09 - ASSESSMENT OF THE GPM IMERG ESTIMATES OF RAINFALL SEASONALITY OVER IRELAND

Safa Mohammed[1] and Ahmed Nasr[1*]
[1] *School of Transport and Civil Engineering, TU Dublin, Dublin, Ireland*
[*]*Corresponding Email: ahmed.nasr@tudublin.ie*

Abstract
Recent climate change projections have predicted frequent occurrence of catastrophic flood events across Europe. Over the last decade, North-western Europe, particularly Ireland, has already begun to witness major flood events. These flood events were associated with apparent spatial variations in magnitude and seasonality of rainfall in Ireland. Therefore, future predictions of flooding will require high spatial rainfall resolution data. Multi-satellite sensors have been considered an essential source for providing such rainfall data for the past three decades due to the rapid advancements in remote sensing technologies. The Global Precipitation Measurement (GPM) satellite can detect and estimate all forms of precipitation using various advanced instruments, including Microwave and Radar technologies. This study investigates the performance of the three Integrated Multi-satellitE Retrievals for GPM (IMERG) precipitation products (i) early run (IMERG-early); (ii) late run (IMERG-late); and (iii) final run (IMERG-final) in capturing the rainfall seasonal variability over Ireland using seven years of data from 2014 to 2020. Ground-based rainfall observation data from 25 Met Éireann synoptic stations across Ireland were used as a reference to assess the IMERG Satellite Precipitation Products (SPPs) during the study period. Assessment results indicated that IMERG SPPs have the capability to reasonably detect the rainfall seasonality, and in particular magnitudes and spatial distribution during the wet (Autumn) and the dry (Summer) seasons. However, the three IMERG SPPs have shown different patterns of rainfall estimates, with the IMERG-final outperforming the other two near-real-time products (IMERG-early and IMERG-late) when compared against the in situ measurements. Moreover, the IMERG-final SPP has shown consistency in capturing the seasonal variation of rainfall over Ireland. Hence, it can be recommended as a source of future rainfall prediction for climate change studies in Ireland.

1. INTRODUCTION
Floods have been widely recognised as one of the most devastating natural disasters during the last two decades in many parts of the world, including Ireland. Climate change, in tandem with alterations in land use and land cover, has been related to the increased frequency and severity of these floods. Therefore, it is vitally important to understand and model the behaviour of the hydrological cycle under different climatic forcing conditions. The availability of precipitation at fine spatio-temporal resolutions provides valuable information utilised in building such hydrological models, which can then be used in a broad range of applications, including analysis, monitoring, and forecasting of floods (NASA, 2011; Schneider *et al.*, 2016; Abbasian, Najafi and Abrishamchi, 2021). Providing this type of precipitation data is challenging, especially in regions with limited observation data or complex surface features.

Generally, rain gauges represent the most precise source of precipitation data. However, they are always limited in numbers and spatial coverage, leading to the inability to capture the spatial variation of precipitation at a finer scale (Villarini *et al.*, 2008) (Petersen, Christian and Rutledge, 2005). Therefore remotely sensed estimates of precipitation, including satellite precipitation products (SPPs), has become a viable alternative since they give accurate representation of amount, patterns, and locations of precipitation at a variety of scales (Hobouchian *et al.*, 2017).

Numerous SPPs, such as Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis (TMPA) (Huffman *et al.*, 2007), the Climate Prediction Center (CPC) MORPHing technique (CMORPH) (Joyce *et al.*, 2004), Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) (Nguyen *et al.*, 2018), and Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) (Huffman, Bolvin and Nelkin, 2017), have been made available to users and have been comprehensively assessed over diverse meteorological and geographical regions.

As a successor to the Tropical Rainfall Measuring Mission (TRMM) (Yong *et al.*, 2015), the Global Precipitation Measurement (GPM) mission was launched in February 2014 by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace and Exploration Agency (JAXA). The name of this mission is the Integrated Multi-satellite Retrievals for GPM (IMERG) which has a temporal resolution of 30 minutes and a spatial resolution of 0.1 meters (Liu, 2016; Tang, Zeng, *et al.*, 2016). The dual-frequency precipitation radar (DPR), which was the first of its type, was included into the GPM core observatory to increase the reliability of IMERG in comparison to previous SPPs (Anjum *et al.*, 2019).

Significant work has been undertaken to evaluate the accuracy and consistency of the upgraded versions of the IMERG algorithm (V3, V4, V5, and V6) (Huffman, Bolvin and Nelkin, 2017). Prakash *et al.* (2016) have revealed that IMERG outperforms TMPA in detecting monsoon precipitation. Furthermore, Khan and Maggioni (2019) evaluated IMERG's capabilities over oceans whereas Omranian et al. (2018) focused on IMERG's ability to replicate hurricanes. Moreover, several studies have been published demonstrating country-level evaluations of IMERG SSPs such as in Spain, Germany, Austria, the Netherlands, Saudi Arabia, Mainland China, Mexico, Bolivia, Brazil, Malaysia, the United Arab Emirates, Cyprus, Finland, Pakistan and Canada (Tang *et al.*, 2016; Rios Gaona *et al.*, 2016; Satgé *et al.*, 2017; Sungmin *et al.*, 2017; Mayor *et al.*, 2017; Mahmoud, Al-Zahrani and Sharif, 2018; Rozante *et al.*, 2018; Tan and Santo, 2018; Ramsauer, Weiß and Marzahn, 2018; Retalis *et al.*, 2018; Mahmoud, Hamouda and Mohamed, 2019; Tapiador *et al.*, 2020; Arshad *et al.*, 2021; Mohammed *et al.*, 2021; Moazami and Najafi, 2021).

IMERG provides two near real time (NRT) products (Early and Late Runs, hereafter referred to as IMERG-early and IMERG-late, respectively) and one post real time (PRT) product (Final Run, hereby referred to as IMERG-final) (Huffman *et al.*, 2019). The main difference is the time latency which is 4 hours in IMERG-E and 14 hours in IMERG-L, while it takes 3.5 months for the IMERG-final to be released as it undergoes calibration and adjustments processes (Huffman *et al.*, 2019). NASA has encouraged researchers to utilise IMERG-F for most research purposes (https://gpm.nasa.gov/taxonomy/term/1417) despite the fact that each of the three Runs of IMERG products may perform best in displaying precipitation variation across distinct locations (Sungmin *et al.*, 2017; Huang *et al.*, 2021).

GPM IMERG SPPs are a potential data source with high temporal and spatial resolutions that may aid in the reduction of uncertainty propagation in hydrological modelling and flood forecasting. In this context, this study aimed to examine the performance of hourly and daily IMERG SSPs datasets in representing the seasonal precipitation variation across Ireland.

2. DATA AND METHODS

The ground observation measurements were considered the reference for the evaluation process for this analysis. Precipitation data for the 25 synoptic stations in Ireland (Figure 1) were downloaded from Met Éireann website (https://www.met.ie/climate/available-data) at two temporal resolutions (daily and hourly) for eight years between 2014 and 2021. As for the IMERG SSPs, the latest (V06B) IMERG SSPs (Early, Late, and Final products) with the highest spatial (0.1 * 0.1) and temporal (half-hourly) resolutions were downloaded from NASA servers (https://gpm.nasa.gov/data/directory) for the study period.

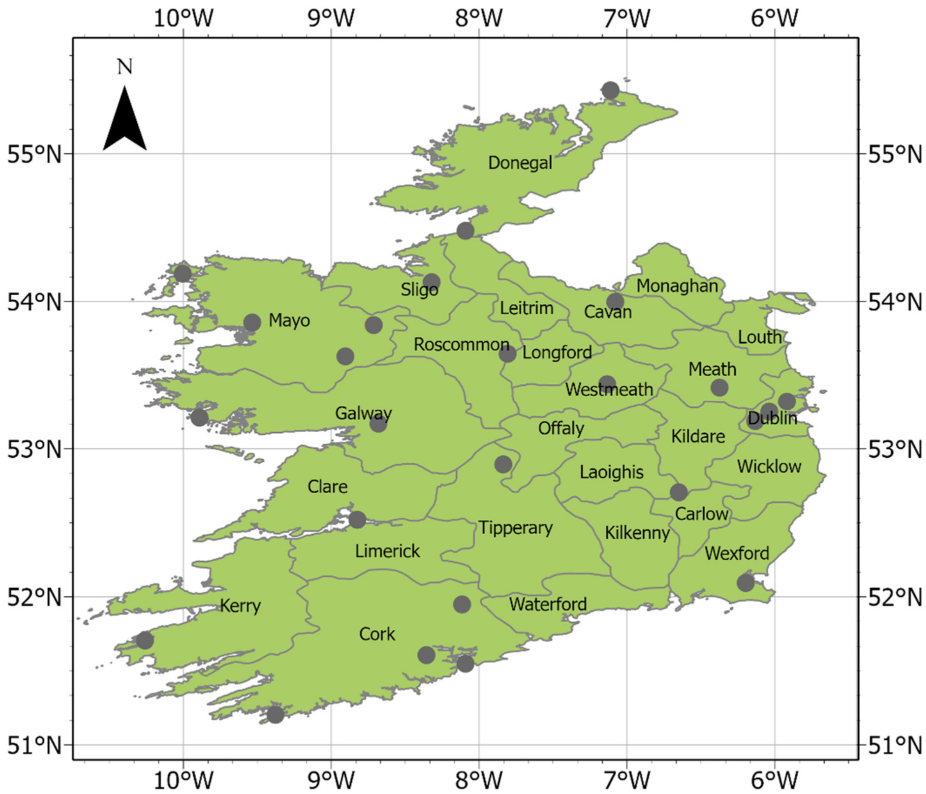

***Figure 1**: Locations of the 25 synoptic stations in Ireland shown in the County Map of Ireland*

Since IMERG data cover the entire world, the data corresponding to the 25 synoptic stations in Ireland were extracted using the Coordinates Matching Process (CMP) which is based on the grid-to-grid concept. The resulting time series of precipitation was then used to obtain the seasonal data for each synoptic station as per the following calendar: Autumn starts on the 1st of September and ends on the 30th of November, Winter starts on the 1st of December and ends on the 28th or 29th of February, Spring starts on the 1st of March and ends on the 31st of May and Summer starts on the 1st of June and ends on the 30th of August. The IMERG SPPs will be evaluated over the four seasons of Ireland using two datasets (hourly and daily) on which these aggregations were performed.

IMERG SPPs' performance was evaluated using five widely applied statistical metrics (Table 1). IMERG SPPs' detectability was assessed using the Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Index (CSI). Root Mean Square Error (RMSE) was used to measure the error associated with the satellite estimates. The Correlation Coefficient (CC) was used to measure the level of consistency between the IMERG SPPs estimations and the ground observations.

Table 1: *Performance measures.*

Measure	Equation	Perfect value	Description
Probability of Detection (POD)	$\frac{H}{H+M}$	1	Used to describe the contingency of satellite estimates
Critical Success Index (CSI)	$\frac{H}{H+F+M}$	1	
False Alarm Ratio (FAR)	$\frac{F}{F+H}$	0	
Root Mean Squared Error (RMSE)	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Po_i - Ps_i)^2}$	0	Used to describe the error of satellite precipitation products
Correlation Coefficient (CC)	$\frac{\frac{1}{n}\sum_{i=1}^{n}(Po_i - \overline{Po})(Ps_i - \overline{Ps})}{\sigma_o \sigma_s}$	1	Used to describe the consistency of rain-gauge data and satellite estimates

Where: H is the number of hit events (detected by both satellite and synoptic stations), M is the number of missed events (missed by the satellite and detected by synoptic stations), F represents the number of false events (detected by the satellite and missed by synoptic stations). n: number of measurements; Ps: satellite estimates; $\overline{Ps}$: average of satellite estimates; Po: gauge measurements; $\overline{Po}$: average of gauge measurements; σ_s: standard deviation for satellite data; σ_g: standard deviation for gauge data.

3. RESULTS

3.1. IMERG SSPs Detection Accuracy

POD, FAR, and CSI are used to evaluate the performance of the IMERG SSPs in detecting the occurrence of precipitation events throughout the study period (Jan 2014 to Sep 2021). Figures 2 and 3 show the spatial distributions of POD at hourly and daily timescales corresponding to the three IMERG SSPs estimates for the eight years 2014–2021. For all four seasons, the PODs of IMERG SSPs based on daily datasets were significantly better than those based on hourly datasets, ranging between 0.7 and 0.99 for the former and 0.3 and 0.69 for the latter.

The spatial distribution of seasonal PODs estimated based on the hourly dataset (Figure 2) showed that IMERG SSPs estimates had high detection rates in the Autumn and Spring seasons with a relatively similar trend, followed by Summer seasons. In contrast, Winter showed poor detection rates (an average of 0.35) across 90% of the synoptic station's measurements. Also, the results clearly showed that the precipitation in the coastal regions was detected more accurate than in inland regions, indicating that IMERG SSPs are superior in detecting precipitation over coastal zones. For all seasons, IMERG-final outperformed the other products, while IMERG-late came in the second rank ahead of the IMERG-early for all the seasons.

The PODs results for the daily data (Figure 3) were consistent with those from the hourly data. The detection levels were comparable over Spring, Summer, and Autumn, with IMERG-final and IMERG-late coming out on top of the IMERG-early. Likewise, Winter results ranked worst in terms of the capability of precipitation events detection compared to the other seasons. It is also observed that PODs of IMERG SSPs were low in the eastern part of the country, particularly in the Winter. Overall, the occurrence of precipitation events observed by the stations on the west coast was reasonably detected by IMERG SSPs.

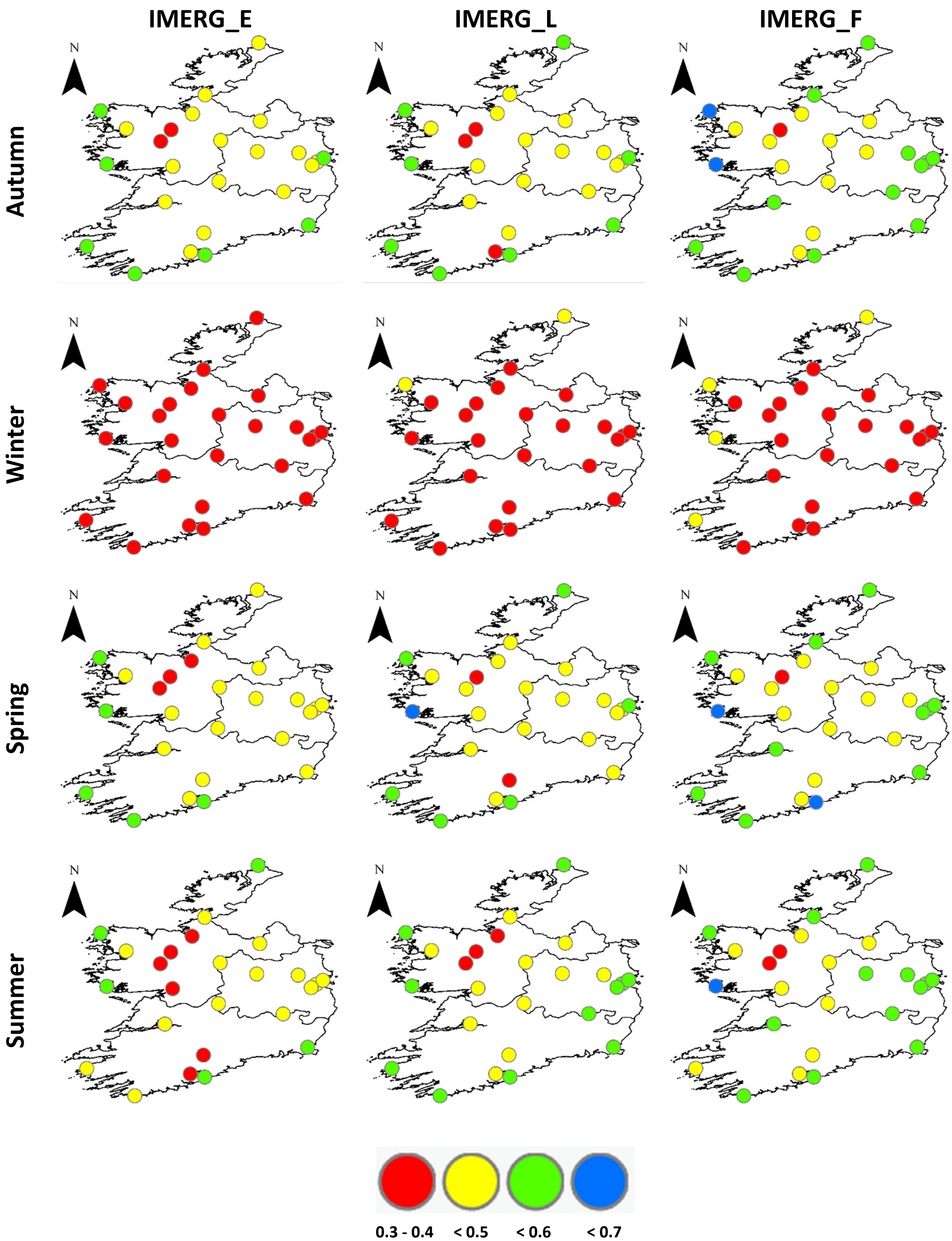

Figure 2: *Spatial distribution of seasonal POD based on hourly IMERG SSPs dataset across 25 synoptic stations during the entire eight-year period*

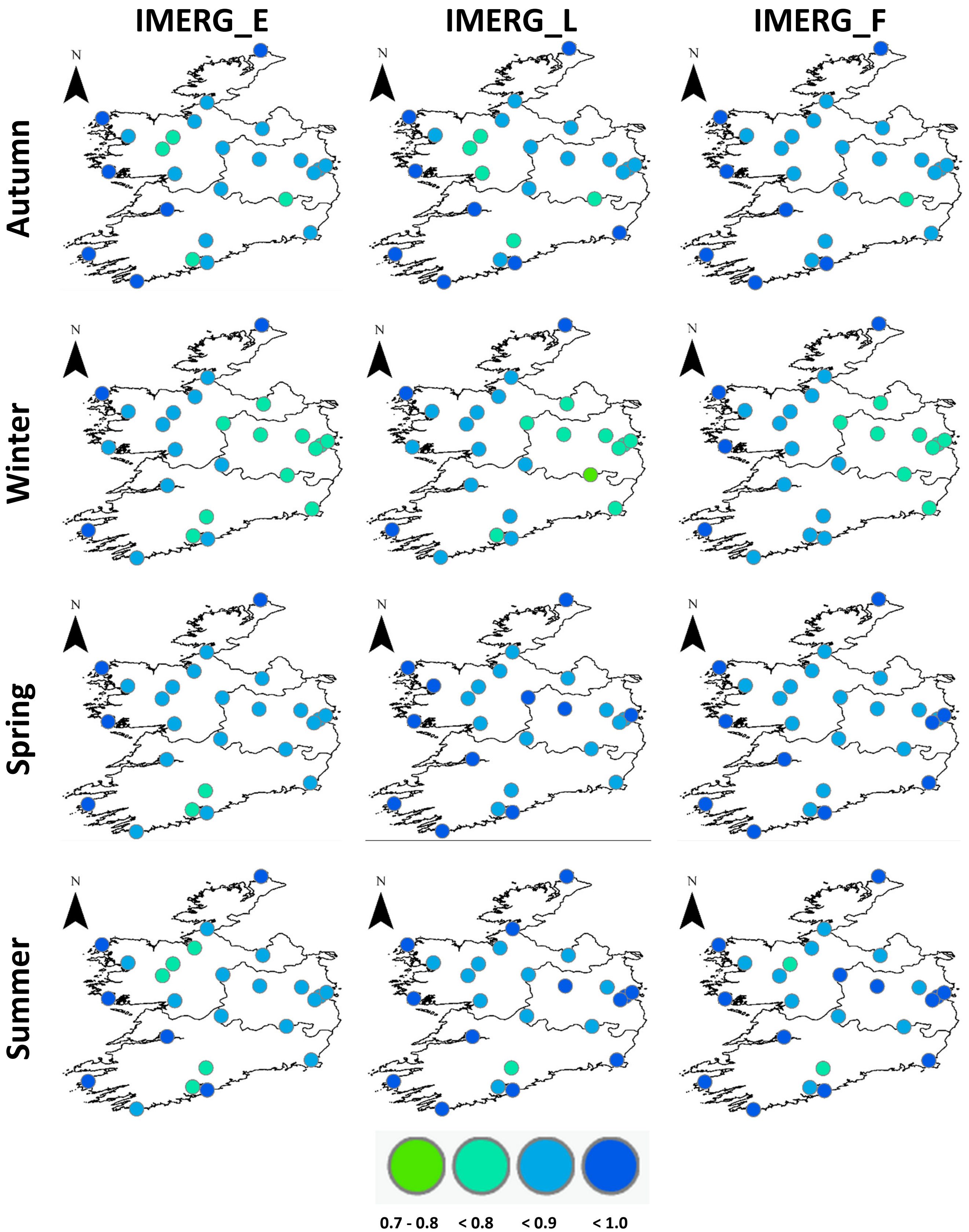

***Figure 3**: Spatial distribution of seasonal POD based on daily IMERG SSPs dataset across 25 synoptic stations during the entire eight-year period*

The results of CSIs and FARs are presented in Figure 4, where the performance of the IMERG SSPs was divided into four zones to compare the results from different seasons. The top left quadrant has the worst performance, with the largest rate of false detection and the lowest CSIs. On the other hand, the bottom right quadrant has the best performance, with the lowest rate of false detection and the highest CSIs. The CSIs and FARs results for the hourly IMERG estimations in the Autumn results are laying in the best zone showing high detection of precipitation events. On the contrary, the Winter results are laying in the worst zone, demonstrating the worst detection of all four seasons.

Comparing the CSI and FARs results for all seasons, it is obvious from Figure 4 that the results for all three IMERG products are within a relatively close range. IMERG-final and IMERG-early were a close match with an average of CSIs (0.3 and 0.29) and FARs (0.57 and 0.56), while IMERG-late performed lower with an average CSI of 0.27 and FAR of 0.6. Spring and Summer results displayed a comparable trend, with IMERG-early outperforming IMERG-final and lastly IMERG-late.

Overall, there is a significant improvement (more than 50%) in CSIs (increasing) and FARs (decreasing) in the daily datasets compared to the hourly dataset. Regarding hourly time step, CSIs ranged between 0.12 and 0.34 and FARs between 0.42 and 0.77. The daily IMERG estimations showed that Autumn was likewise the best season detected by IMERG SSPs, with maximum and minimum CSIs of 0.8 and 0.62 in the three products and maximum and minimum FARs of 0.3 and 0.29, respectively. In the Winter, the performance varied amongst stations, with six performing in the best zone, six performing in the worst zone, and the remaining twelve performing in the middle zone (low FARs and low CSIs). However, compared to the hourly dataset, the detection of precipitation events improved dramatically. It is worth noting that the six best-detected stations are all located in coastal areas. Summer was slightly better represented than Spring, with the three IMERG products performing relatively similarly.

3.2. IMERG SSPs Errors and Consistency

The seasonal errors estimated from hourly and daily IMERG precipitation estimates are evaluated based on RMSE. Box-and-whisker plots showing the first and third Quartiles with maximum and minimum values and the medians of the RMSEs between the 25 synoptic stations across Ireland are presented in Figure 5. Overall, the accuracy of IMERG estimates is relatively high in most locations during Summer, Spring and Autumn. At the same time, Winter shows weaker performance (higher RMSEs), with more considerable variations, including hourly and daily datasets.

On the hourly basis, RMSE ranged from about 0.85 to 2.2 mm/hr, while on a daily basis it ranged between 8.2 and about 18.0 mm/day across all stations. IMERG-early and IMERG-late performed better than IMERG-final in Autumn and Summer, but IMERG-final outperformed both in Winter and Spring based on the hourly dataset. On the other hand, when comparing RMSEs over the daily dataset, IMERG-final performed best in three seasons (excluding Autumn).

Similar Box-and-whisker plots of RMSE were also used for CC to present its results for all seasons as shown in Figure 6. CC values vary across seasons. In the Winter, extremely low correlations were found between IMERG and ground measurements (the medians for hourly and daily datasets are 0.05 and 0.1, respectively). According to the CC coefficient, the best agreement between IMERG estimations and the observed data is found in the Autumn (for IMERG-early and IMERG-late) and Summer (for IMERG-final), with average values ranging between 0.5 and 0.85.

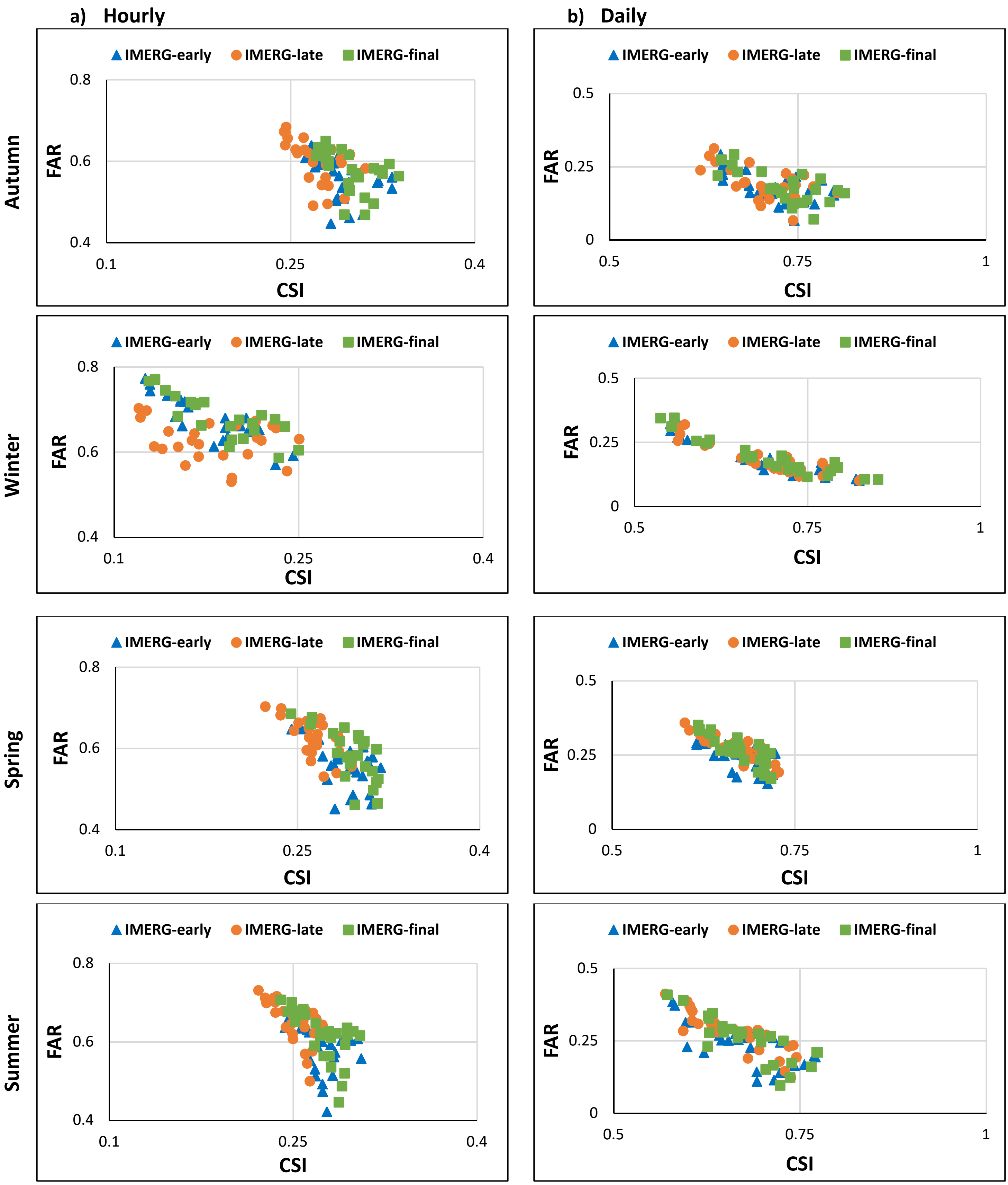

***Figure 4**: Scatterplot for FAR and CSI comparison of seasonal IMERG and ground-based observations (from 25 synoptic stations) based on a) hourly and b) daily datasets*

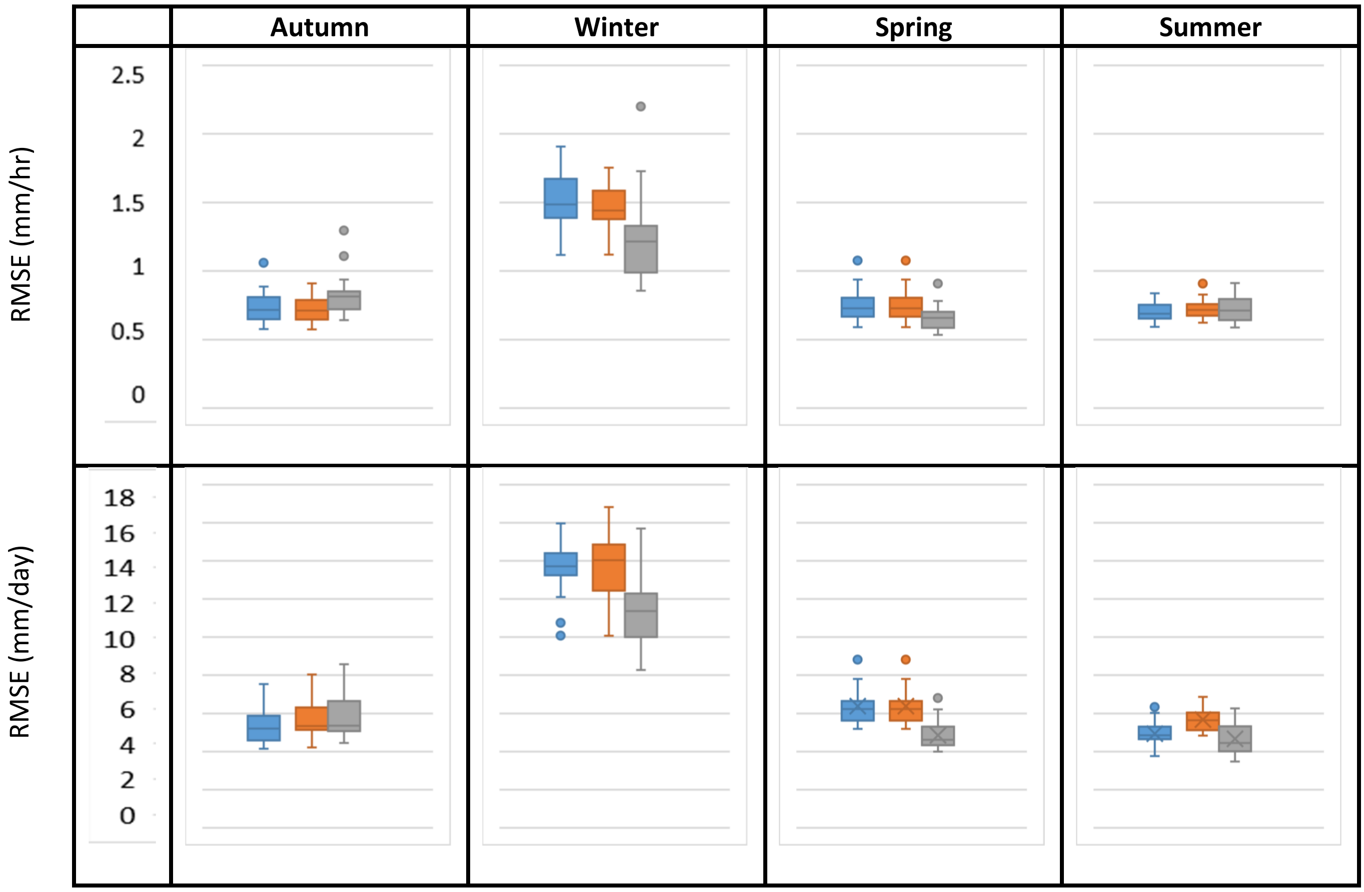

***Figure 5**: Boxplots comparing the RMSE associated with IMERG SPPs estimates (upper is hourly dataset and lower is daily dataset)*

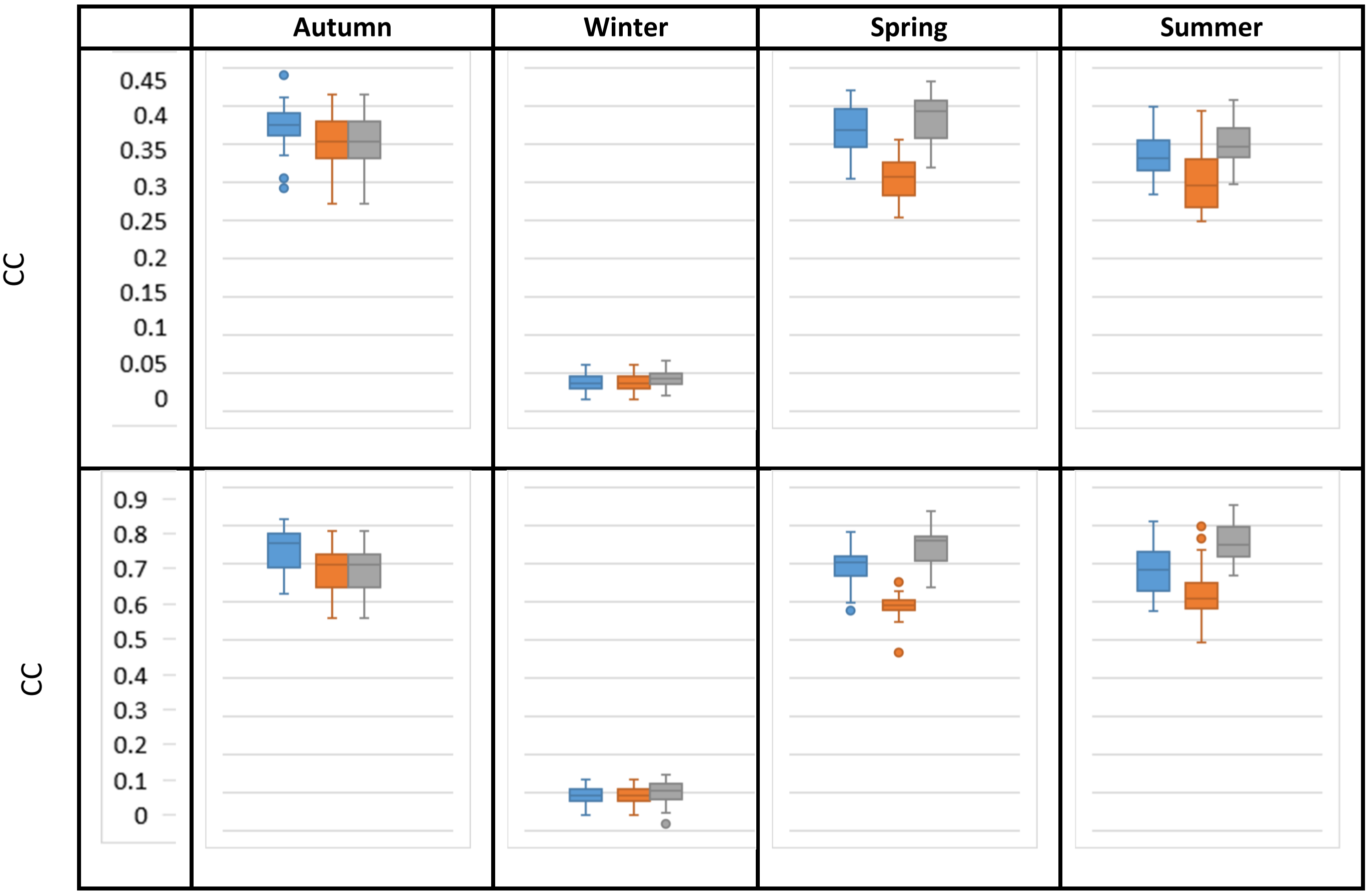

***Figure 6**: Boxplots comparing the CC associated with IMERG SPPs estimates*

4. DISCUSSION AND CONCLUSION

This study uses ground data from 25 synoptic stations across Ireland to assess the estimates of seasonal precipitation by the most recent version of IMERG SSPs (V06) (IMERG-early, IMERG-late, and IMERG-final). A set of performance measures is used to assess the performance of the products. Overall, the results of the daily dataset are promising, given that the median values of POD and CSI are mostly above 0.7 and 0.5, respectively, indicating that precipitation occurrence is frequently detected by the satellite. FAR values varied from 0 to 0.35, showing that the IMERG SSPs overestimate the presence of precipitation in around 0.15% of non-events.

The hourly results show poor performance in representing the seasonal variability compared to the daily results. Thus, this study recommended using IMERG daily dataset. This result is consistent with several previous studies which suggested that the IMERG performs better at a daily timescale than hourly based on all performance measures (Mahmoud, Mohammed, Hamouda, Dal Maso, *et al.*, 2021; Moazami and Najafi, 2021).

The performance of the three different products varies across seasons and locations. While IMERG-final performed better than the near real-time (NRT) products in accurately estimating the quantity of precipitation, IMERG-late showed performance comparable to IMERG-final and better than IMERG-early in most performance metrics.

The detection of precipitation occurrence of all IMERG SSPs is mostly consistent during Autumn, Spring, and Summer, with remarkable performance in Autumn and poor performance in Winter; nevertheless, this performance is significantly enhanced when using IMERG SSPs daily dataset. Also, based on the estimated errors (RMSEs) and the consistency between the satellite measurements and ground observations, Winter ranked the least among the seasons.

Uncertainty in measuring Winter precipitation is exacerbated by the inaccuracy of ground-based precipitation data in hilly regions. There might be several weeks of snow in the mountains but just a few snowy days in the lowlands each year. It implies that rain gauges may not provide accurate measurements during Winter. Moreover, previous studies have revealed inherent problems related to snowfall estimations obtained from satellites due to the utilisation of Passive Microwave (PMW) sensors in satellite products (Moazami and Najafi, 2021). All merged PMW estimates exhibit poor accuracies in areas with frozen or ice surfaces, according to Huffman *et al.* (2019). According to Chen *et al.*(2019), the PMW retrieval, which is in touch with the precipitation particles, has difficulties differentiating between precipitation and frozen surface. In addition, the infrared (IR) input that uses the morphing mechanism is directly deduced from the temperature at the cloud top and is, therefore, less susceptible to the influence that seasonal variability has on the results of retrieval outcomes. Tang *et al.* (2020) recommended that a regionally distributed map of temperature thresholds is required to enhance the satellite estimates for more accurate rain and snowfall classification.

The IMERG SSPs had the highest probability of detection (POD, CSI, and FAR) across coastal stations, but their associated magnitudes were less precise than in other locations. However, it is promising to observe that IMERG (06) showed improved proficiency in coastal locations compared to earlier versions.

5. ACKNOWLEDGEMENT

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