

Meteorological application of a dense GNSS network utilizing atmospheric delay gradient and crustal subsidence: The 2018 disastrous rain episode in SW Japan

大気遅延勾配と地殻上下変動を利用した稠密 GNSS 網の

気象学的応用:平成30年7月豪雨の事例研究

by

Syachrul Arief

シャフルル・アリーフ

A thesis submitted for the degree of Doctor of Philosophy Department of Natural History Sciences, Graduate School of Science, Hokkaido University

September 2020

1 Abstract

2

Heavy rain from late June to early July 2018 brought disastrous flood in Southwest (SW) Japan, especially in Kyushu. By using a dense array of Global Navigation Satellite System (GNSS) receivers in Japan GEONET, I study this episode with two different space geodetic approaches, i.e., measurements of atmospheric water vapor and crustal deformation due to surface water load.

7 The first approach is the recovery of precipitable water vapor (PWV) using the zenith wet delays (ZWD). 8 Because atmospheric water vapor concentrates in relatively low altitudes, 2-D distribution of ZWDs often 9 represent that of elevation of the observing stations rather than the relative humidity of the air column above the 10 stations. To overcome the difficulty, I reconstructed ZWDs converted to sea-level values by spatially integrating 11 the tropospheric delay gradient (azimuthal asymmetry of water vapor) vectors from coastal GNSS stations. I also 12 calculated convergence of such delay gradients, equivalent to water vapor convergence (WVC) index proposed 13 by Shoji (2013). I found that extreme rainfall occurs in the region and time, where both the sea-level ZWD and 14 the WVC index are high. I confirmed this was the case also for similar disastrous heavy rain episodes in SW 15 Japan in 2017 July and 2019 August.

16 Next, I studied vertical crustal movements associated with surface water loads brought by heavy rainfall, using 17 the official F3 solution of the GEONET station coordinates. Rainwater would act as the surface load and depress 18 the ground to a detectable level. I removed common mode errors by adjusting ~100 reference stations to the 19 median positions over a 1-month period using the Helmert transformation. I confirm land subsided by up to ~ 2 20 cm in some areas where major floods occurred. Land subsidence was observed to recover with a time constant of 21 1-2 days, which reflects the rapid drainage of rainwater into the sea due to the large topographic slope of the 22 Japanese Islands and the proximity of the flooded areas to the sea. Then, I estimated the distribution of surface 23 water load over the entire SW Japan using the GNSS station subsidence as the input. The estimated distribution 24 of surface water resembled to the rainfall distribution from the AMEDAS rain gauge data from Japan 25 Meteorological Agency (JMA).

Then, I compared the amount of water of the 2018 heavy rain episode using the three ways, i.e. (1) spatially integrated PWV, (2) cumulative rainfall from AMEDAS rain gage, and (3) surface water distribution estimated from crustal subsidence. Cumulative rain was larger than atmospheric PWV, which is reasonable considering that 29 the atmospheric water vapor only represents the capacity of the "bucket" to carry seawater to land. Regarding the 30 comparison of the rain gauge data and the surface water estimated from crustal subsidence, the latter largely 31 exceeded the former. One may point out that the AMEDAS stations tend to be built in low-altitude valleys and 32 may not represent true amount of rainfall over the whole land. I compared cumulative rain from the AMeDAS 33 rainfall data and radar rain-gauge analyzed precipitation and confirmed that AMeDAS rain gauge data do not 34 seriously underestimate real precipitation. The problem may come from the GEONET station distributions. They 35 tend to be located in low-elevation densely populated area, and stormwater may concentrate on their vicinity. 36 Thick sedimentary layers beneath the GEONET stations may also locally reduce the crustal rigidity.

I performed similar studies using GNSS data taken at stations in Indonesia. I processed the raw GNSS data to estimate ZTD and PWV values using open-source software packages such as goGPS. I validated the derived tropospheric parameters by comparing them with those from other research centers, such as University of Nevada Reno (UNR). Next, I applied the methods to the disastrous heavy rain events that caused floods in Jakarta in early January 2020 and studied the time series of PWV and vertical coordinates. I confirmed the enhancement of PWV prior to the heavy rainfall onset and significant subsidence of GNSS stations located in the flooded area.

44 Acknowledgments

46	I would like to thank my supervisor, Prof. Kosuke Heki, for his support, encouragement, and guidance for four
47	years. The time he spent working with me has greatly improved the quality and increased the depth of this
48	research,
49	I would also like to express my gratitude to all my colleagues in the Space Geodesy laboratory and Seismology
50	Laboratory, Faculty of Science Hokkaido University. Specifically to teachers: Prof. Furuya and Dr. Youichiro
51	Takada were always actively giving input in the "Zemi" week when I made presentations,
52	I also would like to thank Prof. Kiyoshi Yomogida and Dr. Kazunori Yoshizawa for their constructive
53	comments. For all of Natural History Science Department members, many thank for all of your supports, also
54	for the BIG, RISET-PRO KEMRISTEKDIKTI Scholarship program from the Indonesian Government,
55	I also visited MRI/JMA (Meteorological Research Institute/Japan Meteorological Agency) in Tsukuba and met
56	Dr. Yoshinori Shoji, for discussions related to GNSS Meteorology in Japan. Thank you very much for the input
57	in the preparation of this thesis.
58	I also want to thank the staff at the Faculty and the Graduate School of Sciences who helped me both in the
59	learning process and interactions with the environment while in Sapporo,
60	Finally, I also thank my family, my wife, my daughter, and my younger brother, for giving me freedom and
61	support throughout my education to make me think that anything is possible. Without their encouragement and
62	understanding for years, I would not have been able to complete this research process.

Contents

64	Abstr	act	
65	Ackno	owledgments	
66	Conte	ents	5
67	Chap	ter 1. Introduction	
68	1.1	Background	
69	1.2	GNSS Meteorology in Japan and in Indonesia	9
70	1.3	Research Objectives	
71	1.4	Thesis Structure	
72	Chap	ter 2. Ground-based GNSS Meteorology	
73	2.1	Atmosphere Layers	
74	2.2	Sources of Errors in Positioning using GNSS	
75	2.2	2.1 Space segment errors	
76	2.2	2.2 User segment errors	
77	2.2	2.3 Atmospheric errors	
78	2.3	Path Delay and Refractivity	
79	2.3	3.1 Path delay in the atmosphere	
80	2.3	3.2 Calculation of refractivity	
81	2.4	Retrieval of PWV from GNSS Derived Zenith Delays	
82	2.4	1.1 Tropospheric delays derived from refractivity	
83	2.4	1.2 Mapping function	
84	2.5	Model for the Determination of Tropospheric Delays	
85	2.5	5.1 Zenith Hydrostatic Delay (ZHD)	
86	2.5	5.2 Zenith Wet Delay (ZWD)	
87	2.5	5.3 Zenith Total Delay (ZTD)	
88	2.5	5.4 Tropospheric delay gradient	

90	Chapter 3. GNSS meteorology for disastrous rainfalls in 2017-2019 summer in SW Japan: A new	
91	approach utilizing atmospheric delay gradients	29
92	3.1 Introduction	29
93	3.2 Data and methods: Case study for the 2018 heavy rain	31
94	3.2.1 ZWD and tropospheric delay gradients	32
95	3.2.2 Water Vapor Concentration (WVC)	33
96	3.2.3 Sea-level ZWD	34
97	3.3 Results and Discussions	37
98	3.3.1 The 2017 and 2019 heavy rain cases	37
99	3.3.2 Validation of the inversion results and the water vapor scale height	39
100	3.3.3 WVC, sea-level ZWD, and heavy rain	42
101	3.3.4 Time series analysis	44
102	Chapter 4. Crustal subsidence by water load with a dense GNSS network: A case study of the July	y 2018
103	heavy rainfall in SW Japan	47
104	4.1 Introduction	47
105	4.2 Data and Methods	49
106	4.2.1 Correction of common mode errors	49
107	4.2.2 Analysis of station position change for one month	50
108	4.2.3 Crustal subsidence in the 2017 and 2019 heavy rain episodes in Kyushu	52
109	4.2.4 Day-to-day variability of crustal subsidence: The 5-8 July 2018 case	54
110	4.3 Result and discussions	55
111	4.3.1 Estimation of water load from crustal subsidence	55
112	4.3.2 Estimated surface water load	57
113	4.3.3 Amount water vapor in the sky	60
114	Chapter 5. Analysis of the Tropospheric Delays in Indonesia Estimated using the goGPS software	63
115	5.1 Introduction	63
116	5.2 Data and Methods	63
117	5.2.1 Data set	63
118	5.2.2 Software goGPS	64
119	5.2.3 Precision Point Positioning (PPP)	64

120	5.3 Result and discussions	65
121	5.3.1 Comparison of the estimated tropospheric delay gradients with other products	65
122	5.3.2 Comparison of the ZTD values of goGPS, IGS and UNR	66
123	5.3.3 ZTD range value from goGPS	68
124	5.3.4 Comparison of PWV and rainfall	69
125	Chapter 6. Correlation between land subsidence and heavy rainfall in Jakarta on January 1, 2020	72
126	6.1 Introduction Jakarta flood on January 1, 2020	72
127	6.2 Data and Methods	73
128	6.2.1 GNNS data set	73
129	6.2.2 Land Subsidence in Jakarta	73
130	6.3 Result and discussions	74
131	6.3.1 Determination of PWV values at 5 INACORS stations	74
132	6.3.2 Comparison of PWV INACORS with Jakarta Radiosonde Station	76
133	6.3.3 Crustal movement analysis, GNSS station (INACORS-BIG)	77
134	Chapter 7. Conclusion and Recommendation	80
135	7.1 Conclusion	80
136	7.2 Recommendation	81
137	Bibliography	82
138		

141 Chapter 1. Introduction

142 **1.1 Background**

143 One of the similarities between Indonesia and Japan is their geographical setting. The both countries belong to 144 Asia. Besides the geographical similarity, Indonesia and Japan are also located in the Asia-Pacific ring-of-fire 145 where multiple tectonic plates meet. This brings these two countries natural disasters such as volcanic eruptions, 146 large earthquakes, and tsunamis. In addition to such solid earth origin disasters, the two countries suffer from 147 floods caused by heavy rains. For this kind of natural disasters, we should explore common methods to mitigate 148 them. Such a meteorological disaster often causes a lot of casualties and losses of properties. In this study, I pick 149 up the occurrence of a disastrous heavy rain episode that attacked SW Japan in early July 2018. In Indonesia, I 150 focus on the heavy rain that occurred early in January 2020 in Jakarta.

151 In recent times, they deployed many ground stations tracking satellites of Global Navigation Satellite System 152 (GNSS), including the American Global Positioning System (GPS). People have been using them not only for 153 positioning and crustal deformation studies, but also for various fields especially for remote sensing of atmosphere, 154 such as tropospheric water vapor and ionospheric electrons. Among others, the new word "GNSS (GPS) 155 meteorology" was introduced by Bevis et al. (1992) to signify researches making use of GNSS for sensing of the 156 earth's atmosphere using the delay of microwave signals from GNSS satellites. This changed the mind of 157 researchers who considered atmospheric refraction of GNSS signals just an error affecting the positioning 158 accuracies.

In this research, I used the approach of ground-based GNSS-meteorology and give its technical and theoretical
explanations in Chapter 2. GNSS Meteorology has many advantages as listed below.

161 - GNSS data are not affected by weather conditions, i.e. GNSS is an all-weather sensor.

162 - GNSS data are continuously acquired using permanent ground stations.

163 - GNSS data has a high temporal resolution with typical sampling interval of 30 seconds.

164 - GNSS has high accuracy for the estimation of tropospheric delays and its azimuthal asymmetry.

- GNSS is not dependent on other meteorological instruments. GNSS stations are sometimes equipped with
 meteorological sensors, but GNSS data can be obtained independently.

167 - GNSS data has a long-term stability suitable for studying climate changes.

168 As a conventional sensor of atmospheric water vapor, we have been using radiosonde and water vapor radiometers.

169 Radiosonde can make vertical humidity profiles, but it is operated only twice a day in only 10-20 stations in Japan.

170 Water vapor radiometers are not suitable for measurements during rain. In contrast, we have ~1,300 permanent

171 GNSS stations called GEONET (GNSS Earth Observation Network) operated by GSI (Geospatial Information

172 Authority) recording data every 30 seconds regardless of weather conditions. Hence, GNSS-meteorology is a

173 promising technique for meteorology and climatology in Japan.

174

175 **1.2 GNSS Meteorology in Japan and in Indonesia**

As the institutions participating the GNSS meteorology project, "GNSS/MET Japan", two essential organizations in Japan started cooperation, GSI and JMA. GSI is the mapping agency of the Japanese government, and it operates the nationwide GEONET with the primary purpose as the dense land survey infrastructure and sensors of crustal deformation. On the other hand, JMA is responsible for providing information on weather, climate, ocean, volcanoes, and earthquakes in Japan and for maintaining the equipment for relevant observations.

181 GNSS meteorology in Japan entered the stage of implementing concrete actions supported by the two institutions. 182 According to Shoji et al. (2009), the early research activity started when Japanese geodesists and meteorologists 183 held the first workshop on "GNSS Tropospheric Delay" at the Mizusawa Astrogeodynamic Observatory, National 184 Astronomical Observatory (NAO), Japan, being led by Isao Naito of NAO. There, they recognized the importance 185 of water vapor information from GNSS data with the advice of Nobutaka Man'nouji of JMA. After a feasibility 186 study led by Hiromichi Tsuji of GSI, the Japanese GNSS meteorology project "GNSS/MET JAPAN" was 187 launched in 1997. The detail of the "GNSS/MET JAPAN" project is compiled in the special issue of Earth Planets 188 and Space published in 1998 (Tsuda et al., 1998).

189 PWV data from GNSS have been assimilated in the mesoscale model of JMA to improve weather forecast 190 accuracy since 2009 (Shoji, 2015). The latest developments in GNSS meteorology in Japan includes the recent 191 innovation for receiving GNSS signals on the sea. Shoji et al. (2017) installed GNSS antennas on a JMA's research vessel and estimated tropospheric parameters such as PWV. They confirmed that their results agree with PWVfrom radiosonde observations.

From the perspective of geodesy, Heki (2020) suggested that geodesy would play a transdisciplinary role in Japan in future. He gave an example of meteorological application of the dense GNSS network through the measurement of PWV and crustal subsidence caused by surface stormwater. I follow this concept in this study, i.e. I tried to study the 2018 heavy rain episode in SW Japan from multiple aspects using GNSS. One of them is the PWV approach (Chapter 3) and the other is the crustal movement approach (Chapter 4). I am finishing my PhD study with the hope that it can further enhance the transdisciplinary nature of GNSS and geodesy in Japan and the world.

Next, what about the GNSS meteorology in Indonesia? In Indonesia, the number of GNSS stations is still around 200 in spite of its large geographical dimension. The density of the GNSS station is much less than in Japan, where ~1300 stations are deployed. As for the GNSS meteorological researches in Indonesia, I found several theses by students at the university of higher education. For example, the Master Thesis by Susilo, with the title "Monitoring Precipitable Water Vapor (PWV) in the West Java Region Using Continuous GNSS", followed by an undergraduate thesis by Fikri Bamahry with the title "PWV Monitoring Over East Java Region Using Continuous GNSS".

Because the distribution of GNSS stations is still limited in number, the spatial approach of GNSS meteorology (e.g. detailed mapping of water vapor distribution) is still difficult, and the studies are limited to those by the temporal approach (e.g. time series analysis of water vapor at a certain station). In general, they only discuss how to determine the value of PWV in Indonesia using commercial software packages. So far, there are no real political movements driven by the Indonesian government for GNSS meteorology.

In this research, I will try to apply the GNSS meteorological approach for real phenomena in Indonesia with the hope of making GNSS meteorology a part of the new policy put forward in Indonesia. The first part for the case in Indonesia, I will estimate tropospheric parameters from raw GNSS data available in the Receiver-INdependent EXchange format (RINEX format). Then I demonstrate how to determine the PWV values with the open-source software packages. They are described in Chapter 5. In Chapter 6, I study the heavy rain episode in January 2020 in Jakarta, and try to detect crustal subsidence analyzing the time series of PWV and vertical coordinates of GNSS stations.

- 220 **1.3 Research Objectives**
- 221 In general, the purpose of this study is to explore how GNSS can be used for meteorological purposes including
- its potential for studying crustal movements due to heavy rains. I study the cases of heavy rains in Kyushu, Japan,
- in 2017-2019 and in Jakarta, Indonesia, in 2020.
- 224 What I did in this study is summarized as follows.
- 1. To demonstrate the benefit of utilizing tropospheric delay gradients.
- 226 2. To analyze PWV to improve our understanding of water vapor dynamics during heavy rains.
- 227 3. To calculate water vapor concentration (WVC) index and study its behavior together with the in-situ rainfall
- data from AMEDAS (Automated Meteorological Data Acquisition System) stations of JMA.
- 4. To study the temporal evolution of these quantities during the three heavy rain episodes in SW Japan in summer2017-2019.
- 5. To analyze the role of heavy rain as a carrier of water in July 2018 in SW Japan, by inverting surface water
 distribution using vertical crustal movement data.
- 6. To obtain tropospheric parameters from Indonesian GNSS network (INACORS-BIG) RINEX data.
- 234 7. To study PWV behaviors before and after the heavy rain episode in early 2020 in Jakarta.
- 8. To reveal vertical crustal movements during heavy rain episode in Jakarta in early 2020.
- 236

237 **1.4 Thesis Structure**

The structure of this thesis starts from the explanation of the background, why the research was performed, what is the importance of this research, how the research was conducted and what is expected to be achieved in this

- 240 research. Then I describe the overview of the objectives of this study in general and specifically. The ending of
- 241 Chapter 1 is the explanation of the structure of this thesis.
- 242 Chapter 2 contains the basics of the ground-based GNSS Meteorology, from the description of atmospheric layers
- to methods to estimate tropospheric delays.

In Chapter 3, I tried to apply the GNSS meteorology to the disastrous heavy rainfall in SW Japan in July 2018
using tropospheric data from the UNR data base.

In Chapter 4, for the case of heavy rainfall in early July 2018, I studied crustal subsidence by water load using the daily coordinate data from the dense GNSS network. In this chapter I reveal the link between precipitation and the deformation of underlying crust.

In Chapter 5, I describe the GNSS meteorology studies in Indonesia. It starts with the demonstration of the estimation of zenith total delay (ZTD) values from raw GNSS data given in RINEX format using the goGPS open-source software. I confirmed the accuracy of the estimated tropospheric parameter with the results from International GNSS Service (IGS) and UNR.

In Chapter 6, concerning the meteorological application of GNSS in Indonesia, I tried to apply it to the torrential rain events that caused flooding in Jakarta in early January 2020. Here I also detected the vertical crustal movements associated with the heavy rainfalls in Jakarta.

Finally, in Chapter 7, I present the conclusions of the whole content of this thesis and make recommendations forfuture.

258

Chapter 2. Ground-based GNSS Meteorology

In this chapter, I will write about the fundamental principles of GNSS meteorology. Starting with the explanations
of atmospheric layers, path delay, and refractivity, how to retrieve PWV from GNSS-derived zenith delays. Then
I write on the models used for the determination of tropospheric delay parameters.

264 Based on the position of the GNSS receivers for monitoring atmospheric properties, GNSS meteorology can be 265 classified into two basic categories (Businger et al. 1996), namely the space-based and the ground-based GNSS 266 Meteorology. In the space-based GNSS meteorology, they receive microwave signals with receivers on board 267 Low Earth Orbit (LEO) satellites with near-global coverage. Received signals are processed to obtain profiles of 268 atmospheric refractivity. This method is also called as GNSS Radio Occultation (GNSS-RO) (Ware et al. 1996). 269 The refractivity profiles are converted to profiles of various atmospheric properties such as temperature, water 270 vapor content in the lower part of atmosphere, and electron density in the ionosphere. In the ground-based GNSS 271 meteorology, they receive phases of microwave signals at points fixed on the ground, and estimate atmospheric 272 delays (due to dry air and water vapor) included in the phase observables. Figure 2.1 compares the space-based 273 and the ground-based GNSS meteorology.



Figure 2.1 (a) Space-based GNSS meteorology to obtain refractivity profiles of the atmosphere, and (b)
ground-based GNSS meteorology to estimate atmospheric delay of the GNSS signal, or "zenith tropospheric
delay (ZTD)". Such delay is converted to "precipitable water vapor (PWV)". (by Christian Rocken GCOS, May
2006).

279

274

280 2.1 Atmosphere Layers

The solid Earth is surrounded by various kinds of gases which constitute the Earth's atmosphere. Most of the atmosphere (about 80% in weight) is within 16 km of the surface of the Earth. There are no exact "higher ends"

283 of the atmosphere. It just gets thinner and thinner until it merges with the space. The atmosphere of the Earth can

284 be divided into several distinct layers, thereby facilitating specific scientific researches such as weather 285 forecasting, studies of global warming, and space weather, and so on.

286 The troposphere is the lowest layer of the Earth's atmosphere, which extends from the Earth's surface to a height 287 of 9-18 km depending on altitude and weather conditions (Sturman and Tapper, 2006). It contains 99% of water 288 vapor and aerosols. The weather and clouds occur in this layer. The stratosphere extends between 18 and 50 289 kilometers above the Earth's surface. Air flow in the stratosphere is mostly horizontal. The layer of ozone, a 290 particularly reactive form of oxygen protecting human from ultraviolet radiation, is located within the stratosphere. 291 Above the stratosphere is the mesosphere whose altitude ranges from 50 to 80 km. The temperature drops to about 292 -100 °C in this layer, and hence it is the coldest region of the atmosphere. This layer protects the Earth from 293 meteoroids which burn up in this region. The ionosphere (thermosphere) starts at a height about 70-80 km and 294 continues for hundreds of kilometers. It is often assumed that the ionosphere has the average height of 350 km 295 (Xu, 2007). It contains many ions and free electrons (plasma), which are created when sunlight hits atoms and 296 tears off some electrons. The ionosphere layer reflects low frequency radio waves, which makes long-distance 297 radio communication possible.



298

299 300

Figure 2.2 Layers of the atmosphere surrounding the Earth (© Canadian Space Agency)

301 GNSS signals are bent by ionosphere and troposphere when they propagate from satellites to receivers. The first 302 order of ionospheric effect can be eliminated by using ionosphere-free linear combinations of the carrier phases 303 if dual-frequency receivers are used. This is because the ionosphere is a dispersive medium, i.e., the ionospheric 304 delay is frequency-dependent (Xu, 2007; Yan et al., 2014). However, unlike the ionosphere, the troposphere is a 305 non-dispersive medium at the GNSS carrier frequencies (e.g. 1.2 and 1.5 GHz for GPS). In other words, the 306 tropospheric effects on the GNSS signal propagation are independent from the microwave frequencies of the 307 carrier.

308 **2.2 Sources of Errors in Positioning using GNSS**

309 2.2.1 Space segment errors

310 Positioning errors due to space segment consist of two types. One is the satellite ephemeris error, and the other is 311 the satellite clock error. Satellite ephemeris errors occur due to inaccuracies in satellite orbit. This orbital error 312 can be decomposed into three components relative to the satellite movement directions, namely radial, along-313 track and cross-track. The error in the radial direction is small compared to the error in the other two directions. 314 This is favorable for positioning purposes because the influence on the measurement of the apparent range 315 (distance between satellite and receiver) is the largest for the radial component. The Kalman filtering technique 316 is widely used to derive ephemeris parameters (Enge and Misra, 2006). The basic measurement carried out in the 317 GNSS receivers is the transit times of the signals between the satellites and the receiver, which are determined 318 by the difference between the signal transmission time from the satellite and the reception time measured by the 319 receiver (Enge and Misra, 2006). Therefore, the accuracy of the clock is essential. An error of lus can cause an 320 offset of about 300 m because the distance between the satellite and the receiver is obtained by multiplying the 321 travel time by the speed of light (Zinas, 2016). To keep the satellite clock error as small as possible, each GNSS 322 satellite carries an atomic clock. The atomic clocks suffer from noise and drifts, and their corrections need to be 323 made. Such clock corrections are necessary in the data analysis and are stored in navigation files made during the 324 measurements (Enge and Misra, 2006).

325 **2.2.2 User segment errors**

There are two types of user segment errors. One is the receiver clock error, and the other is the multipath error. Usually, microwaves received in the direct line-of-sight paths are received. However, the signal can also go through several paths, after being reflected by surrounding objects or by the ground before reaching the receiver. Multipath is longer than the direct path and therefore suffers from delays (Enge and Misra, 2006). Multipath signals can be characterized by their amplitude, i.e. its signals are usually weaker than direct signals. When several waves are received simultaneously, an interference occurs. Then, the multipath signals change the phase and amplitudes of the direct path signals to some extent (Yedukondalu, 2011). 333

334 2.2.3 Atmospheric errors

Because GNSS signals travel through the atmosphere, they are influenced by the ionosphere and the troposphere.
These two layers cause two different kinds of delays. Such delays need to be corrected for accurate positioning
purposes.

Ionospheric delays can only be measured by using dual-frequency GNSS receivers. The ionosphere ranges in altitude from ~50 km to over 1000 km above the earth's surface, and large number of free electrons and ions are included there. Ionization is caused by the solar radiation, and free electrons cause refraction of the transmitted satellite signal. Because physical characteristics are governed by the Sun, the difference between day and night is very large. During the day, the molecules are decomposed into positive ions and electrons, and thus the electron density increases. However, when the Sun goes down, such ions and electrons recombine, and the electron density decreases.

The speed of the radio signals depends on the electron density, number of electrons per unit volume, in the propagation medium. Therefore, the total delay reflects a quantity called 'total electron content' (TEC). TEC signifies the total number of electrons integrated along the propagation path and expressed as number of electrons found in a 1 m² cross-section column extending from the satellite to the receiver. One way to eliminate ionosphere delays is to use a linear combination of the L1 and L2 phases. The ionospheric group delays at frequency L1 and L2 from code measurements are:

351

352
$$IL_{1} = \frac{f_{L2}^{2}}{f_{L1}^{2} - f_{L2}^{2}} \left(\rho L2 - \rho L1\right)$$
(2.1)

353
$$IL_2 = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} \left(\rho L2 - \rho L1\right)$$
(2.2)

354

Where *I*L1 and *I*L2 stand for ionospheric delays in the L1 and L2 frequency bands respectively, f_{L1} and f_{L2} stand for the L1 and L2 frequencies, ρ L1 and ρ L2 stand for code measurements in the L1 and L2 bands, respectively (Enge and Misra, 2006). Since TEC is large and highly time-variable in the equatorial region, it is essential to
determine the ionospheric delays accurately. Better insight into ionospheric variations in the Ugandan region,
Africa, is explained by Koning (2016), and a suitable way of determining the ionospheric delay component is
explained there.

The tropospheric delay consists of two components: the hydrostatic component, mostly dependent on dry gas, and the wet component coming from the water content in the air. The former component accounts for ~90% of the total delay, but the spatio-temporal variation is far more significant in the latter component. The dry component of the tropospheric zenith total delay (ZTD) is called the Zenith Hydrostatic Delay (ZHD) and is estimated by using models and the accurate pressure measurements at the GNSS station (Gabor, 1997). The wet component of the zenith troposphere is called the Zenith Wet Delay (ZWD). ZWD can be calculated by subtracting ZHD from ZTD; the relationship between the two is as follows (Yedukondalu, 2011).

368

$$2TD = ZHD + ZWD \tag{2.3}$$

370

In this thesis, I tried to learn how to get the ZTD value using the goGPS software. Then I validate the ZTD acquisition process from goGPS, by comparing the ZTD values published from IGS (International GNSS Service) and UNR (University of Nevada, Reno). In the last part of the thesis, I compare the precipitable water vapor (PWV) values from the GNSS stations processed by goGPS, with the PWV values from radiosondes in the same area. In the last part, I analyze ZTD and PWV to study the behavior of ZTD at certain times to explore the possibility of using ZTD information in Indonesia for meteorological purposes.

377 **2.3 Path Delay and Refractivity**

378 **2.3.1 Path delay in the atmosphere**

379 The propagation speed *v* of GNSS signals in the atmosphere can be expressed as

380

- $v = c/n \tag{2.4}$
- 382

383 where *n* is the refractive index and *c* is the speed of light. Sometimes, it is expressed as $n = c_0 / c$ where *c* and c_0 384 are the speed of light in the atmosphere and in the vacuum, respectively. n is a complex number. Its real part 385 relates to the absorption of signals, whereas the imaginary part corresponds to the delay and bending (Hall et al., 386 1996). 387 According to the Snell's law, for the neutral horizontally stratified atmosphere, 388 389 (2.5) $n_i \sin z_i = n_{i+1} \sin z_{i+1}$ 390 391 where z_i and z_{i+1} are the zenith angles of the arriving radio signal for the layers *i* and *i* +1. n_i and n_{i+1} are the 392 corresponding refractive indices. Although the refractive index n depends on atmosphere pressure, temperature, 393 and relative humidity conditions, its value is close to unity. This makes the so-called atmospheric refractivity N394 (in mm/km, or ppm) more convenient to be used instead of *n*. 395 396 $N = (n - 1) \times 10^{6}$ (2.6)397 398 The electro-magnetic (or optical) distance L of a GNSS signal propagating along the path S through the 399 atmosphere will be $L = \int c dt = \int c / v \, ds = \int_{s} n(s) ds$ 400 (2.7)401 402 Let D be the straight-line distance of a GNSS signal in the atmosphere. The atmospheric delay ΔL can be 403 expressed as 404 405 $\Delta L = L - D$ $=\int_{s} n(s)ds - D$ 406 (2.8) $=\int_{S} [n(s)-1] ds + \int_{S} ds - D$ 407 $= 10^{-6} \int_{S} N(s) ds + S - D$ 408 409

410 As such, ΔL contains the two factors. Firstly, the traveling speed of GNSS signal in a region of finite density is

411 slower than in a vacuum (Böhm and Schuh, 2013). Such a "slowing" effect appears as the first term of the right-

412 hand side of equation (2.8). The S - D part of equation (2.8) is called the "bending" effect due to the signal

414 approximately 1 cm or less, which is much smaller than the slowing effect. Usually, the bending term is, by

bending in response to the gradients in the index of refraction of the atmosphere. The bending effect is

- 415 convention, considered to be a part of the hydrostatic delay (Kleijer, 2004)
- 416

413

417 **2.3.2 Calculation of refractivity**

In the troposphere, the refractivity *N* can be divided into dry and wet (water vapor) parts according to (Smithand Weintraub, 1953). That is

$$N = N_{\rm d} + N_{\rm v} \tag{2.9}$$

421 Where N_d and N_v are the refractivity of dry air and water vapor, respectively. Equation (2.9) is useful because 422 the contributions of the dry gases can be expressed as a function of pressure, temperature, and humidity (Smith 423 and Weintraub, 1953) for frequencies up to 20 GHz (Thayer, 1974):

424
$$N_d = k_1 P d / T Z_d^{-1}$$
(2.10)

425
$$N_{\nu} = \left[k_2 \frac{e}{T} + k_3 \frac{e}{T^2}\right] Z_{\nu}^{-1}$$
(2.11)

426 where P_d and e are the partial pressures of dry air and water vapor in Pa (Nm⁻²). *T* is the tropospheric temperature. 427 Z_d and Z_v are the compressibility factors of dry air and water vapor, respectively. k_1 , k_2 , and k_3 are three 428 empirically derived constants.

- 429 The compressibility factors in equation (2.10) and (2.11) are given by
- 430

$$Z_{\rm d} = \frac{PM{\rm d}}{\rho{\rm d}RT}$$
(2.12)

432 and

433
$$Z_{\rm v} = \frac{PM_{\rm v}}{\rho_{\rm v}RT}$$
(2.13)

where *P* and *T* are the tropospheric pressure and temperature, respectively. M_d and M_v are the molar mass of dry air (0.028964 kg.mol⁻¹) and water vapor (0.018016 kg.mol⁻¹), respectively. The values ρ_d and ρ_v are the densities of dry air and water vapor, respectively, and *R* is the gas constant with recommended value 8.3144621±0.0000075 J.K⁻¹ .mol⁻¹ (Mohr et al., 2012). Obviously, for an ideal gas, the compressibility factor is 1. The inverse compressibility factors can also be given by the empirical formulas. A widely used model using a least-squares fitting to thermodynamic data by Owens (1967) is

440

441
$$Z_d^{-1} = 1 + P_d \left[57.97.10^{-8} \left(1 + \frac{0.52}{T} \right) - 9.4611.10^{-4} \frac{T - 273.15}{T^2} \right]$$
(2.14)

442
$$Z_{v}^{-1} = 1 + 1650 \frac{e}{T^{3}} [1 - 0.1317(T - 273.15)]$$

443
$$+ 1.75.10^{-4}(T - 273.15)^2 + 1.44.10^{-6}(T - 273.15)^3$$
] (2.15)

444

445 Moist air contains both dry gases and water vapor. Hence the density of moist air ρ_m is the summation of the dry 446 gas density ρ_d and the water vapor density ρ_{ν} . With equations (2.10) and (2.11), along with the equations of state 447 for dry air and water vapor, equation (2.9) can be expanded as

448
$$N = k_1 R_d \rho_d + k_2 R_v \rho_v + k_3 \frac{e}{T^2} Z_v^{-1}$$

449
$$= k_1 R_d \rho_m - k_1 R_d \rho_v + k_2 R_v \rho_v + k_3 \frac{e}{T^2} Z_v^{-1}$$
(2.16)

450
$$= k_1 R_d \rho_m + (k_2 - k_1 \frac{R_d}{R_v}) R_v \rho_v + k_3 \frac{e}{T^2} Z_v^{-1}$$

451
$$= k_1 \frac{R}{M_d} \rho_m + (k_2 - k_1 \frac{M_v}{M_d}) \frac{e}{T} Z_v^{-1} + k_3 \frac{e}{T^2} Z_v^{-1}$$

452 where R_d and R_v are the specific gas constants of dry gases and water vapor, respectively.

453
$$k'_2 = k_2 - k_1 \frac{M_v}{M_d}$$
(2.17)

454 Then equation (2.16) becomes,

455
$$N = k_1 \frac{R}{M_d} \rho_m + \left(k'_2 \frac{e}{T} + k_3 \frac{e}{T^2}\right) Z_v^{-1}$$
(2.18)

$$456 = N_h + N_w$$

457 The first term N_h is called hydrostatic refractivity, which depends only on the density of moist air ρ_m . The second 458 term N_w is non-hydrostatic refractivity, which is also called wet refractivity. N_w is dependent only on the partial 459 pressure *e* of water vapor and temperature *T*.

460 **2.4 Retrieval of PWV from GNSS Derived Zenith Delays**

461 **2.4.1 Tropospheric delays derived from refractivity**

According to Section 2.3, instead of dividing the refractivity into dry and water vapor parts following equations (2.9) – (2.11), one can also divide it into the hydrostatic and the wet parts (Davis et al., 1985) following equation (2.18). It should be noted that in the two cases, dry refractivity N_d and hydrostatic refractivity N_h are not identical, as part of N_h is caused by water vapor. However, this separation of N_h and N_w will not affect but facilitate the calculation of the total refractivity N (Böhm and Schuh, 2013). This is because the hydrostatic refractivity N_h can be simply calculated using surface pressure measurements. Putting equation (2.18) into equation (2.8) gives

468
$$\Delta L = 10^{-6} \int_{S} N_{h} (S) d_{S} + 10^{-6} \int_{S} N_{h} (S) d_{S} + S - D = \Delta L_{h} + \Delta L_{w} + S - D$$
(2.19)

469 where ΔL_h and ΔL_w are the hydrostatic and wet delays along the path *S*, respectively. The *S* – *D* part is relatively 470 small and usually considered to be part of the hydrostatic delay, as is mentioned in Section 2.3.1.

The atmospheric delay contains the ionospheric part and the tropospheric part. The former can be eliminated using ionosphere-free linear combinations of the phases of the two L-band carrier waves, and the latter contains the hydrostatic and wet delay. In GNSS data processing, it is common that the tropospheric path delay of a signal is mapped from a vertical component using proper mapping functions. Normally, mapping functions are elevation dependent. As such, the corresponding tropospheric path delay becomes

$$\Delta L = z_t \cdot mf_t \tag{2.20}$$

$$\Delta L_h = z_h \cdot m f_h \tag{2.21}$$

$$\Delta L_w = z_w \cdot m f_w \tag{2.22}$$

479
$$z_t = z_h + z_w$$

$$\Delta \mathbf{L} = \Delta L_h + \Delta L_w = z_h \cdot mf_h + z_w \cdot mf_w$$
(2.24)

481 where

482	z_t represents ZTD in troposphere.

- 483 z_h represents ZHD in troposphere,
- 484 z_w represents ZWD in troposphere,
- 485 mf_t represents the total mapping function,
- 486 *mf_h* represents the hydrostatic mapping function,
- 487 mf_w represents the wet mapping function.
- 488

489 **2.4.2 Mapping function**

490 According to the expressions of path delays in equations (2.20) - (2.22), mapping functions are similar to 1/sin 491 (*E*). However, the determination of the mapping functions, in reality, is far more complicated due to the bending 492 and slowing effects in the atmosphere. The accuracies of mapping functions are vital in high-accuracy 493 positioning applications. This is because zenith delays, station heights, and clocks in GNSS observation 494 equations are highly correlated. Any error in mapping functions will result in corresponding errors in other 495 parameters, especially the station height and the clock offset.

In this research, I used tropospheric delay data from the UNR database (Blewitt et al., 2018). They estimated
tropospheric parameters using the GIPSY / OASIS-II Version 6.1.1 software with the Precise Point Positioning
(PPP) technique (Zumberge et al., 1997). They follow the 2010 IERS convention (Gérard and Luzum, 2010) and
used the Global Mapping Function (Böhm et al., 2006a) and troposphere gradient model of Chen and Herring
(1997).

501 The Global Mapping Function (GMF) model is developed in the Vienna University of Technology (Böhm et al., 502 2006a). The coefficients of the GMF were obtained from an expansion of the VMF1 parameters into spherical 503 harmonics on a global grid. The implementation of GMF is simple as only the station coordinates, and the day

(2.23)

504	of the year (DOY) are needed as input. An updated model of GPT/GMF called GPT2 is presented by Lagler e	
505	al. (2013). The updates include the usage of more NWP data, refinement of the horizontal and height resolutions,	
506	refinement of temperature lapse rate, and extra semi-annual harmonics in order to better explain atmospheres in	
507	regions where very rainy periods or very dry periods dominate.	
508		
509	2.5 Model for the Determination of Tropospheric Delays	
510	2.5.1 Zenith Hydrostatic Delay (ZHD)	
511	Integrating the hydrostatic refractivity Nh in vertical direction yields ZHD	
512		
513	$z_{h} = \int_{h0}^{\infty} 10^{-6} N h(h) dh $ (2.25)	
514		
515	where h_0 is the station height in meters above the Mean Sea Level (MSL).	
516	Substitution of the first term on the right side of equation (2.18) in equation (2.25) yields	
517		
518	$z_{h} = 10^{-6} k_{I} \frac{R}{M_{d}} \int_{h_{0}}^{\infty} \rho_{m}(h) dh $ (2.26)	
519		
520	The hydrostatic equation under the condition of hydrostatic equilibrium is	
521		
522	$\frac{dP}{dh} = -\rho_m (h)g(h) \tag{2.27}$	
523		
524	where $g(h)$ is the acceleration of gravity as a function of height above MSL. $g(h)$ can be replaced using a mean	
525	gravity g_m (Saastamoinen, 1972).	
526		
527	$g_m = g_m^0 \cdot f(\varphi h_0) \tag{2.28}$	
528		
529	where φ is the geodetic latitude and $g_m^0 = 9.748 \text{ ms}^{-2}$. According to Davis et al. (1985),	

530

$$f(\varphi, h_0) = 1 - 0.0026\cos 2\varphi - 0.00000028h_0 \tag{2.29}$$

532

533 Integrating equation (2.27) yields

534

535
$$\int_{P_0}^{0} dP = -\int_{h_0}^{\infty} \rho_m(h)g(h)dh = -g_m \int_{h_0}^{\infty} \rho_m(h)dh = -P_0$$
(2.30)

536 where P_0 is the surface air pressure. As such

537

538
$$\int_{h_0}^{\infty} \rho_m(h) dh = \frac{P_0}{g_m}$$
(2.31)

539 Substituting equation (2.31) into equation (2.26) gives

540

541 $z_h = 10^{-6} k_1 \frac{R}{g_m M_d} P_0$ (2.32)

542

543 Using constant $g_m^0 = 9.784$ m s⁻², given in Davis et al. (1985) and equations (2.28) – (2.29), equation (2.32) can 544 be re-written as (in meters)

545

546 $z_h = 0.0022768 \frac{P_0}{f(\varphi, h_0)}$ (2.33)

547

548 So, for any GNSS station with known geodetic latitude and height, its corresponding ZHD can be calculated 549 using equation (2.33) as long as the surface air pressure is given. Surface pressure can also be obtained from 550 empirical models. A widely used pressure model (Kouba, 2009) is as follows.

551

 $P_0 = 1013.25 (1 - 0.0000226h_0)^{5.225}$ (2.34)

553

552

Another widely used ZHD model is the UNB (University of New Brunswick) model. It utilizes the Saastamoinen zenith delays (as modified by Davis et al. (1985)) and a look-up table with annual mean and amplitude for temperature, pressure, and relative humidity varying with respect to latitude and propagated to station height (Leandro et al., 2008).

- According to previous studies (Davis et al., 1985; Böhm and Schuh, 2013), the main errors in equation (2.33)
- are as follows:
- 560 1) an error of 1 hPa in surface air pressure is likely to cause an error of approximately 2.2768 mm in the resultant
- 561 ZHD. So, in order to reach an accuracy of 0.1 mm in ZHD, the surface pressure needs to be as accurate as
- 562 0.05 hPa. This accuracy level is challenging for most of the empirical pressure models.
- 563 2) the coefficient 0.0022768 m hPa⁻¹ is calculated using several constants. Its accuracy is 0.0005 m hPa⁻¹, and
- 564 the error is mainly caused by k_1 (Davis et al., 1985).
- 3) equation (2.33) is based on the assumption of hydrostatic equilibrium, and the wind may cause an error of 20
 mm in ZHD under severe weathers.
- 567

568 2.5.2 Zenith Wet Delay (ZWD)

- 569 The value of ZWD is based on wet refractivity. According to equation (2.18),
- 570

571
$$N_{\rm w} = \left(k'_2 \frac{e}{T} + k_3 \frac{e}{T^2}\right) Z_{\nu}^{-1}$$
(2.35)

572

573 Integrating equation (2.35) along the propagation path yields ZWD z_w

574

575
$$z_{w} = 10^{-6} \left[\int_{h_{0}}^{\infty} (k'_{2} \frac{e}{T} Z_{v}^{-1}) dh + \int_{h_{0}}^{\infty} (k_{3} \frac{e}{T^{2}} Z_{v}^{-1}) dh \right]$$
(2.36)

576

577 Obviously, partial pressure *e* of water vapor and surface temperature *T* as functions of height are needed to 578 calculate ZWD. It should be noted that due to the high variability and unpredictability of water vapor, the 579 determination of ZWD is far more challenging than that of ZHD (Böhm and Schuh, 2013). In this study, besides 580 the *a priori* ZHD and ZWD, an additional parameter is set up to account for the residual ZWD. For the calculation 581 of the a *priori* ZWD, Saastamoinen (1972) used an empirical model

582

583
$$z_{\rm w} = 0.0022768(1255 + 0.05T) \frac{e}{T}$$
(2.37)

585 Other empirical models can be used and found in the literatures (Hopfield, 1969; Askne and Nordius, 1987;

586 Baby et al., 1988; Mendes and Langley, 1999).

587 ZWD is derived from the GNSS processing then converted to PWV by a dimensionless constant of 588 proportionality Π:

589
$$PWV = z_w \Pi \tag{2.38}$$

ZWD can be estimated directly from GNSS data processing. It can also be derived when ZHD is subtracted fromZTD.

592 According to Bevis et al. (1994) and Duan et al. (1996),

593
$$\Pi = \frac{10^6 M_W}{\rho R \left(k_2 - k_1 \frac{M_W}{M_d} + \frac{K_3}{T_m}\right)}$$
(2.39)

594 where ρ is the density of liquid water; T_m is weighted mean temperature of troposphere. Values of constants *R*, 595 *k1*, *k2*, *k3*, $M_w M_d$ discussed in Section 2.3.2 are adopted in this study.

Errors in Π are mainly caused by errors in T_m and the constants in equation (2.39). Foelsche and Kirchengast (2001) proved that the influence of errors in T_m is at least one order of magnitude larger than the errors introduced by the constants. The accurate calculation of T_m requires the vertical profiles of water vapor and temperature (Davis et al., 1985):

$$600 T_m = \frac{\int (\frac{e}{T}) dz}{\int (\frac{e}{T^2}) dz} = \frac{\sum_{i=1}^N (\frac{e_i}{T_i}) \Delta z_i}{\sum_{i=1}^N (\frac{e_i}{T_i^2}) \Delta z_i} (2.40)$$

601 where both *e* and *T* extend from the surface to the top of the atmosphere. For this real-time retrieval of PWVs, 602 the vertical profiles of water vapor and temperature can become available only by introducing external 603 meteorological data.

604 **2.5.3 Zenith Total Delay (ZTD)**

For the determination of ZTD, there are also several empirical models. Saastamoinen (1972, 1973) proposed a
 model:

607
$$z_t = \frac{0.002277}{\sin E} \left[P_0 + \left(\frac{1255}{T} + 0.05 \right) e - B \cot^2 E \right] + \delta R$$
(2.41)

608

609 where E is the elevation angle of the GNSS signal; B and δR are the tabulated functions of station height h_0 and 610 elevation angle E; R_h is relative humidity (in %). Some other empirical ZTD models can be found in the literature 611

(Hopfield, 1971; Chao, 1974)

612 2.5.4 Tropospheric delay gradient

613 The most important part of this research is the tropospheric delay gradient vector (G). According to Iwabuchi et 614 al. (2003) and Miyazaki et al. (2013), the vertical components of the position anomaly and ZTD, respectively, 615 differ between the solutions with and without estimation of such gradients. Gradient model improves accuracies 616 in vertical coordinates as well as those in the horizontal plane. There are several tropospheric delay gradient 617 models. Chen and Herring (1997) proposed a gradient model based on the "tilted" atmosphere assumption, which 618 can be expressed as the first term of the gradient mapping function

619
$$\boldsymbol{G} = (G_N, G_E) \quad delay \ by \ gradient \ (\varepsilon, \ \alpha) = m_g(\varepsilon)(G_N \cos \alpha + G_E \sin \alpha) \tag{2.42}$$

620 where G represents the gradient vector, and G_N and G_E are the north-south and east-west component of the gradient 621 vector, respectively.

$$m_g(\varepsilon) = \frac{1}{\sin\varepsilon \tan\varepsilon + C'}$$
(2.43)

623 where C is a constant of 0.0032.

624 MacMillan (1995) proposed a gradient model similar to the previous one by replacing $m_e(\varepsilon)$ with $m(\varepsilon)$ cot ε :

625 delay by gradient (ε , α) = $m(\varepsilon) \cot \varepsilon$ ($G_{\rm N} \cos \alpha + G_{\rm E} \sin \alpha$) (2.44)

626 where $m(\varepsilon)$ is the mapping function. Macmillan also indicated that no obvious changes were observed by adopting 627 the hydrostatic or wet mapping function.

628 Meindl et al. (2004) proposed another gradient model using a zenith angle z between the propagating path of 629 satellite signals and the tropospheric zenith direction (i.e., the direction in which the tropospheric delay is at its

- 630 minimum) to replace the angle \check{z} between the propagating path of the satellite signals and the geometrical zenith
- 631 direction to represent the "tilted" atmosphere:

632
$$delay \ by \ gradient \ (\varepsilon, \ \alpha) = \frac{\delta f}{\delta z} \left(G_N \cos \alpha + G_E \sin \alpha \right)$$
(2.45)

633 where z is the tropospheric zenith angle and $\frac{\delta f}{\delta z}$ is the derivative of the arbitrary mapping function with respect to 634 the zenith angle z.

Chapter 3. GNSS meteorology for disastrous rainfalls in 2017-2019 summer in SW Japan: A new approach utilizing atmospheric delay gradients

639

640 The content of this chapter was published in a journal, Frontiers in Earth Science, section Atmospheric Science,641 a special issue on the "GNSS, and InSAR Meteorology".

- 642 Arief and Heki (2020), GNSS meteorology for disastrous rainfalls in 2017-2019 summer in SW Japan: A new
- 643 approach utilizing atmospheric delay gradients, *Front. Earth Sci.*, Received: 26 Jan 2020; Accepted: 07 May

644 2020 | https://doi: 10.3389/feart.2020.00182; **Published:** 23 June 2020

645

646 **3.1 Introduction**

647 Disastrous heavy rains in summer 2017 - 2019 in SW Japan caused a lot of damage to property and human lives. 648 The Japan Meteorological Agency (JMA) officially named the extreme rainfall event in 2018 July as "The Heavy 649 Rain Event of July 2018". Precipitations records at meteorological stations show extreme rainfall from 28 June 650 to 8 July 2018, especially in the northern part of the Kyushu District. Figure 3.1 shows the precipitation rate in 651 the high-resolution nowcast rainfall map at 17:00 JST (08:00 UT), July 6, 2018, from JMA. This was obtained 652 by a weather radar with a 250 m resolution every 5 minutes. Such meteorological radars have been operated by 653 JMA at 20 stations throughout Japan. The heavy rain occurred over a patchy region elongated in NE-SW and 654 overlap with the stationary front. Water vapor transported along the front from SW is thought to have caused the 655 heavy rain.



656

Figure 3.1. High-resolution map of the hourly rainfall at 17:00 JST (08:00 UT) July 6, 2018, from JMA (https://www.data.jma.go.jp/fcd/yoho/meshjirei/jirei01/highresorad/index.html).

The concept of ground-based GNSS meteorology was proposed initially by Bevis et al. (1992), and meteorological utilization of the Japanese GEONET (GNSS Earth Observation Network) has been sought (e.g., Tsuda et al. 1998). Nowadays, GNSS meteorology has become one of the essential means to observe precipitable water vapor (PWV), and PWV data from GEONET have been assimilated in the mesoscale model of JMA to improve weather forecast accuracy since 2009 (e.g., Shoji, 2015). In this study, I apply a new method of GNSS meteorology to utilize atmospheric delay gradients, reflecting azimuthal asymmetry of water vapor (Macmillan, 1995) for the 2017-2019 heavy rain cases in SW Japan.

666 Miyazaki et al. (2003) focused on such atmospheric delay gradients and showed that the temporal and spatial 667 variations of the gradients were compatible with the humidity fields derived from ZWD and with the 668 meteorological conditions in 1996 summer over the Japanese Islands (especially during a front passages). Shoji 669 (2013) and Brenot et al. (2013) demonstrated the important role of the atmospheric delay gradients to detect small 670 scale structures of the troposphere than ZWD.

671 Recently, Zus et al. (2019) have successfully processed the Central Europe GNSS network data to show that the

672 interpolation of ZWD observed with a sparse network can be improved by utilizing tropospheric delay gradients.

673 They showed significant accuracy improvement for the simulation of the numerical weather model, and for the

674 agreement of the simulation results with real observations, relative to the cases without utilizing tropospheric

675 delay gradients.

676 In this study, I propose a new method to use tropospheric delay gradients to study heavy rain phenomena in Japan 677 using the data from the GEONET stations. At first, I analyze behaviors of water vapor on July 6, 2018, using 678 tropospheric parameters obtained from the database published by University of Nevada, Reno (UNR) (Blewitt et 679 al., 2018). The data set includes tropospheric delay gradient vectors (G), as well as zenith tropospheric delays 680 (ZTD), estimated every 5 minutes. I interpolate G to obtain those at grid points and calculated their convergence, 681 similar to the index proposed by Shoji (2013) as water vapor concentration (WVC). Then, taking advantage of 682 the dense GNSS network, I try to reconstruct ZWD in inland regions (especially in high altitude regions) by 683 spatially integrating **G**.

The purpose of this study is to show the implication of utilizing tropospheric delay gradients, in addition to ZWD, to improve our understanding of water vapor dynamics during heavy rains. For this purpose, I reconstruct ZWD and calculate WVC, and compare them with in-situ rainfall data from AMeDAS (Automated Meteorological Data Acquisition System) stations of JMA. Then I explore behaviors of these quantities common for the three heavy rain cases in SW Japan in summer 2017-2019.

689 Since its start, the UNR data base published zenith total delay (ZTD) as well as the tropospheric delay gradient 690 vector G (i.e. no ZWD/PWV). Hence, I removed zenith hydrostatic delays (ZHD) calculated assuming 1 atm 691 atmospheric pressure at sea level and GNSS station altitudes to isolate ZWD. I did not convert ZWD to PWV 692 because the mean atmospheric temperature T_m was unknown. Hence, I used ZWD and G for reconstructing sea-693 level ZWDs and water vapor convergence (WVC) indices, as described in this chapter. The paper Arief and Heki 694 (2020) also used ZWD rather than PWV. However, in 2019 autumn, the UNR data base updated their contents 695 and started to provide PWV and T_m in addition to ZTD and G. Hence, it is now easy to replace the sea-level ZWD 696 with the sea-level PWV and to calculate the Laplacian of PWV rather than ZWD in the discussions of this chapter. 697 In this thesis, however, to keep consistency with the paper Arief and Heki (2020), I continue to use ZTD and G698 downloaded from the UNR data base.

699

700 **3.2 Data and methods: Case study for the 2018 heavy rain**

I use the data from the dense GNSS network GEONET for the entire country operated by the Geospatial
Information Authority (GSI) of Japan (Tsuji and Hatanaka 2018). It consists of more than 1,300 continuously

703 observing stations deployed throughout the country with a typical separation distance of 15-30 km. Because its 704 official solution (F3 solution) does not include tropospheric parameters in high temporal resolution (Nakagawa 705 et al., 2009), I used tropospheric delay data from the UNR database (Blewitt et al., 2018). They estimated 706 tropospheric parameters using the GIPSY / OASIS-II Version 6.1.1 software with the Precise Point Positioning 707 (PPP) technique (Zumberge et al., 1997) and the products for satellite orbits and clocks from Jet Propulsion 708 Laboratory (JPL). They employ the elevation cut-off angle of 7° and estimate ZTD and the atmospheric delay 709 gradients every 5 min (Vaclavovic and Dousa, 2015). They follow the 2010 IERS convention (Gérard and Luzum, 710 2010) and used the Global Mapping Function (Böhm et al., 2006a) and troposphere gradient model of Chen and 711 Herring (1997).

712 **3.2.1 ZWD** and tropospheric delay gradients

713 The equation below is formulated by MacMillan (1995) and explains that the slant path delay (SPD) at the 714 elevation angle θ and the azimuth angle ϕ measured clockwise from north can be expressed as follows.

715
$$\operatorname{SPD}(\theta,\phi) = m(\theta) \cdot [\operatorname{ZTD} + \cot\theta \left(G_{n}\cos\phi + G_{e}\sin\phi\right)] + \varepsilon$$
(3-1)

There, $m(\theta)$ is the isotropic mapping function that shows the ratio of SPD to ZTD, and G_n and G_e are the north and east components, respectively, of the tropospheric delay gradient vectors G, and ε is the modeling error. ZTD is the refractivity of the atmosphere integrated in the vertical direction and is the sum of ZHD and ZWD. In this study, I calculated surface pressure at the GNSS stations assuming 1 atm at the sea-level. Then I calculated ZHD and subtracted it from ZTD to isolate ZWD. Considering average variability of surface pressure, errors by this approximation for summer ZWD remains within a few percent (this operation is unnecessary now because of the inclusion of PWV in the UNR new data base since 2019 autumn).

Tropospheric delay gradients are also the sum of hydrostatic and wet contributions. Because I analyze summer data, I assumed that the latter is dominant and used the gradient as those representing the water vapor. Because of the low scale height of water vapor (~2.5 km), ZWD highly depends on the station altitude. That is, small ZWD observed at highland does not always imply low humidity of the troposphere above that station. On the other hand, atmospheric delay gradients are observed by directly comparing atmospheric delays in different azimuths, and little suffer from the station altitude (Shoji, 2013). This is the reason why I use troposphere gradients to reconstruct ZWD converted to sea-level (see Section 3.2.3).

730 **3.2.2 Water Vapor Concentration (WVC)**

731 Shoji (2013) suggested that two new quantities, WVC and WVI (water vapor inhomogeneity) indices, provide 732 valuable information on non-uniform distribution of atmospheric water vapor in meso- β and meso- γ scales. They 733 complement the information from PWV representing water vapor distribution in meso- α scale. WVI is derived 734 from the post-fit phase residuals in the processing of geodetic GNSS data analysis, but such information is not 735 included in the UNR database. In contrast, WVC indices can be derived as the spatial derivative of ZWD. 736 However, as explained in the previous section, low scale height of water vapor makes ZWD highly dependent on 737 station altitudes, and it is difficult to calculate WVC from ZWD in the mountainous Japanese Islands due to large 738 topographic slopes throughout the region. Shoji (2013) suggested that WVC can be calculated directly using the 739 atmospheric delay gradient vector field, which is immune from the height problem and is readily available in the 740 UNR database.

Following Shoji (2013), I study the behavior of WVC to discuss its relationship with heavy rainfalls. WVC index
expresses the degree of divergence/convergence of the atmospheric delay gradient and represent the shortwavelength concentration of PWV.

$$WVC = -\nabla^2 PWV$$
(3-2)

745 ∇ PWV is the spatial gradient of PWV. I here use the observed tropospheric gradient *G*, divided by the scale height 746 *H* of water vapor.

747
$$\nabla PWV = \Pi \times \nabla ZWD = \Pi \times G/H$$
(3-3)

The station of the spatial Π is the coefficient to convert ZWD to PWV and is a function of atmospheric temperature. ∇ ZWD is the spatial gradient of ZWD and can be expressed as G/H (Ruffini et al., 1999). I here assumed 2.5 km for H. In this study, I first obtained the vector G at grid points with east-west separation of 0.20° and north-south separation of 0.15° all over the country. Here I calculated G at grid points as the weighted mean of G at all the GEONET stations. Larger weight was given to nearer stations. The weight was taken proportional to the Gaussian function of the inter-station distance with one-sigma of 20 km.

Unlike the original definition of WVC by Shoji (2013), I did not convert the wet delay to PWV by multiplying with Π in (3-3). So, our WVC index is actually $-\nabla^2 ZWD$ and are calculated numerically as the convergence of *G*, i.e.

$$-\nabla^2 ZWD = -(\partial G_e/\partial x + \partial G_n/\partial y)/H$$
(3-4)

vising *G* at grid values.

Figure 3.2 shows the tropospheric delay gradient vectors at the grid points and its convergence (WVC) calculated by equation (3-4). As the first case study, I investigate water vapor in the heavy rainfall episode at 08 UT (17 JST) July 6, 2018. There are strong southward gradients in southern Hokkaido and central Tohoku, suggesting southwestward increase of water vapor. In northern Kyushu, I can see large gradient vectors line up, suggesting high concentration of water vapor there.

764



765

Figure 3.2. (a) Atmospheric delay gradients at grid points at17 JST (08 UT) on July 6, 2018 (raw gradient data are shown in Figure 3.4a). Using these gradient vectors at grid points, I calculated their convergence shown in (b), similar to WVC index defined by Shoji (2013).

769

770 **3.2.3 Sea-level ZWD**

- 771 In this study, in addition to WVC, I also reconstruct sea-level ZWD using the observed tropospheric delay
- gradients and ZWD at low elevation (< 100 m) stations (they are assumed to be identical to sea-level ZWD there).
- Although the concept of WVC, discussed in the previous section, is adopted from Shoji (2013), it is our original
- technique to estimate the sea-level ZWD using the gradient vector data as the input.



775

Figure 3.3. Inversion scheme of the sea-level ZWD. I estimate ZWD at grid points, with the east-west separation of D_e (0.20°) and north-south separation of D_n (0.15°), as the parameters, using *G* at all the stations and ZWD at stations with altitudes lower than 100 m. The observation equation of the ZWD at the central grid (*i*, *j*) is given by equation (3-5).

In the inversion, I estimate x(i, j) (i=1,2,..., m_e , j=1,2..., m_n), the sea-level ZWD at the grid point with coordinates (*i*, *j*) (*i*=1,2..., m_e , *j*=1,2,..., m_n). The input data are $G(G_n, G_e)$ at all the GEONET stations. Suppose the situation in Figure 3.3, i.e., the *k*'th GNSS station, is located within a rectangle made of four corners (*i*, *j*-1) (*i*+1, *j*-1) (*i*,

783 *j*) (*i*+1, *j*). Then, the observation equation to relate *G* at this GNSS station G(k) to the sea-level ZWD at grid points 784 x(i, j) is

785
$$G_{e}(k) = \{x(i+1, j) - x(i, j)\}H/D_{e}$$
(3-5a)

$$G_{n}(k) = \{x(i, j) - x(i, j-1)\}H/D_{n}.$$
(3-5b)

To regularize the inversion, I constrain the sea-level ZWD at the grids closest to the GNSS stations with altitude less than 100 meters to the observed ZWD. They indicate that the sea-level ZWD at the grid point x(i, j) is the same as the ZWD y(k) observed at the *k*'th GNSS station, i.e.

790 x(i, j) = y(k). (3-6)

When I estimate the sea-level ZWD over the entire Japanese Islands, the number of parameters (number of grids) is ~1,600, and the number of observations is twice as large as the number of GNSS stations, i.e. ~2,600. Number of GNSS stations with altitudes < 100 m are ~100. Although we have enough number of data to estimate the parameters, I applied a continuity constraint, i.e. x ($i \pm 1$, j) = x (i, j) and x (i, $j \pm 1$) = x (i, j), to further stabilize the solution. I constrained the adjacent blocks to have the same values with a tolerance of 50 mm. I also assumed the ZWD measurement errors and gradient observation errors as 10 mm. Because the inversion is not ill-posed, changing the parameters in these constraints little influenced the solution.

In Figures 3.4 and 3.5, I show inputs and outputs of the inversion, respectively. In Figure 3.5b, I confirm that the atmospheric delay gradient vectors at GNSS stations calculated using the estimated distribution of sea-level ZWD. They are similar to the input shown in Figure 3.4a, suggesting that the inversion is successful. The root-meansquare error between the observed and calculated atmospheric delay gradient is ~0.65 mm in this case.

802






Figure 3.5. (a) Output of the inversion, i.e., sea-level ZWD at grid points at 08 UT (17 LT) on July 6, 2018. (b)
 shows the atmospheric gradient vectors calculated at GEONET stations using the equation (3.5) and the estimated
 ZWD, as shown in (a). They are consistent with the observed gradients shown in Figure 3.4a.

3.3 Results and Discussions

Figure 3.5a shows high ZWD throughout SW Japan, but such a ZWD map still lacks spatial resolution to pinpoint heavy rain, as indicated in Figure 3.1. At a glance, WVC in Figure 3.2b shows good coincidence with the heavy rain given in red and orange colors in Figure 3.1. However, there are regions where WVC is high but heavy rain does not occur. This suggests that both two quantities need to be high for the occurrence of heavy rains. In this section, I study long-term and short-term behaviors of the two quantities in several recent heavy rain episodes in SW Japan. For the former, I see hourly changes of WVC and sea-level ZWD over one-month periods, including the heavy rain episodes. For the latter, I study the change of these quantities every 5 minute over the days of heavy rain.

3.3.1 The 2017 and 2019 heavy rain cases

In Figure 3.2b and 3.5b, I show the WVC index and sea-level ZWD at 08.00 UT (17 JST) when heavy rain occurred. This can be compared with the rain images from the JMA, as shown in Figure 3.1. By comparing Figures 3.2b and 1, I can see that the WVC index successfully pinpoints the heavy rain. This is also consistent with the detailed report of this heavy rain episode compiled by JMA (2018).

Here I perform the same calculation for a heavy rain episode on July 5, 2017, at 07 UT (16 JST) and show the results in Figure 3.6. These figures also show, like in the 2018 case, that both the sea-level ZWD and WVC are high where it rains heavily, as shown in JMA (2017). Likewise, Figure 3.7 shows the sea-level ZWD and WVC for a heavy rainfall episode in August 2019. WVC index pinpoints heavy rainfall, consistent with the information released by JMA (2019).





Figure 3.6. Estimated sea-level ZWD (a) and WVC (b) at 07 UT (16 JST) on July 5, 2017. (c) shows the rain rate map from JMA (2017) at the epoch one hour earlier (06 UT) than (a) and (b).



835

Figure 3.7. Estimated sea-level ZWD (a) and WVC index (b) at 20 UT (05 JST) on August 27 (August 28 in JST), 2019. (c) shows the rain rate map from JMA (2019) at the epoch one hour later (21UT) than (a) and (b).

From these results, I hypothesize that heavy rainfall occurs when both the ZWD and WVC are high. Next, I tryto test the hypothesis by studying time series of the two quantities and rain rate.

841 3.3.2 Validation of the inversion results and the water vapor scale height

842 Here I try to validate the inversion of nationwide sea-level ZWD (PWV), I show two different kinds of diagrams 843 for the 2017-2019 SW Japan heavy rain cases. The first is the comparison between the observed ZWD (PWV) at 844 all the stations and those calculated with the method described in section 3.2.3. The second is the confirmation of 845 the scale height of the water vapor assumed in the inversion. As explained at the beginning of this chapter, I 846 assumed the water vapor scale height of ~2.5 km, and its validity could be assessed by comparing the 847 discrepancies between the observed and the calculated ZWD (PWV) as a function of station altitudes. Figure 3.8 848 shows these two kinds of diagrams for the 2017 (a), 2018 (b), and 2019 (c) heavy rain episodes in SW Japan. 849 There, the results are derived by using the new UNR data base including PWV, and the inversions were performed 850 using PWV instead of ZWD.



852 Figure 3.8. The left panels compare the PWV observed by GNSS (horizontal axis) and the PWV calculated 853 by the inversion from the PWV at low-elevation stations and tropospheric delay gradients of all stations 854 (vertical axis). They should coincide for the low-elevation stations if the inversion is successful. However, for 855 high-altitude stations, the observed PWV should be much lower than the calculated zero-level PWV. In the 856 right panels, I plotted the difference between the two (I picked up data with the calculated PWV within the 857 range between the two horizontal lines) as a function of station altitude. The deviation is consistent with the 858 theoretical curve assuming the water vapor scale height of 3.5 km. This is an independent justification of the 859 scale height I assumed in the inversion program.

860 The Figure 3.8 assumes that the spatial variability of the water vapor scale height is small. Actually, the scale

861 height changes from place to place. The left panels of Figure 3.8 demonstrate that observed and calculated PWV

862 coincide with each other with typical deviation within a few mm for low-altitude stations (shown in green). At

the same time, observed PWV are much lower than the calculated PWV for high-altitude stations. The right panels of Figure 3.8 show the altitude dependences of such deviations. The deviations are seen to align on the theoretical curve $PWV_G = PWV_0 \exp(-H_G/H_{WV})$, where PWV_G and PWV_0 indicate PWV values at the GNSS station and at the sea level and H_G and H_{WV} indicate the station altitude and the water vapor scale height (3.5 km).

867 Figure 3.8 also means that one can interplate the PWV for any altitude using PWV_0 and PWV_G . One big problem 868 in using the GNSS-PWV for the numerical weather forecast is the deviation of the real GNSS station altitude and 869 the surface altitude in the topography model assumed in the numerical weather model. They assume fairly simple 870 and smooth topography for JMA's numerical weather model (spatial resolution is 15 km and 5 km for the meso-871 scale and local analyses, respectively), and such models have large discrepancies from the real station altitudes 872 in mountainous area. Currently, JMA uses PWV from GEONET stations whose altitude deviate less than 200 m 873 from the model topography (Y. Shoji, personal communication) and they use simple conversion from PWV_G to 874 PWV values at the modeled altitude. Now, we have two PWV for one GNSS station, i.e. PWV₀ and PWV_G, and 875 a model connecting the two PWV. Then, we can interpolate PWV at the model topography surface altitude and 876 make use of the whole GEONET PWV data in the numerical weather model.

877 Next, I study the spatial variability of water vapor scale heights by comparing the altitude dependence of the 878 difference between the observed and the calculated PWV as shown in Figure 3.8 in different regions, such as 879 Hokkaido and Kyushu, on the same day. I show the example for the Hokkaido region in Figure 3.9a. There I 880 plotted the data on July 6, 2018, selecting data with sea-level PWV within 5-15 mm. In Figure 3.9b, I compare 881 the data with the theoretical curve based on various values for the scale heights. I tried values ranging from 1 km 882 to 8 km and found that the curve best coincides with the data with the scale height of 8 km, significantly higher 883 than 3.5 km I assumed earlier. I think this anomalously large scale height may not represent the vertical 884 distribution of water vapor. Because I study GNSS data in summer, I naturally assumed that the atmospheric 885 delay gradients reflect the azimuthal asymmetry of the water vapor distribution. However, in the case like Figure 886 3.9, PWV is quite small and the significant part of the atmospheric delay gradients may originate from the dry air 887 whose scale height is much higher than water vapor.



Figure 3.9. (a) compares the PWV observed by GNSS and the estimated sea-level PWV, for the stations in
Hokkaido. In (b), I pick up the data with calculated sea-level PWV 5-15 mm and compare the difference
between the two as a function of station height. The data best fit the dashed curve based on the scale height of
892 8 km.

In the Kyushu region, the results of the results are presented in Figure 3.10 (same day as Hokkaido). The sealevel PWV ranges 60-70 mm, which is quite high in comparison with to the Hokkaido region. The scale height

that fits the "Obs-Calc" curve is 3.5 km (Figure 3.10b). This is not so different from the nationwide value shown

896 earlier.

888



897

Figure 3.10. (a) compares the PWV observed by GNSS and the estimated sea-level PWV, for the stations in
Kyushu. In (b), I pick up the data with calculated sea-level PWV 60-70 mm and compare the difference
between the two as a function of station height. The data best fit the dashed curve based on the scale height
of 3.5 km.

902

903 3.3.3 WVC, sea-level ZWD, and heavy rain

Here I try to justify our working hypothesis that heavy rains occur when the WVC index and sea-level ZWD are both high by analyzing the distribution of water vapor every hour in the three cases, July 2017, July 2018, and August 2019. I present the results in Figure 3.11, which explains the scatter plot of sea-level ZWD and WVC along with hourly rainfall data based on observations at the AMeDAS station of JMA.

I selected the AMeDAS station showing the largest rain for the three episodes, i.e., the Asakura station for 2017, the Yanase station for 2018, and the Shiroishi station for 2019. These three stations are all located in northern Kyushu and recorded heavy rains exceeding 50 mm/hour. Then I picked up the grid point closest to these AMeDAS and compare the three quantities over a month, i.e., 2017 July 2018 July and 2019 August. I can see that ZWD values are high up to 400 mm, and WVC index goes up to 40×10^3 mm/km² when heavy rain exceeding 50 mm/hour occurred on July 5, 2017, July 6, 2018, and August 27, 2019 (Figure 3.11).



914

Figure 3.11. Distribution of hourly values of WVC (vertical axis), sea-level ZWD (horizontal axis), and hourly rain rate (color and circle size) for 2017 July (a), 2018 July (b), and 2019 August (c). The rain rate was measured at the Asakura, Yanase, and Shiroishi AMeDAS stations, respectively, and WVC and ZWD are the values at their nearest grid points. (coordinates given at the upper left corner)

919 Next, I look for data from more AMeDAS stations in Japan on the same days showing hourly rain rates exceeding

- 920 50 mm/hour and found 12 stations for the 2018 July and 5 stations for the 2019 August, the months including
- 921 heavy rain episodes. The 2017 heavy rain was quite local (limited to northern Kyushu), I could not find enough
- 922 number of AMeDAS stations showing rains exceeding 50 mm/hour. From Figure 3.12a, I find that the probability

923 of the heavy rain (> 50 mm/hour) was 14 % for the range of ZWD (400-450 mm) and WVC index (35-50 x 10³ 924 mm/km²), for the month July 2018. Likewise, for the month August 2019, the heavy rain occurred 50 % for the 925 same range of ZWD and WVC index. If I count rains exceeding 20 mm/hour, then the percentages go up to 71% 926 for July 2018, and 78% for August 2019. These results indicate that both the WVC index and sea- level ZWD are 927 high when heavy rains occur. The results also suggest that heavy rains may not occur even when these two 928 quantities are high. Next, I will show time series of these quantities.





Figure 3.12. Same as Figure 3.11b, c, but I stacked data for 12 and 5 AMeDAS stations showing hourly rain
rate exceeding 50 mm in 2018 July (a) and 2019 August (b), respectively. Again, I compare hourly rain rates
with the WVC and ZWD, calculated at the nearest grid points of the AMeDAS stations.

933 3.3.4 Time series analysis

In Figure 3.13, I plot the quantities in Figure 3.11 as the function of time. The two quantities WVC and sea-level ZWD, are given at the top while the rain rate is given at the bottom. The bottom panels also include the time series labeled as "Deviation." This quantity indicates the sum of the deviations of WVC and sea-level ZWD from their averages normalized by their standard deviations. For example, if both quantities deviate from the means by 2σ , the "Deviation" is 4.

Figure 3.13 clearly shows that the two quantities show large deviations from the average values whenever heavy

rains occur. I also see sometimes that high "Deviation" does not coincide with a heavy rain, e.g., 2017 July 20

941 and 2018 July 23. Regarding the time sequence, the high WVC / ZWD times seem to "coincide" with heavy rains

- 942 rather than "precede" them, and the usefulness of monitoring these quantities for weather forecast is not clear
- 943 from this figure.





Figure 3.13. Time series of the two quantities shown in Figure 3.11, WVC and sea level ZWD (blue and green in the top panels), and rain rate at the nearest AMeDAS stations (red in the bottom panels). The bottom panels
also show a new quantity (labeled as "Deviation") in black, the sum of the standard deviation of the two quantities. They are for 2017 July (a), 2018 July (b), and 2019 August (c). High hourly rain rates occur when both the WVC and ZWD record very high values.

- Lastly, I analyzed high time resolution (every 5 minutes) behaviors of WVC, ZWD, and rain rate, for the three
- heavy rain days in 2017/7/5, 2018/7/6, and 2019/8/27, selecting two AMeDAS stations from each episode (Figure
- 953 3.14). I estimated the sea-level ZWD and WVC every 5 minutes for these three days. The results show that both
- WVC indices and sea-level ZWD show large values at the start of the heavy rains. However, for many cases (e.g.,
- 955 Fig. 3.12a, e, f), heavy rains already started before the two quantities reach their peaks, suggesting limited
- 956 applicability of these quantities for weather forecast. ZWD often showed rapid declines after the starts of the
- 957 heavy rainfalls, possibly because of the transformation of water vapor to liquid water.



Figure 3.14. High time resolution (5 minutes resolution) behaviors of rain rate in the sea-level ZWD-WVC
space during the heavy rain days, 2017 Jul. 5 (a: Asakura, b:Hita), 2018 Jul. 6 (c: Imari, d: Ureshino), and
2019 Aug. 27 (e: Saga, f: Shiroishi). The color indicates hourly precipitation of AMeDAS stations
interpolated to match the time resolution of sea-level ZWD and WVC.

963 Chapter 4. Crustal subsidence by water load with a 964 dense GNSS network: A case study of the July 2018 965 heavy rainfall in SW Japan

966

967 4.1 Introduction

Disastrous heavy rains in summer 2018 in SW Japan caused a lot of damage to property and human lives. The Japan Meteorological Agency (JMA) officially named the extreme rainfall event in 2018 July as "The Heavy Rain Event of July 2018". Precipitation records at meteorological stations show extreme rainfalls from 28 June to 8 July 2018, especially in the northern part of the Kyushu District. The heavy rain occurred over a patchy region elongated in NE-SW and overlap with the stationary front. Water vapor transported along the front from southwest is thought to have caused the heavy rain. Figure 4.1 shows the report by JMA of the distribution of cumulative rainfall from 28 June to 8 July 2018.

975 GNSS is a system that is operated to study deformation of the earth's crust. In Japan, continuous observation 976 stations are installed at more than 1,300 points all over the country and operated by Geospatial Information 977 Authority of Japan (GSI) as GNSS Earth Observation Network (GEONET). So far, application of GNSS for 978 meteorological purposes has been limited to the measurement of water vapor or GNSS meteorology. The concept 979 of ground based GNSS meteorology was proposed initially by Bevis et al. (1992), and meteorological utilization 980 of the Japanese GEONET has been sought (e.g., Tsuda et al., 1998). Nowadays, GNSS meteorology has become 981 one of the essential means to observe precipitable water vapor (PWV), and PWV data from GEONET have been 982 assimilated in the mesoscale model of JMA to improve weather forecast accuracy since 2009 (e.g., Shoji, 2015). 983 Arief and Heki (2020) applied a new method of GNSS meteorology to utilize atmospheric delay gradients, 984 reflecting azimuthal asymmetry of water vapor (Macmillan, 1995), for the 2017-2019 heavy rain cases in SW 985 Japan. These topics have been explained in detail in the previous chapter of the thesis.





Figure 4.1. Distribution of areas that suffered from disastrous heavy rains from 28 June to 8 July 2018, along with the value of cumulative rainfall, based on reports from JMA
 (http://www.data.jma.go.jp/obd/stats/data/bosai/report/2018/20180713/jyun_sokuji20180628-0708.pdf: page 17)

992 Here I focus on another way of using dense GNSS receivers to study meteorological events, i.e., crustal 993 deformation caused by water load. Researches on the changes of hydrological loads such as snowpack and glaciers 994 have been carried out using time-variable gravity observations with GRACE (Gravity Recovery and Climate 995 Experiment) satellite systems. GNSS can also be used to study such loads. For example, in Japan, a maximum 996 subsidence of 1 to 2 cm can occur in winter, especially on the Sea of Japan side due to increased loads such as 997 snow (Heki, 2001). In Japan, other loads such as atmosphere, non-tidal ocean load, reservoirs are considered to 998 contribute to the seasonal crustal movement of GNSS stations (Heki, 2004). However, crustal movements to 999 transient meteorological phenomena such as heavy rains have never studied before.

Heavy rain, which causes flooding acts as a surface load and presses the crust to the detected level. In North America, Milliner et al. (2018) conducted research on vertical crustal deformation due to rainfall due to a tropical cyclone (hurricane Hurvey) that made landfall on United States using GNSS receivers around the coast of the Gulf of Mexico. Here I try to analyze the link between crustal movements and a heavy rain episode as a carrier of water from ocean to land in the early July 2018 disastrous heavy rains occurred in SW Japan.

1005 **4.2 Data and Methods**

1006 I use the F3 solution (Nakagawa et al., 2009), which is the official solution from the Geospatial Information 1007 Authority of Japan (GSI). This solution is derived using the Bernese software and ITRF (International Terrestrial 1008 Reference Frame) 2005. This solution is used for analysis of crust deformation in Japan. Analysis of the F3 1009 solution is carried out in two stages: estimation of the reference station, Tsukuba, in ITRF, and the static 1010 positioning of other stations relative to Tsukuba. In the first stage, the coordinates of the Tsukuba station are 1011 determined in the ITRF 2005 with respect to several stations in the Asia-Pacific region around the Japanese islands. 1012 Then, they estimate the position of other GEONET stations relative to the Tsukuba reference station. They 1013 estimate atmospheric zenith delays every three hours but estimate only one atmospheric delay gradient vector per 1014 day. In this chapter, I do not use the UNR solution.

Generally speaking, deformation due to the surface load makes about three times as large displacements in the vertical component than in horizontal components. At the same time, the vertical component suffers from a larger positioning errors than the horizontal components. This time, I used the vertical components to capture crustal signatures of surface loads. Another benefit of the vertical is that the azimuth of the horizontal displacement strongly depends on the distribution of the load, while vertical displacement is less sensitive to such distribution.

1020 In the next section, I explain the way to reduce systematic noises in the displacement signals by removing common 1021 mode errors in the daily F3 GNSS solution data. I followed the method of Heki (2020), i.e., I removed common 1022 mode errors by performing the Helmert transformation for the station coordinates so that positions of the selected 1023 \sim 100 stations coincide with their median positions over periods ranging \pm 15 days around the heavy rainy days.

1024

1025 **4.2.1** Correction of common mode errors

1026 The raw time series of the F3 solution often show outliers which deviate largely from the rest of the coordinate 1027 time series. Such deviations often occur uniformly all over the country, suggesting the error in the fixed reference 1028 point (the Tsukuba station). In the analysis of crustal subsidence using the F3 solution, I made such correction to 1029 remove the common mode errors from the F3 solution.



1030

1031 1032 1033

Figure 4.2. Concept of the Helmert transformation of a certain set of stations to the reference positions. I performed this adjustment of daily GEONET coordinates to the reference position defined as the median of a certain period of time.

1034 I used the Helmert transformation to remove such common errors. The Helmert transformation consists of 7 1035 parameters, translation (3 components), rotation (3 components), and scale change (Figure 4.2). This time, I first 1036 selected ~100 stations from the GEONET stations constructed in 1994 because they are uniformly distributed in 1037 the country (station 940001 to 940099, except a few obsolete stations). I then calculated the median of the 1038 coordinate values for these stations over a time period of about a month centered on the heavy rainfall day. There 1039 I assumed that there are no crustal movement of tectonic origin during that period. Then the seven transformation 1040 parameters were estimated for each of the days by the least-squares method so that the individual daily coordinates 1041 would match the median positions as much as possible. All daily GEONET data were transformed using these 1042 seven parameters.

1043 **4.2.2** Analysis of station position change for one month

In Figure 4.3, I illustrate the basic concept of vertical crustal movement due to heavy rainfall. Immediately after the heavy rain, water will remain on the surface and would exert downward force. It will cause crustal subsidence, as shown in Figure 4.3b. For this process, I can use the Green's function to calculate crustal movements due to known surface loads. After rain, surface water would move downward to recharge groundwater. This process may cause uplift of the surface (Figure 4.3c), but it is not straightforward to calculate the displacement because it is difficult to know the amount of groundwater and physical process of crustal inflation due to water.



1058

1051Figure 4.3. Subsidence of GNSS stations due to the surface load caused by rainwater (a). Surface water1052with 1 cm thickness exerts about 1 hPa downward pressure and depresses the ground (b). Uplift may occur1053when surface water goes down to become groundwater (c).

1054 Figure 4.4 shows the vertical coordinate time series of six GNSS stations in northern Kyushu over a month,

1055 including the heavy rain episode in 2018 July after common-mode error removals. I expect that the GNSS stations

- subsided due to water load in the area of the heavy rain. As seen in Figure 4.4, on heavy rainy day (July 5), the
- 1057 stations in Kyushu show subsidence of 1-2 cm.



1059Figure 4.4. (a) Time series of vertical positions of six stations in northern Kyushu before and after the10602018 July heavy rain. They are relative to the median position during this period. The bottom time series1061are derived as the average of these six stations. These stations show subsidence on the day of the heavy1062rain, July 6, 2018. (b) Map of vertical displacements relative to the 1-month median positions of all1063GEONET stations on July 6, 2018. Stations in (a) are taken from the region within the red rectangle and1064spatially smoothed with averaging radius of 20 km.

1065 The vertical component suffers from larger noise than the horizontal components. In Figure 4.4b, I applied spatial

1066 averaging to reduce noise. There, the smoothing is done by calculating weighted averages of all the data, and the

- 1067 weights were determined by putting the distances from the point into the Gaussian function. The standard
- 1068 deviation σ is a measure indicating the averaging radius used for the spatial smoothing, and I set its value as 20
- 1069 km in this study.

- 1070 Based on the flood map from JMA (Japan Meteorological Agency) shown in Figure 4.1, I selected 7 regions
- 1071 affected by floods, the prefectures Saga, Fukuoka, Oita, Hiroshima, Hyogo, Toyama, and Gifu, from west to east,
- and I plot average time series of vertical positions of 5 stations selected from each region in Figure 4.5.

1073 In addition to the amount of maximum subsidence, I can see phase lags of the subsidence coming from the time 1074 lag of strong precipitation, i.e., the largest subsidence occurs later in more easterly regions For example, in the 1075 Hyogo area, the red circle in Figure 4.5a shows the lowest subsidence value occurred on July 6, 2018, the next 1076 day of the precipitation maximum in Kyushu. In the Oita and Toyama areas, the blue circle in Figure 5a, large 1077 subsidence seems to occur over multiple days.

1078



1080Figure 4.5. Average time series of vertical coordinates of five stations (a) taken from 7 regions indicated1081as red squares in (b). Origin of the horizontal axis is taken on July 5, 2018. The largest subsidence in Hyogo1082occurred one day later, i.e., on July 6, 2018 (red circle in a), while they occur on July 5 in other regions. In1083Oita and Toyama, large subsidence continues for two consecutive days (blue circles in a).

1084

1079

1085 4.2.3 Crustal subsidence in the 2017 and 2019 heavy rain episodes in Kyushu

1086 In addition to the 2018 heavy rain episode, similar disastrous heavy rain occurred in July 2017 and August 2019 1087 in northern Kyushu. Here I obtained the time series of multiple GNSS stations and their averages from the heavy 1088 rain area and show them together with the distribution of vertical displacement on the days, 2017 July 05 and 2019 August 28, in Figures 4.6 and 4.7, respectively. The displacement map data are spatially averaged in thesame way as the 2018 case.

In the 2017 episode, the heavy rain was quite local and occurred only in northern Kyushu. Accordingly, as shown
in Figure 4.6, area of large subsidence is limited to northern Kyushu. This situation is very different from the
2018 case, where wide-spread heavy rain caused floods and consequent crustal subsidence throughout SW Japan
(Figure 4.5).



1095

1096Figure 4.6. (a) Time series of vertical position of six stations in northern Kyushu before and after the 20171097July heavy rain. They are relative to the median position during this period. The bottom time series are1098derived as the average of these six stations. These stations show subsidence on the day of the heavy rain,1099July 5, 2017. (b) Map of vertical displacements relative to the 1-month median positions of all GEONET1100stations on July 5, 2017. Stations in (a) are taken from the region within the red rectangle and spatially1101smoothed with averaging radius of 20 km.

1102 For the case of August 28, 2019, I picked up the same region and the same 6 stations and plotted the results in

- 1103 Figure 4.7. There, the average land subsidence reached ~1.5 cm. The area of subsidence is larger than in the 2017
- 1104 event (Figure 4.6) but is less than in the 2018 event (Figure 4.5).



1105

1106Figure 4.7. (a) Time series of vertical position of six stations in northern Kyushu before and after the 20191107August heavy rain. They are relative to the median position during this period. The bottom time series are1108derived as the average of these six stations. These stations show subsidence on the day of the heavy rain,1109August 28, 2019. (b) Map of vertical displacements relative to the 1-month median positions of all GEONET1110stations on August 28, 2019. Stations in (a) are taken from the region within the red rectangle and spatially1111smoothed with averaging radius of 20 km.

1113 4.2.4 Day-to-day variability of crustal subsidence: The 5-8 July 2018 case

1114 Here I focus on the days following the peak heavy rain in 2018 July 5. I study crustal subsidence during the days 1115 after the peak heavy rain, i.e., 6-8 July 2018. I found the migration of the peak subsidence area and changing 1116 amplitude of the subsidence. On the July 6, 2018, I identified 5 subsidence areas, namely Nagasaki, Oita, Ehime, 1117 Hyogo, and Toyama Prefectures (Figure 4.8b). On average, I collected the average subsidence using 5 GNSS 1118 stations representing each of the five areas. On July 7, large subsidence appeared in areas Nagasaki, Shimane, 1119 Okayama, Tokushima, Hyogo, and Shiga Prefectures (Figure 4.8c). However, on the last day of July 8, such 1120 subsidence disappeared except in the Gunma Prefecture (Figure 4.8d). This is in accordance with the conditions 1121 of heavy rain had begun to decrease on July 8. During the period 5-8 July 2018, I identified 14 areas and days 1122 where significant land subsidence occurred, as summarized in Table4.1. The pattern of land subsidence from 5 to 1123 8 July 2018 is characterized as the movement from southwest to central Japan.





Figure 4.8. Smoothed map of subsidence during a 4 days period following the heavy rain day July 5 (a), 6
(b), 7 (c), and 8 (d) July 2018. Red rectangles show areas of significant subsidence on the special days.

1127

Table4.1. Crustal subsidence calculation results on 5-8 July 2018, in 14 regions, (unit = cm)

No.	Region	5-Jul-18	6-Jul-18	7-Jul-18	8-Jul-18
1	Fukuoka	-1.632			
2	Gifu	-1.091			
3	Hiroshima	-1.488			
4	Hyogo	-1.164	-1.911	-0.758	
5	Oita		-1.641		
6	Saga	-1.743			
7	Toyama		-1.055		
8	Ehime		-1.105		
9	Nagasaki		-1.848	-1.114	
10	Okayama			-0.768	
11	Totto			-1.023	
12	Kyoto			-1.52	
13	Tokushima	l		-1.401	
14	Gunma				-1.537

1128

1130 **4.3 Result and discussions**

1131 **4.3.1 Estimation of water load from crustal subsidence**

1132 Next, I estimate surface water load responsible for crustal subsidence, and I follow the way Milliner et al. (2018)

1133 did to infer the dynamics of stormwater from the Hurricane Harvey in southern United States. I use the vertical

displacement field from GNSS station position data over a four-days period, from 5 to 8, July 2018, i.e., thoseshown in Figure 4.8. Only vertical displacements are used.

The vertical station movements observed during this period is considered to be the deformation by the accumulation of water on the surface (including those in the soil or aquifer). The treatment of water within soil and aquifer is not straightforward. Such water may depress the ground as load, just like surface water. At the same time, it may cause uplift by inflating the soil or aquifer, as shown in Figure 4.3c. In this study, I only consider loads, i.e., depression of ground by surface mass, and it is beyond the scope of the thesis to discuss their status, surface water, soil moisture, or groundwater.

First, I set up blocks with dimension 1/4 degrees in latitude 1/6 degrees in longitude and assume that the water depth is uniform within individual blocks. Subsidence *S* by surface load when the earth is treated as an elastic substance is obtained as follows by using the Green's function (Farrell, 1972).

1145
$$S(\theta, \lambda) = \rho_{w} \iint H(\theta', \lambda') Gr(\phi) d\theta' d\lambda'$$
(4.1)

1146 θ , λ : Latitude and longitude in the observing point, θ' , λ' : Latitude and longitude of load

1147 $\rho_{\rm w}$: water density, H: water depth, ϕ : distance between load (θ' , λ') and observing point (θ , λ)

- 1148 *Gr* : Green's function, *S*: Crustal subsidence
- 1149

1150 Actually, the areal integration is replaced by the addition of subsidence caused by discrete number of blocks 1151 whose area is *A*. Subsidence of the *j* 'th GNSS station at (θ_j, λ_j) can be expressed as the sum of the contributions 1152 from *M* loads. Let ϕ_{ij} be the distance between the *i*'th load and the *j*'th GNSS station, then (4.1) becomes

1153 $S(\theta_i, \lambda_i) = \rho_{wA} \Sigma^{M}{}_{i=1} H(\theta_i, \lambda_i) Gr(\phi_{ij}).$ (4.2)

In the forward approach, I could tune the load distribution so that the calculated subsidence at the GNSS stations coincides with the observed values. Here I performed least-squares inversion to estimate $H(\theta_i, \lambda_i)$ (*i*=1... *M*) as the parameters and using S (θ_j , λ_j) (*j*=1,..., *N*) as the input data. In this case, *M* is 1323, i.e., I set up 1323 blocks with the dimension of 1/4 degrees in latitude and 1/6 degrees in longitude covering the land area of SW Japan.

N is the number of GNSS stations, and it is only about a half of the number of load blocks (number of GNSS
stations in SW Japan is about 1/2 of the total GEONET station number). To regularize the inversion, I introduced

- 1160 the continuity constraint, i.e., I assumed the neighboring blocks have same load values *H* with a specific allowance.
- 1161 I gave the allowance of 100 cm, i.e., the standard deviation of the difference between adjacent blocks is ~100 cm.
- 1162 I also assumed the observing error of the vertical position as 5 cm. In addition to the continuity constraint, I

1163 constrained the water load around zero for coastal blocks (blocks with one of the four sides is not connected to

- another block) with allowance equal to the continuity constraint. This is equivalent to the assumption to assume
- 1165 zero load for the ocean (precipitation on ocean flows out and does not stay there).

1166 **4.3.2 Estimated surface water load**

1167 Next, I analyze the terrestrial water load estimated from crustal subsidence. Figure 4.9 compares the observedand calculated subsidence and the distribution of the estimated load.



1169

1170Figure 4.9. The observed (left) and calculated (middle) subsidence of GNSS stations on July 5, 2018. The1171estimated distribution of surface water load (right) shows the total volume of surface water as 68.2 km³ (68.21172Gt as the mass). The number of stations used in the calculation is 613, and the post-fit residual RMS is 2.181173cm. The unit of the water load is 10 cm, and so "10" means 100 cm.

- 1175 5 results in Figure 4.10. The recovered total amount of surface water over the period July 5 -8, 2018, is 68.2 km³,
- 1176 72.3 km³, 67.6 km³, and 19.3 km³ (Figure 4.10). I also can see the eastward migration of the load, i.e., they
- appeared first in northern Kyushu, and the center of load moved to the Chugoku District and then to the Kansai
- 1178 District. Water mostly disappeared on July 8, 2018.
- 1179These results are consistent with the report from Japan Meteorological Agency (JMA)1180(http://www.data.jma.go.jp/obd/stats/data/bosai/report/2018/20180713/jyun_sokuji20180628-0708.pdf : page
- 1181 21-23), i.e., the warning issued first at 08 UT on July 06 in Kyushu, then in Chugoku at 11 UT on the same day,
- and finally in the Kinki District at 14 UT. On July 8, 2018, Figure 4.10 shows some amount of uplift, and this
- 1183 may come from the aquifer inflation after the stormwater became groundwater, as shown in Figure 4.3c.

¹¹⁷⁴ Next, I repeated the same calculation for three more days, 6-8 July 2018. They are shown together with the July



1184

1185Figure 4.10. The calculated vertical movements (top) and load distribution (bottom) for the 4 days period1186July 5-8, 2018. The recovered total amount of surface water over the period July 5-8, 2018, is 68.2 km³, 72.31187km³, 67.6 km³, and 19.3 km³, respectively.

1188 Next, I count the cumulative rainfall that occurred over this period. The data come from AMeDAS rain gauges

- 1189 run by JMA. This shows how much water is recorded at the AMeDAS ground stations. I calculate the daily values
- 1190 of cumulative rains for 4-7 July, 2018, and the results are given in Figure 4.11.



1192Figure 4.11. The cumulative rainfall calculated from rain gauge data at all AMeDAS-JMA stations. These1193values are expected to be correlated with the amount of water load in Figure 4.10 (bottom). For the period 4-11947 July 2018, the daily cumulative precipitation at the AMeDAS stations are 5.2 km³, 16.8 km³, 21.7 km3, and11957.5 km³, respectively.

The results show that the amount of water inferred from crustal subsidence is significantly higher than the AMeDAS rain gauge results. This might be explained by the three factors, (1) The AMeDAS rain is underestimated. In general, there is more water in high mountains, but AMeDAS stations tend to be built in valleys. Hence, the real amount of the rainfall will be more than AMeDAS rain gauge data show. (2) AMeDAS data are cumulative amount of rain over one day, but surface water may reflect rain over the past few days. (3) GNSS stations tend to be installed the valley where rain concentrate (discussed later with Figure 4.13). To address problem (1), I compare the AMeDAS rain gauge data with the radar rain-gauge analyzed precipitation (RRAP) data, obtained by calibrating the rain radar data with the AMeDAS rain gauge data. They cover the land continuously with spatial resolution of ~1 km, and do not suffer significantly from non-uniform distribution of the AMeDAS stations.



1206

1207Figure 4.12. The high-resolution cumulative rainfall calculated using the radar data calibrated with1208conventional rain gauge data (officially called the "Radar Raingauge Analyzed Precipitation"). For the1209period 4-7 July 2018, the daily volume of water from this data set is 5.42 km3, 16.79 km3, 22.11 km3, and12107.60 km³, respectively. These cumulative rainfall values are only slightly lager than the AMeDAS rain1211gauge data shown in Figure 4.11.

- 1212 I also discuss the problem (2), I tried to add up the amount of AMeDAS rainfall water from 4 to 7 July 2018
- 1213 and found the sum around 51.2 km³. This amount is close to the amount of the water load estimated from the
- 1214 crustal movement on July 7, 2018 (67.6 km³), However, the crustal movement time series (Figures 4.5, 4.6, 4.7)
- 1215 suggest rapid drain of rainwater to the sea (with timescales of 1-2 days), and it is difficult to consider the water
- 1216 stay on surface for 4 days or more.
- 1217 To assess problem (3), I compare GNSS station altitudes with the average altitudes of the surrounding terrain.
- 1218 In Figure 4.13, we can see that altitudes of the GNSS stations are significantly lower than the surrouding region
- 1219 (e.g. stations are built along valleys surrounded by highland). This would let rainwater concentrate around
- 1220 GNSS stations, causing extra subsidence of GNSS antenna relative to the average subsidence of the region. By

1221 using such biased subsidence data, one would naturally overestimate the amount of water on the surface. It is

- 1222 likely that this problem (3) is largely responsible for the discrepancy between the estimated water load and
- 1223 precipitation. Additionally, thick sedimentary layers beneath the GEONET stations may also locally reduce the
- 1224 crustal rigidity. After all, it is not a simple matter to evaluate such a "topography factor" quantitatively.



1226Figure 4.13. GEONET stations (black dots) drawn in the ETOPO1 topographic map (left), and1227comparison of GEONET station altitude with the average altitude of a square (20 km x 20 km, with the1228GNSS station at the center). If they coincide, the data would distribute around the dashed line.

1229

1230 **4.3.3 Amount water vapor in the sky**

1231 As shown in Chapter 3 and in Arief and Heki (2020), I estimated sea-level ZWD at grid points all over Japan, for 1232 the heavy rain episodes in 2017, 2018 and 2019. We could convert the estimated sea-level ZWD into the amount 1233 of atmospheric water vapor with the conversion factor \prod , which is approximately 0.15 (this value actually 1234 depends on $T_{\rm m}$). As described in detail in Section 3.1, UNR data base now provides PWV in addition to ZTD and 1235 tropospheric delay gradients. Here I directly used such sea-level PWV data estimated in the same way as the sea-1236 level ZWD. Total amount of PWV tells how much water exists in the sky in the form of water vapor. Then, I 1237 integrated the PWV over Japan by spatially integrating them. I give an example for the 2018 July heavy rain 1238 episode in Figure 4.14.



1239

1240Figure 4.14. Comparison of the total amount of water above SW Japan during the 2018 heavy rain episode,1241inferred in three different ways. The second panel from the left shows the water estimated from the crustal1242subsidence (left panel). The second panel from the right shows the precipitation at the AMeDAS stations1243from rain gauges. The right panel shows the precipitation water vapor (PWV). The volume of water1244estimated from the crustal subsidence, AMeDAS rain gauge, and PWV are, are 72.3 km³, 21.7 km³, and 25.71245km³, respectively.

1246 Figure 4.14 compares the total amount of water above SW Japan during the 2018 heavy rain episode, inferred in

1247 three different ways. They include the amount of water estimated from crustal subsidence, precipitation from

1248 AMeDAS rain gauges, and sea-level PWV reconstructed from PWVs in low-altitude stations by GNSS-MET

approach. In Figure 4.15, I compare these three quantities for the 2017 and 2019 heavy rain episodes.



1250

1251Figure 4.15. Comparison of the amount of water from three approaches for the 2017 and 2019 heavy rain1252episodes in SW Japan. See the caption of Figure 4.14 for detail.

- 1253 As seen from Figures 4.12 and 4.13, the amount of surface water estimated from crustal subsidence exceeds the
- 1254 precipitation. This is physically strange, because only a part of the precipitation would stay on the ground and
- 1255 other parts would run-off to the sea. This paradox stays unsolved in this thesis, and future studies would clarify
- 1256 the origin of the discrepancy.

Chapter 5. Analysis of the Tropospheric Delays in Indonesia Estimated using the goGPS software

1261

1262 **5.1 Introduction**

In the GNSS data analysis to obtain tropospheric parameters (Chapter 3) and station positions (Chapter 4), I did not estimate them myself but downloaded them from appropriate data sets available from various research centers, such as UNR and GSI. These studies are performed for heavy rain episodes in the Japan area where large number of GNSS stations are available. In this chapter, I try to analyze the GNSS data taken in Indonesia. Here, I estimate tropospheric parameters as well as station positions using an alternative way, i.e. data analysis made by myself using an appropriate GNSS software package.

UNAVCO (<u>https://www.unavco.org/software/data-processing/postprocessing/postprocessing.html</u>) says that there are 3 distributions of GNSS software based on their use: "Research-Level", "Open-Source" and "Commercial". I think the use of Open-Source software in Indonesia is quite promising and will develop rapidly considering that it is easy to obtain and simple to operate to get results.

The goal of this chapter is simply to show that GNSS meteorology can be applied in Indonesia as well as in Japan, by estimating zenith tropospheric delays (ZTD) from continuous GNSS stations in Indonesia, using one such software package "goGPS". At first, as the evaluation of the goGPS performance, I compared the estimated tropospheric delay gradients and ZTD from goGPS with other products from IGS and UNR. Then I compare the ZTD values from goGPS during the dry and rainy seasons. Finally, I compare the PWV time series with the daily rain data, during the dry season and the rainy season 2015-2016.

1279 **5.2 Data and Methods**

1280 **5.2.1 Data set**

1281 The primary format of the GNSS data that I use in this study is the Receiver Independent Exchange (RINEX) 1282 format. As the first station, I use the BAKO station with coordinates 106.5E -6.3N managed by BIG / 1283 BAKOSURTANAL, and I use, as the second station, the JOG2 station with coordinates 110.2E -7.4N, which is

- 1284 managed by GFZ (Geoforschungs Zentrum), the German Geo-research Center. As the period of this study, I use
- 1285 days of the year (DOY) 022-025, 22-25 January, and DOY 230-233, August 17-20, 2018. The former represents
- 1286 the rainy season, and the latte represents the dry season. Next, I process RINEX files to estimate tropospheric
- 1287 parameters using sophisticated open-source GNSS software, called goGPS, version 1.0 Beta, from Geomatics
- 1288 Research and Development s.r.l. Lomazzo, Italy (Realini, 2009).

1289 **5.2.2 Software goGPS**

1290 The leading software for processing RINEX data, goGPS. (Realini, 2009), is an open-source software initially 1291 developed by Dr. E. Realini (with contributions from the various thesis works by master students) since 2007 at 1292 the Geomatics Laboratory of Politecnico in Milano, Como Campus. It is specifically designed to improve the 1293 positioning accuracy of low-cost GNSS devices by relative positioning and the Kalman filtering technique. 1294 goGPS code was published online as free and open-source software in 2009. The project is open to collaborations 1295 since its publication, and it has received supports and code contributions by users working in both academy and 1296 business companies in different countries (including Italy, Japan, Switzerland, Spain, and Germany). Strategies 1297 for processing RINEX data with goGPS are as shown below,

goGPS 1.0 Beta				
Strategy	Constellation: multi GNSS			
	Processing technique: precise point positioning (PPP)			
	Elevation cut-off angle: 7°			
	Data processed in a two 24 h sessions (from 00:00 to24:00 UTC			
	and from 12:00 UTC on day D to 12:00 UTC on day $D+1$)			
	Frequency: L1, L2			
Orbits and clocks	Fixed to JPL final orbits and clocks			
Observation rate	30s sampling rate			
Observation weighting	Uniform - all observations equally weighted			
Tropospheric modeling	Niel Mapping Function			
	Macmillan Mapping function for gradients			
	A-priori zenith delay - VMF gridded zenith delays			
	Meteorological data - Standard Atmosphere			
Tropospheric estimates	One ZWD per 30 seconds,			
	One tropospheric gradient per 30 seconds			

1298

1299 **5.2.3 Precision Point Positioning (PPP)**

1300 The precise point positioning is used as a post-processing method for determining the absolute position using

1301 stand-alone (thus un-differenced) GNSS receivers. GNSS PPP processing uses the ionosphere-free combinations

1302 of dual-frequency pseudoranges and carrier-phase observations. The preference for PPP instead of double-

- 1303 difference (DD) processing arises from the benefit that (1) each GNSS station can be processed independently,
- 1304 and that (2) simultaneous observation of the same satellite of the two stations are not needed (Yuan et al. 2014).
- 1305 To compare and validate the ZTD values I estimated with goGPS, I used two international tropospheric products
- 1306 from International GNSS Services (IGS) with commercial software version 5 of the Bernese software, and the
- 1307 other products from University of Nevada Reno (UNR) obtained using the GIPSY / OASIS II software from
- 1308 NASA Jet Propulsion Laboratory (JPL) (Blewitt et al., 2018).

1309 **5.3 Result and discussions**

1310 **5.3.1** Comparison of the estimated tropospheric delay gradients with other products

Here I compare estimated atmospheric delay gradient vectors using the data from the JOG2 station on August 20,
2018 with those from other products, namely those from IGS and UNR. The correlation of the goGPS and IGS
delay gradient values for the north is 0.47 and 0.41 for the east, while the correlation between the goGPS and
1314 UNR delay gradient values is 0.71 for the north and 0.75 for the east. I plot them in Figure 5.1 and Figure 5.2







1318

- 1319Figure 5.2. Comparison of the east component of the atmospheric delay gradient, between goGPS, IGS and
UNR. Correlation of goGPS results with those from IGS and UNR is quite high.
- 1321 From the correlation value the goGPS delay gradients and the IGS and UNR products show good consistency,
- 1322 although the goGPS solution shows more short-period changes. As a whole, the data processing with goGPS is
- 1323 good enough to get accurate values of not only the ZTD (to be discussed in 5.3.3) but also the delay gradients.
- 1324 Therefore, in this research, I estimate ZTD using goGPS software together with the tropospheric delay gradients.

1325 5.3.2 Comparison of the ZTD values of goGPS, IGS and UNR

- 1326 Next, I compare the ZTD values for the three solutions, namely goGPS, IGS and UNR, using the BAKO and
- 1327 JOG2 stations, on January 24, 2018 and August 20, 2018. This is as part of the validation process of determining
- 1328 ZTD values with goGPS.
- 1329 The results show a small RMS value <2 mm. The RMS value is relatively small, meaning that the tropospheric
- 1330 parameters estimated with goGPS show good agreement with the products from UNR and IGS.



1331

1332Figure 5.3. ZTD time series from goGPS, IGS, and UNR, during 24, Jan. 2018, at the BAKO station.1333The standard deviation and RMS of the difference between goGPS and IGS are 12.03, 0.81, respectively1334(in mm). Those for the goGPS-UNR pair are 11.22, 0.66



Figure 5.4. Same as in Figure 5.3, but the BAKO station is replaced by the JOG2 station. The standard deviation and RMS of difference between goGPS and IGS are 16.11 and 1.11, respectively (in mm). Those for the goGPS-UNR pair are 15.00, 1.63.



Figure 5.5. Same as Figure 5.3, but the date is 20 Augt 2018. The standard deviation and RMS of the difference between goGPS and IGS are 7.44 and -0.66, respectively (in mm). Those for the goGPS-UNR pair are 8.09 and 0.26.



1343

1344Figure 5.6. Same as in Figure 5.5, but the BAKO station is replaced by JOG2 station. The standard1345deviation and RMS of difference between goGPS and IGS are 16.99 and -1.32, respectively (in mm).1346Those for the goGPS-UNR pair are 18.33 and -1.08.

The results of the ZTD values that I obtained using goGPS, both in January 24 and August 20 and the BAKO and
JOG2 stations, are shown in Figures 5.3 - 5.6. The whole pictures show the consistency of the ZTD value from

1349 goGPS with other solutions. The goGPS software package works quite well at different times and stations. This

1350 means that it can be an alternative to commercial software systems for the ZTD estimation.

1351 **5.3.3 ZTD range value from goGPS**

1352 Next, I tried to make a range of ZTD values to see the difference between the existing seasons in Indonesia,

1353 namely the rainy season and the dry season. First, I process data from the BAKO and JOG2 stations from 22 to

1354 25 January 2018. The rate of atmospheric parameter estimation is every 5 minutes, and so we get 288 values data

1355 for one day (24 hours). From these 288 data, I get the smallest, the most significant, and the average values, as

- 1356 presented in Figure 5.7.
- 1357 Next, I carried out the same process from 18 to 21 August 2018. I present the results in Figure 5.8. ZTD values
- from 22 to 25 January 2018 (rainy season) in the BAKO station tend to be higher than those from 18 to 21 August
- 1359 (dry season) 2018. Likewise, at the JOG2 station, ZTD in January 2018 is higher than those in August



1361 Figure 5.7. Minimum, maximum, and the average ZTD values for 22-25 Jan 2018 at BAKO and JOG2 stations



1362

Figure 5.8. Minimum, maximum and the average ZTD values for 18-21 Aug. 2018 at the BAKO and JOG2
stations. The difference of about -100 mm from those shown in Figure 5.7 reflects the smaller amount of water
vapor during the dry season.

1366 Figure 5.7 and Figure 5.8 show that there are large seasonal differences in the ZTD value, and this difference

1367 reflects the seasons in Indonesia. The ZTD values obtained by the goGPS software clearly showed the difference

- between the rainy season (January) and the dry season (August). In subsection 5.3.4, I will try to compare ZTD
- 1369 values with daily rainfall conditions and radiosonde data.
- 1370

1371 5.3.4 Comparison of PWV and rainfall

1372 The software package goGPS can estimate not only ZTD but can also isolate ZWD and convert it to PWV. Here

1373 I try to compare the PWV values from GPS receivers at the CMAK station in Makassar, South Sulawesi, with the

- 1374 PWV value observed at the WAAA radiosonde station in Makassar City. The altitudes of the CMAK stations and
- 1375 the WAAA stations are 77,595 m and 13 m, respectively, while the distance between CMAK and WAAA stations

- 1376 is about 18 km. I perform the comparison in the dry season, April September 2015, and in the rainy season,
- 1377 October 2015 March 2016. The results are given in Figures 5.8 and 5.9.



Figure 5.9. Comparison of PWV values from goGPS and radiosonde, together with the daily rainfall data in the city of Makassar during the dry season in 2015.

- 1381 The correlation of PWV values from GPS and radiosonde for the dry season (Figure 5.9) and in the rainy season
- 1382 (Figure 5.10) are 0.84 and 0.73, respectively.
- 1383 Figure 5.9 shows that the PWV value during this dry period has a negative trend. On the other hand, Figure 5.10
- 1384 shows the positive trend of PWV during this period of the rainy season. The RMS values of the differences
- between the goGPS PWV and radiosonde are 0.91mm in the dry season of and 1.31mm in the rainy season. Thus,
- 1386 the PWV values from goGPS and radiosonde are mostly consistent with each other.





- 1391 Figures 5.9 and 5.10 illustrate the contrast between seasons in Indonesia, the dry season of April-September 2015
- and the rainy season of October 2015-March 2016 using the daily rainfall and the PWV values, from the goGPS
- 1393 GNSS data processing and the conventional radiosonde data.

Chapter 6. Correlation between land subsidence and heavy rainfall in Jakarta on January 1, 2020

1396

1397 6.1 Introduction Jakarta flood on January 1, 2020

In this chapter, I try to apply the GNSS meteorology to the heavy rain events in early 2020 in Jakarta, and to study the correlation between rainfall and the land subsidence in the heavy rainfall area. Jakarta suffered from a flood on January 1, 2020. According to a report from the Indonesian Meteorology and Climatology Geophysics Agency (BMKG), the main cause was the heavy rainfall. The rain gauge at the Halim Perdanakusuma station showed the rainfall of 377 mm on that day. The rain gauge at the station Taman Mini and Jatiasih recorded rain amounting to 335 mm/day and 260 mm/day, respectively. This rainfall distribution covers a large area and is quite high in value as in Figure 6.1


1406 Figure 6.1, Map of the areas in Greater Jakarta showing the likely flooded areas (light blue 1407 pixels), based on synthetic aperture radar satellite data before (21 December 2019) and 1408 January 2020) the flood event. Based on the during (02)web page 1409 https://earthobservatory.nasa.gov/images/146113/torrential-rains-flood-indonesia, 1410 I identified at least 5 GNSS stations with separations of ~30 km from each other. 1411 The largest rainfall of 377 mm/day is recorded in BMKG, and this is the highest value in the history of rain 1412 records in Jakarta. Jakarta, as the capital city of Indonesia, is an important area that should get attention related 1413 to the occurrence of floods due to heavy rains. Today, GNNS has been widely used for meteorological purposes, 1414 as explained in the previous chapter, in addition to the primary function for measuring crustal movement and for 1415 mapping surveys. Here, I tried to analyze the link of heavy rainfall to the temporary land subsidence using the 1416 GNSS data. The data were provided from the INACORS network of the Indonesian Geospatial Information 1417 Agency (BIG).

1418 **6.2 Data and Methods**

1419 **6.2.1 GNNS data set**

In the flood area, I identified at least 5 GNSS stations managed by BIG in the INACORS network. The 5 stations
include CJKT in Jakarta, BAKO in Bogor, CBTU in Cibitung, CRKS in Cirakas, and CTGR in Tangerang. I
obtained the GNSS data on the INACORS network in the RINEX format. I used the data over 7 days, from29th
December 2019 to 4th January 2020 in order to see the phenomenon including the changes several days before
and after the flood and heavy rain.

As described in Chapter 5, I used RINEX data to get tropospheric parameters using the goGPS open-source software, version 1.0 Beta from Geomatics Research and Development s.r.l. - Lomazzo, Italy, (Realini, 2009). The wet tropospheric delays are converted to PWV (Precipitable Water Vapor) every 30 seconds. Large PWV brings intensive rainfall, and the record-making rainfall data from BMKG on 1 January 2020 would have been associated with high PWV values. I also analyze the vertical crustal movements using coordinates obtained by analyzing the RINEX data using the goGPS software.

1431

1432 6.2.2 Land Subsidence in Jakarta

Secular land subsidence in Jakarta, due to urbanization, has been studied over a long time. For example, Andreas et al. (2019) showed that Jakarta, compared with major cities on the coast of other countries, occupies the first position in terms of land subsidence since 1920 until now (Figure 6.1). Jakarta is vulnerable to further land subsidence, especially when heavy rain occurs and rainwater pools to cause a flood.





1438Figure 6.2, Land subsidence in several coastal city in different countries1439including Jakarta, Indonesia, from 1920 until recent years (Andreas et al.,14402019).

1441 In this study, I discuss the temporary land subsidence related to the occurrence of heavy rain on January 1, 2020,

1442 using the GNSS data analyzed with the open source software goGPS. When the heavy rain occurs, the water will

1443 gather at the surface of the land. This makes water loads to depress the ground surface and make it subside.

1444 **6.3 Result and discussions**

1445 **6.3.1 Determination of PWV values at 5 INACORS stations.**

1446 As I did in Chapter 5 for the GNSS-meteorological studies, Here I try to study the crustal movements for the

1447 recent of heavy rainfall event in Indonesia on January 1, 2020. This rain caused severe flooding around the Jakarta

- area, and would be an appropriate case to study crustal deformation by surface rainwater load.
- 1449 I analyzed the RINEX data obtained from INACORS-BIG network, using the goGPS open-source software
- 1450 package, as explained in Chapter 5. Before studying crustal deformation, I estimated the ZTD value, and then
- 1451 isolated the ZWD value, and converted the ZWD value into the PWV. In Figure 6.3, I show the result of the PWV
- 1452 time series at five INACORS stations evenly distributed within the flooded area on January 1, 2020.





1457 As seen in Figure. 6.2, the PWV values at the five GNSS stations show similar patterns even in spite of the

1458 average inter-station of ~30km. PWV values appear to increase in the middle of the day of 30 December 2019,

1459 and the peak occurred at the end of the day of 31 December 2019. This condition is consistent with the date of

heavy rain as discussed in Section 6.2.

1461 The PWV value showed a sudden drop in the middle of the day 1 January 2020. At the end of the day, PWV

1462 increased again, but not as high as the first peak. From January 2, 2020, PWV decreased and kept nearly constant

1463 until January 4. In this time range, there were two peak PWV occurrences. The first peak PWV of ~70 mm and

1464 the second peak of ~65 mm, and the largest PWV was recorded at the CJKT station.



1465

1453

1466Figure 6.4. Rain rate and cumulative rain on December 31, 2019, according to the hourly rainfall data1467set from JAXA Global Rainfall Watch. The highest rainfall peak occurred around at 10.00 am (UT) on1468that day.

1469 Next, I analyze the rainfall events on 31 December 2019, using data from JAXA Global Rainfall Watch, which

1470 offers hourly rainfall data. Figure 6.4 shows the hourly rainfall in the Jakarta and surrounding areas obtained from

- 1471 this data set. The increase in rainfall starts at 07.00 (UT) until the peak at 10:00 (UT). Next, I compare this
- 1472 information with the hourly PWV values at GNSS stations shown in Figure 6.5,



1473

- 1478 behaviors. This explains that the heavy rain peak occurs when the PWV value is at its peak. It also
- 1479 indicates that the heavy rain caused a sudden drop of PWV from 10:00 to 12:00, which means that water
- 1480 vapor changed into liquid water (heavy rain). This suggests that monitoring the GNSS-meteorology data
- 1481 from INACORS is useful as a meteorological observation.

1482 6.3.2 Comparison of PWV INACORS with Jakarta Radiosonde Station

- 1483 To compare the GNSS-PWV values with those by other sensors, I obtained the PWV data by radiosondes at
- 1484 BMKG, Jakarta. BMKG serves not only as the GNSS stations but also as a radiosonde station in Jakarta with the
- 1485 name WIII station. Its primary purpose is to serve for flight at the Soekarno Hatta Airport, Cengkareng, Jakarta.
- 1486 The radiosonde PWV data are compared with the PWV data obtained by an INACORS station in Jakarta CJKT
- 1487 in Figure 6.6.

¹⁴⁷⁴Figure 6.5. Hourly PWV values at 4 INACORS GNSS stations, BAKO, CTGR, CJKT, and1475CBTU stations during the day of December 31, 2019. PWV time series show maxima at 10.00,1476the peak rain rate time, at CJKT and BAKO stations.

¹⁴⁷⁷ As seen by comparing Figure 6.4 and Figure 6.5, the rainfall and PWV time series show consistent





Figure 6.6 Comparison of PWV values between GNSS-PWV at CJKT stations estimated every 30 seconds
(orange curve) and radiosonde-PWV recorded every 6 hours at the WIII station (red circle). Correlation
coefficient between PWV data from GNSS and radiosonde is 0.541. The difference between the two stations
is around 26 km.

1493 The correlation between the two PWV values is not so high, probably because of the distance between the two

1494 stations. Nevertheless, at least the PWV from GNSS stations can complement the radiosonde data with their high

spatial and temporal resolution.

1496 6.3.3 Crustal movement analysis, GNSS station (INACORS-BIG)

1497 Next, I test my hypothesis that temporary vertical movements of GNSS stations reflect, to some extent, surface 1498 loads such as rainwater. Here I estimate vertical positions of the GNSS stations to study vertical crustal 1499 movements during the floods on January 1, 2020, and heavy rains on December 31, 2019. I calculated vertical 1500 positions during a time span from 10 days before the flood (December 22-31 December 2019) to 9 days after the 1501 flood. (2-10 Jan 2020).



- 1502
- 1503 1504

1505

Figure 6.7, Vertical position time series over a period spanning 20 days for the 5 GNSS stations in the region flooded by the January 1st, 2020, Jakarta heavy rain. The station bako had a data interruption on January 1, 2020.

1506 I used the GNSS data in RINEX format, with supporting data for the satellite ephemeris. The software outputs 1507 topocentric coordinates, composed of north-south, east-west, and vertical movement components. Here I am 1508 interested in the vertical movements, because the water load will depress the ground vertically. I plot the vertical 1509 coordinate time series in Figure 6.7. From the 5 GNSS-INACORS stations located in the Jakarta flood area, data 1510 on 1 Jan 2020 from the BAKO station could not be processed because the data had experienced an interruption 1511 during the acquisition process.

1512 Figure 6.7 shows that the average vertical coordinates show significant subsidence of nearly 1 cm on December

1513 31, 2019, and January 1, 2020. However, coordinates of the individual stations behave differently. For example,

- 1514 subsidence on December 31, 2019 is clearly seen only at BAKO and CTGR stations. Subsidence on January 1,
- 1515 2020 is clear for the CRKS, CTGR and CBTU stations. These stations are located in the flooded area (light blue
- 1516 colored region in Figure 6.1). On the other hand, CJKT is close to the coast and not included in the flooded
- 1517 area. Anyway, these results suggest that subsidence due to flood water load is quite non-uniform in space, and
- 1518 dense network would be needed to fully understand the crustal response to the surface stormwater load in
- 1519 Indonesia.

1520

1521 Chapter 7. Conclusion and Recommendation

1522

1523 **7.1 Conclusion**

1524 The conclusions of this thesis are summarized as follows,

1525 The atmospheric delay gradients are little influenced by station altitudes and provide useful information 1. 1526 of spatial gradient of relative humidity in lower atmosphere. By using atmospheric delay gradients, I 1527 could estimate distributions of sea-level ZWD, reflecting relative humidity of the air column above the 1528 station. This is possible only in regions with dense GNSS networks like Japan because tropospheric 1529 delay gradients are related to horizontal spatial gradient of ZWD. I also showed the importance of the 1530 water vapor concentration (WVC) index, reflecting small scale enhancement of water vapor. As seen in 1531 the scatter diagrams in Figures 3.8 and 3.9, sea-level ZWD and WVC are not correlated, i.e., high sea-1532 level ZWD does not always mean high WVC and vice versa. I showed that heavy rain occurs only when 1533 both quantities show high values.

1534 2. The results suggest that monitoring these quantities is useful for the nowcast of heavy rains. However, 1535 their ability to forecast heavy rains is yet to be studied. As the next step, I will need to explore the way 1536 to use these two quantities for weather forecast, e.g., by putting them to numerical weather models by some means. Computation time of sea-level ZWD and WVC is short, and we can convert ZTD values estimated by GNSS data analysis in near real-time to sea-level ZWD and WVC.

15393. Crustal subsidence was found to have occur by the water load brought by 2018 July SW Japan heavy1540rain, together with the heavy rains in 2017 July and 2019 August in the same area. In the day-to-day1541variability in crustal subsidence during 5-8 July 2018, I found a pattern of movement of the subsidence1542area from west to east in SW Japan. I have estimated the total water load using the crustal movement1543and compared them with the amount of precipitation from AMeDAS rain gauge data.

I used the open-source goGPS software to determine ZTD in Indonesia and found this software package
quite useful in comparison with other commercial software packages in determining tropospheric
parameters. ZTD values showed different behaviors for different seasons; in Indonesia, the value of
ZTD tends to be high/low during a rainy/dry season.

15485. I analyzed GNSS data from INACORS, a permanent GNSS network in Indonesia, to study tropospheric1549parameters and crustal subsidence. First, I determined the PWV values from GNSS data from Jakarta1550during the heavy rain event on January 1, 2020. Then, I confirmed their consistency with those by1551nearby radiosonde observations. Finally, I analyzed the crustal movement with the same GNSS data.1552The results showed vertical movements during the heavy rain episode in Jakarta, i.e. all of the GNSS1553stations in the Jakarta area showed significant changes from 31 December 2019 to 1 January 2020. They1554indicated that the flood in Jakarta caused temporary land subsidence.

1555

1556 **7.2 Recommendation**

The first recommendation from this thesis is for GNSS meteorology in Japan. From what I have done,
 the quality of numerical weather prediction may further improve by monitoring water vapor
 concentration index together with PWV converted to sea-level values. For this purpose, real-time
 calculation of these quantity would contribute.

The second recommendation is for the Indonesian GNSS meteorology, especially for BIG as an
 institution that manages GNSS in Indonesia. I recommend them to schedule workshops for the GNSS
 meteorology researches in Indonesia, and to start a long-term joint project aimed at the realization of
 GNSS meteorology in Indonesia.

1565

1566 **Bibliography**

- 1567 Andreas, H. et al (2019) IOP Conf. Ser.: Earth Environ. Sci. 389 012034
- 1568 Arief, S., and Heki, K. (2020). GNSS Meteorology for Disastrous Rainfalls in 2017–2019 Summer in SW
- 1569Japan: A New Approach Utilizing Atmospheric Delay Gradients. Front. Earth Sci. 8, doi:
- 1570 10.3389/feart.2020.00182
- Askne, J., and H. Nordius (1987). Estimation of tropospheric delay for microwaves from surface weather data.
 Radio Sci. 22, 379–386. doi:10.1029/RS022i003p00379
- Baby, H. B., P. Golé, and J. Lavergnat (1988). A model for the tropospheric excess path length of radio waves
 from surface meteorological measurements. *Radio Sci.* 23, 1023-1038.
- Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., and Ware, R. H. (1992). GPS meteorology:
 remote sensing of atmospheric water vapor using the global positioning system. *J. Geophys. Res.* 97,
 1577 15787–15801.
- Bevis, M., S Businger, and S. Chiswell (1994). GNSS meteorology: mapping zenith wet delays onto
 precipitable water. *Journal of Applied Meteorology*. 33(3), 379-386.
- Blewitt, G., Hammond, W. C., and Kreemer, C. (2018). Harnessing the GPS data explosion for interdisciplinary
 science. *EOS* 99, 1–2. doi: 10.1029/2018EO104623
- Böhm, J., Niell, A., Tregoning, P., and Schuh, H. (2006a). Global Mapping Function (GMF): a new empirical
 mapping function based on numerical weather model data. J. Geophys. Res. 33, 3–6. doi:
 10.1029/2005GL025546
- Böhm, J., and Schuh, H. (2013). Atmospheric Effects in Space Geodesy, p. 243, Springer Berlin Heidelberg.
- Brenot, H., Neméghaire, J., Delobbe, L., Clerbaux, N., De Meutter, P., Deckmyn, A., et al. (2013). Preliminary
 signs of the initiation of deep convection by GNSS. *Atmos. Chem. Phys.* 13, 5425–5449. doi: 10.5194/acp13-5425-2013
- Businger, S., S. R. Chiswell, M. Bevis, J. Duan, R. A. Anthes, C. Rocken, R. H. Ware, M. Exner, F. S. Solheim
 (1996). The promise of GNSS in atmospheric monitoring. *Bull. Am. Meteorol. Soc.* 77, pp. 5-18.
- Chao, C. C. (1974). The troposphere calibration model for mariner mars 1971. *Technical Report* 32-1587 pp.
 61-76. NASA JPL. Pasadena. CA.
- Chen, G., and Herring, T. A. (1997). Effects of Atmospheric Azimuthal Asymmetry on the Analysis of Space
 Geodetic Data. J. Geophys. Res. 102, 20489–20502. doi: 10.1029/97jb01739

- Davis, J. L., T. A. Herring, I. I. Shapiro, A. E. E. Rogers, and G. Elgered (1985). Geodesy by radio
 interferometry effects of atmospheric modeling errors on estimates of baseline length. *Radio Sci.* 20, 1593 1607.
- Duan J, et al. (1996). GPS meteorology: Direct estimation of the absolute value of precipitable water. *Journal of Applied Meteorology*. 35, 830-838.
- 1600 Enge, P., and Misra, P. (2006). Global Positioning System (2 ed.). Ganga-Jamuna Press.
- 1601 Farrell, W. E. (1972). Deformation of the Earth by surface loads. *Res. Geophys.* 10, 761-797.
- Foelsche, U., and G. Kirchengast (2001). Tropospheric water vapor imaging by combination of ground-based
 and spaceborne GNSS sounding data. *Journal of Geophysical Research D: Atmospheres*. 106, 2722127231.
- Gabor, M. (1997). Remote Sensing of Water Vapor from GNSS Receivers. Retrieved May 16, 2018
 http://www.csr.utexas.edu/texas_pwv/midterm/gabor/gabor.html#anchor561367
- 1607 Gérard, P., and Luzum, B. (2010). *IERS Conventions 2010*. France: Bureau International Des Poids Et Mesures
 1608 Sevres, 1–179.
- Hall, M. P. M., B. L. W., and H. M. T. (1996). Propagation of radiowaves, Institution of Electrical Engineers,London.
- Heki, K. (2001). Seasonal modulation of interseismic strain buildup in northeastern Japan driven by snow load. *Science vol.*293.5527 Pages 89-92.
- Heki, K. (2004). Dense GNSS array as a new sensor of seasonal changes of surface loads, in "The State of the
 Planet: Frontiers and Challenges in Geophysics," edited by R.S.J. Sparks and C. J. Hawkesworth, Geophys.
 Monograph, 150, 177-196, American Geophysical Union, 2004.
- Heki, K. (2020). Geodesy in Japan: Legends and highlights. *Earth Planets Space*, 72, 38, DOI:10.1186/s40623 020-0116408
- Hopfield, H. S. (1969). Two-quartic tropospheric refractivity profile for correcting satellite data, *J. Geophys. Res.* 74. 4487-4499.
- Hopfield, H. S. (1971). Tropospheric effect on electromagnetically measured range. Prediction from surface
 weather data. *Radio Sci.* 6, 357-367
- Iwabuchi, T., Miyazaki, S., Heki, K., Naito, I., and Hatanaka, Y. (2003). An impact of estimating tropospheric
 delay gradients on tropospheric delay estimations in the summer using the Japanese nationwide GNSS
 array. J. Geophys. Res. 108. 10.1029/2002JD002214

- Japan Meteorological Agency [JMA] (2019). *A Heavy Rain Episode Brought by a Stationary Front (2019 Aug. 26-29*). Tokyo: Japan Meteorological Agency.
- Japan Meteorology Agency [JMA] (2017). On the 2017 July Heavy Rain in Northern Kyushu. Tokyo: Japan
 Meteorological Agency.
- Japan Meteorology Agency [JMA] (2018). 2018 July Heavy Rain (heavy rain etc, by the stationary front and
 the typhoon no. 7). Tokyo: Japan Meteorological Agency.
- Kleijer, F. (2004). Troposphere modeling and filtering for precise GNSS leveling. *PhD dissertation*, Delft
 University of Technology, Delft, The Netherlands.
- Koning, A. (2016). Precipitable water vapor estimation using GNSS in Uganda: A study on obtaining the Zenith
 Wet Delay. PhD dissertation, Delft, The Netherlands
- Kouba, J. (2009). Testing of global pressure/temperature (GPT) model and global mapping function (GMF) in
 GNSS analyses. *Journal of Geodesy.* 83, 199-208.
- Lagler, K., M. Schindelegger, Böhm, J., H. Krásná, and T. Nilsson (2013). GPT2: Empirical slant delay model
 for radio space geodetic techniques. *Geophys. Res. Lett.* 40, 1069-1073.
- 1639 Langley, R. B. (1999). Dilution of precision. GPS World. 10, 52-59
- Leandro, R. F., Langley, R. B., and Santos, M. C. (2008). UNB3m_pack: A neutral atmosphere delay package
 for radiometric space techniques. *GPS Solutions*. 12, 65-70.
- MacMillan, D. S. (1995). Atmospheric Gradients from very long baseline interferometry
 observations. *Geophys. Res. Lett.* 22, 1041–1044. doi: 10.1029/95GL00887
- Meindl, M., Schaer, S., Hugentobler, U., and Beutler, G. (2004). Tropospheric Gradient Estimation at CODE:
 Results from Global Solutions, in Applications of GPS Remote Sensing to Meteorology and Related Fields.
 In Journal of the Meteorological Society of Japan, 82, 331 338.
- Mendes, V. B., and Langley, R. B. (1999), Tropospheric zenith delay prediction accuracy for high-precision
 GNSS positioning and navigation. *Navigation.* 46, 25-34.
- Milliner, C., Materna, K., Burgmann, R., Fu, Y., Moore, A.W., Bekaert, D., Adhikari, S., Argus, D.F. (2018).
 Tracking the weight of Hurricane Harvey's stormwater using GNSS data. *Sci Adv* 4, eaau2477.
- Miyazaki, S., Iwabuchi, T., Heki, K., and Naito, I. (2003). An impact of estimating tropospheric delay gradients
 on precise positioning in the summer using the Japanese nationwide GPS array. *J. Geophys. Res.* 108:4315.
 doi: 10.1029/2000JB000113
- Mohr, P. J., B. N. Taylor, and D. B. Newell (2012). CODATA recommended values of the fundamental
 physical constants: 2010, REVIEWS OF MODERN PHYSICS. *Rev Mod Phys.* 84, 1527

- 1656 Nakagawa, H., Toyofuku, T., Kotani, K., Miyahara, B., Iwashita, C., Kawamoto, S., et al. (2009). Development
 1657 and validation of GEONET new analysis strategy (Version 4). J. Geogr. Surv. Inst. 118, 1–8.
- 1658 Owens, J. C. (1967). Optical refractive index of air: dependence on pressure, temperature, and composition.
 1659 *Applied Optics*. 6, 51-59.
- Patel, K. (2020). Torrential Rains Flood Indonesia. *https://earthobservatory.nasa.gov/images/146113/torrential- rains-flood-indonesia*.
- 1662 Realini, E. (2009). goGPS free and constrained relative kinematic positioning with low-cost receivers. Ph. D.
 1663 thesis, http://www.researchgate.net/publication/237520116
- Ruffini, G., Kruse, L. P., Rius, A., Biirki, I. B., and Cucurulll, L. (1999). A Flores. "Estimation of Tropospheric
 Zenith Delay and Gradients over the Madrid Area Using GPS and WVR Data.". *Geophys. Res. Lett.* 26,
 447–450. doi: 10.1029/1998gl900238
- 1667 Saastamoinen, J. (1972). Atmospheric correction for troposphere and stratosphere in radio ranging of satellites.
- 1668 The Use of Artificial Satellites for Geodesy. In *Papers presented at the Third International Symposium on*
- 1669 The Use of Artificial Satellites for Geodesy, Eds. S. W. Henriksen, A. Mancini, B. H. Chovitz, AGU,
- 1670 AIAA, NOAA, U.S.ATC, Washington, D. C., 15-17 April 1971, American Geophysical Union,
- 1671 Washington, D. C., Geophysical monograph 15, pages 247 252.
- Saastamoinen, J. (1973). Contributions to the theory of atmospheric refraction part II. *In Bull. Geod.* 107, 13–
 34.
- Shoji, Y., T. Iwabuchi, Y. Hatanaka, H. Seko, R. Ichikawa, R. Ohtani, and N. Mannoji. 2009. GNSS
 Meteorology: Research on the Construction of GNSS Water Vapor Information System and Application to
 Meteorology, Geodesy, and Hydrology. *Journal of the Geodetic Society of Japan* 55, 17–38.
- Shoji, Y. (2013). Retrieval of water vapor inhomogeneity using the Japanese Nationwide GPS array and its
 potential for prediction of convective precipitation. J. Meteorol. Soc. Jpn. 91, 43–62. doi:
 10.2151/jmsj.2013-103
- Shoji, Y. (2015). Water vapor estimation using ground-based GNSS observation network and its application for
 meteorology. *Tenki* 62, 3–19.
- Shoji, Y., K. Sato, M. Yabuki, and T. Tsuda, (2017). Comparison of shipborne GNSS-derived precipitable
 water vapor with radiosonde in the western North Pacific and in the seas adjacent to Japan. *Earth Planets Space*. 69, 153.
- Smith, E. K., and S. Weintraub (1953). The constants in the equation for atmospheric refractive index at radio
 frequencies. *Proceedings of the IRE*. 41, 1035-1037.

- Sturman, A. P., and N. J. Tapper (2006). The weather and climate of Australia and New Zealand, 2nd ed., pp.
 520, Oxford University Press.
- 1689 Thayer, G. D. (1974). An improved equation for the radio refractive index of air. Radio Sci. 9, 803-807.
- 1690 Tsuda, T., Heki, K., Miyazaki, S., Aonashi, K., Hirahara, K., Nakamura, H., et al. (1998). GPS meteorology
 1691 project of Japan Exploring frontiers of geodesy -. *Earth Planet. Space* 50, 1–5.
- 1692 Tsuji, H., and Hatanaka, Y. (2018). GEONET as Infrastructure for Disaster Mitigation. J. Dis. Res. 13, 424–
 1693 432. doi: 10.20965/jdr.2018.p0424
- Vaclavovic, P., and Dousa, J. (2015). Backward Smoothing for Precise GNSS Applications. *Adv. Space Res.* 56,
 1627–1634. doi: 10.1016/j.asr.2015.07.020
- Ware, R., Exner, M., Feng, D., Gorbunov, M., Hardy, K., Herman, B., Kuo, Y., Meehan, T., Melbourne, T.,
 Rocken, C., Schreiner, W., Sokolovskiy, S., Solheim, F., Zou, X., Anthes, R., Businger, S., Trenberth, K.
 (1996). GPS Sounding of the Atmosphere from Low Earth Orbit: Preliminary Results. *Bull. Amer. Meteor.*
- 1699 Soc. 77, 19 40. https://doi.org/10.1175/1520-0477(1996)077<0019:GSOTAF>2.0.CO;2
- 1700 Xu, G. (2007). GNSS: Theory Algorithms and Applications 2nd ed. *Springer*, Heidelberg.
- Yan, S., Z. Li, K. Yu, and K. Zhang (2014). GNSS-R L1 interference signal processing for soil moisture
 estimation: an experimental study. *EURASIP Journal on Advances in Signal Processing*. 2014, 107
- Yedukondalu, K. A. S. (2011). Estimation and Mitigation of GNSS Multipath Interference Using Adaptive
 Filtering. *Progress in Electromagnetics Research* M, 133-148.
- Yuan, Y., Zhang, K., Rohm, W., Choy, S., Norman, R., and Wang, C. (2014). Real-Time Retrieval of
 Precipitable Water Vapor from GNSS Precise Point Positioning. *J Geophys Res. Atmos.* 119,10044–57.
 https://doi.org/10.1002/2014JD021486
- Zinas, N. (2019). Satellite and receiver clock errors. Retrieved from *Tekmon Geomatics*,
 http://www.tekmon.eu/1-3-2-satellite-and-receiver-clock-errors/.

Zumberge, J. F., Heftin, M. B., Jefferson, D. C., Watkins, M. M., and Webb, F. H. (1997). Precise point
positioning for the efficient and robust analysis of GPS data from large networks. *J. Geophys. Res.* 102,
5005–5017. doi: 10.1029/96JB03860.

- 1713 Zus, F., Douša, J., Kaèmaøík, M., Václavovic, P., Balidakis, K., Dick, G., et al. (2019). Improving GNSS
- 1714Zenith Wet Delay Interpolation by Utilizing Tropospheric Gradients: Experiments with a Dense Station
- 1715 Network in Central Europe in the Warm Season. *Remote Sens.* 11:674. doi: 10.3390/rs11060674

1716