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Development of baseline climate data set and trend analysis in the Mekong Basin

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Executive Summary

The regional Climate Change and Adaptation Initiative (CCAI) of the Mekong River Commission (MRC) addresses the shared adaptation challenges to climate change impacts of the Lower Mekong Basin (LMB). In this context a study was undertaken to (i) build a harmonized climate database for the Lower Mekong Basin, and (ii) undertake a trend analysis over the past climate.

Existing climate station data were used to select the best reanalysis dataset. It was concluded that not one reanalysis dataset outperformances, but that three products have to be used: CRU for long-term analysis (1901-2012), and for more recent analysis PRINCETON and APHRODITE for respectively temperature and precipitation.

The selected products were subsequently corrected using available climate station data. The final result is the best available harmonized daily climate data set covering the entire LMB at a resolution of 25 km including daily precipitation, and average, minimum and maximum temperature.

The climate data sets were used to undertake a trend analysis. Temperature in the LMB has increased by about 0.2^{o}C/10 years over the last 30 years. Precipitation increased by about 50 mm/10 years over the last 30 years. Also a weak signal of a seasonal shift in monsoon has been observed towards a slightly earlier start and end of the monsoon.

The study concluded that based on the analysis: (i) a continuous effort to improve and maintain station data and data handling is needed, (ii) further trend analysis on climate could be undertaken, and (iii) the climate is changing so adaptation strategies have to be developed and implemented.

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1 Background

The Mekong River Commission was established by the 1995 Agreement on cooperation for the Sustainable Development of the Mekong River Basin, between the governments of Cambodia, Laos, Thailand and Viet Nam. The MRC has established a range of initiatives to achieve its objective, among those are the Climate Change Adaptation Initiative.

The Climate Change and Adaptation Initiative (CCAI) is a collaborative regional effort of MRC Member Countries (Lao PDR, Cambodia, Thailand and Vietnam) to support processes of adapting to the new challenges posed by climate change in the Lower Mekong Basin (LMB). The main focus is a basin wide integrated approach to adaptation planning consistent with Integrated Water Resources Management principles and within the Framework of the 1995 Mekong Agreement. The specific aim is to make adaptation a permanent part of development plans and planning process, and to have tools as well as institutional and specialist capacity in place to implement them. The CCAI focuses on the following outcomes: (1) climate change impact and vulnerability assessment, adaptation planning and implementation in priority locations within the LMB; (2) building knowledge and capacity at different levels (institutional, technical and managerial capacity); (3) regional adaptation strategy supporting national frameworks; (4) regional partnership and collaboration. A number of CCAI approaches are designed specifically to ensure the sustainability of its outcomes with the objective of guiding climate change adaptation planning and implementation through improved strategies and plans at various levels and priority locations throughout the LMB.

A number of basin wide studies are planned as part of the work of CCAI (either directly or through support to other programmes) during the period 2013-2015 including the effects of climate change on flood risk, on drought management, on ecosystems and on food security. CCAI coordinates with other MRC programmes and initiatives in the region and has prepared Concept Notes and supporting technical background and consulted on the approach and issues in MRC member countries.

In 2013 CCAI will prepare a key output ‘Status of Climate Change and Adaptation in the Mekong Basin’. This status report must distill the current state of knowledge and will form an important building block for completion of the basin studies and preparation of a Mekong Adaptation Strategy by 2015. This report will include work being completed with GIZ support on a literature review of published knowledge as well as early assessments carried out by CCAI. The status report needs to provide a clear analysis of the best current knowledge of expected climate impacts and issues for the Mekong Basin.

In planning the CCAI, the production of a regional report on the Status of Climate Change and Adaptation in the Mekong Basin was intended to fill a niche and gap left by other researchers working only with national issues (e.g. National Communications or Adaptation Plans) or at a global scale (IPCC). Along with the formation of a panel of riparian experts to guide the Status Reporting Process, the report is a key output of the CCAI aimed to galvanize research at a basin level linking the individual national efforts.

An important component of the Climate Change Status Report will be to provide information on trends in the past climate. For this a detailed and homogenous climate data set is required. Such a data set can be used also for other purposes like modeling and related assessments. Due to the conflicts affecting the nations of the Lower Mekong Basin in the second half of the 20th century, meteorological records have many gaps or discontinuities that affect a long term analysis of the changing climate.

The need of such a climate trend analysis over the past is clear. There is still a lot of uncertainty on the direction of climate change in terms of magnitude as well as spatial distribution. Not only the annual trends, but even more importantly are shifts in seasonality and changes of extremes. So far, no harmonized climate database covering the entire Lower Mekong Basin exists.

Development of reanalysis datasets has been rapidly increases over the last years. The need of these datasets has mobilized a lot of researchers, and many products can be freely obtained over the Internet. Important to realize is that the core of these datasets are still observations. In cases where data are lacking, in time or space, intelligent data assimilation techniques, based on models and/or geostatistical analysis, are used to fill those gaps.

Key strengths of reanalysis data are (NCAR, 2013):

- Global data sets, consistent spatial and temporal resolution over three or more decades, hundreds of variables available; model resolution and biases have steadily improved.
- Reanalyses incorporate millions of observations into a stable data assimilation system that would be nearly impossible for an individual to collect and analyze separately, enabling a number of climate processes to be studied.

Despite these strengths some known weaknesses of reanalysis data should be considered (NCAR, 2013):

- Reanalysis data sets should not be equated with "observations" or "reality".
- The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output.
- Observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered.

This report describes the results of a study on the assessment of available long term global meteorological datasets ('reanalysis data') and analysis of trends apparent as compared with shorter term and sparse observed records.

2 Objective

Global and local concerns about climate change have motivated the Mekong River Commission to better understand how people in the basin can adapt to climate change. The MRC's Climate Change and Adaption initiative (CCAI) is a response to a call from MRC Member States for a collaborative regional adaptation initiative to climate change and its challenges. The goal of the CCAI is to promote “an environmentally sound, economically prosperous and socially just Mekong River Basin, responsive and adapting to the challenges induced by climate change.”

An important objective of the CCAI is developing background material based on various studies that will provide an overview of impact and adaptation options for the LMB. The CCAI is aiming at presenting its findings in a comprehensive report called “Status of Climate Change and Adaptation in the Lower Mekong Basin”.

Meteorological data based on observations are in most cases incomplete and lack continues and error-free records. Also, spatial resolutions are often not in sufficient detail and spatial coverage is often patchy. Therefore, over the last years, climatologist have put efforts to develop consistent climate databases by using all available monitoring data in a systematic way using complex assimilation schemes.

The number of reanalysis data products is increasing rapidly. Some of these products are strong in one region, while other performs better in other regions. A first assessment of which products might perform well for the Mekong will be based on literature review. Based on this up to three products will be selected and will be compared to observational data.

Although reanalysis products are based on observations, difference might occur. The main reason is that not all observational data is forwarded to WMO and therefore not included in the reanalysis datasets. Correction factors will therefore be applied to the reanalysis data.

In general, reanalysis products with a high spatial resolution have a low temporal resolution and vice versa. Based on proven interpolation techniques it is possible to effectively combine these sets of reanalysis data, which will result in high spatial as well as high temporal resolution. This study aims at producing a final product that will be daily and with a spatial resolution of 0.25 x 0.25 degrees (about 25x25 km^2). The following parameters will be included: precipitation, mean temperature, minimum temperature and maximum temperature.

A trend analysis will be undertaken focusing on the period 1980-2010, as in this period most reliable data will be included in the reanalysis datasets. Also, a trend analysis of the period

1900-2010 will be undertaken. These trends will be based on the 15 sub-areas as defined by BDP and will encompass the following parameters: precipitation and mean temperature. The spatial resolution will be annual trends as well as monthly shifts.

In summary the overall objectives of this work are:

- Evaluate global gridded climate data products
- To develop a baseline climate database.
- To undertake a preliminary trend analysis and extreme evaluation based on the developed baseline climate database.

This report starts with describing the existing meteorological data within and outside the Mekong Basin. In Chapter 4 selection of the best dataset will be discussed, and in the following Chapter the development of a based climate dataset is explained. Finally, Chapter 6 describes the climatic trends that occurred in the Mekong Basin over the last 30 and 100 years.

3 Meteorological data

3.1 Introduction

Different sources of meteorological data for the two main climatic parameters (precipitation and air temperature) can be found. Air temperature products are based on in situ measured observations and/or climatic models. Currently no reliable remote sensing products are available to estimate near surface air temperature. In general three groups of products can be distinguished to obtain air temperature data:

- Records of in situ observations
- Gridded products based on interpolation of in situ observed data
- Gridded reanalysis datasets

Understanding the spatial and temporal variability of precipitation in tropical areas remains a key challenge. Point measurements are often not sufficient to capture the strong gradients in the multiple local factors that determine the distribution of precipitation. Remote sensing data is currently providing a new venue for a better quantification of rainfall patterns. Rainfall satellite products are being continuously improved and increasing amounts of remote sensing data are becoming available for indirect indicators for the spatial distribution of precipitation. Four groups of precipitation products can be distinguished:

- Records of in situ observations
- Gridded products based on interpolation of in situ rain gauge data (e.g. APHRODITE, GPCC, CRU)
- Gridded satellite products based on the merging of different remote-sensing and ground-control data (e.g. TRMM, GPCP)
- Gridded reanalysis products (e.g. ERA (Interim/40/15/20CM))

3.2 Meteorological ground observations

3.2.1 Overview observations

Within the LMB meteorological ground observations have been done for over more than a century. However within the LMB reliable precipitation records are consistent for the period 1980-2005. Some of the stations have longer records. The longest records available within the MRC go back until 1950. Based on this it was decided to make a consistent database for a period of 30 years, spanning 1981 until 2010. As the reanalysis products are only available for the 'modern era' (from 1979 onwards), the 1981-2010 period covers the major part of these records too. The MRC precipitation records for the LMB are complemented with temperature (daily mean, maximum and minimum temperature) and precipitation records available in the World Meteorological Organization (WMO)'s Global Summary of the Day (GSOD) database. A consistent database with daily mean, maximum, minimum temperature and daily precipitation sum is created for the entire Mekong river basin, which can be used for comparison with gridded datasets and for bias-correction of gridded datasets.

3.2.2 Quality check and selection of meteorological ground station data

The raw ground station data are subjected to a thorough quality check to filter for wrong data and remove records that cover a very short period or cover only a small part of a year. This is done to ensure a consistent and reliable database for further analysis. The initial database with raw data from GSOD and MRC contains (Figure 1):

- Records of 163 stations for air temperature in the Mekong basin countries
- Records of 386 stations for precipitation in the Mekong basin countries

The precipitation data consists of daily records (Figure 2). These records are aggregated into annual precipitation sums (Figure 3). A first filtering rule is applied for the number years included in the station's record. The recorded number of years should at least cover 10 years out of the 1981-2010 30 years period. Years without observations (NA) or only 0 mm observed are not counted as a recorded year. In Figure 3 the number of recorded years is highlighted green when 10 years or more are included in the record. When less than ten years are recorded, the number of recorded years is highlighted in red. These stations are excluded from later analysis.

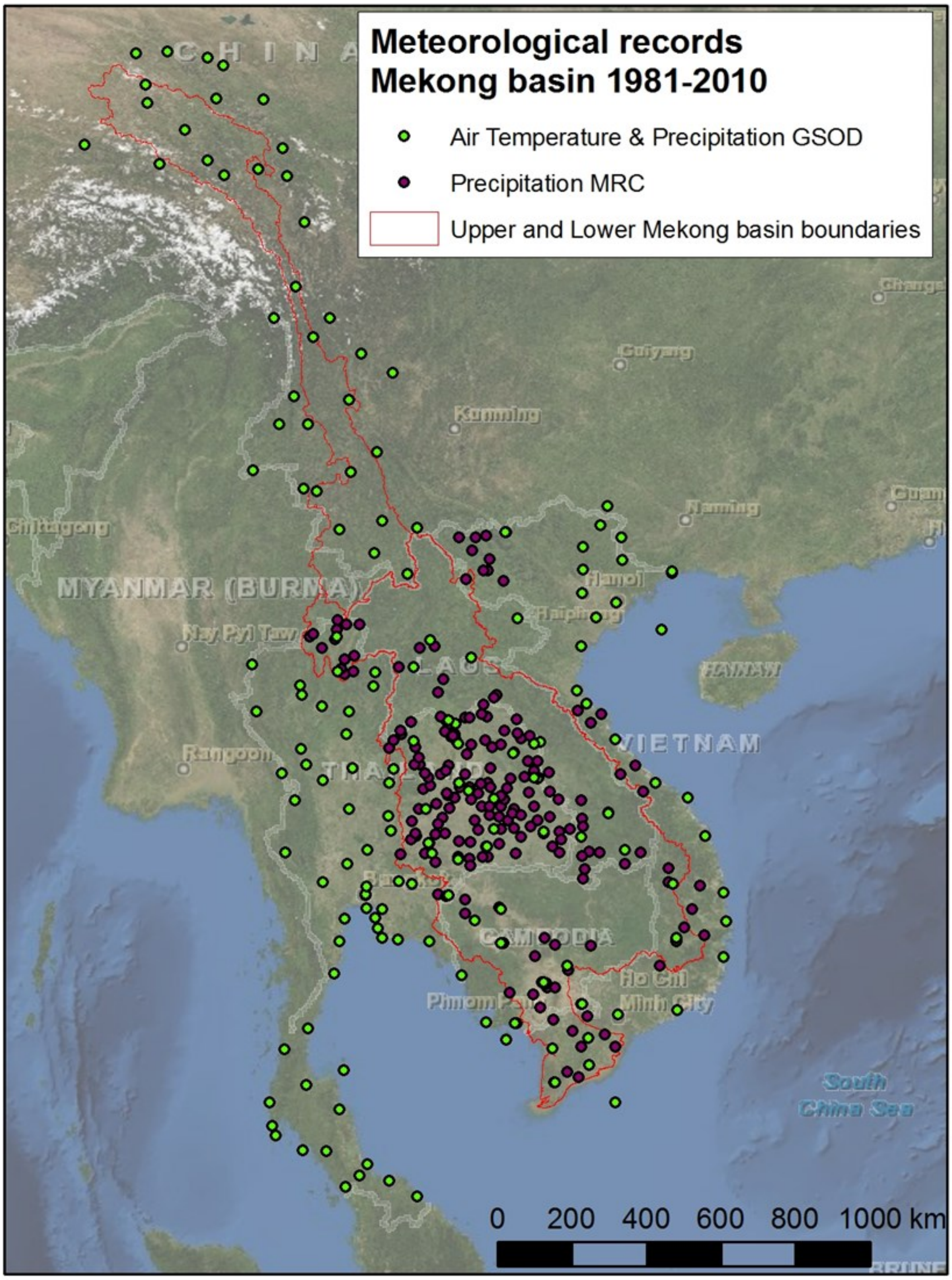

Figure 1. Meteorological station locations in the Mekong river basin with consistent records for 1981-2000.

				STN_IDS -->											
DATE	YEAR	MONTH	DAY	0	1	2	3	4	5	6	7	8	9	10	11
01/01/1981	1981	1	1	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/02/1981	1981	1	2	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/03/1981	1981	1	3	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/04/1981	1981	1	4	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/05/1981	1981	1	5	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/06/1981	1981	1	6	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/07/1981	1981	1	7	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/08/1981	1981	1	8	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/09/1981	1981	1	9	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/10/1981	1981	1	10	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/11/1981	1981	1	11	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/12/1981	1981	1	12	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/13/1981	1981	1	13	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/14/1981	1981	1	14	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/15/1981	1981	1	15	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/16/1981	1981	1	16	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/17/1981	1981	1	17	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/18/1981	1981	1	18	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/19/1981	1981	1	19	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/20/1981	1981	1	20	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/21/1981	1981	1	21	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/22/1981	1981	1	22	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/23/1981	1981	1	23	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/24/1981	1981	1	24	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/25/1981	1981	1	25	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/26/1981	1981	1	26	1.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/27/1981	1981	1	27	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/28/1981	1981	1	28	0.0	1.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/29/1981	1981	1	29	3.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/30/1981	1981	1	30	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
01/31/1981	1981	1	31	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	0.0
02/01/1981	1981	2	1	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	0.0	0.0	NA
02/02/1981	1981	2	2	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	2.0	0.0	0.0
02/03/1981	1981	2	3	0.0	0.0	NA	NA	0.0	0.0	0.0	NA	0.0	11.0	0.0	0.0

Figure 2: First rows and columns of raw daily precipitation database.

Based on the daily records, the maximum and minimum observations of the entire record for each station are displayed. For incomplete records, the annual precipitation sum is interpolated by complementing the recorded precipitation sum with the average daily precipitation for missing days. Daily maximum values larger than 500 mm are flagged with a red pin and checked for plausibility. If the value turns out to be unplausible, the entry is removed (e.g. set to NA) from the daily dataset. Daily minimum values below 0 mm are also flagged with a red bullet, and subsequently removed in the daily dataset.

For the average annual precipitation sums a similar approach is applied. Average annual precipitation sums smaller than 1000 mm or larger than 3000 mm are flagged with a red pin and checked for plausibility. For each year, the annual precipitation sum is compared to the average annual precipitation sum. When the annual precipitation sum is double or more of the average annual precipitation, or half or less of the average annual precipitation, the record is highlighted red and checked for plausibility.

Furthermore, individual years are checked for completeness (Figure 4). Years that are covered for less than 50% by observations are not included in further analysis. A typical example of this procedure is visualized in Figure 3, the year 1999 is characterized by low precipitation sums coinciding with lower record completeness for the majority of stations (Figure 4).

	STN_IDS -->						
	0	**1**	**2**	**3**	**4**	**5**	**6**
1981	1326	1926	#N/A	#N/A	1109	1212	992
1982	1062	1431	#N/A	0	1049	866	947
1983	1058	1710	#N/A	#N/A	842	1263	1126
1984	1395	1548	#N/A	0	1041	834	846
1985	1339	1873	#N/A	2336	1204	1965	840
1986	1045	1354	0	#N/A	742	955	1010
1987	1113	1275	0	#N/A	889	1140	967
1988	1282	1662	1539	1341	1340	1384	1051
1989	1273	1681	1144	1518	676	1217	1024
1990	1325	1594	1236	1223	1098	1170	1171
1991	1289	1419	989	1091	1102	897	710
1992	1238	1524	783	1250	979	1039	1296
1993	1378	1322	787	546	836	926	944
1994	3598	2077	1486	#N/A	1512	2193	2066
1995	1378	1702	1354	2084	1030	1214	980
1996	1275	1373	1041	778	1185	1273	1201
1997	1090	1548	1055	1070	890	914	739
1998	959	1711	1159	1217	726	780	924
1999	213	126	177	61	197	105	111
2000	1143	996	582	914	892	849	806
2001	970	1473	904	1087	623	915	709
2002	1185	1361	1082	1012	967	1549	1115
2003	1137	1452	1093	1187	1019	994	945
2004	1268	1855	1160	1671	1107	1239	861
2005	1673	1718	1658	1927	1496	1475	1192
2006	1593	2088	1397	1528	1107	1585	1535
2007	1248	2044	1224	1290	1307	1175	1166
2008	1594	1836	1241	1926	1213	1217	1098
2009	877	1684	921	1144	1682	1175	1024
2010	1385	1882	1243	1740	1322	1224	1054
No. of years	30	30	23	23	30	30	30
Daily maximum	241	158	134	500	312	384	270
Daily minimum	0	0	0	0	0	0	0
Average annual sum	1290	1575	1010	1198	1039	1158	1015
Max annual sum	3598	2088	1658	2336	1682	2193	2066
Min annual sum	213	126	0	0	197	105	111

Figure 3: Part of annual aggregated precipitation data (top) and data statistics (bottom). Filtered highlighting of cells is active.

Completeness of record per year (%)								
	STN_IDS -->							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1981	100	99	0	0	95	99	100	0
1982	90	100	0	1	80	100	100	0
1983	100	100	0	0	95	100	99	0
1984	100	100	0	0	96	100	100	0
1985	100	100	0	1	92	100	98	1
1986	99	100	0	0	99	99	99	0
1987	100	100	1	0	100	100	100	1
1988	100	100	81	70	100	100	100	81
1989	100	100	100	100	94	100	100	100
1990	100	100	100	90	100	100	100	100
1991	99	99	99	98	98	100	99	99
1992	100	100	100	99	99	100	100	100
1993	100	100	100	41	100	100	100	100
1994	100	100	100	0	100	100	100	100
1995	100	100	99	82	99	100	100	99
1996	100	100	100	59	100	100	100	100
1997	100	100	100	30	100	100	100	100
1998	100	100	100	78	100	100	100	100
1999	75	72	76	61	67	69	81	79
2000	97	96	95	90	93	94	96	96
2001	95	94	94	93	94	90	96	95
2002	98	98	96	97	97	96	97	98
2003	100	100	100	100	100	100	100	100
2004	100	100	100	100	100	100	100	100
2005	99	100	85	85	85	99	99	85
2006	99	100	99	99	99	99	100	99
2007	99	99	99	99	98	99	100	99
2008	99	98	99	100	100	99	99	100
2009	99	99	99	100	100	97	99	99
2010	100	99	99	99	100	98	99	99

Figure 4: Completeness of ground station records per year (%). Years with less than 50% completeness are highlighted red.

As an example, the procedure is explained for one station; Kam Paeng Phet in Thailand, which originates from the GSOD database. For this station, the annual precipitation sums, record completeness and data statistics are displayed in Figure 5. The station has a very incomplete record for 1981-1992, meaning these years will be discarded from the record in any further analysis. The incompleteness of the record for those years partly explains the anomalous annual precipitation sums recorded in a part of this period. From 1992 onwards the reported values are plausible, with the exception of 1999.

1981	#N/A
1982	19710
1983	0
1984	0
1985	33
1986	0
1987	0
1988	#N/A
1989	0
1990	2717
1991	1953
1992	0
1993	890
1994	1578
1995	1374
1996	1512
1997	897
1998	1172
1999	255
2000	1140
2001	1339
2002	1202
2003	1362
2004	1431
2005	1228
2006	1357
2007	1510
2008	1764
2009	1227
2010	1710

1981	0
1982	0
1983	1
1984	0
1985	3
1986	0
1987	1
1988	0
1989	1
1990	5
1991	10
1992	0
1993	58
1994	100
1995	99
1996	100
1997	100
1998	100
1999	81
2000	95
2001	87
2002	97
2003	100
2004	100
2005	85
2006	99
2007	99
2008	100
2009	99
2010	99

No. of years	22
Daily maximum	127
Daily minimum	0
Average annual sum	1691
Max annual sum	19710
Min annual sum	0

Figure 5: Station data for Kam Paeng Phet station in Thailand. Left column: annual precipitation sums. Middle column: completeness of record (%). Right column: data statistics.

Similar quality checks and filters have been applied to the air temperature records. The filter criteria for minimum completeness in terms of number of years and number of days per year are the same as for precipitation. The maximum and minimum entries are reported to find suspicious values. For example, in Figure 6 the minimum value found in the record of the station with station ID 19 is -17.7 °C. In the context of the other values in this record, this must be an erroneous entry, which can be traced in the dataset and removed. The annual average temperatures are also filtered to find suspicious values. Values 3 °C higher or lower than the 30-year average are highlighted red and checked for plausibility.

	13	14	15	16	17	18	19
1981	26.8	26.1	26.5	#DIV/0!	25.6	27.7	27.5
1982	26.8	25.9	26.8	#DIV/0!	25.1	28.0	28.0
1983	26.9	26.3	26.8	#DIV/0!	25.7	27.5	29.2
1984	26.7	25.8	26.5	#DIV/0!	25.3	26.9	27.2
1985	27.0	26.2	26.5	27.0	25.8	27.4	27.4
1986	26.9	26.0	26.6	26.1	25.6	27.2	27.3
1987	27.2	26.4	27.0	24.1	25.8	27.6	27.7
1988	27.0	26.2	26.2	#DIV/0!	25.6	27.3	27.1
1989	26.5	25.8	25.8	27.2	25.4	27.5	27.3
1990	26.7	26.1	25.8	26.0	25.7	27.7	27.3
1991	27.1	26.6	26.4	26.2	26.0	28.0	27.7
1992	26.6	26.2	26.0	23.3	25.0	27.4	27.0
1993	26.7	26.0	25.8	#DIV/0!	25.5	27.8	27.4
1994	26.6	26.3	26.2	#DIV/0!	25.8	27.5	27.7
1995	26.9	26.3	26.3	#DIV/0!	25.9	27.9	27.8
1996	26.3	25.8	25.9	#DIV/0!	25.6	27.3	26.8
1997	26.9	26.3	26.1	#DIV/0!	25.6	28.0	27.5
1998	27.8	27.3	27.2	#DIV/0!	26.7	29.0	28.8
1999	26.5	26.0	26.2	#DIV/0!	25.8	27.6	27.0
2000	26.5	25.9	26.2	#DIV/0!	25.7	27.6	27.1
2001	#DIV/0!	26.5	26.6	26.4	25.9	27.6	27.3
2002	#DIV/0!	26.4	26.4	27.2	26.0	27.8	27.2
2003	#DIV/0!	26.5	26.6	27.1	25.7	27.6	27.3
2004	#DIV/0!	26.0	26.0	26.8	25.9	27.7	27.5
2005	#DIV/0!	26.5	26.7	27.4	26.4	28.1	27.7
2006	#DIV/0!	26.6	26.6	27.1	26.1	27.6	27.1
2007	#DIV/0!	26.4	26.4	26.9	26.0	27.6	27.0
2008	#DIV/0!	25.5	25.5	26.5	25.7	27.3	26.8
2009	#DIV/0!	26.6	26.6	26.9	25.9	27.5	26.9
2010	#DIV/0!	27.1	27.0	27.8	26.9	28.6	28.0
No. of years	20	30	30	17	30	30	30
Daily maximum	35.6	35.3	36.6	33.2	33.6	36.3	36.2
Daily minimum	12.2	11.6	12.8	17.6	13.3	15.7	-17.7
Average annual	26.8	26.3	26.4	26.5	25.8	27.7	27.5
Max annual sum	27.8	27.3	27.2	27.8	26.9	29.0	29.2
Min annual sum	26.3	25.5	25.5	23.3	25.0	26.9	26.8

Figure 6: Part of annual averaged temperature data (top) and data statistics (bottom). Filtered highlighting of cells is active.

3.2.3 Final cleared observation database

Based on these quality checks a total of 119 temperature stations and 303 precipitation stations are remaining in the updated dataset Table 1. The station locations of the updated meteorological database are displayed in Figure 7.

Table 1: Number of stations for the uncleared and cleared database specified per country and per data source.

		Uncleared database			Cleared database		
Variable	Country	Stations	GSOD	MRC	Stations	GSOD	MRC
Temperature	Cambodia	8	8	-	1	1	-
	China	40	40	-	25	25	-
	Laos	7	7	-	1	1	-
	Thailand	77	77	-	68	68	-
	Vietnam	31	31	-	24	24	-
	Total	163	163	-	119	119	-
Precipitation	Cambodia	31	8	23	16	-	16
	China	40	40	-	25	25	-
	Laos	35	7	28	28	-	28
	Thailand	211	77	134	190	66	124
	Vietnam	69	31	38	44	6	38
	Total	386	163	223	303	97	206

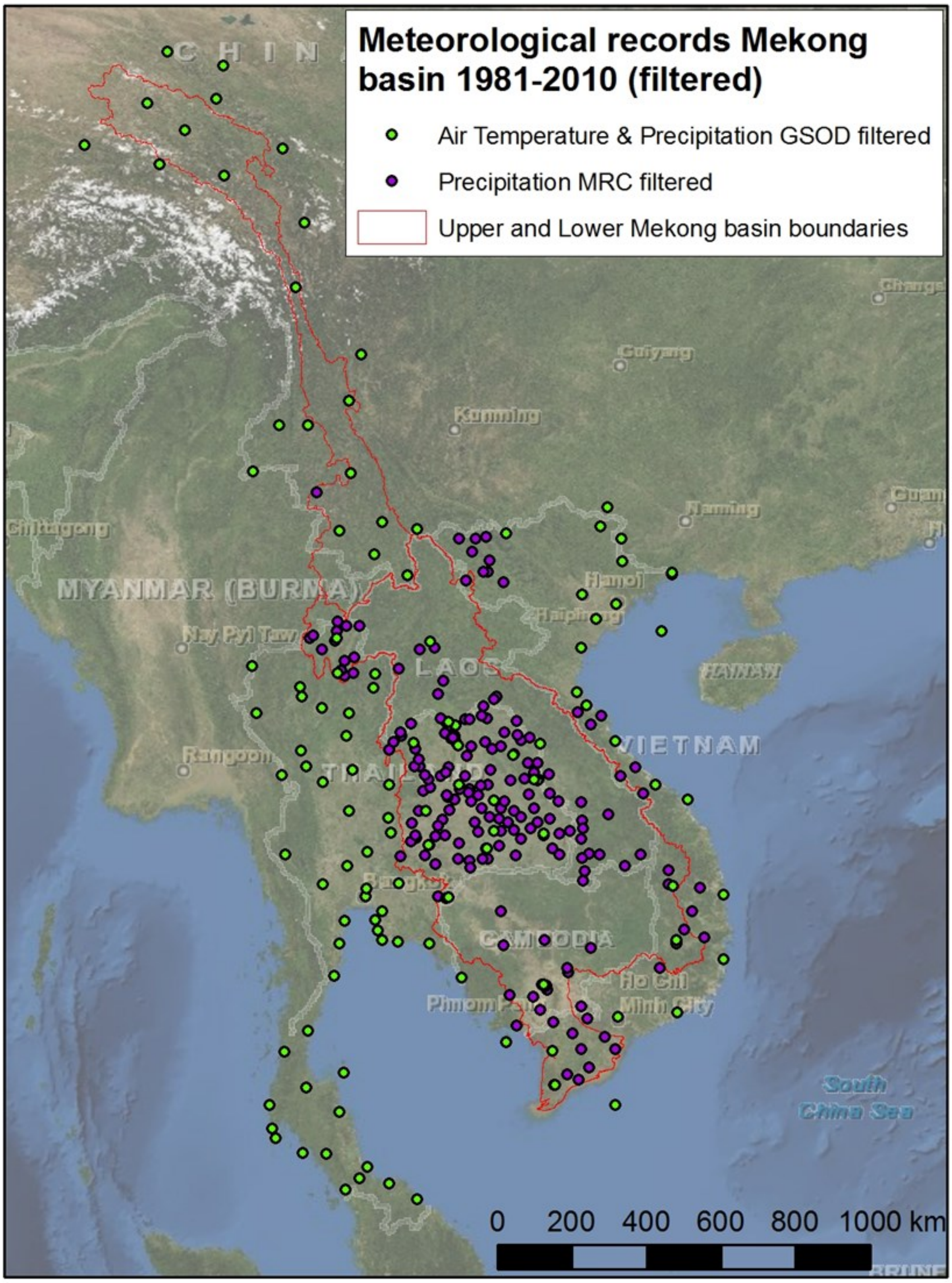

Figure 7: Locations of meteorological stations used in meteorological database after quality checks and filtering.

The station data can be interpolated to generate maps covering the spatial domain of the basin. Many spatial interpolation techniques can be used and based on the applied technique outcome can be very different [*Droogers and Miranzadeh*, 2001]. It is also known that especially for precipitation spatial interpolation can reduce rainfall extremes substantially and only Thiessen Polygons should be used. A typical example of using this method to produce spatially average air temperature and the average annual precipitation sums are displayed in **Figure 8**. Other interpolation techniques will provide different results. The maps plotted here serve only as an example to demonstrate that in order to represent the basin-wide precipitation and temperature reanalysis techniques are needed. This will be discussed in the following Chapters.

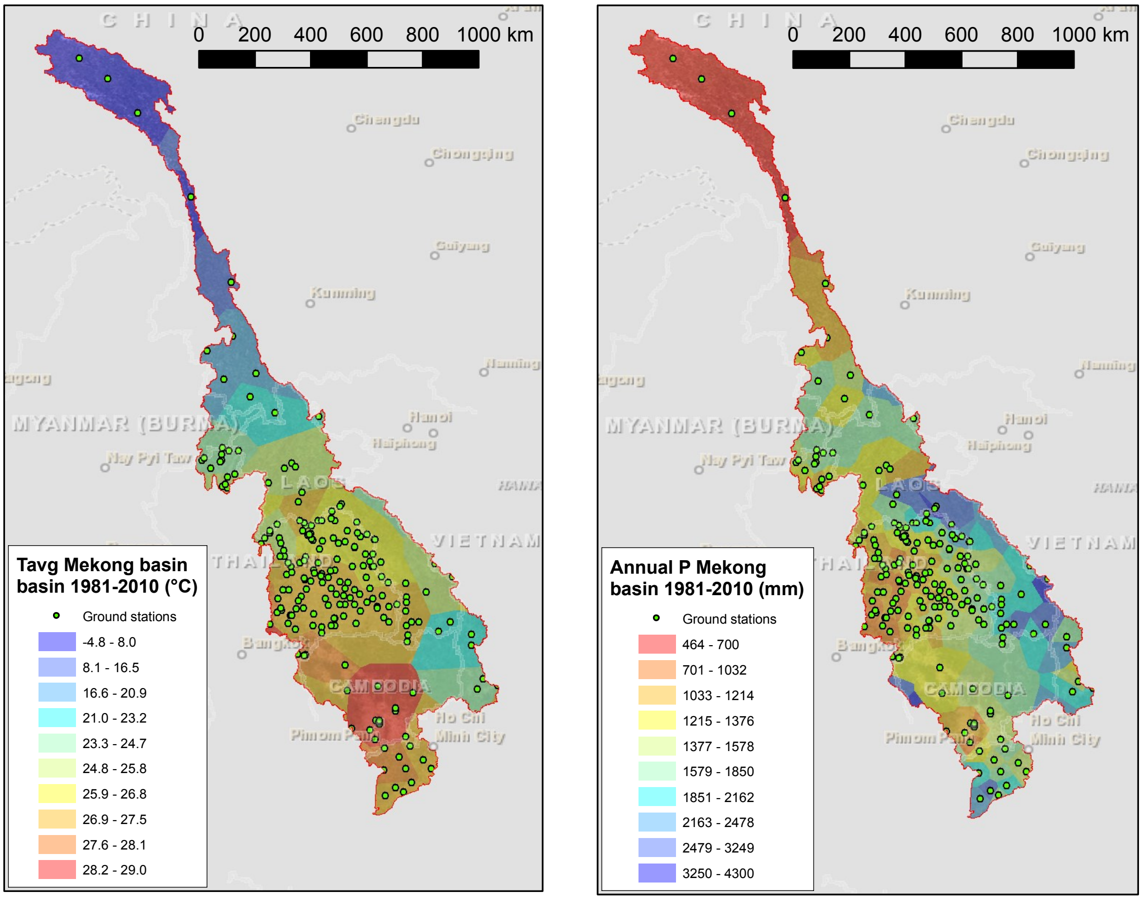

Figure 8: Average air temperature (left panel) and average annual precipitation sum (right panel) in the Mekong basin for 1981-2010 based on interpolated ground station data using the Thiessen Polygons approach.

3.3 Gridded meteorological datasets

Climatologists have created numerous gridded datasets, based on observations. These datasets were developed to support climate research and have therefore many parameters at many elevations less interesting for water resources application. However, since a couple of products include precipitation and temperature at ground level, they can be used to overcome data gaps in observations.

A distinction in two groups can be made regarding gridded datasets for temperature and precipitation: (i) datasets based created using advanced geo-statistical interpolation techniques, and (ii) datasets based on climate models (often referred to as reanalysis products). Obviously, both approaches rely completely on the availability and quality of the observations used. In this chapter an overview of the available gridded datasets is provided, and strengths and weaknesses of the different products are highlighted and compared. A selection of products to be used is made based on well-defined selection criteria. Only datasets covering the complete Mekong basin are considered in this analysis. A tabular overview of all evaluated datasets and their key characteristics is provided in **Table 2**.

Table 2: Gridded meteorological data products available in the Mekong basin.

Dataset	Type	Coverage	Resolution	Frequency	Period	Parameters	Institute	Freely available
(1) CRU TS 3.10.01	Geo-statistical	Global	~ 50 km (0.5 degree)	Monthly	1901-2009	cloud cover, DTR, frost days, precipitation, daily minimum temperature, daily mean temperature, daily maximum temperature, vapour pressure,wet days, ETpot	Climate Research Unit at the University of East Anglia	YES
(2) APHRODITE	Geo-statistical	Asia	~ 25 km (0.25 degree)	Daily	1961 - 2007	Prec, Tavg	Meteorological Research Institute of Japan	YES
(3) GPCC	Geo-statistical	Global	~ 50 km (0.5 degree)	Monthly	1901-2007	Precipitation	Global Precipitation Climatology Centre	YES
(4) GPCP	Geo-statistical	Global	~ 250 km (2.5 degrees)	Monthly	1979 - present	Precipitation	GEWEX	YES
(5) CPC-UGBAGDP	Geo-statistical	Global	~ 50 km (0.5 degree)	Daily	1979-present	Prec	CPC	YES
(6) DEL	Geo-statistical	Global	~ 50 km (0.5 degree)	monthly	1900-2008	Prec, Tair	CCR Univ of Delaware	YES
(7) NCEP-NCAR	Model	Global	~209 km (T62 grid)	6 hourly	1948 - present	Prec, Tmax, Tmin, Tavg (+ many more)	NCEP/NCAR	YES
(8) NCEP-DOE	Model	Global	~209 km (T62 grid)	6 hourly	1948 - present	Prec, Tmax, Tmin, Tavg (+ many more)	NCEP/NCAR	YES
(9) NCEP-CFSR	Model	Global	~ 50 km (0.5 degree)	1 hourly, 6 hourly, monthly	1979-2010	Prec, Tmax, Tmin, Tavg (+ many more)	NCEP	YES
(10) ERA 15	Model	Global	~ 250 km (2.5 degrees) ~ 120 km (N80 grid)	monthly	1979 - 1994	Prec, Tmax, Tmin, Tavg (+ many more)	ECMWF	YES / NO (120 km)
(11) ERA 40	Model	Global	~ 250 km (2.5 degrees) ~ 120 km (N80 grid)	6 hourly	1957 - 2002	Prec, Tmax, Tmin, Tavg (+ many more)	ECMWF	YES / NO (120 km)

(12) ERA Interim	Model	Global	~ 70 km (N128 grid)	6 hourly	1979 - present	Prec, Tmax, Tmin, Tavg (+ many more)	ECMWF	YES
(13) NASA MERRA	Model	Global	~ 70 km (0.5 x 0.67 degrees))	3 hourly	1979 - present	Prec, Tmax, Tmin, Tavg (+ many more)	NASA	YES
(14) Princeton	Mixture	Global	~ 50 km (0.5 degree)	3 hourly	1948 - 2008	Prec, Tmax, Tmin, Tavg (+ many more)	Princeton University	YES
(15) ERA 20 CM	Mixture	Global	~ 120 km (N80 grid)	3 hourly	1900-2009	Prec, Tavg	ECMWF	YES

3.3.1 Gridded datasets based on geo-statistical analysis

(1) CRU TS 3.10.01

The CRU dataset can be considered as the oldest and most widely-used gridded meteorological dataset. The first version of the CRU dataset was released in 2000 by the Climate Research Unit at the University of East Anglia [*New et al.*, 1999, 2000], while the latest version was released in 2013 [*Harris et al.*, 2013]. The CRU Global Climate Dataset, consists of a multi-variate 0.5º by 0.5º resolution mean monthly climatology for global land areas, excluding Antarctica. Together with a mean climatology, which is strictly constrained to the period 1961-1990, there is a monthly time series at the same resolution for the period 1901-2000. The mean 1961-1990 climatology comprises a suite of eleven surface variables, including precipitation, mean, maximum and minimum temperature. Fields of monthly climate anomalies, relative to the 1961–90 mean, were interpolated from surface climate data. The anomaly grids were then combined with a 1961–90 mean monthly climatology to arrive at grids of monthly climate over the 1901-2009 period.

(2) APHRODITE

The “Asian Precipitation—Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE)” dataset [*Yatagai et al.*, 2012] is constructed by interpolation of rain-gauge data to create at 57-year daily precipitation dataset. APHRODITE’s daily gridded precipitation is the only long-term (1951 onward) continental-scale daily product that contains a dense network of daily rain-gauge data for Asia including the Himalayas, South and Southeast Asia and mountainous areas in the Middle East. The number of valid stations was between 5000 and 12,000, representing 2.3 to 4.5 times the data available through the Global Telecommunication System network, which were used for most daily grid precipitation products. The product contributes to studies such as the diagnosis of climate changes, evaluation of Asian water resources, statistical downscaling, forecast improvements, and verification of numerical model simulation and satellite precipitation estimates.

(3) GPCP

The Global Precipitation Climatology Project (GPCP) released the version 1 Combined Precipitation Dataset in 1997 [*Huffman et al.*, 1997], while version 2 was released in 2003 [*Adler et al.*, 2003]. The product is a global, monthly precipitation dataset covering the period 1979 through 2003. The primary product in the dataset is a merged analysis incorporating precipitation estimates from low-orbit-satellite microwave data, geosynchronous-orbit-satellite infrared data, and rain gauge observations. The dataset is extended back into the premicrowave era (before mid-1987) by using infrared-only observations calibrated to the microwave-based analysis of the later years. The combined satellite-based product is adjusted by the rain gauge analysis.

(4) GPCC

The precipitation dataset developed by the Global Precipitation Climatology Centre (GPCC) was firstly constructed in 1989 and the latest version was published in 2013 [*Schneider et al.*, 2013].. The GPCC has calculated a precipitation climatology for the global land areas for the target period 1951– 2000 by objective analysis of climatological normals of about 67,200 rain gauge stations from its database. GPCC actually published four gridded products, i.e. the Climatology (CLIM) V2011, the Full Data Reanalysis (FD) V6, the Monitoring Product (MP) V4, and the First Guess Product (FG); all publicly available. Depending on the product, four (0.25°, 0.5°, 1.0°, 2.5° for CLIM), three (0.5°, 1.0°, 2.5°, for FD), two (1.0°, 2.5° for MP) or one (1.0° for FG) resolution is provided. The FG product is a global gridded product of the monthly precipitation, provided on 1.0° resolution, based on interpolated precipitation anomalies from more than 6000 stations worldwide and is available in near real time. The MP is available within two months after the observation period at 2.5° and 1.0° resolution. This is the oldest GPCC product that went operational in 1986 and has continuously been updated every month since then. Major sample application of the FD product is the verification of reanalysis products like the ERA-Interim reanalysis. It uses the same stations applied to calculate the GPCC Climatology product, i.e. more than 67 200 stations for Version 6. Grid resolutions are 0.5°, 1.0° and 2.5°. The QC is extended by an additional manual control. Upon substantial improvements of the database, a new version of this product is released, which happens approximately every 1–3 yr.

(5) CPC-UGBAGDP

The Unified Gauge-Based Analysis of Global Daily Precipitation (UGBAGDP) dataset has two components: (a) the "retrospective version" which uses 30,000 stations and spans 1979-2005 and (b) the "real-time version" which uses 17,000 stations and spans 2006-present. The daily analysis is constructed on a 0.125° grid over the entire global land areas, and released on a 0.5° grid over the global domain for a period from 1979 [*Xie et al.*, 2007]. This dataset is a predecessor of the APHRODITE dataset (Section 0).

(6) DEL

The University of Delaware has put data together from a large number of stations, both from the GHCN2 (Global Historical Climate Network) and, more extensively, from the archive of Legates & Willmott [*Willmott and Rowe*, 1985]. The result is a monthly climatology of precipitation and air temperature, both at the surface, and a time series, spanning 1900 to 2010, of monthly mean surface air temperatures, and monthly total precipitation. It is land-only in coverage.

3.3.2 Gridded datasets based on models (reanalysis)

The general purpose of conducting reanalyses is to produce multiyear global state-of-the-art gridded representations of atmospheric states, generated by a constant model and a constant data assimilation system. To use the same model and data assimilation over a very long period was the great advance during the 1990s, because gridded datasets available before 1995 had been created in real time by ever-changing models and analysis methods, even by hand analyses prior to about 1965. The hope was that a reanalysis, made after real time, would help in advancing climate studies by eliminating fictitious trends caused by model and data assimilation changes in real time [*Saha et al.*, 2010].

Global and regional atmospheric retrospective analysis models (reanalyses) play a crucial role in today's hydrological and hydrometeorological research. These global atmospheric reanalyses aim at assimilating a large amount of historical observation data to provide a physically consistent basis for the most important hydrological, hydrometeorological, and atmospheric quantities. To bring these various observations into a consistent scheme, computation of the reanalysis models is performed via state-of-the-art data assimilation methods like three- or four dimensional variational data assimilation (3DVAR or 4DVAR) that constrain the observations with physically reasonable time evolution and budget equations. These reanalyses can be used to analyze the global climate system, atmosphere, and land surface processes on large to continental scales and to understand exchange processes between these different regimes. Global atmospheric reanalyses also are often used as forcing data for regional hydrological or hydrometeorological simulations, such as numerical weather predictions and regional climate simulations [*Lorenz and Kunstmann*, 2012].

Development of reanalysis[1] datasets has been rapidly increased over the last years. The need of these datasets has mobilized a lot of researchers, and many products can be freely obtained over the Internet. Important to realize is that the core of these datasets are still

---

[1] Reanalysis a systematic approach to produce data sets for climate monitoring and research. Reanalyses are created via a data assimilation scheme and model(s) which ingest all available observations every 6-12 hours over the period being analyzed. Currently, approximately 7-9 million global observations are ingested at each time step. (NCAR, 2013).

observations. In cases where data are lacking, in time or space, intelligent data assimilation techniques, based on models and geostatistical analysis, are used to fill these gaps.

Key strengths of reanalysis data are (NCAR, 2013):

- Global data sets, consistent spatial and temporal resolution over 3 or more decades, hundreds of variables available; model resolution and biases have steadily improved.
- Reanalyses incorporate millions of observations into a stable data assimilation system that would be nearly impossible for an individual to collect and analyze separately, enabling a number of climate processes to be studied.

Despite these strengths some known weaknesses of reanalysis data should be considered [*NCAR*, 2013]:

- Reanalysis data sets should not be equated with "observations" or "reality".
- The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output.

Observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered.

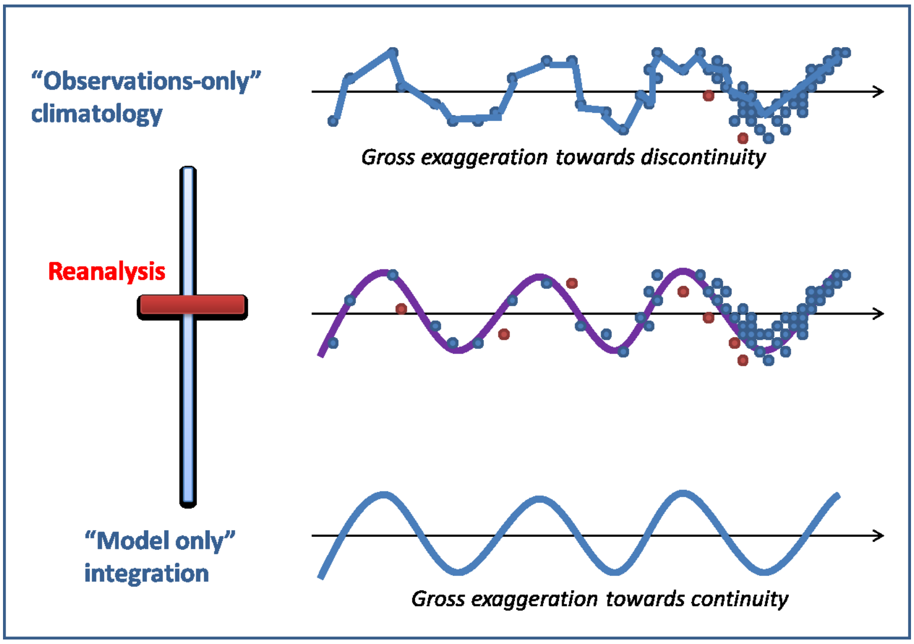

Figure 9: Concept of Reanalysis. Source: Paul Poli, 2012. ECMWF ReAnalysis (ERA) Data assimilation aspects. Presentation MRCS, 12-Jan-2012.

(7) NCEP/NCAR Reanalysis 1

The NCEP/NCAR reanalysis 1 was published in 1996 [*Kalnay et al.*, 1996]. This product is a first generation reanalysis. It uses a frozen global data assimilation system (as of 11 January 1995), which is quite outdated nowadays. Originally planned to span 1957-96 ("40-Year Reanalysis Project"), it was extended back to 1948 and continues to this day. It is used in many publications, making it a useful baseline reference for many computations.

(8) NCEP-DOE Reanalysis 2

NCEP-DOE Reanalysis 2 [*Kanamitsu et al.*, 2002] is an improved version of the NCEP-NCAR Reanalysis 1. The improvements include an updated model, better physical parameterizations and assorted error fixes. However, it is still a first generation product.

(9) NCEP-CFSR

The NCEP Climate Forecast System Reanalysis [*Saha et al.*, 2010] is the third generation successor of the NCEP/NCAR Reanalysis 1 and 2 (Section 0 and 0). Compared to Reanalysis 1 and 2, CFSR has improved routines and higher spatial resolution. The product covers 1979 to 2010.

Key Strengths [*NCAR*, 2013]:

- Superior to previous NCEP reanalyses with respect to: improved model, finer resolution, advanced assimilation schemes, atmosphere-land-ocean-sea ice coupling, assimilates satellite radiances rather than retrievals
- Accounts for changing CO2 and other trace gasses, aerosols, and solar variations
- Approaches the horizontal resolution of regional reanalyses like the NARR and Arctic System Reanalysis

Key Limitations [*NCAR*, 2013]:

- Relatively few evaluations of CFSR have been conducted so the performance is not well-known

(10) ERA 15

The ERA-15 production system generated re-analyses for 15 years (1979-1993) using a special version of their 1995 operational data assimilation system and model. The resulting analyses include full model resolution analyses or reduced resolution analyses and climate and statistics data. ERA-15 is the precursor to ERA-40 and ERA-Interim. It is recommended that the ERA-Interim products be used rather the ERA-15 or ERA-40 [*NCAR*, 2013]. Key Limitations [*NCAR*, 2013]:

- Excessive tropical precipitation.
- Hydrologic budget was not 'closed'.
- Also there was an incorrect southward shift in the ITCZ over Africa in 1987 most likely due to the assimilation and bias correction of satellite data

(11) ERA 40

ERA 40 is a second generation reanalysis [*Uppala et al.*, 2005]. It is the first reanalysis to directly assimilate satellite radiance data (TOVS, SSM/I, ERS and ATOVS). Cloud Motion Winds are also used. The result is better circulation over the tropics and southern hemisphere.

Key Strengths [*NCAR*, 2013]:

- Assimilates satellite radiances directly (TOVS, SSM/I, ERS and ATOVS data).
- Cloud Motion Winds will be used from 1979 onwards.

Key Limitations [*NCAR*, 2013]:

- Tropical moisture (precipitation, total column water vapor) larger than observed from 1991 onward
- Precipitation greatly exceeds evaporation
- Brewer Dobson circulation is too intense; Spurious Arctic temperature trends

(12) ERA Interim

Using a much improved atmospheric model and assimilation system from those used in ERA-40, ERA-Interim represents a third generation reanalysis [*Dee et al.*, 2011]. Several of the inaccuracies exhibited by ERA-40 such as too-strong precipitation over oceans from the early 1990's onwards and a too-strong Brewer-Dobson circulation in the stratosphere, were eliminated or significantly reduced. ERA-Interim now extends back to 1979 and the analysis continues to be extended forward in near-real-time.

Key Strengths [*NCAR*, 2013]:

- Spatially and temporally complete data set of multiple variables at high spatial and temporal resolution
- Improved low-frequency variability (compared to ERA-40)
- Improved stratospheric circulation (compared to ERA-40)

Key Limitations [*NCAR*, 2013]:

- Too intense of a water cycling (precipitation, evaporation) over the oceans
- In the Arctic: positive biases in temperature and humidity below 850hPA compared to radiosondes; does not capture low-level inversions

(13) NASA MERRA

The Modern Era Retrospective-Analysis for Research and Applications (MERRA) [*Rienecker et al.*, 2011] was undertaken by NASA's Global Modeling and Assimilation Office with two primary objectives: to place observations from NASA's Earth Observing System satellites into a climate context and to improve upon the hydrologic cycle represented in earlier generations of reanalyses. MERRA was generated with version 5.2.0 of the Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system (DAS), and covers the modern satellite era from 1979 to the present. Specifically, the GEOS-DAS Version 5 implements Incremental Analysis Updates (IAU) to slowly adjust the model states toward the observed state. MERRA is a 3rd generation reanalysis product [*NCAR*, 2013].

Key Strengths [*NCAR*, 2013]:

- Significant improvement in precipitation and water vapor climatology over older reanalyses
- The IAU procedure in which the analysis correction is applied to the forecast model gradually ameliorates precipitation spin-down during early stages of the forecast, and allows for higher frequency output including selected hourly fields
- Provides vertical integrals and analysis increment fields for the closure of atmospheric budgets

Key Limitations [*NCAR*, 2013]:

- Changes in the observing system strongly affect trends in many fields (as for other reanalyses); for example P-E exhibits spurious increases associated with assimilating radiances from the AMSU starting in 1998 and to a lesser extent, SSM/I in 1987
- Spatial discontinuity in central African moisture fields associated with rawinsonde input
- The assimilation routine is "frozen" and will not be updated for newer satellite instruments, so quality will eventually degrade as current instruments expire

3.3.3 Other products

<u>(14) Princeton Global Meteorological Forcing Dataset for land surface modeling</u>

The Global Meteorological Forcing Dataset for land surface modeling [*Sheffield et al.*, 2006] provides near-surface meteorological data for driving land surface models and other terrestrial modeling systems. The dataset is constructed by combining a suite of global observation-based datasets with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. Known biases in the reanalysis precipitation and near-surface meteorology have been shown to exert an erroneous effect on modeled land surface water and energy budgets and are thus corrected using observation-based datasets of precipitation, air temperature, and radiation.

Corrections are also made to the rain day statistics of the reanalysis precipitation, which have been found to exhibit a spurious wavelike pattern in high-latitude wintertime. Wind-induced under- catch of solid precipitation is removed using the results from the World Meteorological Organization (WMO) Solid Precipitation Measurement Intercomparison. Precipitation is disaggregated in space to 1.0° by statistical downscaling using relationships developed with the Global Precipitation Climatology Project (GPCP) daily product. Disaggregation in time from daily to 3 hourly is accomplished similarly, using the Tropical Rainfall Measuring Mission (TRMM) 3-hourly real-time dataset. Other meteorological variables (downward short- and longwave radiation, specific humidity, surface air pressure, and wind speed) are downscaled in space while accounting for changes in elevation.

The dataset is currently available at 0.5 degree, 3-hourly resolution globally for 1948-2008.

(15) ERA-CLIM reanalysis products

ECMWF is currently developing the next generation of reanalysis products. One of them (ERA-20CM) was recently released. The ERA-20CM is an ensemble of ten model integrations for 1900-2009. The spatial resolution is 125 x 125 km. Sea-surface temperature and sea-ice cover are prescribed by an ensemble of realizations (HadISST2), as recently produced by the Met Office Hadley Centre within ERA-CLIM. Variation in these realizations reflects uncertainties in the available observational sources on which this product is based.

Forcing terms in the model radiation scheme follow CMIP5 recommendations, without variations, i.e. any effect on their uncertainty is neglected. These include solar forcing, greenhouse gases, ozone and aerosols. Both the ocean-surface and radiative forcing incorporate a proper long-term evolution of climate trends in the 20th century, and the occurrence of major events, such as the El Nino-Southern Oscillations and volcanic eruptions. No atmospheric observations were assimilated. For this reason ERA-20CM is not able to represent actual synoptic situations. The ensemble should, however, be able to provide a statistical estimate of the climate. This is indeed confirmed. Overall, the temperature rise over land is in fair agreement with the CRUTEM4 data set. Over the last two decades the warming over land exceeds the warming over sea, which is consistent with models from the Intergovernmental Panel on Climate Change (IPCC), as well with the currently state-of-the-art ECMWF reanalysis (ERA-Interim) [*Peubey et al.*, 2013].

Other products that will be released by ERA in the framework of the ERA-CLIM project are ERA-20C (end 2013), ERA-20CL (end 2013) and ERA-SAT (2015) [*Dee*, 2013]. ERA-20C is a reanalysis of surface pressure variables based on a revised version of the ERA-20CM model and forcings. ERA-20CL is for the land surface only and is forced by ERA-20C. ERA-SAT is a new reanalysis of the satellite era to replace ERA-Interim and will have a 40x40 km spatial resolution.

3.4 Selection of datasets

A homogenous and detailed climate data set is required to provide information on trends in the past climate. This information is an important component of the first Climate Change Status Report to be developed by MRC's CCAI. Besides, a homogenous dataset can be used for other purposes like hydrological modeling and related assessments. Based on selection criteria, a number of datasets is selected and subjected to further analysis and validation to ground station data. As there are two groups of gridded meteorological datasets, a selection of the best products is made for both groups, based on different selection criteria.

To choose the most suitable reanalysis dataset, the following criteria are formulated:

- Based on state-of-the art, yet proven reanalysis techniques
- High spatial resolution
- High temporal resolution
- Good consistency with ground-observations
- Closing water balances[2]
- Suitable for tropical areas like the Mekong basin
- Well documented

To select the most suitable observations-based dataset, similar criteria are formulated, with slight modifications:

- Based on proven techniques
- High spatial resolution
- High temporal resolution
- Large temporal coverage
- Suitable for tropical areas like the Mekong basin
- Well documented

For each of these criteria, a score varying from one to three points is assigned to each of the data products (**Table 4**, **Table 3**). The scores for all selection criteria are summed to calculate a final total score for each data product. The products with the highest scores are selected for further analysis and validation.

For the reanalysis products it is obvious that a third generation reanalysis product should be selected, to ensure that the product is based on state-of-the-art methodologies. On the other hand, the methodologies have to be proven, and the product should be suitable for the climatic characteristics prevailing in the Mekong basin. To quantify the 'state-of-the-art' criterion, three points are assigned to third generation products, two points are assigned to second generation products and one point is assigned to first generation products. For spatial resolution, three points are assigned to products with spatial resolution smaller than 100x100 km. Products with a spatial resolution larger than 200x200 km are assigned one point. Products with a spatial resolution between 100x100 km and 200x200 km are assigned two points. For temporal resolution, one point is assigned to products with monthly resolution and three points are assigned to datasets with daily or higher temporal resolutions. The temporal coverage indicates how large part of the total period (1901-2010), is covered by the data product. This criterion is only applicable to observations-based datasets since the reanalysis products have a similar length in terms of temporal coverage. Products covering

[2] Some gridded data products based on models do not consider a closed water balance, but focus only on a closed energy balance.

the entire period from 1901 until 2010 are assigned three points. Products covering only the modern era (from 1979 onwards), are assigned one point. Products covering a longer period than the modern era, but not the entire period from 1901 until 2010 are assigned two points.

Products are to a lesser or higher degree established in scientific literature. For this criterion a score from one to three points is assigned to each dataset. In several global-scale studies the reanalysis datasets are validated to ground observations and the closing of the water budget is tested. For these criteria scores ranging from one to three are assigned to all datasets. When no data regarding the criterion is available, the score assigned is two points. When weaknesses regarding the criterion are reported in literature, the score assigned is one point. On the other hand, when good performance regarding the criterion is reported, the score assigned is three points. The same methodology is applied regarding the criterion for the suitability in tropical areas. As the gridded data products are based on complex methodologies and have sometimes complex data formats, it is important that the used products have sufficient documentation and are easily accessible. For this criterion, well documented and good accessible products are assigned three points, medium documented and accessible products are assigned two points and poorly documented products and/or poorly accessible datasets are assigned one point.

Table 3: Scores for selection criteria for geo-statistical based products (1=lowest, 3=highest).

Dataset	Type	Parameters	Spatial resolution	Temporal resolution	Temporal coverage	Suitable for tropical areas	Established in scientific literature	Documentation/Accessibility	Score
(1) CRU TS 3.10.01	Geo-statistical	Prec, Tmax, Tmin, Tavg	3	1	3	3	3	3	16
(2) APHRODITE	Geo-statistical	Prec, Tavg	3	3	2	3	3	3	19
(3) GPCC	Geo-statistical	Prec	3	1	2	2	2	3	13
(4) GPCP	Geo-statistical	Prec	1	1	1	2	2	3	10
(5) CPC-UGBAGDP	Geo-statistical	Prec	3	3	1	2	2	2	13
(6) DEL	Geo-statistical	Prec, Tavg	3	1	3	2	2	1	12

Table 4: Scores for selection criteria for model (reanalysis) products (1=lowest, 3=highest).

Dataset	Type	Parameters	State-of-the-art	Spatial resolution	Temporal resolution	Suitable for tropical areas	Established in scientific literature	Consistent with ground observations	Closing water balance	Documentation/Accessibility	Score
(7) NCEP/NCAR	Model	Prec, Tmax, Tmin, Tavg	1	1	3	2	3	2	1	3	**16**
(8) NCEP/DOE	Model	Prec, Tmax, Tmin, Tavg	2	2	3	2	1	2	2	3	**17**
(9) NCEP/CFSR	Model	Prec, Tmax, Tmin, Tavg	3	3	3	2	1	2	2	2	**18**
(10) ERA 15 basic	Model	Prec, Tmax, Tmin, Tavg	1	1	1	3	3	2	1	3	**15**
(10) ERA 15 advanced			1	2	1	3	3	2	1	1	**14**
(11) ERA 40 basic	Model	Prec, Tmax, Tmin, Tavg	2	1	3	3	3	2	2	3	**19**
(11) ERA 40 advanced		Prec, Tmax, Tmin, Tavg	2	2	3	3	3	2	2	1	**18**
(12) ERA Interim	Model	Prec, Tmax, Tmin, Tavg	3	3	3	3	2	3	3	3	**23**
(13) NASA MERRA	Model	Prec, Tmax, Tmin, Tavg	3	3	3	2	2	2	2	2	**19**
(14) Princeton	Mixed	Prec, Tmax, Tmin, Tavg	2	3	3	2	2	3	3	3	**21**
(15) ERA 20 CM	Mixed	Prec, Tavg	3	2	3	3	1	1	2	1	**16**

Based on those scoring tables and evaluations in the previous sections it was concluded that four products should be selected for further analysis.

The first one is the ERA-Interim as it the highest scoring amongst the reanalysis data product. Moreover, it has been proven that the ERA datasets perform very well in resolving the Asian monsoon system, compared to other gridded data products [*Annamalai et al.*, 1999].

APHRODITE has the highest score in the geo-statistical gridded products. Research on the first and second generation reanalysis datasets points out that reanalysis data can have large errors over tropical areas, especially for precipitation [*Trenberth et al.*, 2001, 2007], and interpolation of ground observations often provides more reliable grids. Given the general doubt of usability of reanalysis data (previous paragraph) and reported problems over tropical areas, we also consider geo-statistical data products for the period 1979-2010. Moreover, APHRODITE was developed for Asia specifically.

The Princeton data set has the second highest score amongst the reanalysis products. Although it is not based on a third generation reanalysis product, but on the first generation NCEP-NCAR Reanalysis, it has been corrected using the observations-based CRU, GOCP and TRMM datasets.

Finally, the CRU dataset is the only “pre-modern era” (starting in 1901) datasets based on geostatistical analyses. CRU TS 3.10.01 covers the entire period from 1900 to 2010, has a high score and includes all four desired meteorological variables (mean, maximum, minimum air temperature and precipitation sum). Therefore the CRU TS 3.10.01 dataset is selected to complement the “modern era” dataset.

Summarizing, for the pre-modern era (1900-2010), one dataset has clear advantages over other datasets for this period based on the literature research and is thus selected to conduct a long-term climatic trend analysis:

- CRU TS 3.10.01 (Tavg, Tmin, Tmax, Precipitation): monthly, 50 km

For the modern era, three datasets are selected given their comparative strengths, that will be compared to ground observations to verify their performance over the Mekong basin specifically, for the recent climate (1981-2010):

- ERA-Interim (Tavg, Tmax, Tmin, P): daily, 70 km
- APHRODITE (Tavg, P): daily, 25 km
- Princeton Global Meteorological forcing dataset (Tavg, Tmax, Tmin, P): daily, 50 km

4 Evaluation of data products

4.1 Introduction

The four selected data products that will be used for further analysis over the period are (i) APHRODITE, (ii) ERA-Interim, (iii) Princeton, and (iv) CRU. These four datasets are selected based on various criteria as described in the previous Chapter. The performance of these four products will be scrutinized using the quality controlled and cleaned observations, which will ultimately lead to selecting one of the datasets for bias-correction and trend analysis.

4.2 APHRODITE

The performance of the APHRODITE product is evaluated for the Mekong river basin by comparing the gridded products of average air temperature and precipitation to ground observations at the geographical locations of the ground stations.

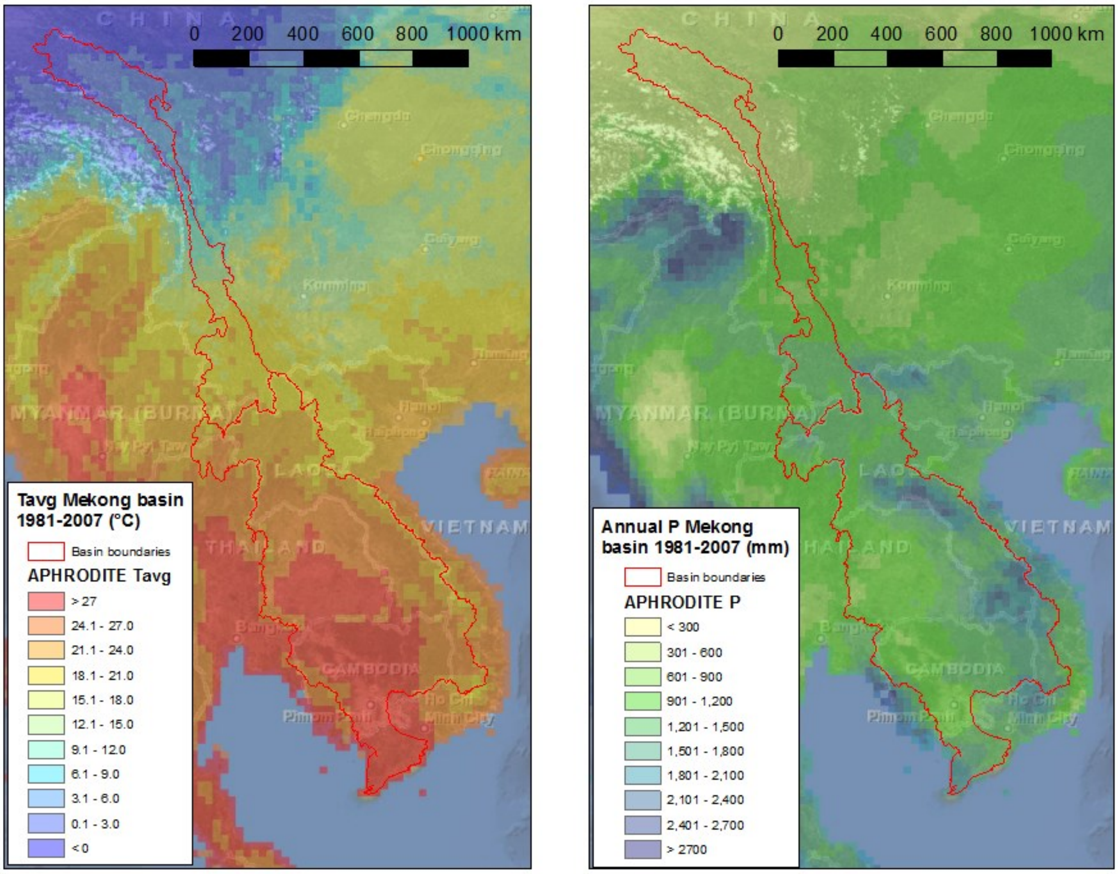

Figure 10: Average air temperature (left panel) and average precipitation sum (right panel) for 1981-2007 according to APHRODITE product at nominal 0.25° spatial resolution.

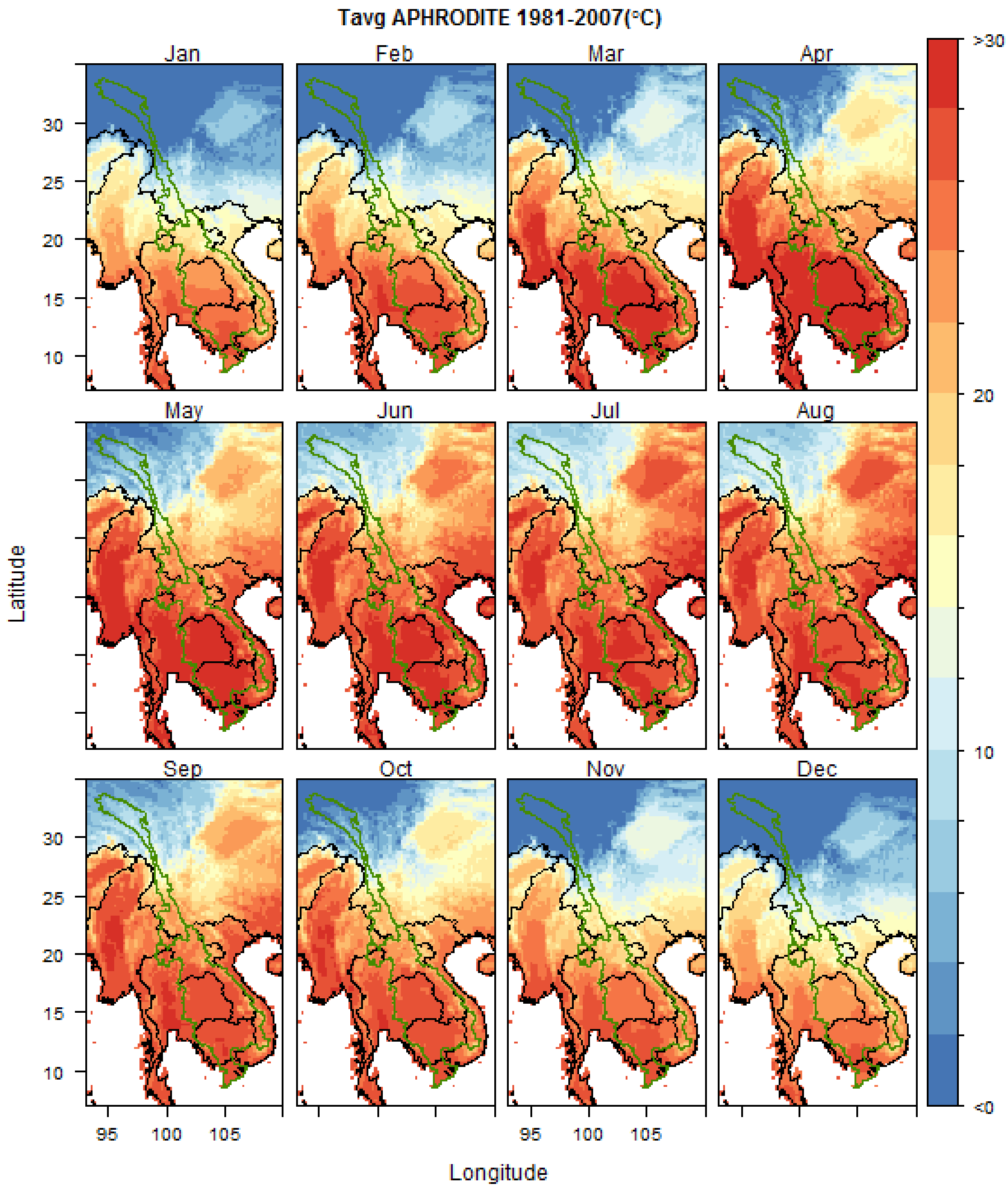

Figure 11: Average air temperature per month for 1981-2007 according to APHRODITE product at nominal 0.25° spatial resolution.

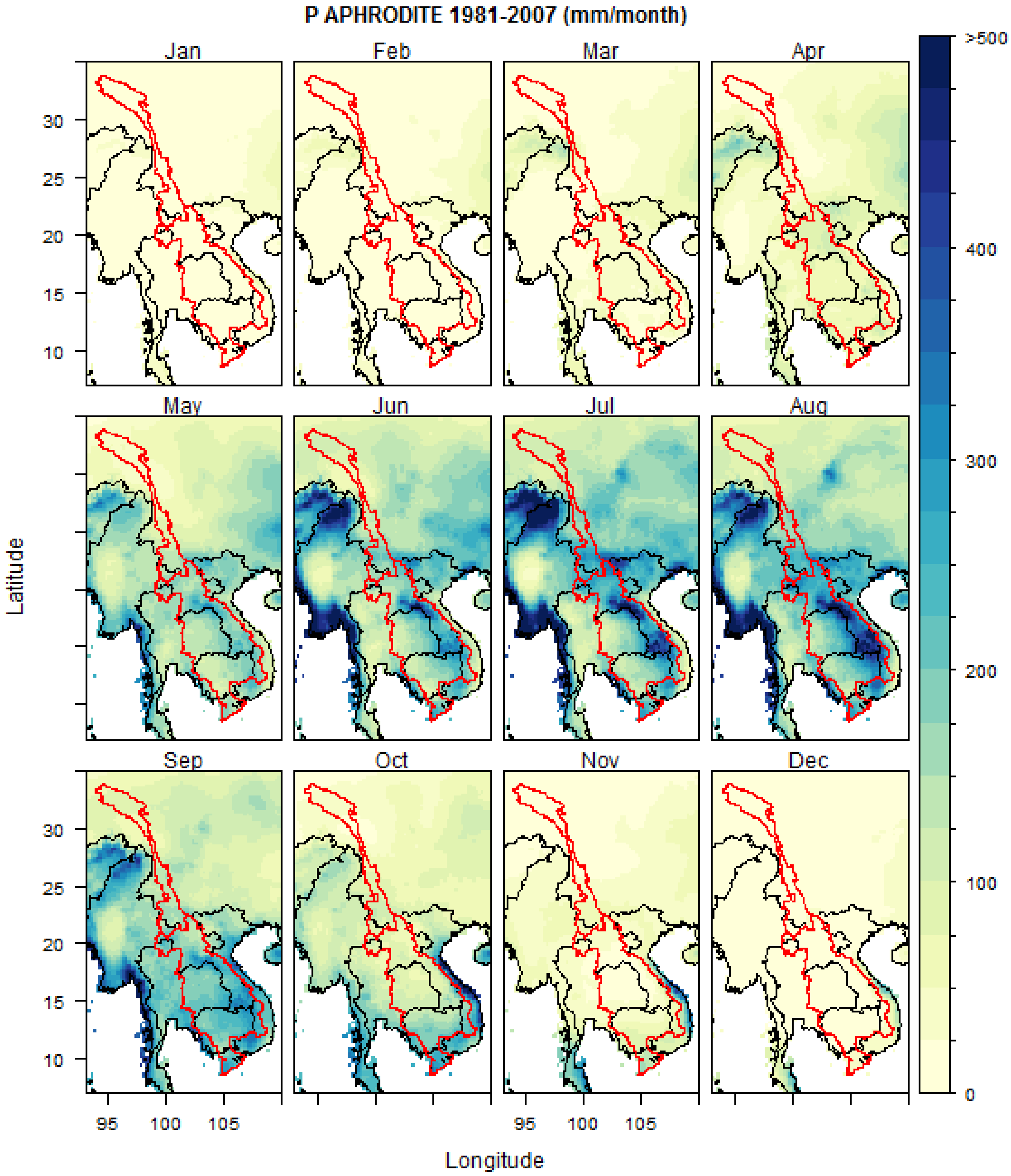

Figure 12: Average precipitation sum per month for 1981-2007 according to APHRODITE product at nominal 0.25° spatial resolution.

4.2.1 Average air temperature

To evaluate the performance of the APHRODITE product for air temperature, the correlation between the ground observation and the gridded temperature is determined. For this the quality checked and filtered observation database has been used. The correlation is determined at the daily scale as well as the monthly scale. To make a reasonable comparison between the different datasets, the air temperature in the APHRODITE grid is corrected for elevation differences between the elevation of the APHRODTE grid cell and the exact elevation of the station with a temperature lapse rate:

$$T_{APHRO_{STN}} = T_{APHRO} + (H_{STN} - H_{APHRO}) * T_{LAPSE}$$

Where $T_{APHRO_{STN}}$ is the corrected APHRODITE temperature for the station location, T_{APHRO} is the original temperature according to APHRODITE, H_{APHRO} is the average elevation of a 0.25° APHRODITE grid cell, H_{STN} is the exact station elevation and T_{LAPSE} is a temperature lapse rate (fixed at -0.0065 °Cm^{-1} for this study). Station locations with a very large difference between the exact station location and the elevation of the grid cell are excluded from the analysis, under the assumption that either the reported station elevation or the station's geographical location is wrong.

For the determination of the correlation, only complete pairs of ground observations and grid values are considered. This means that for each specific case no correlation is determined when either the ground station or the grid (or both) have no value. This holds for the determination of correlation at daily as well as monthly scale. The correlation of all daily average air temperature values from 1981 until 2007 is plotted in Figure 13. Figure 14 shows the same daily correlation values, but sorted per month. The ending year is 2007 and not 2010 because the APHRODITE product ends in 2007 at the moment. The APHRODITE Tavg product has good correlation with ground observations. In general temperatures are slightly overestimated for places with low temperatures, like on the Tibetan Plateau. In January and December there are some outliers. These outliers are related to anomalous values in the APHRODITE dataset for one cell during part of one month. The correlation is also determined for monthly aggregated values (Figure 15, Figure 16). For the aggregated monthly values, the correlation between the grid values and the ground observations is even better.

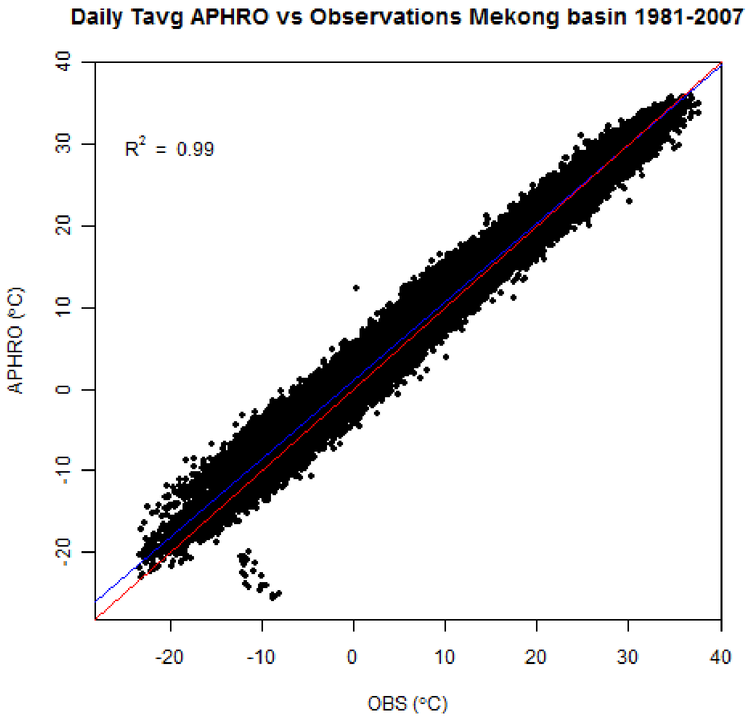

Figure 13: Correlation of ground observations and APHRODITE (daily values 1981-2007) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

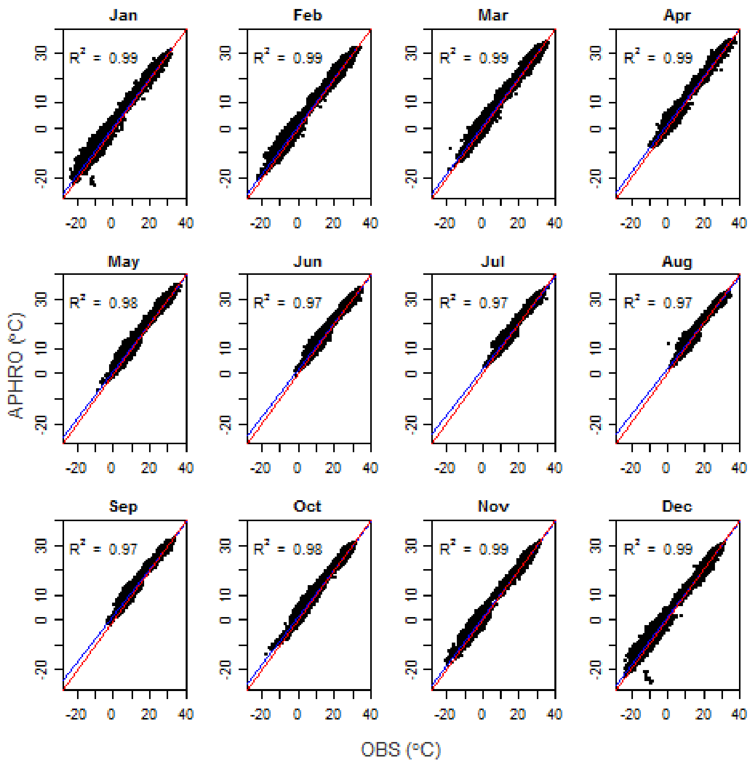

Figure 14: Correlation of ground observations and APHRODITE (daily values 1981-2007) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

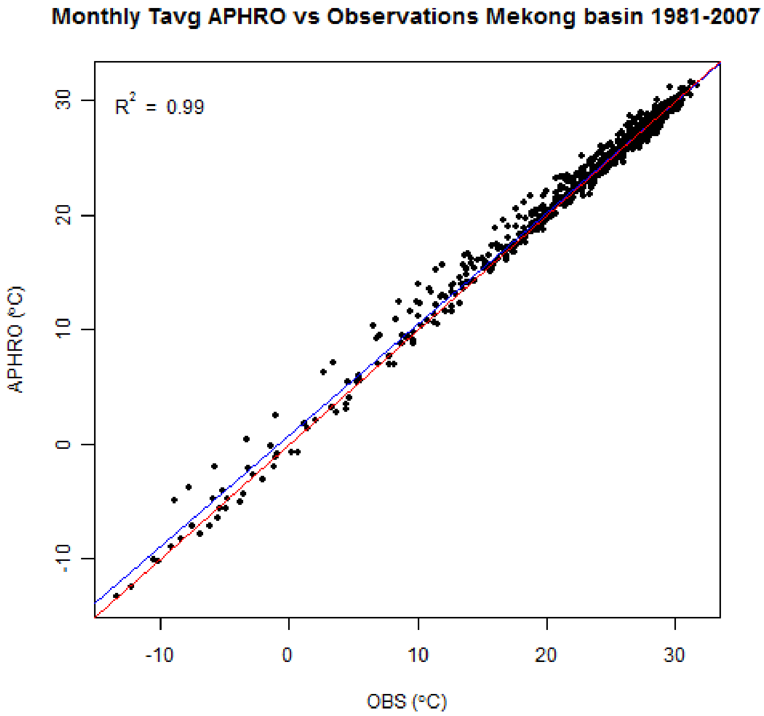

Figure 15: Correlation of ground observations and APHRODITE (monthly averaged values 1981-2007) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

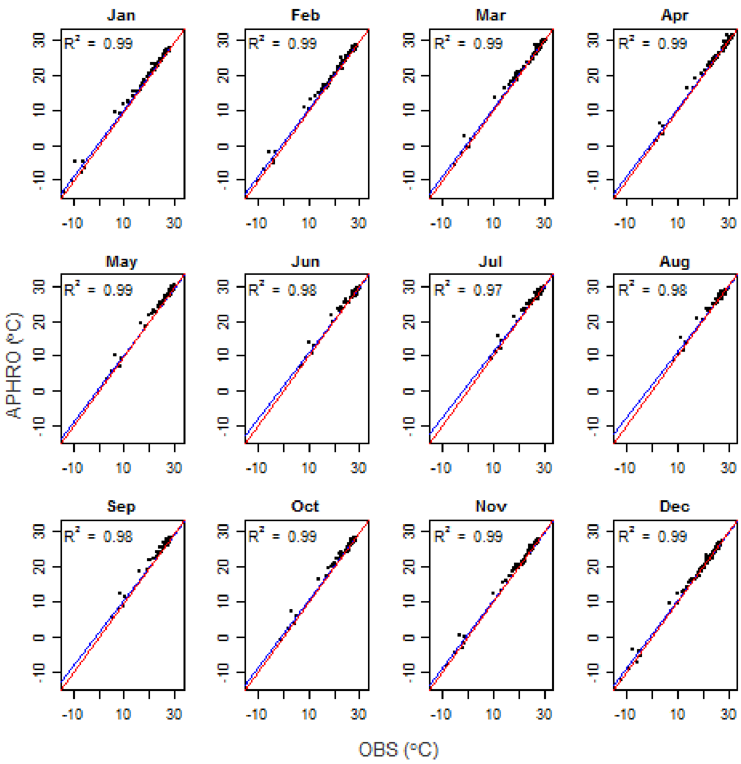

Figure 16: Correlation of ground observations and APHRODITE (monthly averaged values 1981-2007) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.2.2 Precipitation

To evaluate the performance of the APHRODITE product for precipitation, the correlation between the ground observation and the gridded precipitation values is determined. The correlation is determined at the daily scale as well as the monthly scale. Unlike for air temperature, no correction for elevation differences between the grid cell and the exact station location are made, as a precipitation lapse rate is very local dependent. In Figure 17 the correlation between APHRODITE and the ground stations for all daily values between 1981 and 2007 is shown. As is evident from the linear regression line, the general observation is an underestimation of daily precipitation in APHRODITE compared to the ground stations and the scatter is quite large. Looking at the correlation of daily values sorted by month (Figure 18), shows that the underestimate and scatter are similar for all months. The best correlation is observed for October (R^2=0.54), while the correlation is worst for February (R^2=0.36).

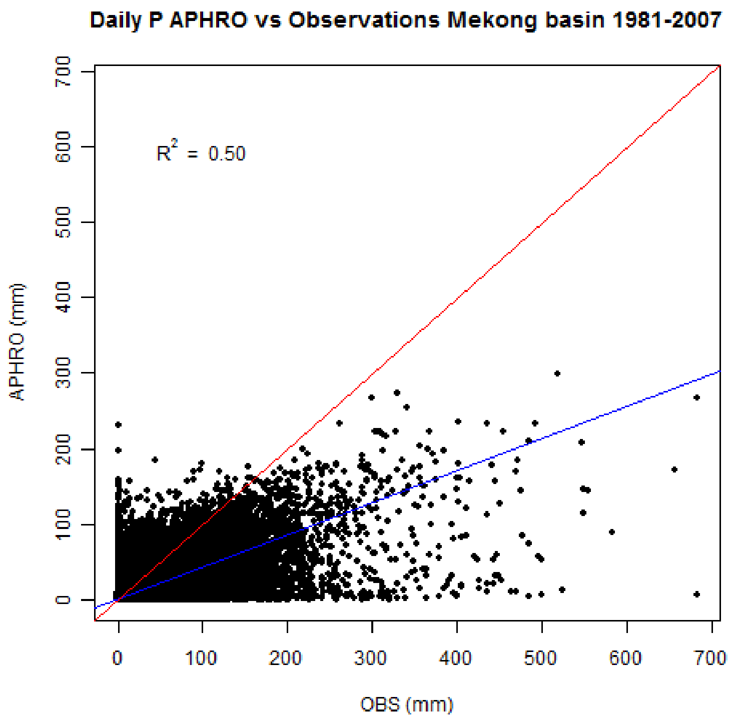

Figure 17: Correlation of ground observations and APHRODITE (daily values 1981-2007) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

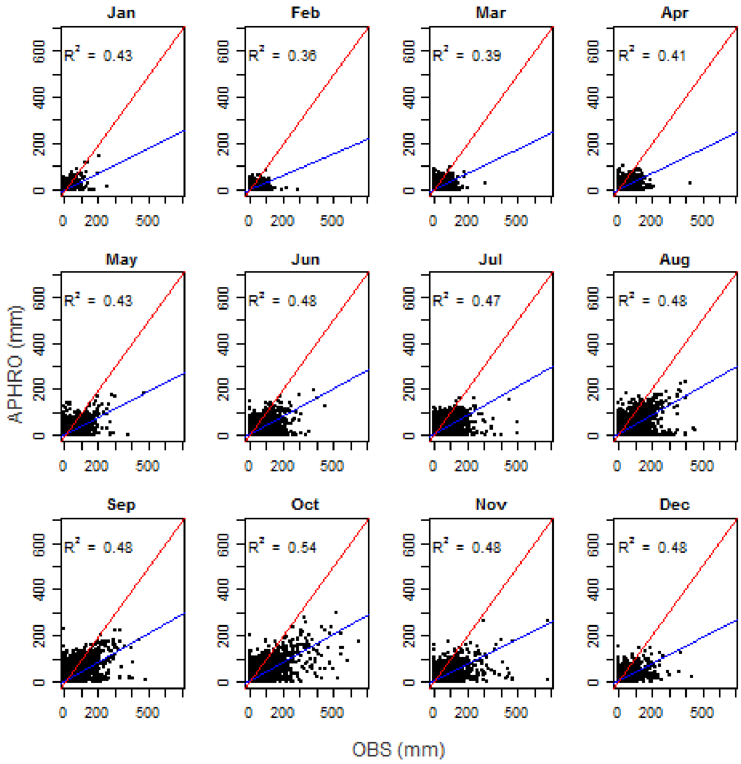

Figure 18: Correlation of ground observations and APHRODITE (daily values 1981-2007) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

For precipitation, the correlation between APHRODITE and the ground observations is much stronger for monthly aggregated values compared to daily values (Figure 19). Although the precipitation is still underestimated by APHRODITE, the correlation is quite strong (R^2=0.84). There are differences in correlation for the twelve months of the year (Figure 20). The largest underestimate is seen in January and February, while the underestimate during the monsoon months is smallest. This is positive for the total underestimation on annual basis. The correlation is strongest in October (R^2=0.80) and weakest in February (R^2=0.52).

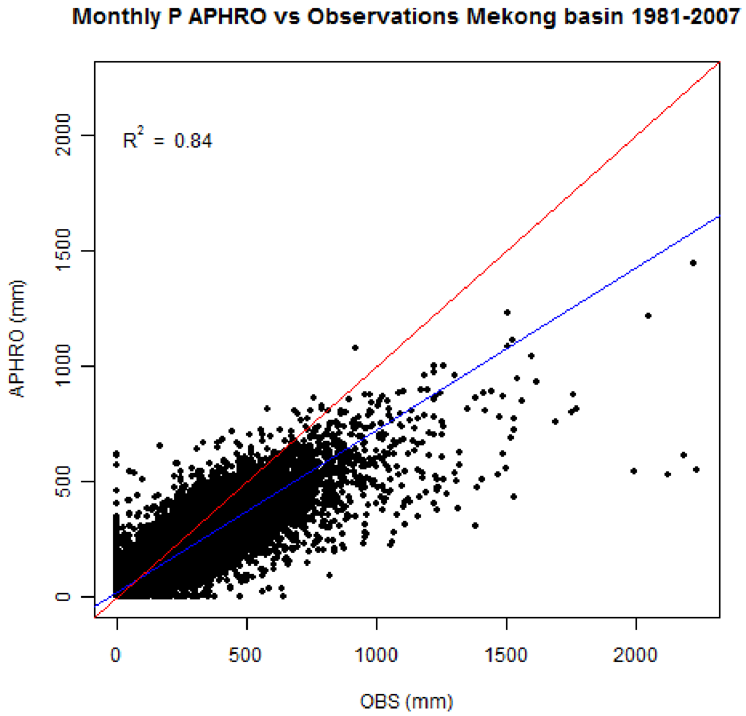

Figure 19: Correlation of ground observations and APHRODITE (monthly summed values 1981-2007) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

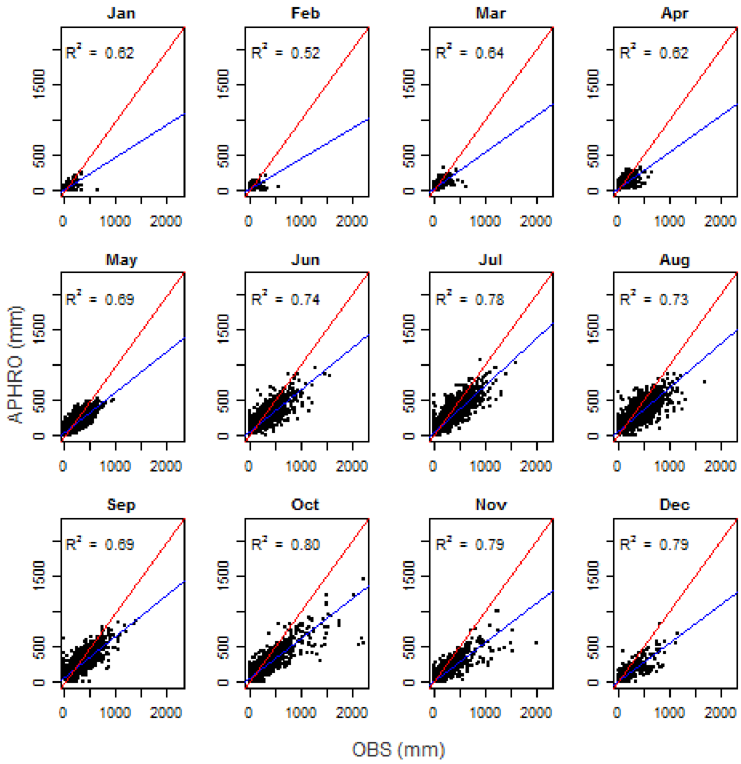

Figure 20: Correlation of ground observations and APHRODITE (monthly summed values 1981-2007) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.3 ERA-Interim

As for the APHRODITE product, the performance of the ERA-Interim product is evaluated for the Mekong river basin by comparing the gridded products of average air temperature and precipitation to ground observations at the geographical locations of the ground stations.

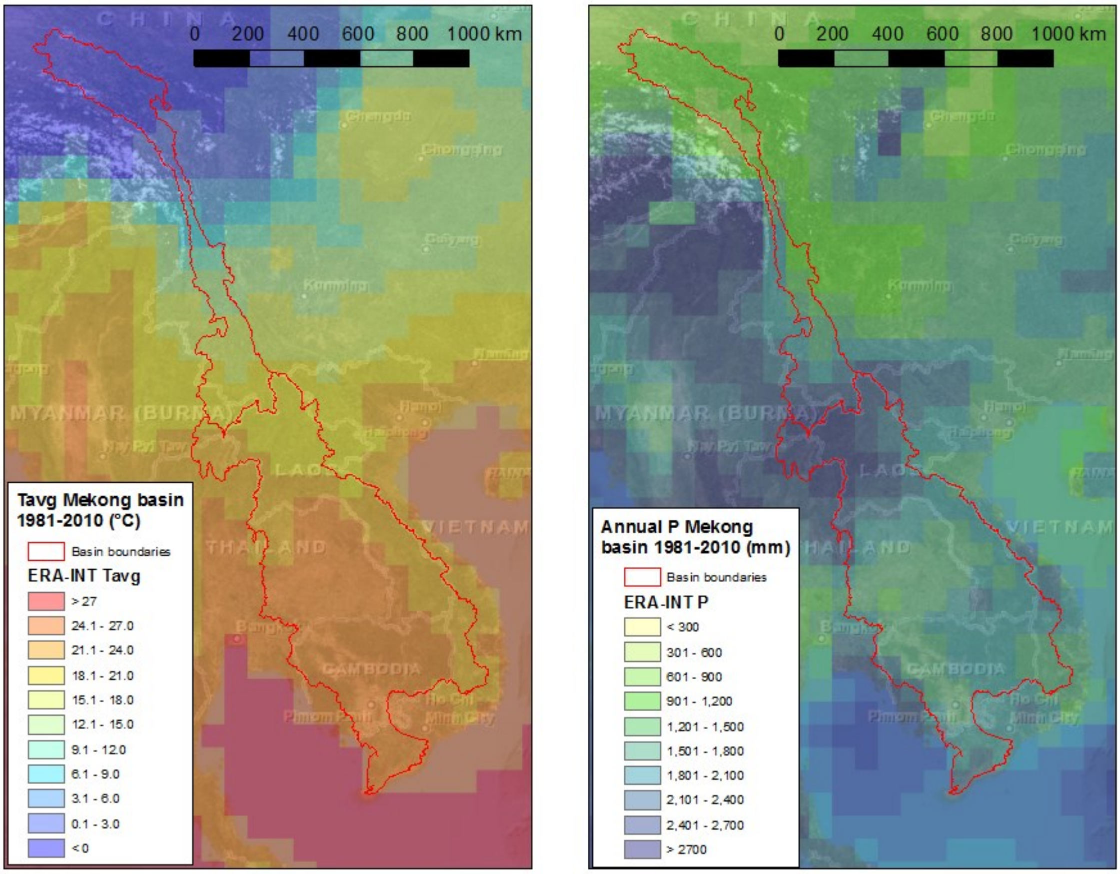

Figure 21: Average air temperature (left panel) and average precipitation sum (right panel) for 1981-2010 according to ERA-Interim product at nominal 0.75° spatial resolution.

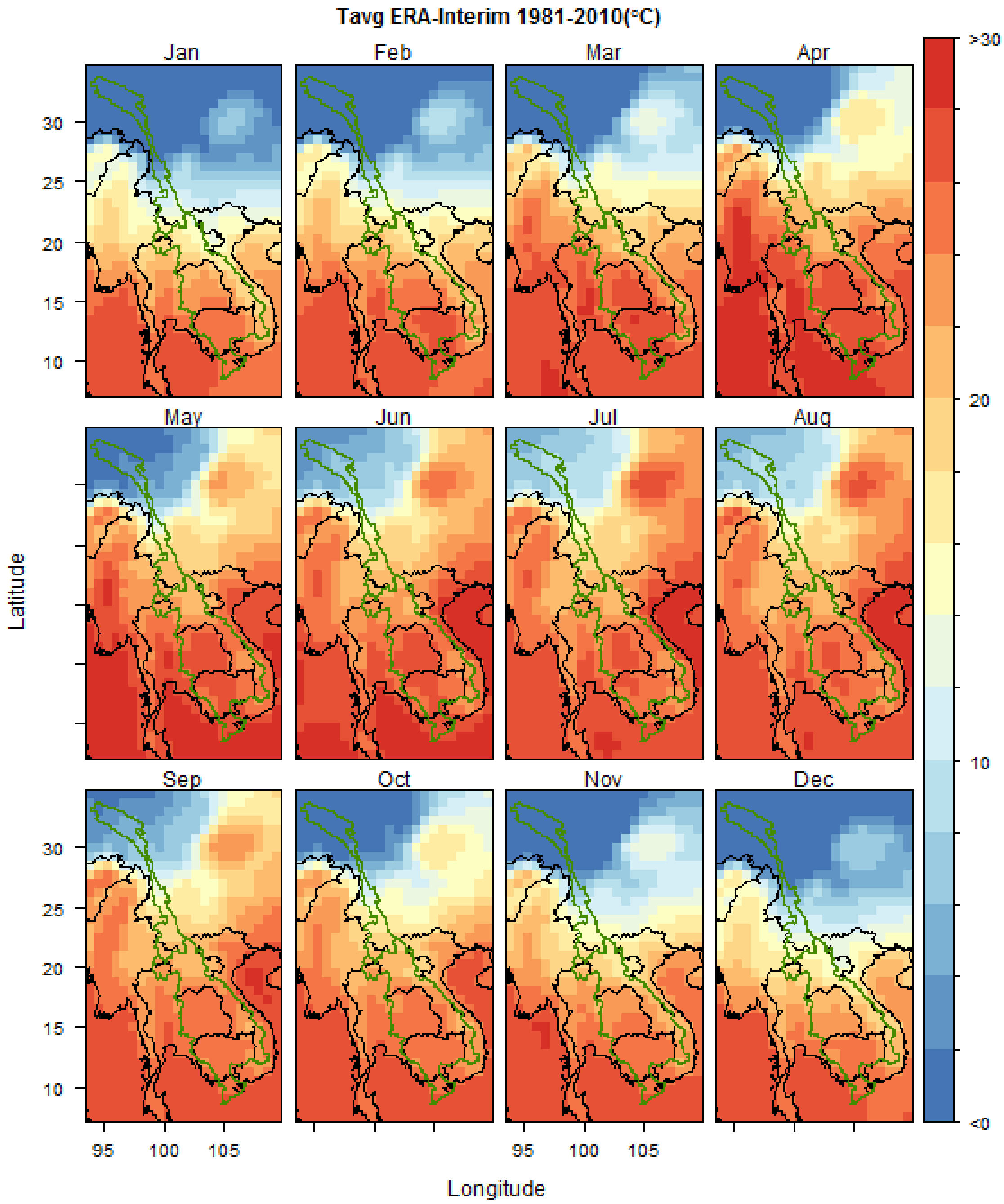

Figure 22: Average air temperature per month for 1981-2010 according to ERA-Interim product at nominal 0.75° spatial resolution.

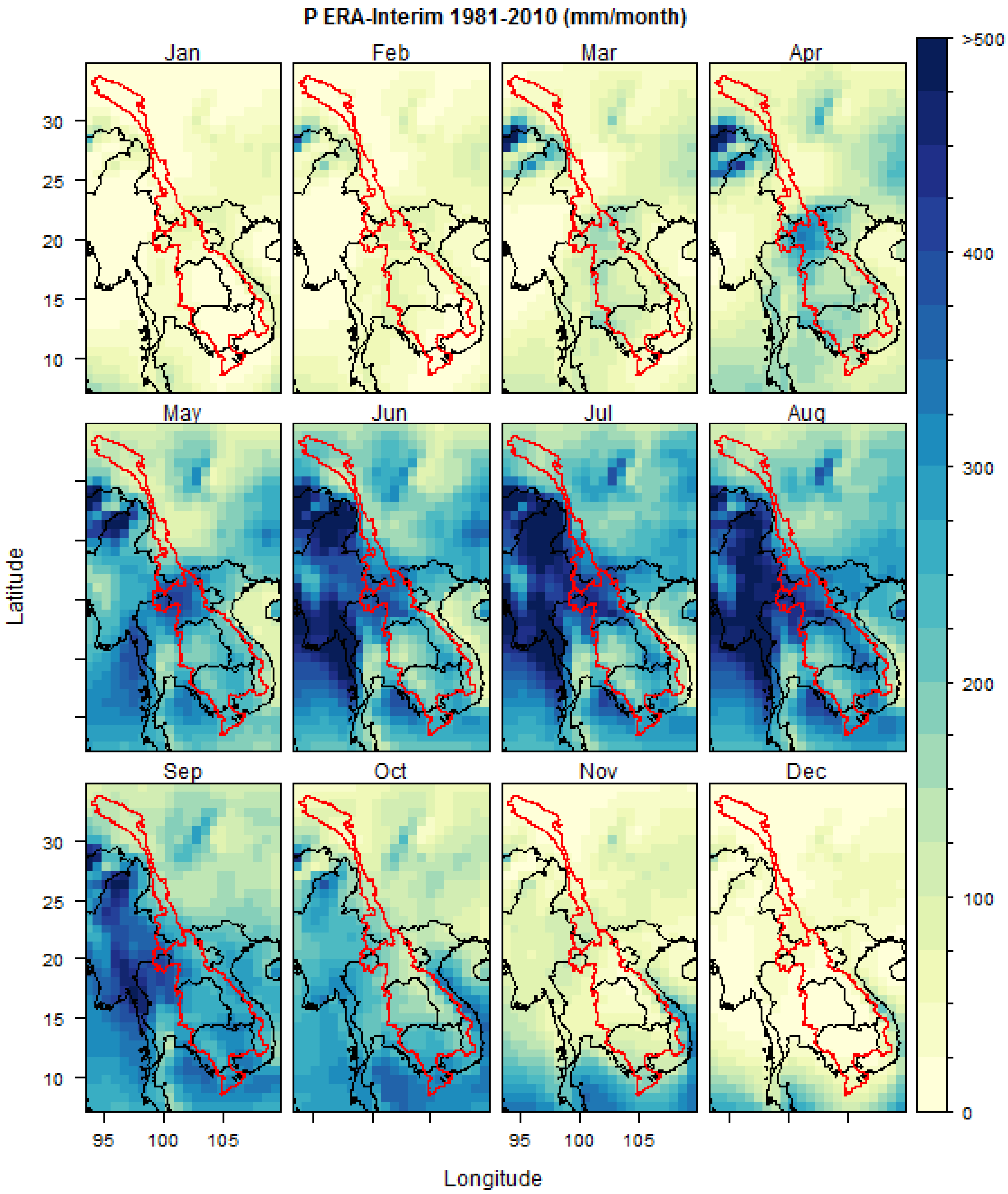

Figure 23: Average precipitation sum per month for 1981-2010 according to ERA-Interim product at nominal 0.75° spatial resolution.

4.3.1 Average air temperature

To evaluate the performance of the ERA-Interim product for air temperature, the correlation between the ground observation and the gridded temperature is determined. The correlation is determined at the daily scale as well as the monthly scale. Similar as for APHRODITE, to make a reasonable comparison between the different datasets, the air temperature in the ERA-INTERIM grid is corrected for elevation differences between the elevation of the APHRODTE grid cell and the exact elevation of the station with a temperature lapse rate:

$$T_{ERA-INT_{STN}} = T_{ERA-INT} + (H_{STN} - H_{ERA-INT}) * T_{LAPSE}$$

Where $T_{ERA-INT_{STN}}$ is the corrected ERA-Interim temperature for the station location, $T_{ERA-INT}$ is the original temperature according to ERA-Interim, $H_{ERA-INT}$ is the average elevation of a 0.75° ERA-Interim grid cell, H_{STN} is the exact station elevation and T_{LAPSE} is a temperature lapse rate (fixed at -0.0065 °Cm^{-1} for this study). Station locations with a very large difference between the exact station location and the elevation of the grid cell are excluded from the analysis, under the assumption that either the reported station elevation or the station's geographical location are wrong. The same stations are excluded for the analysis of APHRODITE as well as ERA-Interim and PRINCETON for a consistent comparison. The same hold for the temperature lapse rate, which is kept constant for all of the three temperature datasets.

For the determination of the correlation, only complete pairs of ground observations and grid values are considered. This means that for each specific case no correlation is determined when either the ground station or the grid (or both) have no value. This holds for the determination of correlation at daily as well as monthly scale. The correlation of all daily average air temperature values from 1981 until 2010 is plotted in **Figure 24**. **Figure 25** shows the same daily correlation values, but sorted per month. The ERA-Interim Tavg product has a slightly worse correlation with ground observations compared to APHRODITE. In general temperatures are slightly overestimated for places with low temperatures, like on the Tibetan Plateau, and slightly underestimated for the places with the highest temperatures in the Mekong basin. The spread in ERA-Interim temperature data is larger than for APHRODITE showing the larger deviation from the ground station data for the ERA-Interim product. The correlation is also determined for monthly aggregated values (**Figure 26**, **Figure 27**). For the aggregated monthly values, the correlation between the grid values and the ground observations is better.

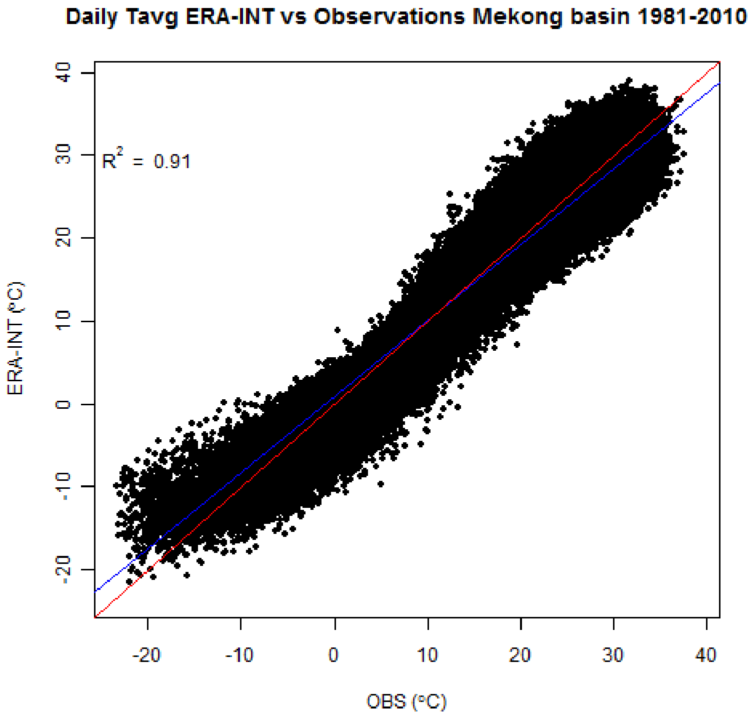

Figure 24: Correlation of ground observations and ERA-Interim (daily values 1981-2010) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

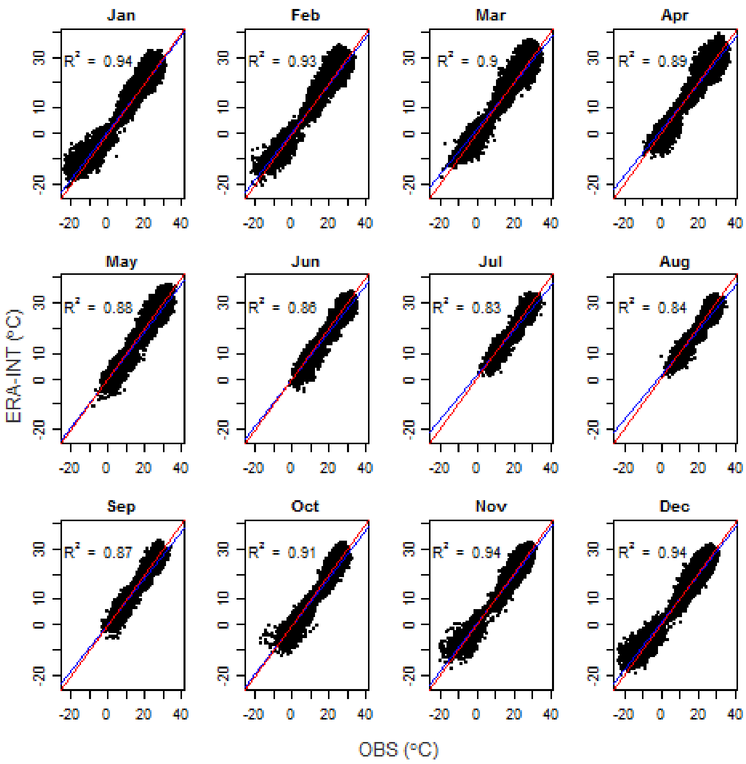

Figure 25: Correlation of ground observations and ERA-Interim (daily values 1981-2007) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

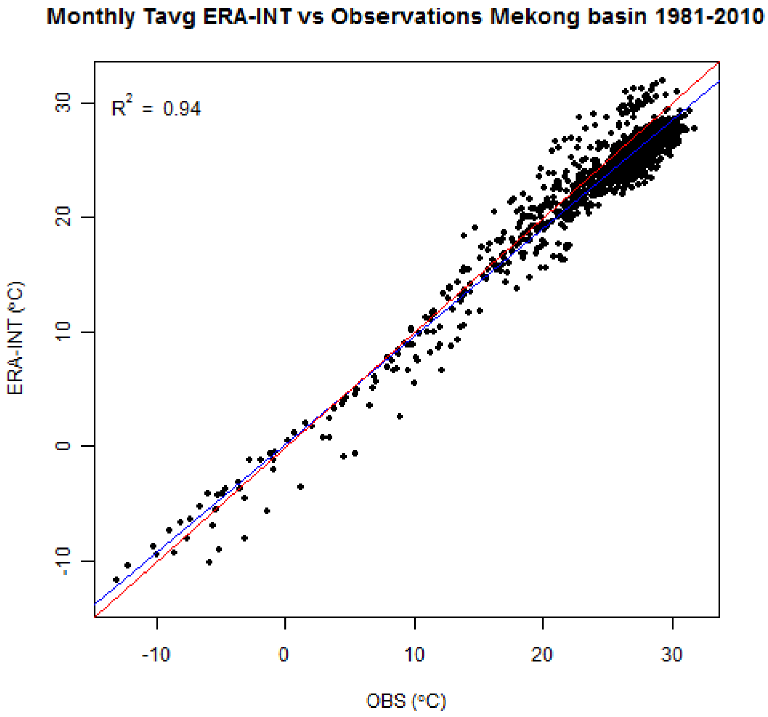

Figure 26: Correlation of ground observations and ERA-INTERIM (monthly averaged values 1981-2010) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

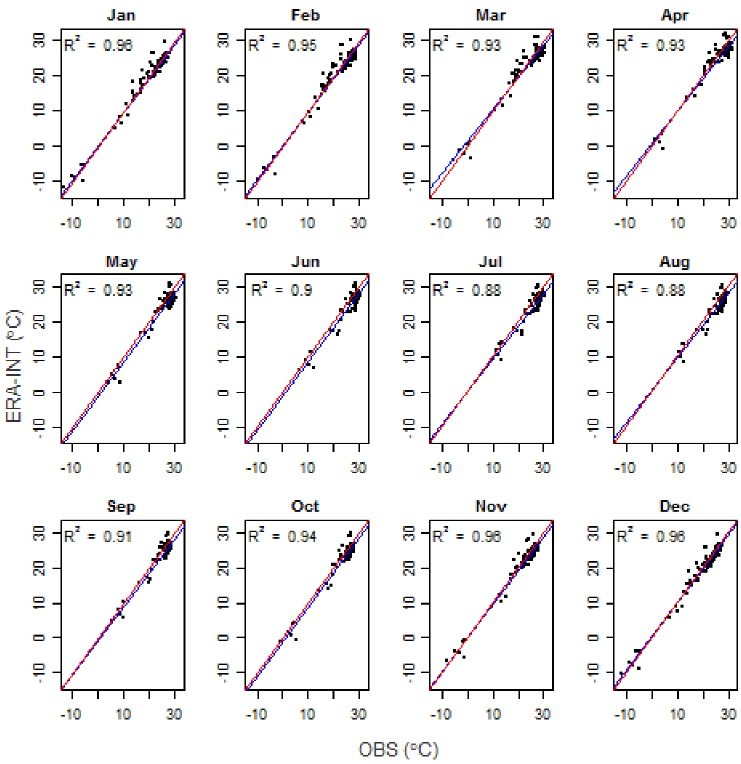

Figure 27: Correlation of ground observations and ERA-INTERIM (monthly averaged values 1981-2010) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.3.2 Precipitation

To evaluate the performance of the ERA-Interim product for precipitation, the correlation between the ground observation and the gridded precipitation values is determined. The correlation is determined at the daily scale as well as the monthly scale. Unlike for air temperature, no correction for elevation differences between the grid cell and the exact station location are made. In Figure 28 the correlation between ERA-Interim and the ground stations for all daily values between 1981 and 2010 is shown. As is evident from the linear regression line, the general observation is an strong underestimation of daily precipitation in ERA-Interim compared to the ground stations and the scatter is quite large. The underestimation in ERA-Interim is larger than in APHRODITE. Looking at the correlation of daily values sorted by month (Figure 29), shows that the underestimate and scatter are similar for all months. The correlation is clearly not as good as for APHRODITE.

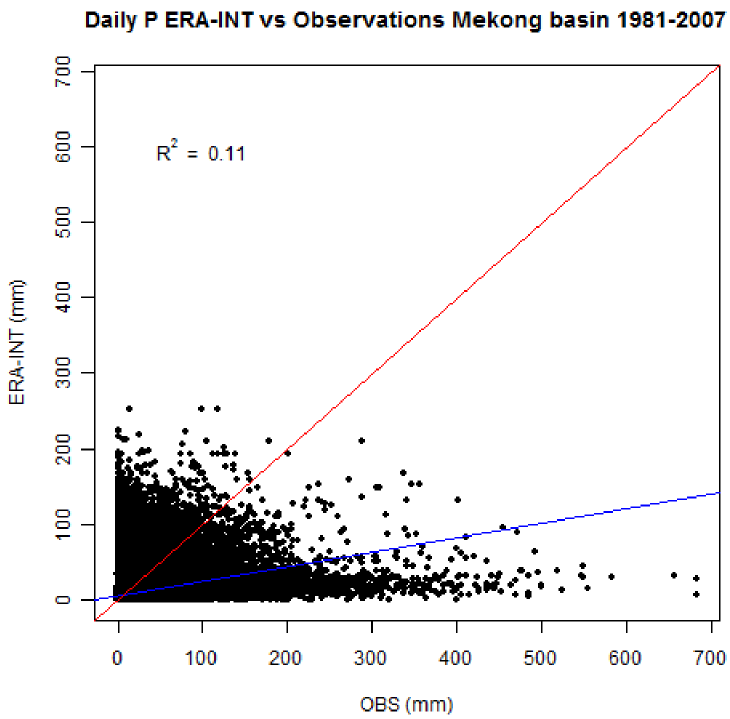

Figure 28: Correlation of ground observations and ERA-INTERIM (daily values 1981-2010) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

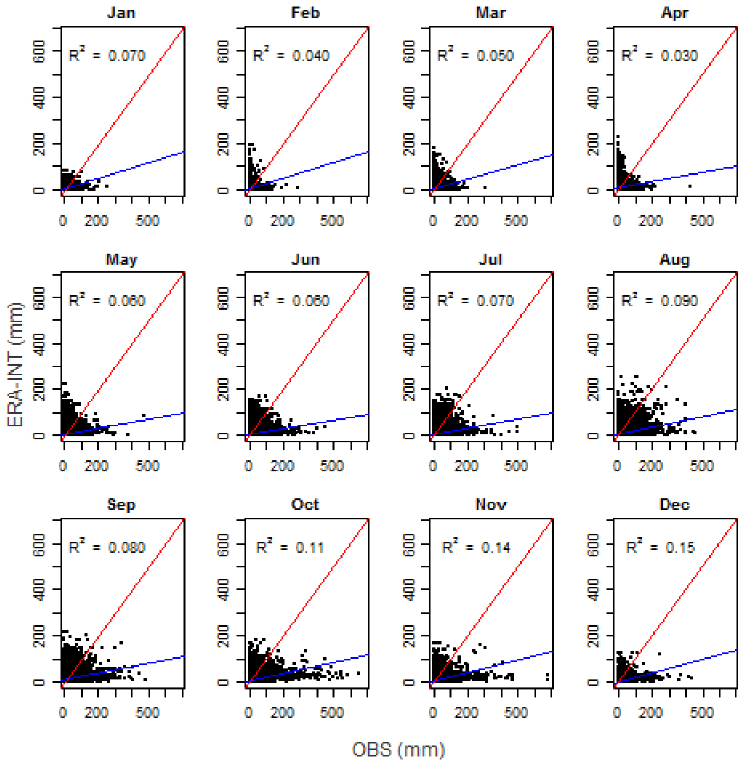

Figure 29: Correlation of ground observations and ERA-INTERIM (daily values 1981-2010) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

Similar as for APHRODITE, for ERA-Interim precipitation, the correlation between ERA-Interim and the ground observations is much stronger for monthly aggregated values compared to daily values (Figure 30). Although the precipitation is still underestimated by ERA-Interim, the correlation is reasonable (R^2=0.46). There are differences in correlation for the twelve months of the year (Figure 31). The largest underestimate is seen in the monsoon months, when gross of the precipitation occurs, while the underestimate during the winter months is smallest, when only little precipitation occurs. This observation is the opposite of what is observed for monthly aggregated APHRODITE precipitation. The stronger underestimation during monsoon months means that there is a strong underestimation of the total annual precipitation. The correlation is strongest in December (R^2=0.55) and weakest in February (R^2=0.10).

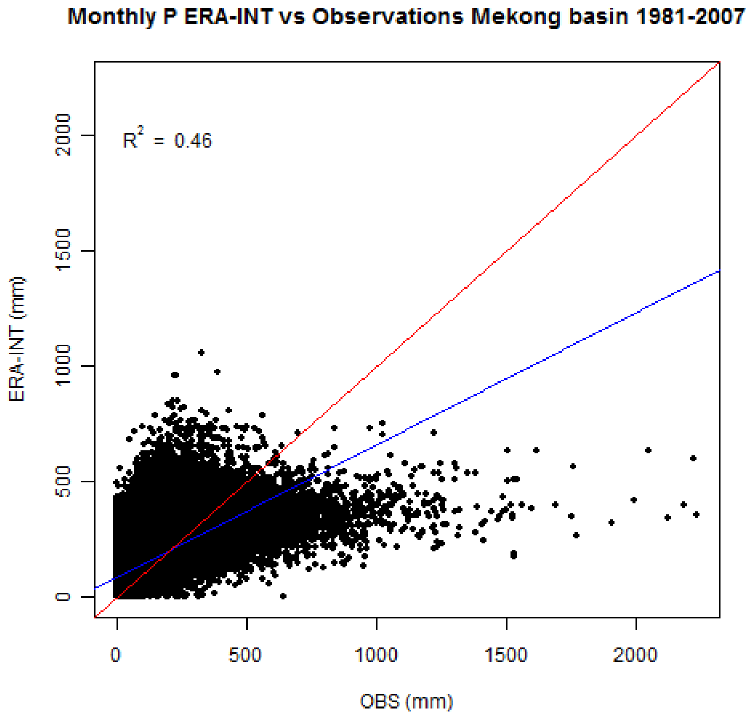

Figure 30: Correlation of ground observations and ERA-INTERIM (monthly summed values 1981-2010) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

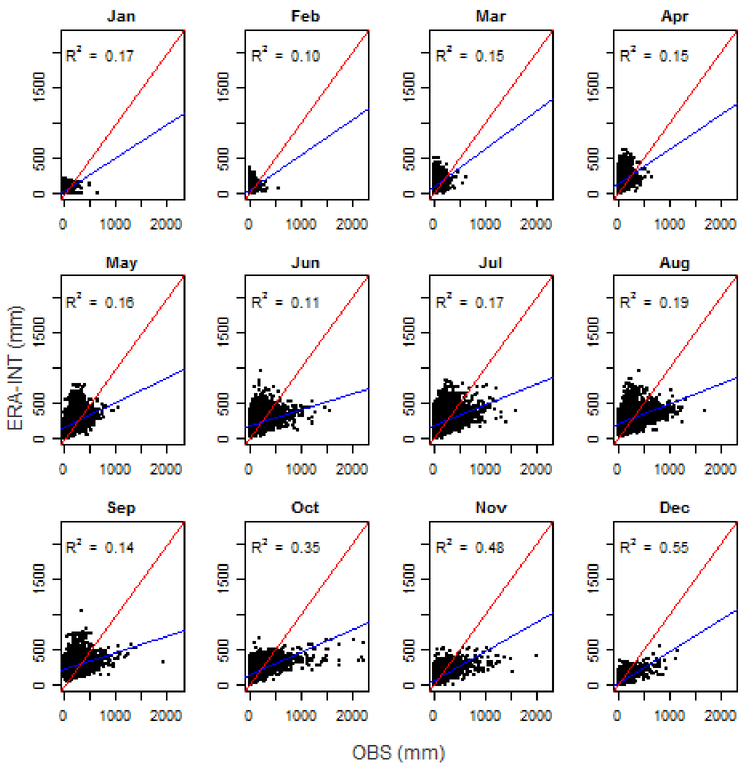

Figure 31: Correlation of ground observations and ERA-INTERIM (monthly summed values 1981-2010) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.4 PRINCETON

As for the APHRODITE and ERA-Interim products, the performance of the Princeton meteorological forcing dataset (PRINCETON) is evaluated for the Mekong river basin by comparing the gridded products of average air temperature and precipitation to ground observations at the geographical locations of the ground stations.

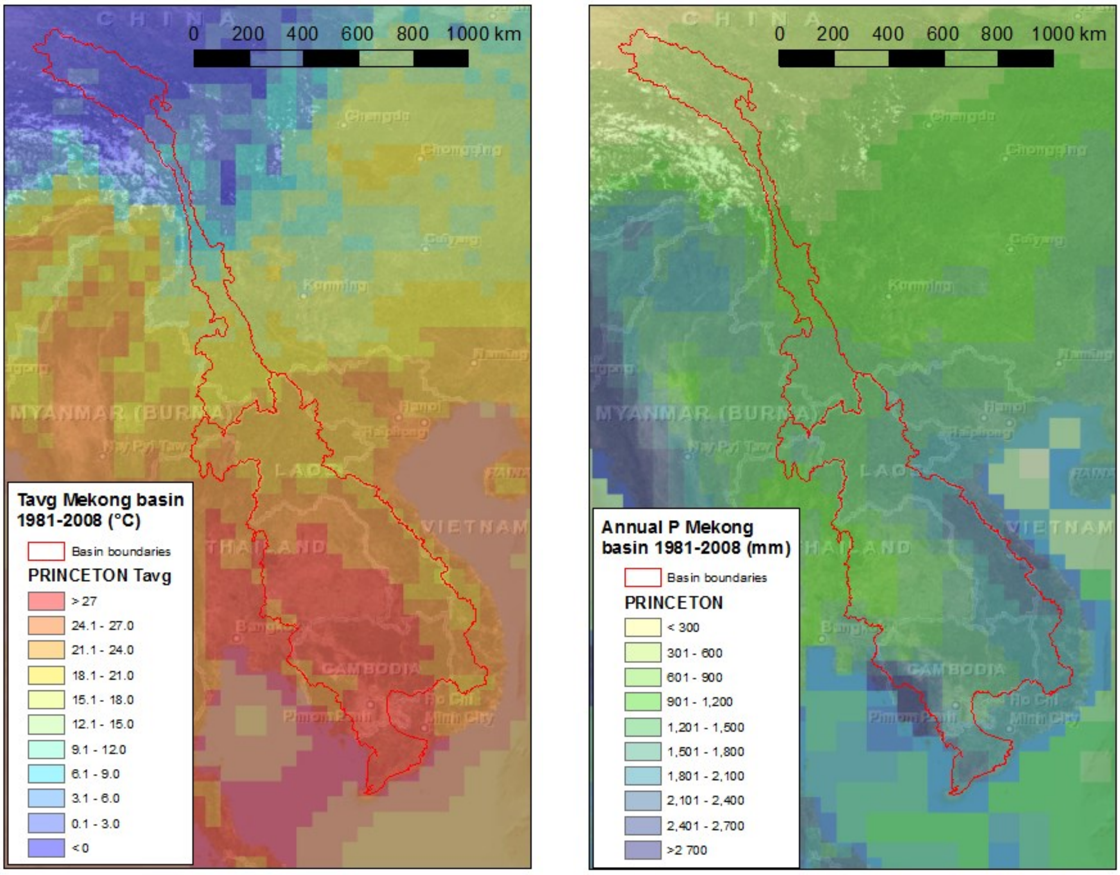

Figure 32: Average air temperature (left panel) and average precipitation sum (right panel) for 1981-2008 according to PRINCETON product at nominal 0.50° spatial resolution.

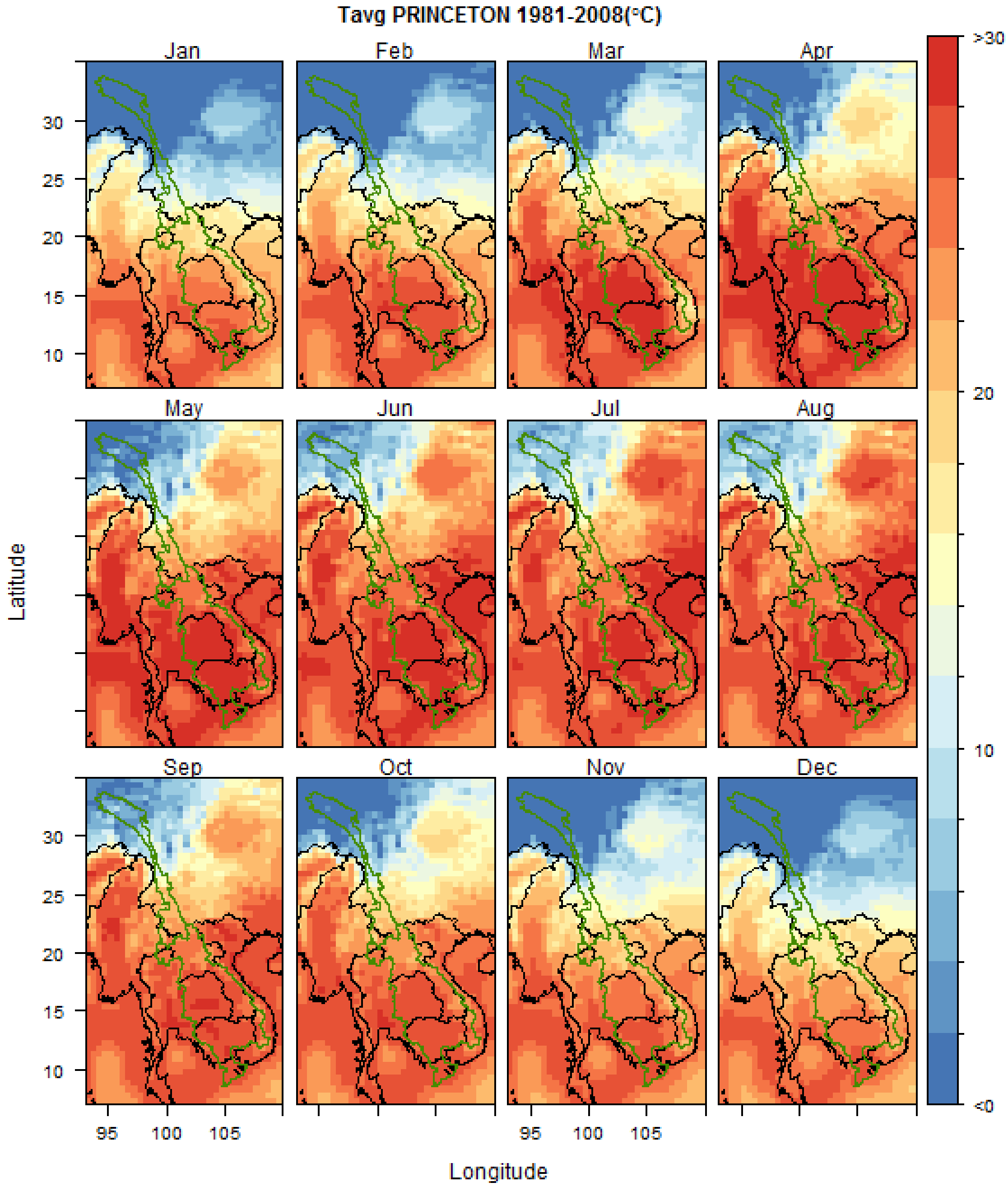

Figure 33: Average air temperature per month for 1981-2008 according to PRINCETON product at nominal 0.50° spatial resolution.

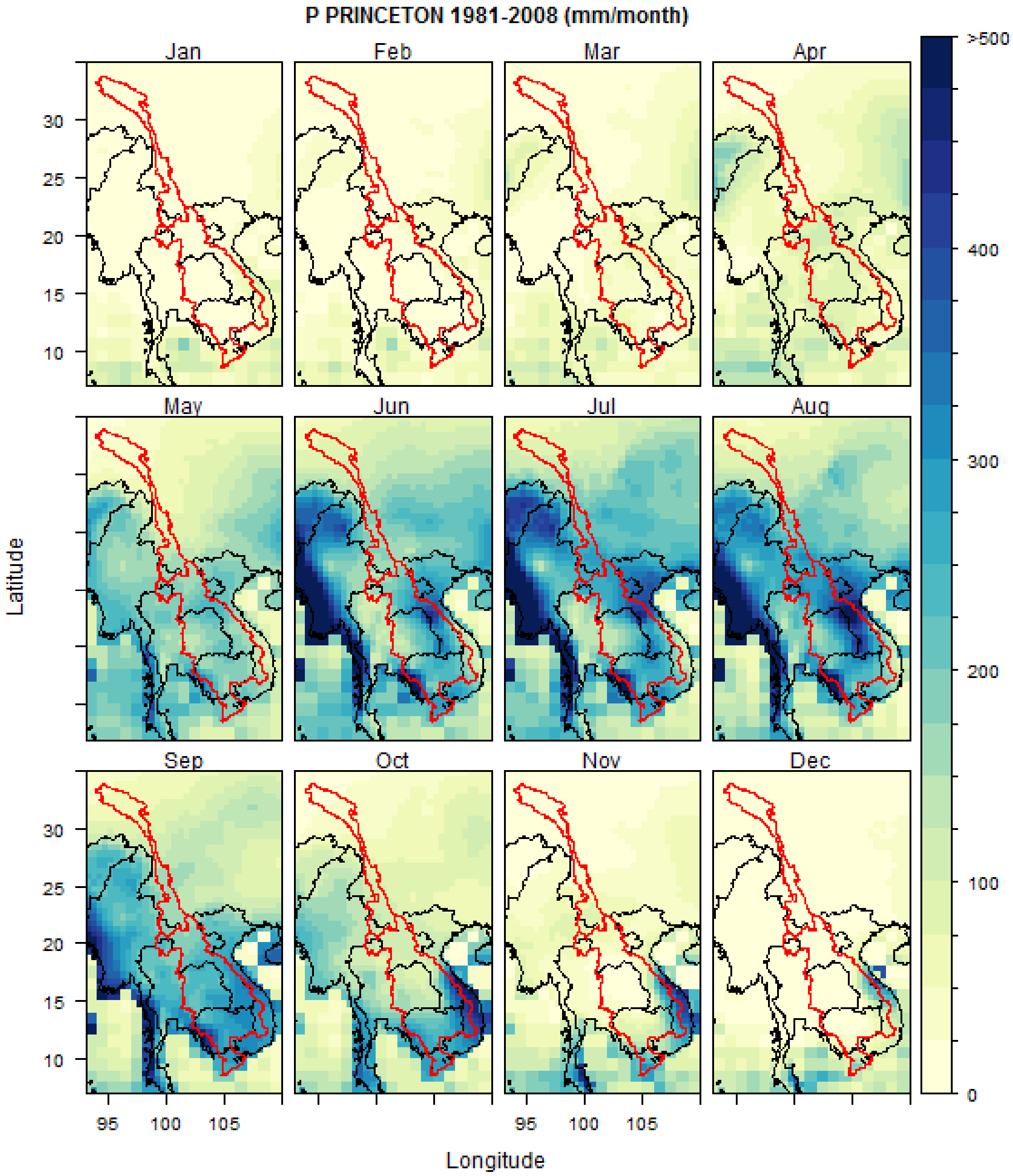

Figure 34: Average precipitation sum per month for 1981-2008 according to PRINCETON product at nominal 0.50° spatial resolution.

4.4.1 Average air temperature

To evaluate the performance of the PRINCETON product for air temperature, the correlation between the ground observation and the gridded temperature is determined. The correlation is determined at the daily scale as well as the monthly scale. Similar as for APHRODITE and ERA-Interim, to make a reasonable comparison between the different datasets, the air temperature in the PRINCETON grid is corrected for elevation differences between the elevation of the PRINCETON grid cell and the exact elevation of the station with a temperature lapse rate:

$$T_{PRNCETON_{STN}} = T_{PRINCETON} + (H_{STN} - H_{PRINCETON}) * T_{LAPSE}$$

Where $T_{PRINCETON_{STN}}$ is the corrected PRINCETON temperature for the station location, $T_{PRINCETON}$ is the original temperature according to the PRINCETON grind, $H_{PRINCETON}$ is the average elevation of a 0.5° ERA-Interim grid cell, H_{STN} is the exact station elevation and T_{LAPSE} is a temperature lapse rate (fixed at -0.0065 $°Cm^{-1}$ for this study). Station locations with a very large difference between the exact station location and the elevation of the grid cell are excluded from the analysis, under the assumption that either the reported station elevation or the station's geographical location are wrong. The same stations are excluded for the analysis of APHRODITE as well as ERA-Interim and PRINCETON for a consistent comparison. The same hold for the temperature lapse rate, which is kept constant for each of the three temperature datasets.

For the determination of the correlation, only complete pairs of ground observations and grid values are considered. This means that for each specific case no correlation is determined when either the ground station or the grid (or both) have no value. This holds for the determination of correlation at daily as well as monthly scale. The correlation of all daily average air temperature values from 1981 until 2008 is plotted in Figure 35. Figure 36 shows the same daily correlation values, but sorted per month. A comparison until 2008 and not until 2010 is made because the PRINCETON dataset ends in 2008 at the moment. The PRINCETON Tavg product has a similar correlation with ground observations compared to ERA-Interim, but a slightly wider range of errors as becomes clear when comparing Figure 35 to **Figure 24** and Figure 36 to **Figure 25**. In general temperatures are slightly underestimated for places with low temperatures, like on the Tibetan Plateau. The spread in PRINCETON temperature data is larger than for APHRODITE and ERA-Interim showing the largest deviation from the ground station data for the PRINCETON product. The correlation is also determined for monthly aggregated values (Figure 37, Figure 38). For the aggregated monthly values, the correlation between the grid values and the ground observations is better.

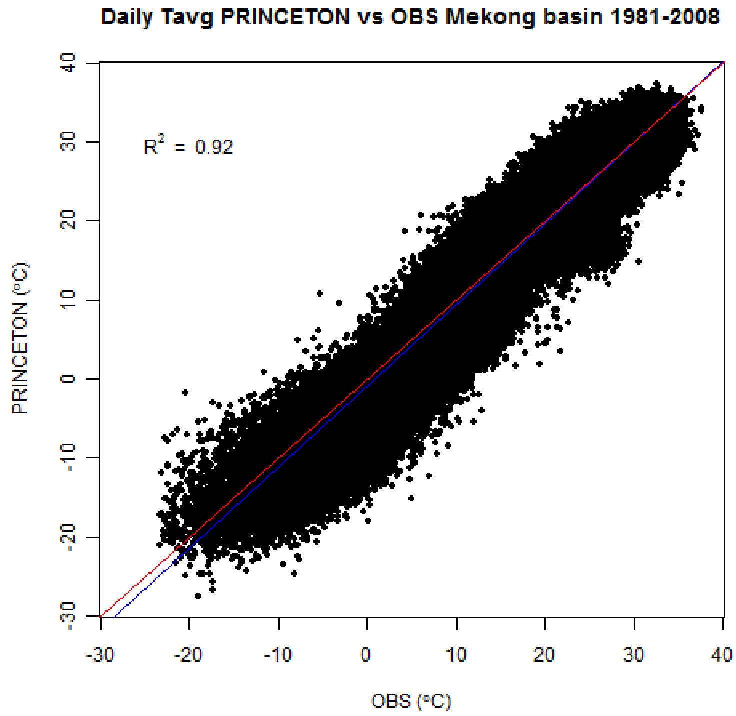

Figure 35: Correlation of ground observations and PRINCETON (daily values 1981-2008) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

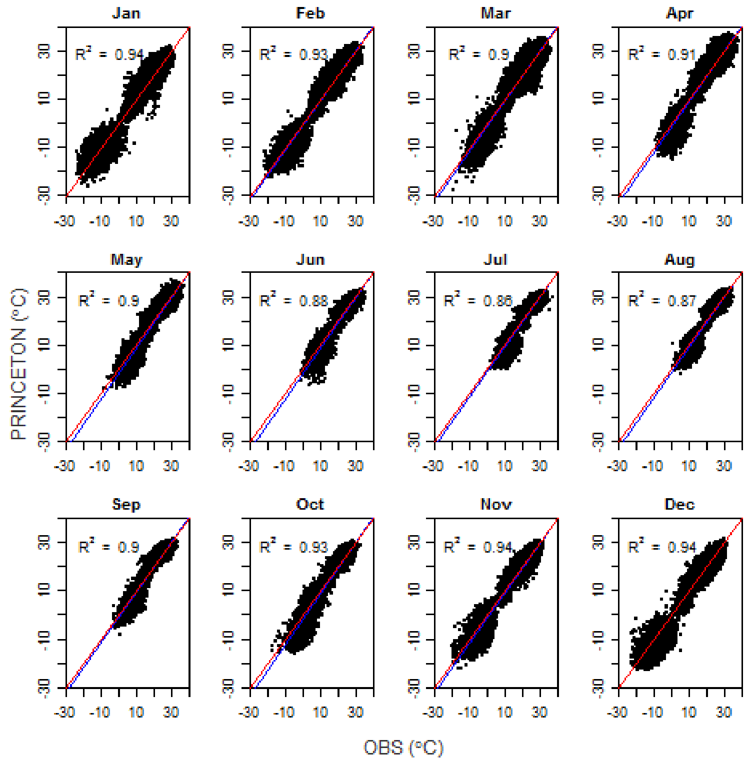

Figure 36: Correlation of ground observations and PRINCETON (daily values 1981-2008) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

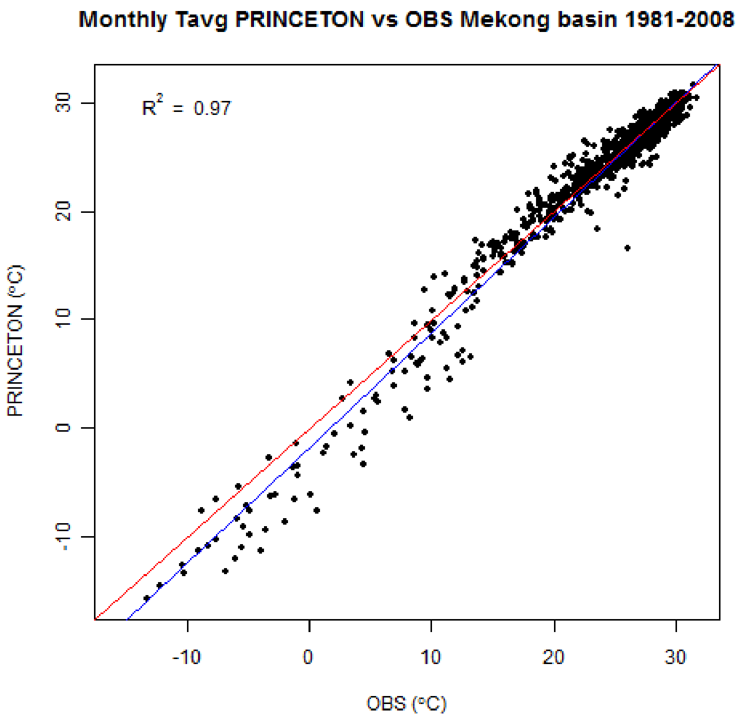

Figure 37: Correlation of ground observations and PRINCETON (monthly averaged values 1981-2007) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

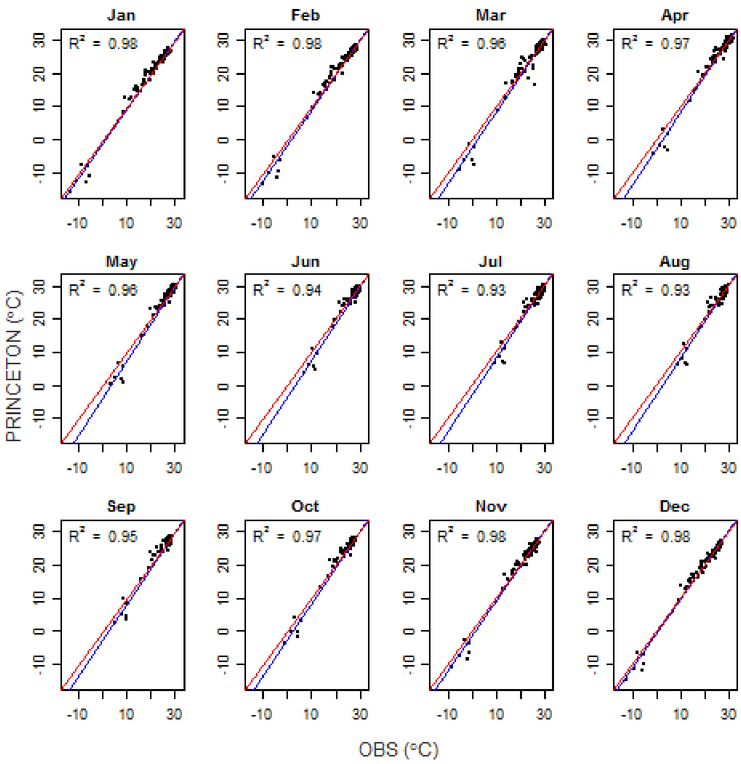

Figure 38: Correlation of ground observations and PRINCETON (monthly averaged values 1981-2008) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.4.2 Precipitation

To evaluate the performance of the PRINCETON product for precipitation, the correlation between the ground observations and the gridded precipitation values is determined. The correlation is determined at the daily scale as well as the monthly scale. Unlike for air temperature, no correction for elevation differences between the grid cell and the exact station location are made. In Figure 39 the correlation between PRINCETON and the ground stations for all daily values between 1981 and 2008 is shown. As is evident from the linear regression line, the general observation is a very strong underestimation of daily precipitation in PRINCETON compared to the ground stations and the scatter is very large, leading to a very low R^2 (0.01) The underestimation in PRINCETON is much larger than in APHRODITE and ERA-Interim. Looking at the correlation of daily values sorted by month (Figure 40), shows that the underestimate and scatter are similar for all months. The correlation is clearly much worse as for APHRODITE and ERA-Interim.

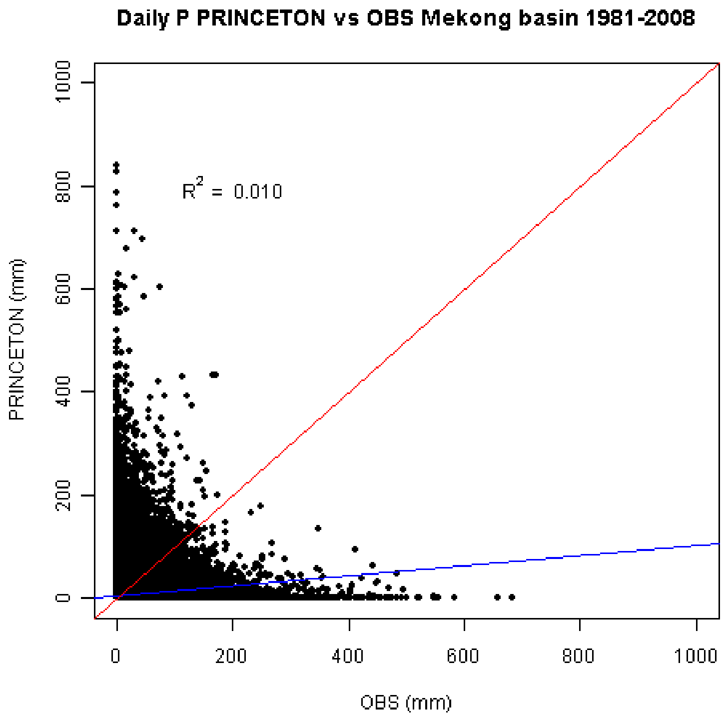

Figure 39: Correlation of ground observations and PRINCETON (daily values 1981-2008) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

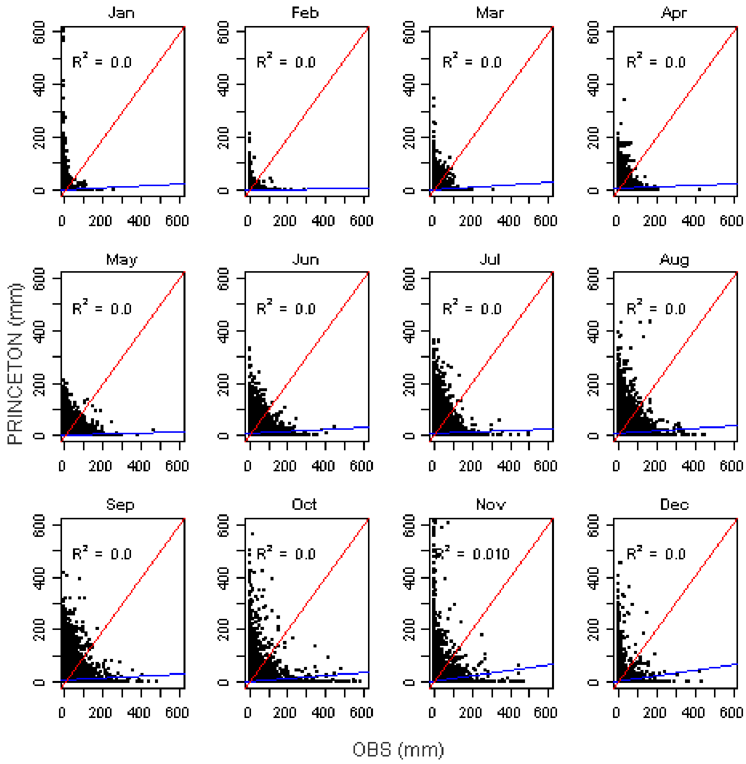

Figure 40: Correlation of ground observations and PRINCETON (daily values 1981-2008) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

Similar as for APHRODITE, and ERA-Interim, the correlation between PRINCETON and the ground observations is stronger for monthly aggregated values compared to daily values (Figure 41). Although the precipitation is still underestimated by PRINCETON, this underestimation is similar as for ERA-Interim. The correlation is stronger than for ERA-Interim (R^2=0.53 vs. R^2=0.46) but much weaker than APHRODITE (R^2=0.84). There are minor differences in correlation for the twelve months of the year (Figure 42). The underestimate is smallest during November and December, but during these months there are also extreme errors occurring with precipitation sums higher than 2500 mm reported for PRINCETON grid cells. The correlation is similar to ERA-Interim, but much weaker than for APHRODITE.

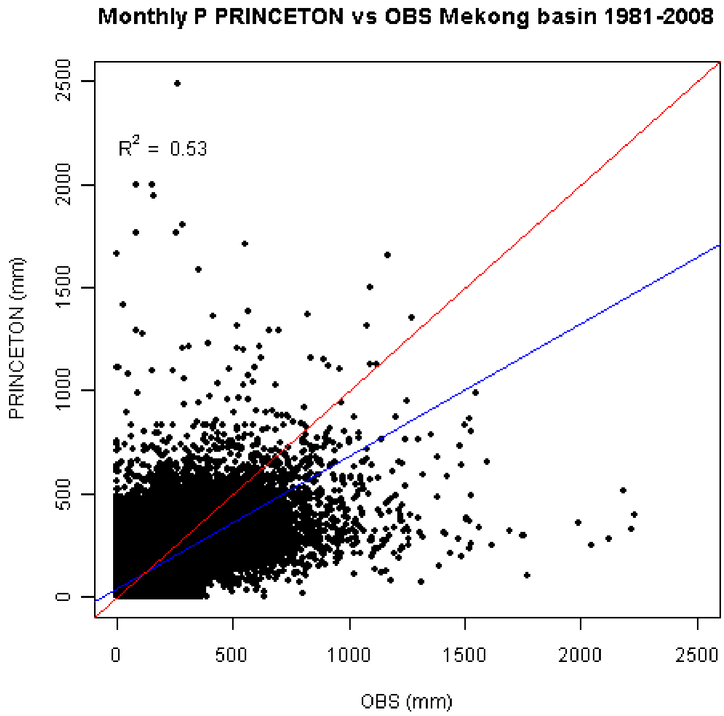

Figure 41: Correlation of ground observations and PRINCETON (monthly summed values 1981-2008) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

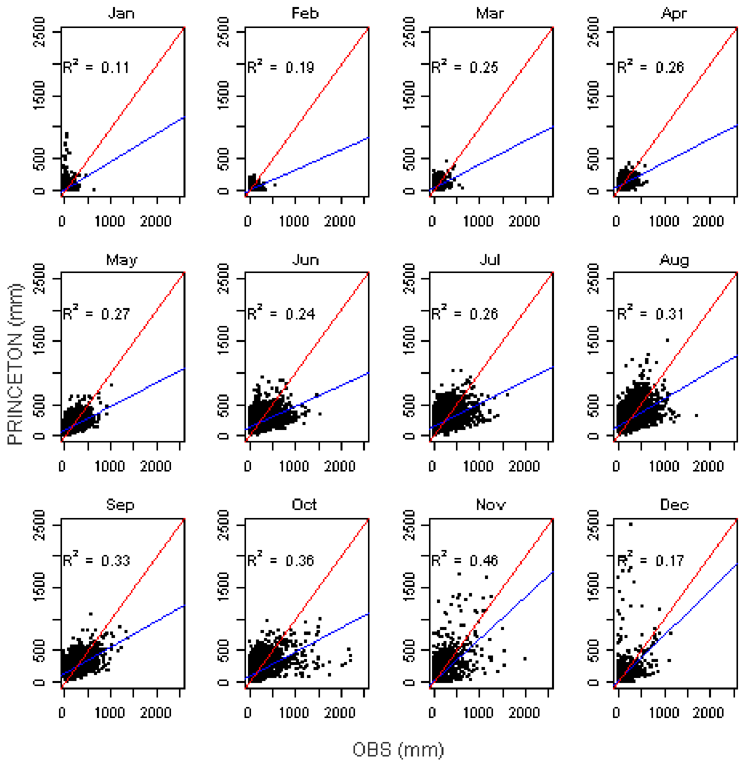

Figure 42: Correlation of ground observations and PRINCETON (monthly summed values 1981-2008) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.5 CRU

As for the APHRODITE, ERA-Interim and PRINCETON products, the performance of the CRU dataset is evaluated for the Mekong river basin by comparing the gridded products of average air temperature and precipitation to ground observations at the geographical locations of the ground stations. Although the CRU dataset spans 1901-2010, the comparison with ground stations is done for 1981-2010, using the same meteorological ground observations database as for the APHRODITE, ERA-Interim and PRINCETON products. Furthermore, the performance of CRU is only assessed at a monthly timescale and not at a daily timescale, as is the case for the other products. This is because the CRU dataset in only available at monthly time scale.

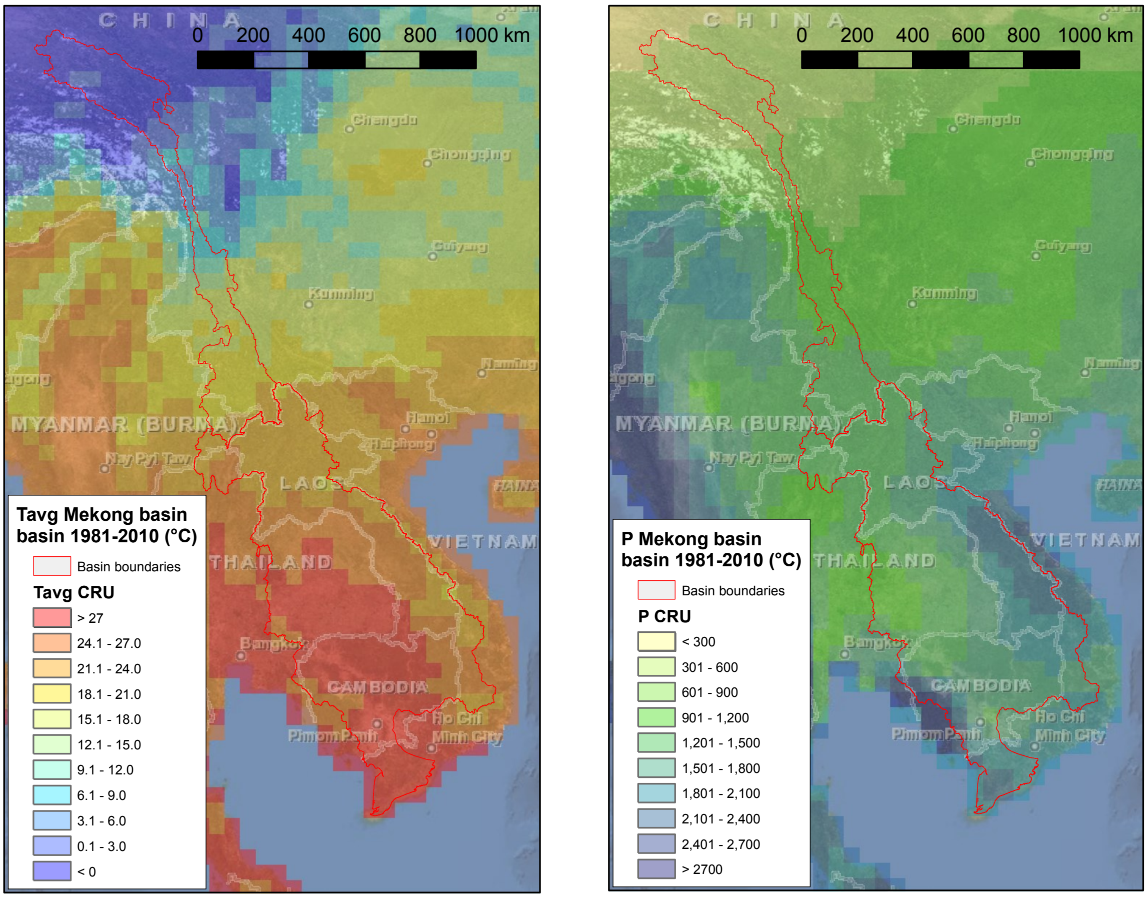

Figure 43: Average air temperature (left panel) and average precipitation sum (right panel) for 1981-2010 according to CRU product at nominal 0.5° spatial resolution.

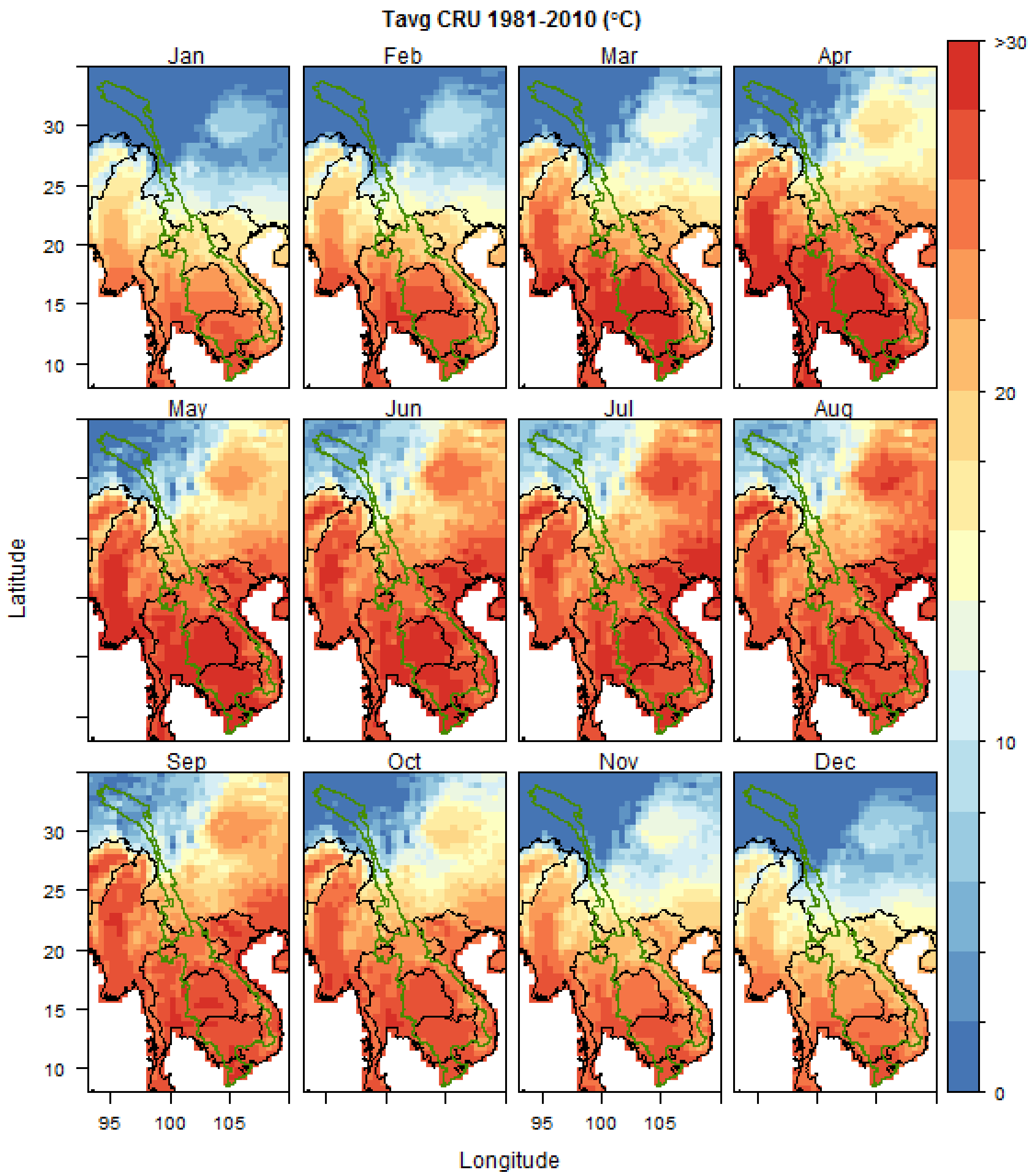

Figure 44: Average air temperature per month for 1981-2010 according to CRU product at nominal 0.5° spatial resolution.

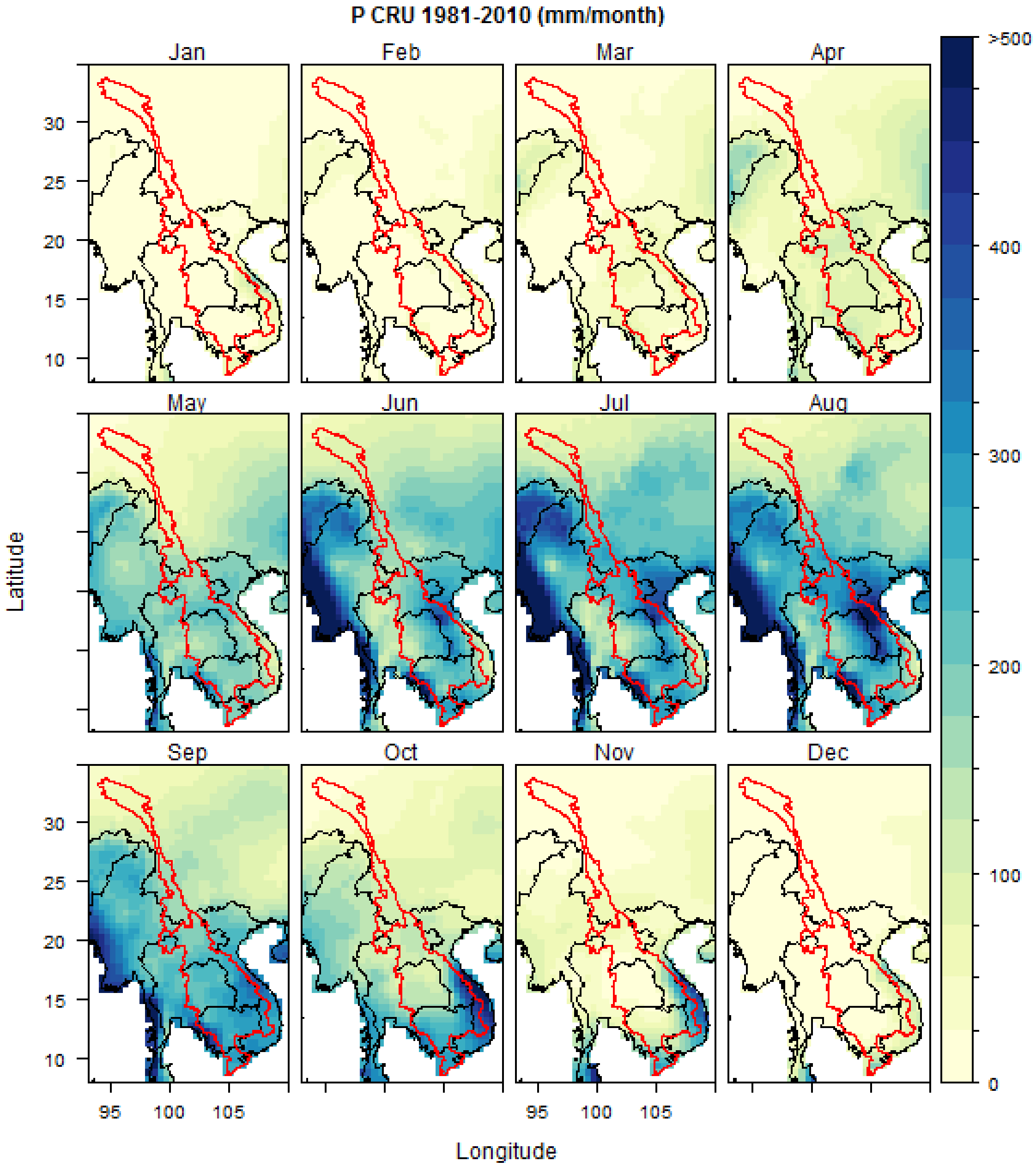

Figure 45: Average precipitation per month for 1981-2010 according to CRU product at nominal 0.5° spatial resolution.

4.5.1 Average air temperature

To evaluate the performance of the CRU product for air temperature, the correlation between the ground observation and the gridded temperature is determined. For this the quality checked and filtered observation database has been used. The correlation is determined at the daily scale as well as the monthly scale. The air temperature in the CRU grid is corrected for elevation differences between the elevation of the CRU grid cell and the exact elevation of the station with a temperature lapse rate:

$$T_{CRU_{STN}} = T_{CRU} + (H_{STN} - H_{CRU}) * T_{LAPSE}$$

Where $T_{CRU_{STN}}$ is the corrected CRU temperature for the station location, T_{CRU} is the original temperature according to CRU, H_{CRU} is the average elevation of a 0.5° CRU grid cell, H_{STN} is the exact station elevation and T_{LAPSE} is a temperature lapse rate (fixed at -0.0065 °Cm^{-1} for this study). Station locations with a very large difference between the exact station location and the elevation of the grid cell are excluded from the analysis, under the assumption that either the reported station elevation or the station's geographical location is wrong.

For the determination of the correlation, only complete pairs of ground observations and grid values are considered. This means that for each specific case no correlation is determined when either the ground station or the grid (or both) have no value. The correlation of all monthly average air temperature values from 1981 until 2010 is plotted in Figure 46. Figure 47 shows the same monthly correlation values, but sorted per month. The CRU Tavg product has good correlation with ground observations. In general there is an underestimation for the colder areas with lower temperatures. Table 5 lists the correlation parameters for average air temperature in CRU and corresponding ground observations in the Mekong basin.

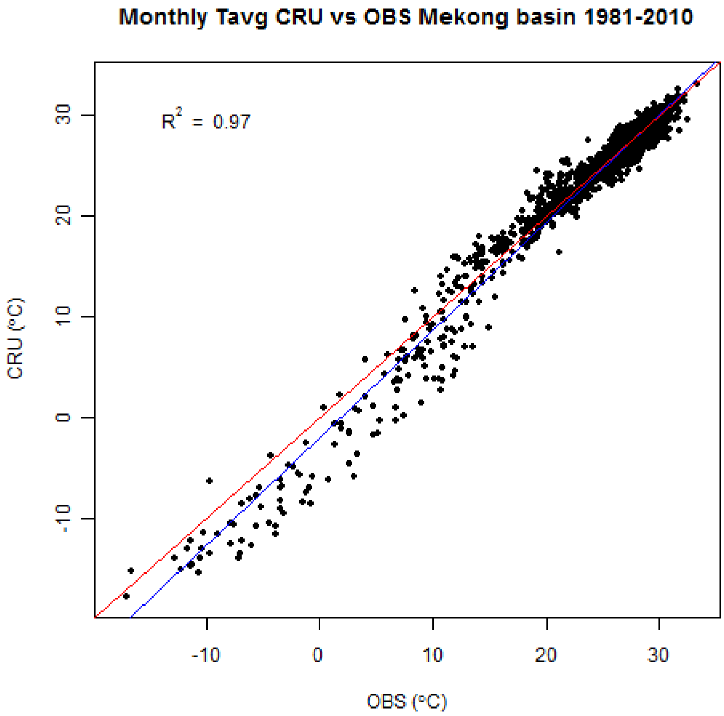

Figure 46: Correlation of ground observations and CRU (monthly values 1981-2010) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

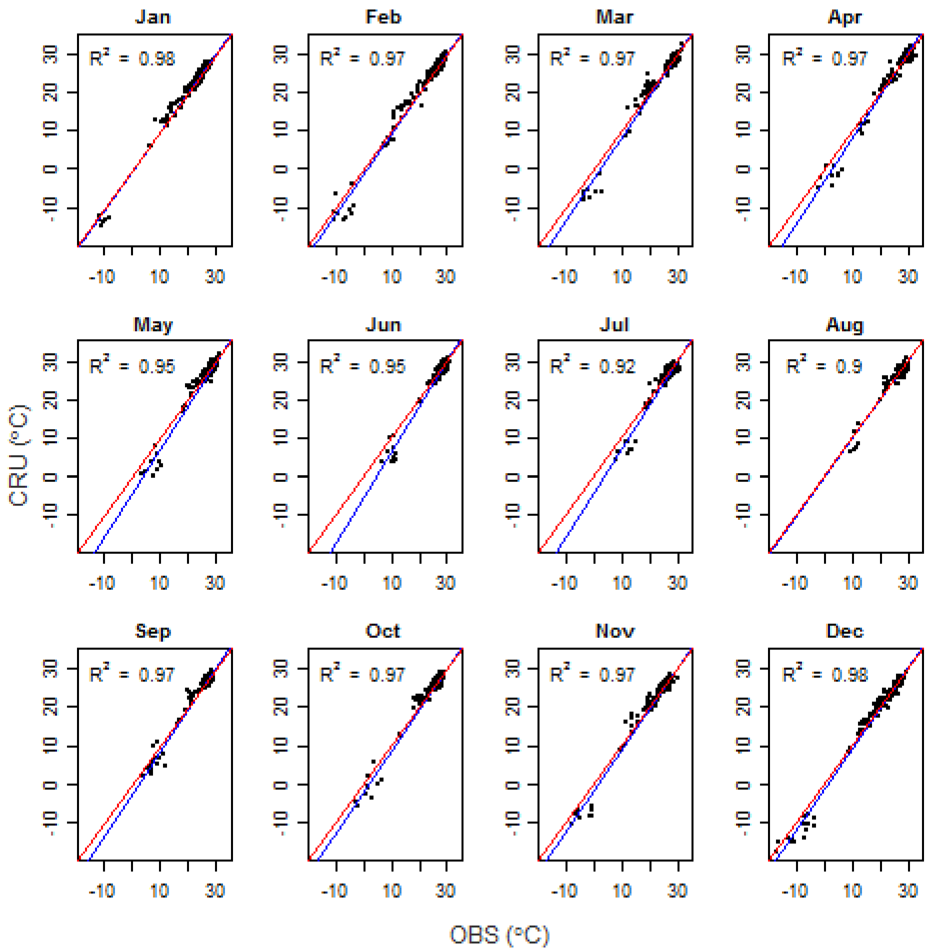

Figure 47: Correlation of ground observations and CRU (monthly values 1981-2010) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.5.2 Precipitation

To evaluate the performance of the CRU product for precipitation, the correlation between the ground observations and the gridded precipitation values is determined. Unlike for air temperature, no correction for elevation differences between the grid cell and the exact station location are made. In Figure 48 the correlation between CRU and the ground stations for all monthly values between 1981 and 2010 is shown. As is evident from the linear regression line, the general observation is a slight underestimation of daily precipitation in CRU compared to the ground stations and the scatter is quite large ($R^2 = 0.56$). Looking at the correlation of daily values sorted by month (Figure 49), shows that the underestimate is largest during the months with high precipitation values. Table 5 lists the correlation parameters for precipitation in CRU and corresponding ground observations in the Mekong basin.

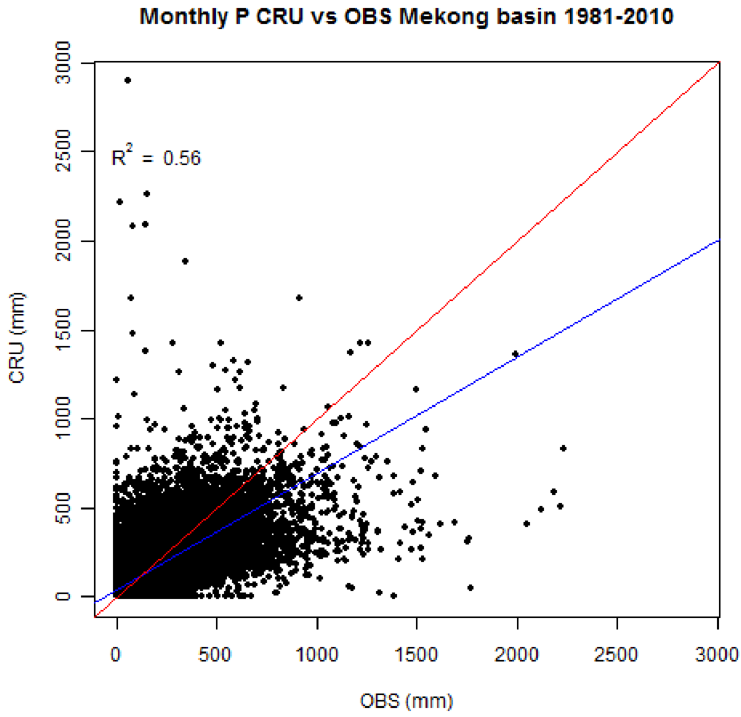

Figure 48: Correlation of ground observations and CRU (monthly values 1981-2010) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

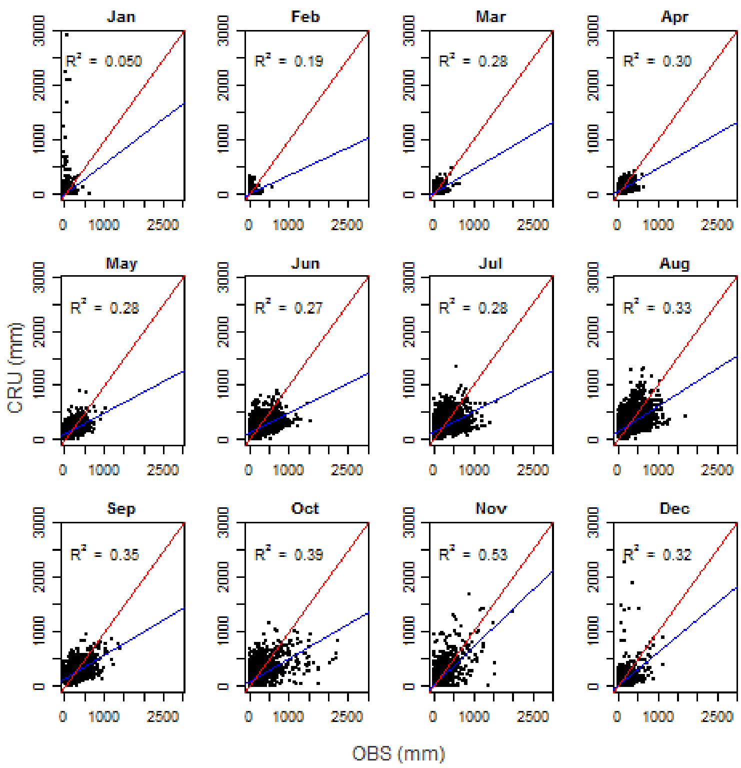

Figure 49: Correlation of ground observations and CRU (monthly values 1981-2010) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

4.6 Data product selection

Based on the analysis of the performance of the APHRODITE, ERA-Interim and PRINCETON and CRU data products in the Mekong basin as described in the previous paragraphs, a selection can be made which data product best reflects the observed temperature and precipitation in the Mekong basin. Selection is based on the correlation graphs as presented as well as on the summary statistics as show in Table 5. The following three statistical parameters have been used:

- Bias expresses the average difference between the gridded data and the observed data in %.
- Pearson coefficient of correlation (R) is dimensionless. A value of 1 means exact linear fit.
- Nash-Sutcliffe criterion is widely used for evaluation of (hydrological) models with observed data. N-S is dimensionless criterion in the range between negative infinitive to 1.0. With 1.0 indicating that model data is exactly same as observations.

CRU was selected for the long-term trends (1901-2010) since this is the only data product available covering such a long period. The performance of the CRU dataset, compared to observations, is good. For temperature the correlation (R) is high, and the bias is low. For precipitation this also holds.

PRINCETON was selected to be used for the recent climate regarding temperatures. Although the APHRODITE dataset performs even somewhat better the product only offers average temperature and no minimum or maximum ones.

APHRODITE was selected as the best data product to represent precipitation. From the Table is clear that the product has a better performance in the Mekong basin than the ERA-Interim and PRINCETON products. The APHRODITE product performance is very high during the monsoon months, when most of the precipitation in the Mekong basin occurs.

Table 5: Statistical parameters comparing gridded data products to observations.

			Pearson's correlation coefficient	Bias (%)	Nash-Sutcliffe criterion
Tavg	Daily data	APHRODITE	0.99	0.5	0.99
		ERA-Interim	0.96	-5.0	0.88
		PRINCETON	0.96	-1.1	0.91
	Monthly aggregated data	APHRODITE	1.00	0.2	0.99
		ERA-Interim	0.97	-5.1	0.91
		PRINCETON	0.98	-1.1	0.96
		CRU	0.98	-1.4	0.96
P	Daily data	APHRODITE	0.71	-13.5	0.49
		ERA-Interim	0.33	28.7	0.05
		PRINCETON	0.09	0.9	-0.99
	Monthly aggregated data	APHRODITE	0.91	-13.6	0.80
		ERA-Interim	0.68	28.1	0.38
		PRINCETON	0.73	0.3	0.50
		CRU	0.75	0.6	0.54

5 Baseline climate dataset

5.1 Bias correction

The previous Chapter showed that the PRINCETON product was selected as it represents the temperature best, and APHRODITE represents precipitation best. Both products have been generated based on observations from all around the world. Despite this, the fit between the observations in the LMB and the gridded dataset is still not optimal as shown in the previous Chapter. The first reason for this is that during the generation of these products most likely a limited number of station data within the LMB were used as the product was generated at the global level. Second reason is that the gridded products were not specifically focusing on precipitation and temperature only, but other observations (and at other heights) might have compromised the fit with the observations used in the previous Chapter.

It was therefore selected to undertake an additional bias correction for the PRINCETON and APHRODITE products to create the best base line data set available for the LMB. Since observation before 1980 are rare and unreliable it was decided not to undertake a bias correction for the CRU dataset.

5.1.1 Air temperature

The PRINCETON product is selected as a basis for the baseline climate dataset in the Mekong basin (section 4.6). This dataset is bias-corrected using the updated meteorological ground dataset (section 3.2.2). The bias-correction is applied on a monthly basis. Therefore the bias of the PRINCETON product with respect to the ground observations is calculated for monthly aggregated data. The daily temperature data is averaged to monthly data for the ground observations as well as the gridded data. This is done for each month from 1981 until 2008 (336 months).

$$T_{PRINCETON_{y,m}} = \frac{1}{n}\sum_{i=1}^{n} T_{PRINCETON_{y,m,i}}$$

$$T_{OBS_{y,m}} = \frac{1}{n}\sum_{i=1}^{n} T_{OBS_{y,m,i}}$$

Subsequently, for 12 months (January-December) average temperatures are calculated by averaging the monthly temperatures for the period 1981-2008.

$$T_{PRINCETON_{m}} = \frac{1}{28}\sum_{i=1981}^{2008} T_{PRINCETON_{y,m}}$$

$$T_{OBS_m} = \frac{1}{28}\sum_{i=1981}^{2008} T_{OBS_{y,m}}$$

For each station, the average bias of the PRINCETON grid value with respect to the ground observation is calculated for each of the 12 months (January-December).

$$Bias_m = T_{OBS_m} - T_{PRINCETON_m}$$

Thus, for each station (102 stations), 12 values for the bias (in °C) are calculated (January-December). These biases are subsequently used to generate 12 interpolated bias-grids, which are used to correct the original daily PRINCETON gridded data. A positive bias indicates overestimated temperature in the PRINCETON product with respect to ground observations; a negative bias indicates underestimated temperature in the PRINCETON product with respect to ground observations. During the data processing according to the equations listed above, only complete pairs of records are considered. For the PRINCETON dataset, the grids are always complete during the 1981-2008 period. The ground station records are not always complete. Thus, when averaging daily values, to monthly values, only months, completely covered by daily observations are considered. The same months are then excluded from the PRINCETON dataset, to ensure a consistent comparison and derivation of average bias.

The average bias for each month at each station location is spatially interpolated to create the possibility to apply a bias-correction to each individual grid cell. A well-established spatial interpolation method is 'kriging' [*Stein*, 1999]. One of the main advantages of using kriging instead of other interpolation techniques is that kriging compensates for data clustering. This is important as the station locations in the Mekong basin are irregularly distributed over the area, and data clustering is therefore a concern. We apply an ordinary kriging interpolation to generate spatially interpolated bias-grids.

As an example, Figure 50 shows the average bias at station locations for July and the resulting bias grid after spatial interpolation, which is subsequently used to correct all daily grids for days in July in the original PRINCETON datasets. The bias-grids for all months are displayed in Appendix 1.

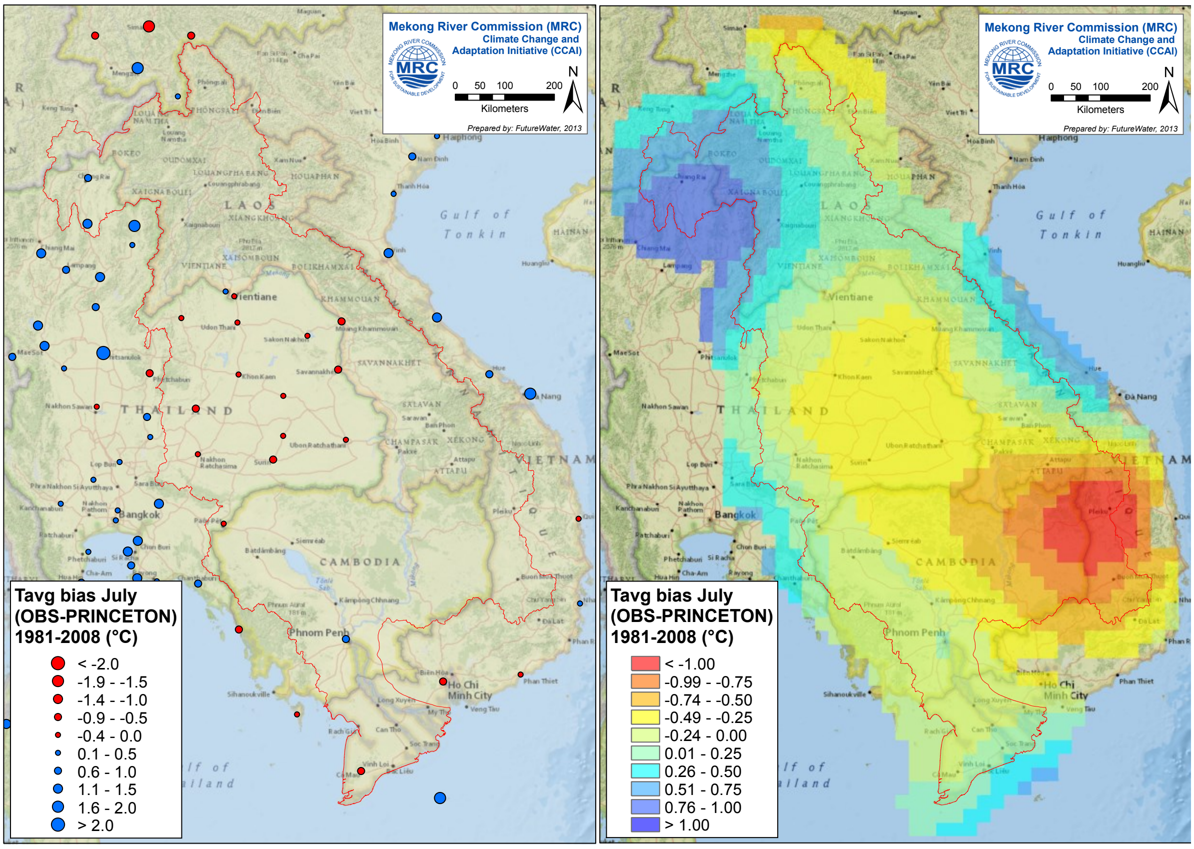

Figure 50: Average temperature bias for July 1981-2008 at station locations (left panel) and interpolated gridded bias at 0.25° spatial resolution (right panel). A positive bias indicates overestimated temperature in the PRINCETON product with respect to ground observations; a negative bias indicates underestimated temperature in the PRINCETON product with respect to ground observations.

The PRINCETON temperature data is bilinearly interpolated from 0.5° to 0.25° spatial resolution, before the bias-correction is applied at 0.25° spatial resolution:

$$T_{bias-corrected_{y,m,i}} = T_{PRINCETON_{y,m,i}} - Bias_m$$

Subsequently a correction is done using a digital elevation model (DEM) at 0.25° spatial resolution to incorporate this additional information when interpolating from 0.5° to 0.25° spatial resolution. The difference in elevation between the DEM at 0.5° and the DEM at 0.25° spatial resolution is used in combination with a temperature lapse rate to correct for the elevation differences:

$$T_{bias-and\ elevation-corrected_{y,m,i}} = T_{bias-corrected_{y,m,i}} + T_{lapse} \cdot (H_{0.5} - H_{0.25})$$

We use the same environmental temperature lapse rate as used in the original PRINCETON dataset (0.0065 °C m^{-1}, [*Sheffield et al.*, 2006]).

5.1.2 Precipitation

The APHRODITE product is selected as a basis for the baseline climate dataset in the Mekong basin (section 4.6). This dataset is bias-corrected using the updated meteorological ground dataset (section 3.2.2). The bias-correction is applied on a monthly basis. Therefore the bias of the APHRODITE product with respect to the ground observations is calculated for monthly aggregated data. The daily precipitation data is summed to monthly data for the ground observations as well as the gridded data. This is done for each month from 1981 until 2007 (324 months).

$$P_{APHRODITE_{y,m}} = \sum_{i=1}^{n} P_{APHRODITE_{y,m,i}}$$

$$P_{OBS_{y,m}} = \sum_{i=1}^{n} P_{OBS_{y,m,i}}$$

Subsequently, for 12 months (January-December) average precipitation sums are calculated by averaging the monthly precipitation sums for the period 1981-2008.

$$P_{APHRODITE_m} = \frac{1}{27} \sum_{i=1981}^{2007} P_{APHRODITE_{y,m}}$$

$$P_{OBS_m} = \frac{1}{27} \sum_{i=1981}^{2007} P_{OBS_{y,m}}$$

For each station, the average bias of the APHRODITE grid value with respect to the ground observation is calculated for each of the 12 months (January-December).

$$Bias_m = \left(-1 \cdot \left(1 - \frac{P_{APHRODITE_m}}{P_{OBS_m}}\right)\right) \cdot 100\%$$

Thus, for each station (386 stations), 12 values for the bias (in %) are calculated (January-December). These biases are subsequently used to generate 12 interpolated bias-grids, which are used to correct the original daily APHRODITE gridded data. During the data processing according to the equations listed above, only complete pairs of records are considered. For the APHRODITE dataset, the grids are always complete during the 1981-2007 period. The ground station records are not always complete. Thus, when summing daily values to monthly values, only months, completely covered by daily observations are considered. The same months are then excluded from the APHRODITE dataset, to ensure a consistent comparison and derivation of average bias.

The average bias for each month at each station location is spatially interpolated to create the possibility to apply a bias-correction to each individual grid cell. A well-established spatial interpolation method is 'kriging' [*Stein*, 1999]. One of the main advantages of using kriging instead of other interpolation techniques is the feature of kriging to compensate for data clustering. As the station locations in the Mekong basin are irregularly distributed over the area, data clustering is an issue here. We apply an ordinary kriging interpolation to generate spatially interpolated bias-grids.

Figure 51 shows the average bias at station locations for September and the resulting bias grid after spatial interpolation, which is subsequently used to correct all daily grids for days in September in the original APHRODITE datasets. The bias-grids for all months are displayed in Appendix 1.

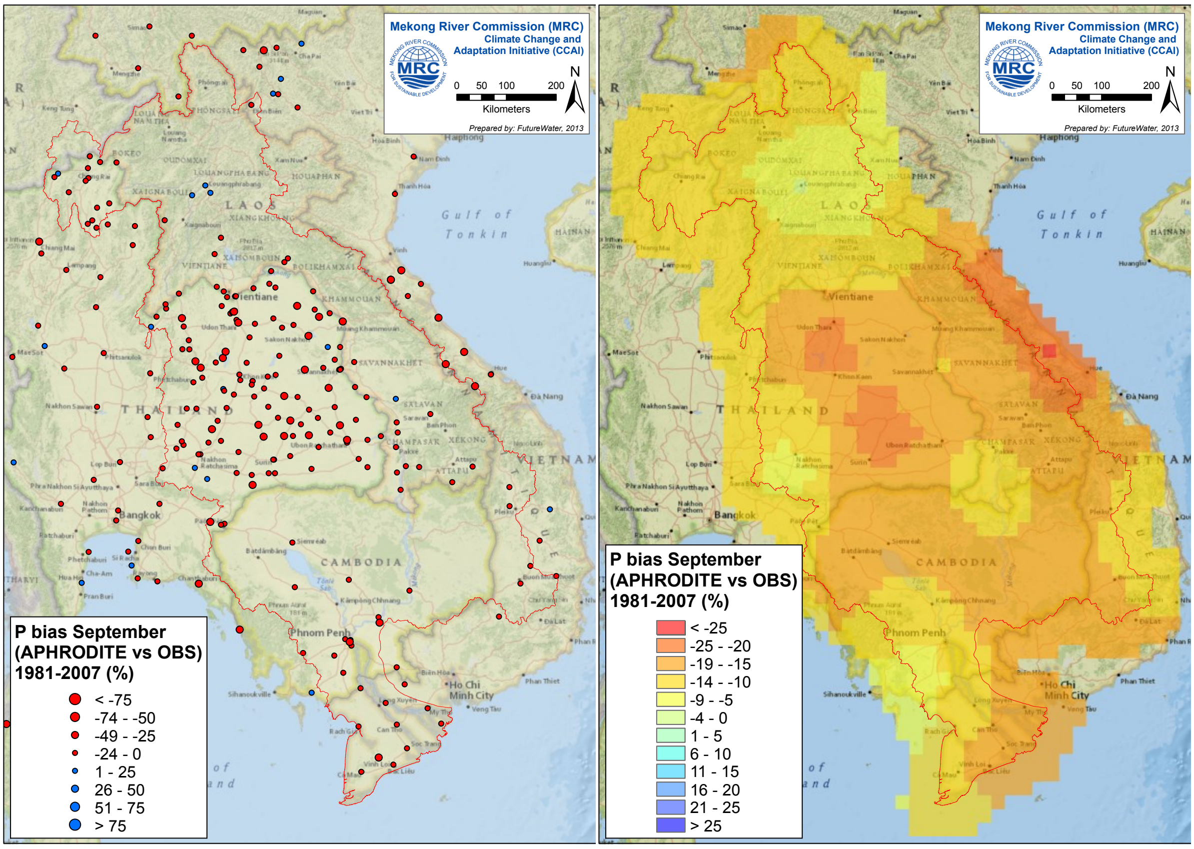

Figure 51: Average precipitation bias for September 1981-2007 at station locations (left panel) and interpolated gridded bias at 0.25° spatial resolution (right panel). A positive bias indicates overestimated precipitation in the APHRODITE product with respect to ground observations; a negative bias indicates underestimated precipitation in the APHRODITE product with respect to ground observations.

The APHRODITE precipitation data is bias-corrected at 0.25° spatial resolution:

$$P_{bias-corrected_{y,m,i}} = \frac{P_{APHRODITE_{y,m,i}}}{\frac{1}{100} \cdot (100 + Bias_m)}$$

5.2 Final data product

5.2.1 Air temperature

Figure 52 shows the average annual air temperature for the bias-corrected average air temperature product for 1981-2008 in comparison to the uncorrected product. Apart from the slightly changed temperatures resulting from the bias-correction, it is also clear that the additional downscaling from 0.25° to 0.5° spatial resolution using the digital elevation model provides additional details in the temperature fields. The monthly averaged grids for mean, maximum and minimum air temperature are listed in Appendix 2.

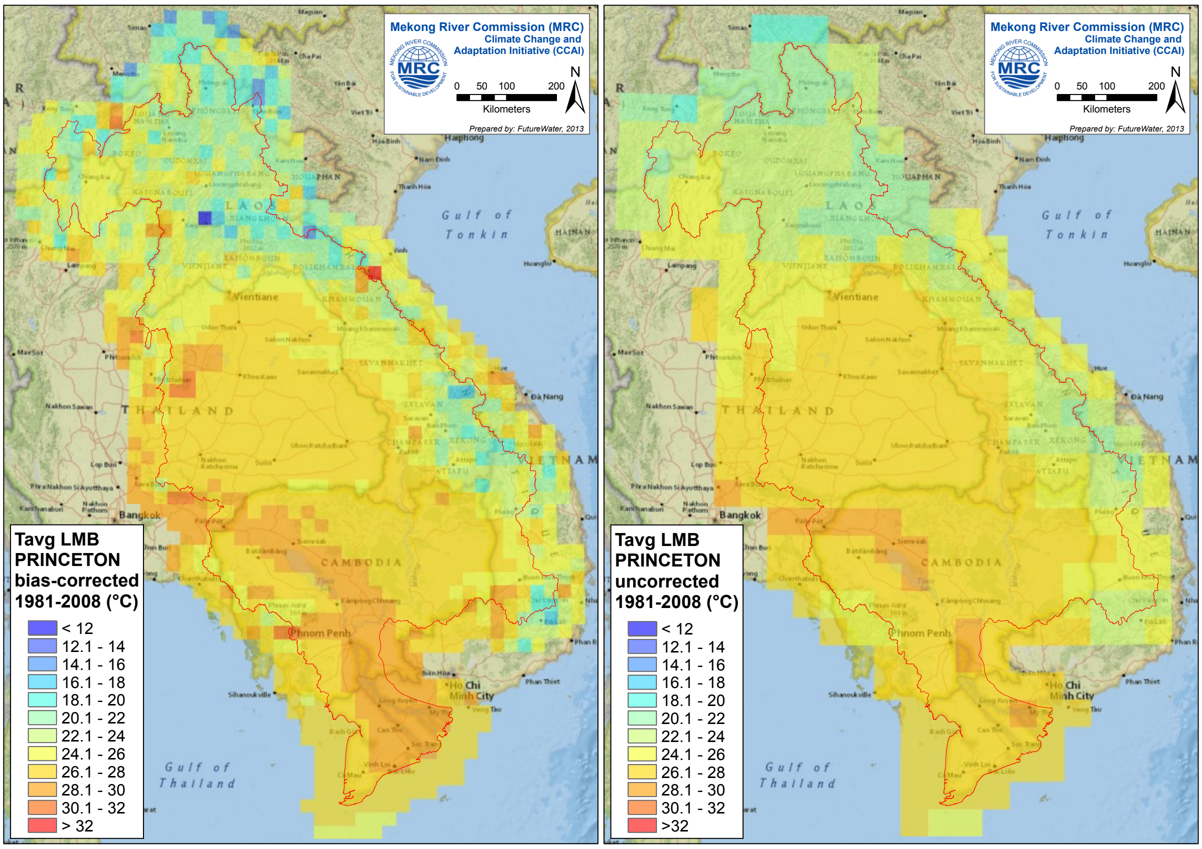

Figure 52: Bias corrected average air temperature 1981-2008 (left panel) and uncorrected average air temperature 1981-2008 (right panel).

Figure 53 and Figure 54 show the results of renewed calculations for the correlation of the bias-corrected gridded average air temperature and the ground observations. The blue linear regression line has moved closer to the 1:1 line compared to Figure 37 and Figure 38, indicating the better correlation of the bias-corrected product to the ground observations.

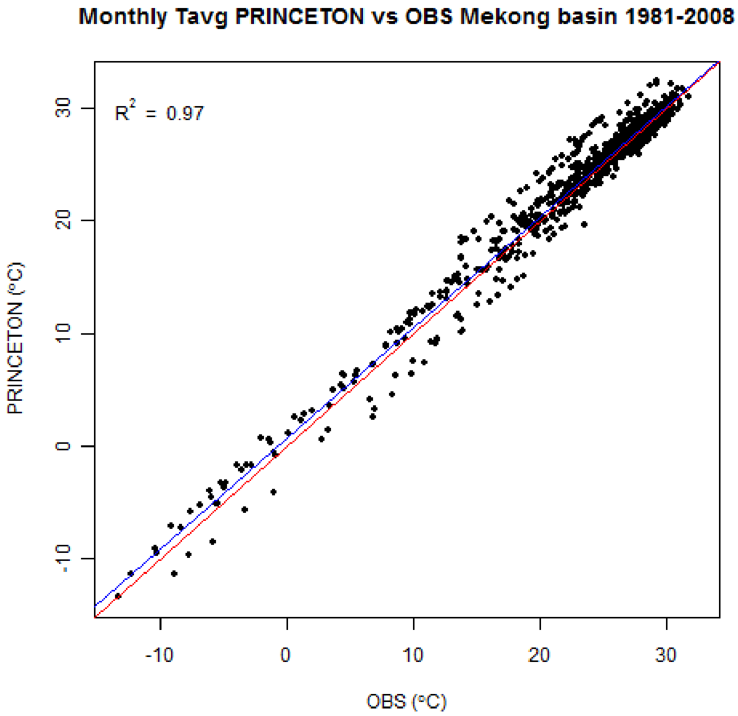

Figure 53: Correlation of ground observations and bias-corrected PRINCETON (monthly averaged values 1981-2008) for average air temperature in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

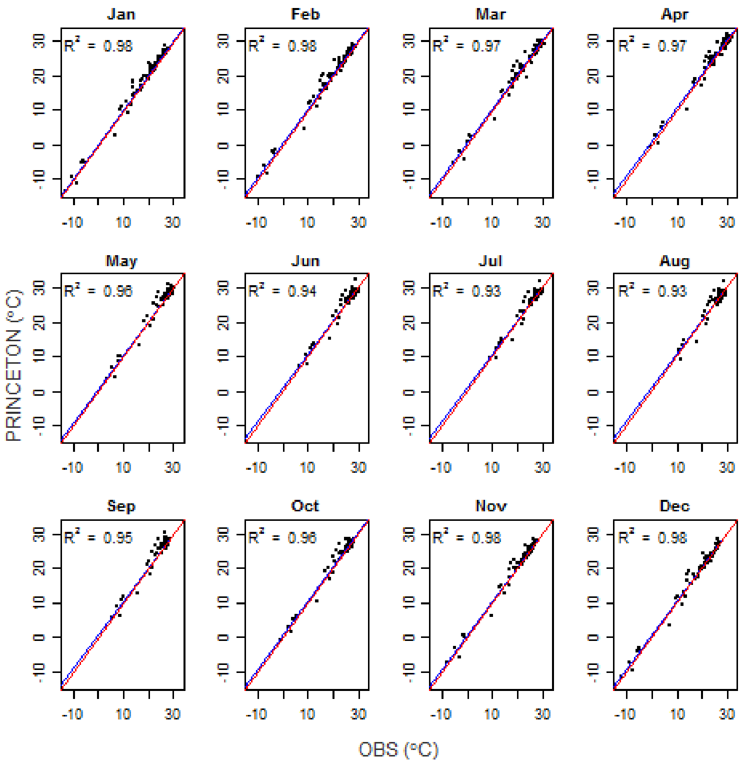

Figure 54: Correlation of ground observations and bias-corrected PRINCETON (monthly averaged values 1981-2008) for average air temperature in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

Table 6 lists the correlation parameters for the uncorrected and bias-corrected temperature data for direct comparison. Although the correlation was already very good, bias-correction lead to an even higher correlation.

5.2.2 Precipitation

Figure 55 shows the average annual precipitation sum for the bias-corrected precipitation product for 1981-2007 in comparison to the uncorrected product. As it is obvious from the bias grids that precipitation was in general underestimated in the original APHRODITE product, the bias-corrected product shows a significant increase in precipitation for most areas. The monthly averaged precipitation grids are listed in Appendix 2.

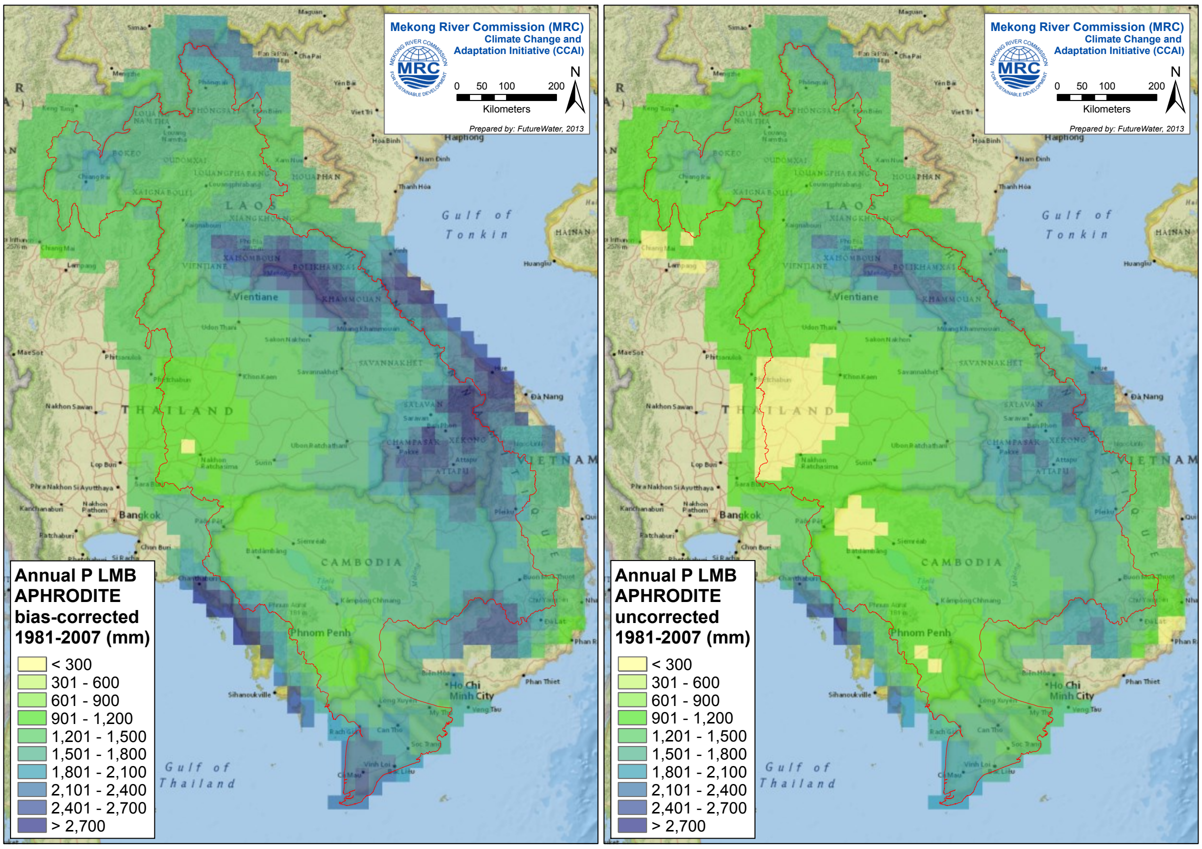

Figure 55: Bias corrected average annual precipitation 1981-2007 (left panel) and uncorrected average annual precipitation 1981-2007 (right panel).

Figure 56 and Figure 57 show the results of renewed calculations for the correlation of the bias-corrected gridded precipitation and the ground observations. The blue linear regression line has moved much closer to the 1:1 line compared to Figure 19 and Figure 20, indicating the better correlation of the bias-corrected product to the ground observations. The general underestimate that is observed for the original APHRODITE product is still visible for the largest precipitation events, although the magnitude of underestimation is smaller. Total precipitation sums are now overestimated slightly (Table 6)

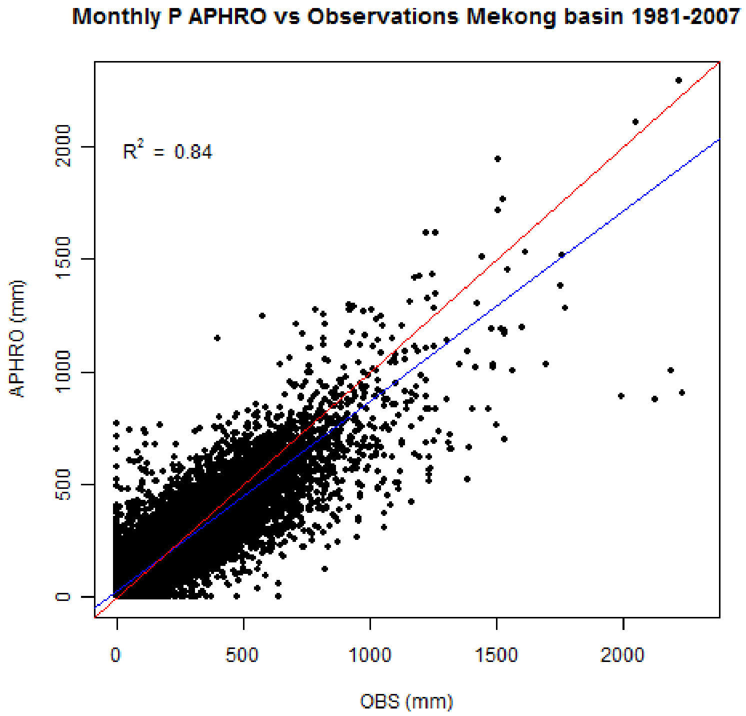

Figure 56: Correlation of ground observations and bias-corrected APHRODITE (monthly summed values 1981-2007) for precipitation in the Mekong basin. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

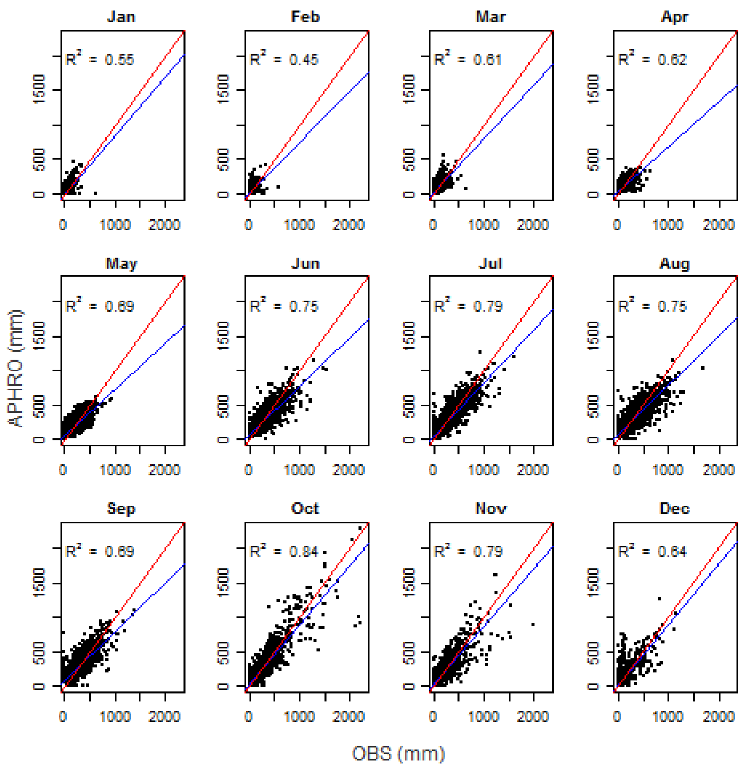

Figure 57: Correlation of ground observations and bias-corrected APHRODITE (monthly summed values 1981-2007) for precipitation in the Mekong basin per month. The blue line indicates a linear regression line, the red line indicates the 1:1 correlation.

Table 6 lists the correlation parameters of the bias-corrected precipitation dataset and the uncorrected dataset for direct comparison. The improvement of the bias-correction is clear from this table.

5.3 Conclusions

The best performance gridded datasets over the LMB (PRINCETON for temperature and APHRODITE for precipitation) have been corrected using monthly bias correction grids. These bias correction grids are based on the differences between observations and the original data product. The final bias-corrected harmonized gridded data have a somewhat better correlation compared to the original products (Table 6). Since the correlations were already high, further improvement was minor. Also bias improvement for temperature was small, since the original product was already having a very small bias (~ 1%). However, the bias correction for precipitation was very effective and the remaining bias is about 5%.

Overall, it can be concluded that the created gridded data is the best available harmonized climate database over the LMB at a resolution of 25 km and including daily precipitation, and average, minimum and maximum temperature.

Table 6: Correlation parameters for uncorrected and bias-corrected temperature and precipitation data.

			Pearson's correlation coefficient	Bias (%)	Nash-Sutcliffe criterion
Tavg	Daily data	Uncorrected	0.96	-1.1	0.91
		Corrected	0.96	1.0	0.93
	Monthly data	Uncorrected	0.98	-1.1	0.96
		Corrected	0.99	0.9	0.97
P	Daily data	Uncorrected	0.71	-13.5	0.49
		Corrected	0.71	5.4	0.49
	Monthly data	Uncorrected	0.91	-13.6	0.80
		Corrected	0.92	5.0	0.84

6 Climatic trend analysis

6.1 Introduction

One of the most relevant questions asked is whether the climate in the LMB has been changing over the last decades. In order to answer this question the datasets as selected and corrected as described in the previous Chapters will be analyzed.

The so-called climatic trend analysis will take place at two time frames. First of all, the long-time trends over the period 1901-2012 will be assessed. As discussed previously the CRU dataset will be used to this end. Given the fact that most climate change can be expected over the last few decades (and which will be proven in the next sections) also focus will be put on the period 1981-2010 using the PRINCETON (temperature) and APHRODITE (precipitation) bias-corrected datasets.

The climatic trend analysis will be performed for the entire basin as well as for each individual BDP sub-area within the LMB. An overview of the 15 sub-areas within the Mekong River Basin is shown in Figure 58. The corresponding sub-areas names can be found in Table 7.

Table 7: Sub-area descriptions and surface areas. (Source: BDP Atlas, 2011).

Region and catchment groupings	Sub-area code	Area (km²)
A: Northern Highlands		
Northern Lao PDR	1L	80,544
Chiang Rai, northern Thailand	2T	17,321
B: Central Plateau & Highlands		
Nong Khai / Songkhram	3L (Lao PDR)	3,299
	3T (Thailand)	47,260
Central Lao PDR	4L	87,093
Mun / Chi River Basin	5T	119,163
C: Southeast Highlands		
Southern Lao PDR	6L (Lao PDR)	15,861
	6C (Cambodia)	3,210
Se San / Sre Pok / Se Kong river basins	7L (Lao PDR)	22,585
	7C (Cambodia)	26,377
	7V (Viet Nam)	29,385
D: Southern Region		
Kratie	8C	22,680
Tonle Sap basin	9C	86,045
Mekong delta	10C (Cambodia)	23,346
	10V (Viet Nam)	35,158

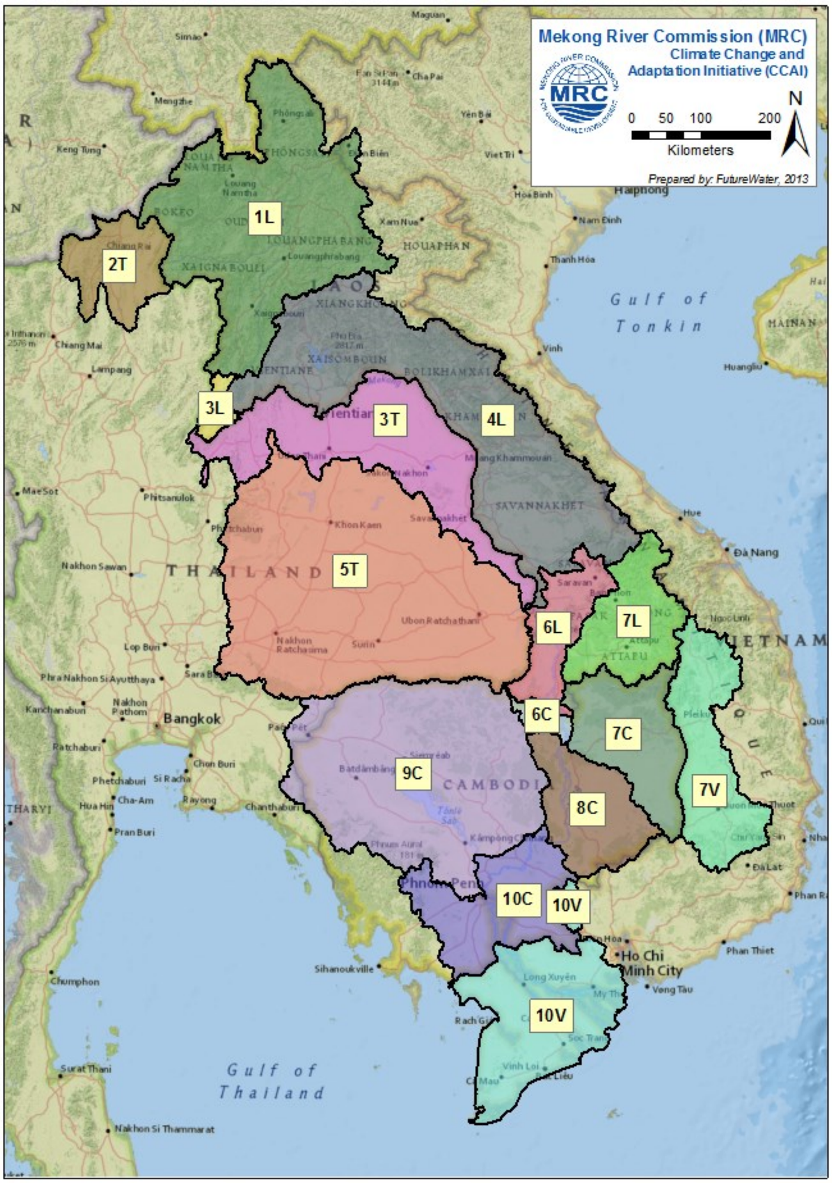

Figure 58: Overview of the 15 selected sub-areas and their IDs within the LMB (Source: BDP, 2011).

6.2 Long-term climatic trend analysis (1901-2012)

6.2.1 Basin analysis

The climatic trend analysis over the entire LMB is performed on an annual and monthly basis, and is conducted for precipitation and the average temperature. The entire analysis will cover the period 1901-2012 (113 years). For climate trend analysis it is interesting to analyze the individual years and months throughout the entire period, as well as comparing periods with each other, that include multiple years. Four periods are defined that contain multiple years of climate data:

- P_{all}: Years 1901-2012 (entire period, 113 years)

- P_1: Years 1901-1940 (40 years)
- P_2: Years 1941-1980 (40 years)
- P_3: Years 1981-2012 (32 years)

Century analysis

For each month in the period 1901-2012, the monthly values were averaged over the 15 sub-basins in order to calculate monthly basin average for both precipitation and average temperature. Subsequently the annual basin precipitation was calculated by summarizing these monthly basin averages, while the annual basin temperature was calculated by averaging the monthly basin averages.

Figure 59 represents the annual precipitation and average temperature for the entire basin over the period 1901-2012. The solid line represents the 10-year moving average. Considering the entire period, it is clear that there is an overall increasing precipitation trend. During the first 30 years a distinct decreasing trend is present, where after it increases during 1935-1950. Another strong increasing trend can be noticed during the period 1990-2012. Linear regression shows an increasing trend of approximately 15 mm/10 years throughout the entire period 1901-2012.

For the period 1901-1970 there is no distinct trend in temperature. However, a strong increasing trend in temperature can be noticed from 1970 onwards. Also the largely debated stabilizing temperatures during the 2000-2012 can be observed. Linear regression shows an increase of 0.05 °C/10 years throughout the period 1901-2012.

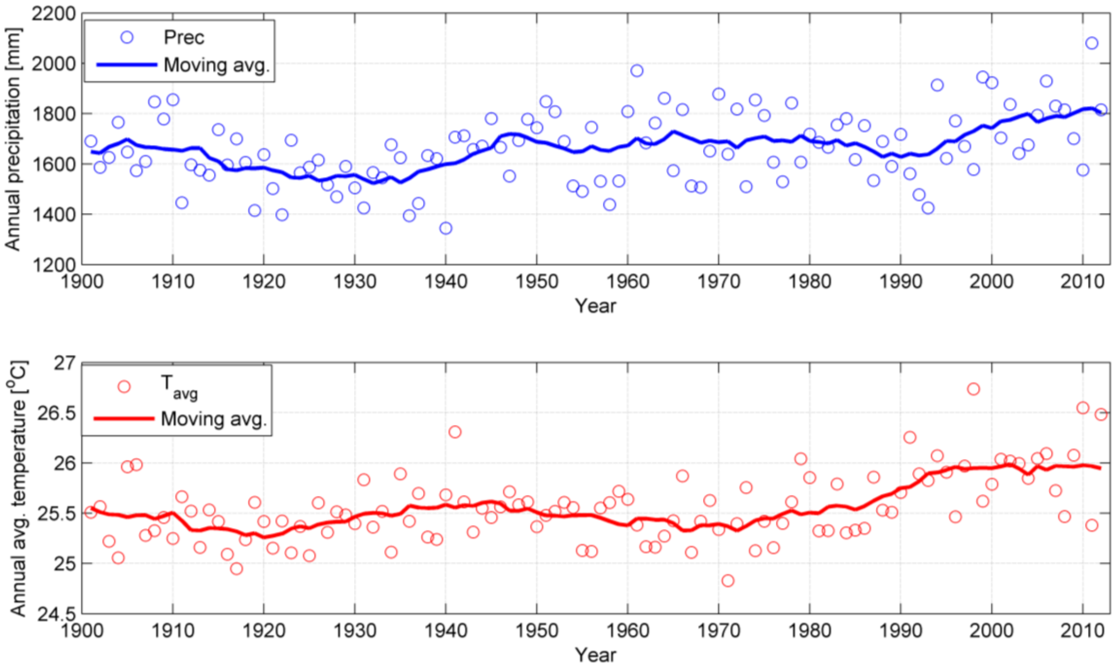

Figure 59: Annual precipitation (top) and annual average temperature (bottom) for the period 1901-2012, over the LMB. Solid lines represent the 10-year moving average.

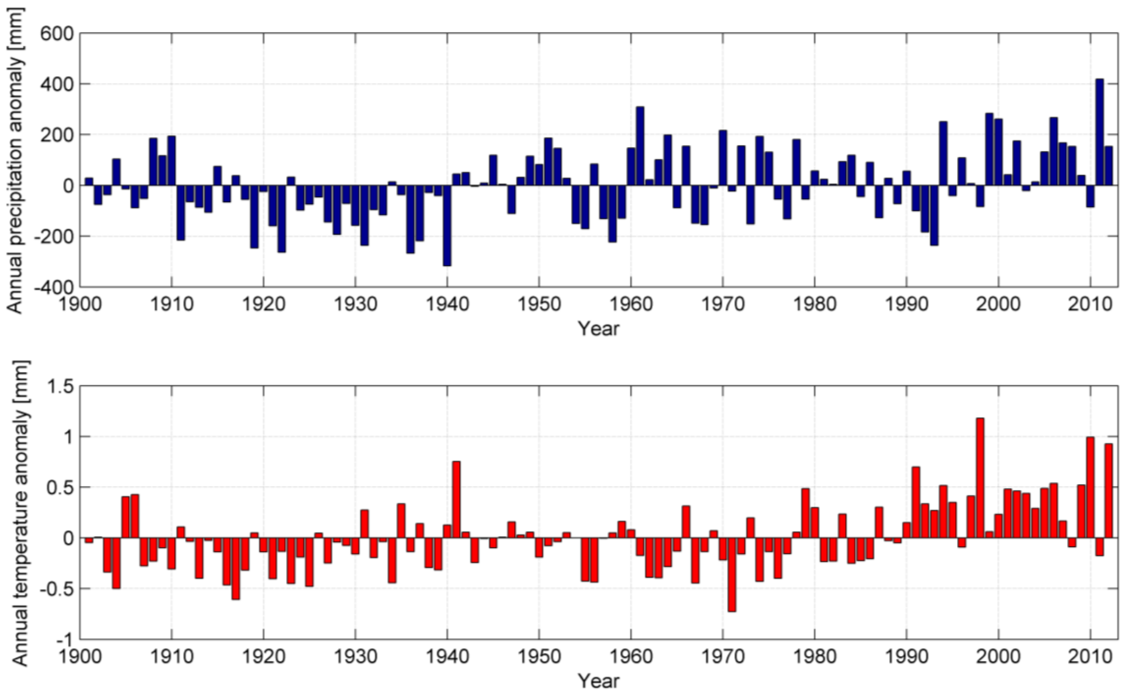

Figure 60: Annual precipitation (top) and temperature (bottom) anomalies with respect to the long-term average (1901-2012).

Annual precipitation and temperature anomalies with respect to the long-term average (1901-2012) are shown in Figure 60. It is clear that the first 40 years are drier with respect to the long-term average. The period 1941-1998 shows year-to-year fluctuations in above and below average precipitation. Finally, the period 1999-2012 is the wettest period with respect to the long-term average. For temperature, the period 1901-1990 is mainly colder than the long-term average, whereas the period from 1990 onwards is warmer than the long-term average.

Multi-decade analysis

The entire period (P_{all}) was split into three blocks, denoted as P_1 (1901-1940), P_2 (1941-1980), and P_3 (1981-2012), as was mentioned under Section 6.2.1. A boxplot was made for each of these blocks, both for precipitation and temperature. These results are shown in Figure 61. For the precipitation it can be concluded that the median annual precipitation during P_2 and P_3 has increased with respect to P_1. The median annual precipitation during P_2 and P_3 is more or less equal. Another interesting aspect is that the inter-annual variability during P_2 was larger than during the other two periods, especially with respect to P_1.
A final note that can be made is that the number of drier years has decreased in P_3 with respect to P_2.

For temperature there is no substantial difference between P_1 and P_2. There is, however, a clear shift for P_3 with respect to the previous two periods. The median temperature has increased with approximately 0.3 °C from P_2 to P_3. Also the distance between the upper and lower end of the box has increased, which denotes a more extreme climate during the last period 1981-2012.

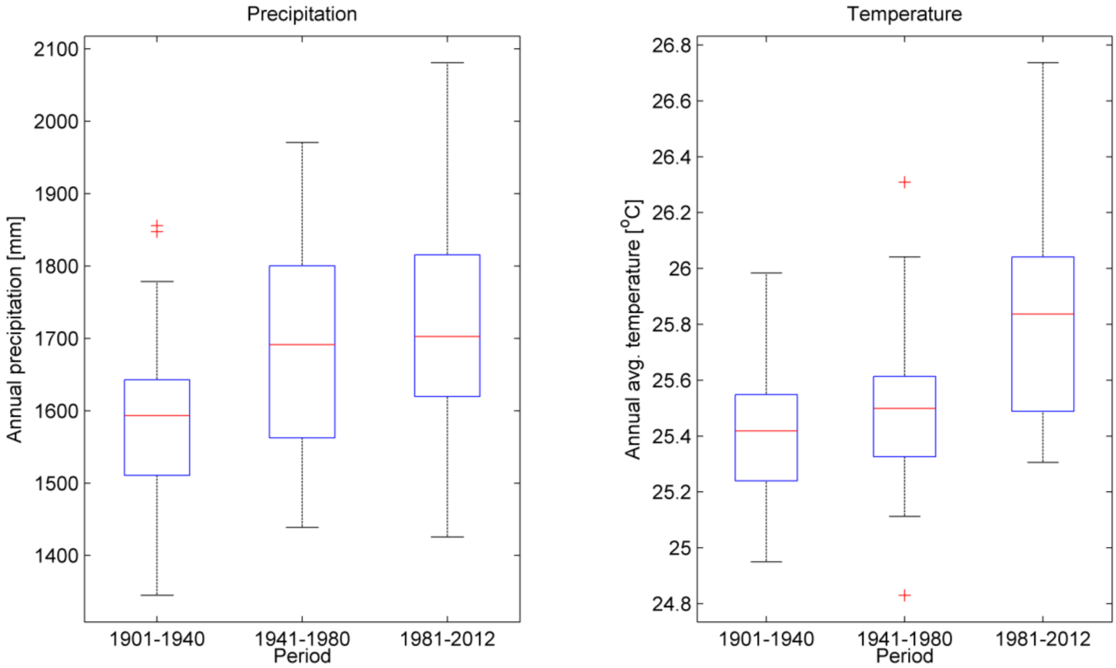

Figure 61: Boxplots[3] of annual precipitation (left) and annual average temperature (right). Each box represents the variation in annual precipitation or average temperature within the specified period. Horizontal red lines represent the median. Outliers are denotes as red crosses.

Monthly analysis

Besides the annual analysis, the basin precipitation and average temperature have been analyzed on a monthly basis as well. These monthly results are shown in Appendix 3.

For precipitation, the months November through April can be categorized as being the dry months (<100 mm precipitation). May through October are the wetter months. These wetter months also show a substantial variation in monthly precipitation. Based on these monthly results it cannot be concluded that there is a strong monthly trend visible, although there is a small increasing trend for April, July, October and November.

For temperature the picture is more evident. During the drier months (Nov-Apr), monthly temperature variations are more apparent than during the wet months. An increase in temperature can be seen for the months November through March, with the December-February having the strongest temperature increase throughout 1901-2012. January shows a

[3] A boxplots displays variation within data. The bottom and top of the box indicate the first and third quartiles, and the band inside the box is the second quartile (the median). The lines indicate the minimum and maximum. Outliers are presented as a small +.

small decrease during the first 60 years of the 20th century, where after a strong increase in temperature can be seen for the remainder of the period.

Summarizing

A summary of the basin climate analysis is shown in Table 9 and **Error! Reference source not found.**. This table shows the trend per period, annual averages per period, and finally, monthly averages per period.
For precipitation it is clear that the strongest increase (61.3 mm/10 year) was noticed during the period 1981-2012, while the first period (1901-1940) a strong decrease of 48.6 mm/10 year occurred. The entire period (1901-2012) shows an increase of approximately 15 mm/10 year.

Temperature also shows the strongest increase (approx. 0.2 °C/10 year) during the period 1981-2012. During 1901-1940 a small increase of 0.01 °C/10 year was noticed, while a small decrease of 0.04 °C/10 year was noticed during 1941-1980. The entire period 1901-2012 shows an increase in temperature of 0.05 °C/10 year.

Table 8: Summary of precipitation statistics for the entire LMB. Arrows up indicate a increase in precipitation by more than 10 mm compared to the entire period of 112 years (1901-2012). Arrows down indicate decrease in precipitation by more than 10 mm compared to the entire period. Horizontal arrows indicate precipitation changes less than 10 mm compared to entire period.

Precipitation	*1901-2012*	*1901-1940*	*1941-1980*	*1981-2012*
Annual Total [mm]	1662	↓ 1589	↑ 1688	↑ 1721
Trend [mm/10 year]	15.0	-48.6	0.7	61.3
Monthly Average [mm]				
Jan	16	→ 14	→ 15	→ 18
Feb	18	→ 18	→ 17	→ 18
Mar	39	→ 38	→ 42	→ 38
Apr	79	→ 70	→ 85	→ 84
May	182	→ 173	→ 185	→ 190
Jun	228	→ 221	→ 234	→ 229
Jul	249	→ 243	→ 249	→ 256
Aug	282	↓ 266	→ 291	→ 291
Sep	270	→ 266	→ 279	→ 265
Oct	181	↓ 167	→ 176	↑ 204
Nov	88	→ 83	→ 82	↑ 102
Dec	29	→ 29	→ 32	→ 27

Table 9: Summary of temperature statistics for the entire LMB. Arrows up indicate a temperature increase more than 0.1°C compared to the entire period of 112 years (1901-2012). Arrows down indicate temperature decrease by more than 0.1°C compared to the entire period. Horizontal arrows indicate temperature change less than 0.1°C compared to entire period.

Temperature	*1901-2012*	*1901-1940*	*1941-1980*	*1981-2012*
Annual Average [°C]	25.6	↓ 25.4	→ 25.5	↑ 25.8
Trend [°C/10 year]	0.05	0.01	-0.04	0.20
Monthly Average [°C]				
Jan	22.3	↓ 22.0	↓ 22.1	↑ 22.8
Feb	24.1	↓ 23.8	↓ 23.9	↑ 24.6
Mar	26.0	→ 25.9	↑ 26.1	↑ 26.2
Apr	27.8	→ 27.8	→ 27.7	↑ 28.0
May	27.7	→ 27.7	→ 27.7	→ 27.7
Jun	27.3	→ 27.2	→ 27.2	→ 27.3
Jul	26.8	↓ 26.6	→ 26.8	↑ 27.0
Aug	26.7	→ 26.6	→ 26.6	↑ 26.9
Sep	26.3	→ 26.3	→ 26.2	↑ 26.6
Oct	25.5	↓ 25.3	→ 25.5	↑ 25.8
Nov	23.9	→ 23.8	→ 23.8	↑ 24.4
Dec	22.3	↓ 22.0	→ 22.2	↑ 22.6

6.2.2 Sub-area analysis

For each of the 15 sub-areas (Table 5), the trend in annual precipitation and annual average temperature has been analyzed for the entire period 1901-2012 (Pall), as well as for the three periods 1901-1940 (P1), 1941-1980 (P2), and 1981-2012 (P3). Figure 62 and Figure 64 represent the average annual values for these periods for precipitation and temperature, respectively. The trend for each of these periods is shown in Figure 63 for precipitation and in Figure 65 for temperature.

It is clear that the trend in precipitation over the entire period 1901-2012 do not present any clear sub-area specifics (Figure 63, top-left). However, trend in precipitation over the last 30 years (Figure 63, bottom-right) indicate that increases in precipitation happened in the northern and western sub-areas, while the eastern sub-areas show a decreasing precipitation amount. The signals are however not completely clear and the more detailed analysis over the last 30 years (as presented in the following sections) will provide more clarity.

The maps with temperature trends (Figure 65) highlight again that most increase in temperature happened over the last 30 years, with trends going up to 0.3°C per 10 years. A clear geographic trend with respect to the sub-areas is not very clear although the middle part of the LMB has the highest increase in temperature.

A time-series for the entire period 1901-2012, a boxplot for the periods 1901-1940, 1941-1980, 1981-2012, and a climate summary table is shown for each sub-basin in Appendix 4 through 18. The following sections provide a brief climate trend analysis description per sub-area.

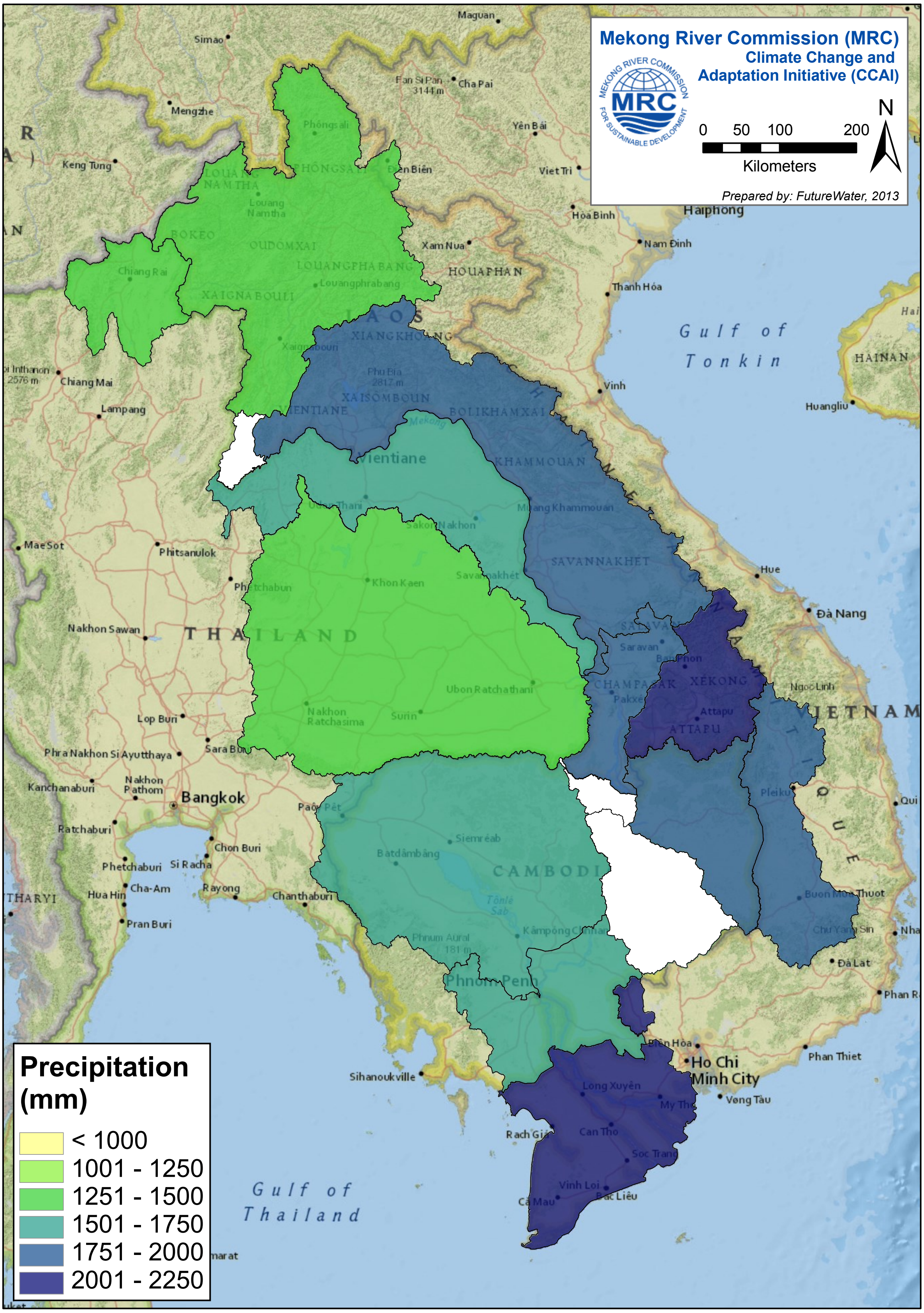

Figure 62. Mean annual precipitation according to CRU for 1901-20102 averaged for each of the 15 sub-areas.

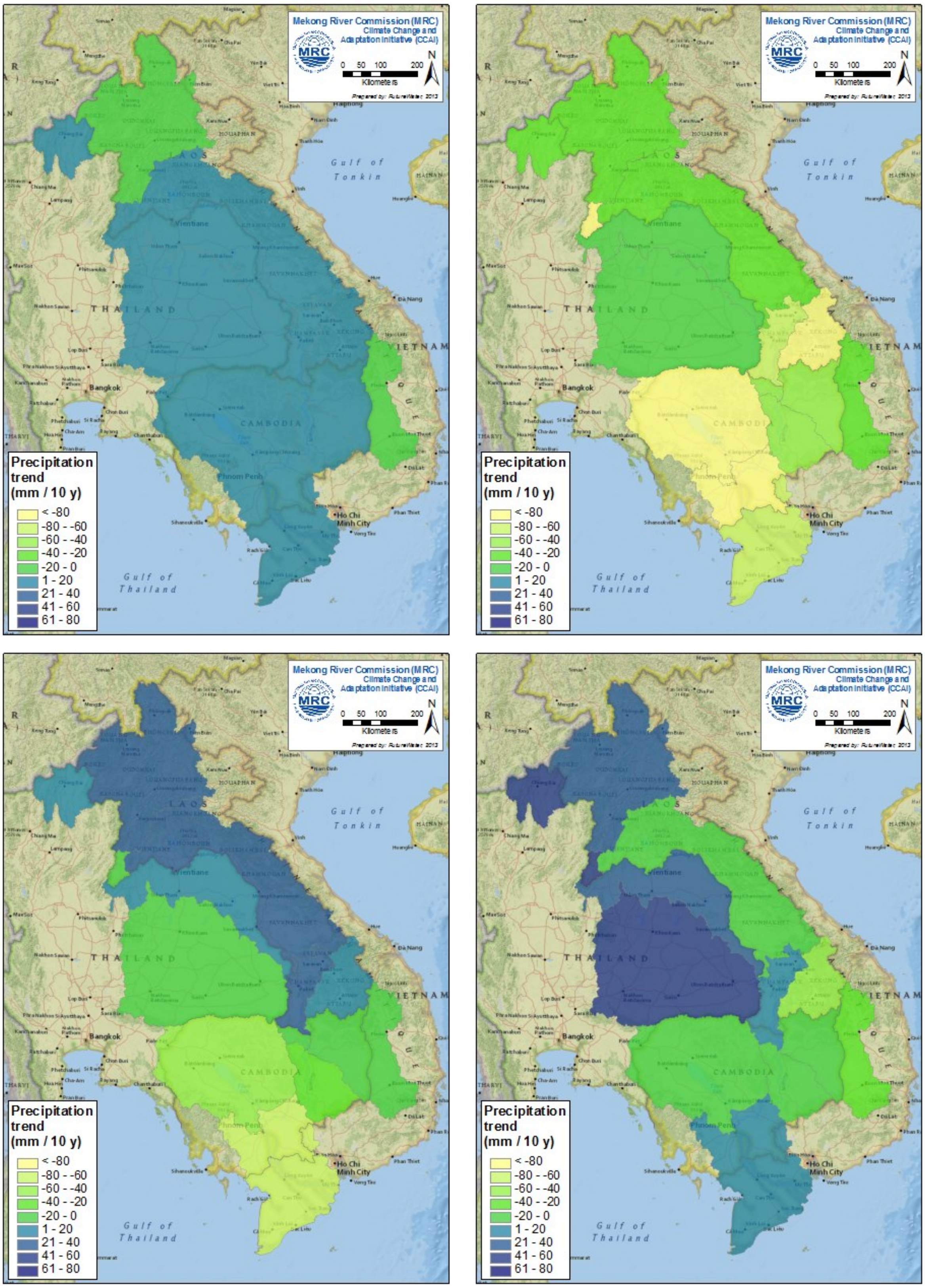

Figure 63: Precipitation trend [mm/10 year] for each sub-areas based on CRU for the periods 1901-2012 (top left), 1901-1940 (top right), 1941-1980 (bottom left), 1981-2012 (bottom right).

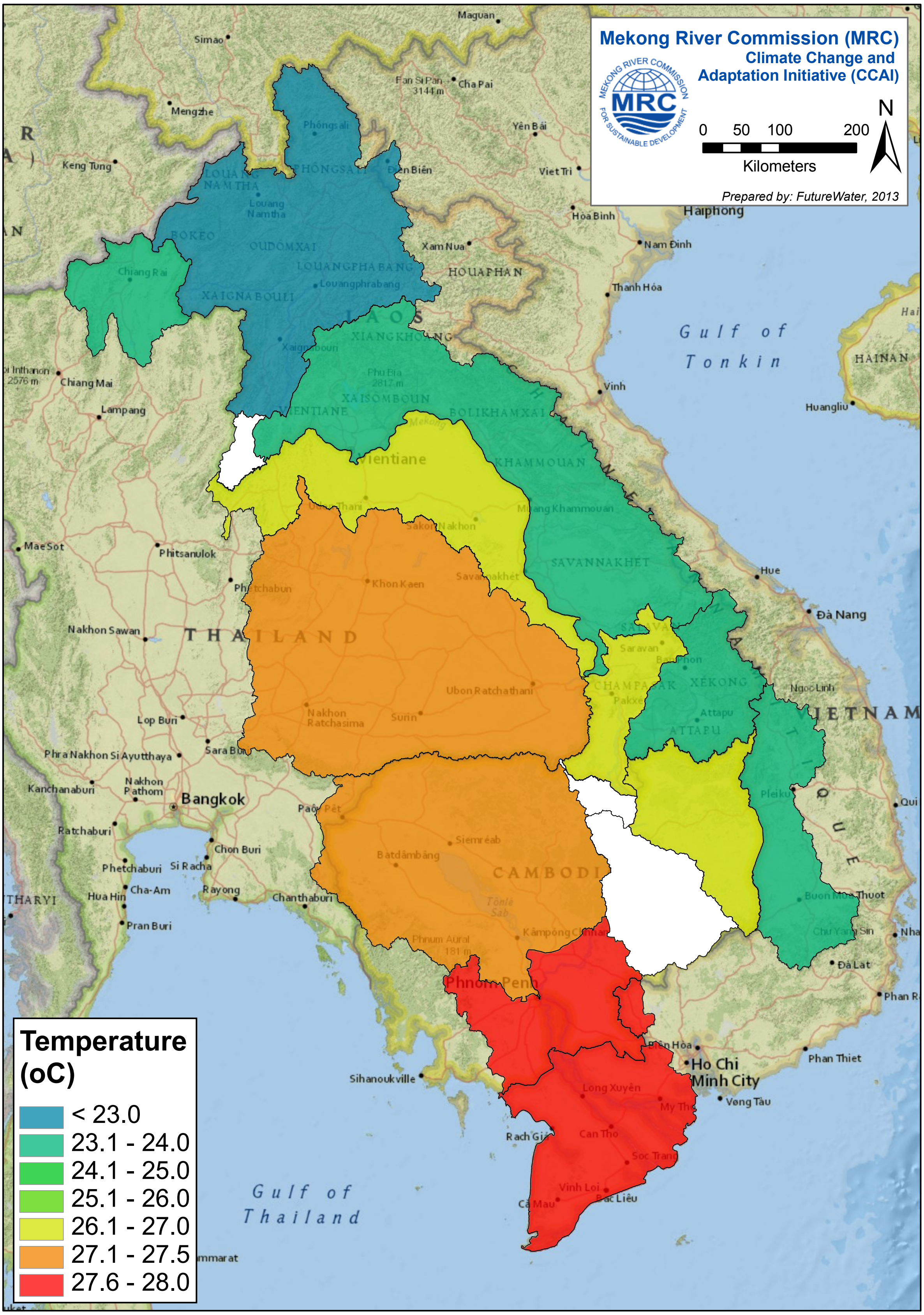

Figure 64: Mean annual temperature based on CRU for 1901-2012, aggregated over the 15 sub-areas.

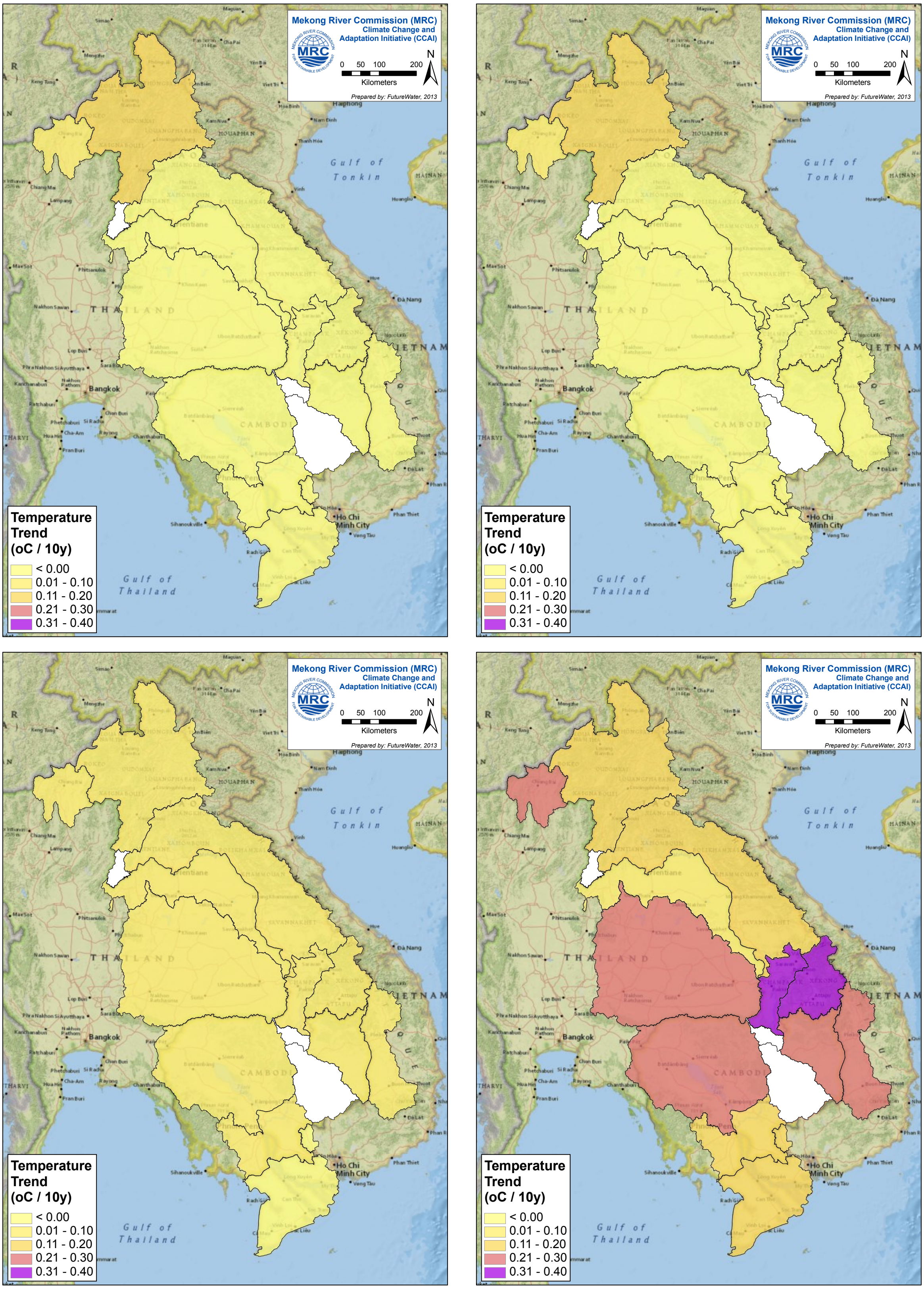

Figure 65: Mean annual temperature trends for each of the 15 sub-areas based on CRU for 1901-2012 (top left), 1901-1940 (top right), 1941-1980 (bottom left), 1981-2012 (bottom right).

Se San / Sre Pok / Se Kong river basins (ID 1)

The average annual precipitation in the Se San / Sre Pok / Se Kong river basins (ID 1) during 1901-2012 is approx. 1865 mm. During 1901-1940 the average annual precipitation is 1792 mm while this increases to 1966 mm in 1981-2012. The overall precipitation increase over the entire period is 20 mm/10 year. The latest period shows the strongest precipitation increase (approx. 85 mm/10 year), while the period 1901-1940 shows a precipitation decrease of approx. 52 mm/10 year.

Temperature shows an overall increase of 0.06 °C/10 year throughout 1901-2012, with the strongest increase (0.22 °C/10 year) during 1981-2012. The size of the boxplots indicates that the variation in annual temperature has become more extreme during this most recent climate period. The average annual temperature has increased from 25.9 °C at the beginning of the 20th century, to a value of 26.5 °C during 1981-2012.

Se San / Sre Pok / Se Kong river basins (ID 2)

The average annual precipitation in the Se San / Sre Pok / Se Kong river basins (ID 2) during 1901-2012 is approx. 1880 mm. Although the annual precipitation remains more or less the same during the largest part of this period, a strong precipitation increase (approx. 126 mm/10 year) can be noticed during 1981-2012. Linear regression shows a decreasing trend of 42.5 mm/10 year during 1901-1940, where after a small increase (17.2 mm/10 year) can be noticed during 1941-1980. Considering the entire period 1901-2012, a linear trend of 22 mm/10 year can be noted. Precipitation increased from 1814 mm during 1901-1940 to an annual average of 1994 during 1981-2012.

The average annual temperature during 1901-2012 was 23.6 °C. Although both the period 1901-1940 and 1981-2012 show an increasing trend in temperature, with the strongest increase (approx. 0.2 °C/10 year) during the latter period, temperature shows a small decrease (approx. 0.06 °C/10 year) during 1941-1980. Overall the average annual temperature has increased from 23.4 °C in 1901-1940 to 23.9 °C in 1981-2012.

Mekong delta (Cambodia, ID 7)

The Mekong delta (Cambodia, ID 7), with an average annual precipitation of 1749 mm (1901-2012), shows a strong precipitation decrease (approx. 96 mm/10 year) during 1901-1940. Linear regression also indicates a precipitation decrease during 1941-1980, although less substantial, where after precipitation increases (approx. 40 mm/10 year) again during 1981-2012. The average annual precipitation has increased from approx. 1650 mm in 1901-1940 to approx. 1800 mm in 1941-1980 and 1981-2012.

Also for the Mekong delta (Cambodia, ID 7) an overall increase in temperature over the period 1901-2012 can be noticed. The average temperature for the entire period is 27.5 °C, while this is 27.4 °C for 1901-1940, and increases to 27.8 °C during the most recent period.

The increase in temperature is strongest during 1981-2012, with an increase of 0.22 °C/10 year. 1981-2012 is also known to have the largest variation in annual temperatures.

Kratie (ID 8)

For the Kratie river basin, both precipitation and temperature show an increasing trend throughout 1901-2012. The average annual precipitation for the entire period is 1704 mm, while this increases from 1634 mm in 1901-1940 to 1773 mm in 1981-2012. An overall precipitation increase of 14.4 mm/10 year can be noticed for the period 1901-2012, while the increase is strongest (approx. 44 mm/10 year) during 1981-2012. The period 1981-2012 was wetter and had larger variations in annual precipitation with respect to P_1 and P_2.

An obvious trend in temperature is visible throughout 1901-2012, with an increase of 0.05 °C/10 year. This trend is strongest during 1981-2012, where it increases with 0.23 °C/10 year. Considering P_1 (1901-1940) and P_3 (1981-2012), temperature has increased from an annual average of 26.8 °C to 27.3 °C, with the latest period being the period with the largest annual variations in temperature.

Tonle Sap basin (ID 9)

The average annual precipitation for the Tonle Sap basin (ID 9) is 1699 mm throughout 1901-2012. Linear regression shows an overall increasing trend for precipitation for the period 1901-2012, with 19.5 mm/10 year. However, a strong precipitation decrease (approx. 88 mm/10 year) can be noticed during 1901-1940. The average annual precipitation increases from 1574 mm in 1901-1940 to 1771 mm in 1981-2012.

Temperature shows a more or less similar pattern as was observed with previous basins; an overall increase in temperature throughout the entire period 1901-2012, with the strongest trend observed during P_3. Linear regression revealed an increase of 0.06 °C/10 year for 1901-2012, but a much stronger trend of 0.25 °C/10 year during the most recent period. Considering annual average temperatures, the increase went from 27.2 °C during 1901-1940 to 27.6 °C during 1981-2012. The latest period is known to have the largest variations in annual temperatures as well.

Southern Lao PDR (ID 12)

For Southern Lao PDR (ID 12), an overall precipitation increase of 16.6 mm/10 year can be noticed during 1901-2012. The average annual precipitation throughout the entire period is 1766 mm, but the trend results in an increase from 1684 mm in 1901-1940 to 1840 mm in 1981-2012. 1901-1940 is the driest period with respect to 1941-1980 and 1981-2012. This period also shows a decrease in precipitation. Precipitation shows the strongest increase (32.4 mm/10 year) during 1981-2012.

The average annual temperature for the entire period is 27.2 °C, while linear regression shows an increase of 0.06 °C/10 year during this period. This leads to the fact that temperature increases from an average of 27 °C during 1901-1940 to an average of 27.6 °C during 1981-2012. The boxplots reveal that the latest period is also the period with the largest variations in annual temperature.

Mun / Chi river basin (ID 13)

The Mun / Chi river basin (ID 13) has an average annual precipitation of 1292 mm throughout 1901-2012. The average annual precipitation sum is relative low compared to the other sub-basins. The entire period 1901-2012 has an overall precipitation increase of 8.9 mm/10 year. Precipitation shows the strongest increase during 1981-2012, with 40.2 mm/10 year. Average annual precipitation has increased from 1241 mm in 1901-1940 to 1311 mm in 1981-2012. Although the latest period is drier with respect to its previous period, it is wetter than the beginning of the 20^{th} century. Annual variations in precipitation were largest during P_1.

The average annual temperature has increased from 26.9 °C in 1901-1940 to 27.3 °C in 1981-2012. Again the latest period shows the strongest trend in temperature increase with 0.19 °C/10 year. Considering the period 1901-2012, an overall temperature increase of 0.05 °C/10 year is noticed.

Mekong delta (Vietnam, ID 14)

The Mekong delta (ID 14) has an average annual precipitation of 2050 mm throughout 1901-2012. Linear trend analysis shows a slightly increasing precipitation trend over the entire period (5.6 mm/10 year). A strong anomaly with low precipitation is observed during the 1930's. Precipitation has been decreasing during P_1 and P_2, and is increasing in P_3 (approx. 46 mm/10 year). Annual variations in precipitation were largest during P_2.

The average annual temperature has increased slightly from 27.6 °C in 1901-1940 to 27.9 °C in 1981-2012. Again the latest period shows the strongest trend in temperature increase with 0.2 °C/10 year. Considering the period 1901-2012, an overall temperature increase of 0.03 °C/10 year is noticed.

Southern Lao PDR (ID 18)

Southern Lao PDR (ID 18) has an average annual precipitation of 1925 mm during 1901-2012. Linear regression shows a precipitation increase of 23.4 mm/10 year throughout this period. Precipitation increased from 1818 mm in 1901-1940 to 2025 mm in 1981-2012. Precipitation increase is strongest during P_3, with an increase of approx. 63 mm/10 year.

The average annual air temperature in this sub-area is 26.1 °C during 1901-2012. A strong temperature increase is noticed during 1985-2000. Linear regression for the period 1981-2012 shows an increase of 0.23 °C/10 years. Before 1980 temperature stayed fairly constant. Annual variation in temperature was also largest for 1981-2012. The average annual temperature has increased from 25.9 °C in 1901-1940 to 26.5 °C in 1981-2012.

Se San / Sre Pok / Se Kong river basins (ID 19)

Precipitation in the Se San, Sre Pok and Se Kong river basins has been fairly constant during the entire 1901-2012 period. However, linear regression shows a precipitation decrease of approx. 100 mm/10 year throughout 1901-1940. Hereafter, precipitation increases again with approx. 51 mm/10 year during 1941-1980. A strong precipitation increase is noticed during 1981-2012 (168 mm/10 year). Overall, the average annual precipitation has increased from 1984 mm in 1901-1940 to 2307 mm in 1981-2012.

For average temperature, a strong increase is noticed throughout 1970-2000. Linear regression for the period 1981-2012 shows 0.22 °C temperature increase per 10 years. Furthermore, temperature variability has increased during this period with respect to the other periods (P_1 and P_2). Average temperature has increased from 23.7 °C during 1941-1980 to 24.3 °C during 1981-2012.

Nong Khai / Songkhram (Lao PDR, ID 21)

As for some of the other sub-areas, the Nong Khai/Songkhram area shows relatively low precipitation during ~1920-1940. The average annual precipitation throughout 1901-2012 is 1231 mm. Over the entire period 1901-2012 linear regression shows an increase in precipitation by 15.1 mm/10 years. Over the last period 1981-2012 the precipitation increase is strongest: 80.9 mm/10 years. During P_1 the precipitation trend was negative (-78.6 mm/10 year).

Over the entire period, average temperature has an increasing trend of 0.03 °C/10 years. The trends during all of the three periods are small. Average temperature during the last period is slightly higher than during the two preceding periods, but differences are small. Overall, the average annual temperature has increased from 24 °C in 1901-1940 to 24.3 °C in 1981-2012.

Nong Khai / Songkhram (Thailand, ID 22)

Precipitation in the Nong Khai / Songkhram subarea has increased from 1475 mm/year during 1901-1940 to 1618 mm/year during 1981-2012. The linear regression for the entire period shows an average increase by 17.8 mm/10 years. A strong precipitation decrease is present during 1901-1915, leading to a precipitation dip in 1915-1925. Linear regression shows the strongest precipitation increase during 1981-2012 (approx. 33 mm/10 year).

Average temperature shows an increasing trend (0.04 °C/10 year) over the entire period (26 °C for P_1 to 26.4 °C for P_3). The strongest increase can be observed during P_3 (0.13 °C/10 year).

Central Lao PDR (ID 23)

Precipitation in Central Lao PDR increases by 18.8 mm/10 year during 1901-2012. For P_1 the precipitation has been decreasing by 46.6 mm/10 years followed by 20.2 mm/10 years increase during P_2. Subsequently an increasing trend (68.6 mm/10 year) is observed for P_3. The annual variability of precipitation has been increasing from P_1 to P_2, while his remains more or less the same for P_2 and P_3. Overall, average annual precipitation has increased from 1781 mm in 1901-1940 to 1937 mm in 1981-2012.

Temperature shows an increasing trend for 1981-2012 by 0.16 °C/10 years. Over the entire period 1901-2012 temperature is increasing by 0.05 °C/10 years. During P_1 the change in temperature is almost zero. Average annual temperature has increased from 23.6 °C in 1901-1940 to 24 °C in 1981-2012.

Chiang Rai northern Thailand (ID 24)

Compared to most other subareas, the Chiang Rai northern Thailand area shows large variability in trends for precipitation. Not many clear trends can be observed, although linear regression shows a precipitation decrease (approx. 27 mm/10 year) during 1901-1940, and an overall precipitation increase (approx. 40 mm/10 year) during 1981-2012. Considering the entire period 1901-2012, precipitation increase is very weak (8.7 mm/10 year). Average annual precipitation has increased from 1365 mm in 1901-1940 to 1434 mm in 1981-2012, with the highest average annual precipitation (1485 mm) during 1941-1980.

Average annual temperature has increased from 23.9 °C in 1901-1940 to 24.1 °C in 1981-2012. This means that the overall temperature increase is quite weak (0.03 °C/10 years). Temperature increase is strongest during P_3 with 0.16 °C/10 years. The strongest temperature increases can be noticed during ~1970-1983 and from 2003 onwards.

Northern Lao PDR (ID 27)

Precipitation in Northern Lao PDR has remained fairly constant during the entire century, with a strong increase that can be noticed during 1981-2012. The average annual precipitation during 1901-2012 is 1484 mm/year. Precipitation slightly increased from 1471 mm in 1901-1940 to 1525 mm in 1981-2012. The inter-annual variability between the three periods remains more or less the same.

For Northern Lao PDR (ID 27) the average annual temperature has increased from 22.2 °C in 1901-1940 to 22.5 °C in 1981-2012. Linear regression shows a temperature increase of 0.04 °C/10 years for the entire period. Although the overall trend is an increase in temperature, there was a decrease in temperature during ~1925-1970. From ~1970 onwards temperature increased with approx. 0.23 °C per 10 years.

6.3 Recent climatic trend analysis

6.3.1 Basin analysis

The climatic trend analysis over the entire LMB is performed on an annual and monthly basis, and is conducted for precipitation and average, maximum and minimum temperature. Besides, precipitation trends are analyzed at the daily scale in terms of extreme events. Given restrictions in data availability the entire analysis covers a period of 27 years (1981-2007), rather than a more commonly used period of 30 years. However, considering the data for the years 2008-2010 in the CRU dataset, no significant differences in trends will be expected looking at 27 instead of 30 years. For climate trend analysis it is interesting to analyze the individual years and months throughout the entire period, as well as comparing periods with each other, that include multiple years. Four periods are defined that contain multiple years of climate data:

- P_{all}: Years 1981-2007 (entire period, 27 years)
- P_1: Years 1981-1990 (10 years)
- P_2: Years 1991-2000 (10 years)
- P_3: Years 2000-2007 (7 years)

The climatic trend analysis ends in 2007 since this is the most recent year included in the original APHRODITE dataset.

<u>Modern-era analysis</u>

For each month in the period 1981-2007, the monthly values are averaged over the 15 sub-areas in order to calculate monthly basin average for precipitation and average, maximum and minimum temperature. Subsequently the annual basin precipitation is calculated by summarizing these monthly basin averages, while the annual basin temperature is calculated by averaging the monthly basin averages.

Figure 66 represents the annual precipitation and average, maximum and temperature for the entire basin over the period 1981-2007. The solid line represents the 5-year moving average. Considering the entire period, there is a slight trend in the annual precipitation, towards increasing precipitation. In the first decade (1981-1990) precipitation decreases, and increases after that. Linear regression shows an increasing trend of approximately 53 mm/10 years throughout the entire period 1981-2007.

The trend for the average temperature also shows an increase over the total period. Between 1981 and 1990, temperature increases approximately 0.24 °C/10 years. Also the largely debated stabilizing temperatures during the 2000-2007 can be observed. Linear regression even shows a decrease of -0.33 °C/10 years during this period. The minimum and maximum air temperatures show the same trends as the average air temperature.

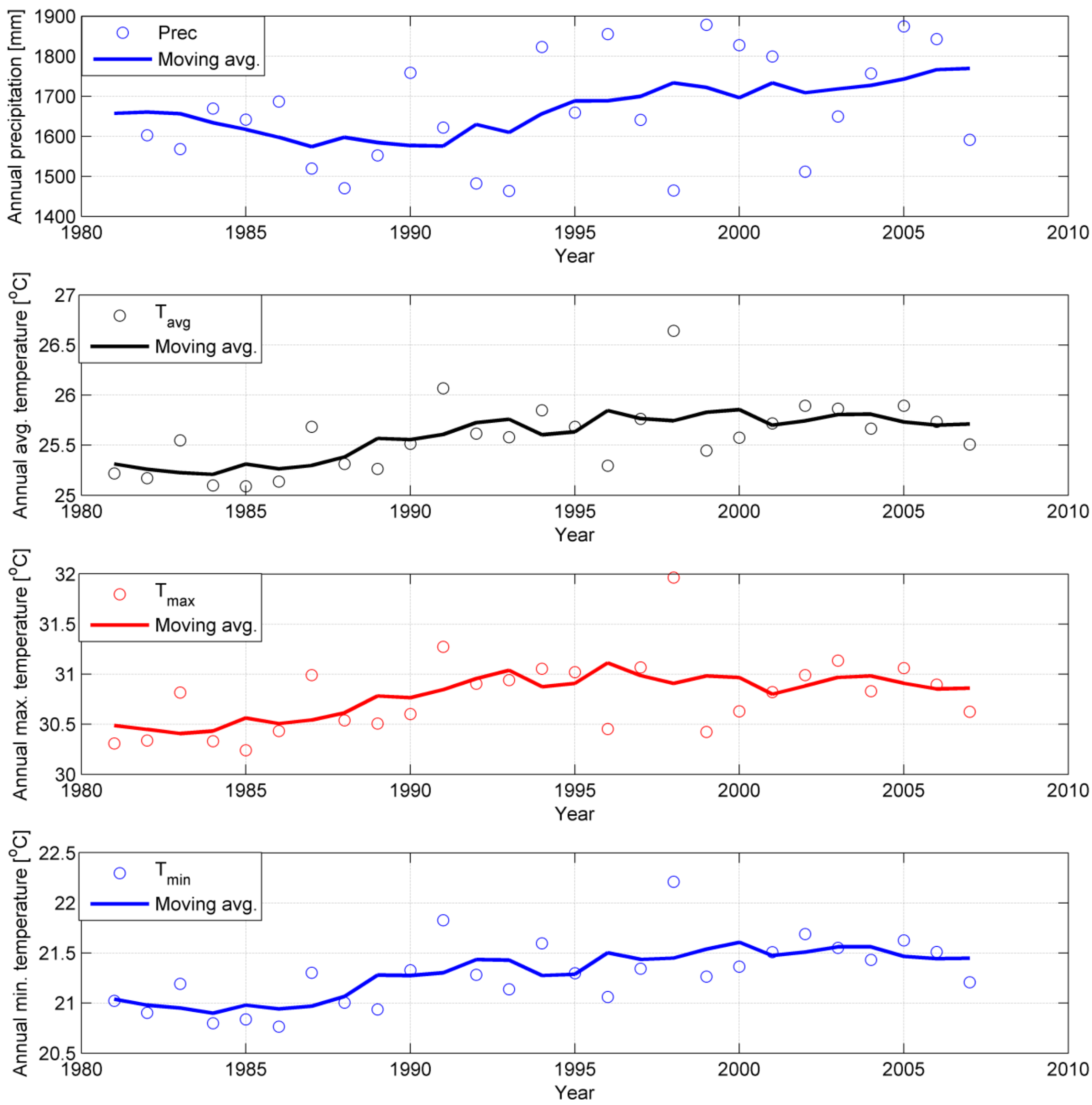

Figure 66: Annual precipitation (top), annual average temperature (2nd), maximum temperature (3rd) and minimum temperature (bottom) for the period 1981-2007, over the LMB. Solid lines represent the 5-year moving average to present short-term trends.

Multi-decade analysis

The entire period (P_{all}) was split into three blocks, denoted as P_1 (1981-1990), P_2 (1991-2000), and P_3 (2001-2007), as mentioned before. A boxplot is made for each of these blocks, for precipitation and temperature (average, maximum and minimum). These results are shown in Figure 67. For the precipitation it can be concluded that the median annual precipitation during keeps increasing for the entire period. Another interesting aspect is that the inter-annual variability during P_2 was larger than during the other two periods.

For temperature the clear increase between P_1 and P_2 is significant. The difference between P_2 and P_3 however is small. Furthermore, the interannual variablility is decreasing from P_2 to P_3.

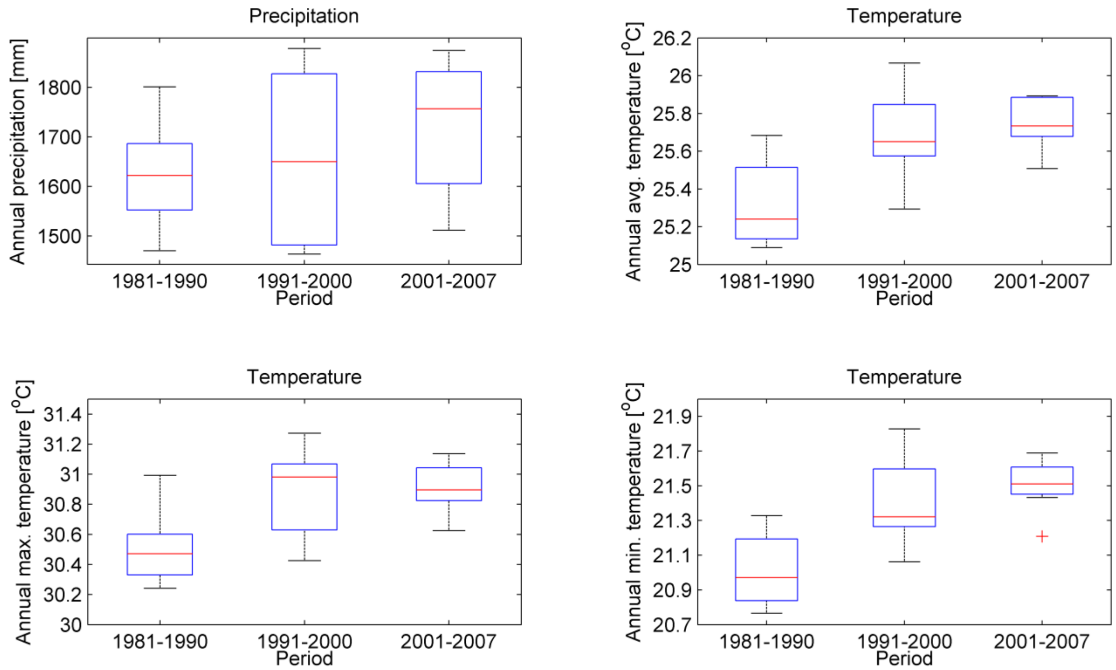

Figure 67: Boxplots of annual precipitation (top left), annual average temperature (top right), maximum temperature (bottom left) and minimum air temperature (bottom right). Each box represents the variation in annual precipitation or temperature within the specified period. Horizontal red lines represent the median. Outliers are denotes as red crosses.

<u>Monthly analysis</u>

Besides the annual analysis, the basin precipitation and average, maximum and minimum temperature have been analyzed on a monthly basis as well. These monthly results are shown in Appendix 19 in for precipitation and average, maximum and minimum temperature, respectively.

For precipitation, the months November through April can be categorized as being the dry months (<100 mm precipitation). May through October are the wetter months. These wetter months also show a substantial variation in monthly precipitation. Based on these monthly results it can be concluded that there is an increasing trend for July and August and a small decreasing trend for June and October.

For temperature trends are different. January, March, May, June, August, September, October and December show the increasing temperature trend from 1981 until ~2000. For February the increase is strongest 2000. Most months show stable or decreasing temperatures after 2000.

Summarizing

A summary of the basin climate analysis is shown in Table 10 and Table 11. This table shows the trend per period, annual averages per period, and finally, monthly averages per period. For precipitation it is clear that the strongest increase (260 mm/10 year) was noticed during the period 1991-2000, while the first period (1981-1990) shows a strong decrease of 99 mm/10 year. The entire period shows an increase of approximately 53 mm/10 year.

Temperature also shows the strongest increase (approx. 0.2 °C/10 year) during the period 1981-1990. During 1991-2000 a small decrease of 0.06 °C/10 year was noticed, while the period 2001-2007 shows a decrease in temperature of 0.33 °C/10 year. The arrow up next to the monthly temperature values indicate that for all months, except for May, June and August, the latest period is the warmest with respect to the previous two periods.

A small seasonal shift in precipitation could be observed over the last 30 years, with a somewhat earlier wet season (Figure 68). Precipitation at the onset of the wet season (March to May) was 319 mm in the period 1981-1990, while this was 361 mm in the period 2001-2007. Similar, at the end of the wet season (October to December) precipitation decreased from 260 mm (1981-1990) to 242 mm (2001-2007). However, this observed earlier monsoon should be considered as indicative, since it is based on looking at periods of 10 years and can therefore be also a result of natural variation in weather patterns rather than climate change.

Table 10: Summary of temperature statistics for the entire LMB. Arrows up indicate temperature increase more than 0.1°C compared to the 30 years average. Arrows down indicate temperature decrease by more than 0.1°C compared to the 30 years average. Horizontal arrows indicate temperature change less than 0.1°C compared to the 30 years average.

Temperature	*1981-2007*	*1981-1990*	*1991-2000*	*2001-2007*
Annual Average [°C]	25.6	↓ 25.3	↑ 25.8	↑ 25.8
Trend [°C/10 year]	0.24	0.24	-0.06	-0.33
Monthly Average [°C]				
Jan	22.4	↓ 21.9	↑ 22.7	↑ 22.6
Feb	24.2	→ 24.1	→ 24.1	↑ 24.6
Mar	26.4	↓ 26	↑ 26.7	↑ 26.5
Apr	28.0	↓ 27.7	↑ 28.1	↑ 28.3
May	27.6	↓ 27.4	↑ 27.9	→ 27.5
Jun	27.3	↓ 27	↑ 27.5	→ 27.4
Jul	26.7	↓ 26.5	→ 26.7	↑ 26.9
Aug	26.6	→ 26.5	↑ 26.8	→ 26.6
Sep	26.2	↓ 26	↑ 26.4	↑ 26.3
Oct	25.3	↓ 25.1	→ 25.4	↑ 25.6
Nov	24.0	→ 23.9	↑ 24.1	↑ 24.1
Dec	22.2	↓ 21.5	↑ 22.6	↑ 22.6

Table 11: Summary of precipitation statistics for the entire LMB. Arrows up indicate precipitation increase more than 10 mm compared to the 30 years average. Arrows down indicate precipitation decrease by more than 10 mm compared to the 30 years average. Horizontal arrows indicate precipitation change less than 10 mm compared to the 30 years average.

Precipitation	*1981-2007*	*1981-1990*	*1991-2000*	*2001-2007*
Annual Total [mm]	1667	↓ 1627	↑ 1671	↑ 1718
Trend [mm/10 year]	52.6	-98.7	259.6	94.3
Monthly Average [mm]				
Jan	13	→ 10	→ 12	→ 17
Feb	21	→ 18	→ 22	→ 23
Mar	47	↓ 36	→ 45	↑ 65
Apr	93	→ 94	→ 96	→ 86
May	194	→ 189	→ 189	↑ 210
Jun	229	→ 238	→ 227	→ 219
Jul	260	↓ 239	↑ 274	↑ 271
Aug	305	→ 297	→ 301	↑ 320
Sep	259	↓ 246	→ 266	→ 266
Oct	157	↑ 172	↓ 145	→ 152
Nov	63	↑ 73	→ 57	→ 58
Dec	27	↓ 15	→ 36	→ 32

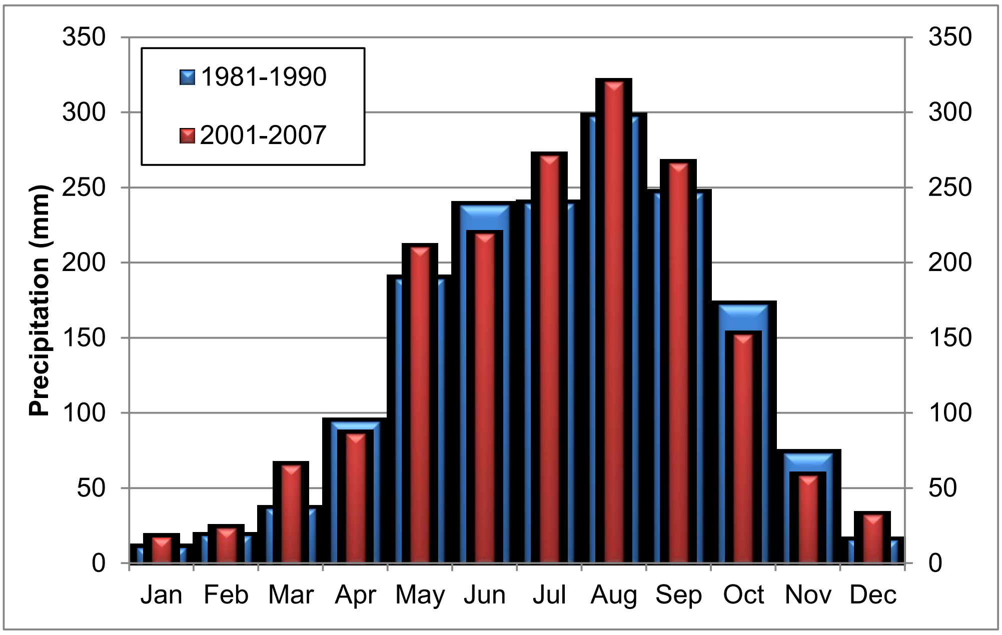

Figure 68: Monthly average precipitation over the entire LMB for two time periods.

6.3.2 Sub-area analysis

For each of the 15 sub-areas (Table 5), the trend in annual precipitation and annual average temperature has been analyzed for the entire period 1981-2007 (Pall), as well as for the three periods 1981-1990 (P1), 1991-2000 (P2), and 2001-2007 (P3). Figure 69 and Figure 71 represent the average annual values for these periods for precipitation and temperature, respectively. The trend for each of these periods is shown in Figure 70 for precipitation and in Figure 72 for temperature.

It is clear that the trend in precipitation over the entire period 1981-2007 is slightly positive for almost all sub-areas (Figure 70, top-left). However, trend in precipitation over the last 7 years (Figure 70, bottom-right) shows increasing precipitation trends in the southern areas, while the northern areas show a decreasing precipitation amount. These trends however must be considered with care because they are based on a relatively limited number of years (7-10 years).

The maps with temperature trends (Figure 72) highlight the decreasing temperature trend observed during the last decade. This observation is strongest in the southeastern areas and less pronounced or absent in the most northwestern areas.

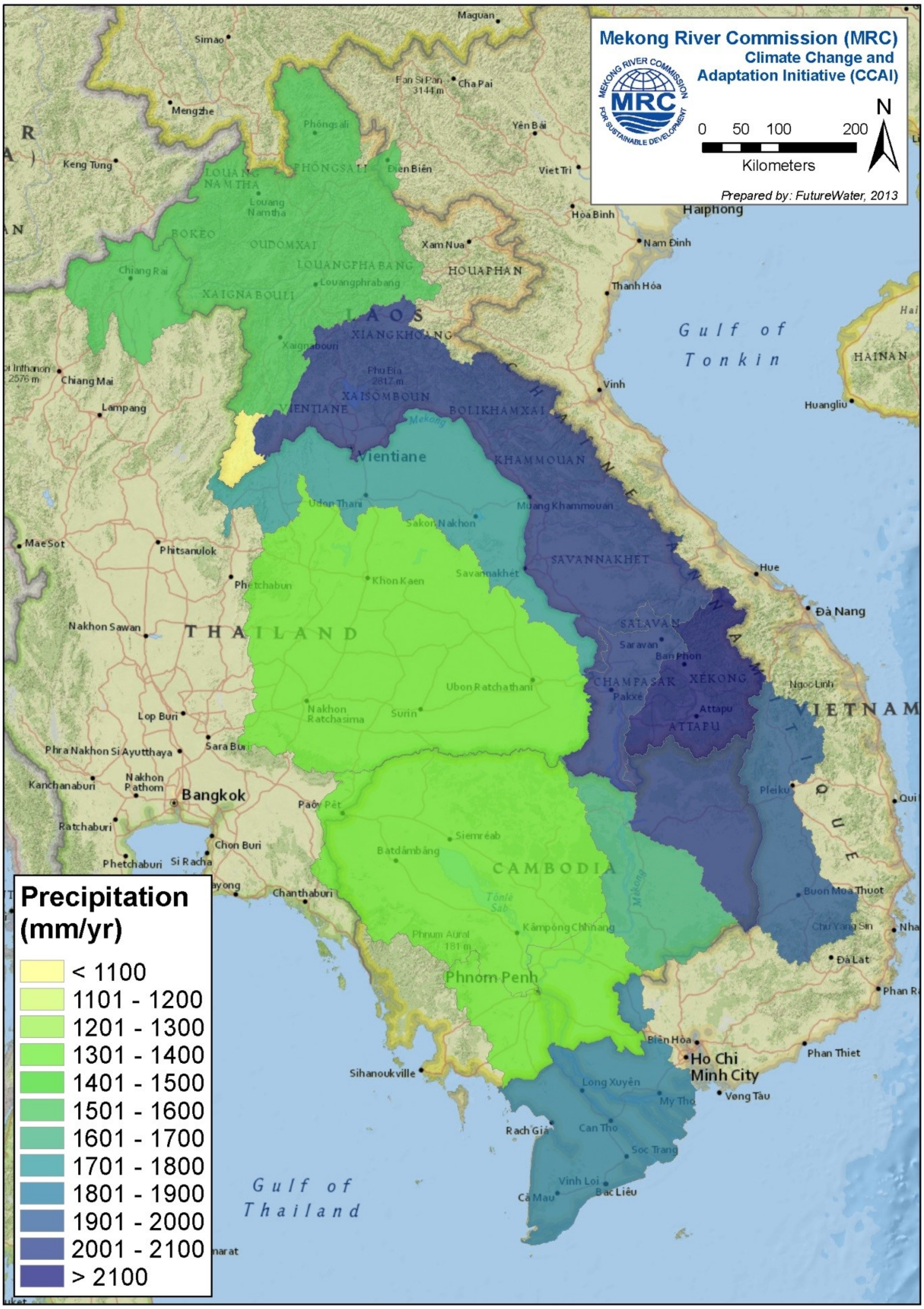

Figure 69: Mean annual precipitation according to bias-corrected APHRODITE for 1981-2007

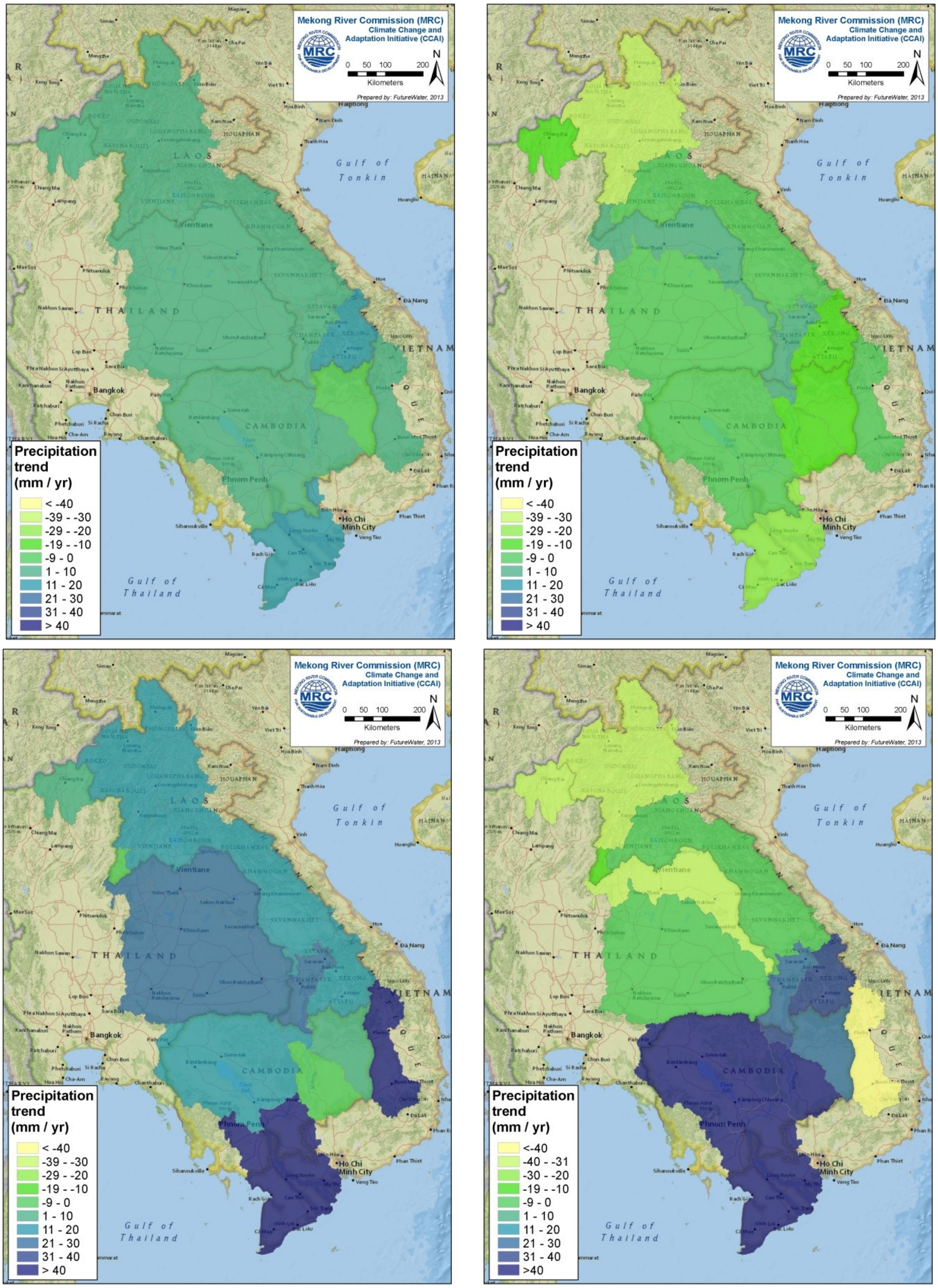

Figure 70: Precipitation trend [mm/year] for each sub-basin for the periods 1981-2007 (top left), 1981-1990 (top right), 1991-2000 (bottom left), 2001-2007 (bottom right).

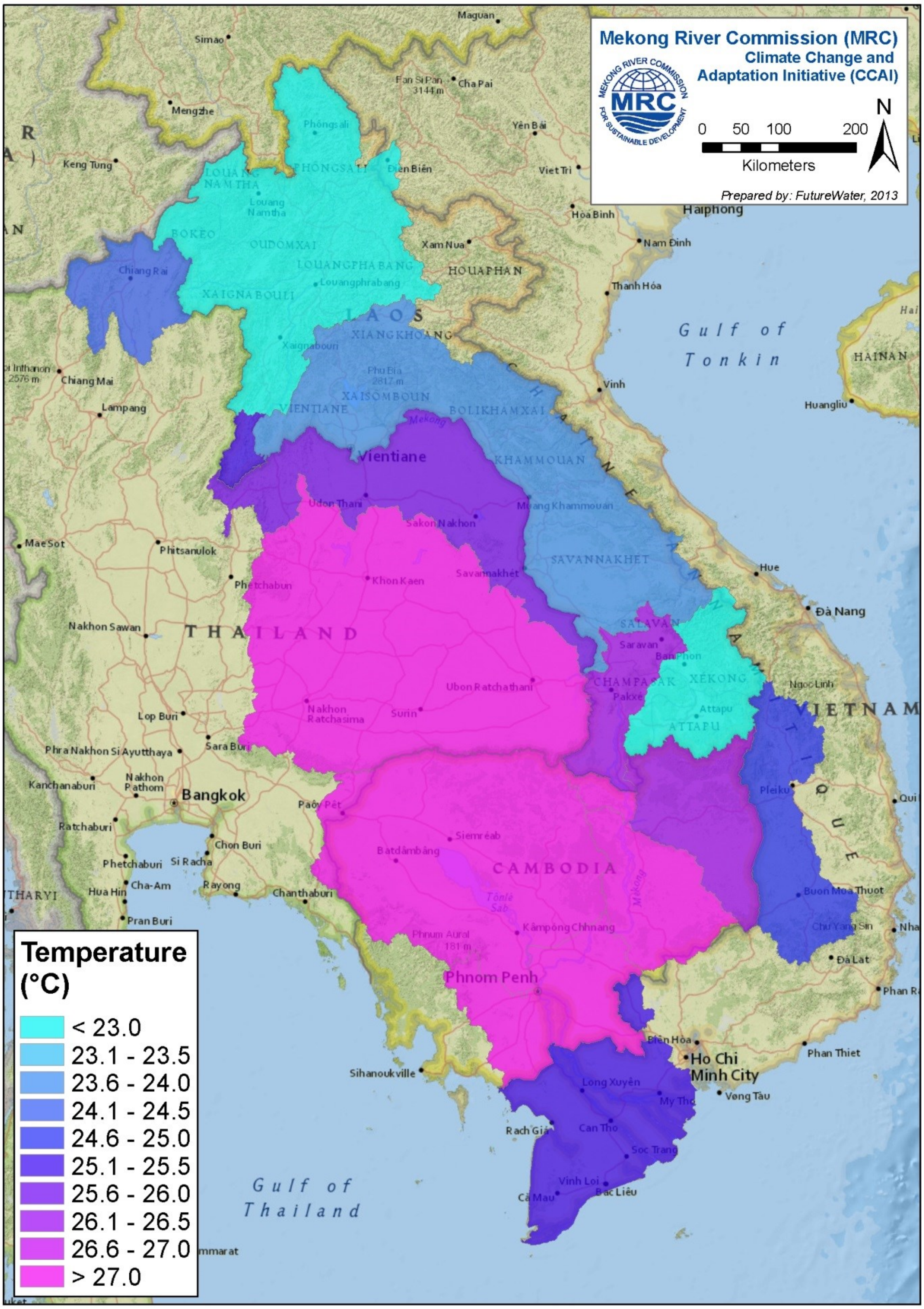

Figure 71: Average temperature according to bias-corrected PRINCETON for 1981-2007

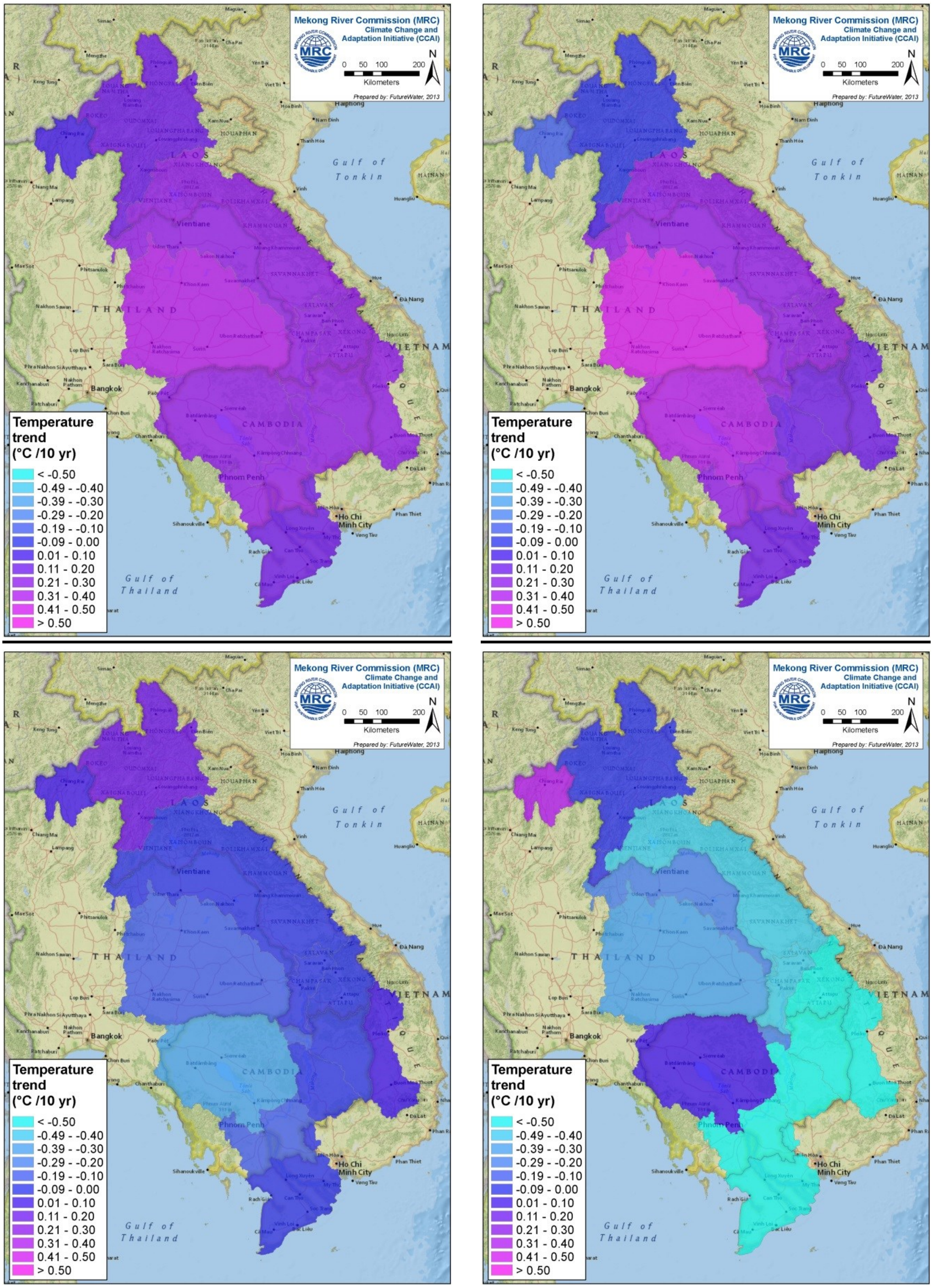

Figure 72: Mean annual temperature trends based on bias-corrected PRINCETON for 1981-2007 (top left), 1981-1990 (top right), 1991-2000 (bottom left), 2001-2007 (bottom right).

A time-series for the entire period 1901-2010, a boxplot for the periods 1901-1940, 1941-1980, 1981-2010, and a climate summary table is shown for each sub-basin in Appendix 20 through 34. The following sections provide a brief climate trend analysis description per sub-area.

Se San / Sre Pok / Se Kong river basins (ID 1)

Precipitation does not show strong trends during the entire 1981-2007 period. A slight decrease can be noted during 1981-1990 and an increase can be noted during 2001-2007. The variability in annual precipitation is larger for the last period compared to the two preceding periods.

Average air temperature shows an increasing trend from 1981 until ~2003. A decreasing trend seems to have started from 2004 onwards. Notably is the seemingly stronger decreasing trend for maximum air temperature from 2004 onwards compared to the minimum air temperature.

Se San / Sre Pok / Se Kong river basins (ID 2)

Average precipitation sums in the Se San / Sre Pok and Se Kong river basins are constant when the three periods are compared. Nevertheless an increasing trend (487 mm/10 years) can be observed for 1991-2000 and a decreasing trend (-384 mm/10 years) can be observed for the last period (2001-2007). The variability in annual average precipitation is largest for the last period including more years with low precipitation.

Over the entire period, temperature shows an increasing trend. During 1981-1990, average air temperature was 24.6 °C compared to 24.9 °C during 2001-2007. Temperatures seem to be decreasing however during the last years of P_3.

Mekong delta (Cambodia, ID 7)

In the Cambodian part of the Mekong delta precipitation shows an increasing trend from P_1 to P_2 and from P_2 to P_3. During 1981-1990 average annual precipitation was 1268 mm/year. During 2001-2007 it was 1406 mm/year. Besides, variability in precipitation increases as well from P_1 to P_2 and from P_2 to P_3.

Temperature shows the same trends as most subareas. The temperature increase is strongest during the late 1980's and the early 1990's. From around 2003 temperatures are decreasing during the most recent years in the data.

Kratie (ID 8)

Precipitation in the Kratie subarea shows a decreasing trend during 1981-1990 (-197 mm/10 year) and 1991-2000 (-38 mm/10 year). During 2001-2007 the precipitation shows an increasing trend (543 mm/10 years). Variablility in precipitation is also largest during 2001-2007.

Temperature trends are similar to most other subareas. From ~1985 to ~1995 increase is strongest, but temperature keeps increasing until 2003. After 2003 temperature shows a decreasing trend. This decrease is stronger for the maximum air temperature than for the minimum air temperature.

Tonle Sap basin (ID 9)

Average precipitation during 1981-1990 in the Tonle Sap basin was 1386 mm/year. During 1991-2000 the average precipitation was highest (1425 mm/year). During the last period (2001-2007) precipitation was lower again (1348 mm/year). Interannual variablility in precipitation was largest during P_2.

Temperature trends are in general similar to other subareas. Notably however is the difference between the minimum and the maximum temperature. During the last period (2001-2007) minimum air temperatures have increased stronger than maximum air temperatures.

Southern Lao PDR (ID 12)

In the Southern Lao PDR subarea precipitation is quite variable compared to other subareas. During the last period (2001-2007) this variability is highest. Linear regression shows increasing precipitation trends for each of the three periods.

Average air temperature has increased from P_1 to P_2 by 0.5 °C. Between P2 and P3 temperature has increased by another 0.1 °C. As for most other subbasins, temperatures have started a dreceasing trend from 2004 onwards.

Mun / Chi river basin (ID 13)

In the Mun/Chi river basin precipitation shows a decreasing trend during the first period (-8.5 mm/10 years and an increasing trend during the second period (+275 mm/10 years). During the last period the trend is decreasing again. The last period however has the largest average annual precipitation (1389 mm/year). Interannual variablility is largest during P_2.

Average air temperature has increases strongest from P_1 to P_2, from 26.9 to 27.5 °C. Average temperature during the third period is equal to the average temperature during the second period. However, also for this subarea a decreasing trend in temperatures is present during the third period.

Mekong delta (Vietnam, ID 14)

In the Vietnamese part of the Mekong delta, precipitation shows a clear trend. From 1981 until 1990 precipitation is decreasing and shows very low interannual variability. A strong increasing trend is observed from 1991 to 2000. After 2000 the increase stabilizes, but interannual variablility is very high.

Temperature trends in the Vietnamese part of the Mekong delta are similar to other subareas. For the maximum temperature a strong decreasing trend is observed from 2003 onwards. This decreasing trend is less strong for the average temperature and minimum temperature.

Southern Lao PDR (ID 18)

Precipitation in the Southern Lao PDR shows a slightly increasing trend over the entire 1981-2007 period. Linear regression shows an increasing trend of 95 mm/10 years. Interannual variability is large; especially during the first and second periods. Average annual precipitation in 2001-2007 is 2154 mm/year, compared to 1998 mm/year during 1981-1990.

Temperature shows the same increasing trend as most other subareas. Linear regression shows an increasing trend by 0.3 °C/10 years. Temperature is highest during 2001-2007, although a decreasing trend (-0.47 °C/10 years) can be observed for this period.

Se San / Sre Pok / Se Kong river basins (ID 19)

Precipitation in the Se San / Sre Pok and Se Kong river basin shows an increasing trend over the entire 1981-2007 period. The linear regression depicts a trend of 138.1 mm/10 years increase. The increasing trend is strongest during P_3 (350 mm/10 years increase). Interannua variability is highest during the first and second period.

The widely observed increasing temperatures during the 1981-2007 period are observed as well for this subarea. Average temperature during P_1 is 22.3 °C, while during P_3 it is 22.9 °C. The decrease in temperatures during the most recent years is clear for this subarea as well.

Nong Khai / Songkhram (Lao PDR, ID 21)

In the Lao part of Nong Khai /Songkhram precipitation also shows the widely observed slight increase in precipitation over the 1981-2007 period. The linear regression over this period shows a 57.6 mm/10 years increasing trend for precipitation. For the last part of the period (2001-2007) however, a decreasing trend can be depicted.

Average temperature shows an increasing trend during the first and second period. During the last period temperatures show a slightly decreasing trend. The trends, however, are small. Interannual variability has decreased during the second and third period with respect to the first period.

Nong Khai / Songkhram (Thailand, ID 22)

In the Nong Khai / Songkhram subarea, precipitation shows an increase from P_1 to P_2 and from P_2 to P_3. Interannual variability is slightly smaller for P_3 compared to P_1 and P_2. The precipitation trend during the last period is however negative.

Over the entire 1981-2007 period average temperature has increased by 0.21 °C/10 years. For this subarea, temperature seems to show a decreasing trend from 2000 onwards. Linear regression reveals a -0.26 °C/10 years trend for 2001-2007.

Central Lao PDR (ID 23)

In the Central Lao PDR, precipitation shows relatively large interannual variation. This variation seems to be smallest during 2001-2007. Overall, precipitation is increasing by 59 mm/10 years over 1981-2007.

The trends for temperature are again similar as for the other subareas. Temperature shows and increasing trend from ~1985 until ~1995. From 1996 onwards temperature stays relatively stable and tends to decrease from 2005 onwards.

Chiang Rai northern Thailand (ID 24)

In the Chiang Rai northern Thailand subarea precipitation is somewhat higher during 2001-2007 (1687 mm/year) compared to P_1 and P_2 (1476 mm/year and 1517 mm/year, respectively). Linear regression reveals a strong negative trend during the most recent years (2001-2007).

For temperature the trends are similar to other subareas although less pronounced. Notably is the relatively large interannual variation in temperature for this subarea. Furthermore, the decreasing temperature trend that is hinted in most other subareas for the last few years, is not observed for this subarea.

Northern Lao PDR (ID 27)

Interannual variation in precipitation is large for the Northern Lao PDR subarea, making it difficult to depict trends, especially during sub-periods of the 1981-2007 period. Over the entire 1981-2007 period, linear regression indicates 28.6 mm/10 years increase in precipitation.

For temperature the trend over the entire 1981-2007 period indicates a 0.15 °C/10 years increase. Temperature has been rising strongest during the 1991-2000 period. Variability in temperature is largest for the last period (2001-2007). There seems to be tendency to lower temperatures in the most recent years, although not as clear as for some of the other subareas.

6.4 Precipitation extremes

One advantage of using a dataset with a daily time step is the possibility to analyze extremes in precipitation. Since daily precipitation data is available at the grid cell level, the analysis is done at the grid cell level, rather than at the level of subareas. In this way, more detail is provided and the high resolution of the bias-corrected precipitation dataset is used to its maximum. The analysis is conducted according ETCCDI indices in the guidelines on analysis of extremes in a changing climate as defined by the World Meteorological Organization [*Klein Tank et al.*, 2009].

Five different precipitation indices are analysed:

- Maximum one-day precipitation (ETCCDI index no. 17, RX1day)
- Simple daily intensity index (ETCCDI index no. 18, SDII)
- Very heavy precipitation days (ETCCDI index no. 22, Rnnmm)
- Consecutive dry days (ETCCDI index no. 23, CDD)
- Consecutive wet days (ETCCDI index no. 24, CWD)

These analyses are performed for three periods separately (1981-1990, 1991-2000, 2001-2007), for direct comparison and analysis of trends.

The maximum one-day precipitation index indicates the highest amount in daily precipitation observed for each grid cell during the three periods (Figure 73). In the northwestern part of the LMB the maximum one-day precipitation increases from 1981-1990 to 1991-2000 and decreases from 1991-2000 to 2001-2007. In the South, where one-day precipitation maxima are lower, the trend is also an increase from 1981-1990 to 1991-2000 and decrease from 1991-2000 to 2001-2007.

The simple daily intensity index indicates the mean precipitation amount on a wet day, observed for each grid cell during the three periods (Figure 74). The differences between the three periods are small. The areas with high daily intensity have an increased intensity during 1991-2000 compared to 1981-1990. A decreasing intensity is observed for the entire LMB from 1991-2000 to 2001-2007.

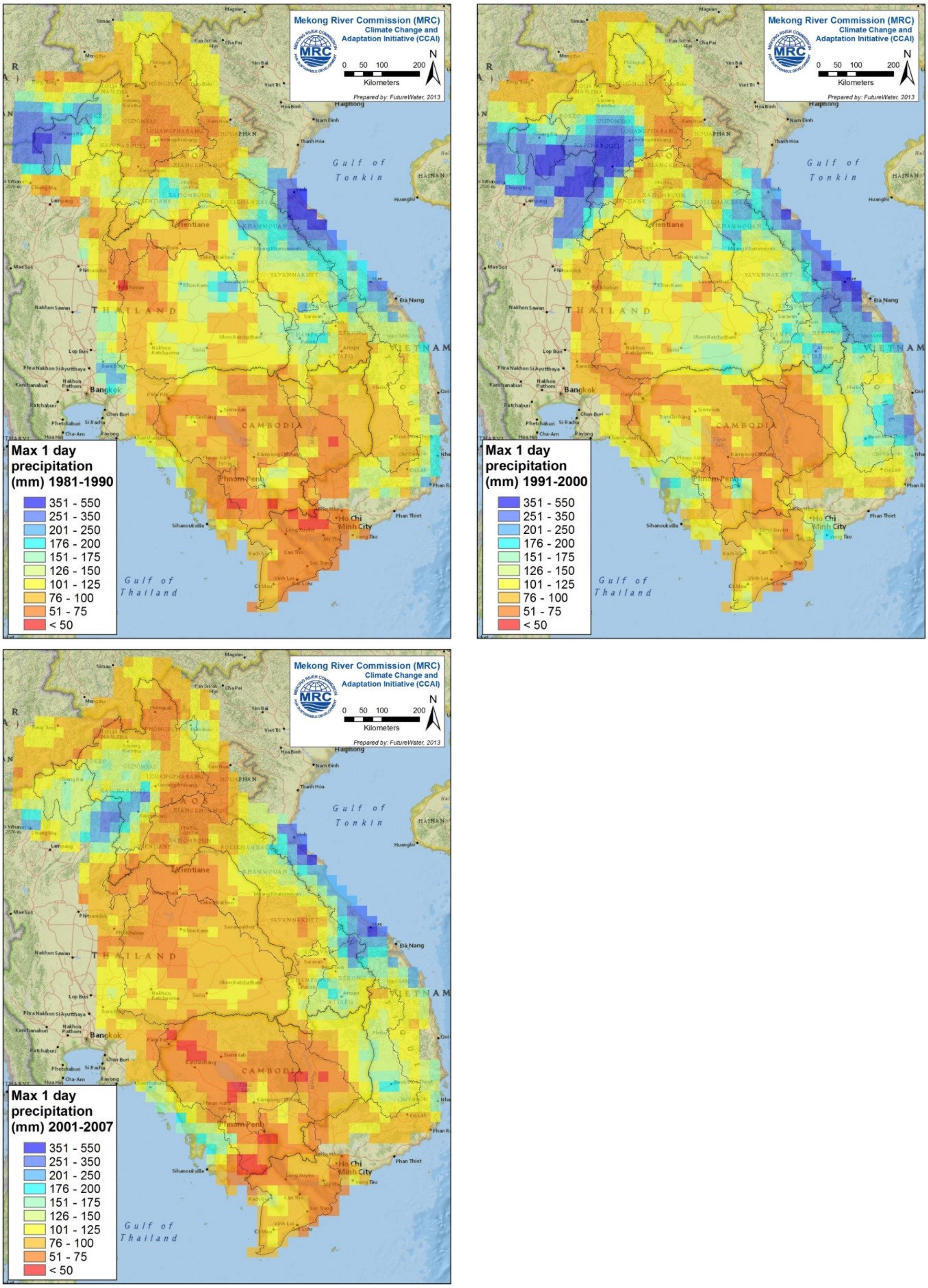

Figure 73: Maximum one-day precipitation in the LMB. The values represent the highest daily precipitation (mm) during 1981-1990 (top left), 1991-2000 (top right) and 2001-2007 (bottom left). ETCCDI precipitation index no. 17 (RX1day).

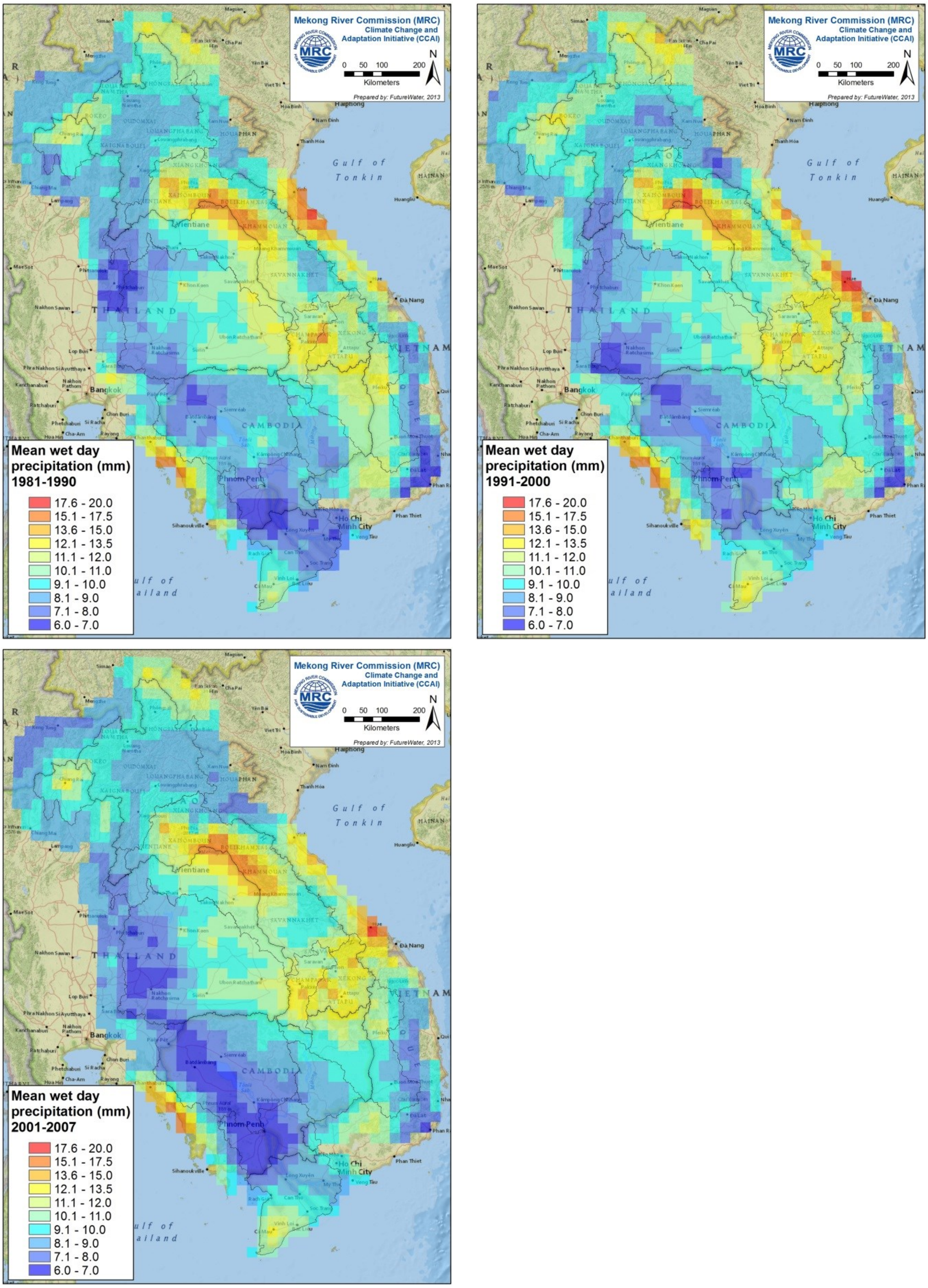

Figure 74: Simple daily intensity index. The values represent the mean precipitation amount on a wet day (P ≥ 1 mm) during 1981-1990 (top left), 1991-2000 (top right) and 2001-2007 (bottom left). ETCCDI precipitation index no. 19 (SDII).

Analysis of very heavy precipitation days (ETCCDI index no. 22) is conducted for two categories of extreme events. The first category includes all precipitation events with a daily precipitation sum above 50 mm (less extreme events). The second category includes the very extreme events, which are defined as precipitation events with a daily precipitation sum above 100 mm. For both categories the analysis is conducted by calculating the average number of days per year where the event threshold (e.g. 50 mm or 100 mm) is exceeded. The results of these analyses are shown in Figure 76 for the less extreme events and in Figure 77 for the very extreme events. The figures clearly indicate that the vast majority of extreme events occur in the areas with the highest annual precipitation, which are the areas just outside the boundaries of the Lower Mekong Basin, namely the northeastern coast of Vietnam and the Thai coastal area. However, also within the LMB areas with numerous extreme events are present. Comparing 1981-1990 to 1991-2000 in Figure 76 indicate only minor changes regarding less extreme precipitation events. When comparing 1981-1990 to 1991-2000 in Figure 77 however indicates a clear increase of very extreme events in the LMB. Looking at the differences between 1991-2000 and 2001-2007 for the very extreme events shows a general decrease of very extreme events in the LMB between these two periods. For less extremes on the other hand, the average number of days per year with threshold exceeding precipitation seems to increase very slightly in general from 1991-2000 to 2001-2007, although a decrease can be observed in the most northern parts of the LMB.

These events where daily rainfall exceeded 50 and 100 mm were also added for the entire LMB Figure 75. Over the period 1981-2007 on average around 2500 events per year occurred where the rainfall exceeded 50 mm / day. This is calculated based on the 25 x 25 km^2 grid size. Since the LMB is covered by about 1300 of these grid cells, on average an area in the LMB has twice a year a rainfall event above 50 mm/d. As can be seen in Figure 76 and Figure 77 quite some spatial differences can be found.

Rainfall events exceeding 100 mm/d were also evaluated. During the period 1981 to 2007 this happened on average 313 times per year. Converting these numbers to the entire LMB, shows that on average in 25% of the areas rainfall exceeds 100 mm/d in a year.

Looking at trends in precipitation extremes no clear picture can be seen. A linear trend over the entire period 1980 to 2007 does not show any significant trend. However, if we consider the three periods (1981-1990, 1991-2000, 2001-2007) it is clear that extremes over the last years are happening more frequent. However, given this short period of seven years it is not clear whether this will continue in the future.

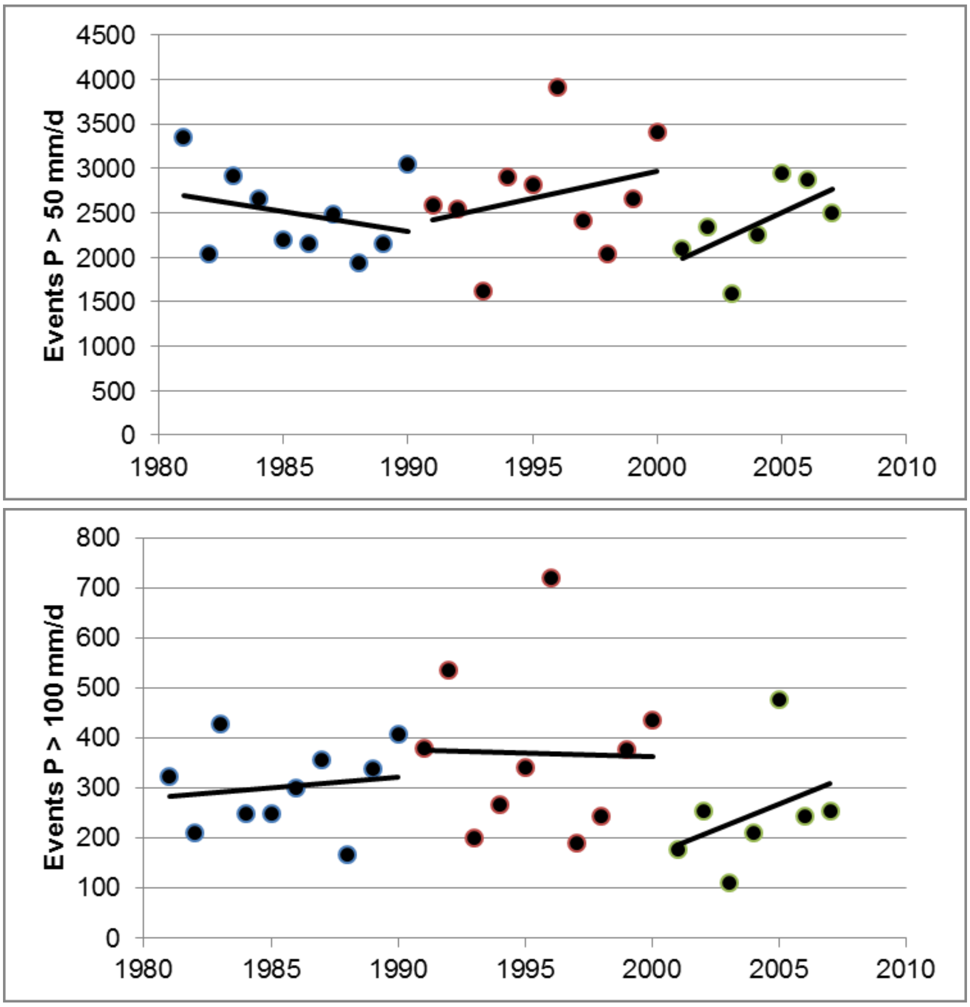

Figure 75: Extreme precipitation events in the LMB. Values represent the average number of days per year with daily precipitation above 50 mm (top), and 100 mm (bottom) over the entire LMB based on grids of 25x25 km^2.

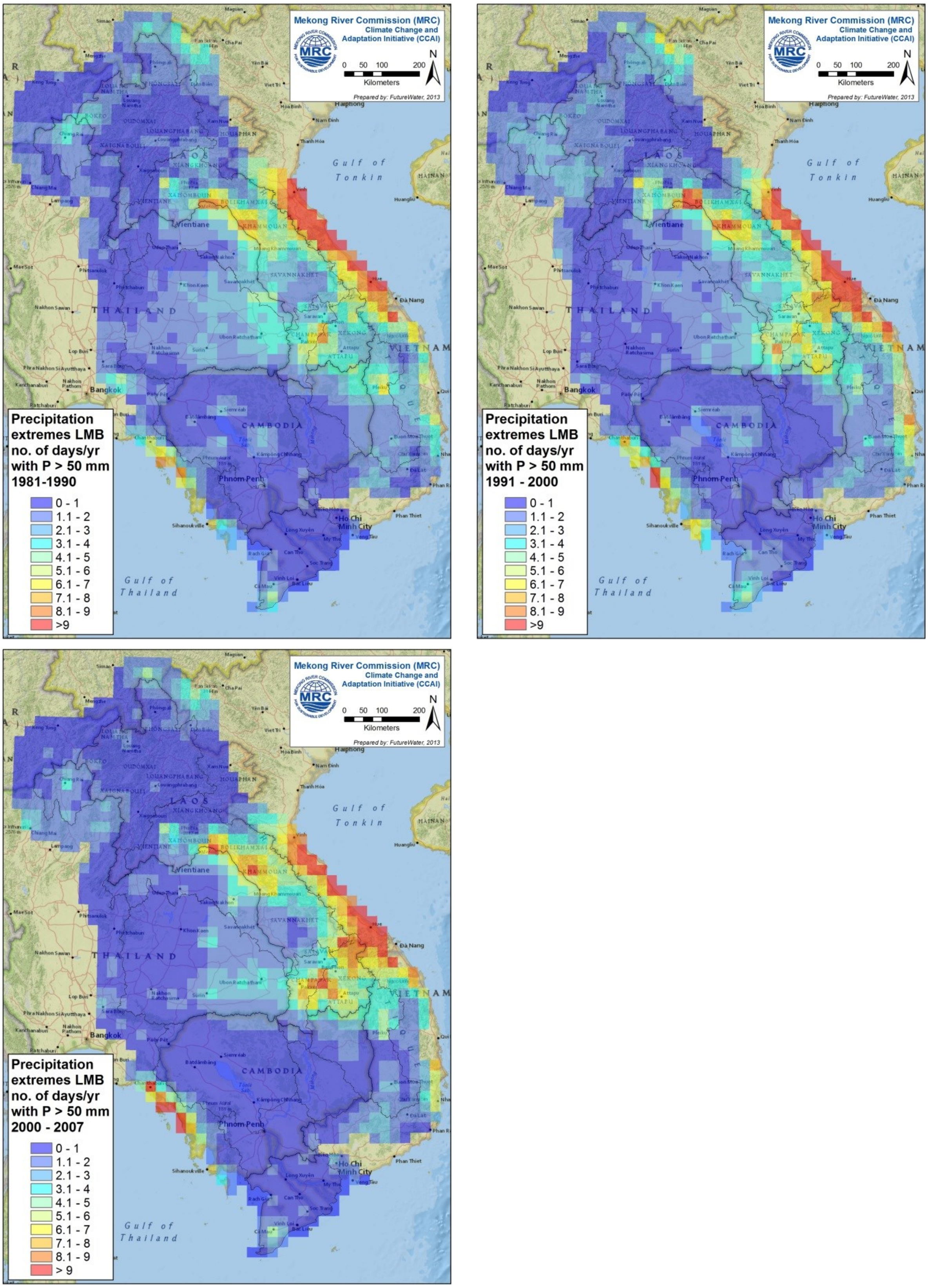

Figure 76: Extreme precipitation events in the LMB. Values represent the average number of days per year with daily precipitation above 50 mm for 1981-1990 (top left), 1991-2000 (top right) and 2001-2007 (bottom left).

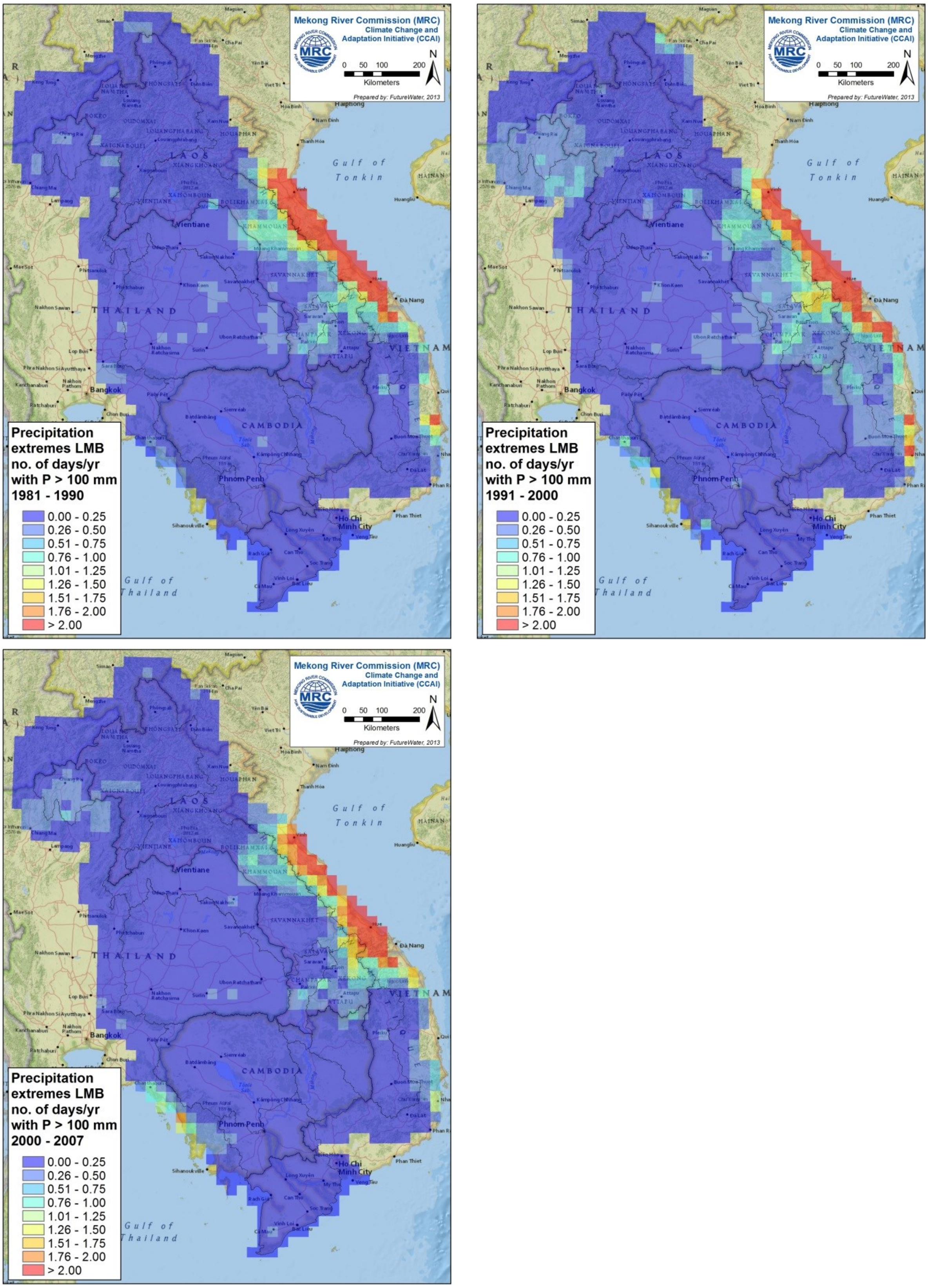

Figure 77: Extreme precipitation events in the LMB. Values represent the average number of days per year with daily precipitation above 100 mm for 1981-1990 (top left), 1991-2000 (top right) and 2001-2007 (bottom left).

The consecutive dry day index represents the maximum length of a dry spell as a number of days for each grid cell during each of the three periods (Figure 78). Dry spells are periods of consecutive days with a daily precipitation sum below 1 mm. Trends in the consecutive dry day index are quite pronounced. For the central LMB, a longer dry spell has occurred during 1981-1990 compared to 1991-2000. In the northwestern part of the LMB however, a longer dry spell has occurred during 1991-2000 than during 1981-1990. This is also true for the most southern part. Remarkable is the long dry spell observed in the Kratie subarea during 1991-2000 compared to the surrounding areas. During 2001-2007 a very long dry spell has occurred in large parts of Cambodia. Most other regions on the other hand, seem to have witnessed shorter longest dry spells compared to the preceding 1991-2000 period.

The consecutive wet day index indicates the maximum length of a wet spell as a number of days for each grid cell during each of the three periods (Figure 79). Opposite to dry spells, wet spells are periods of consecutive days with a daily precipitation sum higher or equal to 1 mm. Also for the wet spells, pronounced differences can be observed between the three periods. During 1991-2000 it is clear that in most of the LMB, the longest observed wet spell is longer than the longest observed wet spell during 1981-1990. For most areas this trend is continued between 1991-2000 and 2001-2007. For the most southern part of the LMB, the longest wet spell during 2001-2007 was shorter compared to 1991-2000. This observation also holds in the far north of the LMB and the north of the Central Lao subarea. In this last mentioned area a long wet spell occurred during the 1991-2000 period.

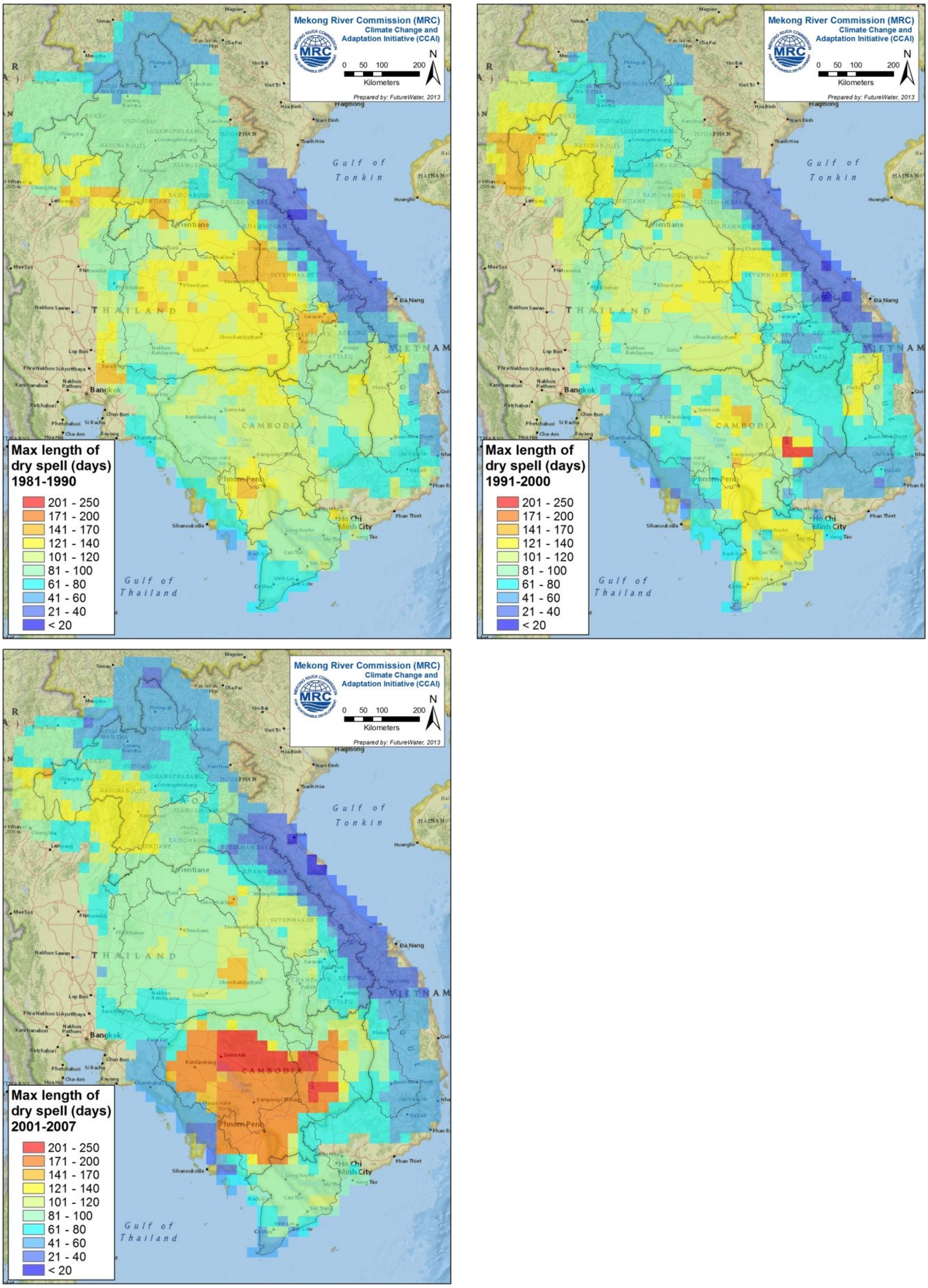

Figure 78: Consecutive dry days. The values represent the maximum length of a dry spell (days, P ≤ 1 mm) during 1981-1990 (top left), 1991-2000 (top right) and 2001-2007 (bottom left). ETCCDI precipitation index no. 23 (CDD).

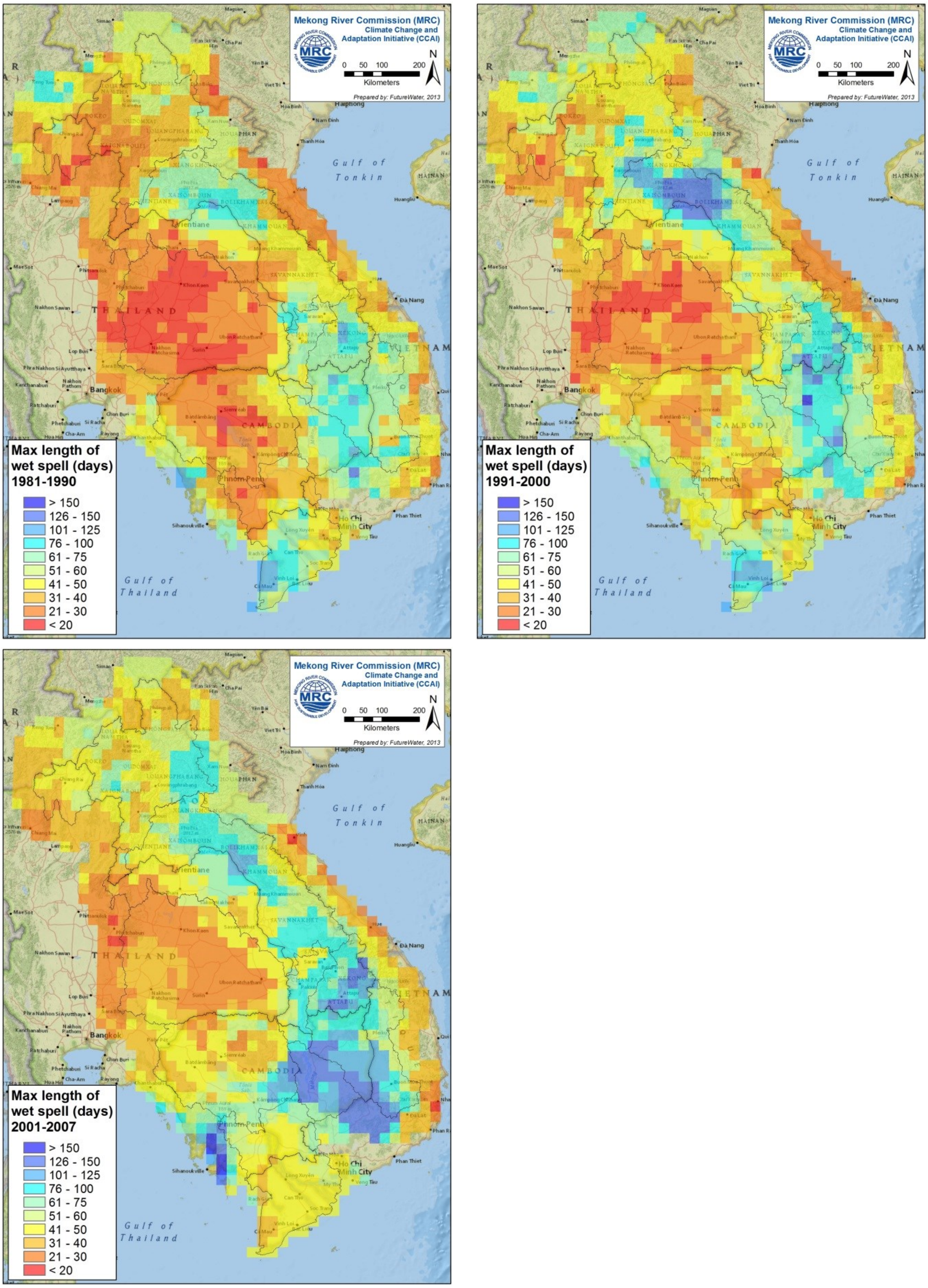

Figure 79: Consecutive wet days. The values represent the maximum length of a wet spell (days, P ≥ 1 mm) during 1981-1990 (top left), 1991-2000 (top right) and 2001-2007 (bottom left). ETCCDI precipitation index no. 24 (CWD).

7 Conclusions

The MRC-CCAI overall objective is to support the process of adapting to the new challenges posed by climate change in the Lower Mekong Basin. CCAI is doing this by ensuring that knowledge on climate, climate impact, and climate adaptation will be generated and distributed. This report describes two important components of knowledge generation: (i) building a harmonized climate database covering the entire Lower Mekong Basin, and (ii) undertaking a trend analysis over the past climate.

The harmonized climate database was created by assessing all the information and data available and combining this in a scientific proven state-of-the-art approach. In general climate data is available from four distinct sources: (i) local observations, (ii) gridded products based on interpolation of local observations, (iii) reanalysis data, and (iv) satellite data. Note that the bases for the last three products are still the local observations. In this study 14 existing data products have been evaluated on its usefulness and accuracy for the LMB. Based on literature and a set of selection criteria four products were selected for further quality check using local observations: CRU, ERA-Interim, APHRODITE and Princeton. The first one, CRU, was selected for its long-term monthly climate data (1900-2012), while the latter three provide daily data for the period 1981-2010.

These four selected data products are analyzed using a rigorous comparison to observations. This scrutinizing included enhanced statistical comparison on daily, monthly, and annual scales over various spatial ranges (LMB, sub-basins and grids). This analysis concluded that for the long-term climate data the CRU data set was most suitable. For the more recent time the three daily products perform all very well concerning temperature. It was selected to use PRINCETON as this product offers besides average temperature also minimum and maximum ones and outperforms ERA-INTERIM slightly. For precipitation the APHRODITE product is much better to represent observations compared to the other two products. So in summary three products were selected to build a harmonized dataset and to undertake trend analysis: CRU for the long-term temperature and precipitation; PRINCETON for the more recent daily temperature; and APHRODITE for the more recent precipitation.

The harmonized database was further refined by creating bias correction grids based on the differences between observations and data product. For each month bias corrected grids were created and used to improve the gridded products. The final bias-corrected harmonized database has an R of 0.96 (daily) and 0.99 (monthly), and a bias of 1.0^{o}C (daily) and 0.9^{o}C (monthly) for the temperature data compared to observations. For precipitation these numbers are R of 0.71 (daily) and 0.92 (monthly), and a bias of 5.4% (daily) and 5.0% (monthly).

The long-term trend analysis (1901-2012) revealed that: (i) temperature increased by 0.05 °C/10 year over the entire period, (ii) 0.2 °C/10 year over the period 1981-2010. (iii) Precipitation increased by 15 mm/10 year over the entire period, and (iv) 61 mm/10 year over the period 1981-2010.

The recent trend analysis (1981-2007) showed that: (i) temperature increased by 0.2 °C/10 year over the entire period, (ii) and decreased by 0.3 °C/10 year over the period 2001-2007. (iii) Precipitation increased by 53 mm/10 year over the entire period, and (iv) 94 mm/10 year over the period 1981-2010. In terms of precipitation extremes (daily precipitation exceeding 50 and 100 mm/day) no significant trends could be detected, although extremes of the last 10 years have the tendency to occur somewhat more frequent. Since the recent trend analysis is based on products that were bias-corrected one can assume that for the last 30 years the recent trend analysis is somewhat more accurate compared to the long-term term analysis.

A weak signal of seasonal shift in precipitation is observed over the last 30 years in a slightly earlier onset of the monsoon combined with a slightly earlier end of the monsoon.

The overall conclusions based on results presented above are:

- Temperature in the LMB has increased by about 0.2°C/10 years
- Precipitation increased by about 50 mm/10 years.
- A weak signal of a seasonal shift in monsoon has been observed towards a slightly earlier start and end of the monsoon.

The work presented in this report is a rigorous analysis of the past climate in the Lower Mekong Basin. Based on this work the following recommendations for following up activities emerge:

- Since all reference climate information is based on observations, a continuous effort to improve quality and quantity in meteorological observations should be taken.
- The trend analysis as presented here should be considered as explorative. A more rigorous trend analysis, based on station data as well as the newly developed base line data, is recommended.
- Finally, based on results described in this study it is clear that the climate is changing and that adaptation strategies have to be developed and implemented.

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