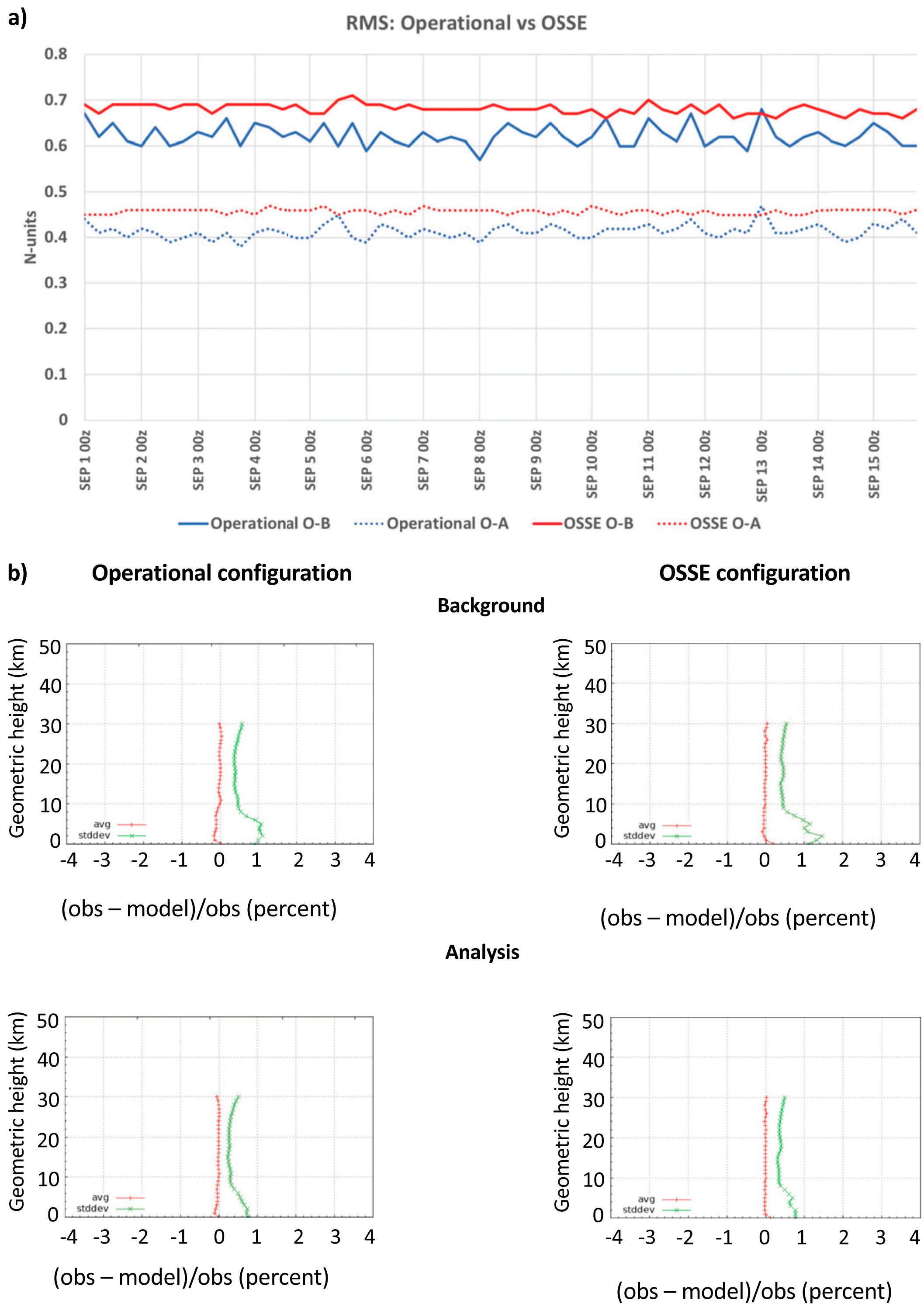


FIG. 1. (a) Time series of the root-mean-squared refractivity difference (N-units) between COSMIC observations and model simulations in the operational and OSSE configurations. (b) Bias and standard deviation of the refractivity differences (percentage) between COSMIC observations and model simulations during 1–15 Sep as a function of the vertical height for the operational and OSSE configurations.

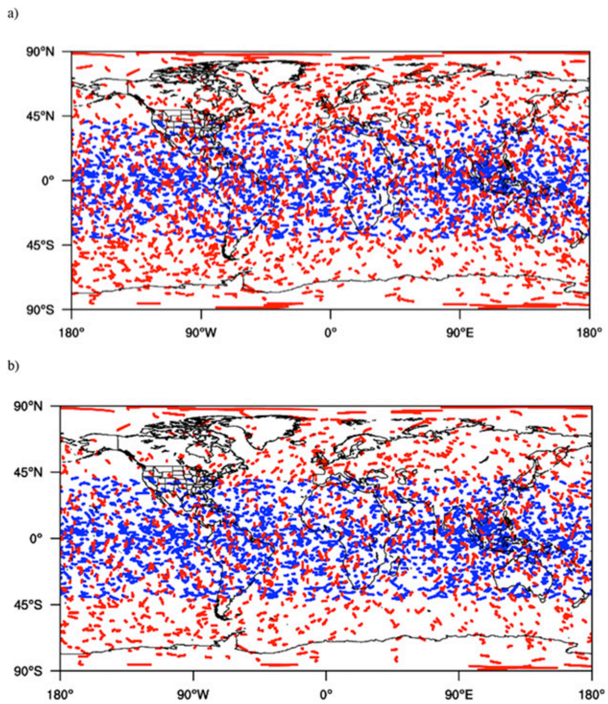


FIG. 2. Spatial distribution of the COSMIC-2 observations from equatorial (blue) and polar (red) components for (a) six receiver satellites as in COSMIC2 and (b) four receiver satellites as in COSMIC2_4PO for a 6-h assimilation time window.

(GSI) analysis at a resolution of T254 (~50 km). Eighty reduced-resolution T254L64 ensemble members were generated to estimate background error covariance via the ensemble Kalman filter. Although NCEP's 2015 operational model configuration assimilated RO bending angle profiles, our experiments used RO refractivity soundings instead. This allowed us to quantify the impact of the different RO configurations investigated here relative to the findings from Cucurull et al. (2017, 2018). Furthermore, differences in global forecast skill between the use of refractivity and bending angle profiles with real RO observations have been shown to be small (e.g., Cucurull et al. 2013). All the experiments run from 1 August to 30 September 2006. GFS produced once-daily 168-h global forecasts initialized at 0000 UTC. The first month was used for model spinup, and verification against the nature run was done for 1–30 September 2006. All forecast skill metrics are calculated with respect to the nature run.

3. Impact of COSMIC-2

a. *COSMIC-2A soundings*

Figures 3a and 3b show the anomaly correlation (AC) skill for the 500-hPa geopotential heights for the Northern Hemisphere (NH; 20°–80°N) and Southern Hemisphere (SH; 20°–80°S) extratropics, respectively, as a function of the forecast lead time. The impact of the assimilation of RO profiles in COSMIC2A is overall neutral in the NH and neutral to slightly negative in the SH (results are only statistically significant for the first 48 h). Although results for the NH are consistent with the results found in Cucurull et al. (2017), when an older OSSE configuration was used, the RO impact from COSMIC-2A in the SH is now found to be lower. (These authors found a slight positive impact from the assimilation of COSMIC-2A soundings in the SH.) This is a result of using more recent OSSE configuration and data assimilation systems, which have resulted in an improvement of the CONTROL mass field in the SH. As an example of a particular forecast length, time series of the AC at day 5 for NH and SH are shown in Figs. 4a and 4b, respectively. Differences between CONTROL and COSMIC2A are in general very small and not statistically significant through the experimental period.

Figure 5 shows global root-mean-squared (RMS) wind errors at day 3. Upper-level (200 hPa) wind errors

TABLE 1. Observations used operationally at NCEP as of 2014.

Observation type	Observation IDs	Description
Surface pressure	120, 180, 181, 182, 187	Rawinsonde, surface marine, surface land, dropsonde, surface METAR
Wind	220, 221, 223, 224, 229, 230, 231, 232, 233, 242, 243, 244, 245, 246, 250, 252, 253, 257, 258, 259, 280, 290	Rawinsonde, PIBAL, NPN wind profiler, NEXRAD, wind profiler–PIBAL decoded, aircraft, dropsonde, aircraft, JMA, EUMETSAT, NESDIS-GOES, MODIS-POES (*Aqua*), surface marine, ASCAT
Temperature	120, 130, 131, 132, 133, 180, 182	Rawinsonde, aircraft, dropsonde, aircraft, surface marine, dropsonde
Moisture	120, 132, 180, 182	Rawinsonde, dropsonde, surface marine
Radiance		*MetOp-A* (HIRS4, AMSU-A, MHS, IASI), *MetOp-B* (AMSU-A,MHS, IASI), *GOES-15* (Sounders 1–4), *Suomi NPP* (ATMS, CriS), *Aqua* (AIRS, AMSU-A), *NOAA-15* (AMSU-A), *NOAA-18* (AMSU-A, MHS), *NOAA-19* (AMSU-A, MHS), *F17* (SSMIS), *F18* (SSMIS), *Meteosat-10* (Seviri)
RO refractivity	746–751, 752–757	COSMIC-2A, COSMIC-2B

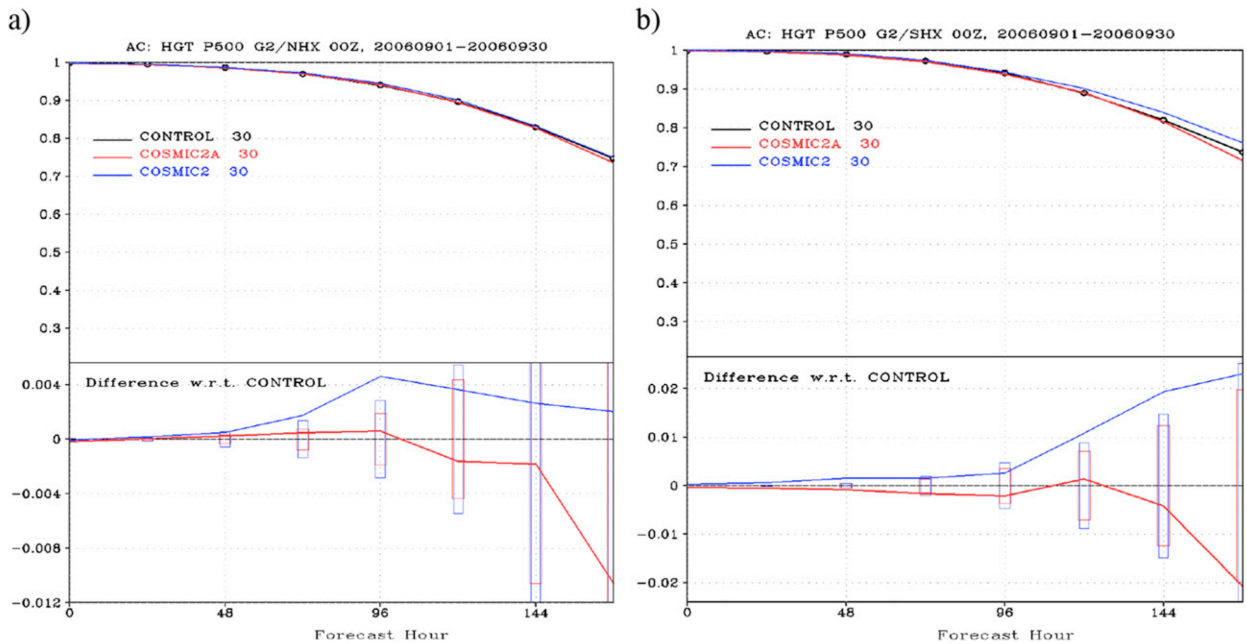


FIG. 3. Anomaly correlation score for the 500-hPa geopotential heights for CONTROL (black), COSMIC2A (red), and COSMIC2 (blue) for the (a) Northern Hemisphere and (b) Southern Hemisphere. The lower parts of each panel show differences with respect to CONTROL, with positive being an improvement. Bars show limits of statistical significance at the 95% confidence level; values outside bars are statistically significant.

improve with the assimilation of COSMIC-2A observations, in agreement with the results from Cucurull et al. (2017). As expected, the improvement of COSMIC2A over the CONTROL experiment is larger in the tropics (TR; 20°S–20°N) than in the extratropics, where the density of RO observations is lower. At day 3 (Figs. 5a,c,e), the assimilation of COSMIC-2A observations results in a $0.6\,\mathrm{m\,s^{-1}}$ reduction in RMS wind error in the TR (a significant 8.2% improvement), $0.1\,\mathrm{m\,s^{-1}}$ in the NH (1.3% improvement), and $0.1\,\mathrm{m\,s^{-1}}$ in the SH (1.8% improvement). As compared to the results from Cucurull et al. (2017), the impact of COSMIC-2A is now found to be larger in the TR, similar in the NH, and smaller in the SH. These authors found an improvement of $0.3\,\mathrm{m\,s^{-1}}$ (3.7% improvement) in the TR and of $0.4\,\mathrm{m\,s^{-1}}$ (5.1% improvement) in the SH at day 3.

In the TR, the benefits from assimilating COSMIC-2A observations at 200 hPa in COSMIC2A extend to different lead times, and differences between the COSMIC2A and CONTROL experiments are statistically significant at the 95% confidence level until day 5 (Fig. 6c). Differences between CONTROL and COSMIC2A are smaller in the SH and only statistically significant until day 3 (Fig. 6e). In the NH, differences in RMS wind error are smaller and not statistically significant except at the analysis time (Fig. 6a).

The benefits from the assimilation of COSMIC-2A profiles are smaller for the lower level (850 hPa) winds, in both magnitude and percentage. At day 3, COSMIC2A decreases RMS wind error over the CONTROL experiment by a negligible 0.1% in the NH (Fig. 5b), 1.5% in the TR (Fig. 5d), and it slightly increases the error in the SH by 0.5% (Fig. 5f). These impacts are smaller in magnitude and percentage as compared to the findings in Cucurull et al. (2017), in particular in the SH where a significant improvement of 4.7% was found. Looking at the extended forecast lead times, the impact of the assimilation of COSMIC-2A profiles is neutral in the NH (Fig. 6b), slightly positive in the TR (Fig. 6d), and marginally negative (although not statistically significant beyond the first 24 h) in the SH (Fig. 6f).

The assimilation of RO observations in COSMIC2A also results in a slight improvement of the relative humidity field (Figs. 7a–c) in the TR. The use of COSMIC-2A soundings decreases the RMS errors for most of the forecast lead times, with the largest impact found during the first 3-day forecasts (2.7% improvement at the analysis time). The impact in the NH and SH is much smaller and only during the first 48 h in the NH (0.4% improvement at the analysis time) and 24 h in the SH (0.2% improvement at the analysis time).

b. *Added benefits of COSMIC-2B soundings*

The polar component of the COSMIC-2 mission was originally planned as a constellation of six satellites

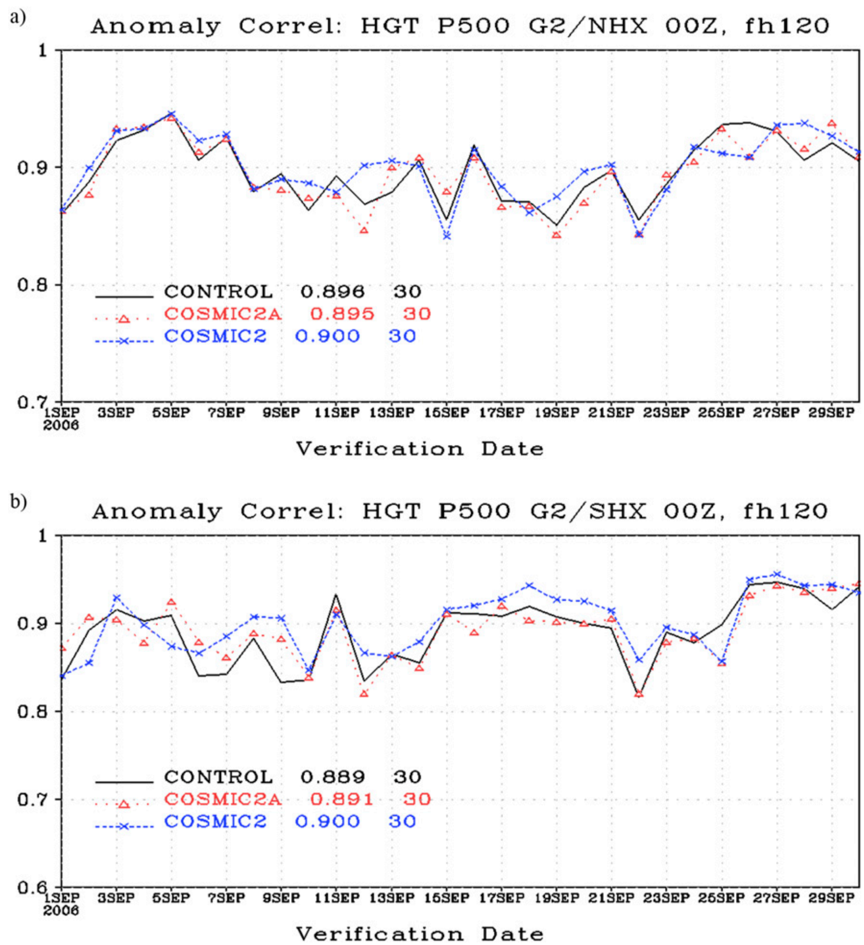


FIG. 4. The 5-day anomaly correlation score for the 500-hPa geopotential heights for CONTROL (black), COSMIC2A (red), and COSMIC2 (blue) for the (a) Northern Hemisphere and (b) Southern Hemisphere.

at 72° inclination. The impact of COSMIC-2A and COSMIC-2B combined was already investigated in Cucurull et al. (2018), and we focus here on the added benefits of COSMIC-2B only. Expanding the work from Cucurull et al. (2017), we made use of a higher resolution nonhydrostatic nature run, a state-of-the-art operational forecast model and hybrid ensemble data assimilation system, and realistic errors for the simulated observations.

When compared to COSMIC2A, it is found that the assimilation of COSMIC-2B soundings in COSMIC2 slightly improves the AC at 500 hPa in the extratropics across all the forecast lead times (Figs. 3a,b). The impact is larger in the SH, consistent with Cucurull et al. (2017). At day 5, the difference between COSMIC2 and COSMIC2A in AC at 500 hPa is 0.005 (0.5% improvement) in the NH (Fig. 4a) and 0.01 (1.0% improvement) in the SH (Fig. 4b). The assimilation of COSMIC-2B soundings also avoids a sudden drop in forecast skill found in COSMIC2A and it improves the skill over CONTROL on 12 September 2006, particularly in the NH. Since the impact of COSMIC-2A to improve the anomaly correlation score was found overall neutral in both extratropics, this result seems to indicate that a constellation of RO receiver satellites at higher inclination orbit is necessary to improve the mass field globally.

Upper-level winds are slightly improved in COSMIC2 as compared to COSMIC2A (Figs. 6a,c,e). The improvement is larger in the SH (3.7% improvement at day 3, Fig. 5e), where the impact is statistically significant for most lead times (Fig. 6e). The SH also benefits from the assimilation of COSMIC-2B observations for the lower-level winds (Fig. 6f), with an improvement of 3.2% at day 3 (Fig. 5f). Although to a lower extent, the RO impact in COSMIC2 is also positive beyond the first 24 h for the lower-level winds in the NH (Fig. 6b), with a 1% reduction of RMS wind error at day 3 (Fig. 5b). Finally, benefits from the assimilation of RO observations

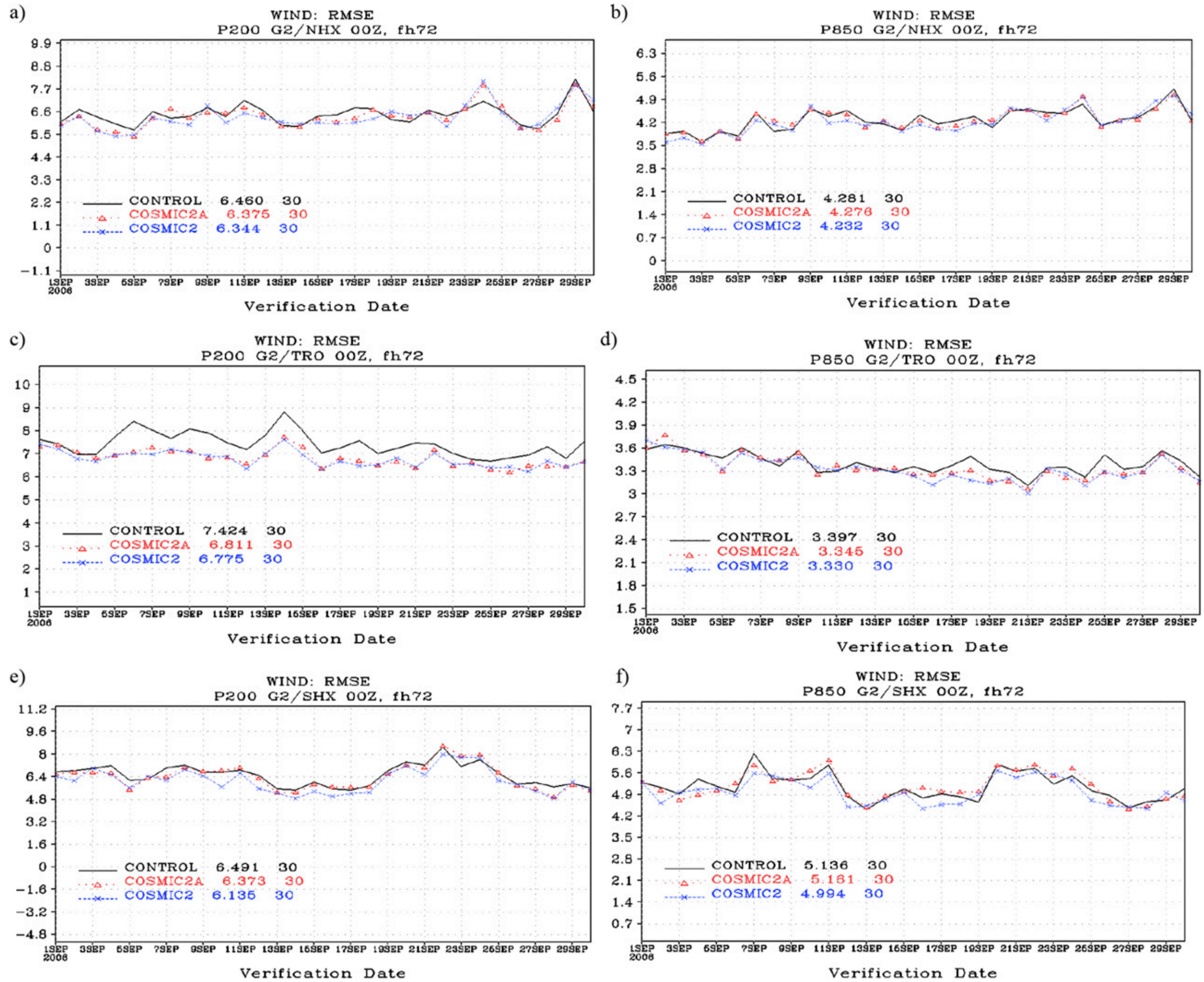


FIG. 5. (left) Upper (200 hPa) and (right) lower (850 hPa) root-mean-squared wind errors (m s^{-1}) at day 3 for the (a),(b) NH, (c),(d) TR, and (e),(f) SH for CONTROL (black), COSMIC-2A (red), and COSMIC-2 (blue).

from COSMIC-2B are also found in the moisture field, particularly in the SH (Figs. 7a–c).

4. Trade-off studies for COSMIC-2B

a. Lower number of RO receiving satellites (COSMIC2_4PO)

We removed two of the six polar satellites from the COSMIC-2B constellation to quantify the impact of reducing the number of polar RO satellite receivers from six (COSMIC2) to four (COSMIC2_4PO). The four satellites were chosen so their orbits would minimize the geographical and temporal gap in observation coverage. Accordingly, the distance between two consecutive orbital planes in COSMIC2_4PO is not larger than 60°. The number of satellites and vertical coverage for the COSMIC-2A soundings were not changed. The geographical coverage from COSMIC2_4PO is shown in Fig. 2b for a 6-h assimilation time window. When compared to the coverage of COSMIC2 (Fig. 2a), the overall RO sounding coverage is slightly reduced in the extratropics with the use of a reduced number of high-inclination satellites.

Reducing the COSMIC-2 polar constellation from six to four satellites results in a slight degradation of the AC at 500 hPa in the NH after day 3 (Fig. 8a). In the SH, the impact is overall neutral (Fig. 8b). Furthermore, the use of the RO soundings from the two additional satellites in COSMIC2 appears to avoid a drop in skill of 0.03 points at day 5 in the SH (Fig. 9b). The drop in AC at day 5 on 14 September in experiment COSMIC2_4PO in the SH also exists for other forecast lead times (not shown), pointing to an error in the COSMIC2_4PO analysis five days prior to the verification date (9 September). This

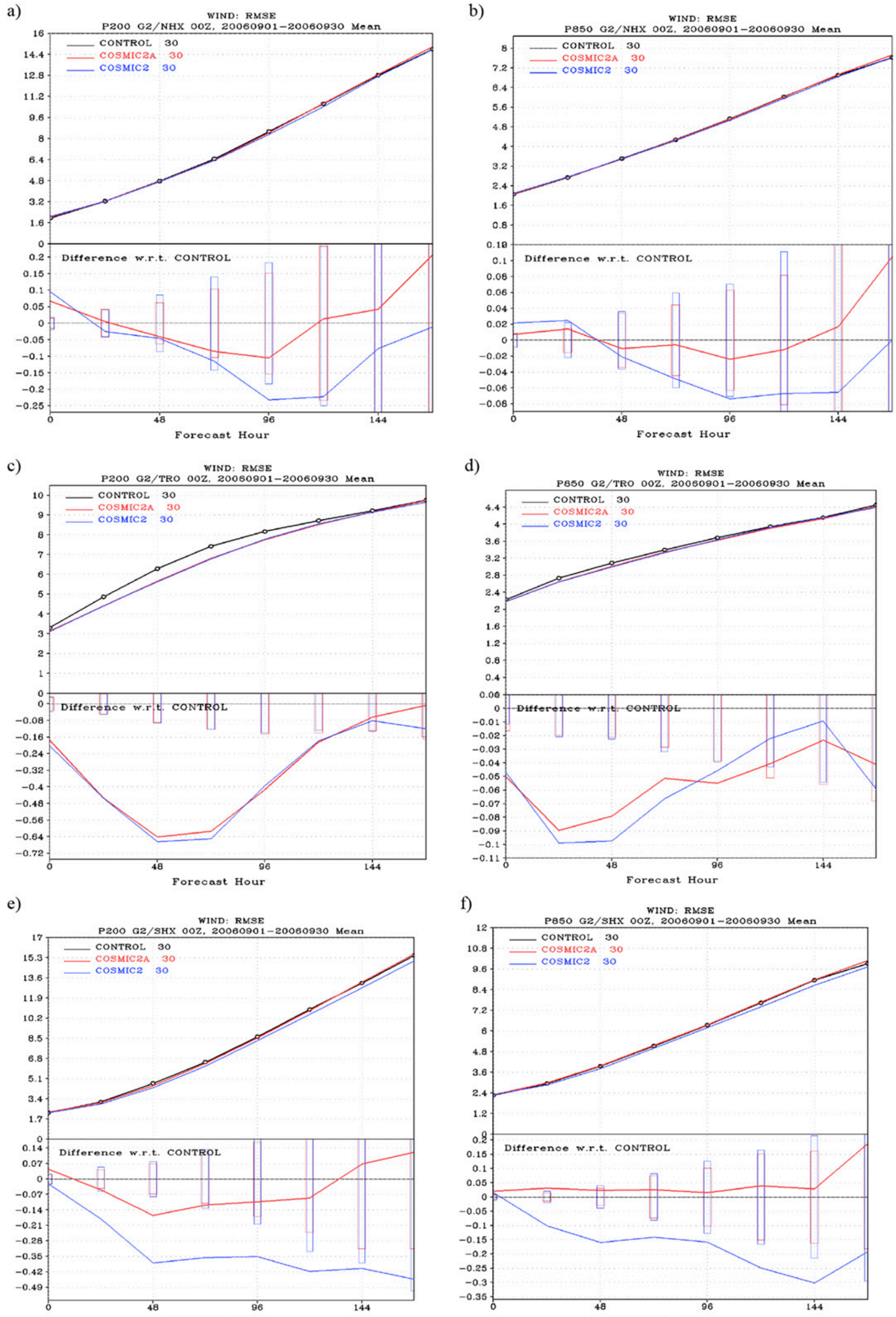
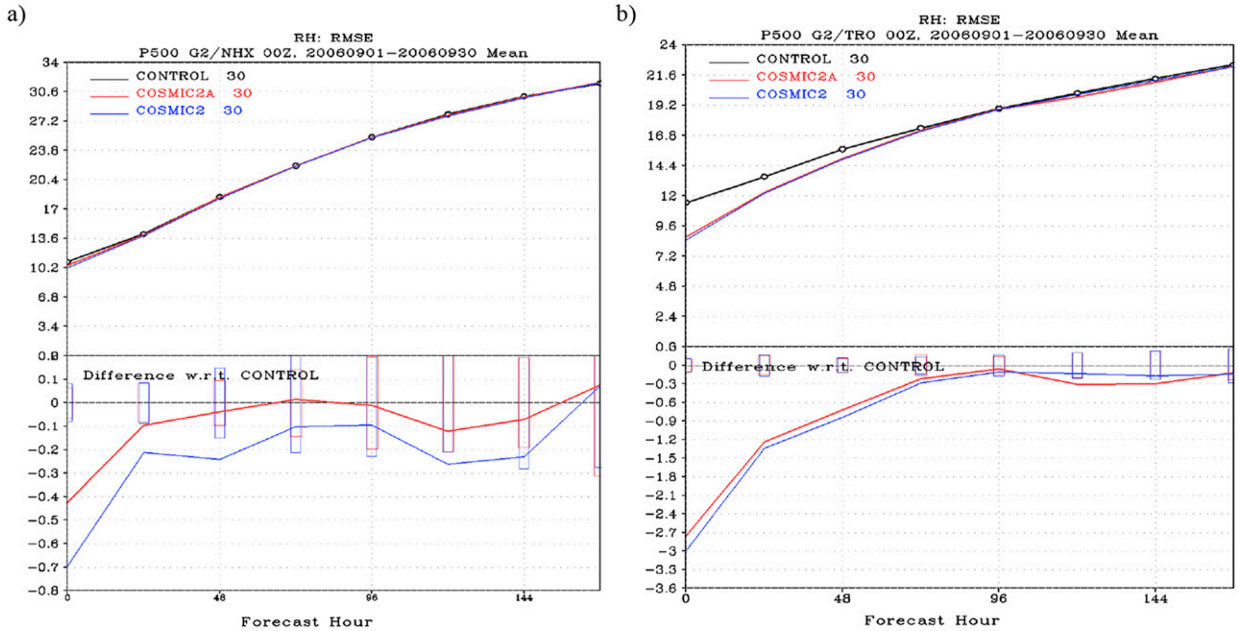


FIG. 6. (left) Upper (200 hPa) and (right) lower (850 hPa) root-mean-squared wind errors (m s^{-1}) for the (a),(b) NH, (c),(d) TR, and (e),(f) SH as a function of the forecast hour for CONTROL (black), COSMIC2A (red), and COSMIC2 (blue).



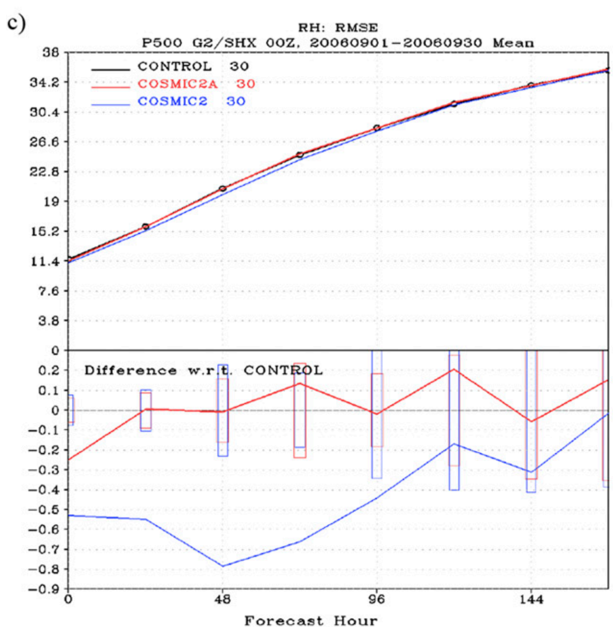


FIG. 7. The 500-hPa root-mean-squared errors for the relative humidity field (percentage) for (a) NH, (b) TR, and (c) SH as a function of the forecast hour for CONTROL (black), COSMIC2A (red), and COSMIC2 (blue).

error might have growth with the extended forecasts. Figures 10a and 10b show the differences in the 500-hPa geopotential heights between COSMIC2_4PO and COSMIC2 at the analysis time (0000 UTC 9 September) and 5-day forecasts (0000 UTC 14 September), respectively. The location of the extra RO soundings available in COSMIC2 but not in COSMIC2_4PO are shown as red dots at the analysis time (Fig. 10a). These extra soundings sample areas of larger differences between both analyses in the SH (e.g., the region extending between 50°–80°S and 0°–60°E), and which correspond to areas where the analysis error is larger in COSMIC2_4PO than in COSMIC2. After 5 days, these forecasts differences grow, covering a larger horizontal area (Fig. 10b). In addition, it is possible that other non-RO observations that might have been affected differently by the quality control procedures in experiments COSMIC2 and COSMIC2_4PO might have further contributed to the differences in AC skill.

In general, experiment COSMIC2_4PO provides similar or slightly larger upper-level RMS wind errors than COSMIC2 in the extratropics (Figs. 11a,e) and slightly lower errors in the TR (Fig. 11c). The use of fewer satellite

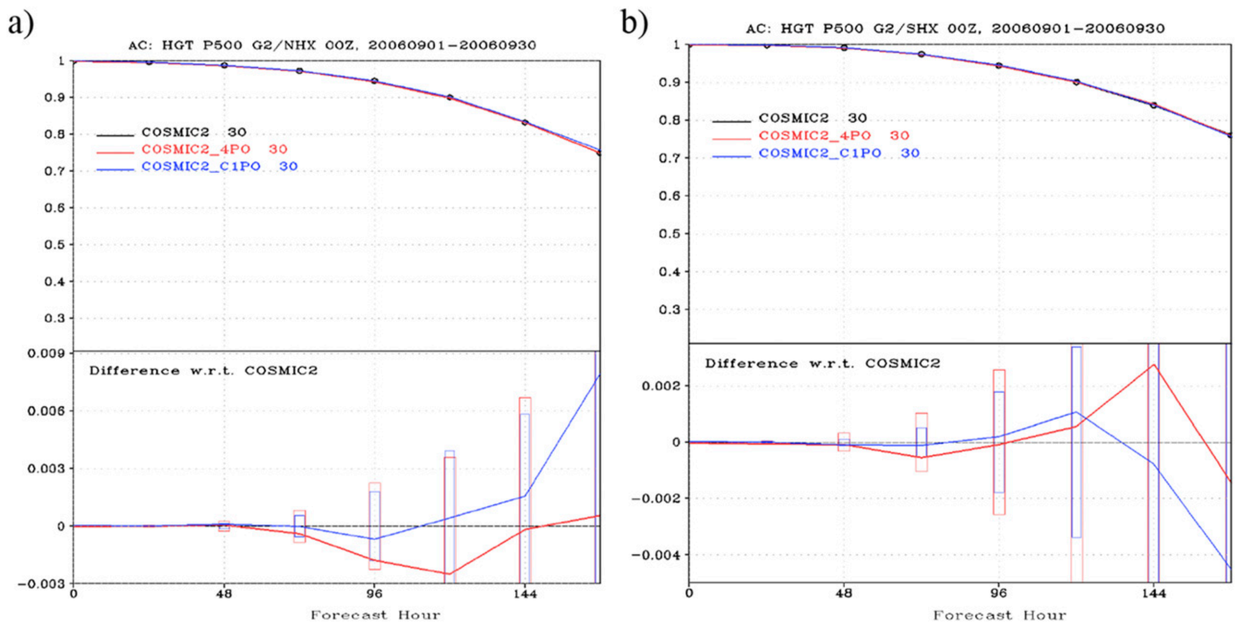


FIG. 8. Anomaly correlation score for the 500-hPa geopotential heights for COSMIC2 (black), COSMIC2_4PO (red), and COSMIC2_C1PO (blue) for the (a) Northern Hemisphere and (b) Southern Hemisphere. The lower parts of each panel show differences with respect to COSMIC2, with positive being an improvement. Bars show limits of statistical significance at the 95% confidence level; values outside bars are statistically significant.

receivers tends to slightly degrade the lower-level RMS wind error in the extratropics (Figs. 11b,f) and the impact is overall neutral in the TR (Fig. 11d). Overall, differences in wind errors are not statistically significant. Finally, the use of four instead of six polar RO receiver satellites has an overall little impact on the moisture field (Figs. 12a–c).

b. COSMIC-level of accuracy for RO receiving satellites (COSMIC2_C1PO)

Current COSMIC levels of penetration into the lower troposphere were used in COSMIC2_C1PO to evaluate the impact of lower vertical coverage (COSMIC-level) for the polar component, as compared to the expected improved penetration in the lower atmosphere with COSMIC-2. As in the previous section, the vertical coverage for the COSMIC-2A soundings was not changed.

The impact of the lower level of accuracy for COSMIC-2B is neutral in terms of 500-hPa AC for both NH and SH (Figs. 8a,b), as differences between COSMIC2 and COSMIC2_C1PO are not statistically significant. Furthermore, the drop in skill found in COSMIC2_4PO on 14 September in the SH does not exist in COSMIC2_C1PO (Fig. 9b), confirming that the vertical coverage in COSMIC2_C1PO is good enough to prevent the error in geopotential heights found in the COSMIC2_4PO analysis on 9 September. Differences between COSMIC2 and COSMIC2_C1PO analyses at 0000 UTC 9 September are shown in Fig. 10c. The figure also depicts the RO observations available in COSMIC2 but not in COSMIC2_C1PO due to the deeper penetration in the lower atmosphere expected in COSMIC-2 due to an improved RO receiver and higher antenna gain. The difference between the level of penetration in the lower troposphere between COSMIC-2 and COSMIC soundings is expected to be larger in the TR (Cucurull et al. 2018). Therefore, the number of additional low-level observations in COSMIC2, shown as red dots in Fig. 10c, is larger in the TR than in the extratropics, and this difference is negligible over the areas where the larger differences in analyses between COSMIC2 and COSMIC2_4PO were found (Fig. 10a). As a result, differences in 5-day forecast 500-hPa geopotential heights are also smaller (Fig. 10d), preventing the drop in AC skill found in COSMIC2_4PO.

COSMIC2_C1PO upper-level RMS wind errors are similar to COSMIC2 errors in the NH, and lower than COSMIC2_4PO errors. Wind errors slightly improve in COSMIC2_C1PO over COSMIC2 (and over COSMIC2_4PO) for other latitude bands, in particular in the TR, where results are statistically significant after day 2 (Fig. 11c). Although the impact is overall neutral for the lower-level winds in the extratropics (with a slight improvement in COSMIC2_C1PO in the NH), RMS errors decrease in COSMIC2_C1PO as compared to COSMIC2 and COSMIC2_4PO in the TR.

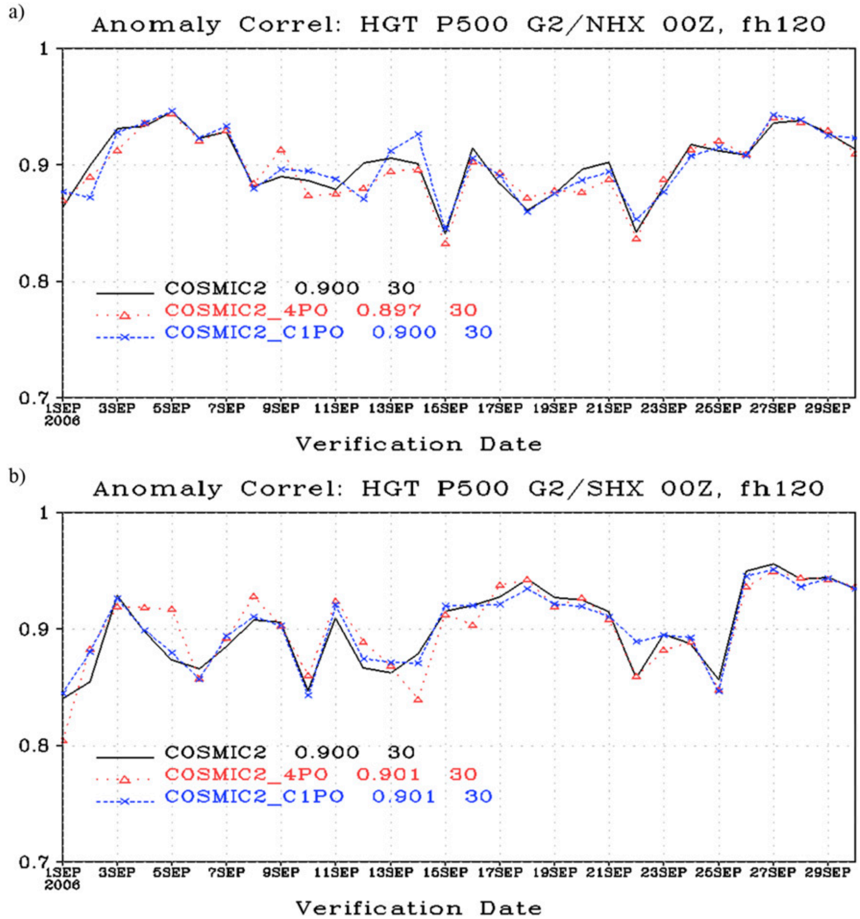


FIG. 9. The 5-day anomaly correlation score for the 500-hPa geopotential heights for COSMIC2 (black), COSMIC2_4PO (red), and COSMIC2_C1PO (blue) for the (a) Northern Hemisphere and (b) Southern Hemisphere.

Differences in RMS relative humidity errors between COSMIC2_C1PO and COSMIC2 at 500 hPa are overall small and not statistically significant (Figs. 12a–c). At lower levels, where the levels of penetration into the lower troposphere are most different, differences in moisture also appear to be small and not statistically significant (not shown).

5. Conclusions

This study is an extension of the work that NOAA conducted on radio occultations in support of H.R. 353, the "Weather Research and Forecasting Innovation Act of 2017" (Public Law 115–25). Results from previous OSSE studies with RO observations have been extended to evaluate the impact of the first launch of the initially proposed COSMIC-2 constellation (equatorial component), as well as the impacts of alternatives for the polar component. Experiments used a newly developed global OSSE system that includes a higher resolution nonhydrostatic nature run, a state-of-the-art operational forecast model and hybrid ensemble data assimilation system, and realistic simulated observation errors.

The largest benefit from the assimilation of COSMIC-2A, with denser equatorial coverage, is to improve tropical winds. An improvement in relative humidity in the tropics is also found during the first 72 h. The impact of COSMIC-2A observations is found to be overall neutral in the extratropics for the mass field, reducing the benefits found in previous studies in the SH where a simplified OSSE configuration was used. When soundings from the high-inclination orbit are assimilated in addition to COSMIC-2A, small positive benefits are found globally. This seems to confirm that a high-inclination orbit constellation of RO receiving satellites is necessary to improve weather forecast skill globally. The benefits from the polar component of COSMIC-2 are more significant in the SH.

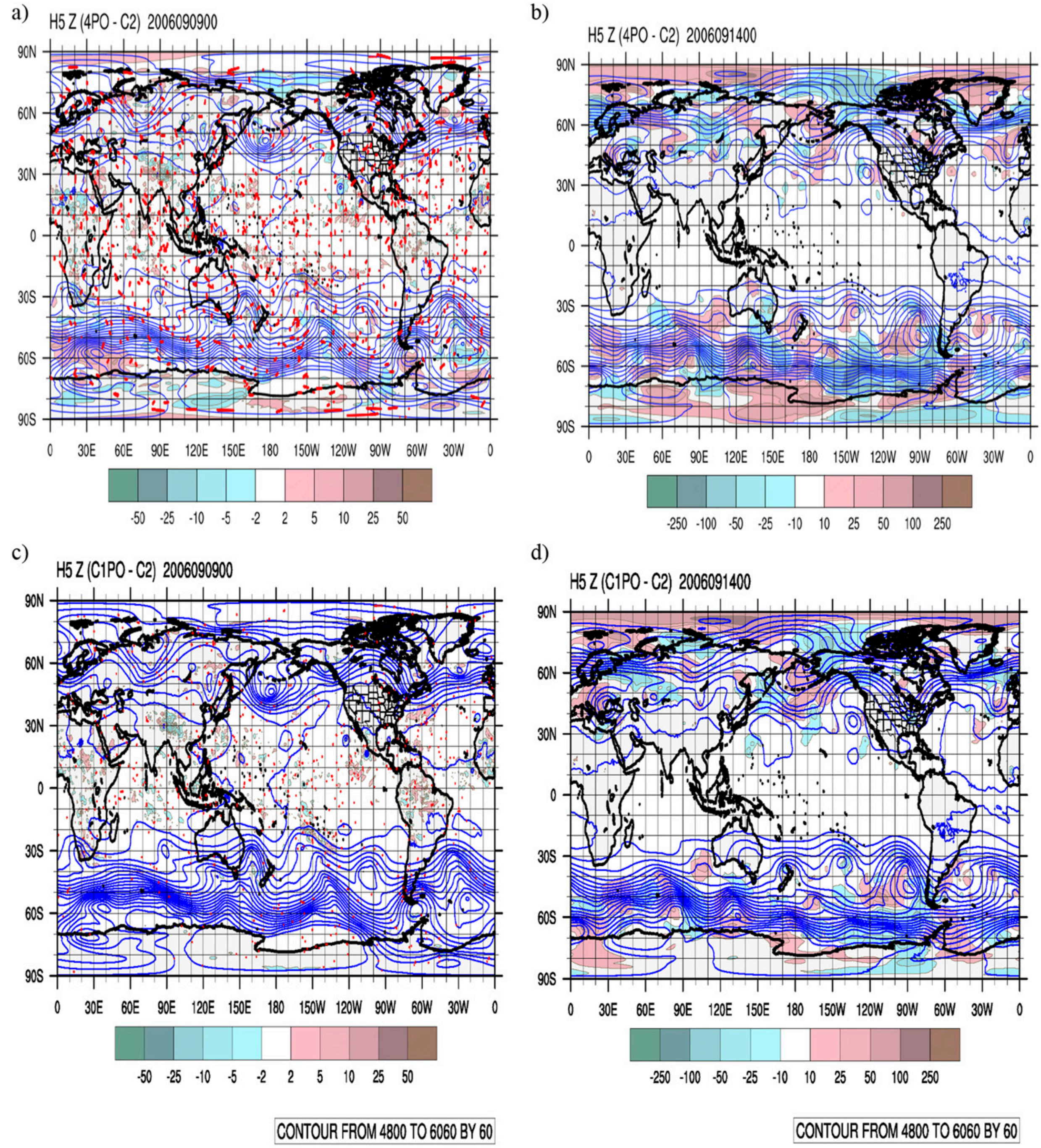


FIG. 10. Differences in 500-hPa geopotential heights between (a) COSMIC2_4PO and COSMIC2 analysis on 9 Sep 2006; (b) COSMIC2_4PO and COSMIC2 5-day forecasts valid on 14 Sep 2006; (c) COSMIC2_C1PO and COSMIC2 analysis on 9 Sep 2006; and (d) COSMIC2_C1PO and COSMIC2 5-day forecasts valid on 14 Sep 2006. In the left panels, the red dots indicate the additional observations that are available in COSMIC2 vs the other experiments. In all panels, blue lines show the geopotential heights for COSMIC2 in meters.

When alternatives to COSMIC-2B were analyzed, it was found that the largest impact from reducing COSMIC-2B from six to four satellites was to slightly degrade the forecasts of the mass and wind fields in the NH. Furthermore, the additional RO soundings in the six-satellite constellation alleviated a reduction in skill identified in SH during the experimental period. The impact of degrading COSMIC-2B to COSMIC level of accuracy on weather forecast skill is neutral in the extratropics.

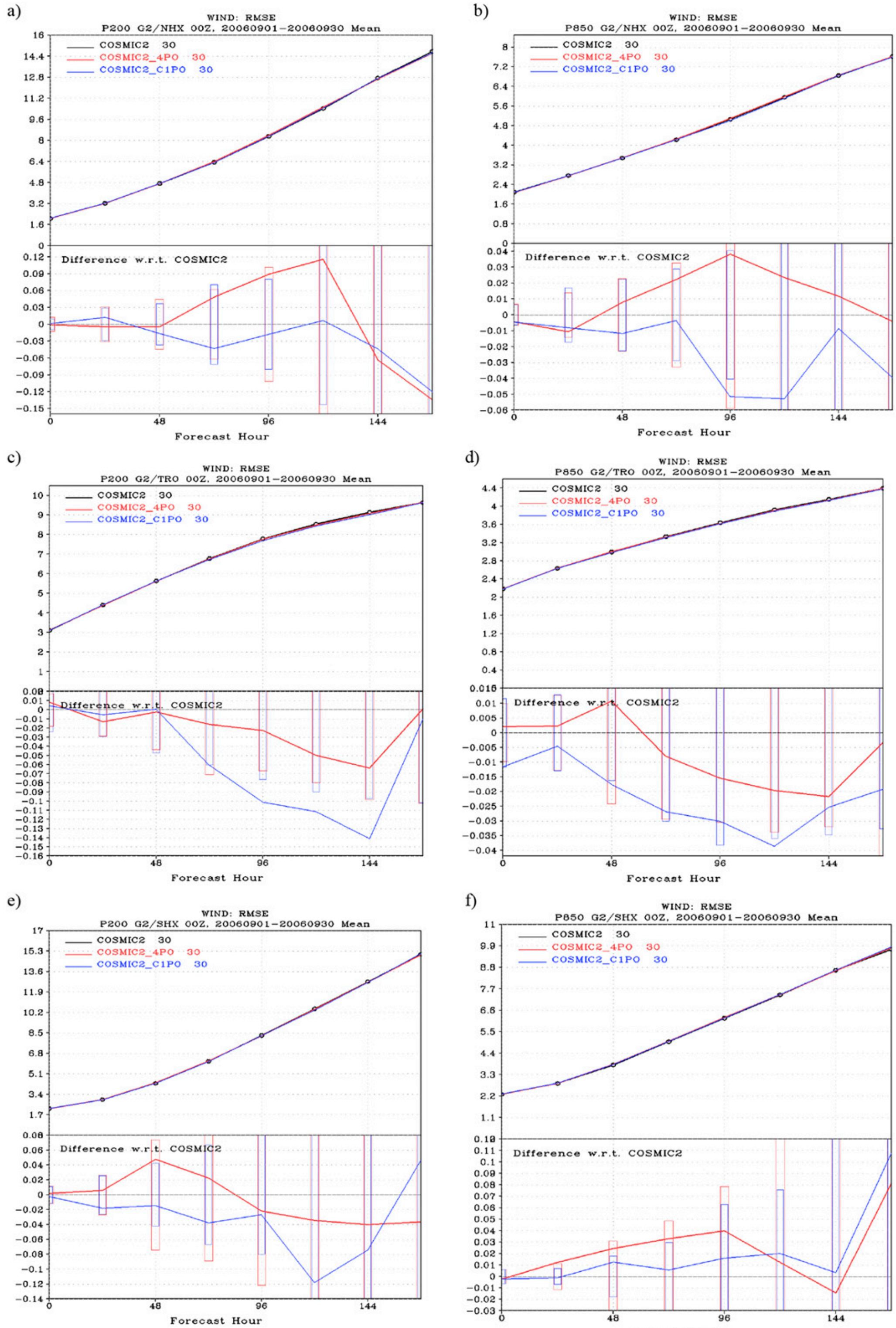


FIG. 11. (left) Upper (200 hPa) and (right) lower (850 hPa) root-mean-squared wind errors (m s^{-1}) for the (a),(b) NH, (c),(d) TR, and (e),(f) SH as a function of the forecast hour for COSMIC2 (black), COSMIC2_4PO (red), and COSMIC2_C1PO (blue).

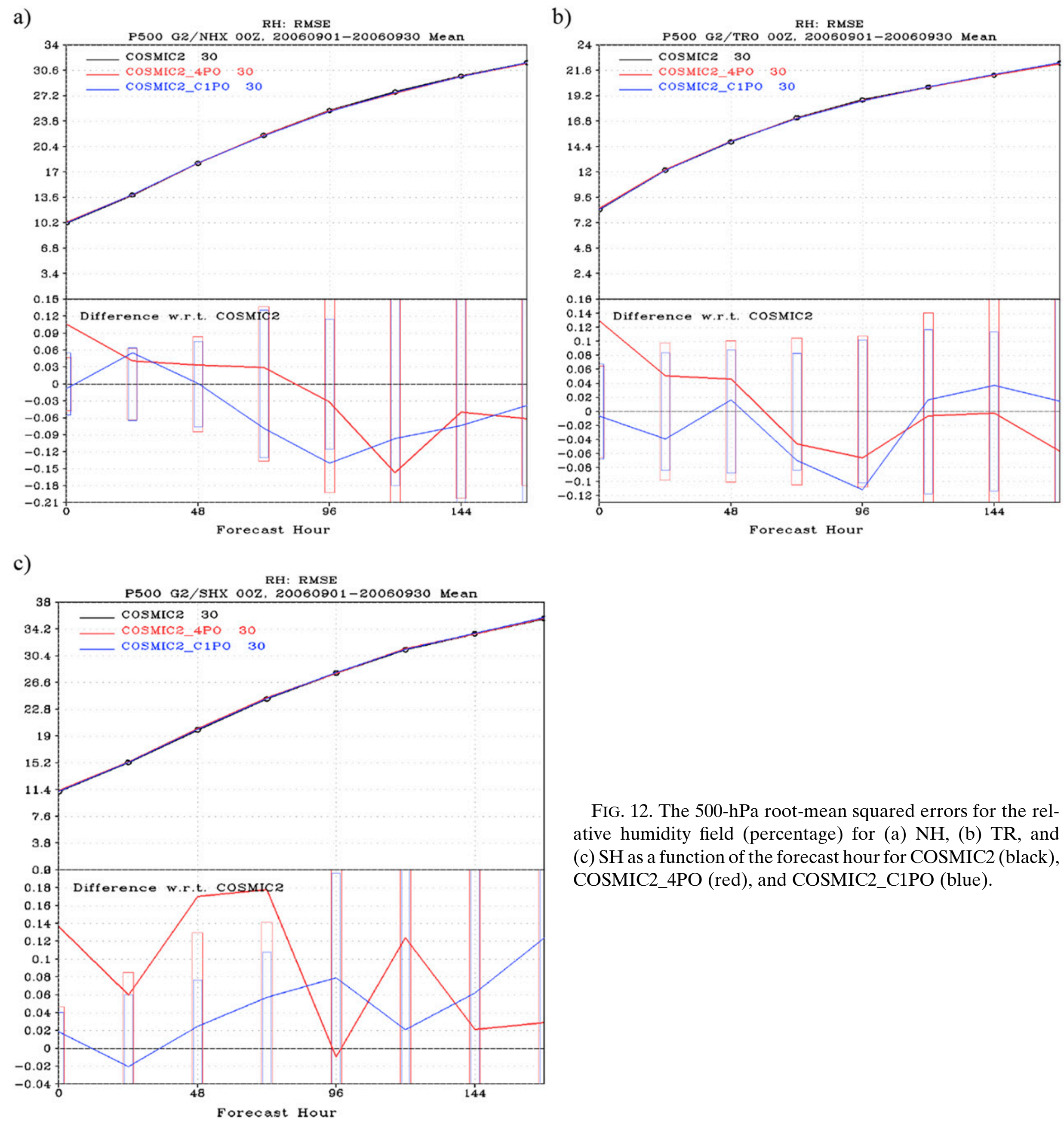


FIG. 12. The 500-hPa root-mean squared errors for the relative humidity field (percentage) for (a) NH, (b) TR, and (c) SH as a function of the forecast hour for COSMIC2 (black), COSMIC2_4PO (red), and COSMIC2_C1PO (blue).

With current data assimilation algorithms and model resolution, observation coverage appears to have a larger impact than instrument accuracy (in terms of vertical coverage) when RO observations are evaluated. However, the lower number of polar satellites with higher instrument accuracy were selected from the existing satellites so their orbits would minimize the geographical and temporal gap in observation coverage. Ideally, each of the polar satellites would be in different planes equally spaced. The use of the same methodology in the simulation and assimilation of the observations and the assumption that observation errors are uncorrelated also contribute to the limitations of the study. As the OSSE system continues to improve, we are repeating some of the experiments with RO and other observing systems. Furthermore, additional and longer experimental periods should be evaluated. The short one-month time period investigated here might have likely contributed to the lack of statistical significance in some of the results. Additional studies might quantify the impact of the different RO constellations on high-impact weather events, including hurricanes, and on space weather applications.

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