Chapter

WMO Space-Based Weather and Climate Extremes Monitoring Demonstration Project (SEMDP): First Outcomes of Regional Cooperation on Drought and Heavy Precipitation Monitoring for Australia and Southeast Asia

Yuriy Kuleshov, Toshiyuki Kurino, Takuji Kubota, Tomoko Tashima and Pingping Xie

Abstract

To improve monitoring of extreme weather and climate events from space, the World Meteorological Organization (WMO) initiated the space-based weather and climate extremes monitoring demonstration project (SEMDP). Presently, SEMDP is focused on drought and heavy precipitation monitoring over Southeast Asia and the Pacific. Space-based data and derived products form critical part of meteorological services' operations for weather monitoring; however, satellite products are still not fully utilized for climate applications. Using SEMDP satellite-derived precipitation products, it would be possible to monitor extreme precipitation events with uniform spatial coverage and over various time periods – pentad, weekly, 10 days, monthly and longer time-scales. In this chapter, SEMDP satellite-derived precipitation products over the Asia-Pacific region produced by the Earth Observation Research Center/Japan Aerospace Exploration Agency (EORC/JAXA) and the Climate Prediction Center/National Oceanic and Atmospheric Administration (CPC/NOAA) are introduced. Case studies for monitoring (i) drought in Australia in July-October 2007 and September 2018 and (ii) heavy precipitation over Australia in December 2010 and Thailand and the Peninsular Malaysia in November-December 2014 which caused widespread flooding are also presented. Satellite observations are compared with in situ data to demonstrate value of satellite-derived estimates of precipitation for drought and heavy rainfall monitoring.

Keywords: weather and climate extremes, drought, heavy rainfall, space-based observations, Asia-Pacific

1. Introduction to SEMDP

Meteorological observations clearly demonstrate that the global climate change occurs since the beginning of the industrial revolution, with particular rapid change since about 1950, including changes in weather and climate extreme events [1]. This increase in weather and climate extremes leads to significant increase in impact of natural disasters on society worldwide. One of the world's most disaster-prone regions is Asia-Pacific. In this region, almost 2 million people were killed in disasters between 1970 and 2011, representing 75% of all disaster fatalities globally; the most frequent hazards in the region are hydrometeorological [2]. The increase in frequency and severity of weather and climate extreme events and their impact on society requires the development and implementation of new tools for monitoring these hazardous phenomena globally using modern satellite remote sensing techniques.

Recognizing the importance of this issue, in February 2017 the World Meteorological Organization organized a workshop on operational space-based weather and climate extremes monitoring demonstration project which was attended by representatives of satellite operators, research and development space agencies, Regional Climate Centres (RCCs), and National Meteorological and Hydrological Services (NMHSs) to stimulate a dialog about enhancing utilization of space-based observation data and products for monitoring weather and climate extremes.

The workshop recognized that significant progress has been made in recent years in developing space-based observations in most geophysical fields and that several high-resolution satellite products were available on a quasi-real-time basis, enabling enhanced utilization for monitoring weather and climate extremes from space. It was also recognized that for many developing and least developed countries, strengthening human and technological capacity is required to provide an adequate level of services. As such, transfer of knowledge from countries with greater technological developments is essential, in order to fully utilize advantages of modern space-based data and derived products in developing countries.

Following the workshop's recommendations, WMO initiated SEMDP – the space-based weather and climate extremes monitoring demonstration project. SEMDP is established to run initially for 2 years (2018–2019) and be focused on weather and climate extremes such as drought and heavy precipitation over the Southeast Asia region and the Pacific Ocean. Space-based data and derived products form critical part of operations at NMHSs and RCCs for weather monitoring; however, satellite products are not fully utilized yet for climate applications.

Most NMHSs in countries of Southeast Asia and the Pacific use conventional surface-based rain gauge observations for extreme precipitation monitoring. Rain gauge observations provide accurate measurements of precipitation; however, data are restricted to locations of meteorological observation stations. For example, spatial distribution of rain gauges over Australia is not uniform: while eastern and southern parts of the country, southwest of Western Australia and northern and eastern parts of Tasmania, are densely covered by observation stations, spatial coverage of interior parts of Australia is poor. This issue of nonuniform spatial coverage is typical for countries in the Asia-Pacific region, and the density of rain gauges in many areas is considered as inadequate by users. In contrast with conventional surface-based observations, rainfall estimates derived from global space-based observations better address users' needs for precipitation information providing uniform spatial coverage.

The satellite-based rainfall estimates are based on retrieval algorithms of passive instrumental measurements (radiometry) relating radio signals recorded in infrared and microwave bands of electromagnetic spectrum to the occurrence and intensity of precipitation. Infrared instruments record signals around 11 μm wavelength providing information about cloud top temperature and then applying mathematical retrieval algorithms converting it to estimates of precipitation. Microwave instruments utilize a broad range of electromagnetic spectrum from 10 to 100 GHz. Channels up to 37 GHz primarily provide information about liquid precipitation in the lower parts of clouds; retrieval algorithms are based on assumption that larger amounts of liquid emit higher amount of microwave radiation. Radio signals received through channels above 37 GHz are primarily used for precipitation estimates in the upper parts of clouds due to scattering microwave radiation by solid precipitation. Microwave satellite-borne instruments are employed on the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM) mission.

Space-based observations can also address users' needs for information about precipitation extremes on short time scales. Current operational climate products for drought monitoring derived from surface-based observations are typically focused on identifying rainfall deficits over extended periods (months to years) using percentile and/or decile analysis. As for heavy precipitation, they are typically diagnosed on a monthly time scale. Using space-based observations, it would be possible to monitor extreme precipitation events over shorter time periods—pentad (5 days), week (7 days), and longer periods of up to a month—in order to respond to current and future users' requirements. Monitoring weather and climate extremes on shorter time scales is considered by RCCs and NMHSs as a valuable extension of their operational products to enhance climate services for users in Asia-Pacific.

In this chapter, WMO SEMDP and its implementation strategy are described, and first outcomes of Asia-Pacific regional cooperation on drought and heavy precipitation monitoring from space are presented.

2. SEMDP precipitation products

SEMDP is designed as a demonstration project to bring benefits of utilizing space-based observations of extreme precipitation to operational services of RCCs and NMHSs. During the project's first implementation stage, SEMDP's geographical domain covers the Southeast Asia region and the Pacific Ocean—area from 40°N to 45°S and 50°E to 160°W. Two agencies—the Earth Observation Research Center/Japan Aerospace Exploration Agency and the Climate Prediction Center/National Oceanic and Atmospheric Administration—provide satellite data and products for the SEMDP region. It is planned to (i) gradually expand SEMDP's geographical domain during subsequent stages of the project's implementation to accomplish the global coverage for SEMDP products and (ii) involve more space and meteorological agencies from around the world to contribute to providing RCCs and NMHSs with a range of SEMDP products.

SEMDP is focused on monitoring extreme events. "Extreme weather event" and "extreme climate event" according to the IPCC AR5 WG I report are defined as follows. "An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season)." [3]. Thus, SEMDP approach to defining drought and heavy rainfall is based on the above definitions.

Based on the workshop's recommendations and consequent consultations with the satellite data providers (EORC/JAXA and CPC/NOAA) and users (RCCs and NMHSs in Southeast Asia and the Pacific), SEMDP aims to satisfy users' requirements for monitoring precipitation extremes on short time scales, i.e., on pentad (5 days) to weekly up to monthly basis utilizing satellite-based products available on near real-time basis for monitoring "heavy precipitation" and "drought" events on a routine basis ("operationally") for climate analysis and monitoring and for the development of improved climate services. Brief introduction of EORC/JAXA and CPC/NOAA satellite-derived data and products available for RCCs and NMHSs in Asia-Pacific is given below.

SEMDP precipitation products produced by EORC/JAXA are based on the Global Satellite Mapping of Precipitation (GSMaP) [4]. GSMaP products are in high demand—more than 4200 users from 114 countries from around the world are registered for the GSMaP data distribution. For SEMDP users in Asia-Pacific, EORC/JAXA provides mean precipitation estimates derived from GSMaP version 6 for hourly, daily (00–23 UTC), pentad (5 days), weekly (Monday–Sunday), 10-day, and monthly precipitation with spatial resolution of 0.1°lat/lon grid box (an example of monthly precipitation for July is given in **Figure 1**). In addition, statistics for daily, pentad, and weekly extreme precipitation (90th–99th percentiles) and percentage of rainy (≥1 mm/day) days in a month is provided (examples are presented in **Figures 2** and **3**). For drought monitoring, the standardized precipitation index (SPI; 1 month, 2 months, and 3 months) for grid boxes over land with spatial resolution of 0.25°lat/lon grid box is provided.

CPC/NOAA provides SEMDP users with a similar set of products using the Climate Prediction Center morphing technique (CMORPH) satellite precipitation

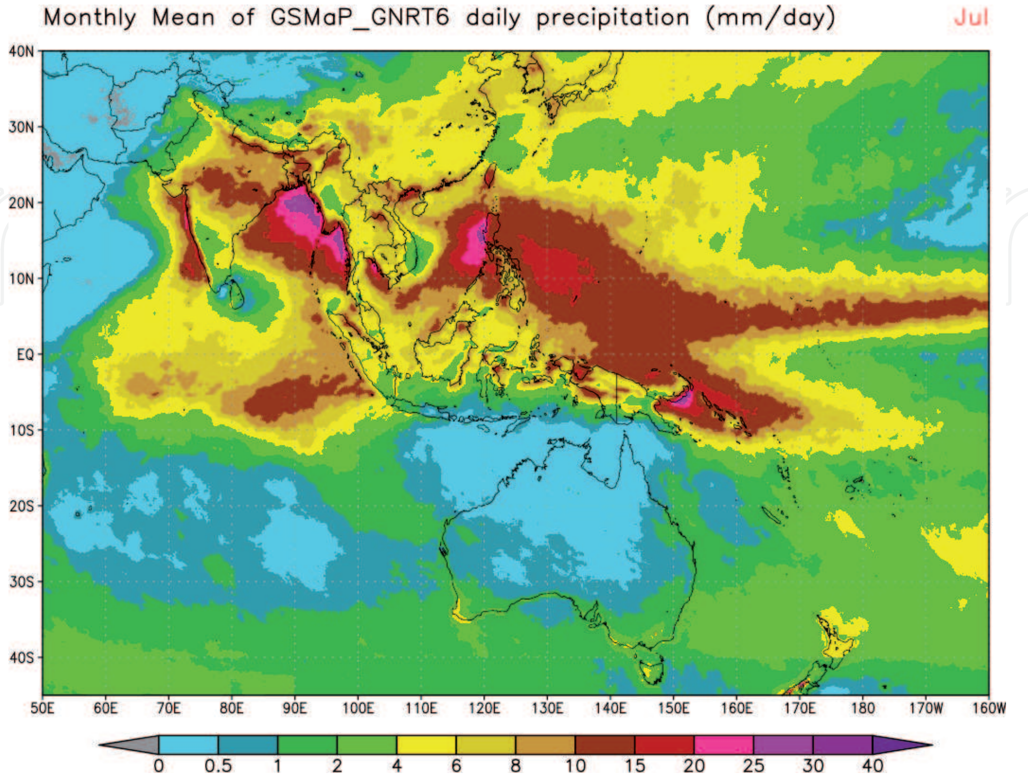

Figure 1.
EORC/JAXA GSMaP monthly mean of daily precipitation for the month of July.

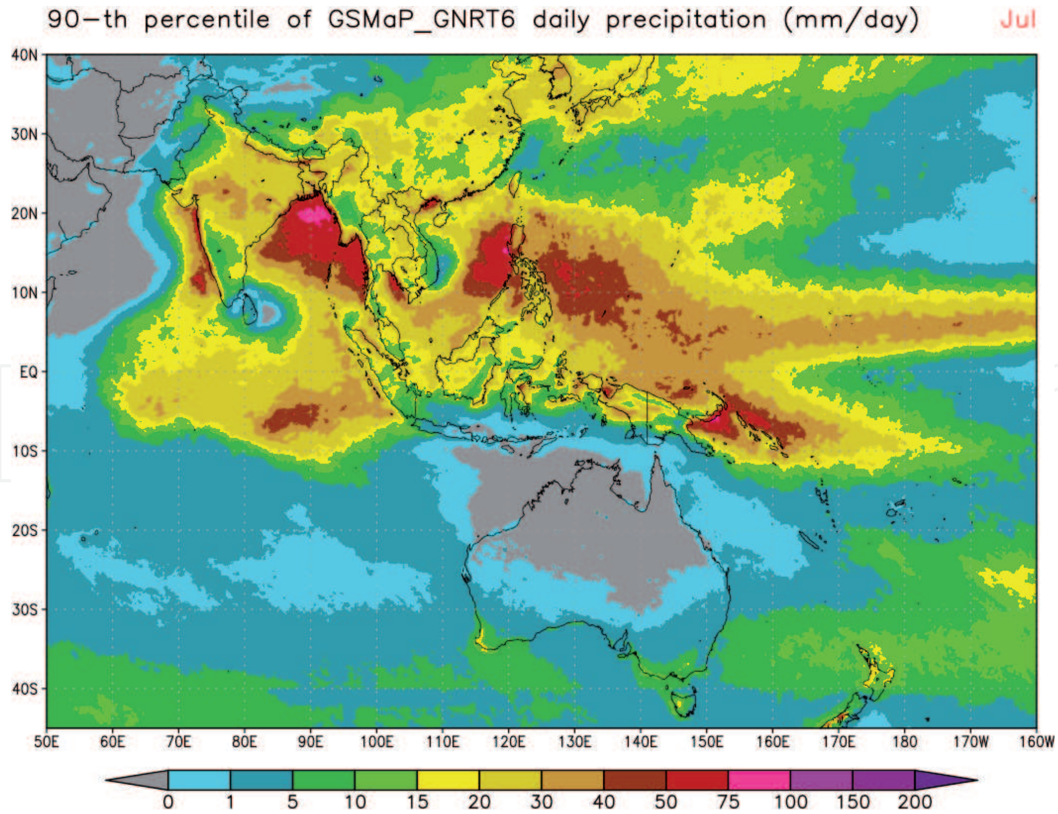

Figure 2.
EORC/JAXA GSMaP 90th percentile of daily precipitation for the month of July.

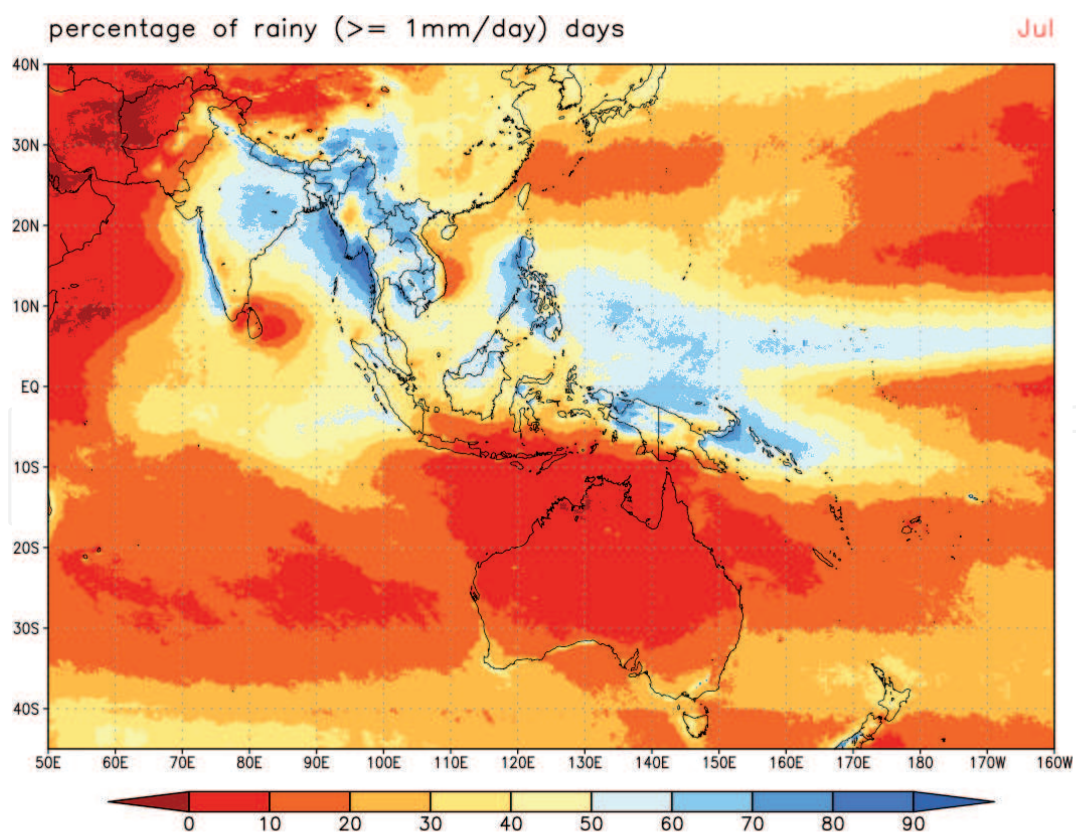

Figure 3.
EORC/JAXA GSMaP percentage of rainy days for the month of July.

estimates (see [5] for detail). In addition to the SPI, weekly normalized differential vegetation index (NDVI; **Figure 4**) and the vegetation health index (VHI) are also available for SEMDP region.

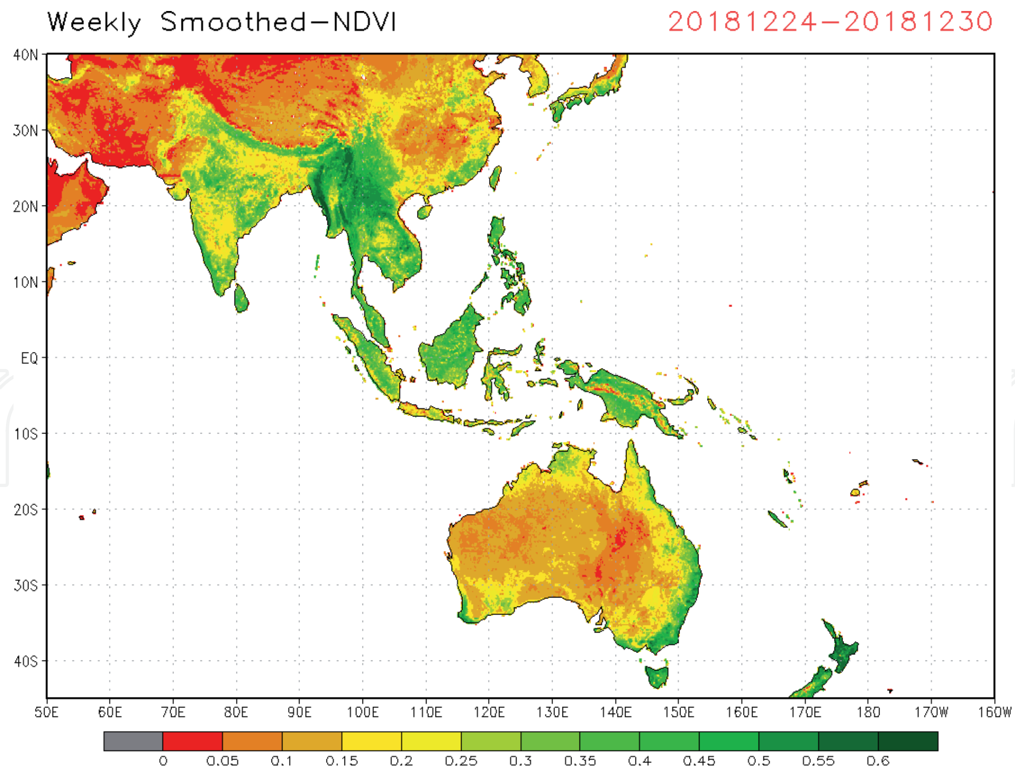

Figure 4.
CPC/NOAA CMORPH weekly NDVI for 24–30 December 2018.

3. Drought monitoring using SEMDP products

In this section, case studies for drought monitoring in Australia using SEMDP products are presented. Australia is the driest continent on the Earth, apart from Antarctica. About 70% of Australia receives less than 500 mm of rain annually, which classifies those parts of the continent as arid or semiarid areas. Drought monitoring is vital for informed decision-making in agriculture, disaster risk management, water management, and other sectors.

In Australia, the Bureau of Meteorology defines drought in the affected region when the rainfall over a 3-month period is being in the lowest decile of what has been recorded for that region in the past [6]. Drought often affects Australia—rainfall observations which the Bureau of Meteorology conducts since the middle of the nineteenth century show that on average drought occurs once every 18 years; severity and duration of drought vary. The worst drought which affected Australia since the European settlement—the Millennium drought—occurred in the 2000s.

The Millennium drought affected southern and eastern regions of the continent (states of Victoria, New South Wales, Queensland, and South Australia), southwest of Western Australia, and Tasmania. The largest Australian agricultural region—the Murray-Darling basin—was severely affected, and water resources which supply cities and towns including capital cities of Melbourne, Sydney, Brisbane, Adelaide, and many other cities and towns were also severely affected.

The Millennium drought commenced with rainfall deficit in 1996–1997 and continued during very dry years in 2001–2002 (**Figure 5**); it was clear that this is the worst drought in Australia on record [7].

During the year 2006 southeastern parts of Australia had the second driest year on record [8]; agricultural region of the Murray-Darling basin was particularly severely affected by drought conditions (**Figure 6**). Drought continued to affect the Murray-Darling basin in 2007; it was already seventh consecutive year of below average rainfall for the basin. Dry and hot conditions continued to affect Australia through to early 2010.

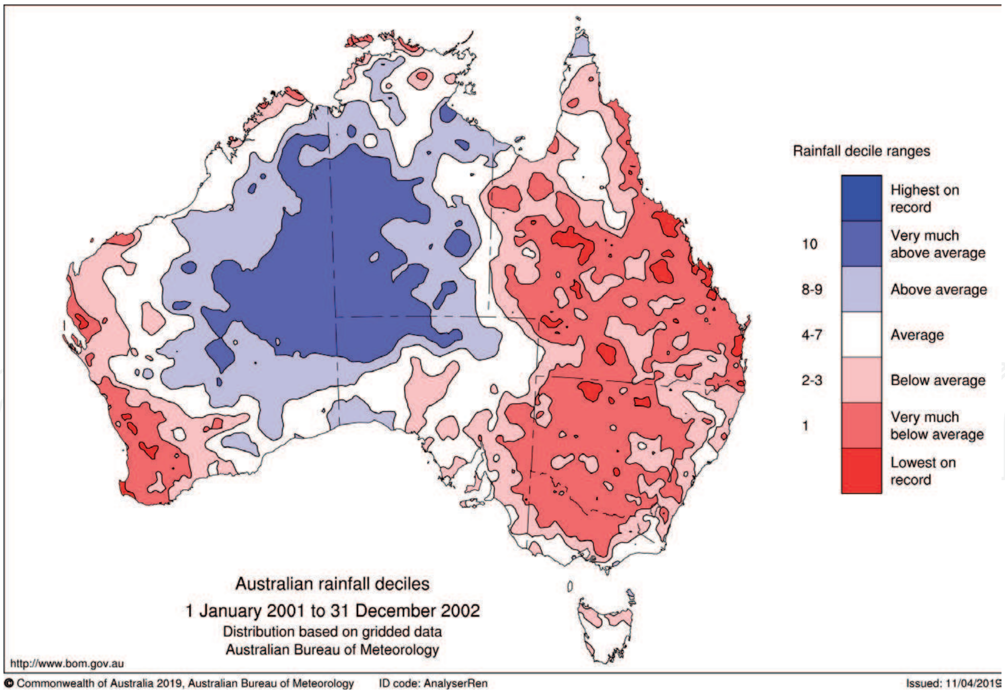

Figure 5.
Rainfall deciles for Australia in January 2001–December 2002 derived from the Australian Bureau of Meteorology rain gauge observations.

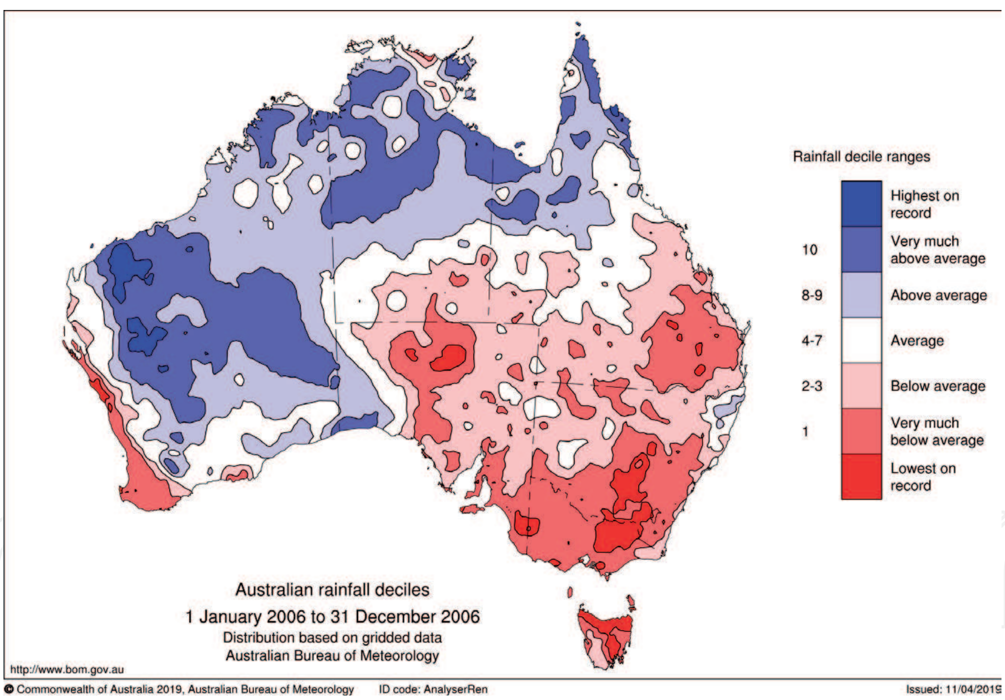

Figure 6.
Rainfall deciles for Australia in January–December 2006 derived from the Australian Bureau of Meteorology rain gauge observations.

The 2010–2011 La Niña event brought the Millennium drought to the end. This La Niña event was one of the strongest on records, and it resulted in record-breaking rainfall in the Murray-Darling basin and above average rainfall over the southeast parts of the country (**Figure 7**). Significant increase in surface water storage and soil moisture due to continuing above average rainfall ended drought conditions in the southeastern parts of Australia [9].

The Millennium drought was the most severe drought which affected Australia over the past few centuries. It is pertinent to examine the usefulness of space-based observations for drought monitoring over Australia; here

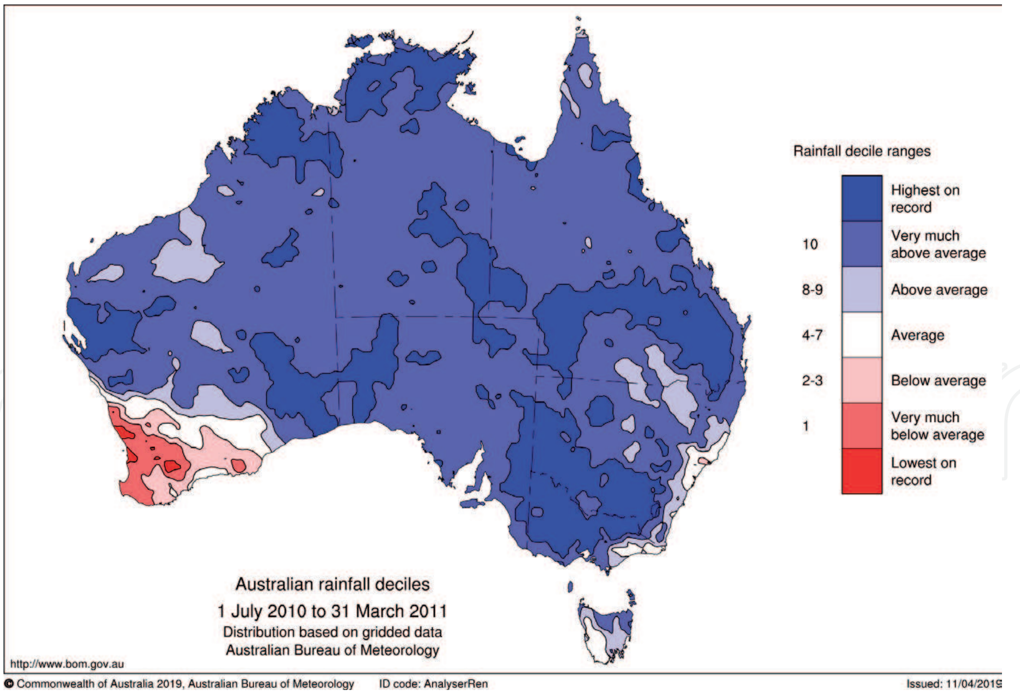

Figure 7.
Rainfall deciles for Australia in July 2010–March 2011 derived from the Australian Bureau of Meteorology rain gauge observations.

we present a case study for the year 2007 of the Millennium drought utilizing rainfall percentile, 1-month and 3-month SPI values derived from the EORC/JAXA GSMaP data.

The SPI is an index which is widely used for meteorological drought detection and monitoring. Positive values of the SPI correspond to precipitation above median, and negative values of the SPI correspond to precipitation below median. Drought conditions are classified when the SPI values are equal to or below −1.0. Specifically, for the SPI values −1.0 and below conditions are classified as "moderately dry," for −1.5 and below as "severely dry," and for −2.0 and below as "extremely dry."

As described above, the main agricultural region in southeastern Australia—the Murry-Darling basin—was severely affected by the Millennium drought. Examining 1-month SPI for August 2007 (**Figure 8**) and rainfall percentile (**Figure 9**) derived from EORC/JAXA GSMaP, one can find that drought-affected areas where the SPI values are less than −1.5 (i.e., "severely dry") correspond well to areas of rainfall below the 10th percentile. The detected by space-based observations drought-affected areas are in good correspondence with areas defined as "very much below average" on rainfall decile map for August 2007 derived from the Australian Bureau of Meteorology rain gauge observations (**Figure 10**). Similarly, areas where values of 3-month SPI for July–September 2007 (**Figure 11**) are below −1.5 are in good correspondence with areas of "very much below average" rainfall on rainfall decile map (**Figure 12**).

It should be noted that space-based and in situ observations are in good agreement over the Murry-Darling basin in southeastern Australia where the density of surface-based observations is high; however, there are noticeable discrepancies between them over the central parts of the continent where the density of surface-based observations is very low. It clearly demonstrates value of space-based rainfall estimates for drought detection and monitoring, especially for regions where rain gauge observations are limited or unavailable.

SEMDP products became available to NMHSs and RCCs in Asia-Pacific on a quasi-operational basis from December 2018, thanks to the dedicated efforts of

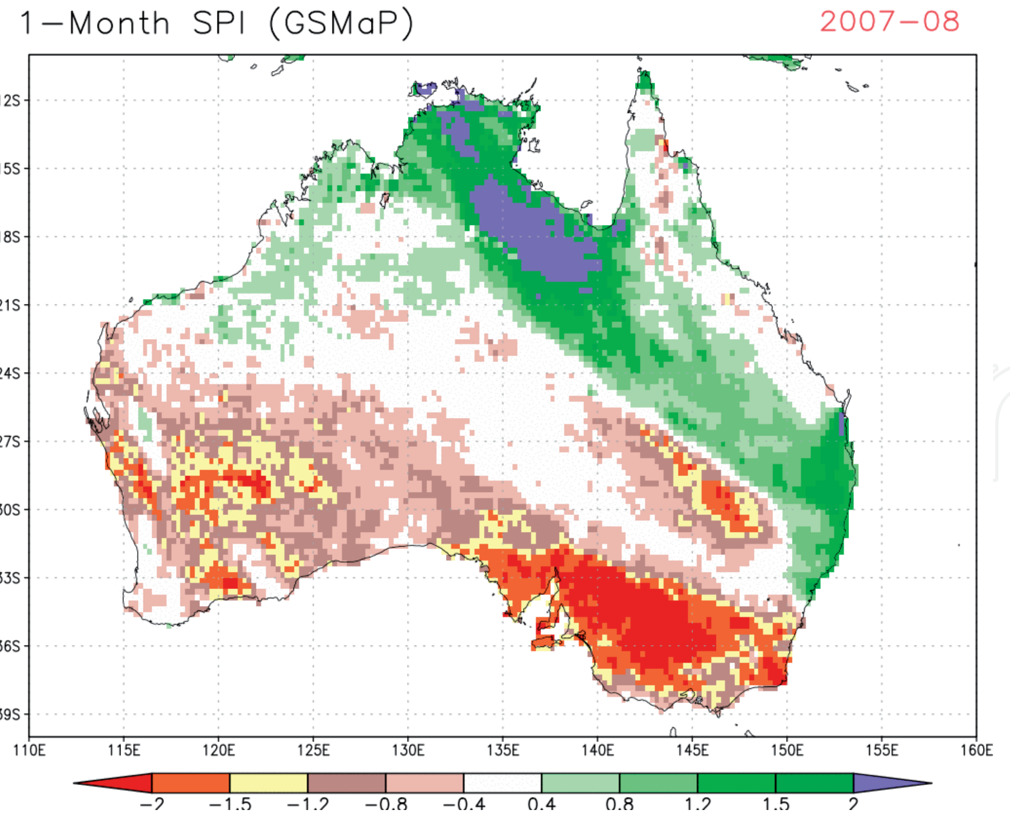

Figure 8.
SPI for Australia in August 2007 derived from the EORC/JAXA GSMaP data.

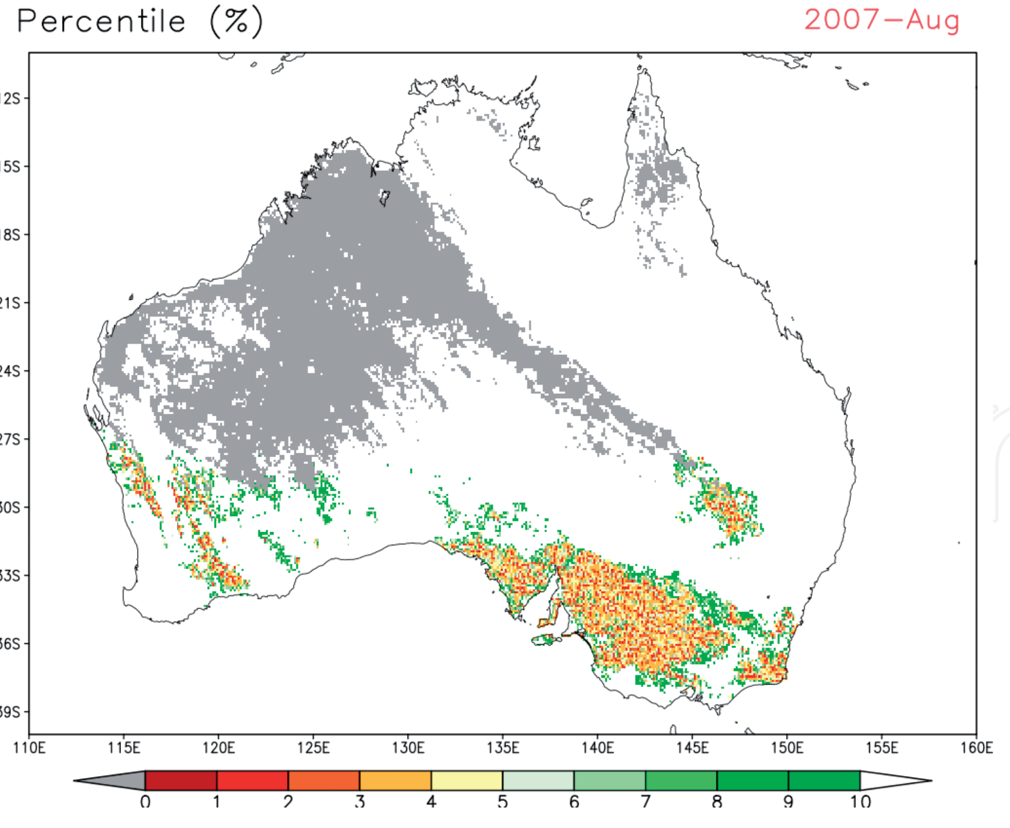

Figure 9.
Rainfall percentiles for Australia in August 2007 derived from the EORC/JAXA GSMaP data.

scientists and IT experts from the EORC/JAXA and the CPC/NOAA. Here we demonstrate usefulness of available SEMDP products for operational drought monitoring in Australia using the VHI. 2018 for Australia was a year of persistent warmth (the third warmest year on record with mean temperature 1.14°C above the

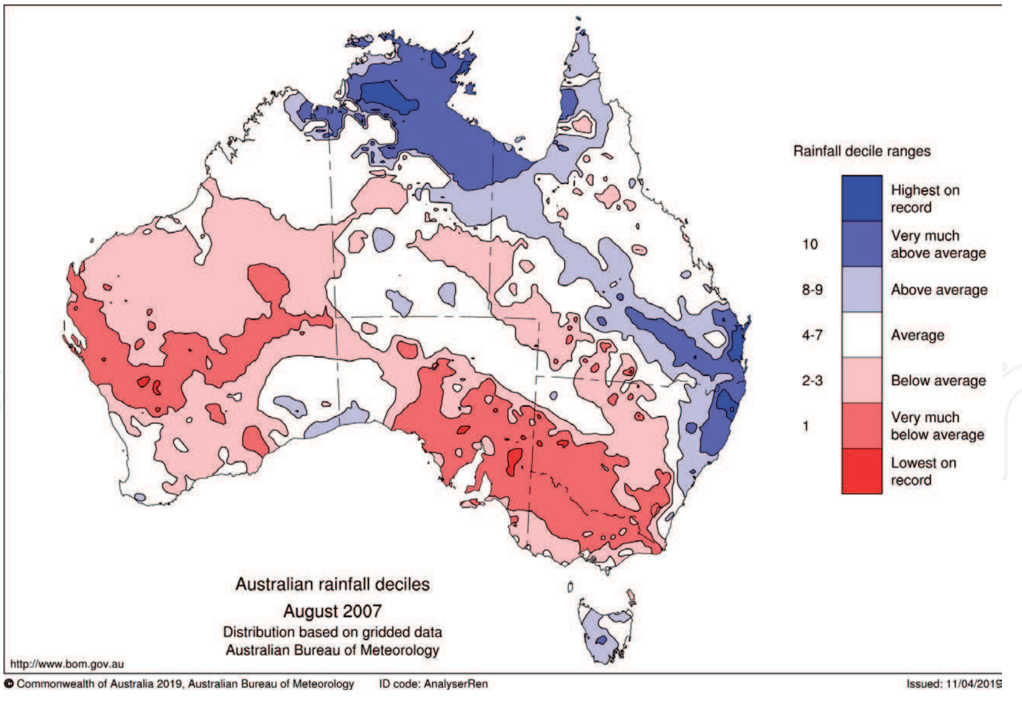

Figure 10.
Rainfall deciles for Australia in August 2007 derived from the Australian Bureau of Meteorology rain gauge observations.

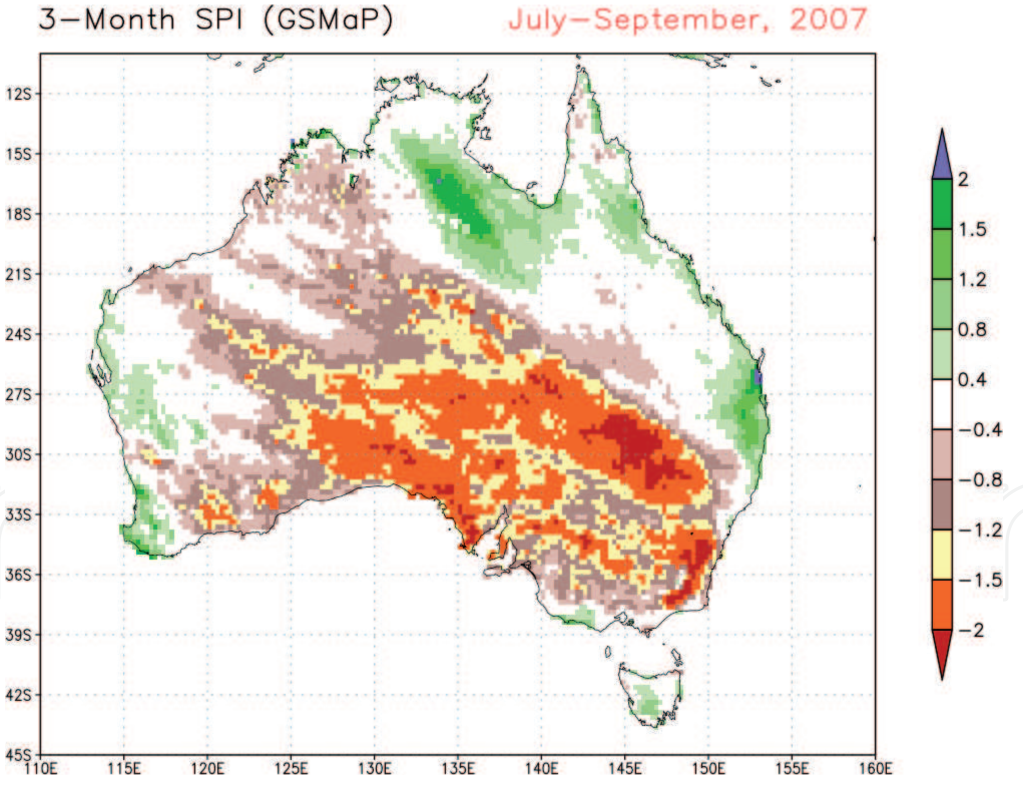

Figure 11.
SPI for Australia for 3 months (July–September 2007) derived from the EORC/JAXA GSMaP data.

1961–1990 average) and protracted drought (average rainfall was 412.8 mm which is 11% below the 1961–1990 average of 465 mm) [10]. Annual rainfall was very low ("very much below average" and "lowest on record") over the southeastern parts of the country and above average in the area between the northwest and southeast of Western Australia (**Figure 13**). Rainfall was particularly low over the southeast from April; September was record-dry. Dry conditions had an impact on vegetation which could be estimated by the vegetation health index.

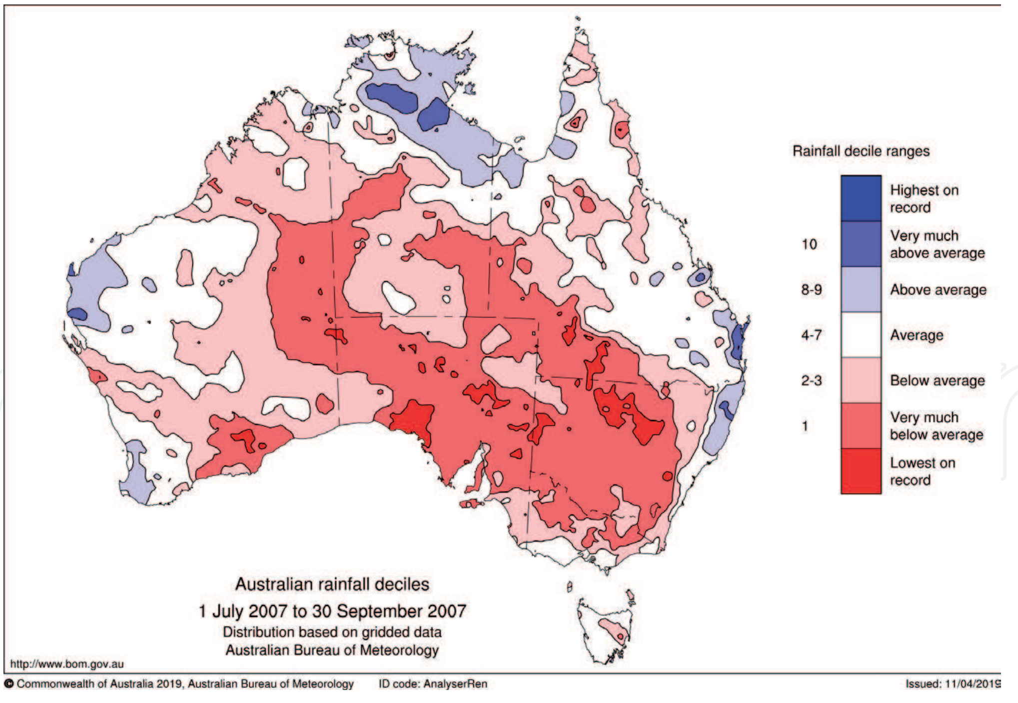

Figure 12.
Rainfall deciles for Australia in July–September 2007 derived from the Australian Bureau of Meteorology rain gauge observations.

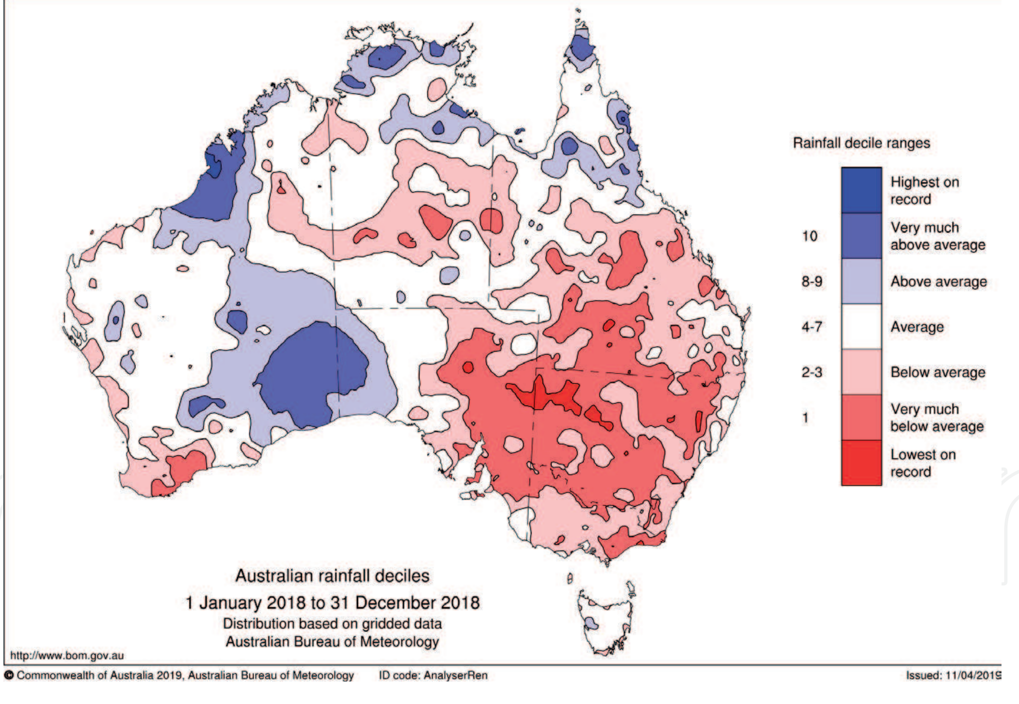

Figure 13.
Rainfall deciles for Australia in January–December 2018 derived from the Australian Bureau of Meteorology rain gauge observations.

The VHI is computed using observations from Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA polar orbiting satellites in the visible, infrared, and near-infrared bands and used to identify stress on vegetation related to drought [11]. Maps of the VHI for the last week of September 2017 (above average rainfall for Australia was observed in that year) and the last week of September 2018 are presented in **Figure 14** demonstrating difference between relatively healthy vegetation over Australia in September 2017 (**Figure 14a**) and stressed vegetation in September 2018 (**Figure 14b**) due to impact of dry conditions.

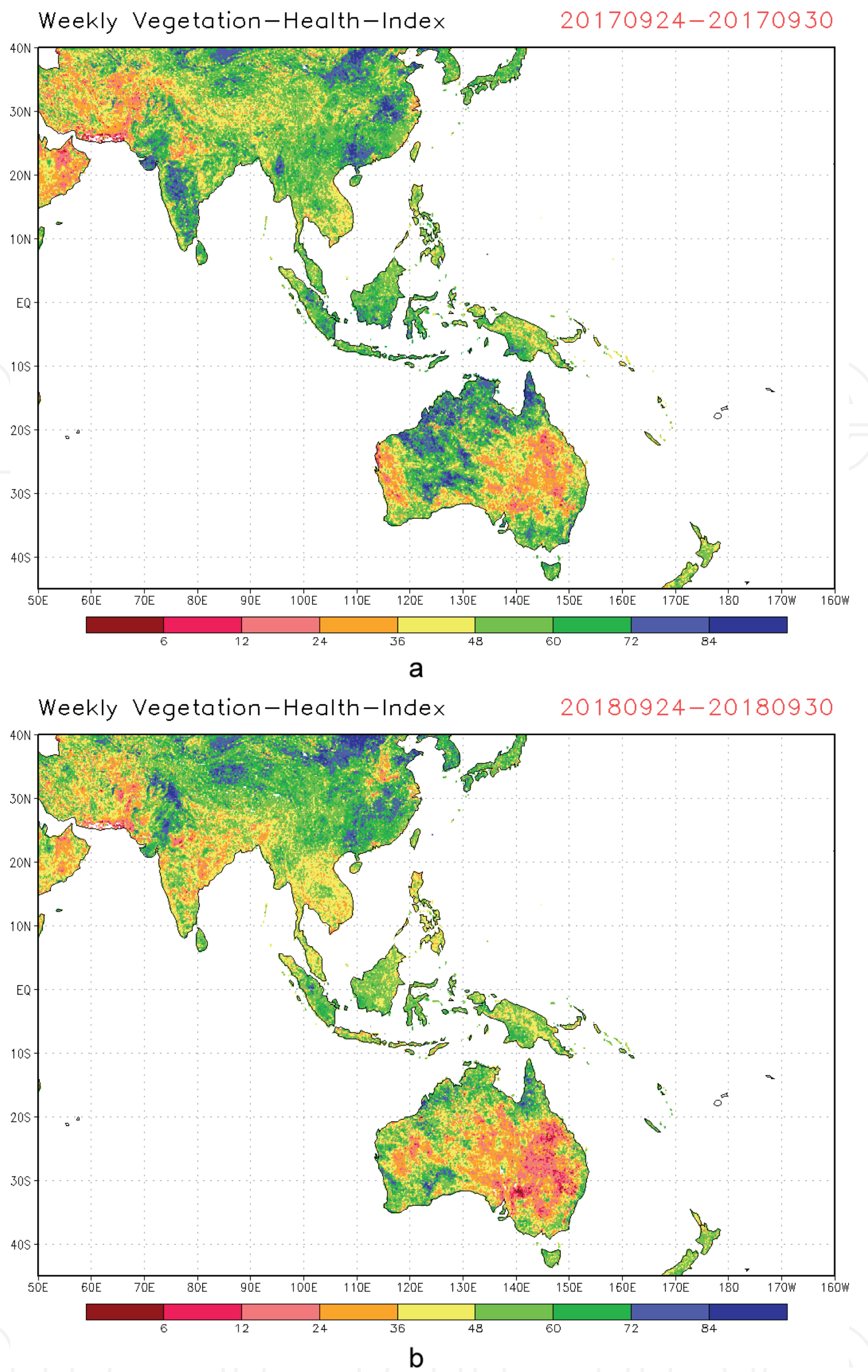

Figure 14.
CPC/NOAA VHI for (a) 24–30 September 2017 and (b) 24–30 September 2018.

4. Heavy precipitation monitoring using SEMDP products

In this section, case studies of heavy precipitation over Australia in December 2010 and Thailand and Peninsular Malaysia in November–December 2014 which caused widespread flooding are presented.

An "extreme rainfall" is defined when a mean rainfall for a specified period is higher than a certain percentile threshold, e.g., 90th–99th percentile (**Figure 15**).

Extreme rainfall associated with La Niña event has been observed over Australia in 2010 and 2011. In 2011, Australia experienced its third wettest year since national rainfall records began in 1900 [12]. Averaged across Australia, both years experienced rainfall well above average—690 mm (225 mm above the long-term average of 465 mm) in 2010 [9] and 699 mm (234 mm above the long-term average of 465 mm) in 2011 [12].

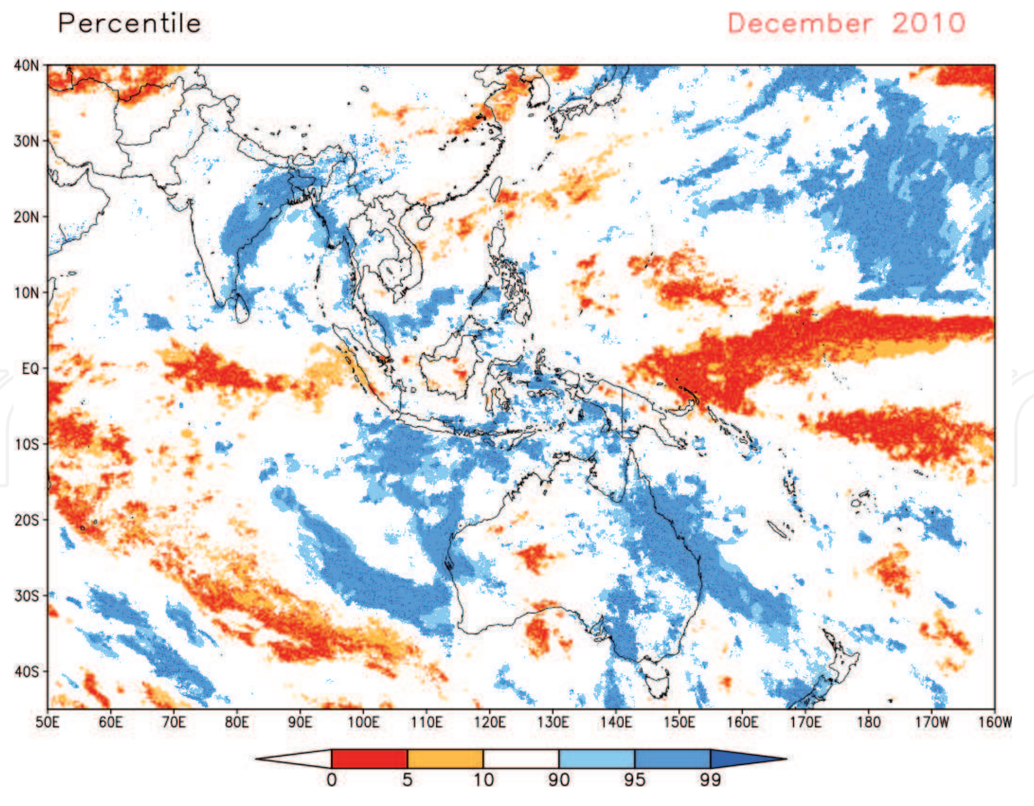

Figure 15.
EORC/JAXA GSMaP rainfall percentile over SEMDP domain for December 2010.

The 2010–2011 La Niña event was one of the strongest on record, comparable in strength with the La Niña events of 1917–1918, 1955–1956, and 1975–1976, and it has significant impact on Australian rainfall. La Niña is typically associated with increased rainfall in northern and eastern Australia. During the 2010–2011 La Niña, most of the mainland Australia experienced significantly higher than average rainfall over the 9 months from July 2010 to March 2011 (**Figure 7**). A number of new Australian rainfall records were set: wettest September, December, and March on record and second wettest October and February. Extreme rainfall associated with La Niña event has been observed over parts of western and eastern Australia in December 2010 (**Figure 16**). The record-breaking rainfall during the 2010–2011 La Niña led to widespread flooding in many regions between September 2010 and March 2011 including southeast Queensland, large areas of northern and western Victoria, New South Wales, northwestern Western Australia, and eastern Tasmania that were subject to significant flooding.

In **Figure 17**, EORC/JAXA GSMaP rainfall percentile over Australia for December 2010 is presented. An area above 95th percentile derived from GSMaP approximately corresponds to an area of rainfall deciles "very much above average" as derived from rain gauge observations by the Australian Bureau of Meteorology (**Figure 16**); it demonstrates that this extreme rainfall event was well detected using GSMaP.

The second case study examines episodes of heavy precipitation over Thailand and Peninsular Malaysia in November–December 2014 [13]. In November 2014, an episode of heavy rainfall and subsequent flooding in the coastal area of northeastern Peninsular Malaysia occurred from 13 to 20 November 2014. In the second half of December 2014, two episodes of heavy precipitation caused widespread flooding in south of Thailand, Kelantan, Terengganu, and Pahang and on the east coast of Peninsular Malaysia.

Accumulated rainfall over Peninsular Malaysia in November and December 2014 derived from GSMaP is presented in **Figure 18a** and **b**, respectively. Time series of daily precipitation for November–December 2014 averaged over land in

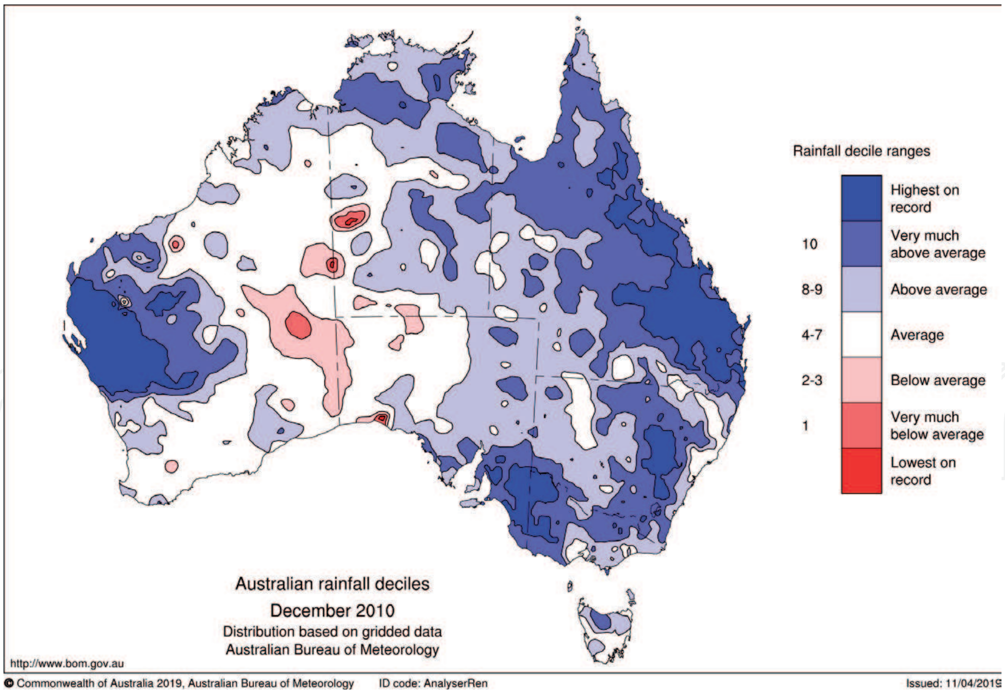

Figure 16.
Australian rainfall deciles for December 2010 derived from the Australian Bureau of Meteorology rain gauge observations.

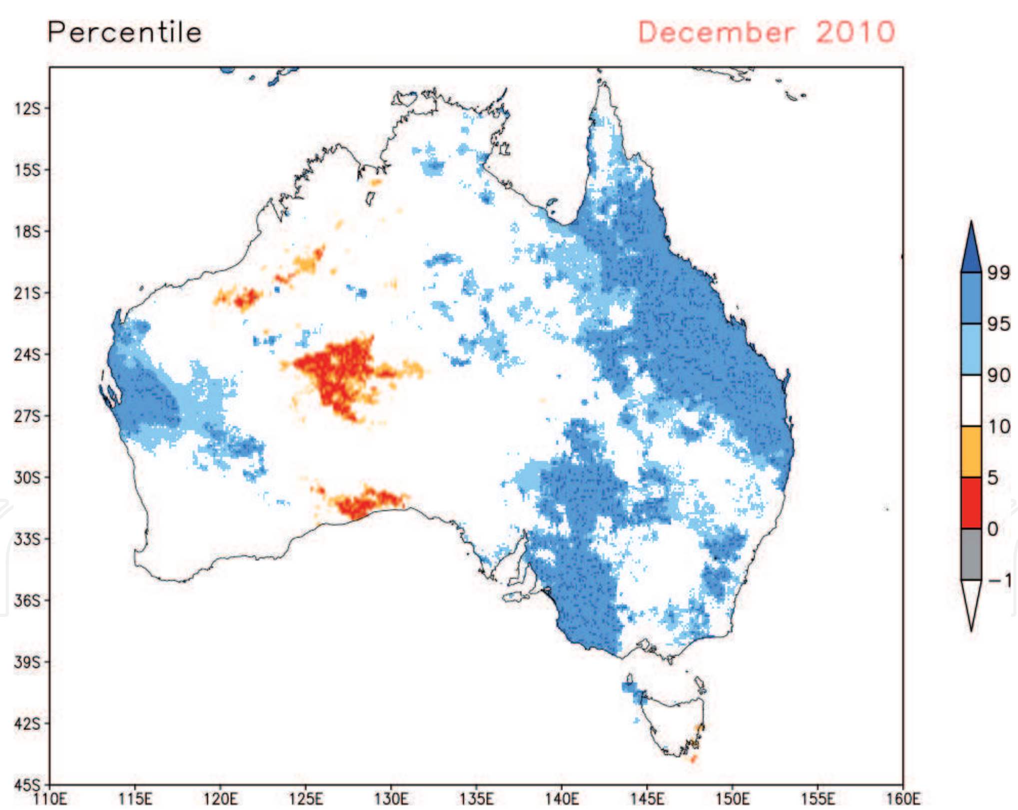

Figure 17.
EORC/JAXA GSMaP rainfall percentile over Australia for December 2010.

the area from 100°E to 105°E; EQ to 8°N is presented in **Figure 19**. In November 2014, accumulated rainfall exceeded 1000 mm along the east coast of Peninsular Malaysia. The first episode of persistent heavy rainfall occurred from 13 to 20 November. In December 2014, areas of monthly total rainfall above 500 mm expand over the southern part of Thailand and the most of Malaysia. Particularly heavy

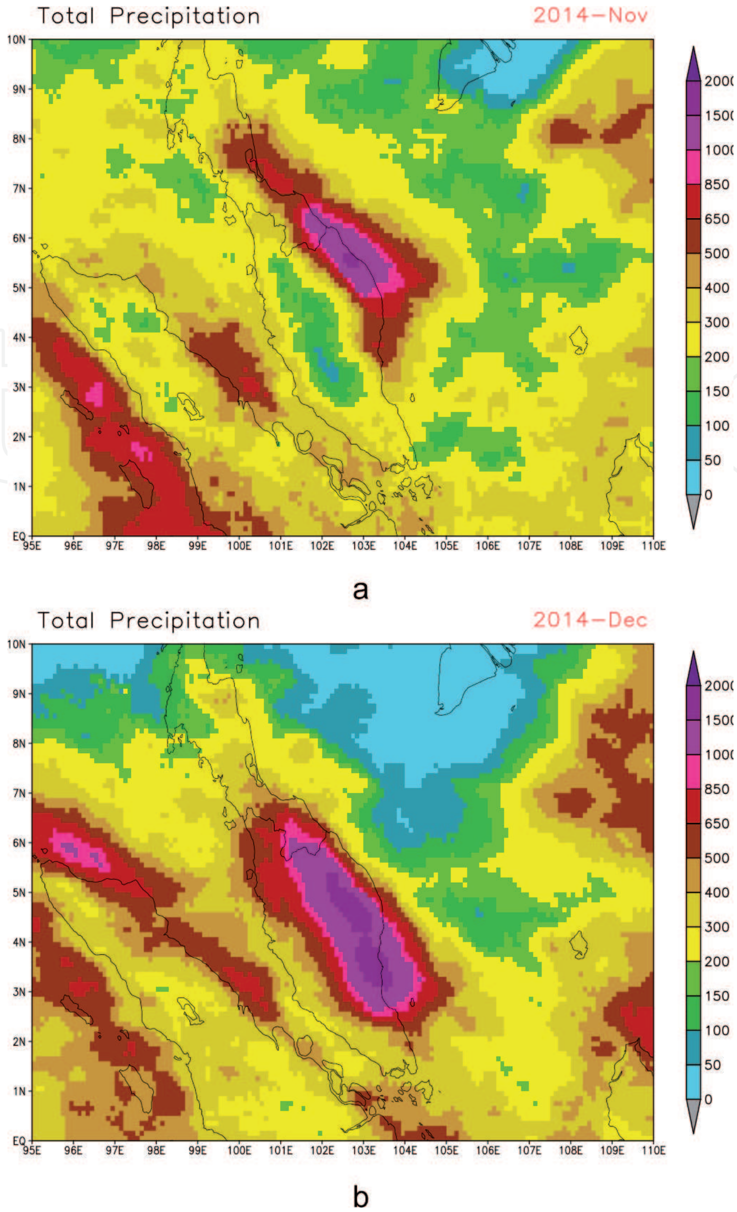

Figure 18.
EORC/JAXA GSMaP total precipitation over Peninsular Malaysia in (a) November 2014 and (b) December 2014.

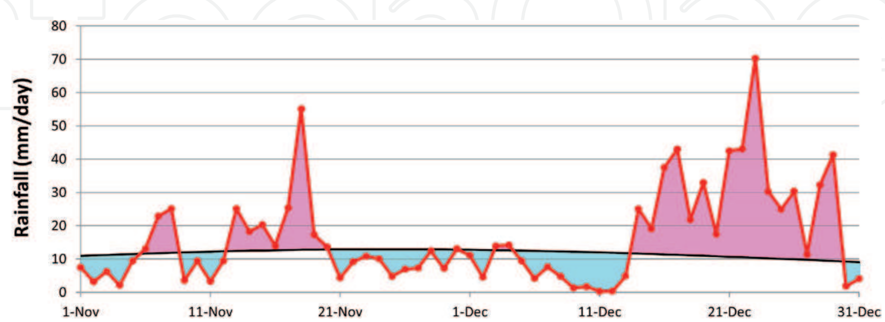

Figure 19.
EORC/JAXA GSMaP time series of daily precipitation for November–December 2014 averaged over land in the area from 100°E to 105°E; EQ to 8°N; solid black line represents 18-year mean.

precipitation occurred over the eastern parts of the Peninsular with monthly total rainfall estimated at 1500 mm and above. Second episode of long-lasting heavy rainfall occurred from 14 to 30 December. Results obtained from space-based observations are in correspondence with results presented in [13].

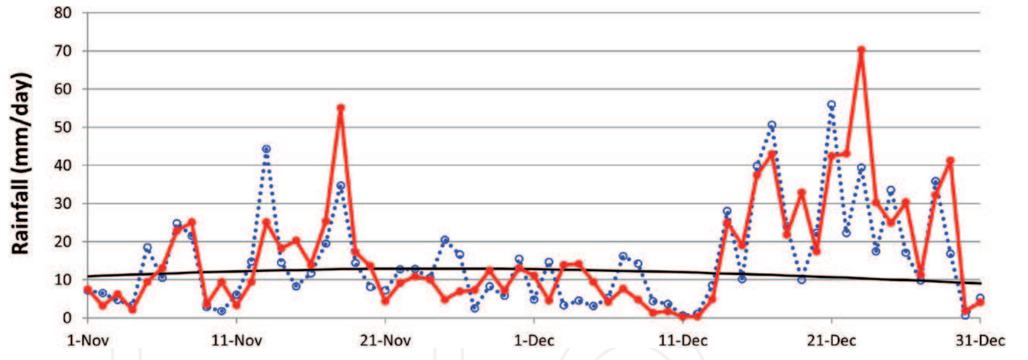

Figure 20.
Time series of daily precipitation for November–December 2014 averaged over land in the area from 100°E to 105°E; EQ to 8°N derived from (a) EORC/JAXA GSMaP (red line) and (b) CPC GAG (blue line).

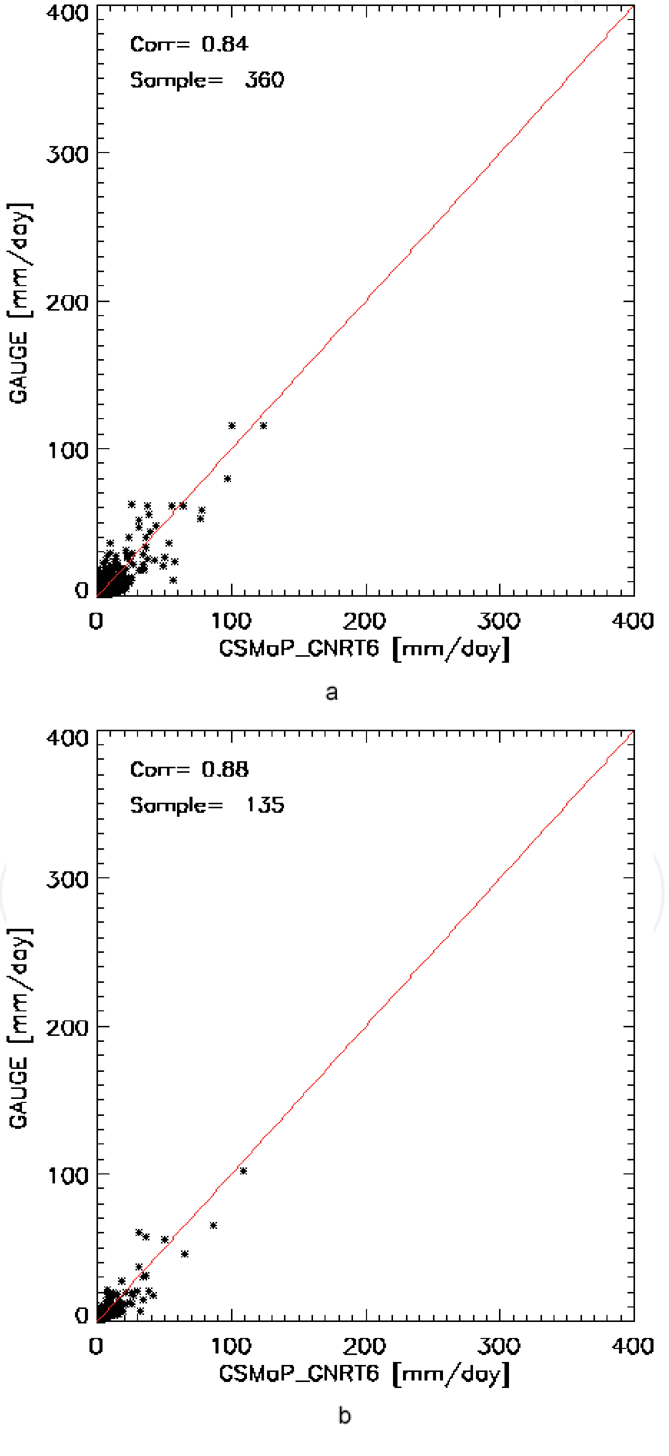

Figure 21.
Scatter plot of (a) pentad (5-day) and (b) 10-day precipitation averaged over land in the area from 100°E to 105°E; EQ to 8°N for November–December 2014 derived from the EORC/JAXA GSMaP versus the CPC GAG.

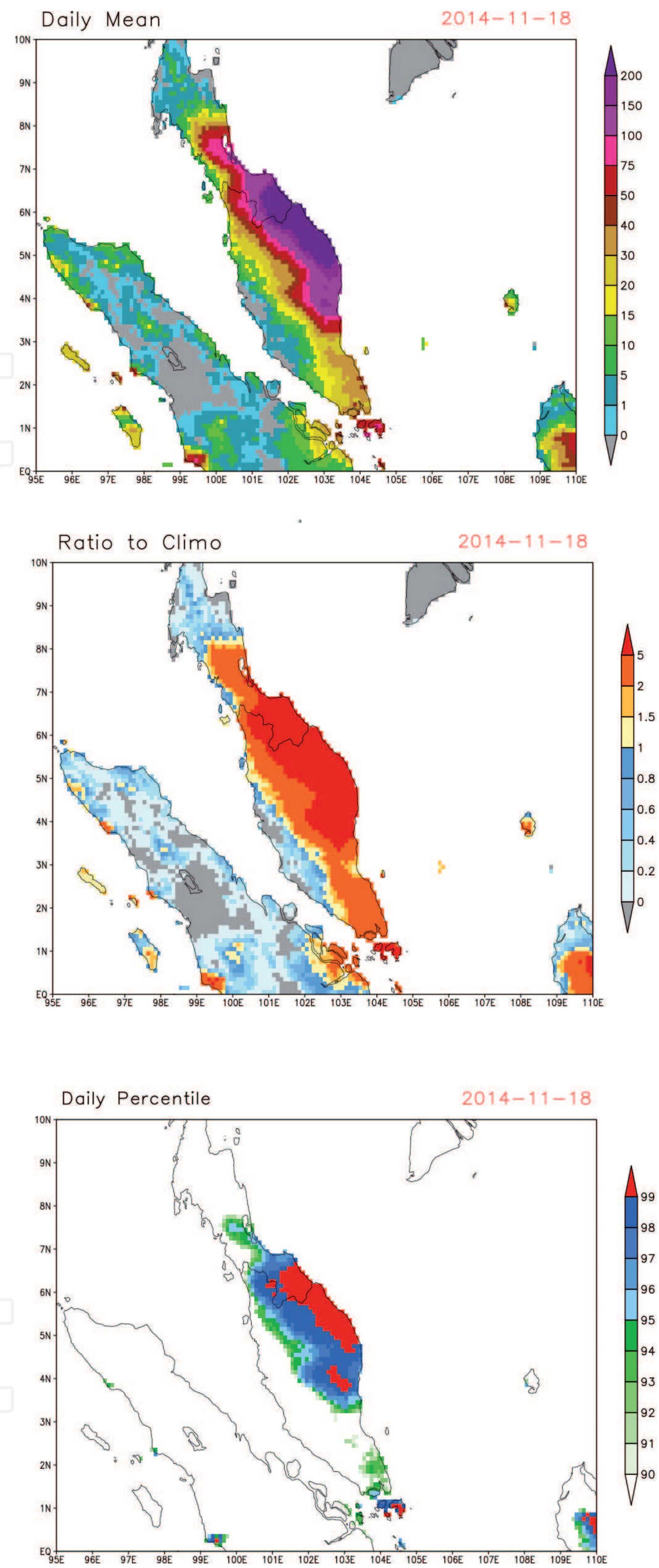

Figure 22.
EORC/JAXA GSMaP (a) daily precipitation over the Peninsular Malaysia on 18 November 2014, (b) ratio of the daily precipitation to 18-year climatology, and (c) daily percentile.

In **Figure 20**, time series of daily precipitation derived from the EORC/JAXA GSMaP data and in situ observations derived from the CPC rain gauge analysis (CPC GAG) for November–December 2014 averaged over land in the area from 100°E to 105°E; EQ to 8°N are presented. All episodes of heavy precipitation in November and December 2014 are detected well by space-based observations. In general, there is a good correspondence between the EORC/JAXA GSMaP space-based rainfall estimates and the CPC GAG rain gauge analysis.

Scatter plot—comparison between CPC GAG and GSMaP satellite precipitation estimates—is presented in **Figure 21**; results for pentad (5-day) and 10-day mean precipitation (mm/day) are plotted on the top and bottom panels, respectively. Only data pairs of precipitation over a 0.25°lat/lon grid box with at least one reporting rain gauge are included in the comparison. The correlation coefficients of pentad and 10 days are 0.84 and 0.88, respectively, indicating good agreement between space-based estimates and surface-based rain gauge observations.

An example of detecting daily heavy precipitation using GSMaP data is presented in **Figure 22**. Precipitation was particularly heavy across the eastern coast of the peninsular with daily totals above 200 mm (**Figure 22a**); this exceeded 18-year climatology more than five times (**Figure 22b**). In Narathiwat province of Thailand and Kelantan and Terengganu provinces of Malaysia, the daily precipitation was higher than the 99th percentile (**Figure 22c**) causing widespread flood in the affected areas.

In summary, presented case studies of detecting extreme precipitation in Australia, Thailand, and the Peninsular Malaysia demonstrate that space-based observations provide valuable information for monitoring heavy rainfall.

5. Conclusions

These first results of implementation of WMO SEMDP demonstrate that space-based estimates of extreme precipitation are an effective solution to enhance capacity of RCCs and NMHSs for monitoring drought and heavy rainfall assisting governments and local communities with informed decision-making in adaptation to climate variability and change.

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Conflict of interest

Declaration: There is no conflict of interest.

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