AMERICAN UNIVERSITY OF BEIRUT

EVALUATION OF CHIRPS AND GPM-IMERG PRECIPITATION ESTIMATES AGAINST GROUND RAIN GAUGE OBSERVATIONS OVER LEBANON

by
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ABSTRACT
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Title: Evaluation of CHIRPS and GPM IMERG Precipitation estimates against Ground Rain Gauge Observations over Lebanon

The objective of this paper is to assess two satellite precipitation products, Climate Hazards Center's Infrared Precipitation with Stations (CHIRPS) and the product of the Global Precipitation Mission; the Integrated Multi-satellitE Retrievals for GPM (GPM IMERG v4) against ground rain gauges over Lebanon. A network of around 84 rain gauge stations distributed over the area was used after extensive data quality control. This evaluation focuses on annual precipitation from hydrologic year 2000-2001 till 2016-2017, and on a monthly basis from January 2000 till April 2018 since this period was the common data available from CHIRPS and Ground stations. As for the common period between Ground data and IMERG, it was from 2014 till 2017. On a yearly basis CHIRPS recorded better results than IMERG (R^2_{CHIRPS}= 0.353 whereas R^2_{IMERG}= 0.084). Monthly analysis showed good performance by both satellite products with general underestimation by IMERG and slight overestimation by CHIRPS during wet months. January is the rainiest month in Lebanon with an average monthly precipitation of 163 mm. Moreover, the effects of longitude, latitude, elevation and location (topography) on precipitation readings were examined. Longitude values were categorized into 3 classes whereas Latitudes were divided into four due to the longitudinal geographical borders of Lebanon and based on a precipitation map. Results revealed that annually CHIRPS performed better at "Long2" (from 35.5 to 36) and "Long3" (from 36 to 36.6) than "Long1" (from 35.1 to 35.5). Also it overestimated rainfall at "Long1" and "Long2" when Ground-observed rainfall was below 800 mm and underestimated it when it reached above 800 mm. IMERG did not record a specific trend. As for the effect of Latitude, CHIRPS and IMERG performed better over the South at "Lat 4" (from 34.3 to 34.7) with R^2_{CHIRPS}= 0.515, RE_{CHIRPS}= 22% and R^2_{IMERG}= 0.688, RE_{IMERG}= 13.3%. On a monthly basis, neither latitude nor longitude had a noteworthy effect on the bias between remotely sensed and ground-observed precipitation.
As for the analysis of elevation influence, this aspect was divided into 3 categories C1 from 0 to 800m, C2 from 800m to 1500m and C3 > 1500m. Annual records showed underestimation by CHIRPS (around 10%) at C1 and C2 and for IMERG by 23% at C1 and 36% at C2 areas. However, at high elevations (C3) both products overestimated precipitation by 6% for CHIRPS and 2% for IMERG. On a monthly basis, January

recorded as the rainiest month in Lebanon over C1 and C3 (162 mm). CHIRPS overestimated over all categories with better results during rainy months whereas IMERG underestimated over C1 and C2. CHIRPS showed slightly better results at low elevations (R^2_{CHIRPS} =0.669, $RMSE_{CHIRPS}$ = 43 and R^2_{IMERG} =0.657, $RMSE_{IMERG}$ = 32), however IMERG performed better at higher ones (R^2_{CHIRPS} =0.565, $RMSE_{CHIRPS}$ =53 and R^2_{IMERG} =0.761, $RMSE_{IMERG}$ =32). Also with respect to location, average precipitation over the coast observed by ground stations was around 834 mm whereas that detected by CHIRPS was 766 mm. CHIRPS underestimated rainfall by around 10%. IMERG showed a better correlation with rain gauges than CHIRPS did (R^2_{CHIRPS} =0.196, RE_{CHIRPS} = 23.5% and R^2_{IMERG} =0.678, RE_{IMERG} = 10.4%). Over the inland area, annual rainfall ranged between 373 mm and 1201 mm. CHIRPS and IMERG slightly overestimated precipitation with CHIRPS performing better (R^2_{CHIRPS} =0.621, RE_{CHIRPS} = 20.5%. Lastly, over the mountains both products yielded lower estimates than ground observations that ranged between 410 mm and 1603 mm. On a monthly scale, CHIRPS and IMERG performed better over the coastal area (R^2_{CHIRPS} = 0.701 and R^2_{IMERG} = 0.756) than they did over the inland and mountainous ones. IMERG tends to overestimate over inland and underestimate rainfall over the mountains (higher % difference). This can be explained by the topography of Lebanon that is constituted of narrow plains followed by a complex terrain of relatively high elevation mountains. This type of landscape can hinder the proper functioning of both satellite products. These results highlight the ability of satellite products to record precipitation as well as the need for improving their predictions to detect light rain and snowfall. This work emphasizes the importance of accurate and good quality ground rainfall measurements in a small country like Lebanon known for its complicated topography and problematic geographical location.

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ABBREVIATIONS

AAP: Average Annual Precipitation

CCD: Cold Cloud Duration

CHIRPS: Climate Hazards Center’s Infrared Precipitation with Stations

CSI: Critical Success Index

ECMWF: Era-Interim product from the European Centre for Medium Range Weather Forecasts

FAR: False Alarm Ratio

GMI: GPM Microwave Imager

GPM: Global Precipitation Mission

IMERG: Integrated Multi-satellitE Retrievals for GPM

JAXA: Japanese Aerospace Exploration Agency

NASA: National Aeronautics and Space Administration

POD: Probability of Detection

PR: Precipitation Radar

R^2: R-squared

RE: Relative Error

RMSE: Root Mean Square Error

RRMSE: Relative Root Mean Square Error

SPI: Standardized Precipitation Index

TMI: TRMM Microwave Imager

TMPA: TRMM Multi - satellite Precipitation Analysis

TRMM: Tropical Rainfall Measuring Mission

CHAPTER I

INTRODUCTION

A. Water Cycle

Knowing the importance of water for agriculture and food security, industry, transportation, hydropower production, and domestic use makes it inevitable to study and quantify the water cycle around the globe. Water links together lands, oceans and atmosphere into a unified system. The vital cycle starts from the evaporation of water from land and ocean to its condensing in the atmosphere in form of clouds to falling back in different forms of precipitation on the planet. This allows the circulation of heat in the atmosphere from cooling down of ocean's surfaces to buffering the greenhouse effect. Precipitation is the major process in the water cycle controlling a continuous source of fresh water. A total of 78% of precipitation falls over the ocean and 86% of total evaporation occurs from the surface of the ocean (Nagaraja, 2020).

According to the World Bank Group, the mean annual precipitation over Lebanon from 1901 till 2016 was 586 mm. However, Lebanon has witnessed more dry years since the 1900s, which have affected fresh water availability, surface runoff and aquifer recharge. Annual precipitation has decreased by 11 mm/month every century since 1950 ("World Bank Climate Change Knowledge Portal", 2021). It's expected that global warming will make dry regions even drier. Moreover, snow cover, density, and the time it takes to start melting have decreased from what it was before the 1990s (110 days) to what it's now after 1990 (90 days) (MOE/UNDP/ECODIT, 2011). The groundwater discharges also lessened due to the drop in the water table resulting from overexploitation of wells and boreholes. This decrease in water resources and storage processes are great evidence of climate change. Therefore, the obligation to correctly anticipate future variations and trends is inevitable.

The challenge lies in the appropriate gathering of satisfactory information about Eco hydrological processes and conditions that can lead to extreme climatic events. Recently, humans have had a major effect on the global water cycle resulting in water crisis for billions all over the world. However, this effect has been neglected in many water-related representations. Being a fundamental unit of the water cycle, precipitation rates (frequency, intensity and duration) and types (rain, drizzle, hail, snow etc…) are major aspects worth studying and quantifying. Precipitation datasets can be generated using ground-based networks or satellite measurements. Ground networks are limited to specific reachable areas around the world where locations are protected from climatic extremes that can affect the measurement quality standards. While satellite-based measurements address this limitation, they require regional validation and long-term availability of datasets. In attempt of optimizing results and understanding the whole Earth system, many efforts have been put in integrating both datasets by filling observational gaps and discontinuities in data archives (Levizzani & Cattani, 2019).

B. Precipitation Measurements in Remote Areas

Some examples of remote areas where satellite observations can complete the water cycle due to insufficient ground networks are the Mediterranean basin (including Lebanon), the Arctic and high mountains (glaciers). The Mediterranean Sea is highly influenced by atmospheric changes and pollution due to its relatively small semi-closed area and geographic location. The circulation of water and the environment of the Mediterranean Sea influence a global Mediterranean climate in Southwest Cape, Southwest Australia, central Chile as well as California ("Mediterranean-Type Ecosystems", 2020). It is characterized by warm, mild and rainy climate as well as wide seasonal variations in temperature and rainfall. It experiences dry summers, intense seasonal precipitation (between October and November) and Mediterranean cyclones (also known as Medicanes). The Mediterranean basin represents a concentration basin of evaporation much higher than annual rainfall and river run-off leading to more saline water leaving the sea and entering the Atlantic Ocean (Li et al., 2012). The importance of this basin lies in its contribution in water vapor supply to the atmosphere which is directly related to precipitation rates. On the other hand, the Artic climate is characterized by runoff rates larger than precipitation increases resulting in fluctuations in groundwater and evapotranspiration. These can be assessed by addressing the sparseness of networks to achieve sufficient information about sea ice volume, precipitation and river discharge fluxes. Lastly the melting of glaciers due to the recent global warming require enhanced observations to evaluate its effect on the water cycle. The challenges of unevenly distributed rain gauges, deployment of radar networks by developed countries and the inconsistent coverage of oceans demand the development of data gathering techniques through the use of satellites (Levizzani & Cattani, 2019).

C. History of Satellite Precipitation Products

The employment of satellites in precipitation measurements evolved from the pre- Tropical Rainfall Measuring Mission (TRMM) era constellation to the TRMM era that improved global estimates into more quantitative datasets especially in the tropics. Later, the Climate Hazards Center’s Infrared Precipitation with Stations (CHIRPS), a global infrared-based dataset, covered longer time spans (Levizzani & Cattani, 2019).

The Global Precipitation Mission and its product the Integrated Multi-satellitE Retrievals for GPM (GPM IMERG) followed the TRMM mission with a wider coverage that goes beyond the tropicals. Numerous studies and research were executed to make the retrievals from space flawless, however, the estimation of the solid component is still unsatisfactory. Radars and radiometers still fail in distinguishing between falling snow and snow or ice on the ground, as well as the identification of snowfall below clouds. The GPM Microwave Imager (GMI), though, has the capability of mapping global snowfall and snow depth but cannot accurately identify non-spherical cloud ice particles. It's worth noting that no one satellite product is ideal for observing extreme events and almost all satellite products have the probability of missing an important amount of rain. This depends on the spatial domain chosen and calls for regional validation (Levizzani & Cattani, 2019).

The collection of precipitation data is witnessing around the clock improvements in remote sensing techniques and in monitoring and redesigning networks in sparsely gauged regions. These actions are crucial knowing the influence of water cycle variations on humanity and the whole globe. Water security presses an urgent need for integrated hydrologic modeling for water management, hydrogeological hazards and optimizing food security and public health. Satellite precipitation data allows the assessment of landslide hazards globally through a stochastic algorithm that combines landslide susceptibility with rainfall estimates. Although these hazards might not be resulting from intense rainfall only but from earthquakes or snow melt on complex topography. Satellite data can be utilized in erosivity mapping in areas with insufficient data like Africa. Last but not least, climate anticipation and agroclimatic monitoring provide security to billions of people especially those dependent on rainfed agriculture and livestock. Many projects have been executed to allow easy access to climate information and availability for usage specifically in Africa to assist in decision making. Finally, climate change and extreme events have great influence on public health and water-related diseases that are highly reliant on sanitation and clean water availability. Those being responsible for 17% of all infectious diseases worldwide.

Therefore, taking the above into consideration, it is important to have accurate rainfall data that can be forecasted ahead of time. In order to attain this goal, the work in this paper aims to validate two satellite products CHIRPS and IMERG against ground rain gauges over the area of Lebanon. In addition to evaluating whether this satellite data can be used over this region and the type of correction it might need for better analysis.

CHAPTER II

LITERATURE REVIEW

A. Importance of Measuring Precipitation

Researchers from all over the world have worked on the validation of satellite precipitation estimates against rain-gauge measurements over a specific region or country. The reason behind the numerous attempts is the fact that satellite products measure precipitation quantities over areas of several kilometers around the ground stations. However, rain-gauge recordings are point measurements specific to a few centimeters area (Retails et al., 2018). Every attempt is specific to its study area and atmospheric characteristics like wind and moisture that can affect rain gauge readings. It is very important to assess satellite estimates over different regions to accomplish a global view of their performance. Many studies were executed over regions in Western Asia, China, Latin America and Africa. This ability of satellites to detect rainfall has increased the climatological dataset in terms of precipitation. However, its accuracy remains uncertain. Therefore, this study is the first at validating GPM IMERG v4 and CHIRPS estimates over Lebanon and assessing their correlation with elevation, latitude, longitude, location and topographic variations.

Precipitation does not fall uniformly over the world, however, every region, country or even city receives a different amount annually. Throughout the last century or so, global precipitation has been fluctuating above and below the average precipitation of the years 1901 to 2000. In 1902, it reached its minimum of less than the average by 1.96 inches and its maximum of 2.15 inches more than the average in 2010 (Richie and Roser, 2019). Flood and drought events cannot be generalized over the whole globe. For example, in the same country during the same year, some regions might experience intensive rainfall while others face severe droughts. The US economic damage costs of floods and droughts combined increased from $29.46 billion in 2000 to $40.9 billion in 2015. Moreover, the fatalities due to floods only, increased from 130,000 deaths (2000) to 550,000 (2015) (Richie and Roser, 2019). It is noteworthy to consider lack of media reporting disasters in the past, but climate change and manmade disasters are enough proof of this increase in the number of disasters globally.

Floods and droughts are lethal and damaging disasters directly correlated to precipitation rates. Therefore, one way to mitigate their effects would be the possibility of correctly anticipating when, where and how much it will rain. Sudden excess or shortage in precipitation affects various fields from urban safety and wellbeing to agriculture and hydropower production. This type of before-hand management can help alerting citizens and authorities take the required precautions. Estimating precipitation using satellite products have been implemented over many regions of the world.

B. The Tropical Rainfall Measurement Mission (TRMM)

The first product introduced by the National Aeronautics and Space Administration (NASA) and the Japanese Aerospace Exploration Agency (JAXA) in 1997 was the Tropical Rainfall Measurement Mission (TRMM). It was shut down on April 8, 2015 ending 17 years of data availability (Harrington, 2015). The product was responsible for precipitation measurements over the tropical and subtropical regions. Its primary component, the Precipitation Radar (PR), was the first spaceborne radar to measure rainfall with a ground horizontal resolution of 5 km and swath width of 274 km. It delivered 3D maps of storm structure that provided critical information about rain intensity, distribution and type as well as storm depth and the height at which snow turns into rain ("Precipitation Radar (PR) | Precipitation Measurement Missions"). Most importantly, PR can detect rain and snow vertical profiles up to 20 km from the surface thus identifying light rain down to 0.7 mm/hr. In addition to other instruments aboard the TRMM observatory that sense radiation (Visible and Infrared Scanner), lightning (Lightning Imager Sensor) and cloud effects (Clouds and the Earth's Radiant Energy System); the TRMM Microwave Imager (TMI) quantifies cloud water, water vapor, and rainfall intensity. This is possible due to the ability of the passive microwave sensor to measure very low quantities of microwave energy emitted ("TRMM Microwave Imager (TMI) | Precipitation Measurement Missions").

C. Climate Hazards Group Infrared Precipitation with Stations (CHIRPS)

In this paper, instead of using data from the TRMM, the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) dataset will be assessed. It is a quasi-global dataset of daily, pentadal and monthly precipitation records of 5.4 km horizontal resolution (0.05°) (Funk et al., 2015). It spans 50°S-50°N with all longitudes since 1981 to near-present. Its records are based on infrared observations of Cold Cloud Duration (CCD) which refers to the duration a cloud top is having a temperature below a critical threshold at a given pixel. Below this threshold of -40 and -70°C (depending on latitude and season), water held in clouds will precipitate. Therefore, the coldest cloud tops will result in the heaviest rain (WHO, 2001). CHIRPS uses the TRMM Multi - satellite Precipitation Analysis (TMPA 3B42) to calibrate CCD rainfall estimates. In addition to this interpolation, it also combines station data with CCD-derived estimates for every pentad (every 5 days of a month) to produce 2-day latency rainfall product. Likewise, monthly station data are blended with monthly

CCD-derived estimates to establish gridded monthly station products (Funk et al., 2015).

Datasets with low latency and long periods of record are rare to find since most datasets with long record have very long latency (like the Global Precipitation Climatology Centre GPCC) or those with low latency are founded solely on satellite input (like TMPA 3B42). CHIRPS, on the other hand, succeeded in providing gauge-satellite estimates covering most global regions at high resolution, low latency, low bias and a record since 1981. It can be employed to monitor shifts in precipitation rates and forecast mid-season droughts (Funk et al., 2015).

D. Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG)

TRMM is the predecessor of the Global Precipitation Measurement (GPM) mission that was launched in 2014 and is still operating. Along with the Precipitation Measurement Mission constellation and TRMM, GPM has a dataset of about twenty years. The final product is known as Integrated Multi-satellitE Retrievals for GPM (IMERG) ("IMERG: Integrated Multi-satellitE Retrievals for GPM | NASA Global Precipitation Measurement Mission", 2020). The core satellite of the GPM-IMERG, known as the GPM Core Observatory, combines measurements from an assembly of international satellites. It carries an advanced version of the radar, the Dual-frequency Precipitation Radar (DPR), which employs a Ka-band precipitation radar (KaPR) functioning at 35.5 GHz and Ku-band precipitation radar (KuPR) operating at 13.6 GHz. The DPR detects 3D measurements of rainfall structure over swaths of 125 km and 245 km ("Global Precipitation Measurement (GPM) Mission Overview |

Precipitation Measurement Missions", n.d.). These improvements allow IMERG to outperform TRMM at measuring light rain and snowfall. Moreover, it possesses a multi-channel instrument, the GPM Microwave Imager (GMI) with a swath of 885 km and thirteen channels of frequencies from 10 GHz to 183 GHz. Through testing the polarization difference at every channel, optical thickness and water content can be assessed resulting in better detection of heavy, moderate and light rainfall.

CHIRPS data will be compared to precipitation estimates of IMERG. Both datasets will be validated against ground rain gauge observations obtained from stations distributed all over Lebanon. This type of analysis describes which data is more reliable to use in our region that has wide variations in topography and climatic characteristics. The establishment of reliable datasets leads to a more precise forecasting of natural hazards, weather events, agricultural crops and freshwater resources. The validation of these satellite products over Lebanon is essential for the advanced understanding of the water cycle and its relation to climate change. This knowledge allows for a better knowledge of atmospheric processes, storm structures and hydrology.

E. Recent Works

1. Four regions of different weather and topographic conditions; Mountainous wet region, Mountainous rainy region, Arid region and Semi-arid region

Sharifi et al. (2016) assessed the 3 satellite products IMERG, TRMM and Multi-satellite Precipitation Analysis (TMPA-3B42) and the Era-Interim product from the European Centre for Medium Range Weather Forecasts (ECMWF). The precipitation estimates were compared to measurements from 43 rain-gauges over Iran at daily, monthly and seasonal time scales. Four regions of different topography and climate conditions were studied from March 2014 to February 2015. The first was a mountainous region, Kermanshah, located west Iran at the Zagros mountains with an average annual precipitation (AAP) of 700 mm at the highlands and 400 mm at the city. Guilan is the second mountainous region with convective high amounts of rainfall and humid climate at the shoreline (AAP = 1500 mm) and the mountains (AAP ≈ 2000 mm) surrounding a sub-humid area. Thirdly, arid and sub-tropical Bushehr (AAP = 230 mm) also including two topographical aspects; plains along the Persian Gulf and mountain ranges. Lastly, Tehran (AAP = 400 mm) with its semi-arid climate characterized by its Northern Alborz Mountains and Southern desert. Daily and seasonal evaluations revealed that all products underestimated rainfall but IMERG performed best in daily scale while ERA represented significant agreement in seasonal. However, results showed that each of ERA and IMERG excelled over one region but wasn't accurate over others. ERA recorded best results over North Iran with high Probability of Detection (POD) and low False Alarm Ratio (FAR). In Bushehr, Kermanshah and Tehran, IMERG had highest POD. ERA performed better at low rainfall intensities whereas IMERG did better at higher ones.

2. Humid weather, mountainous complex topography

Xu et al. (2017) also evaluated the performance of GPM IMERG and TRMM 3B42 v7 over the southern Tibetan Plateau (TP) depending on rainfall intensities and topographic variations (Xu et al., 2017). The study period was focused within the rainy period of 2014 (1 May to 31 October). The TP region is considered as the Asian water tower where the headwater of 10 major rivers originate. After strict quality control measures, 194 of 537 gauges with a complete daily time series of 6 months were finally selected. Overall results showed better performance by IMERG than TRMM.

3. Semi-humid to humid weather, plain topography surrounded with mountains

Chen et al. (2018) performed a comparison between precipitation estimates of GPM IMERG v5 and TRMM 3B42 v7 over The Huaihe River basin in eastern China from 2015-2017 (Chen et al., 2018). The large watershed (270,000km^2) is characterized by a semi humid to humid climate with abundant but uneven annual rainfall concentrated between May and October. It is rich in water bodies like lakes and tributaries and have an annual average rainfall of 920mm. Forty-three ground stations were used for the evaluation of these satellite products at different temporal scales. All data was subjected to a sequence of quality controls where pixels with no rain gauges were eliminated. The basin was divided into 43 polygons using the Thiessen polygon method. Also, the effects of latitude and elevation on precipitation were assessed. Evaluation assessment indicated that both products showed low accuracy and underestimation at daily scale but high accuracy and overestimation at monthly and annual scales. IMERG v5 recorded better performance than TRMM 3B42 v7 with lower relative root mean square error (RRMSE) and higher Pearson correlation coefficient *r*. Furthermore, TRMM 3B42 v7 displayed overestimation over water bodies but IMERG v5 had more consistent estimates. Both satellite products tend to overestimate rainfall of intensity between 0.5 and 25mm/day and underestimate light rainfall (0-0.05mm/day) and heavy rainfall (>25mm/day). IMERG v5 recorded higher probability of detection (POD), critical success index (CSI) and lower false alarm ratio (FAR) than those of TRMM 3B42 v7 indicating better performance.

4. Dense forests and natural fields with rainy tropical climate

Santos et al. (2018) validated IMERG estimates over the Southern Amazonas state in Brazil for 2015 and 2016. The average precipitation in this area reaches up to 2500 mm annually being concentrated during the rainy season (October to March). The study was focused on five municipalities with a rich ecosystem of high evergreen forests, grasses fields, and palm trees. Different statistical indices were used to evaluate the correlation between measured values and estimated ones. GPM properly estimated monthly and annual rainfall with correlations of more than 73%. Pearson correlation coefficient “r” ranged between 0.74 and 0.95 among the 5 municipalities with different underestimation.

5. Hot desert climate with low average annual precipitation at the shores

The first validation for CHIRPS, IMERG and the gauge corrected Global Satellite Mapping of Precipitation (GSMaP) against ground stations done over Egypt was by Nashwan et al. in 2019. Daily data from 29 ground weather stations and the three satellite products were evaluated for the period from March 2014 till May 2018 (Nashwan et al., 2019). The 3 products presented the same spatial distribution of the annual average precipitation showing more rainfall at the Mediterranean shores and less rain towards the inner region. In addition to that, CHIRPS also revealed higher precipitation amounts at the Red Sea shores and Sinai Mountains whereas GSMaP underestimated overall rainfall. Root mean square error (RMSE) and Kling-Gupta efficiency index (KGE to integrate correlation, bias and variability) were used to assess the performance of satellite products. In addition to probability distribution function (PDF) skill score (SS to quantify the overlap between the PDF retrievals from ground gauges and satellite products). Also, 4 categorical indices were evaluated including probability of detection (POD), false alarm ratio (FAR), critical success index (CSI) and the hit BIAS which is the fraction of wet days predicted by satellite products to that observed by ground gauges. Daily rainfall intensities were classified into 6 event classes; all-events, no or tiny rain ($P < 1$mm), light ($1 \text{ mm} \leq P < 2$ mm), low moderate ($2 \text{ mm} \leq P < 5$ mm), high moderate ($5 \text{ mm} \leq P < 10$ mm), and heavy rainfall ($P \geq 10$ mm). Results revealed that at the all-events and no/tiny rain classes, CHIRPS performed best with lowest RMSE in most stations. In the light rainfall and low moderate classes, GSMaP performed best. As for the high moderate and heavy rain classes, IMERG was the best. According to the four categorical indices, all products performed almost ideally in estimating no or tiny rainfall. However, for the other rainfall classes, IMERG recorded the best indices whereas GSMaP the worst.

As a conclusion, even though all satellite products were gauge corrected but none had reliable readings. If one recorded best results in one statistical index of a region, it performed the worst in another of the same region. Overestimating rainfall is the main disadvantage of satellites over arid regions like Egypt. Some reasons for this would be the high cloud evaporation which is due to hot atmospheric layers that evaporate the raindrops before they reach the rain gauges even though detected by the satellite. This study was restricted by the poor ground gauge network that resulted in unsatisfactory results.

6. Arid to semiarid climate, Mediterranean regime at high elevations

In 2019, CHIRPS performance for detecting wet and dry events over the CWA region was evaluated by Rivera et al (Rivera et al., 2019). The comparison was done between CHIRPS data and 49 meteorological stations from 1987 till 2016. The study area is known for its complex topography; high Andes peaks and lower slopes. High elevations are characterized by a Mediterranean climate of rainy cold April to September and dry warm October to March. However, the region east of the Andes has arid to semiarid climate due to the high peaks (over 6,000 m asl) that hinder Pacific air masses to reach the slopes. This area receives its precipitation from the warm moist air from the Amazon and Atlantic. The Standardized Precipitation Index (SPI) was used to identify wet and dry conditions on a 1-month, 3-month and 6-month basis. The seven SPI categories used were extremely wet (≥2.00), severely wet (1.50≤SPI≤1.99), moderately wet (1.00≤SPI≤1.49), normal (-0.99≤SPI≤0.99), moderately dry (-1.49≤SPI≤ -1.00), severely dry (-1.99≤SPI≤ -1.50) and extremely dry (≤-2.00). To compare between rain gauge SPI and CHIRPS SPI, Pearson correlation coefficient was used along with mean absolute error. The study area was also divided into two climatic regions; warm season (WS) of monsoonal regime as well as dry cold season and cold season (CS) of Mediterranean regime. Results revealed that on a regional level, CHIRPS and rain gauge data had a good agreement of wet and dry conditions. CHIRPS approximation is better at timescale higher than 1 month. It captured wet periods on 3-month and 6-month basis with an overestimation over CS region and good agreement with extreme drought events. On a monthly basis, CHIRPS slightly underestimated rainfall in WS area but highly overestimated it in CS area.

CHAPTER III

METHODOLOGY

A. Study Area

Lebanon is a small Mediterranean country with an area of 10,452 km^2 located in the South Western region of Asia. It has a long coastline of about 220 km which forms its entire western border. Syria borders it from the north and east and Palestine from the south. Generally, Lebanon has a hot summer and a cool rainy winter. Fall and Spring are transitional seasons. After summer, temperatures are lowered gradually during Fall with little rain whereas the opposite occurs in Spring allowing vegetation to revive after the winter rain.

Lebanon is characterized by countless topographic variations that create local modifications in the general climatic profile. It has about 70 – 75% of its area as mountainous terrain (Fig. 1). These variations form 3 main climatic areas: the coastal area (0-200 m.a.s.l) (Fig. 2), the Lebanese Mountainous region (600-3000 m.a.s.l) and the Bekaa Inland Valley (average of 1000 m.a.s.l). During Winter, the coastal area receives great amounts of precipitation for a short period mainly after December. Frosts and hail might hit this area infrequently whereas snowfalls can occur every decade or so. Spring is warm and sunny and might carry sandy hot winds from the Egyptian desert. The nearby sea provides a cool alteration on the climate allowing narrower temperature fluctuations than those of the Bekaa area. Summer is hot and humid while Fall is rainy and windy increasing total annual precipitation to reach a range of 600 mm and 800 mm in this area (MOE/UNDP/ECODIT, 2011).

Winter is much colder at the Western Lebanese Mountains due to the increase in elevation thus witnessing more precipitation, snow and frost periods. The cool winds blowing from Europe gather moisture when passing over the Mediterranean. When the packed clouds rise with the peaking mountains they become cooler and saturated resulting in precipitation. Summer days can be as hot as they are at the coast with less humidity but the nights are cooler inducing a wider range of daily temperature. Visitors benefit from the healthy weather by spending summer in these villages and leaving in Fall which can also be much rainy. The total annual precipitation might range between 1000 mm and 1400 mm with peaks stretching up to 2000 mm occasionally (MOE/UNDP/ECODIT, 2011). Winter is severe in the Eastern Mountains bordering Syria but with less rain and more snow due to harsh low temperatures.

The Bekaa valley is shielded from the effect of the Mediterranean by the Western Mountains. So it receives between 200 mm and 600 mm of rain annually (MOE/UNDP/ECODIT, 2011). However, the valley doesn’t have uniform climatic conditions over its whole area. The decrease in the height of the Western range southwards, shifts the environment from Northeastern semi-desert to Southwestern wetlands (Lateef, 2004). Rainfall in the southern regions ranges between 600 mm to 1000 mm (Farajallah et al., 2014). Also, snow might fall more at some areas in the valley than it does at areas of same altitudes on the Lebanese Mountains.

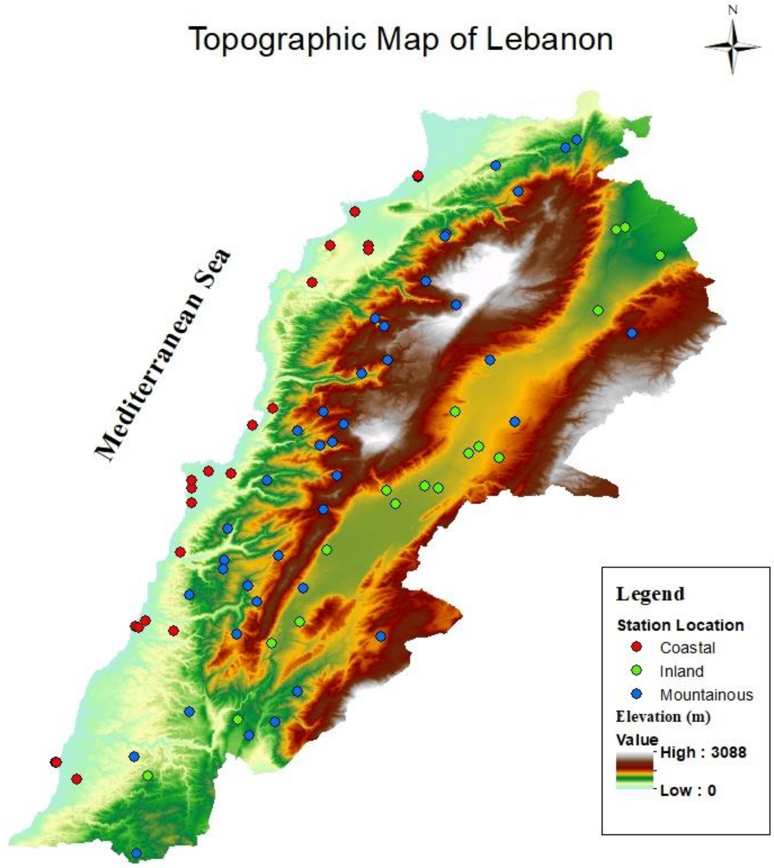

Figure 1: Stations distribution on Lebanon topographic map based on SRTM 30 DEM

B. Data

1. Ground Weather Station Data

The ground data is based on records from 86 ground weather stations distributed over different regions in Lebanon. Eleven stations were removed due to duplication or erroneous data like Bar Elias, Markaba, Mshaytiye, Btedii and Al Fekha to have a total of 75 stations. Data from all stations were subject to quality control. Daily missing data was identified and documented whereas unusual observations like very high values were discarded. Due to the absence of one party controlling all stations, the period of record is discontinuous from September 2000 until April 2018. The hydrologic year was chosen to be from September till August. So the annual analysis was done from

September 2000 till August 2017 and the monthly analysis from September 2000 till April 2018. Around thirty-five stations had a record period mainly from 2000 until 2012. Although there was some missing data in some stations like Marjayoun, Douris, Zahrani, Kfarkour and others. Another 34 stations had data from 2013 till April 2018.

Monthly data was inferred from the daily directory and plotted for every station. Then the summation of monthly data was used to produce annual data.

Satellite Precipitation Data

CHIRPS v2 global monthly precipitation data from 2000 till 2018 was downloaded from the Climate Hazards Group US Santa Barbara website. The images were projected on the WGS84 – 36 UTM coordinate system and precipitation values were extracted at every station using the “Extract Values by Point” Tool on ArcMap. A detailed quality control check was performed to assess any illogical values. When compared to ground station data, high CHIRPS precipitation values were discarded.

IMERG v5 global monthly precipitation data from 2000 till 2018 was downloaded from NASA’s Precipitation Measurement Missions website in the form of HDF5 files. They were later converted to Geotiff files displaying the subset “precipitation” and projected to the convenient coordinate system. Same concept of quality control as for CHIRPS data was executed for IMERG. Satellite data values (CHIRPS and IMERG) higher than 10 mm per day when ground data equals to zero were also removed.

2. Elevation Data

Four Digital Elevation Model (DEM) images of Shuttle Radar Topography Mission 1 Arc-Second Global (SRTM 30) covering Lebanon were downloaded from Earth Explorer and merged into a mosaic using the "Mosaic to New Raster" Tool on ArcMap. The DEM values were extracted from the combined image at every station to assess the relation between precipitation rates and topographic elevations (Fig. 3).

3. Methodology used for Analysis

a. Statistical Analysis and Indices

In order to test for several relations between annual and monthly rain gauge observations and satellite estimates, different aspects were taken into consideration. The effects of latitude, longitude, topography and location on the correlation between satellite and ground precipitation data were assessed.

The statistical indices used are the R-squared, root-mean-square error (RMSE) and Relative error (RE). The R-squared index measures the degree of correlation between the two precipitation data, in other words, how close is satellite data to ground data. RMSE refers to the average error magnitude or differences between CHIRPS data or IMERG and station data, whereas RE is a measure of precision obtained by dividing RMSE by Ground Mean of Response (MoR) then multiplying by 100.

Annual and monthly means were obtained on JMP using Oneway Analysis Means/Anova, also the above statistical indices were obtained by finding the linear fit of the Bivariate Fit between ground rain gauge data and satellite data. Percent difference of CHIRPS was calculated by subtracting CHIRPS mean precipitation from Ground mean precipitation, then dividing it by their sum and multiplying by 100.

b. Categorical Analysis of Rain Gauges

Information about all stations was gathered including longitude, latitude, elevation above sea level, and location. All ground and satellite precipitation data were combined with station characteristics and analyzed on JMP software (JMP, 2013).

Stations were divided into 3 Longitude classes according to a precipitation map derived from Ground data during Winter months. This was performed to standardize and compare classes among CHIRPS and IMERG since each product has a different resolution. “Long1” included longitudes between 35.1 and 35.5, “Long2” from 35.5 to 36 and “Long 3” from 36 to 36.6. Likewise, to study the effect of Latitude on precipitation measurements, stations were categorized into 4 Latitude classes as shown below. Four classes were chosen for Latitude classification due to the fact that Lebanon’s geography is elongated vertically.

Latitude Class	**Latitudes included**
Lat1	between 33 and 33.5
Lat2	between 33.5 and 33.9
Lat3	between 33.9 and 34.3
Lat4	between 34.3 and 34.7

Ground stations were classified into 3 elevation categories; C1 for elevations less than 800m, C2 between 800m and 1500m and C3 above 1500m. This grouping permits analyzing the effect of elevation on precipitation rates as well as assessing the performance of each satellite product at different elevation ranges. Moreover, due to the complicated topography of Lebanon, rain gauges were also classified according to their locations into West and Inland stations for further assessment of the relation between different climatic regions and rainfall. West stations are those located west of the border of all river watersheds discharging in the Mediterranean. Inland stations are located east of this border mainly in the Bekaa valley area. This was done specifically to study the differences in precipitation rates of the two regions without allowing the geographic characteristics of one region affect the rates of the other. West stations were also divided into Coastal and Mountainous stations for a more accurate analysis on topography and precipitation.

Note that mean annual Ground precipitation varies when analyzing the performances of CHIRPS and IMERG products since each product has a different period of record. CHIRPS shows 17 years of data whereas IMERG has only three. It is important to evaluate IMERG against the corresponding Ground data for the 3 years and not the ones before.

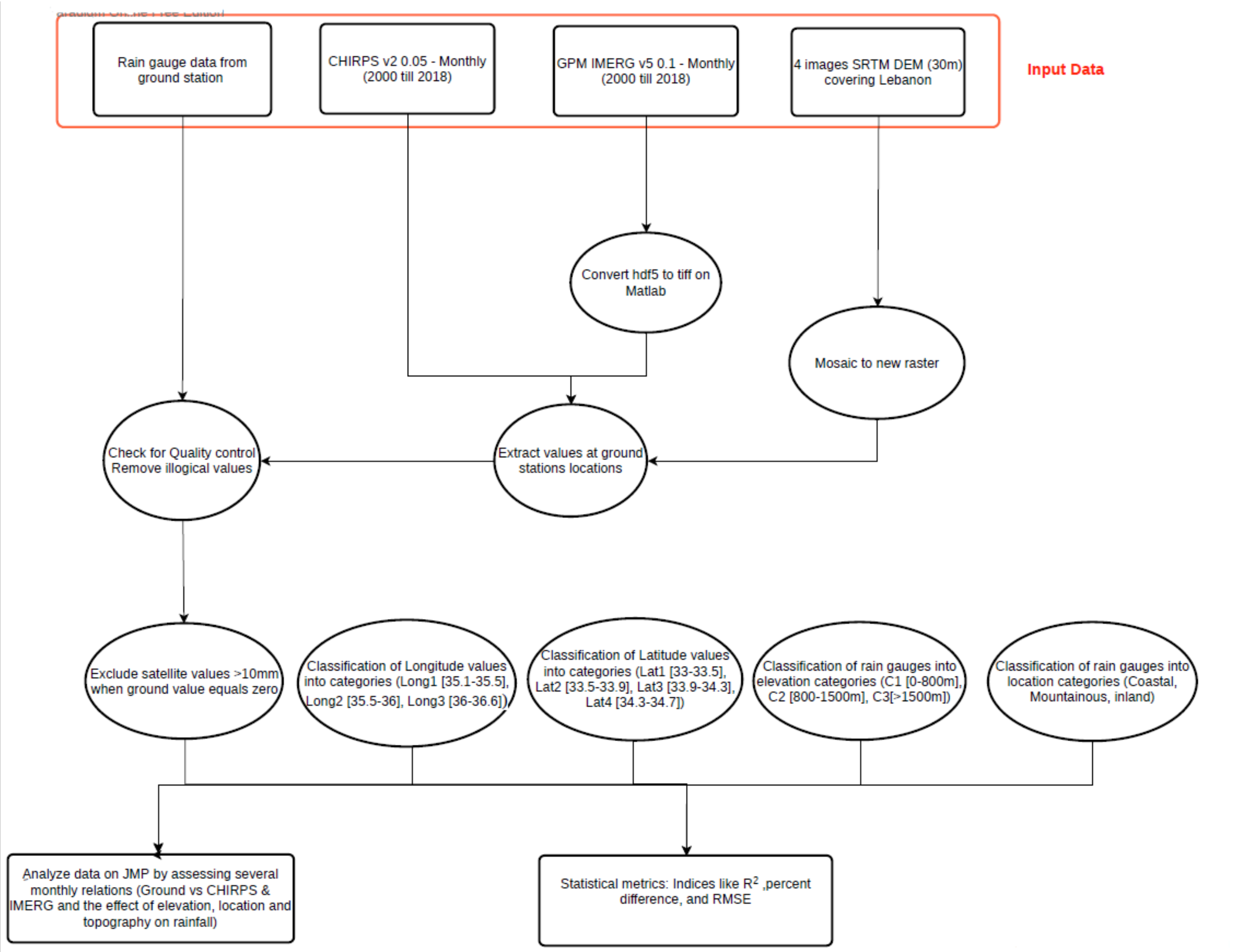

Figure 2: Flowchart illustrating the methodology used

CHAPTER IV

RESULTS

A. Correlation between Satellite Data and Ground rain gauge data

1. Yearly Analysis

For unbiased analysis, only stations with 12 months' record per year were used. Annual CHIRPS data showed a better correlation with ground gauge data (R^2=0.353, Relative error (RE) = 20.4%) (fig.3) than IMERG did (R^2 = 0.084, RE= 16.7%) (fig.4). Table 1 shows that the hydrologic years 2002-2003 and 2011-2012 were the wettest, whereas 2000-2001 and 2012-2013 were the driest according to the ground data. During the driest years, R^2 of CHIRPS data marked very low values (like 0.028) (fig. 6) indicating weak correlation with ground data unlike those of wet years (700 - 900mm/year). Since GPM IMERG was not launched until 2014, there is complete record for only 3 years. This satellite product showed weak correlation with Ground data.

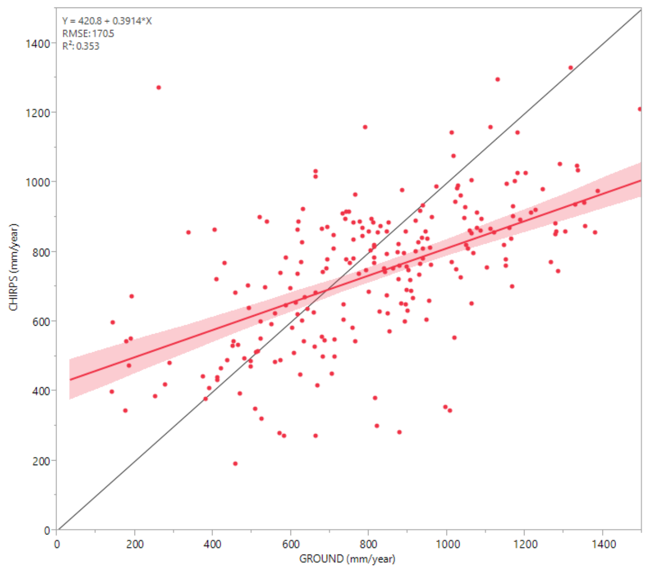

Figure 3: Scatterplot (CHIRPS vs ground rainfall) of mean annual precipitation over Lebanon from year 2000 till 2017

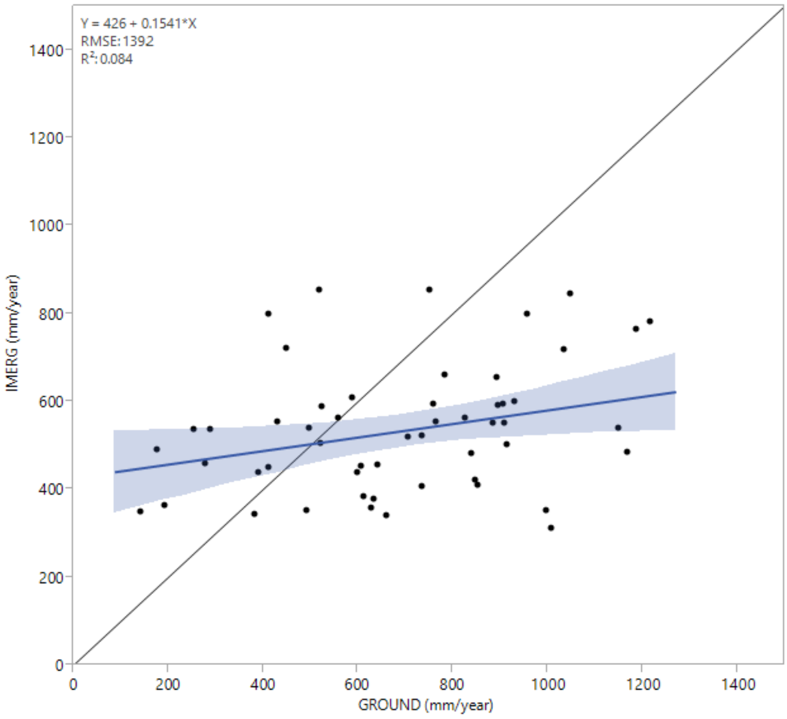

Figure 4: Scatterplot (IMERG vs ground rainfall) of mean annual precipitation over Lebanon from year 2000 till 2017

Table 1: Annual mean precipitation of Ground, CHIRPS and IMERG data

Year	Ground (mm/year)	CHIRPS (mm/year)	IMERG (mm/year)	% diff CHIRPS	% diff IMERG
2000-2001	551	621		-11.88	
2001-2002	876	805		8.43	
2002-2003	1155	1080		6.75	
2003-2004	766	749		2.27	
2004-2005	824	887		-7.29	
2005-2006	798	726		9.45	
2006-2007	725	721		0.56	
2007-2008	776	537		36.39	
2008-2009	872	784		10.70	
2009-2010	975	846		14.16	
2010-2011	988	780		23.58	
2011-2012	1062	760		33.18	
2012-2013	533	698		-26.77	
2014-2015	729	682	669	6.65	8.61
2015-2016	650	577	463	11.84	33.48
2016-2017	731	580	452	22.96	47.10
Annual mean	**836**	**748**	**534**	**8.87**	**29.7**

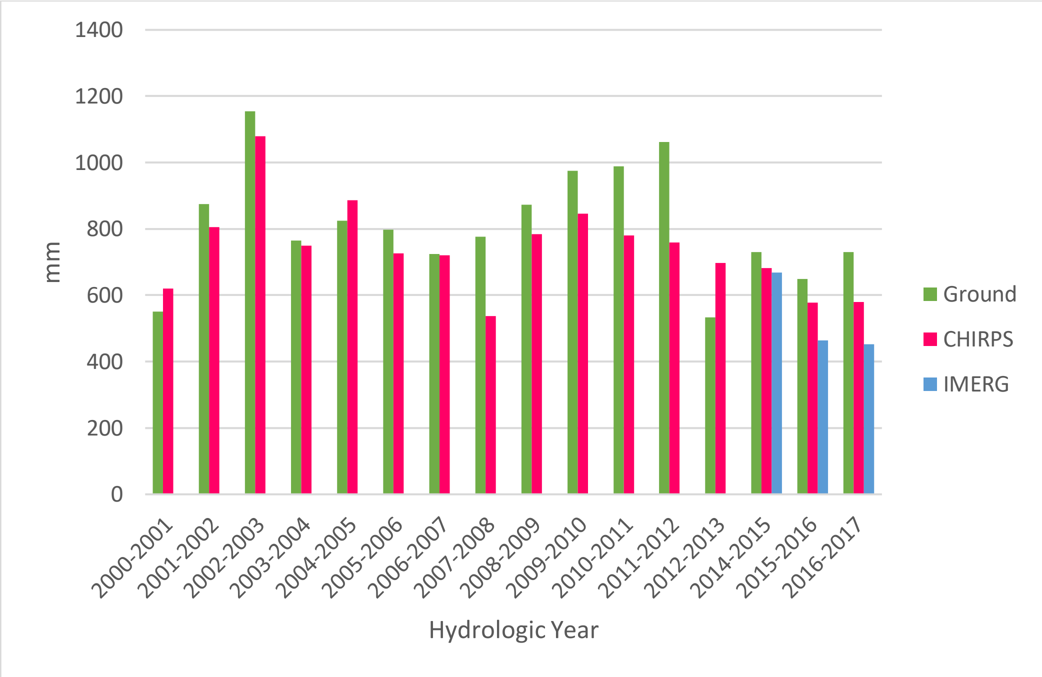

Figure 5: Annual average precipitation from 2000-2001 till 2016-2017

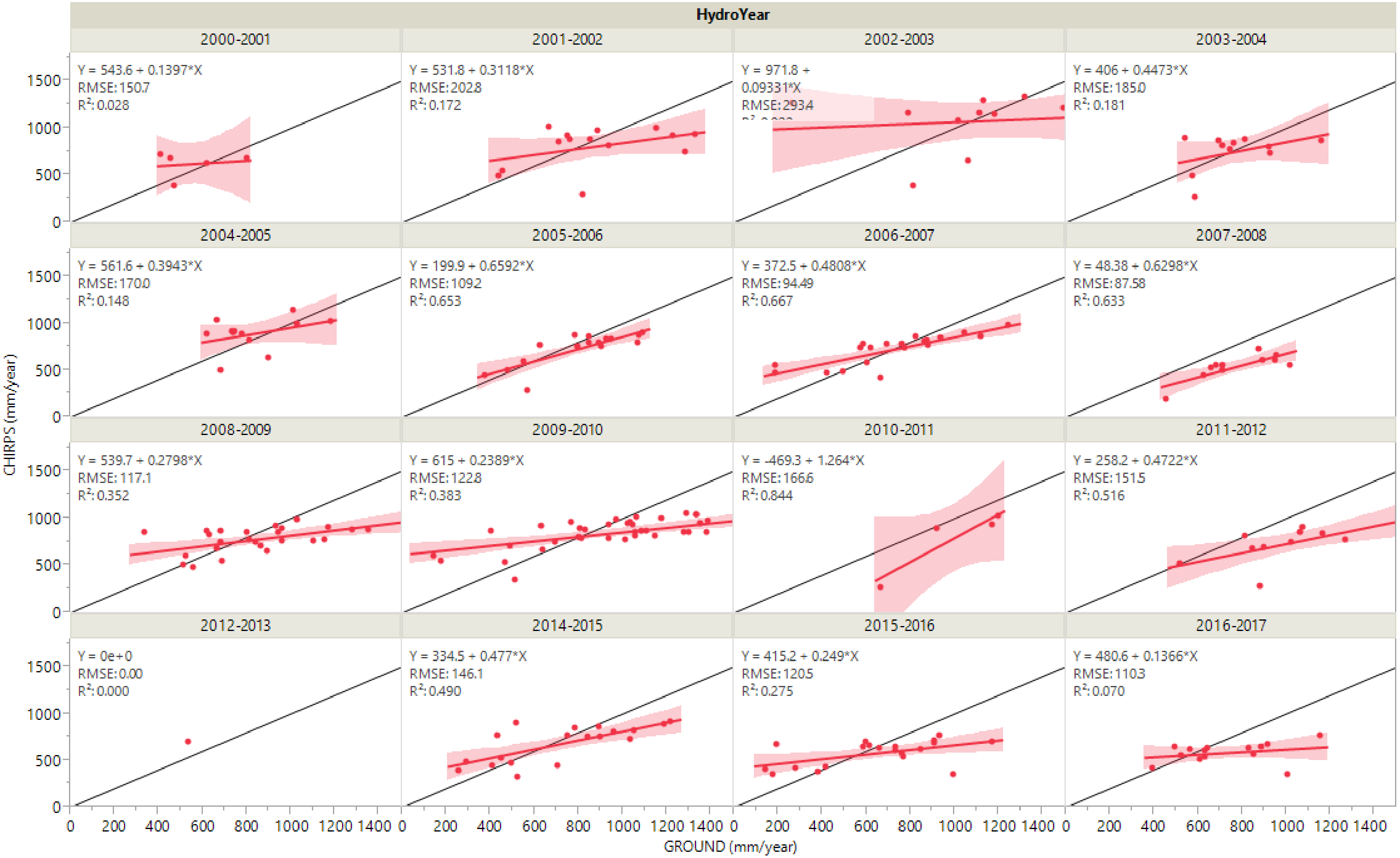

Figure 6: Yearly precipitation over Lebanon detected by satellite product CHIRPS vs Ground data

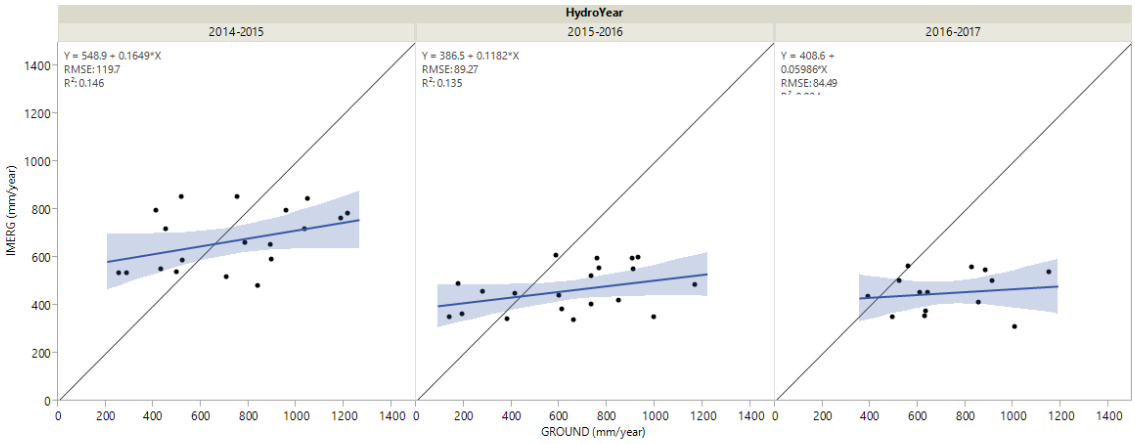

Figure 7: Yearly precipitation over Lebanon detected by satellite product IMERG vs Ground data

2. *Monthly Analysis*

The monthly performances of CHIRPS and IMERG products showed very similar positive correlation with rain gauge data (Fig. 8 and 9).

This relation is clearer during rainy months (mainly November, December, January and February) (Fig.10). January recorded highest rainfall amounts by the three measuring products; 163 mm by Ground rain gauges, 171 mm and 130 mm by CHIRPS and IMERG respectively. On a broader level, CHIRPS tends to overestimate precipitation during rainy months (Dec, Jan, Feb and Mar) and underestimate during drier ones (Sep, Oct, Nov, and May) (Fig. 10). On the other hand, IMERG underestimated during all months except in February where it overestimated by about 8% (fig. 11). Also better correlation was during Fall and Winter (fig. 13)

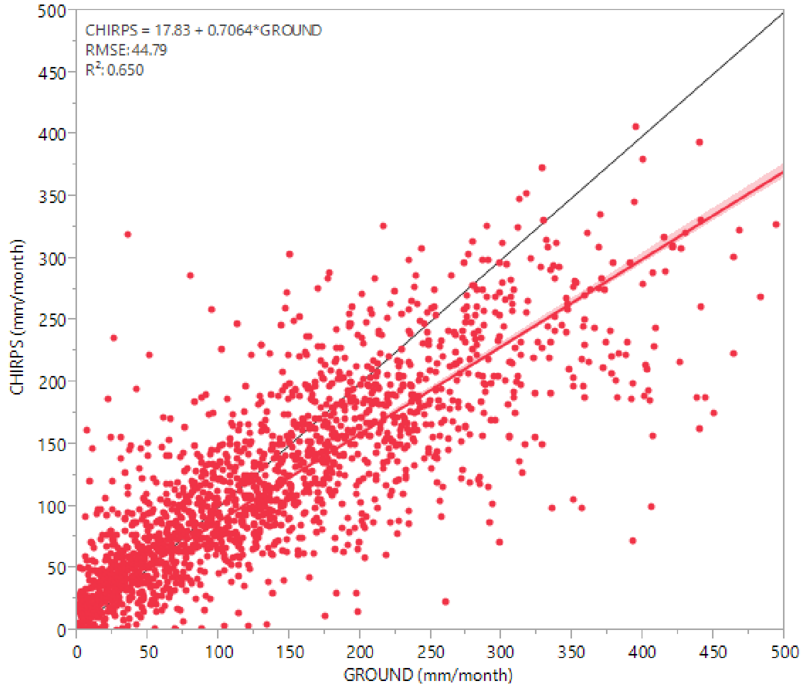

Figure 8: Average Monthly precipitation over Lebanon detected by CHIRPS product vs Ground data

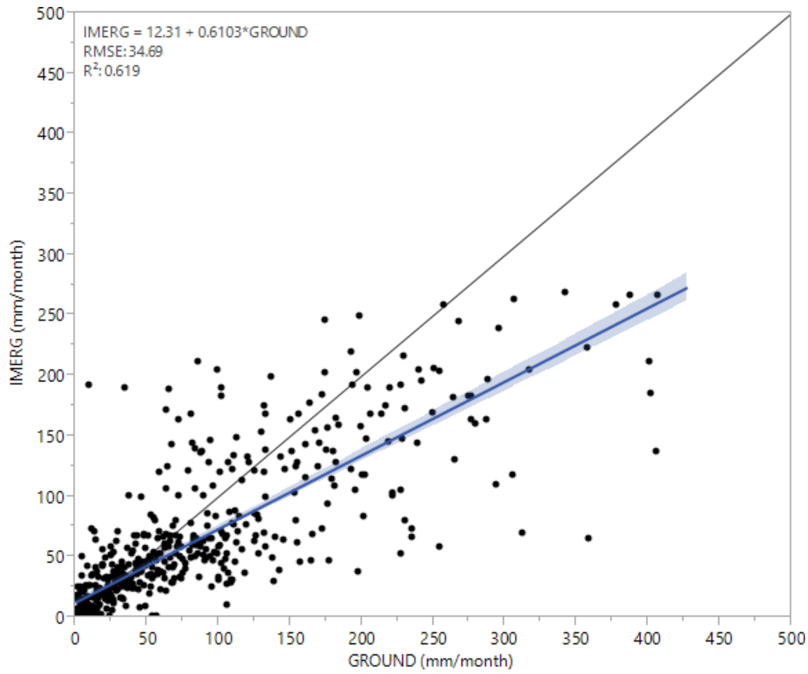

Figure 9: Average Monthly precipitation over Lebanon detected by IMERG product vs Ground data

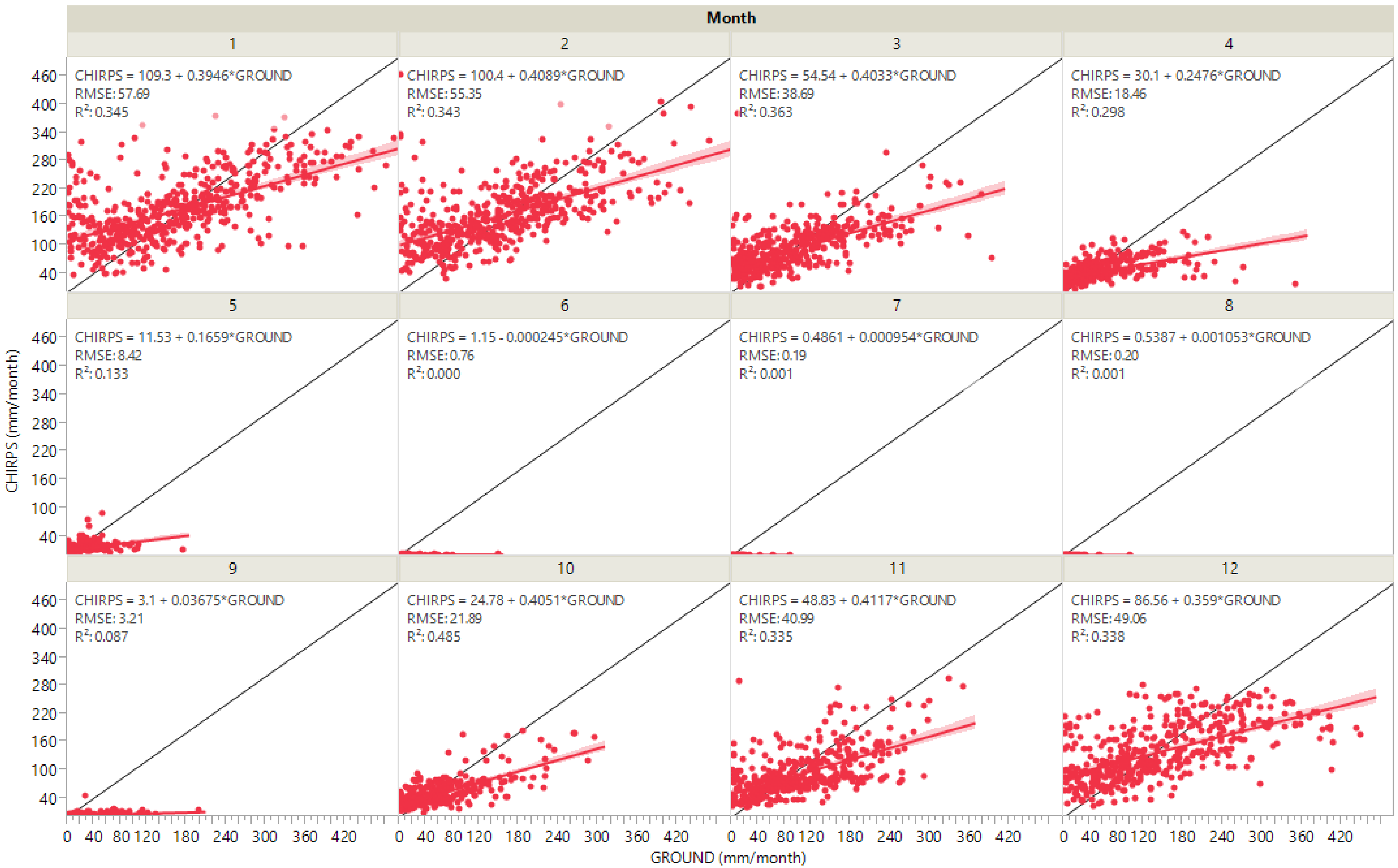

Figure 10: Monthly rainfall variation of CHIRPS satellite product vs Ground data

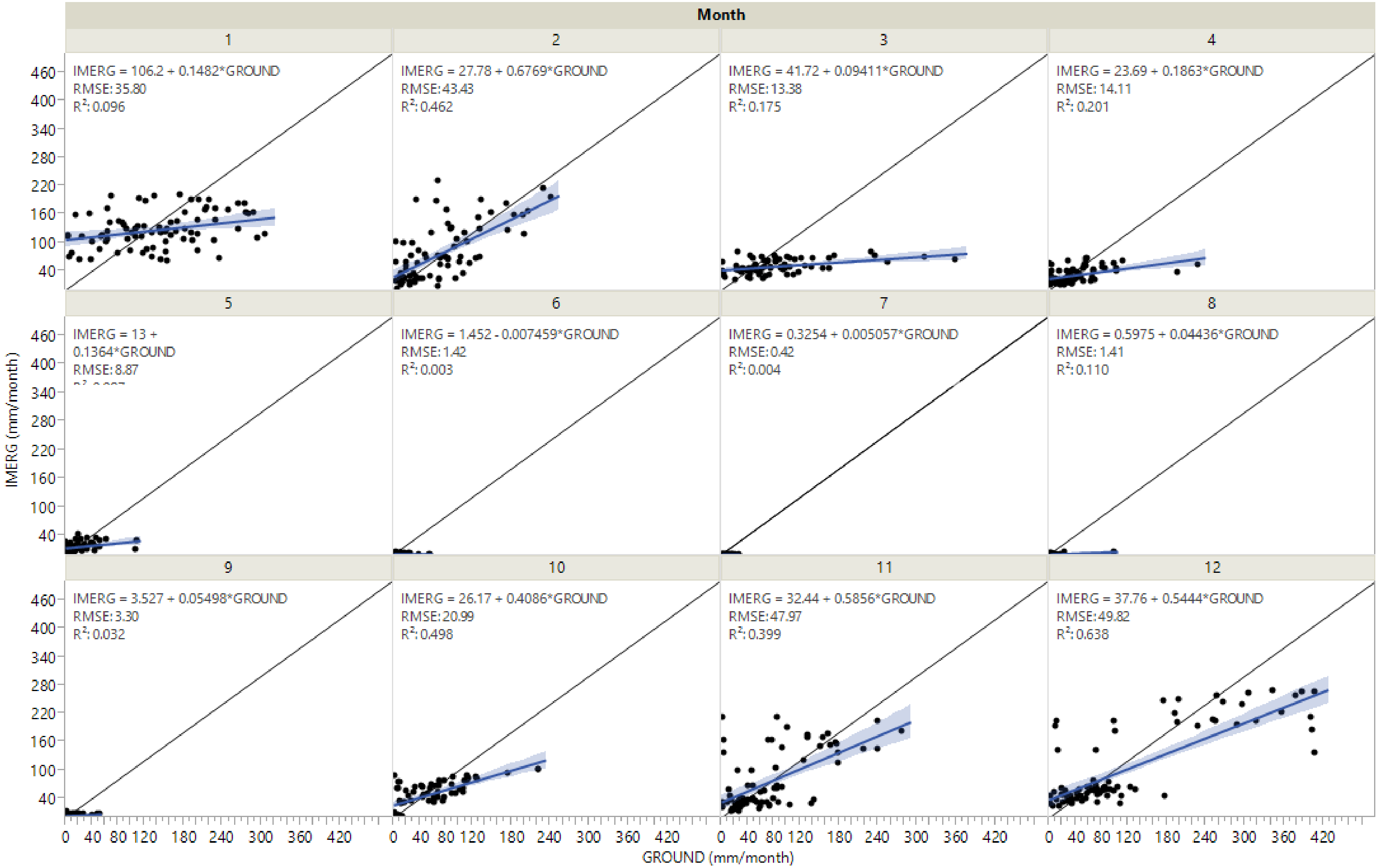

Figure 11: Monthly rainfall variation of IMERG satellite product vs Ground data

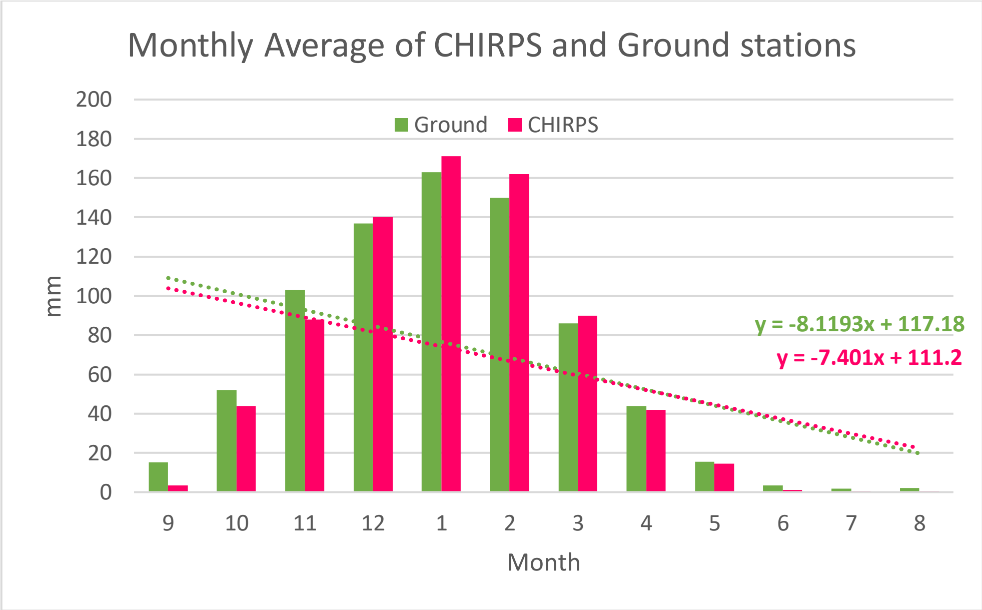

Figure 12: Monthly average precipitation by CHIRPS and ground stations from September till May mainly

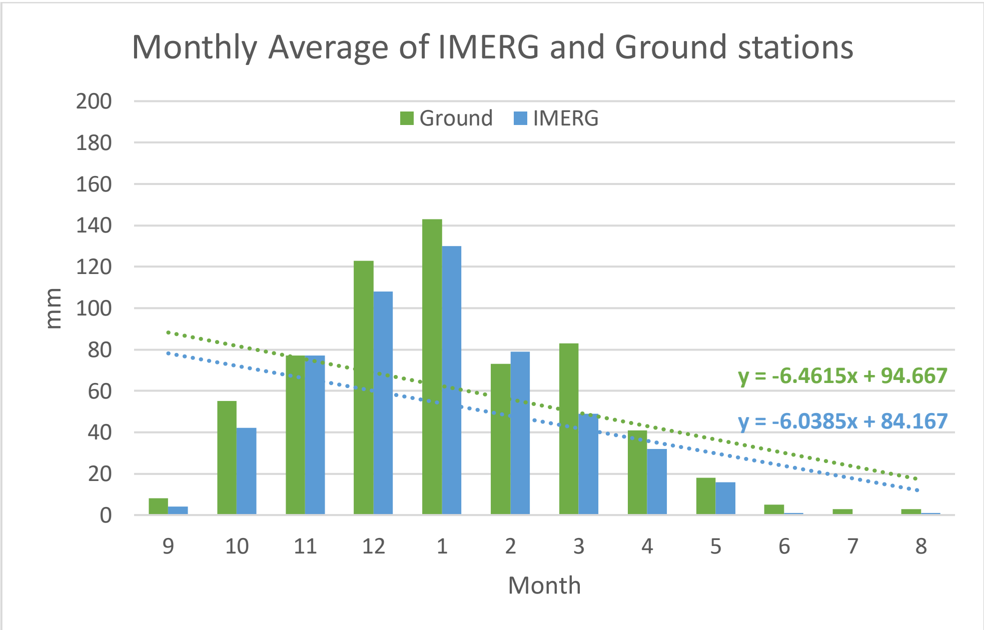

Figure 13: Monthly average precipitation by IMERG and ground stations from September till May mainly

B. Effect of Longitude and Latitude on the correlation between Ground rain gauge and satellite data

1. Yearly Analysis

Lebanon spreads between latitudes 33° and 35°N and longitudes 35° and 37° E. As we move eastwards across Lebanon there is better correlation between CHIRPS and Ground data (better R^2 and RMSE values at classes Long2 and Long3 than those at Long1) (Fig 14). Also results showed that at Long1 and Long2, CHIRPS tends to overestimate precipitation when rainfall is below 800 mm and underestimate it above 800 mm. However, at Long3 it underestimated precipitation when it was above 600 mm. As for IMERG, there was no specific trend or better statistical values in one class than the other. According to figure 15, this satellite product underestimated precipitation when rainfall was above 500 mm.

As we move upwards towards the North of Lebanon, CHIRPS detects precipitation better than it does over the Southern areas (Fig 16). Likewise, IMERG recorded an R^2 of 0.688 and RE= 13.3% (where RE = RMSE/[$Mean_{Ground}$ x 100], where $Mean_{Ground}$ = 679 mm) over Lat4 class.

A precipitation map was derived from the rainiest months of the Winter season (December, January and February) (fig. 18). This map was used for the classification of Longitude and Latitude categories.

2. Monthly Analysis

Both satellite products detected precipitation similarly at the different Longitude and Latitude classes (fig. 19 to 22). This indicates that both factors do not have a significant influence on monthly precipitation detected by CHIRPS and IMERG

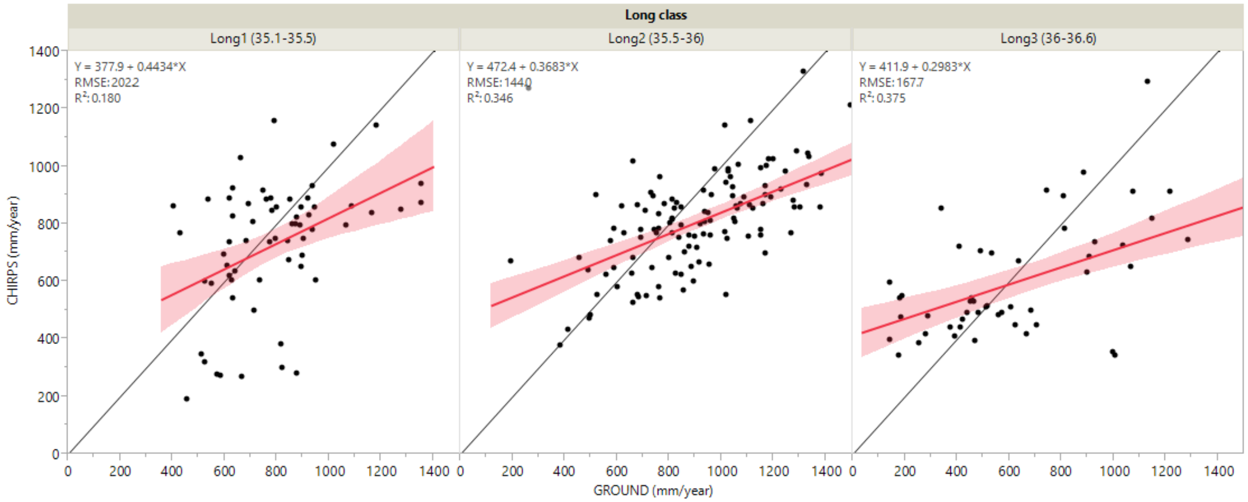

Figure 14: Annual Precipitation comparison between CHIRPS and Ground data as a function of Longitude

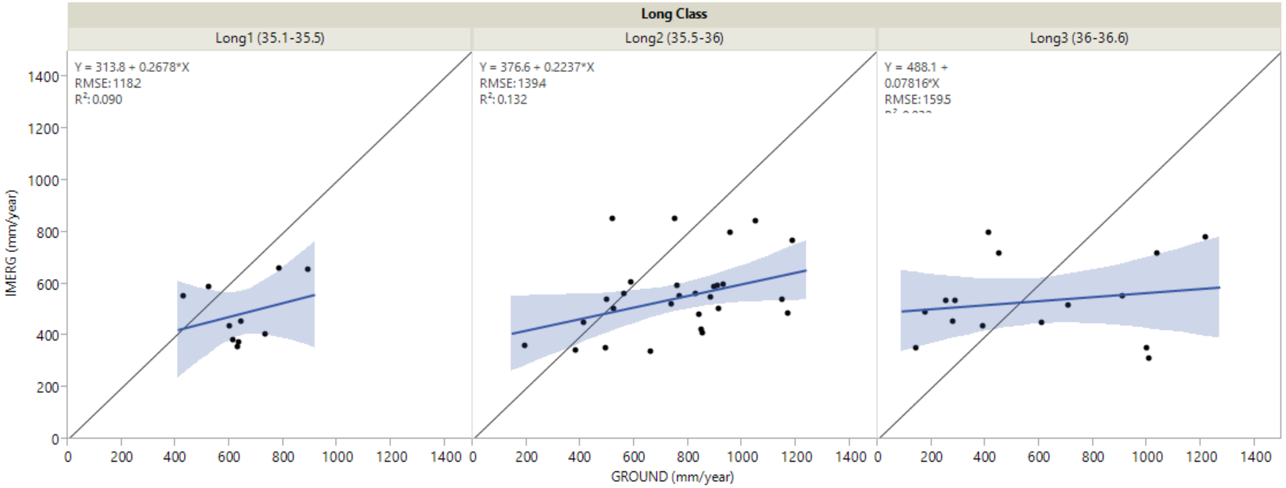

Figure 15: Annual Precipitation comparison between IMERG and Ground data as a function of Longitude

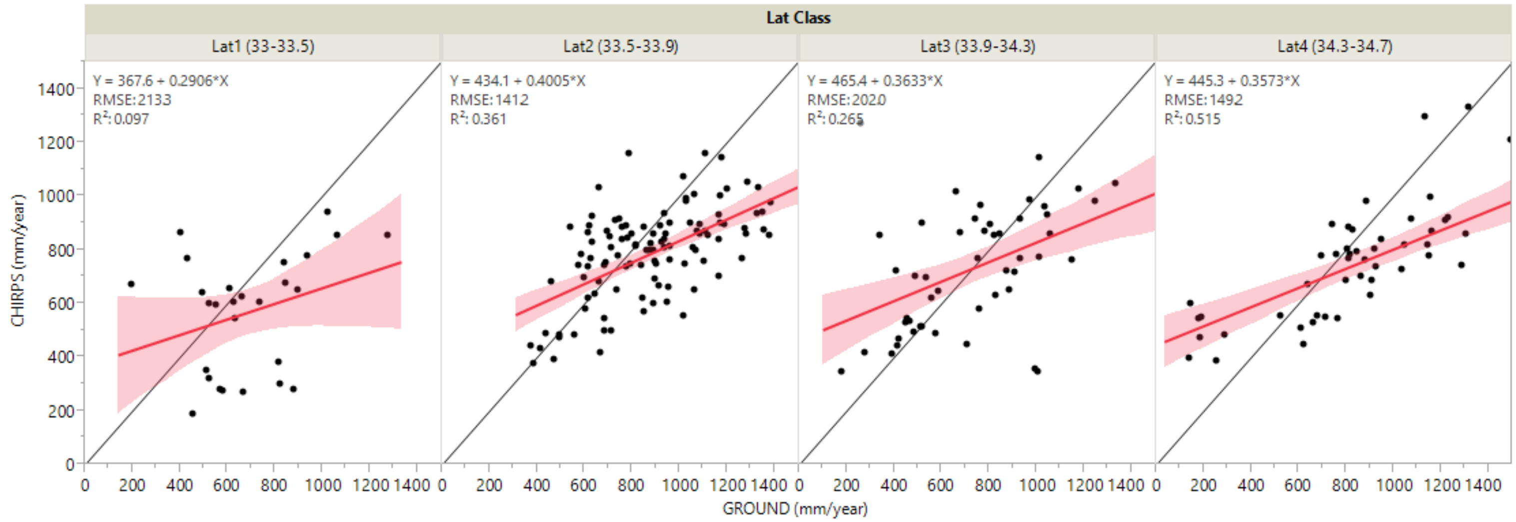

Figure 16: Annual Precipitation comparison between CHIRPS and Ground data as a function of Latitude

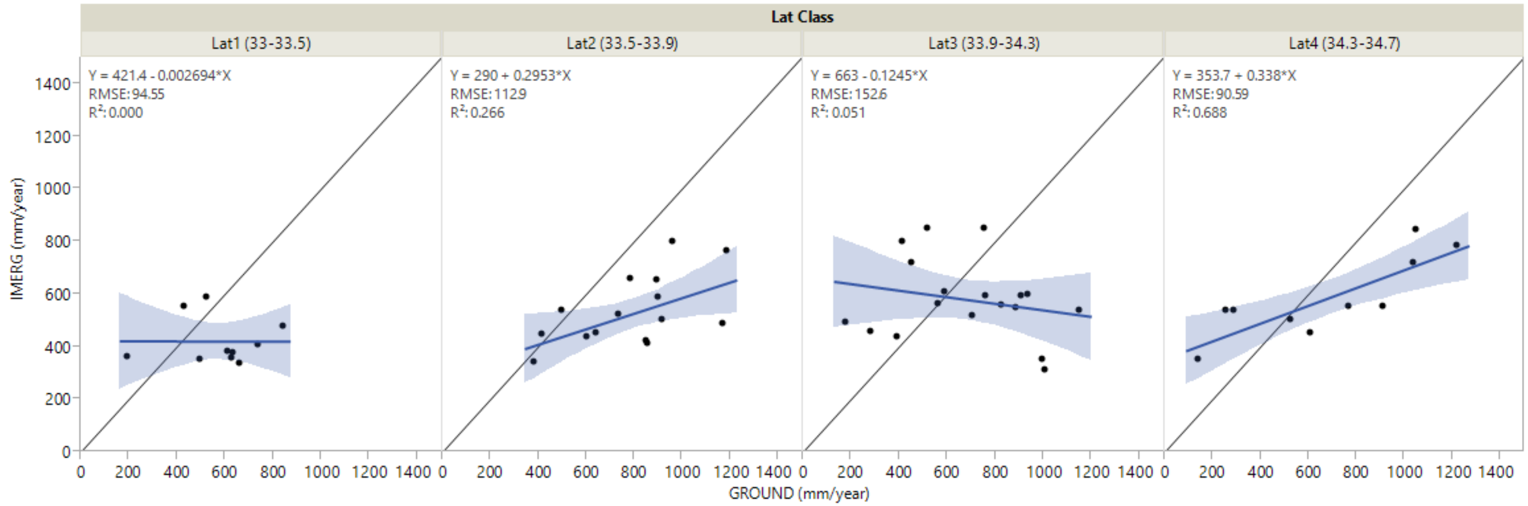

Figure 17: Annual Precipitation comparison between IMERG and Ground data as a function of Latitude

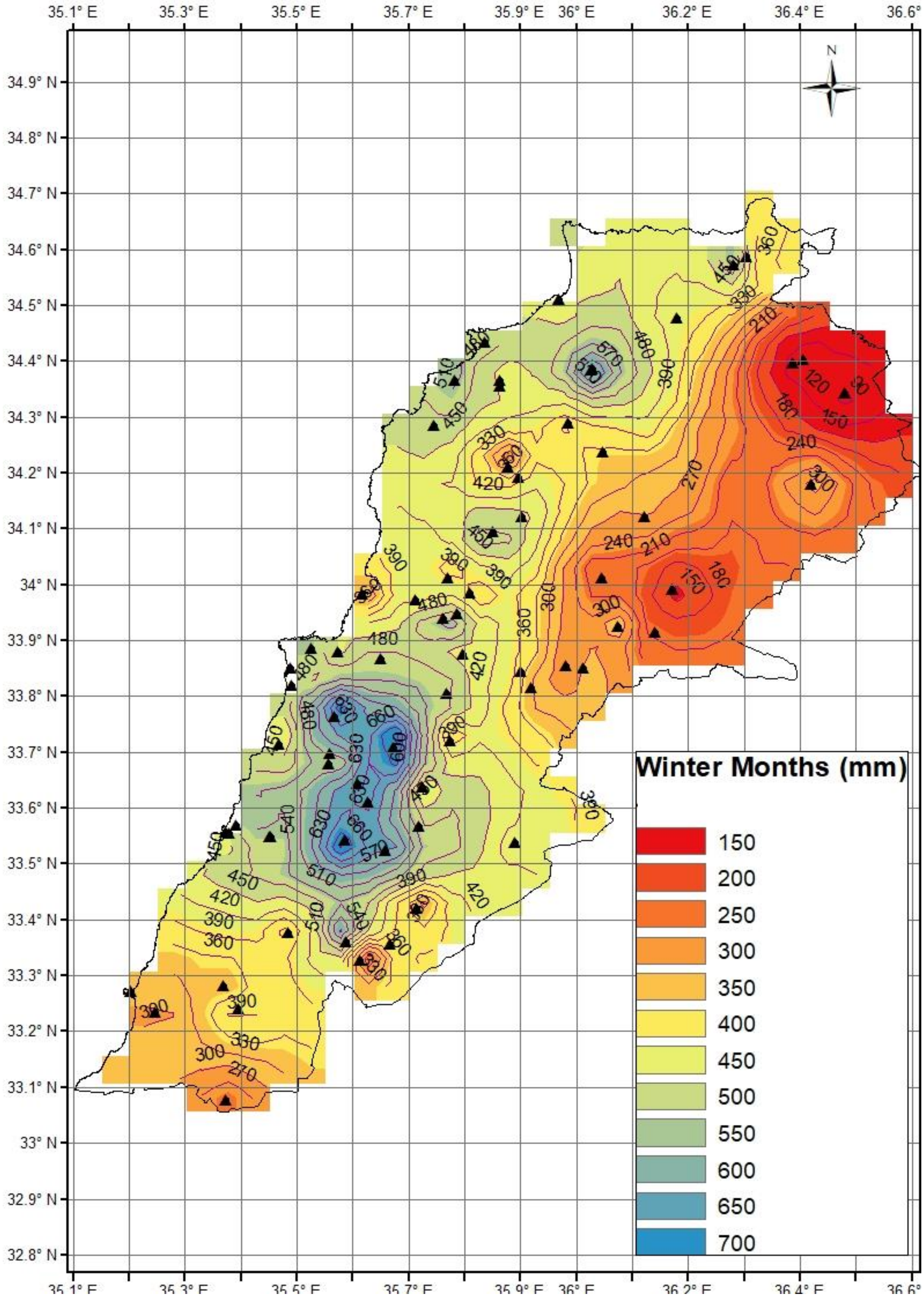

Figure 18: Average Winter Precipitation map over Lebanon (December, January and February) from 2000-2001 till 2016-2017

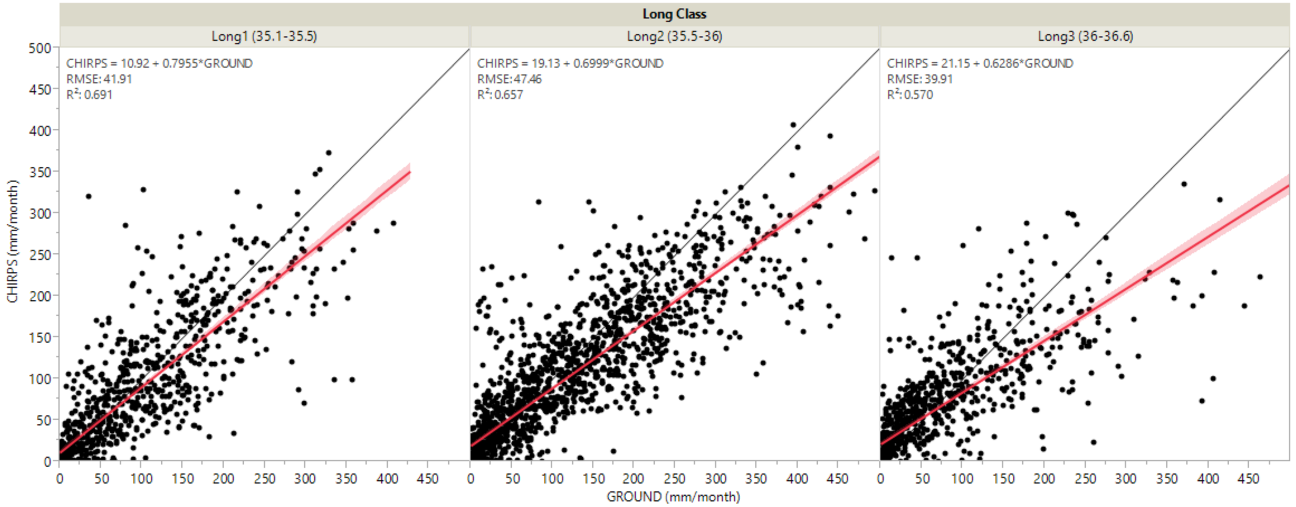

Figure 19: Monthly Precipitation comparison between CHIRPS and Ground data as a function of Longitude

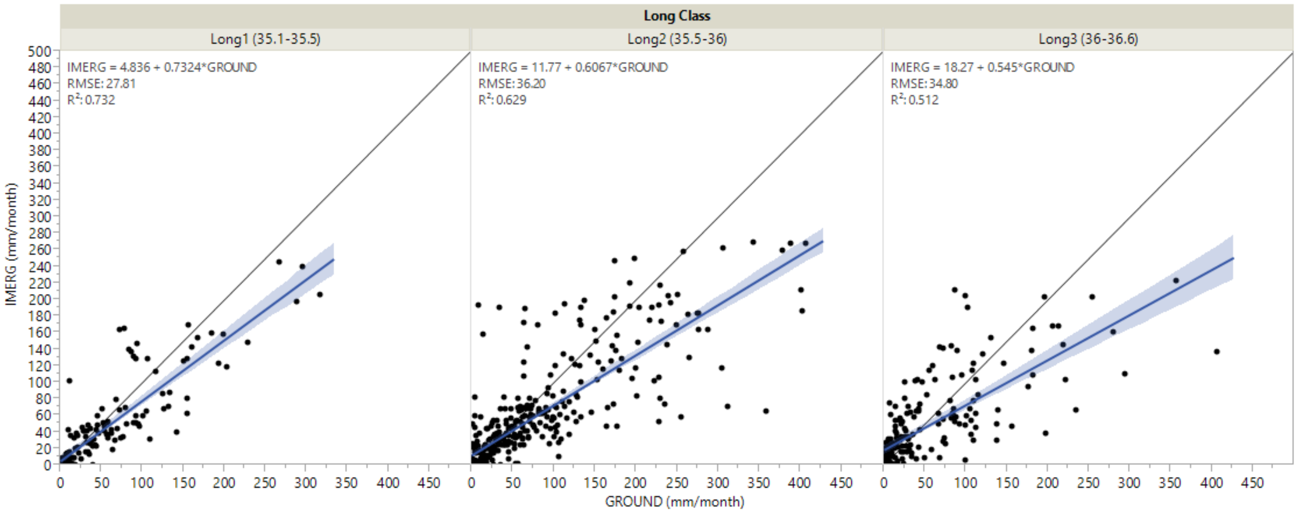

Figure 20: Monthly Precipitation comparison between IMERG and Ground data as a function of Longitude

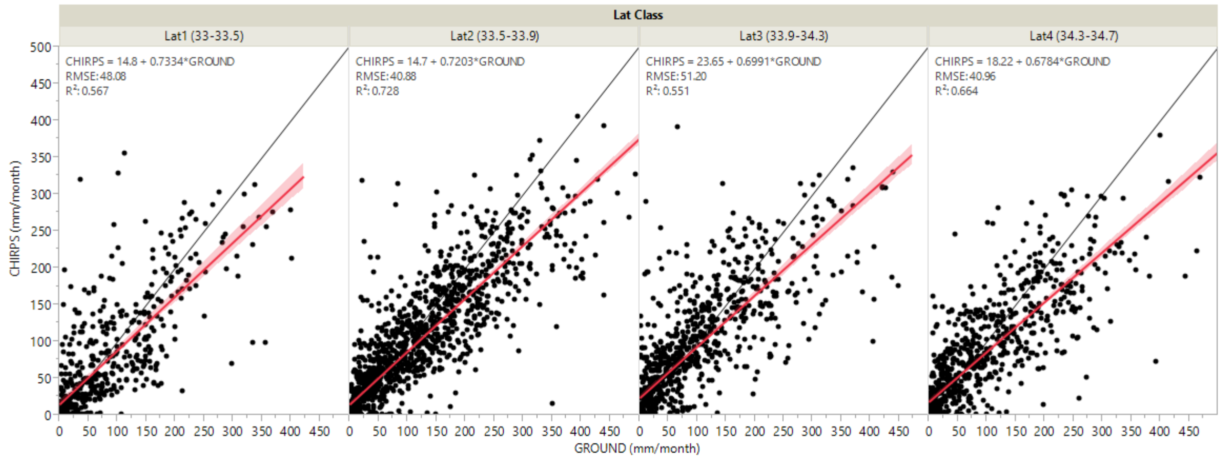

Figure 21: Monthly Precipitation comparison between CHIRPS and Ground data as a function of Latitude

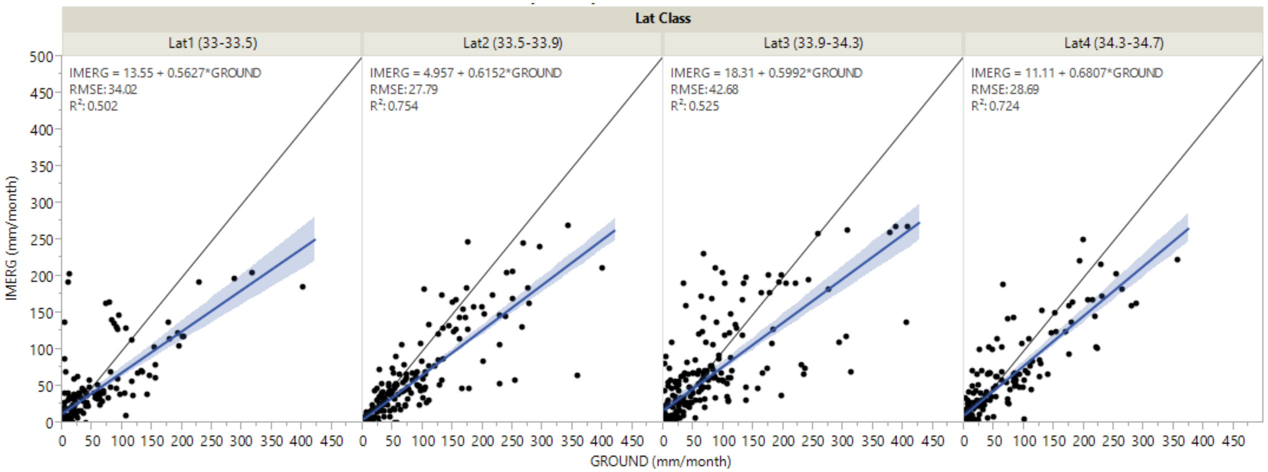

Figure 22: Monthly Precipitation comparison between IMERG and Ground data as a function of Latitude

C. Effect of Elevation on the correlation between Ground rain gauge and satellite data

1. Yearly analysis

Knowing the complex topography of Lebanon, it is important to assess its effect on precipitation and the accuracy of products detecting it (Ground stations or satellite). Elevation values were divided into 3 categories of low (0 < C1 < 800m), mid (800m < C2 < 1500m) and high elevations (C3 > 1500m) (Table 3). Annual precipitation data ranged from around 555 mm to 1173 mm at low elevation (Table 4), from 464 mm to 1201 mm at mid elevation (Table 6) and from 410 mm to 1053 mm at high elevation (Table 8). The widest range is at elevation C2; this can be explained by the topographic complexity in this zone that result in big temperature and precipitation fluctuations. On average from hydrologic year 2000-2001 till 2016-2017, the percent difference between CHIRPS and Ground showed an underestimation of 10% at C1 and around 9% at C2 (Tables 4 and 6). CHIRPS also showed better correlation with Ground data at C2 than in the other classes ($R^2 = 0.465$, Re = 18.8%) (fig. 23). IMERG underestimated precipitation but at a higher rate than CHIRPS (23.3% and 36% at C1 and C2, respectively). It had better correlation at low elevation (fig. 24). However, both satellite products overestimated precipitation at high elevation (6.2% and 2.0%) (Table 6). Knowing that precipitation is mainly snow at C3, it might have hindered the accurate reading of satellite products since they detect the moisture in the atmosphere but it falls as snow.

Table 2: Average Annual Precipitation over different elevation categories

	Ground (mm/year) for 15 years	CHIRPS (mm/year) for 15 years	IMERG (mm/year) for 3 years
C1	828	756	505
C2	847	729	552
C3	823	834	585

Table 3: Annual percent differences between Ground rain gauge data and CHIRPS product over C1 (0<C1<800m)

Year	Ground (mm/year)	CHIRPS (mm/year)	Diff CHIRPS (%)
2000-2001	709	653	8.2
2001-2002	982	844	15.1
2002-2003	1173	1094	6.9
2003-2004	793	766	3.5
2004-2005	788	888	-11.9
2005-2006	828	729	12.7
2006-2007	738	767	-3.8
2007-2008	726	490	38.9
2008-2009	903	783	14.2
2009-2010	867	805	7.4
2010-2011	917	698	27.2
2011-2012	1019	684	39.3
2012-2013			
2013-2014			
2014-2015	669	672	-0.4
2015-2016	555	605	-8.7
2016-2017	624	600	3.9
AVERAGE	**828**	**756**	**10.2**

Table 4: Annual percent differences between Ground rain gauge data and IMERG product over C1

Year	Ground (mm/year)	IMERG (mm/year)	% Diff IMERG
2014-2015	669	628	6.3
2015-2016	555	419	27.8
2016-2017	624	434	35.9
AVERAGE	**617**	**505**	**23.3**

Table 5: Annual percent differences between Ground rain gauge data and CHIRPS product over C2 (800-1500m)

Year	Ground (mm/year)	CHIRPS (mm/year)	Diff CHIRPS (%)
2000-2001	464	538	-14.8
2001-2002	621	715	-14.1
2002-2003	1102	1035	6.3
2003-2004	692	702	-1.3
2004-2005	810	843	-3.9
2005-2006	749	721	3.7
2006-2007	708	660	7.0
2007-2008	908	660	31.6
2008-2009	882	768	13.9
2009-2010	1076	878	20.3
2010-2011	1201	1026	15.7
2011-2012	1120	852	27.2
2012-2013	533	698	-26.8
2013-2014			
2014-2015	779	691	11.9
2015-2016	718	552	26.1
2016-2017	833	560	39.1
AVERAGE	**847**	**730**	**8.9**

Table 6: Annual percent differences between Ground rain gauge data and IMERG product over C2

Year	Ground (mm/year)	IMERG (mm/year)	% Diff IMERG
2014-2015	779	703	10.3
2015-2016	718	480	39.7
2016-2017	833	452	59.3
AVERAGE	**769**	**552**	**36**

Table 7: Annual percent differences between Ground rain gauge data and CHIRPS product over C3 (>1500m)

Year	Ground (mm/year)	CHIRPS (mm/year)	Diff CHIRPS (%)
2000-2001	410	721	-55.0
2001-2002	937	809	14.7
2002-2003			
2003-2004			
2004-2005	961	971	-1.0
2005-2006			
2006-2007			
2007-2008			
2008-2009	634	886	-33.1
2009-2010	1053	913	14.2
2010-2011			
2011-2012	1025	750	31.0
2012-2013			
2013-2014			
2014-2015			
2015-2016	588	646	-9.5
2016-2017	560	622	-10.5
AVERAGE	**823**	**834**	**-6.2**

Table 8: Annual percent differences between Ground rain gauge data and IMERG product over C3

Year	Ground (mm/year)	IMERG (mm/year)	% Diff IMERG
2014-2015	**-**	**-**	**-**
2015-2016	588	608	-3.3
2016-2017	560	563	-0.5
AVERAGE	**574**	**585**	**-2**

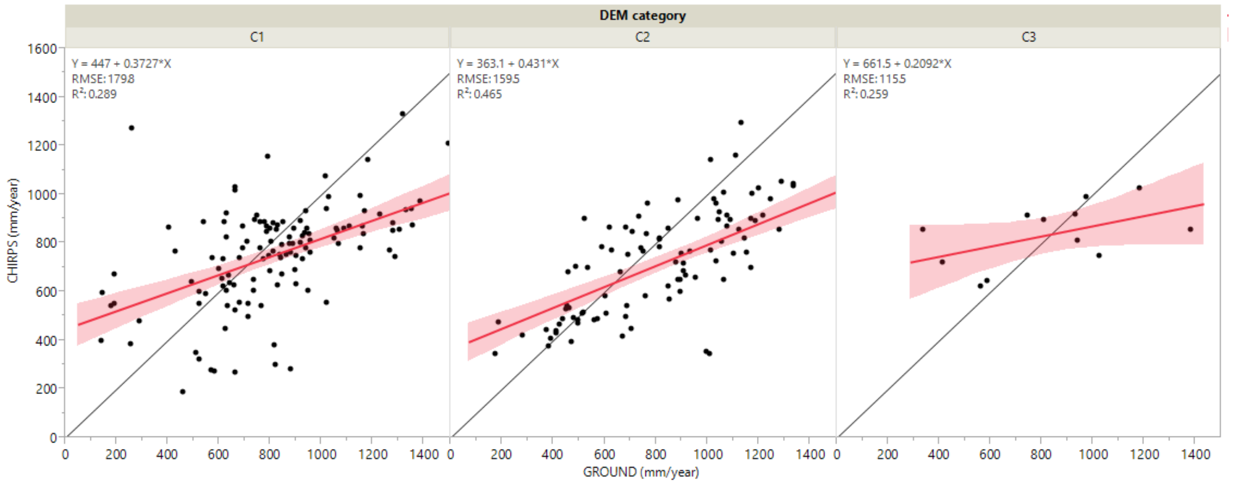

Figure 23: Annual precipitation comparison between CHIRPS product and Ground data over 3 DEM categories

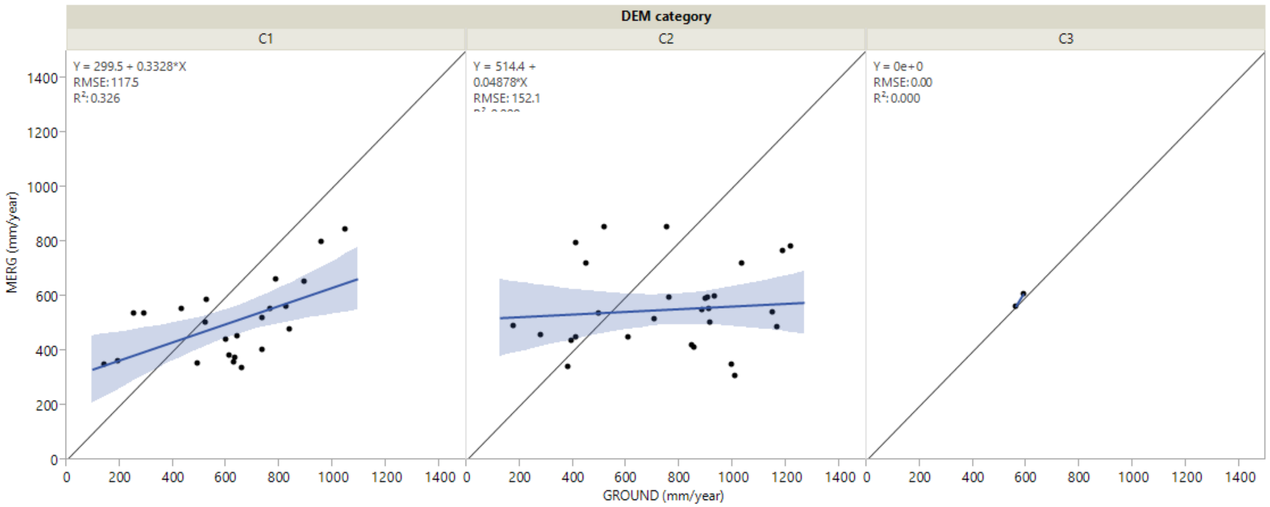

Figure 24: Annual precipitation comparison between IMERG product and Ground data over 3 DEM categories

2. *Monthly analysis*

Monthly average precipitation from the year 2000 till 2017 recorded around 62 mm over C1 category elevation and 66 mm over C2 and C3 elevations as per ground weather stations data. Rainfall reaches around 162 mm over C1 and C3 during January, being the rainiest month in Lebanon. As for C2, records show 2 mm higher than the other two categories. The performances of both CHIRPS and IMERG were better on monthly basis than they were annually. CHIRPS tends to overestimate precipitation over all categories during rainy months with better results over C1 (R^2 = 0.669) (fig. 27) and C2 than C3. On the other hand, IMERG performed better over C1 and C3 (R^2 = 0.761) than it did over C2 (fig. 28). However, the underestimation of IMERG over C2 is higher than that of CHIRPS at the same elevation category. Generally, the average monthly percent difference of IMERG to Ground data is higher than % difference of CHIRPS over all categories.

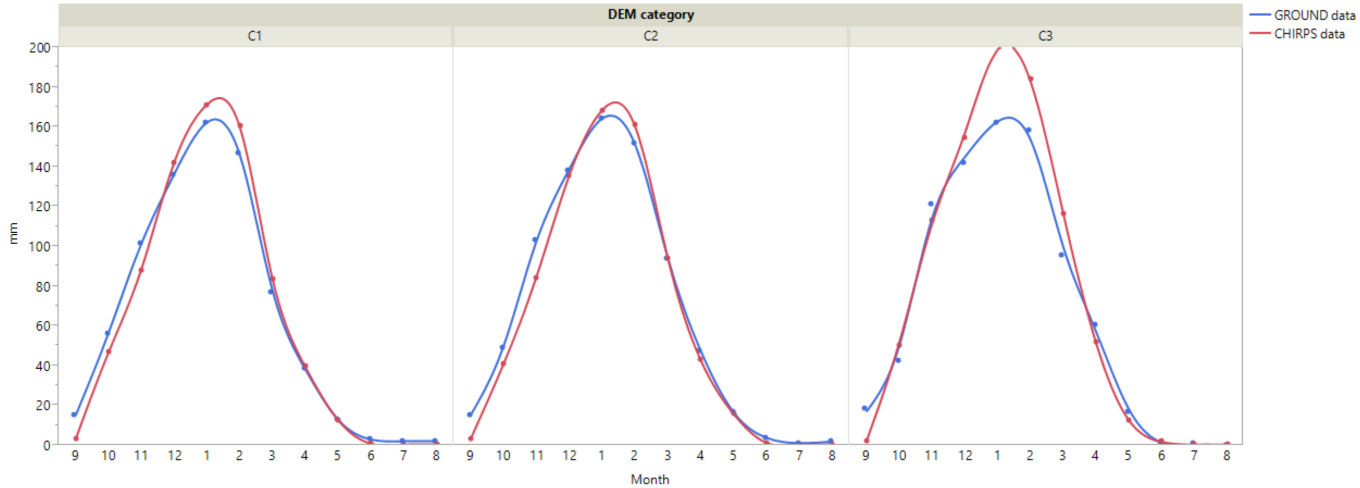

Figure 25: Monthly comparison between Ground and CHIRPS data at different elevations

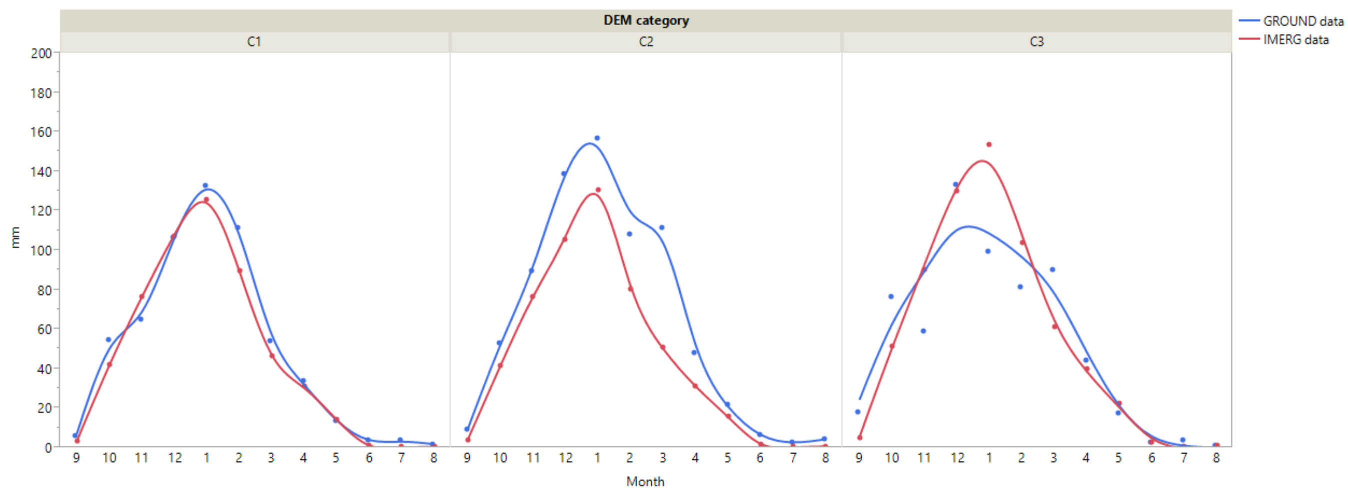

Figure 26: Monthly comparison between Ground and IMERG data at different elevations

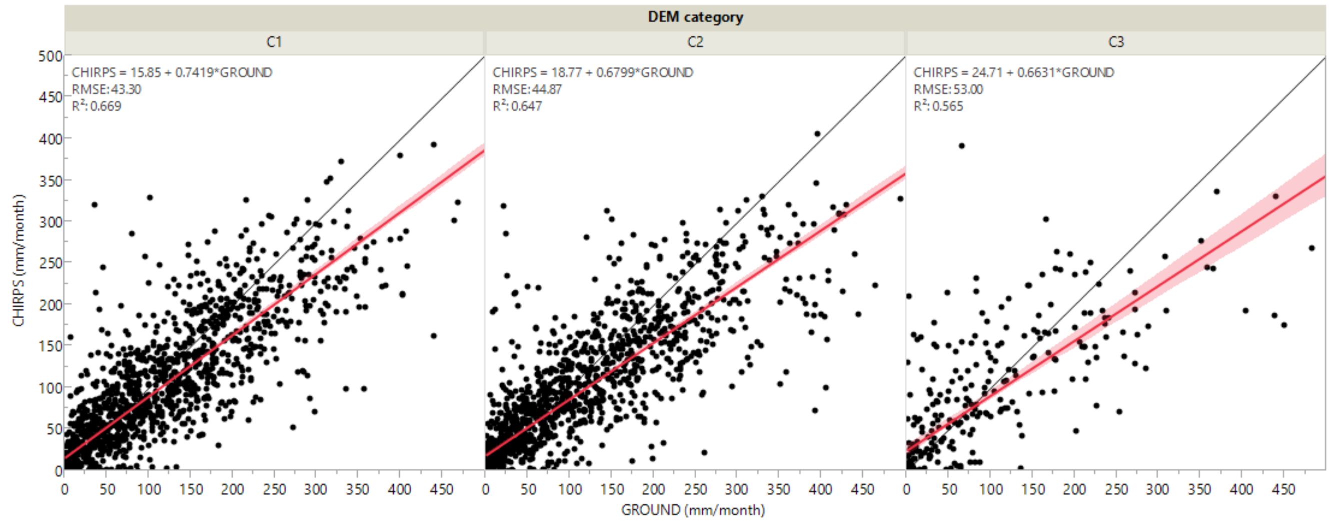

Figure 27: Monthly precipitation recorded by Ground stations and CHIRPS product at different elevation

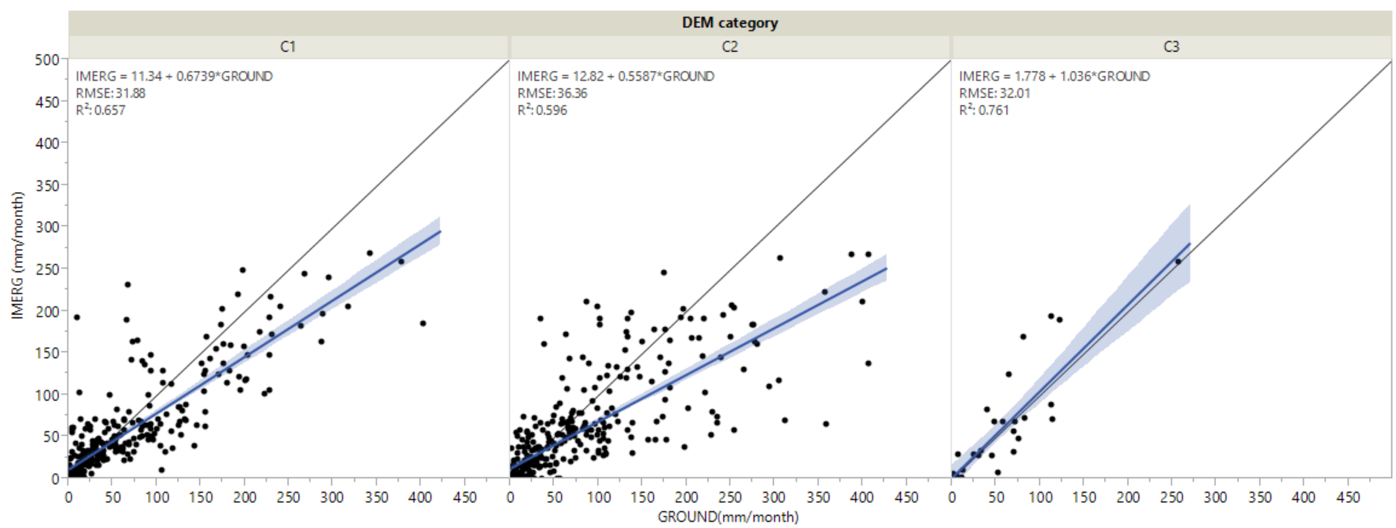

Figure 28: Monthly precipitation recorded by Ground stations and IMERG product at different elevation ranges

D. Effect of Location on the correlation between Satellite and Ground rain gauge data

1. Yearly analysis

Lebanon is divided here into 3 regions; Coastal, Inland and Mountainous. This will give an idea about the degree of consistency of satellite data with ground gauge data as location varies. Average precipitation over the coastal area was around 834 mm as per the ground rain gauges, however, that observed by CHIRPS was almost 766 mm (Table 9). For every year, the percent difference between rain gauge data and satellite data was conducted. On average CHIRPS underestimated precipitation over the coast by around 10% (Table 11). IMERG showed better correlation with Ground data over the coast (R^2 = 0.678, Re = 10.4%) (fig. 30) than did CHIRPS (R^2 = 0.196, Re = 23.5%) (fig. 29).

The Inland area, also known as the Bekaa valley is characterized by an elevation ranging between 800m and 1400m. When observed on the map it might be misconceived as a plateau, however, its topography is more complicated in reality. Precipitation ranged between 373 mm and 1201 mm (Table 13). It's important to note that the years that marked lowest and highest values collected by the ground gauges do not correspond to the same years as those observed by CHIRPS or IMERG. Over this area CHIRPS and IMERG tend to slightly overestimate rainfall (Tables 13 & 14). This difference is due to the peaking mountains surrounding the valley and hindering saturated clouds to reach it. Even though no actual rain reaches the ground, CHIRPS can still detect atmospheric moisture. It showed good correlation with Ground data over this area with R^2 = 0.621 and Re = 20.5% (fig. 29).

As for the mountainous area, precipitation ranged between 410 mm and 1603 mm according to ground stations (Average = 962 mm) (Table 15) over the 17 years and average annual rainfall recorded by CHIRPS was 797 mm. However, that detected by IMERG over the 3 years was 524 mm while ground stations recorded up to 794 mm (Table 16). As an average both satellite products underestimated rainfall with CHIRPS performing slightly better (R^2_{CHIRPS}=0.280, Re_{CHIRPS} = 16.5%) (fig. 29). This can be explained by Lebanon's nature and its high mountains (peaking at 3,088 m) (Highest Mountains Lebanon) that almost divide the country into two greatly diverse regions. In addition to the fact that the snow cover in winter hinders the proper satellite calculation of rainfall. Lebanon is characterized by steep and complicated topography that can result in different rainfall amounts within one pixel captured by CHIRPS or IMERG, knowing that the two products have different resolutions and calibration methods.

Table 9: Annual comparison between ground gauge data and CHIRPS data over coastal, inland and mountainous areas

Location	Ground (mm/year)	CHIRPS (mm/year)
Coastal	834	766
Inland	611	626
Mountainous	962	797

Table 10: Annual comparison between ground gauge data and IMERG data over coastal, inland and mountainous areas

Location	Ground (mm/year)	IMERG (mm/year)
Coastal	754	598
Inland	448	505
Mountainous	794	524

Table 11: Annual Coastal percent difference between Ground rain gauge data and CHIRPS satellite data

Year	Ground (mm/year)	CHIRPS (mm/year)	Diff CHIRPS (%)
2000-2001	709	653	8.2
2001-2002	889	845	5.1
2002-2003	982	1082	-9.7
2003-2004	774	770	0.5
2004-2005	700	926	-27.8
2005-2006	828	729	12.7
2006-2007	773	781	-1.0
2007-2008	695	488	35.0
2008-2009	869	774	11.6
2009-2010	960	823	15.4
2010-2011	792	581	30.7
2011-2012	947	621	41.6
2014-2015	841	731	14.0
2015-2016	700	629	10.7
2016-2017	664	605	9.3
Average	**834**	**766**	**10.4**

Table 12: Annual Coastal percent difference between Ground rain gauge data and IMERG satellite data

Year	Ground (mm/year)	IMERG (mm/year)	% Diff IMERG
2014-2015	841	709	4
2015-2016	700	505	8
2016-2017	664	507	7
Average	754	598	6

Table 13: Annual Inland percent difference between Ground rain gauge data and CHIRPS satellite data

Year	Ground (mm/year)	CHIRPS (mm/year)	Diff CHIRPS (%)
2000-2001	464	538	-14.8
2001-2002	533	627	-16.2
2002-2003	1088	905	18.4
2003-2004	692	702	-1.4
2004-2005	743	743	0.0
2005-2006	493	568	-14.1
2006-2007	425	529	-21.8
2007-2008	728	635	13.6
2008-2009	789	772	2.2
2009-2010	1201	1026	15.7
2010-2011	797	727	9.2
2011-2012	533	698	-26.8
2014-2015	466	536	-14.0
2015-2016	373	452	-19.2
2016-2017	622	541	13.9
Average	**611**	**626**	**-3.7**

Table 14: Annual Inland percent difference between Ground rain gauge data and IMERG satellite data

Year	Ground (mm/year)	IMERG (mm/year)	% Diff IMERG
2014-2015	466	619	-7
2015-2016	373	418	-3
2016-2017	622	427	9
Average	448	505	0

Table 15: Annual Mountainous percent difference between Ground rain gauge data and CHIRPS satellite data

Year	Ground (mm/year)	CHIRPS (mm/year)	Diff CHIRPS (%)
2000-2001	410	721	-55.0
2001-2002	1109	867	24.5
2002-2003	1603	1191	29.5
2003-2004	928	736	23.1
2004-2005	973	942	3.3
2005-2006	1004	874	13.9
2006-2007	990	831	17.4
2007-2008	873	596	37.7
2008-2009	973	895	8.3
2009-2010	1025	875	15.8
2010-2011	1168	932	22.5
2011-2012	1313	890	38.4
2014-2015	843	753	11.2
2015-2016	775	626	21.3
2016-2017	773	581	28.4
Average	**962**	**797**	**16.0**

Table 16: Annual Mountainous percent difference between Ground rain gauge data and IMERG satellite data

Year	Ground (mm/year)	IMERG (mm/year)	% Diff IMERG
2014-2015	843	681	5
2015-2016	775	476	12
2016-2017	773	441	14
Average	794	524	10

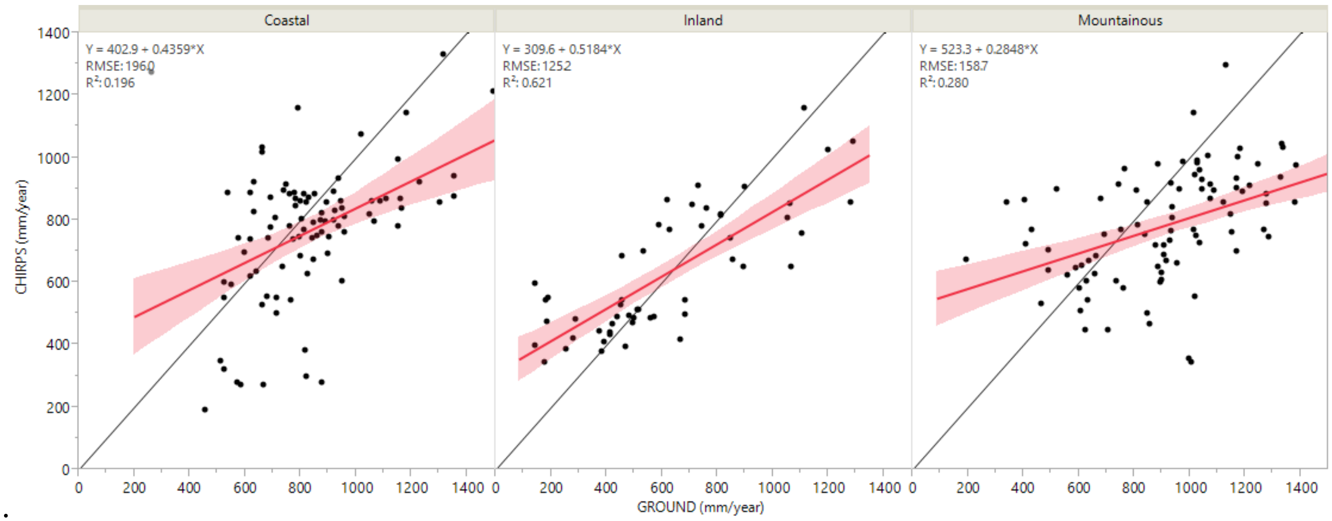

Figure 29: Annual precipitation comparison between CHIRPS product and Ground data over 3 locations

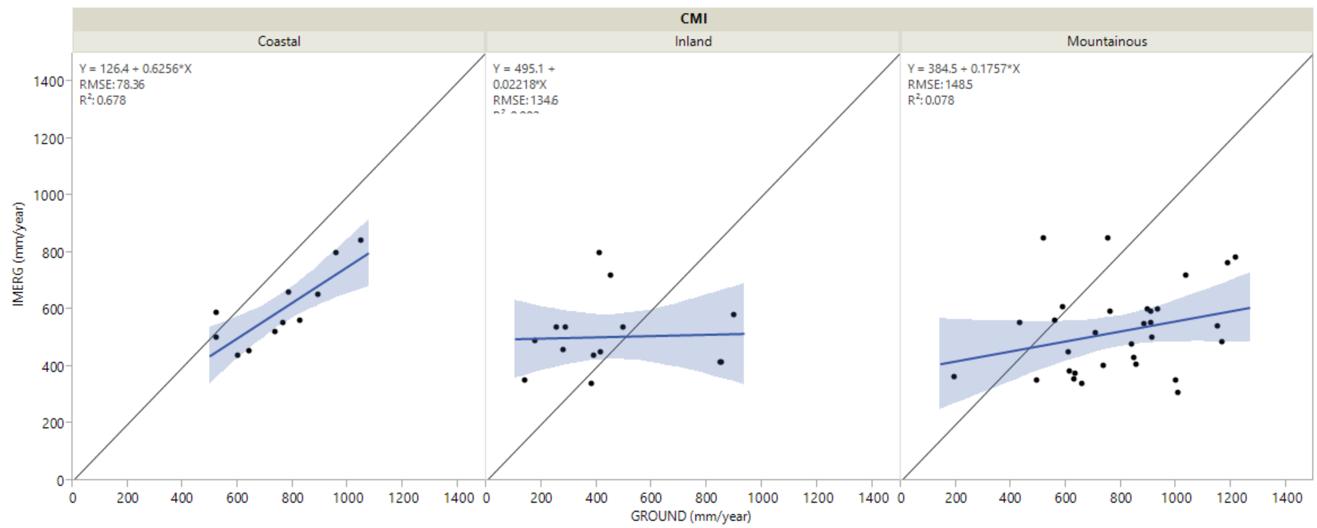

Figure 30: Annual precipitation comparison between IMERG product and Ground data over 3 locations

2. Monthly analysis

The correlation between satellite products and ground rain gauge data was also analyzed on a monthly basis. The average monthly precipitation was conducted showing around 63 mm/month over the coastal area with similar records by CHIRPS (Table 17). Over the inlands, CHIRPS overestimated rainfall especially during rainy months. According to the rain gauge stations, the rainiest month over Lebanon is January followed by February and December. The average precipitation in January over the coastal, inland and mountainous regions were 172 mm, 119 mm and 178 mm respectively. However, the driest months were July and August. Results here also show that CHIRPS tend to overestimate in rainy months but underestimate during dry months.

Both satellite products, CHIRPS (R^2 = 0.701 and Re = 65%) and IMERG (R^2 = 0.756 and Re = 55.8%) performed better over the Coastal area than they did over other areas (fig. 33 & 34). IMERG tends to overestimate on a monthly basis over the Inland area (Table 20) and underestimate at the mountains (Table 22). It's worth noting that IMERG recorded high percent differences over the mountainous area.

Table 17: Monthly Coastal percent difference between Ground rain gauge data and CHIRPS satellite data

Month	Ground (mm/month)	CHIRPS (mm/month)	Diff CHIRPS (%)
9	15	3	133.3
10	65	52	22.2
11	106	97	8.9
12	143	146	-2.1
1	172	175	-1.7
2	155	160	-3.2
3	81	82	-1.2
4	41	39	5.0
5	12	12	0.0
6	2	1	66.7
7	2	0	200.0
8	2	1	66.7
Average	**63**	**64**	**41.2**

Table 18: Monthly Coastal percent difference between Ground rain gauge data and IMERG satellite data

Month	Ground (mm/month)	IMERG (mm/month)	% Diff IMERG
9	7	3	80.0
10	80	46	54.0
11	81	84	-3.6
12	130	119	8.8
1	174	138	23.1
2	84	91	-8.0
3	67	50	29.1
4	38	34	11.1
5	16	15	6.5
6	3	1	100.0
7	3	0	200.0
8	2	0	200.0
Average	**55**	**49**	**58.4**

Table 19: Monthly Inland percent difference between Ground rain gauge data and CHIRPS satellite data

Month	Ground (mm/month)	CHIRPS (mm/month)	% Diff CHIRPS
9	6	3	66.7
10	31	29	6.7
11	70	62	12.1
12	94	112	-17.5
1	119	135	-12.5
2	111	135	-19.5
3	59	74	-22.6
4	38	35	8.2
5	12	15	-22.2
6	4	1	120.0
7	2	0	200.0
8	2	0	200.0
Average	**47**	**50**	**43.3**

Table 20: Monthly Inland percent difference between Ground rain gauge data and IMERG satellite data

Month	Ground (mm/month)	IMERG (mm/month)	% Diff IMERG
9	4	4	0.0
10	30	37	-20.9
11	52	66	-23.7
12	77	90	-15.6
1	96	110	-13.6
2	45	62	-31.8
3	52	46	12.2
4	28	27	3.6
5	10	14	-33.3
6	6	2	100.0
7	5	1	133.3
8	1	1	0.0
Average	**34**	**38**	**9.2**

Table 21: Monthly Mountainous percent difference between Ground rain gauge data and CHIRPS data

Month	Ground (mm/month)	CHIRPS (mm/month)	% Diff CHIRPS
9	20	3	147.8
10	50	44	12.8
11	110	90	20.0
12	151	153	-1.3
1	178	190	-6.5
2	159	169	-6.1
3	101	101	0.0
4	46	46	0.0
5	19	15	23.5
6	4	1	120.0
7	2	1	66.7
8	2	1	66.7
Average	**72**	**69**	**37.0**

Table 22: Monthly Mountainous percent difference between Ground rain gauge data and IMERG data

Month	Ground (mm/month)	IMERG (mm/month)	% Diff IMERG
9	10	4	85.7
10	55	42	26.8
11	87	79	9.6
12	142	110	25.4
1	154	134	13.9
2	82	80	2.5
3	105	50	71.0
4	49	32	42.0
5	22	16	31.6
6	6	2	100.0
7	3	0	200.0
8	5	1	133.3
Average	**58**	**46**	**61.8**

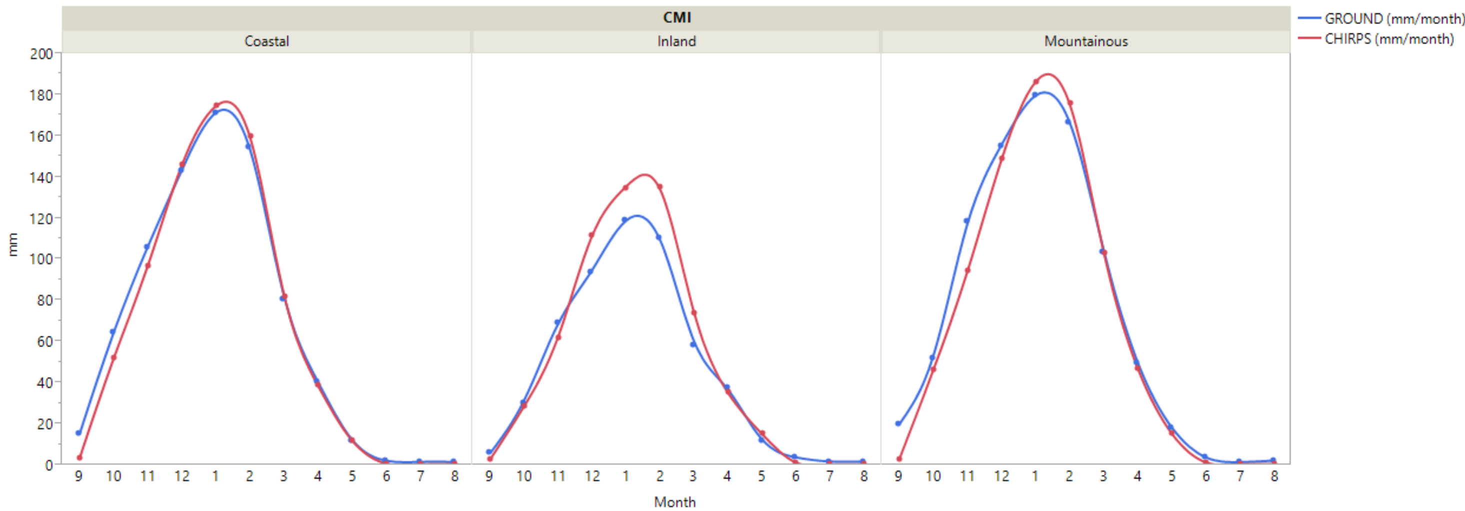

Figure 31: Monthly comparison between Ground and CHIRPS data at different locations

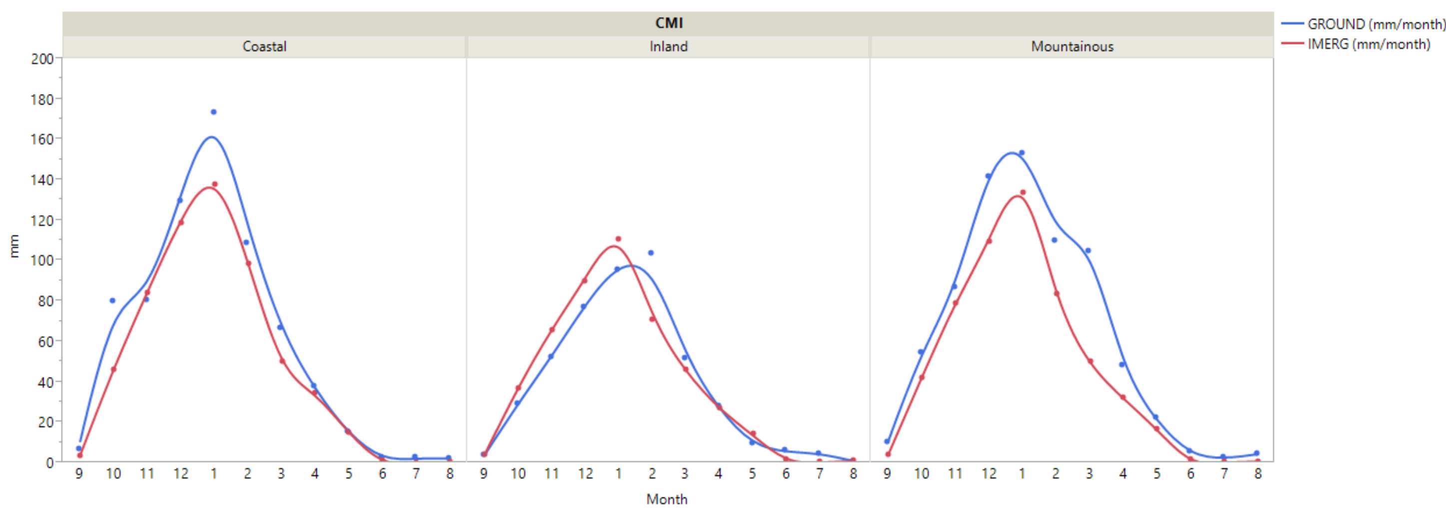

Figure 32: Monthly comparison between Ground and IMERG data at different locations

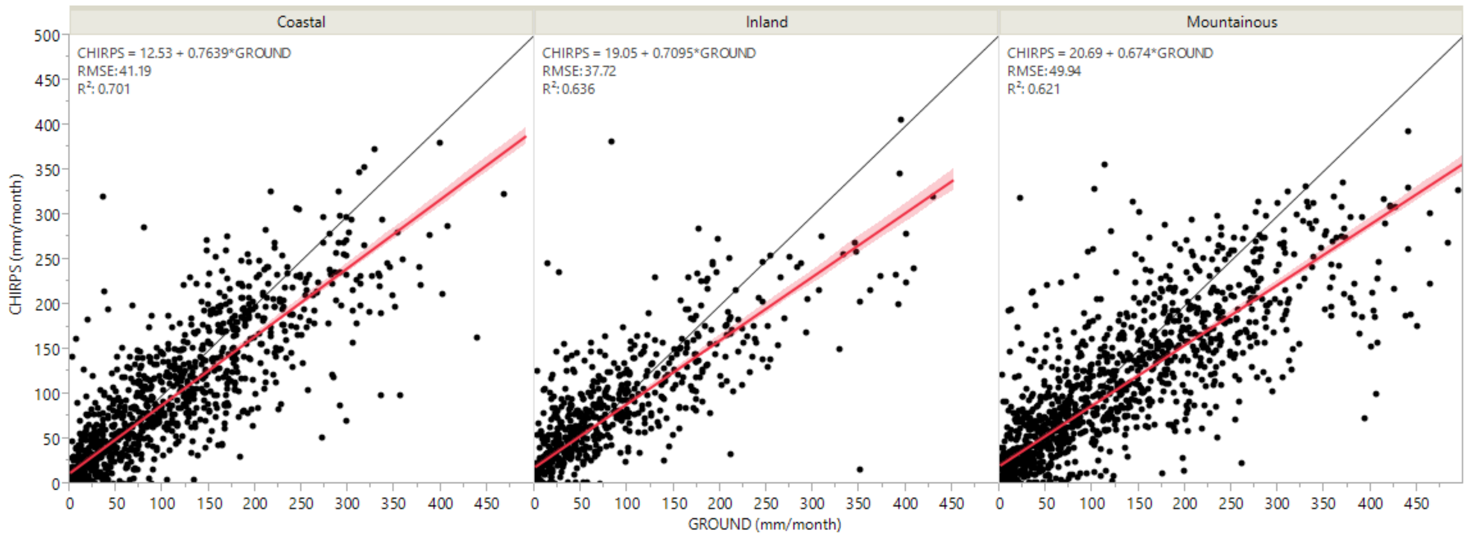

Figure 33: Monthly precipitation comparison between CHIRPS product and Ground data over 3 locations

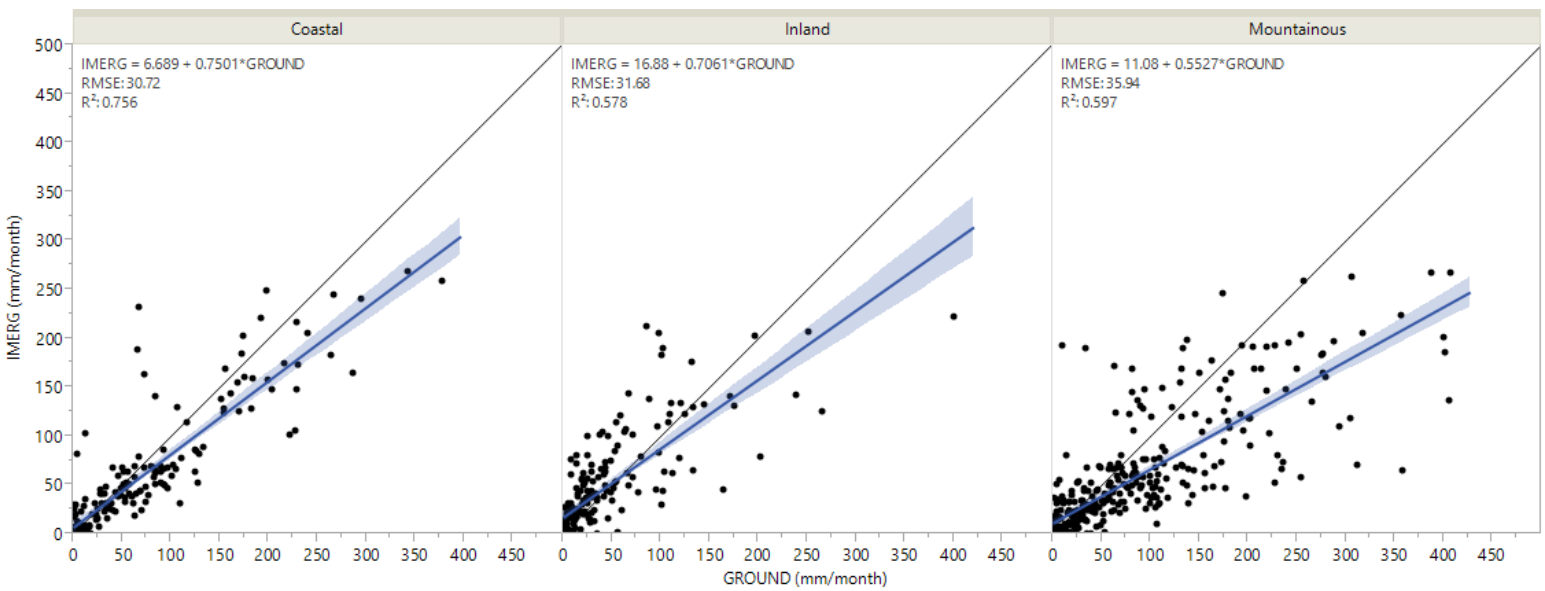

Figure 34: Monthly precipitation comparison between IMERG product and Ground data over

CHAPTER V

DISCUSSION

Average annual results over Lebanon (2000-2001 till 2016-2017) revealed that both satellite products performed better during wet years than during dry ones. CHIRPS was slightly more correlated with ground rain gauge data than IMERG due to the richer period of record; 16 years for CHIRPS versus 3 years for IMERG. Likewise, in Brazil, IMERG showed low underestimation in the wet season but higher underestimation during the dry season that is a result of reduced convective and stratiform rain (Santos et al., 2018). Santos et al. (2018) worked on validating IMERG estimates over the mesoregion of Southern Amazonas state in Brazil. GPM estimated monthly and yearly rainfall with high correlations and general underestimation of dissimilar differences. As a result, total annual estimated values were similar to measured values. However, more calibration adjustments for every region are necessary to obtain fully reliable estimates.

On a monthly basis CHIRPS slightly overestimated rainfall during the wet months (December, January, and February) and highly underestimated it in dry months. Similar results over the Central Western Argentina (CWA) were revealed by Rivera et al. (2019) that CHIRPS was able to detect with overestimation of extremely wet specific events in warm season region and an underestimation of extremely dry events. In 2019, CHIRPS performance for detecting wet and dry events over the CWA region, known for its complex terrain, was evaluated (Rivera et al., 2019). CHIRPS approximation was better at timescale higher than 1 month. On a monthly basis, CHIRPS largely overestimated in Cold season (CS) area and slightly underestimated in warm season (WS) area. This study presents the good ability of CHIRPS to monitor drought and flood events while acknowledging the necessity for future improvements like defining thresholds for dry and wet conditions.

According to the above monthly results, when taking elevation into consideration, CHIRPS tends to overestimate precipitation over all categories. It performed better over C1 and C2 unlike IMERG that performed better over C1 and C3 than C2. However, the underestimation of IMERG over C2 is higher than that of CHIRPS at the same elevation category. The lower amounts of rainfall and different results in category 3 can be due to the hail or snowfall that cannot be fully captured by ground stations nor detected by satellite products. IMERG showed good correlation at high elevations with R^2 up to 0.761, whereas CHIRPS performed best at low elevations (R^2 = 0.669). Also according to Xu et al. (2017) IMERG performed slightly better than TRMM in terms of consistency with gauge observation at much higher elevations. They evaluated the performance of GPM IMERG and TRMM 3B42 v7 over the southern Tibetan Plateau (TP) depending on rainfall intensities and topographic variations (Xu et al., 2017). Statistical analysis was based on 3 indicators; Relative bias, correlation coefficient and root-mean-square error. Rain gauges were classified into 5 elevation categories; <3000 m, 3000 - 3500 m, 3500 - 4000 m, 4000 - 4500 m, and >4500 m. IMERG appeared to underestimate rainfall at lower elevation but overestimate it at higher elevation whereas the opposite was true for TRMM. Rainfall intensities were divided into 3 categories; light rain (0-1 mm/d and 1-5 mm/d), moderate rain (5-10 mm/d and 10-50 mm/d), and heavy rain events (50-100 mm/d and >100 mm/d). IMERG presented better ability in detecting light rainfall knowing its ability to identify light and solid precipitation at very high elevations. Both satellite products showed no detection skill in estimating precipitation at high elevations.

In addition to that, CHIRPS and IMERG performed better over the Coastal area than they did over other areas. CHIRPS slightly overestimated rainfall whereas IMERG underestimated it. Also the latter overestimated over the Inland area and underestimated at the mountains. Overestimating rainfall is the main disadvantage of satellites over arid regions. Some reasons for this would be the high cloud evaporation which is due to hot atmospheric layers that evaporate the raindrops before they reach the rain gauges even though detected by the satellite. This finding was similar to the results obtained by Sharifi et al. (2016) who assessed the 3 satellite products IMERG, TMPA-3B42 and the Era-Interim product. Four regions in Iran of different topographic characteristics were studied. Results of monthly evaluation were not unanimous over the 4 regions, some products overestimated while others underestimated precipitation. The false detection of precipitation that actually did not fall puts satellites under further research for adjustments and calibration. For precipitation above 15 mm, IMERG performed better than ERA due to its Ku-band Precipitation Radar than can detect heavy rainfall. However, at this high precipitation, all products recorded rainfall events since high moisture levels were observed.

CHAPTER VI

CONCLUSION

For decades, conventional precipitation observations like ground stations have been used for the analysis of weather parameters and climatic variations. Rain gauges can provide archives of precipitation data for many years. The availability of continuous record data is inevitable for the detection of historical trends and the variables affecting rainfall observations. However, these records are restricted to the locations of ground stations that is highly dependent on area accessibility. Therefore, it is crucial to recognize the importance of remote sensing in this field and its potential in being superior to meteorological stations. These stations can have high maintenance cost as well as erroneous data in remote areas.

CHIRPS and IMERG satellite products have been evaluated in this study to monitor whether it is reliable to use satellite precipitation data over Lebanon or not. Annual and monthly data have been assessed against ground rain gauge data from networks distributed randomly across the country. The annual record period was from hydrologic year 2000-2001 till 2016-2017 and the monthly period was from Jan 2000 till April 2018. Ground stations database have undergone extensive quality check and scrutiny before using in analysis. The location of these stations must be in open space away from any obstructions, buildings or vegetation to minimize splashing recording of runoffs. However, this type of optimal data was not available and lead to the tedious quality check of ground data.

Results revealed that precipitation detected by satellite products can be highly reliable on the location and topography of the area. With a terrain as complex as the Lebanese one and an overall small total area, further studies and investigations are crucial for more reliable records. Also technical knowledge in the machines and software used is extremely important to calibrate, improve and minimize bias in precipitation data. Alongside, ground stations and satellite data can present an upgrade in rainfall observation when employed and monitored properly.

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