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Preliminary Results of Integrated Water Vapor Estimated from Sentinel-3 Observations in Turkey

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Integrated Water Vapor; Sentinel-3; GNSS; OLCI

Abstract

Water vapor in the atmosphere is directly related to weather conditions and climate variations. Therefore, estimation of water vapor in the troposphere has become one of the hot subjects for meteorology-related studies. Advancement of the technology allowed scientists to use different methods such as Radiosonde balloons, Global Navigation Satellite System (GNSS), Ground-based Microwave Radiometers (MWR), and satellite images obtained from different missions such as Moderate Resolution Imaging Spectro-Radiometer (MODIS). Every method has its own pros and cons with respect to spatial and temporal resolution and estimation accuracy. In this study, Integrated water vapor (IWV) values obtained from Sentinel-3 Level-2 OLCI (Ocean and Land Colour Instrument) products are compared with GNSS IWV in Turkey that has a variety of climate conditions and topographical differences between regions. Results show that in July, root mean square (RMS) of Sentinel-3 IWV are at the limit of 2-4 mm at all stations compared to GNSS IWV and have over 0.7 correlation coefficient at most of the stations. In November, results are 0.5-2.5 mm RMSE and over 0.85 correlation coefficient at most of the stations with the exception of SAMN station. In Samsun city where SAMN station is located, humidity levels are off the charts due to the coastline of the Black Sea and have rainy weather throughout the year. This study proves that the IWV values obtained from Sentinel-3 are accurate enough especially in the winter season to be used if the cloud coverage allows it.

Türkiye'de Sentinel-3 Gözlemlerinden Elde Edilen Bütünleşik Su Buharı Ön Sonuçları

Anahtar kelimeler
Bütünleşik Su Buharı; Sentinel-3; GNSS; OLCI

Öz

Atmosferdeki su buharı; hava koşulları ve iklim ile doğrudan ilişkilidir. Bu nedenle troposferdeki su buharı tahmini, meteoroloji ile ilgili çalışmalar için önemli konulardan biri haline gelmiştir. Teknolojinin ilerlemesi ile birlikte atmosferdeki su buharı miktarının belirlenmesinde geleneksel radyosonda balonlarına ek olarak, Global Navigasyon Uydu Sistemleri (GNSS), Yer Tabanlı Mikrodalga Radyometreler (MWR) ve Orta Çözünürlüklü Görüntüleme Spektro-radyometresi (MODIS) gibi farklı teknikler de kullanılmaya başlamıştır. Konumsal ve zamansal çözünürlük ve tahmin doğruluğu açısından kullanılan tüm yöntemlerin kendi artıları ve eksileri bulunmaktadır. Bu çalışma kapsamında, farklı iklim koşulları ve ciddi topografik farklılıklara sahip olan Türkiye'de, Sentinel-3 Seviye-2 OLCI (Okyanus ve Kara Renk Enstrümanı) ürünlerinden ve GNSS ile elde edilen bütünleşik su buharı (IWV) değerleri karşılaştırılmıştır. Değerlendirme sonucunda Temmuz ayında, Sentinel-3 IWV değerlerinin karesel ortalama hatası (RMS), GNSS IWV ile karşılaştırıldığında tüm istasyonlarda 2-4 mm sınırında olduğu ve IWV değerlerinin SAMN hariç tüm istasyonlarda 0.7'nin üzerinde korelasyon ile uyuştuğunu göstermektedir. Ek olarak, Kasım ayında, IWV farklarının 0.5-2.5 mm RMS'e sahip olduğu ve IWV değerlerinin, SAMN istasyonu haricindeki istasyonların hepsinde 0.85'in üzerinde korelasyon katsayısı ile uyuştuğunu göstermektedir. SAMN istasyonunda oluşan bu farklı sonuçların sebebinin istasyonun bulunduğu Samsun ilinin, Karadeniz'e kıyısı olması ve yoğun yağış alması nedeniyle nem seviyelerinin normalin çok üstünde olması düşünülmektedir. Çalışma sonucunda, Sentinel-3 ile elde edilen IWV değerlerinin bulutluluk oranın izin verdiği sürece özellikle kış aylarında yeterince iyi olduğu ancak uydu yörüngesinin çalışma bölgesinden geçişinin limitli olması sonucunda zamansal çözünürlüğün düşük kaldığı ortaya çıkmıştır.

1. Introduction

Accurate estimation of the water vapor in the lower atmosphere called the troposphere is not only one of the key parameters for climate studies but also one of the challenges of satellite geodesy studies. Its inhomogeneous distribution makes it nearly impossible to be modelled and its nondispersive structure makes it ineffective to use second or third frequencies in case for GNSS (Global Navigation Satellite System) studies. Also water vapor with other atmospheric parameters such as pressure, temperature, humidity affects all satellite geodesy observations which use different frequencies that have to pass through the troposphere. This effect propagates while the signal enters the troposphere until reaching the receiver or reflecting back to the satellite, therefore it is an error source for all the remote sensing studies.

The atmospheric water vapor contained in a vertical column of the troposphere called Precipitable water vapor (PWV) (Ferrare et al. 2002). It is important to obtain precise and accurate PWV for forecasting and climate related studies as well as GNSS applications which causes 25 m deviation with usage of 0-degree elevation cut-off angle for the satellites at zenith. Understanding seasonal variations of water vapor and its estimation accuracy are the objectives of this study. For this purpose, PWV obtained from different techniques at different seasons are compared.

Although PWV obtained from radiosondes are used as reference data in PWV related studies, radiosondes have low spatial (9 stations in Turkey) and temporal (two times in a day) resolutions. Therefore, to understand hourly or real-time variations of PWV different techniques should be used. GNSS plays an important role for determining continuous and accurate ZTD (Zenith Total Delay) and PWV with the high temporal resolution (Jin and Luo 2009, Jin et al. 2011, 2011) and high accuracy (1–2 mm) (Ware et al. 2000). Also spatial resolution of PWV estimated by GNSS is related with the number of GNSS stations in the study area, therefore more GNSS stations used in the study, higher spatial resolution will be.

However, GNSS estimated PWV is also constrained by the point based information with respect to GNSS station number or the density. Therefore, to obtain area, region, nation or worldwide PWV from GNSS observations, PWV values should be interpolated using various methods. This also means that the more GNSS stations used in the estimations, the higher accuracy PWV for the specific study area. In case of Turkey, PWV can be obtained from 9 radiosonde stations or 146 CORS-TR stations (varies if GNSS stations belong to City municipalities or private GNSS stations are included). But, even this number is not enough to estimate PWV for whole country accurately and precisely. At this point other satellite geodesy techniques can show their value for the PWV estimations, such as Moderate Resolution Imaging Spectro-radiometer (MODIS) (Gurbuz and Jin 2016) and Sentinel-3. Sentinel-3 is one of the important members of the large satellite family that belongs to the European Union’s Copernicus project. This project was developed for Earth observation. In this way, our planet and its surroundings can be monitored for the benefit of all users. Sentinel-3 measures with high precision and reliability to support the topography of the sea surface, the temperature of the sea and land surface, the colour of the ocean and land surface, and ocean prediction systems. In addition, it also has applications in environmental and climate monitoring (Drinkwater and Rebhan 2007, Donlon 2012). Also, IWV obtained from Sentinel-3 is expressed in kg/m2 which is equivalent to the PWV expressed in mm. Therefore, from here on only PWV values will be mentioned in the study. In this paper, accuracy of Sentinel-3 IWV values and its seasonal variations are investigated using data from July and November months of 2019.

2. Data and Method

2.1. GNSS Observations

PWV in the troposphere, can be estimated using Zenith Wet Delay (ZWD) which is a part of the total tropospheric delay called Zenith Total Delay (ZTD) from GNSS observations. ZTD, directly computed from the propagating GNSS signal through the troposphere. However, wet delay is unpredictable and can only be estimated by subtracting hydrostatic part of the delay (ZHD), which can be computed, from the total delay at the processing phase of GNSS data. The data has been processed through GAMIT/GLOBK software to obtain tropospheric parameters (Herring et al. 2015). The coordinates of the GNSS points used are given in Table 1.

Table 1. GNSS station locations used in the evaluations.

GNSS Station	Latitude	Longitude
ADAN	37° 00′ 12″.6	35° 20′ 37″.4
ANRK	39° 53′ 14″.5	32° 45′ 30″.5
DIYB	37° 57′ 15″.9	40° 11′ 14″.9
ERZR	39° 54′ 20″.2	41° 15′ 19″.7
ISPT	37° 47′ 06″.3	30° 34′ 01″.1
ISTN	40° 59′ 27″.5	28° 49′ 53″.9
IZMI	38° 23′ 41″.3	27° 04′ 54″.6
KAYS	38° 42′ 30″.1	35° 31′ 28″.1
SAMN	41° 20′ 38″.4	36° 15′ 20″.3

The ionosphere free LC (L3) data which are the linear combination of original L1 and L2 carrier waves phase data has been utilized for the observation. FES2004 Ocean Loading model (OTL) integrated in GAMIT software has been utilized which proved to be the most successful among the other OTL models at Turkey (Lyard et al. 2006, Gurbuz and Jin 2016). Other parameters used in GNSS processing are given in Table 2.

Table 2. GNSS processing parameters.

Parameters	Used Values
Data Sampling Frequency	30 seconds
Cut-off of the Elevation Angle	10°
Earth Orientation Parameters	IERS Bulletin-B
Ionospheric Solution	Iono-free
Satellite Ephemeris	IGS Final
Antenna Phase Center Model	IGS08
Tropospheric Model	GPT2
Mapping Function (Wet-Dry)	VMF1
Ocean Tidal Loading	FES2004
Solar Radiation Pressure	Berne
Polar and Earth Tides	IERS2003

ZHD is computed with the Formula 1 given below (Jin et al. 2008, 2014).

$$ZHD = \frac{2.2768+0.0005}{1-0.00266*\cos(2\varphi)-0.00028*h} * p \qquad (1)$$

where φ latitude, h is the height from the geoid and p is the atmospheric pressure at the antenna height. The relation between PWV and ZWD is expressed as Formula 2 (Bevis et al. 1994, Jin and Luo 2009),

$$PWV = \Pi * ZWD \qquad (2)$$

where Π is a water vapor conversion factor, which can be expressed as Formula 3,

$$\Pi = \frac{10^6}{\rho R_v\left[\left(\frac{k_3}{T_m}+k_2'\right)\right]} \qquad (3)$$

where ρ is the density of liquid water R_v is the specific gas constant for water vapor, k_3, k_2' are physical constants, T_m is the mean temperature of the atmosphere expressed as Formula 4,

$$T_m = \frac{\int(e/T)dh}{\int(e/T^2)dh} \qquad (4)$$

which can be computed from surface temperature as T_m= 70.2+0.72*T_s (Bevis et al. 1992, 1994).

2.2. Sentinel-3 Observations

Sentinel-3 is designed as two identical polar orbital satellites separated by 180° to provide long-term and continuous maritime and terrestrial operational service (Donlon 2011). Sentinel-3 satellites give users an opportunity for a short temporal resolution of less than two days for the OLCI (Ocean and Land Colour Instrument) sensor (Figure 1) and less than one day for the SLSTR sensor above the equator. The satellite orbit provides a 27-day recurrence for the topographical package, with a 4-day sub-cycle (Int Ref. 1).

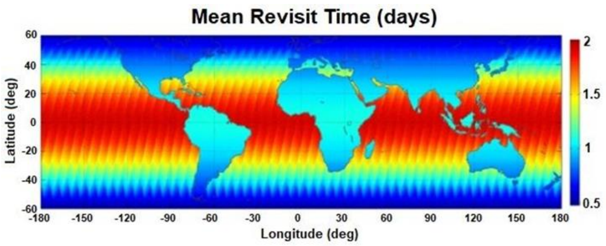

Figure 1. Global revisit time for OLCI with a two-satellite configuration (Int Ref. 2).

This mission can provide very useful data with its features, high data product availability and fast delivery times. In order to obtain this multitude of data, Sentinel-3 carries a considerable sensory compartment consisting of OLCI, SLSTR (Sea and Land Surface Temperature Instrument), SRAL (SAR Radar Altimeter) and MWR (Microwave Radiometer).

Performance evaluation of Sentinel-3 is made by comparing IWV values with GPS IWV, using Level-2 OLCI IWV product. The OLCI sensor has a very detailed spectral resolution, consisting of 21 spectral bands ranging from 400 to 1020 nm (Table 3). The spatial resolution of this sensor varies depending on whether it is flying over the mainland or the ocean. In the open sea, the spatial resolution is 1.2 km and as it approaches the coast it decreases to 300m in the mainland. (Team 2016).

Table 3. Band characteristics of OLCI sensor (Team 2016).

Band	λ centre (nm)	Width (nm)	Function
Oa01	400	15	Aerosol correction, improved water constituent retrieval
Oa02	412.5	10	Yellow substance and detrital pigments (turbidity)
Oa03-11	442.5-708.75	7.5-10	Chlorophyll absorption maximum, biogeochemistry, vegetation, sediment loading, red edge
Oa12-15	753.75-767.5	2.-7.5	O_2 absorption/clouds, vegetation, corrections
Oa16-21	778.75-1020	15-40	Atmospheric/aerosol correction, Water vapor absorption, vegetation monitoring

The Water Vapor Retrieval algorithm applied to the signals obtained from the OLCI sensors ensures the atmospheric water vapor content of the open sky pixels. As a result of this algorithm, two products are obtained: Marine and inland waters products and surface products. Level 2 products have an internal subdivision originating from the object property to be observed. For this reason, when it is aimed to observe the data of the earth, the product is presented in two maximums and reduced spatial resolutions. These are referred to as OL_2_LFR (Land Full Resolution) and OL_2_LRR (Land Reduced Resolution) (Int Ref. 3). In this study, OL_2_LFR IWV column was used and the parameters of the product are given in Table 4. Sentinel-3 data acquired from 1-31 July 2019 (62 images) and 1-30 November 2019 (60 images) for the GNSS station locations given in Table 1 is used to compare the retrieved PWV with GNSS estimated PWV. Due to images taken from two identical orbit satellites is obtained for evaluation, average values for each pixel is used. Not every Sentinel-3 image includes the corresponding locations. In Figure 2, OLCI LFR images and GNSS points of the study area are given. Therefore, an algorithm is developed to extract necessary information for specific coordinates. In case of missing data for exact coordinates due to cloud coverage, secondary data search for the range of 1 minute Euclidean distance is integrated to the algorithm. Using the algorithm IWV values can be obtained that belong approximately 1-2 km distance from the specific locations. This approach is acceptable for tropospheric studies under the assumption there are no drastic topographic changes between locations.

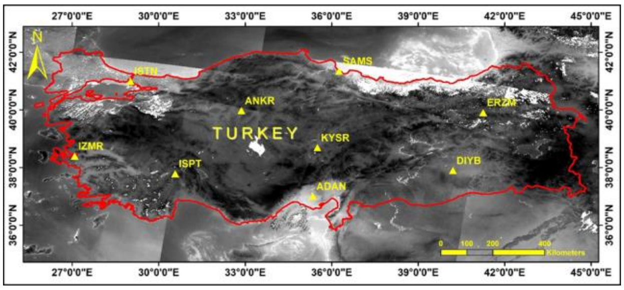

Figure 2. Study area and GNSS stations overlaid on OLCI LFR images.

Table 4. The main characteristics of IWV (Int Ref. 3).

Product Level	2
Description	Total amount of water vapor integrated over an atmosphere column and associated error estimates.
Coverage	global
Packaging	half-orbit
Latency	NRT, NTC
Units	kg/m2
Range	1-70
Sampling	300 m x 300 m (FR) / 1.2 km x 1.2 km (RR)
Frequency	1 product per orbit
Input Bands	Oa18 (885 nm), Oa19 (900 nm)

3. Results and Discussion

Performance evaluation of the PWV obtained from Sentinel-3 is made by comparing the results with GNSS PWV. Focusing different seasons of the year 2019, July and November months are chosen. Summer months in Turkey, along with high temperature, high humidity values are expected. However, in November, very low temperatures and average humidity can be seen. Apart from pure meteorological conditions, Turkey's topography is also a factor that affects PWV. Turkey is surrounded by sea from north, south and east which also significantly effects the humidity therefore the PWV. Additionally, climate varies from coastline to inland areas with the change of height. So, comparisons should be carefully made with respect to climate and topographical variations.

Results of the comparisons for July month between Sentinel-3 and GNSS estimated PWV is given at Table X4. RMSE of Sentinel-3 PWV are at the limit of 2-4 mm at all station locations compared to GNSS estimated PWV. Focusing Sentinel-3 PWV values at inland stations such as ANKR, ISPT and ERZR station evaluated best with RMSE of 2-2.7 mm with GNSS PWV (Table X4). The correlation coefficients of 8 stations are 0.7 or higher except for SAMN station with 0.48 correlation that is near the coastline of the Black Sea. Similar to Gurbuz and Jin (2016), the inland stations have lower RMSE, this shows that they agree well with GNSS estimated PWV. While topographic differences affect the climate of the region, RMSE of PWV estimation of Sentinel-3 should be further inspected whether the RMSE values only related with the topographic differences.

Results of the comparisons for November month between Sentinel-3 and GNSS estimated PWV is also given at Table 5. RMSE of Sentinel-3 PWV are at the limit of 0.5-2.5 mm at all stations when compared to GNSS estimated PWV. Sentinel-3 PWV values at inland stations such as ANKR, ISPT and ERZR station evaluated best with RMSE of 1 mm with GNSS PWV (Table 5). The correlation coefficients of 8 stations are close to 0.9 except for SAMN station that has the same low correlation coefficient in July. The location that has the worst performance is SAMN. This related with both topographical and climate conditions. SAMN station is located at Samsun City that has coastline to Black Sea and has a very humid climate which can rain all year along. Other stations near coastline are also has high RMSE value and low correlation coefficient.

Table 5. July and November evaluation results.

Stations	July				November			
	RMS	Min	Max	Corr.	RMS	Min	Max	Corr.
ADAN	3.05	0.02	13.10	0.92	1.84	0.94	6.80	0.94
ANRK	2.06	-4.20	4.95	0.92	1.88	-3.69	6.01	0.88
DIYB	2.28	1.27	10.06	0.78	1.24	-1.65	3.71	0.89
ERZR	2.79	-4.53	6.21	0.85	0.34	-0.49	0.90	0.99
ISPT	2.56	-3.77	8.49	0.81	0.87	-1.53	2.36	0.97
ISTN	2.92	0.20	10.26	0.70	2.47	-4.41	8.31	0.92
IZMI	3.64	-7.93	9.99	0.77	2.64	-3.42	10.55	0.86
KAYS	2.64	-3.88	6.91	0.82	0.72	-0.46	2.24	0.98
SAMN	3.92	-5.92	9.73	0.48	3.26	-1.88	10.01	0.66

As an example view to monthly variations of PWV, Figure 3 shows difference of PWV at ERZR station location for July and November months. Although there are couple missing data due to cloud coverage of the area, 95% data at July and 80% data at November is used in the evaluations. Figure 3 shows that, PWV values retrieved from Sentinel-3 is highly consisted with GNSS estimated PWV values at November. In July however, some deviations could be seen both positive and negative direction at the time series. This behaviour is seen at all the station locations that used in this study which proved that there is no systematic variation between Sentinel-3 PWV and GNSS PWV for the evaluated period of time. In the Figure 3, m GNSS PWV and m Sentinel-3 PWV represents the estimation errors of actual PWV at the processing.

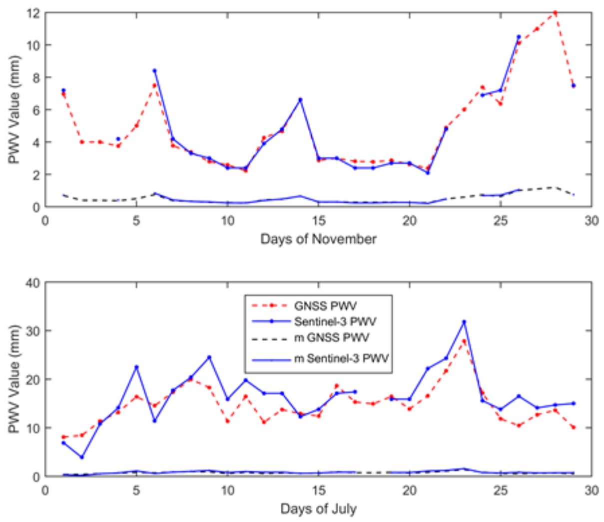

Figure 3. PWV differences for November and July 2019 for ERZR station.

In Figure 4, Sentinel-3 PWV interpolated from more than 12 million pixel values and GNSS PWV interpolated from 9 GNSS stations. It can be seen that Sentinel-3 PWV interpolation map is much more detailed under the assumption that there is no cloud coverage for the whole study area and PWV estimation accuracy of Sentinel-3 is on par with GNSS as seen at this study.

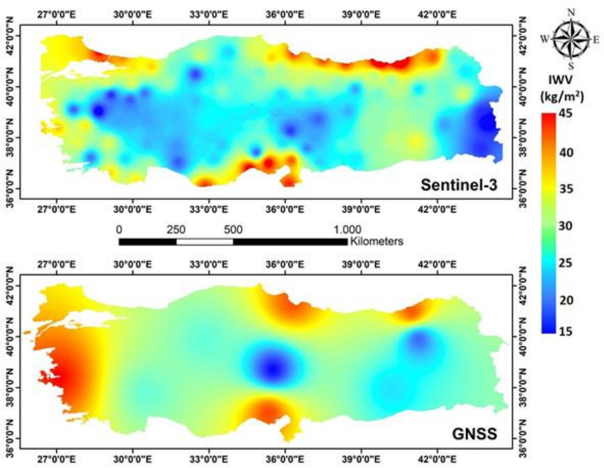

Figure 4. PWV interpolation maps of Sentinel-3 PWV and GNSS PWV at 16 June 2019.

4. Conclusions

In this study, the seasonal behaviours and variations of PWV obtained from Sentinel-3 over Turkey are inspected. PWV obtained from GNSS, Sentinel-3, are compared. Sentinel-3 PWV performance is evaluated for the first time using GNSS estimated PWV at Turkey. Even though previous studies such as Gurbuz and Jin (2017) evaluated MODIS PWV over Turkey, performance of MODIS evaluated as average. However, Sentinel-3 estimated PWV performance is very close to GNSS results especially in the winter period if the PWV value can be retrieved due to cloud coverage. While, missing data due to cloud coverage was 5% for July month, for November was 20%. Additionally, over Turkey only one pair image of Sentinel-3 can be retrieved which is generally around 08:00 UTC on daily basis.

Even though daily data from Sentinel-3 is limited and can be obstructed by the cloud coverage, results show that Sentinel-3 PWV performance is better than its peers such as MODIS PWV (Gurbuz and Jin 2017). Results show that in July, RMSE of Sentinel-3 PWV are at the limit of 2-4 mm at all stations compared to GNSS PWV and have over 0.7 correlation coefficient at most of the stations which is expected due to climate and topographic variations. Winter results are much better with 0.5-2.5 mm RMSE and over 0.9 correlation coefficient at most of the stations with the exception of SAMN station. In Samsun city which is SAMN station is located, humidity levels are off the charts due to the location of the city that has coastline to the Black Sea and have rainy weather throughout the year. In addition to SAMN station, ISTN (Istanbul) and IZMI (Izmir) stations also have relatively high RMSE which supports the idea of being close to sea affects the humidity level and therefore the PWV values. This differences for all the stations can be explained by the fact that in summer temperature and humidity levels are higher than the other periods. Evaluations show that PWV values at inland stations have lower RMSE values with higher correlations that highly related with the climate differences and station locations. Also, in summer period even though positive and negative deviations are seen which are not systematic, therefore one should evaluate more data to see if these behaviours could be modelled.

Performance of PWV estimated from different techniques have their short comings. As such GNSS estimated PWV is point based and require dense GNSS network, radiosonde balloon used as reference data in many studies but has low spatial and temporal resolution. Additionally, space-borne sensors like MODIS estimate PWV using optic images that is drastically affected by weather conditions and have low temporal resolution. However aforementioned techniques have their strong sides. GNSS estimates the PWV with very high temporal resolution that PWV for every epoch of the observation period, radiosonde balloon computes PWV from actual atmospheric parameters which is why in scientific studies PWV computed from radiosonde observations are used as reference data. For space-borne observations PWV is generally low accuracy when compared to GNSS but data itself have good spatial resolution and area coverage.

This study proves that the PWV values obtained from Sentinel-3 are accurate enough to be used in climate studies and might be comparable with GNSS estimated PWV especially November if the cloud coverage allows it. Additionally, this study investigated PWV values at 9 points specifically to compare the results with GNSS observations. However, with the success of Sentinel-3 PWV values at this study, authors suggest that Sentinel-3 PWV values could be used directly at other locations apart from aforementioned 9 stations. Therefore, instead of interpolating results of point based PWV, Sentinel-3 PWV could be used for larger areas and regions.

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