Assessment of Accuracy of COSMIC and KOMPSAT Radio Occultation Temperature and Pressure

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Abstract. Radio Occultation is a technique used by orbiting satellites to measure planetary atmosphere properties like temperature, pressure, and water vapor. The aim of this study is to assess the radio occultation temperature and pressure profiles from the Constellation Observing System for Meteorology, Ionosphere and Climate 2 (COSMIC-2) and Korean Multi-purpose Satellite 5 (KOMPSAT-5) using data from collocated radiosonde stations over the Philippines. Their deviations are analyzed using their mean and standard deviations. COSMIC-2 and KOMPSAT-5 temperature and pressure have good agreement with radiosondes in the stratosphere. From January to April of 2020, COSMIC-2 temperature standard deviation peaks with 0.072 K at 24.6 km. COSMIC-2 and KOMPSAT-5 pressure generally decreases with altitude. COSMIC-2 pressure standard deviation peaks with 0.06 hPa at 15 km. KOMPSAT-5 temperature standard deviation gradually increases with altitude with observed deviation peaks with 0.6 K at ~26.5 km. KOMPSAT-5 pressure standard deviation peaks with 0.02 hPa at 15 km. Seasonal variations between KOMPSAT-5 and radiosonde are usually lower in pressure deviation compared to temperature deviation. KOMPSAT-5 temperature standard deviation peaks at 23.24 km with 0.07 K during summer. KOMPSAT-5 pressure deviation is generally larger in the autumn season with a value of ~>0.02 hPa at 15 km. The quality of these results shows potential in COSMIC and KOMPSAT as high-quality applications for weather prediction.

1 Introduction

A radiosonde is a type of weather instrument device with different sensors like a barometer and thermometer, that is attached to a weather balloon and is launched into the atmosphere. Radiosondes (RS) have been launched on a daily or twice-daily basis at stations around the globe since the 1940s. During its 1- or 2-h ascent from the ground into the stratosphere, a radiosonde transmits its measurements to a ground receiving station, and these measurements include pressure, temperature, dewpoint depression, and geopotential height [1]. The cheap costs of

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radiosonde materials make for easy construction of high accuracy measuring devices. However, radiosondes are limited to the ground-based stations, meaning they cannot record profiles that are in other coordinates, or in large bodies of water like the ocean. Radiosondes are also released from their respective stations during midnight and midday (Coordinated Universal Time or UTC). In addition, radiosondes are susceptible to weather events like storms and typhoons, and such events can affect the measuring of data by these radiosondes [2]. GNSS Radio Occultation (RO) is a remote sensing technique that allows the Earth's weather parameters to be obtained through GNSS signals received by low-earth orbit (LEO) satellites. When the radio signals pass through the atmosphere, their paths are bent by molecules and their signals are delayed. Profiles that are retrieved from these signals include refractivity, bending angle, pressure, temperature, electron density within the ionosphere and water vapor. The GNSS RO technique improves many limitations of the RS capabilities, such as a 24-h runtime and global coverage of the data, including coordinates within oceans, and reliable profiling even during major weather disturbances like storms. The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) is an example that utilizes the GNSS RO technique. COSMIC-1 is its first satellite that was launched in April of 2006 until its retirement in 2020. Starting June 2019, COSMIC-2 continued its mission to present time. The Korean Multi-purpose Satellite (KOMPSAT) is another example that makes use of the RO technique as a secondary mission.

The general aim of this study is to assess the accuracy of satellite temperature and pressure profiles, using radiosonde-based measurements in the Philippines. Specifically, this study aims to:

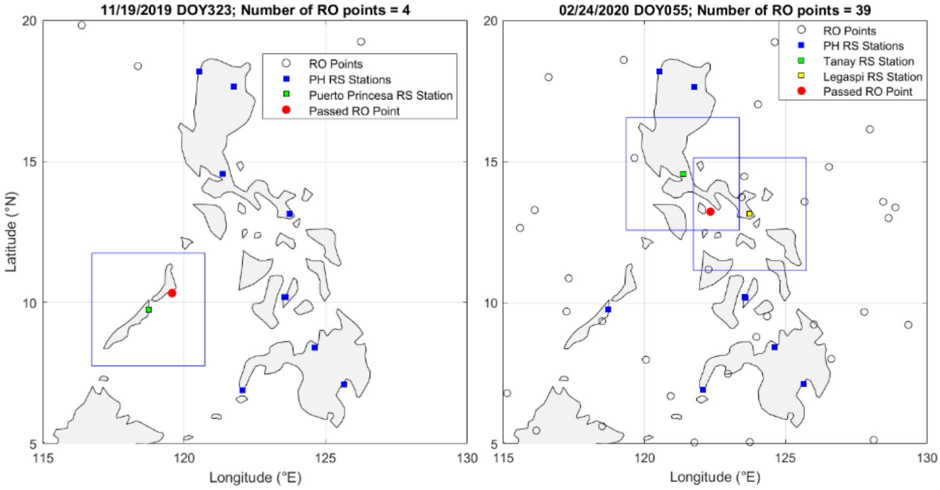
1.) Compare temperature and pressure measurements from radiosonde stations and radio occultations from COSMIC and KOMPSAT satellites.
2.) Measure the temperature and pressure deviation between RO profiles and RS profiles as a function of mean sea level altitude.
3.) Measure the seasonal variation of pressure and temperature deviation between satellite and radiosonde data.

2 Methodology

Temperature and Pressure profiles are obtained from COSMIC-2 and KOMPSAT-5 datasets using the *atmprf* product, which is the atmospheric profiling without moisture. Radiosonde datasets, on the other hand, are obtained from the University of Wyoming. The radiosonde stations used in this study are shown in Figure 1 (square markers). This study focused on the period of 2019-2020, with KOMPSAT-5 to be assessed for 2019, and COSMIC-2 to be assessed for 2020, as COSMIC-2's data for 2019 only stretches from June to December. This study used the altitude range of 15-27 km, based on the available height measurements of the radiosonde stations in the Philippines. Fan et.al (2015) noted in their study that the height range of 15-32 km is the reliable range of assessment and made use of specific parameters in the collocation of radiosonde and satellite datasets [3]. The following parameters are applied in this assessment with respect to the limitations of radiosonde stations and satellites:

- A spatial difference of ±2° are applied in both latitude and longitude coordinates.
- A temporal difference of ±2h UTC are applied between radio occultation occurrence and radiosonde launch time.
- COSMIC-2 and KOMPSAT-5 profiles should have a "bad" attribute of 0.

Using these parameters, the RO point that best satisfies them is collocated with the closest radiosonde station using a map of all RO points in the country for a specific day, as shown in Figures 1a and 1b below, and in this case, it is the Tanay, Legaspi, and Puerto Princesa radiosonde stations, marked by a green and yellow square. The stations are surrounded by a blue 2°×2° box, which contains all RO points that satisfy the spatial difference parameter. Details of the chosen RO points are shown below. In the scenario that an RO point is within the spatial grid of more than one radiosonde station, the closest station is chosen.



(a) (b)

Fig. 1. Sample map of Radio Occultations from (a) COSMIC-2 and (b) KOMPSAT-5. The large blue squares represent the 2°×2° spatial grid around the RS station, marked by a green and yellow squares.

This study determined the temperature deviation, mean and standard deviation to compare the temperature and pressure profiles obtained from RO and radiosonde measurements, as discussed by Fan et al. (2015) [3]. For the individual comparison of satellite and radiosonde profiles in each day, the equations are shown below:

The temperature/pressure deviation (ΔX) is given by:

$$\Delta X_i = X_i^S - X_i^R,\ i = 1,2,3,\dots,N \tag{1}$$

The mean deviation ($\Delta\bar{X}$) equation is given by:

$$\Delta\bar{X} = \frac{1}{N}\sum_{i=1}^{N}(X_i^S - X_i^R) \tag{2}$$

Finally, the standard deviation (SD) equation is given by:

$$SD_{\Delta X} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i^S - X_i^R)^2} \tag{3}$$

In these formulas, the superscripts S and R represent the satellite and radiosonde data, respectively. On the other hand, the subscript i represents the height serial number, with N heights pertaining to the total number of height profiles measured. Once the mean and standard deviation results are obtained, they are averaged over all heights. The statistical comparative method involves the comparison of matching data obtained from the individual method above and comparing all datasets for the entire year. The formulas used by Fan et al. (2015) are as follows:

$$\Delta\overline{X_i} = \frac{1}{M}\sum_{j=1}^{M}(X_{i,j}^S - X_{i,j}^R) \tag{4}$$

$$SD_{i,\Delta X} = \sqrt{\frac{1}{M}\sum_{j=1}^{M}(X_{i,j}^{S} - X_{i,j}^{R})^2} \tag{5}$$

In these formulas, the subscript j represents the serial number of the matching data M in all profiles. Finally, to analyze the error of the mean deviations of temperature and pressure between satellite and radiosonde profiles, the standard error of the mean (SEM) is given by:

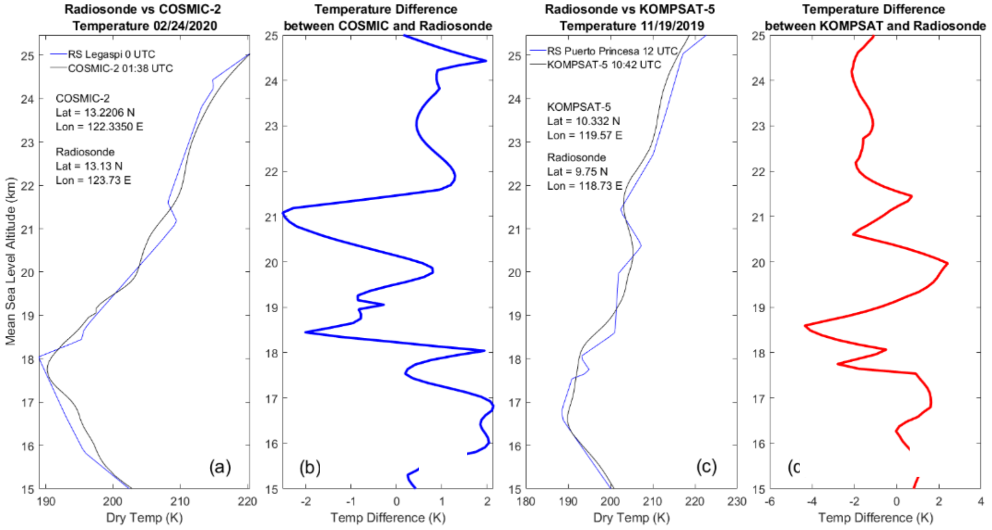
$$SEM_{i,\Delta X} = \frac{SD_{i,\Delta X}}{\sqrt{M}} \tag{6}$$

The seasonal changes of temperature and pressure on the temperate climate season are also studied where a total of 14, 14, 24, and 19 matching pairs are found during winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November), respectively. The mean deviation and standard deviation are then grouped and calculated with respect to each season.

3 Results and Discussion

3.1 Individual Temperature/Pressure Deviation between Satellite and Radiosonde

Figure 2 shows the individual comparison of vertical profiles of temperature between COSMIC-2 and interpolated radiosonde data from the Legaspi station for February 24, 2020, and between KOMPSAT-5 and interpolated radiosonde from the Puerto Princesa station for November 19, 2019. Although the Tanay station is also collocated with the RO point from COSMIC-2, the Legaspi station is much closer to the RO point. The latitude-longitude coordinates of the radiosonde station and the radio occultation occurrence are shown in the graph, which satisfy the mis-time and mis-distance parameters.

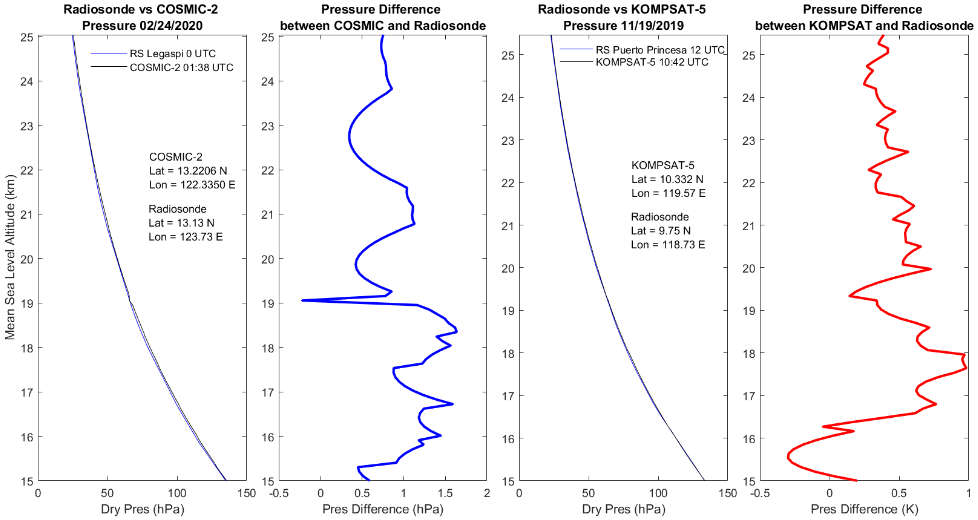


(a) (b) (c) (d)

Fig. 2. (a) Interpolated Radiosonde Temperature versus COSMIC-2 Temperature profiles, (b) Temperature difference between COSMIC and RS profiles, (c) Interpolated Radiosonde Temperature versus KOMPSAT Temperature profiles, and (d) Temperature difference between KOMPSAT and RS profiles.

As seen in Fig.2a and Fig.2c, the vertical profiles of satellite and radiosonde are close to each other at varying heights within the lower stratosphere. Based on Fig.2b and Fig.2d, the temperature difference between COSMIC and radiosonde reaches 0 K at ~18.2 km, ~21.4 km, and 25 km, while the difference between KOMPSAT-5 and radiosonde reaches ~-4 K at ~18.5 km. In addition, it is observed that the lowest points of temperature measurements in Fig.2a and Fig.2c are to be within the tropopause region. This is consistent with that of Eugenio and Macalalad (2021), showing a similar behavior where the temperature reaches its lowest at the range of 16-18 km [4]. When taking their average differences, the temperature differences are -0.5709 K, and -0.6213 K, respectively. This is due to the differences in the latitude and longitude coordinates, and the amount of mis-time. Fan et al. (2015) shows a similar behavior between COSMIC and radiosonde profiles of temperature in China in June 2-3 of 2008, having almost identical spatial distribution, with the time gap between their recorded profiles being over 90 minutes [3]. Another possible explanation is that radiosondes are susceptible to solar radiation absorbed by the ozone layer in the stratosphere. Von Rohden et al. (2022) stated that the temperature sensor of radiosondes are warmed by solar radiation, which is a main error source for daytime radiosonde temperature measurements [5]. Similar observations were found by Randel and Wu (2006), in which they found significant bias in radiosonde measurements during the daytime which is possibly caused by solar heating. In addition, the biases in radiosonde measurements may have been caused by the overestimation of radiosondes regarding the stratospheric cooling [6]. This is further proven by He et al. (2009), in which they found that warm biases in one of their radiosondes, MRZ, is caused by solar heating during the day, while another radiosonde, VIZ-B2, has a cold bias relative to COSMIC due to the solar cooling at night [7].

Meanwhile, figure 3 shows the individual comparison of vertical profiles of pressure between COSMIC-2 and interpolated radiosonde data from the Legaspi station for February 24, 2020, and between KOMPSAT-5 and interpolated radiosonde from the Puerto Princesa station for November 19, 2019. As seen in Fig.3a and Fig.3c, the vertical profiles of satellite and radiosonde are generally close to each other at all heights. Based on Fig.3b and Fig.3d, the temperature difference between COSMIC and radiosonde reaches a peak of 1.63 hPa at ~18.3 km, while the difference between KOMPSAT and radiosonde reaches a peak of 0.9 hPa at ~17.5 km. When taking their average differences, the pressure differences are 0.2550 hPa, and 0.4154 hPa, respectively. Zhang et al. (2011) yielded results that were observed to have small differences between GPS RO and radiosonde when the collocation parameter criteria is tight. However, they noted that there are insignificant differences in the results, even in the larger spatial and temporal criteria between GPS RO and radiosondes, but greater differences are still expected within the looser collocation criteria [8].

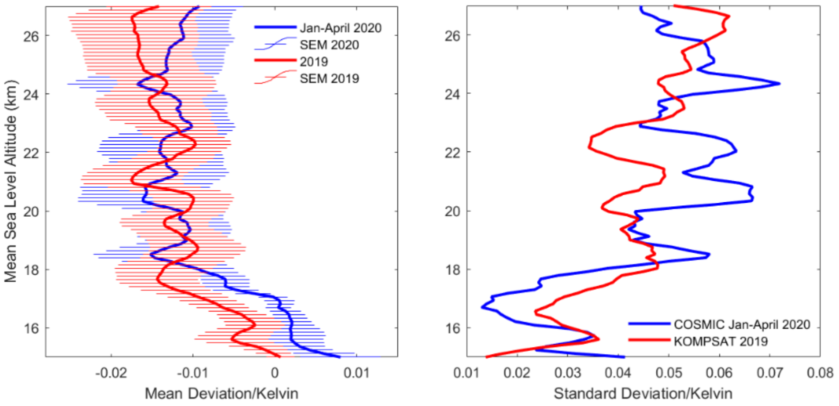


(a) (b) (c) (d)

Fig. 3. (a) Interpolated Radiosonde Pressure versus COSMIC-2 Pressure, (b) Pressure difference between COSMIC and RS profiles, (c) Interpolated Radiosonde Pressure versus KOMPSAT Pressure, and (d) Pressure difference between KOMPSAT and RS profiles.

3.2 Statistical Comparison of Temperature/Pressure Deviation between Satellite and Radiosonde

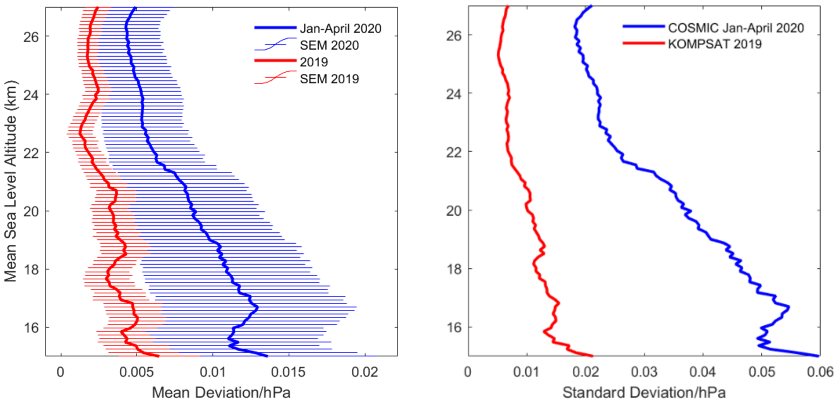
The statistical comparison between the radiosonde and COSMIC-2 temperature data, for January to April of 2020, and radiosonde and KOMPSAT-5 temperature data for 2019 is shown in figure 4. From Fig.4a, it is shown that the temperature mean deviation is generally small within the reliable altitude range, mostly within the negative range, with an average mean deviation of -0.0095 K for COSMIC-2, and an average of 0.0136 K for KOMPSAT-5. Fig.4b shows the temperature standard deviation is generally higher than the mean, with COSMIC-2 versus radiosonde standard deviation peaking at 24.3 km with ~0.07 K, and an average standard deviation of ~0.046 K. For KOMPSAT-5 during 2019, the standard deviation peaks at ~26.5 km with a value of 0.6 K, and an average of ~0.043 K for the whole year. Again, this may be due to the differences in latitude and longitude coordinates, as well as the time difference, the effects of solar radiation on the radiosonde temperature measurements during daytime, and overestimation of the radiosondes regarding the stratospheric cooling. Ho et al. (2015) compared COSMIC-2 profiles with RS-41 profiles from June to October of 2019 to assess the accuracy of COSMIC-2 temperature, and they have shown similar results in an average mean deviation of close to zero, both for day and night [9]. This shows the reliability and quality of temperature measurements from COSMIC-2 and KOMPSAT-5 within the lower stratosphere region.



(a) (b)

Fig. 4. (a) Mean deviation between satellite and radiosonde temperature, and (b) Standard deviation between satellite and radiosonde temperature. The SEM is superimposed as an error bar.

On the other hand, figure 5 shows the statistical comparison between radiosonde and satellite pressure profiles. Fig.5a shows both mean deviations generally decrease with altitude, and Fig.5b shows the standard deviations generally decrease with altitude as well. In both cases, the pressure mean deviation and standard deviation peak at 15 km. COSMIC-2 versus radiosonde pressure mean and standard deviation reaches a peak of ~0.013 hPa and ~0.059 hPa respectively, while KOMPSAT-5 versus radiosonde pressure mean and standard deviation reaches a peak of ~0.006 hPa and ~0.021 hPa, respectively. Although Ho et al. (2020) mentioned that KOMPSAT-5 is known to have a low Signal-to-Noise ratio (SNR) of 700 v/v compared to COSMIC-2 with a value of around 1200 v/v, these results show the quality and reliability of COSMIC-2 and KOMPSAT-5 pressure measurements within the lower stratosphere region as well [9]. Sun et al. (2010) found results that are consistent with those made by Zhang et al. (2011), in which the statistical differences of the results in different collocation parameters are insignificant, and it was observed that the standard deviation generally increases for every increase in the mismatch of collocation time and distance [8,10].

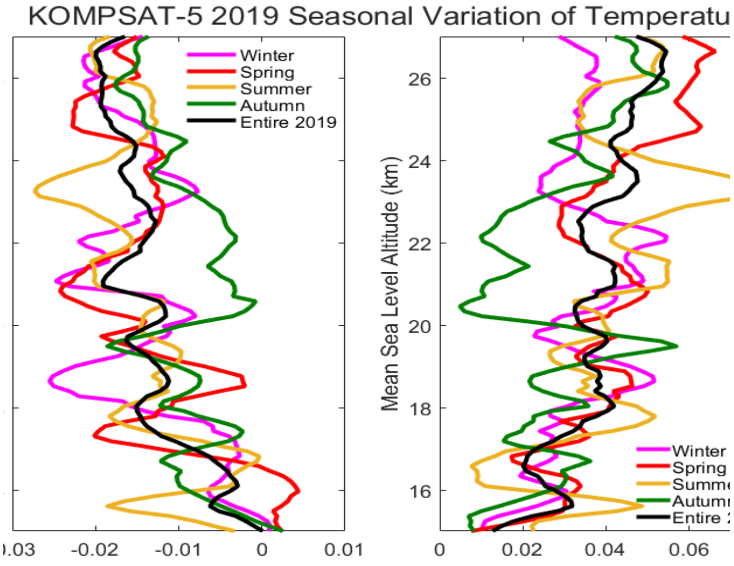


(a) (b)

Fig. 5. (a) Mean deviation between satellite and radiosonde pressure, and (b) Standard deviation between satellite and radiosonde pressure. The SEM is superimposed as an error bar.

3.3 Temperature/Pressure Deviations between KOMPSAT-5 and radiosondes during each season of 2019

The temperature deviations between KOMPSAT-5 and radiosondes per season of 2019 is shown in figure 6. As seen in figure 6a, the mean temperature deviation is generally between -0.03 and 0.005 K in all seasons of 2019, reaching almost identical deviations in varying heights. The mean temperature deviation for the whole year reaches a peak of ~-0.019 K at the altitude of ~21 km. Fig.6b shows that the standard deviation is larger during the summer season, reaching a peak of 0.077K at ~23.24 km. When taking the average temperature mean deviation during each season, it is found that the mean deviation reaches -0.0135 K during the winter season, -0.0129 K during the spring season, -0.0147 K during the summer season, and -0.0090 K during the autumn season. When taking the average temperature standard deviation during each season, it is found that the standard deviation reaches 0.0335 K during the winter season, 0.0410 K during the spring season, 0.0408 K during the summer season, and 0.0282 K during the autumn season.

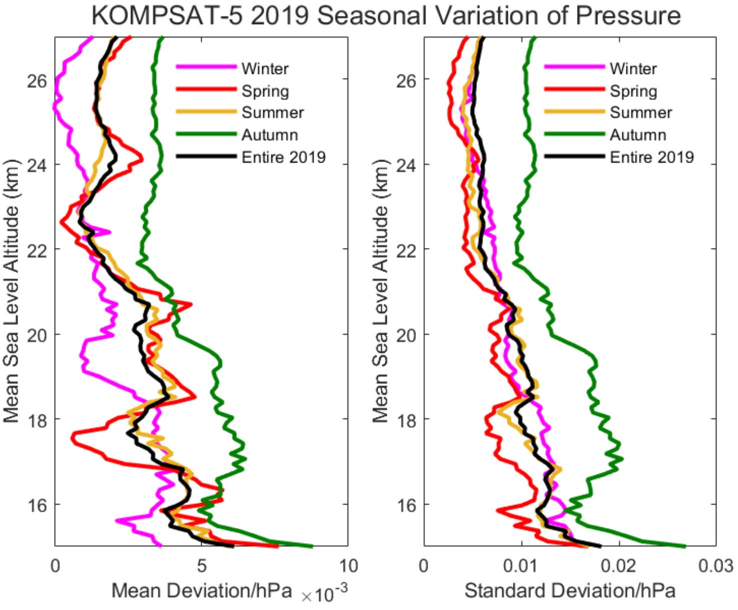


(a) (b)

Fig. 6. (a) Mean deviation, and (b) Standard deviation between KOMPSAT and Radiosonde temperature profiles in 2019, during each season.

The solar radiation during these seasons may be a contributing factor to the average deviations between KOMPSAT-5 and radiosonde profiles. In the case of the other seasons, a contributing factor to the deviations could be the distances between the RO point and the collocated RS station, as well as the time gap between recorded measurements, considering that KOMPSAT-5 only has one satellite in each day, whereas COSMIC-2 is known to have six orbiting satellites in each day, and therefore would lead to a more precise selection of matching pairs.

Figure 7 shows the differences of pressure mean deviation between KOMPSAT-5 and radiosonde during each season of 2019. Fig.7a shows the season mean deviations to be small at all altitude levels, generally less than 0.008 hPa. Fig.7b shows a similar behavior with the standard deviation being generally less than 0.03 hPa, although in both figures, Autumn usually has the highest mean and standard deviation values compared to other seasons. When taking the average pressure mean deviation during each season, it is found that the pressure mean deviation reaches 0.0017 hPa during the winter season, 0.0027 hPa during the spring season, 0.0027 hPa during the summer season, and 0.0044 hPa during the autumn season. When taking the average pressure standard deviation during each season, the standard deviation reaches 0.0086 hPa during the winter season, 0.0064 hPa during the spring season, 0.0081 hPa during the summer season, and 0.0138 hPa during the autumn season.



(a) (b)

Fig. 7. (a) Mean deviation, and (b) Standard deviation between KOMPSAT and Radiosonde temperature profiles in 2019, during each season.

The autumn season is the season with the second least amount of matching pairs during 2019, with an amount of 20 days in total. In addition, the month of September did not contain any valid data to be assessed from KOMPSAT-5, which can be explained either by the failure to satisfy the mis-time and mis-distance parameters mentioned above, as well as quality control. The months of October and November may have slightly higher differences in latitude-longitude coordinates and/or recorded times between KOMPSAT-5 and radiosonde profiles in general. Again, this is due to KOMPSAT-5 having only one satellite per mission, which usually results in only a few recorded points over the Philippines every day, or no recorded points.

4 Summary and Conclusion

Based on the observations made from the comparison between KOMPSAT-5, COSMIC-2 and radiosonde profiles during 2019 and January to April 2020 respectively, it is found that both COSMIC-2 and KOMPSAT-5 generally agree with radiosonde profiles of temperature and pressure within the lower stratosphere region of 15-27 km. Both COSMIC-2 and KOMPSAT-5 maintain a high precision that does not decrease compared to radiosondes. They both have generally negative mean deviations of temperature at heights within 15-27 km, and they have generally decreasing mean pressure deviations with height. Temperature standard deviations generally increase with altitude for both COSMIC-2 and KOMPSAT-5 with radiosondes, with an average of ~0.04 K for their respective periods. The deviations may be explained by the effects of solar radiation in the stratosphere towards the temperature sensors of the radiosondes during daytime and nighttime measurements, as well as the possible overestimation of radiosondes toward the stratospheric cooling [5-7]. The mean pressure deviations and standard deviations between satellite and radiosonde generally decrease as we go higher up the atmosphere. This means that the dry *atmprf* measurements of pressure and temperature generally agree with the radiosonde measurements of pressure within the stratosphere.

This shows confidence that COSMIC-2 and KOMPSAT-5 are both reliable application tools for weather analysis within the stratosphere region. While the troposphere region was not shown in the results of the study, the studies shown by Fan et al. (2015) and Ho et al. (2020) show that the deviations between satellite and radiosonde measurements of dry temperature are higher within their troposphere region. Given their observations, the measurements of temperature and pressure within the troposphere should come from the *wetPf2* profiles, or the atmospheric profiles with moisture, to avoid larger deviations. Chen et al. (2021) has shown temperature deviations between their RO *wetPf2* profiles from FS7 and radiosonde profiles of less than 0.5°C within the troposphere region from October 2019 to March 2020, which contrasts those from Fan et al. (2015) and Ho et al. (2020), which show larger deviations within the troposphere compared to the stratosphere [3,9,11].

During 2019, the average mean temperature deviation is high during the summer season and the average standard deviation of temperature between KOMPSAT-5 and radiosonde is high during the spring season, which may be explained by the solar radiation effects, the distances between the recorded radio occultation profiles and the collocated radiosonde stations, or the recorded time between the two profiles. The average mean pressure deviation and standard deviation between KOMPSAT-5 and radiosonde are high during the autumn season, which may be explained by the distances between the coordinates and the recorded times of the profiles. However, only 71 valid KOMPSAT-5 profiles were recorded in the Philippines during 2019, and as such, the lack of samples may have contributed to the amount of deviations between KOMPSAT-5 and radiosondes. In addition, its SNR of 700 v/v mentioned by Ho et al. (2020) may be another contributing factor to the deviations between the two datasets [9].

Since there is only one known study that implements radio occultation within the Philippine context, it is recommended that the study be further pursued by assessing other satellites that implement the radio occultation technique [4]. While radiosondes have been launched twice-daily for years, the author recommends that radiosonde data must be updated constantly, as missing data from different stations leads to difficulty with assessing variables measured by other sources.

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