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1 **Assessing total water storage and identifying flood events over Tonlé Sap basin in**
2 **Cambodia using GRACE and MODIS satellite observations combined with hydrological**
3 **models**

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15

16 **Abstract**

17 In this study, satellite observations including gravity (GRACE), terrestrial reflectance (MODIS), and
18 global precipitation (TRMM) data, along with the output from the PCR-GLOBWB hydrological model,
19 are used to generate monthly and sub-monthly terrestrial water storage (TWS) estimates and quantify
20 flood events over the Tonlé Sap basin between 2002 and 2014. This study is the first time GRACE data
21 have been used to investigate the hydrological processes over the Tonlé Sap basin. To improve the
22 accuracy of the TWS estimates from GRACE, a signal restoration method was applied in an effort to
23 recover the signal loss (i.e., signal leakage) inherent in the standard GRACE post-processing scheme. The

24 method applies the correction based on the GRACE observations only, requiring no external data or
25 hydrological models. The effectiveness of the technique over the Tonlé Sap basin was validated against
26 several independent data sets. Based on the GRACE observations since 2002, the 2011 and 2013 flood
27 events were clearly identified, and measured to have basin-averaged TWS values of 42 cm (40% higher
28 than the long-term mean peak value) and 36 cm (34% higher) equivalent water height, respectively. Those
29 same years also coincide with the largest observed flood extents, estimated from the MODIS data as 6,561
30 km² (91% above the long-term mean peak value) and 5,710 km² (66% above), respectively. Those flood
31 events are also linked to the observed inter-annual variations of water storage between 2010 and 2014. It
32 was shown that those inter-annual variations mainly reflect the variations in the surface water and
33 groundwater storage components, influenced by the change of the precipitation intensity. In addition, this
34 study presents a new approach for deriving monthly and sub-monthly TWS variations over a regularly
35 inundated area by using MODIS reflectance data in addition to GRACE solutions. The results of this study
36 show that GRACE data can be considered as an effective tool for monitoring certain small-scale (82,000
37 km²) hydrological basins.

38 **Keywords:** GRACE, MODIS, TWS, Tonlé Sap, signal restoration, inundation area, PCR-GLOBWB

39

40 **1. Introduction**

41 The main goal of this study is to quantify flood events in the Tonlé Sap basin in Central Cambodia at both
42 basin and sub-basin scales. It is shown that a combination of several satellite data products in this data-
43 sparse region can yield valuable insight into flood pulses during the last 15 years.

44 The Tonlé Sap basin has an area of approximately 82,000 km² and contains the largest freshwater lake
45 (Tonlé Sap Lake) in Southeast Asia, which serves as the primary fresh water resource for various food and
46 agricultural activities of Cambodia (Lamberts, 2001). Apart from precipitation, the Tonlé Sap Lake
47 regularly receives water from the Mekong River through the Tonlé Sap River. In addition, the Mekong

48 River brings sediment and nutrients to the soil, making the Tonlé Sap basin favorable for fisheries and the
49 cultivation of rice and other crops. The agricultural activities in the Tonlé Sap basin require irrigation, and
50 the irrigated area has been expanded in the past decade in line with the implementation of a national
51 strategic plan (Yu and Diao, 2011). This has facilitated agriculture growth in the area, so that now more
52 than half of the Cambodian rice fields are located within the basin. Importantly, several new hydro-electric
53 power plants have been constructed in the regions upstream of the Mekong River (outside Cambodia).
54 These developments have altered the natural flows of Mekong mainstream, which has a direct impact to
55 on the Tonlé Sap water level (Arias et al., 2012; Kummu et al., 2014; Cochrane et al., 2014). Compounded
56 by climate variability, the frequency and intensity of drought and flood events in the region have become
57 more severe and have led to the destruction of irrigation fields and civilian casualties (NCDM and UNDP,
58 2015). It is clear that for the development and prosperity of all of the countries dependent on the Mekong
59 and Tonlé Sap basins, improved long-term monitoring of the region's water resources is needed. Such
60 monitoring will serve inter-governmental agencies like the Mekong River Commission (MRC), which aim
61 to optimize the usage of water resources during the country's development while minimizing the harmful
62 effects on people and the environment of the region. Despite the clear need for hydrological information,
63 the vast and inaccessible nature of the Tonlé Sap area makes it difficult to collect in situ observations. As
64 a result, remote sensing observations have to be exploited. This study is a first attempt to provide a
65 comprehensive assessment of the large-scale variations of the water storage as well as to explore flood
66 events in the Tonlé Sap basin over the past decade, using various data sets delivered by remote sensing
67 satellites.

68 In several studies in the past, terrestrial surface reflectance data have been used to identify the spatial
69 flooding patterns over the Tonlé Sap Lake (Xiao et al., 2005; Sakamoto et al., 2007; Arias et al., 2012).
70 However, that analysis did not allow the total water storage variations to be accurately quantified. To
71 address this issue, data from the Gravity Recovery And Climate Experiment (GRACE) satellite mission
72 (Tapley et al., 2004) are used in our study. In contrast to the terrestrial surface reflectance observations,

73 GRACE senses the total Terrestrial Water Storage (TWS) variations in all components (e.g., surface water,
74 soil moisture, and groundwater) (Bettadpur, 2012). For this reason, GRACE data have been used in many
75 hydrological applications at both global and regional scales, e.g., groundwater depletion in India (Rodell
76 et al., 2009), flood prediction for Mississippi River basin (Reager et al., 2014) and characterization of
77 regional (e.g., Amazon, Zambezi, Texas) drought signatures (Thomas et al., 2014). However, to date
78 GRACE data have never been applied to study hydrological processes over the Tonlé Sap basin. The
79 results based on GRACE data are supported and validated by means of other satellite remote sensing
80 datasets and hydrological models.

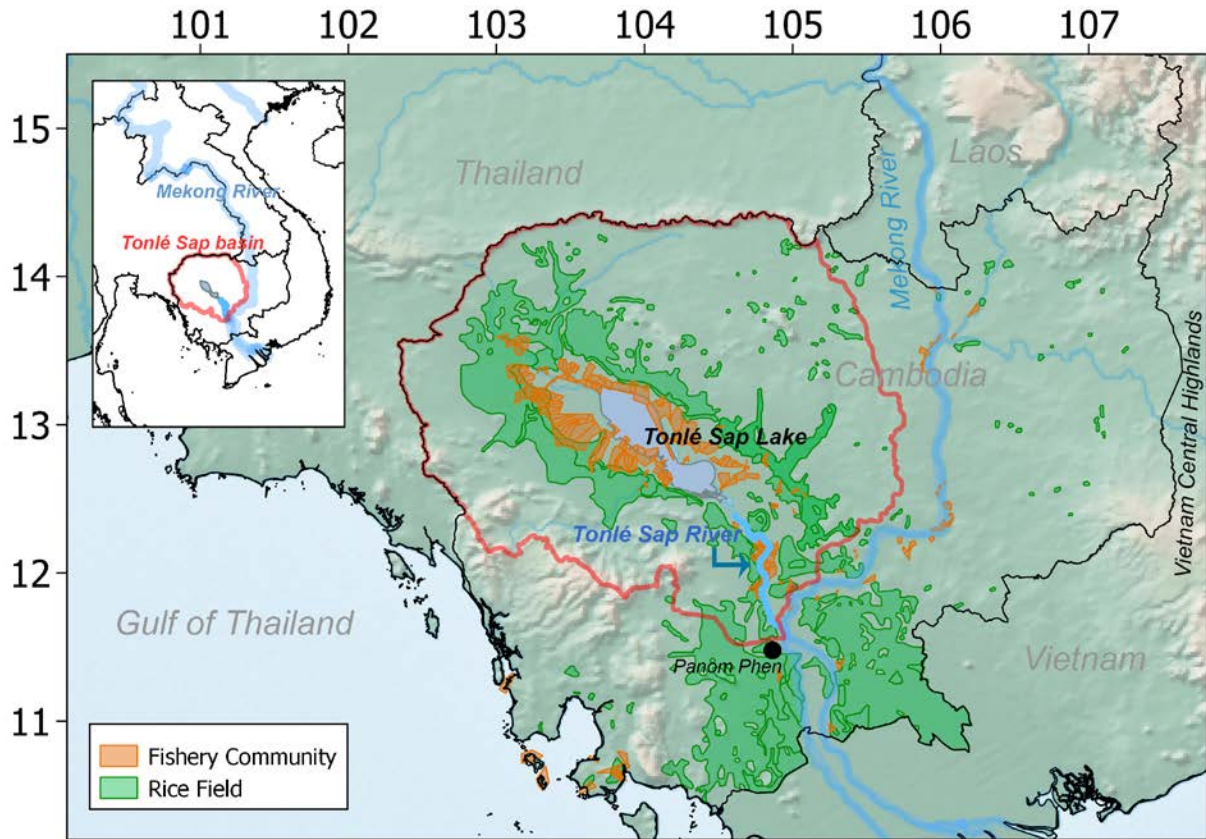
81 One of the challenges in using GRACE data is their temporal resolution, which is limited to one month, as
82 well as their coarse spatial resolution (typically > 300 km). Unconstrained GRACE products require the
83 application of some form of spatial filtering to reduce the effects of high-frequency errors inherent to the
84 publicly available GRACE fields. This spatial filtering redistributes the signal over the filter radius,
85 commonly referred to as signal leakage, requiring additional processing to restore this leaked signal if
86 accurate TWS results over a specific target area are desired. Several signal restoration methods have been
87 described in the literature for this purpose. Landerer and Swenson (2012) applied a scaling factor
88 computed as the ratio between the true TWS and filtered TWS, based on a hydrological model. The
89 procedure is simple but may introduce a bias caused by the dependency on a particular hydrological model.
90 Baur et al. (2009) applied a correction based on known signal geometry. Their method was developed to
91 restore the signal along the coastal zone of Greenland. The method does not rely on external data and can
92 be very effective, but requires a controlled environment, where the surrounding signal is smaller than the
93 target one, and the signal location is known. More recently, Chen et al. (2013, 2014) proposed a strategy
94 similar to that of Baur et al. (2009) but without the known signal geometry requirement. The main idea is
95 to mitigate the leakage out signal (from land to ocean) using GRACE data directly, so that the signal
96 damping effect near the coast is effectively reduced (Chen et al., 2013). This strategy is straightforward,
97 easy to implement, and has been proven effective for inland applications (Chen et al., 2014). As will be

98 shown later, the results produced compared well with independent validation data, suggesting the
99 approach is suitable for this study as well.

100 Apart from GRACE observations, precipitation data from the Tropical Rainfall Measuring Mission
101 (TRMM, Kummerow et al., 1998), as well as three hydrological models are used in an attempt to better
102 understand the processes responsible for the observed TWS variations. The hydrological models used are:
103 (i) the Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis-Interim (ERA-Interim) Full
104 Resolution (Dee, 2011); (ii) the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004); and
105 (iii) the PCRaster Global Water Balance (PCR-GLOBWB) (Van Beek et al., 2011; Sutanudjaja et al.,
106 2014; Wada et al., 2014). In contrast to the ERA-Interim and GLDAS models that construct TWS based
107 on soil moisture storage, the PCR-GLOBWB model also contains surface water and groundwater storage
108 components and can be used to distinguish the contribution of different storage components to the TWS.

109 Furthermore, the coarse temporal and spatial resolution of GRACE requires supporting information to
110 cover smaller temporal and spatial scales. This information is obtained from the terrestrial surface
111 reflectance data provided by the Moderate-Resolution Imaging Spectroradiometer (MODIS; Vermote et
112 al., 2011), which form images with a spatial resolution of 500 m every 8 days. To distinguish the open
113 water from soil and vegetation, the Normalized Different Water Index (NDWI; McFeeters, 1996) is used.
114 In the first instance, NDWI data are used to quantify variations of the inundated area, which is essential
115 for flood area planning. However, by using an empirical relationship between GRACE (TWS) and
116 MODIS (NDWI-based) data over the inundated area, it is also possible to estimate the TWS variations
117 from the MODIS data. This is important because it enables the estimation of TWS variations at sub-
118 monthly time scales. To the author's knowledge, this is the first time that TWS variations have been
119 produced from MODIS data.

120 This paper begins with an overview of the Tonlé Sap basin, given in Sect. 2. The description of all data
121 and their processing are presented in Sect. 3. The GRACE signal restoration scheme is described in Sect. 4.



122

123 **Fig. 1:** Geographical location of the Tonlé Sap basin (red line). The shapefiles of the Tonlé Sap basin,
 124 Tonlé Sap Lake, fishery community and rice field were obtained from the Open Development Cambodia
 125 website (<http://www.opendevdevelopmentcambodia.net/maps/downloads>).

126

127 Sect. 5 focuses on the results obtained. The performance of the signal restoration method, as well as of the
 128 hydrological models, is evaluated in Sect. 5.1. Precipitation is analyzed in Sect. 5.2. In Sect. 5.3, we
 129 demonstrate the usage of MODIS data to estimate the TWS variations over the Tonlé Sap Lake floodplain.
 130 Sect. 5.4 is focused on the investigation of the inter-annual signal over the Tonlé Sap basin. Finally, Sect.
 131 6 discusses and summarizes the main results of the study.

132

133 **2. Study region**

134 The Tonlé Sap basin extends over eight major Cambodian provinces and occupies approximately 46% of
135 the land area of Cambodia. Tonlé Sap Lake (Fig. 1) located in the center part of the basin has an area in
136 the dry and wet seasons of approximately 2,500 km² and 16,000 km², respectively (Lim et al., 1999). The
137 region has a monsoon climate, which is characterized by a rainy period between May and October and a
138 dry period between November and April, with an average rainfall of approximately 1,750 mm/year. Under
139 normal conditions, the lake releases water through the Tonlé Sap River, which connects to the Mekong
140 River near Panom Phen. However, in a wet season (when the amount of rainfall by far exceeds the
141 average level), the lake receives the return flow water from the Mekong River leading to flooding over the
142 Tonlé Sap Lake floodplain. The flood extent is particularly large when the Tonlé Sap basin (and Mekong
143 river basin) experiences a high level of rainfall from strong tropical cyclones (e.g., Typhoon Nesat and
144 Nalgae in 2011, Typhoon Haiyan in 2013).

145

146 **3. Data and data processing**

147 **3.1 GRACE**

148 In this study, the GRACE CSR-Release05 monthly gravity field products from April 2002 to October
149 2014 were used. These fields were produced at the University of Texas at Austin, Center for Space
150 Research (CSR) (Bettadpur, 2012). The products come in the form of spherical harmonic coefficients
151 (SHC) up to degree and order 60, corresponding to a (half-wavelength) spatial resolution of approximately
152 330 km). The degree-1 coefficients are provided by Swenson et al. (2008). Because of large uncertainties
153 in the degree-2 coefficients of the GRACE solutions, the values obtained by satellite laser ranging (Cheng
154 and Tapley, 2004) are used instead. In the months without GRACE gravity solutions (e.g., June and July
155 2003, June 2004), the SHC values were calculated using a cubic-spline interpolation. Then, the long-term

156 mean of the SHC (between April 2002 and October 2014) was computed and removed from each monthly
157 SHC to obtain the monthly variations of the gravity field.

158 Next, high-degree errors were alleviated by using de-stripping (Swenson and Wahr, 2006) and Gaussian
159 smoothing (Jekeli, 1981) filters. The parameters of de-stripping filter used in this study were similar to
160 those discussed in Duan et al. (2009) ($A=30$, $K=10$ in equation (1)). A polynomial of degree 2 was used,
161 and the orders lower than 5 were kept unchanged. The radius (R) of the Gaussian smoothing filter was 350
162 km. After filtering, the SHCs were converted to the 0.5-degree gridded TWS variations over the Tonlé Sap
163 basin. The effects of post-glacial rebound (Peltier, 2004) over the study area are negligibly small, so no
164 correction was made for them.

165 **3.2 Hydrological models**

166 Three hydrology models were used in this study, and the definition of TWS varied depending on the
167 storage components considered in each of the models:

- 168 1. GLDAS-NOAH Version 1: Monthly one-degree nearly-global gridded data are provided for
169 different storage components separately. The TWS was constructed as the sum over all
170 available components, i.e., four soil moisture layers: 0–10, 10–100, 100–150, and 150–200 cm,
171 and the total canopy water storage. Note that contribution of the total canopy water storage is
172 minor (<1%) over the Tonlé Sap basin.
- 173 2. ERA-Interim Full Resolution: The reanalysis volumetric soil moisture from the ECMWF is
174 available every 6 hours at approximately 80-km spatial resolution. The volumetric soil moisture
175 was converted to equivalent water height by multiplying by the thickness of the layer. Similar
176 to GLDAS, TWS was computed as the sum over 4 soil moisture layers: 0–7, 7–28, 28–100, and
177 100–289 cm. The monthly TWS was then computed by averaging the 6-hour data over the
178 month.

179 3. PCR-GLOBWB Version 2.0: daily 0.5-degree TWS estimates are provided globally as the sum
180 of 7 water storage components: snow, interception, river channels (including lakes), irrigation,
181 upper soil moisture (0–30 cm depth from the surface), lower soil moisture (30–150 cm depth),
182 and groundwater. The monthly TWS was computed by averaging the daily data of the month. A
183 further description of PCR-GLOBWB can be found in Appendix A.

184 The monthly TWS values from all 3 models were constructed for the time interval between April 2002
185 and October 2014. For every model, the long-term mean of the TWS was computed and removed from
186 each monthly estimate to obtain the TWS variation consistent with the one derived from GRACE data.

187 **3.3 MODIS-derived NDWI**

188 The MODIS sensors on board NASA’s Terra and AQUA satellites have been successfully collecting
189 spectral imaging data for more than a decade. Among more than 20 product types, the MODIS Surface-
190 Reflectance Product (MOD 09) provides the surface reflectance in 7 different frequency bands every 8
191 days (Vermote et al., 2011). Combinations of specific frequency bands can be used to identify open water
192 bodies of the size of approximately 500 m and more (MOD 09 spatial resolution). Therefore, it is possible
193 to calculate the variations of the inundated area of the Tonlé Sap Lake from this product. In this study, the
194 NDWI derived from MYD09A1 (AQUA) product was used. The surface reflectance in different
195 frequency bands was extracted from the MODIS tile h28v07 (covering the floodplain of the Tonlé Sap
196 Lake). Based on the data quality control information, the pixels flagged with cloud cover or fill values
197 were masked. The NDWI was computed based on reflectance from green and near infrared (NIR)
198 channels as follows:

199

$$200 \text{ NDWI} = (\text{green} - \text{NIR}) / (\text{green} + \text{NIR}). \quad (1)$$

201

202 The range of NDWI is between -1 and 1. Positive NDWI values represent the open water while the zero or

203 negative values represent soil and terrestrial vegetation (McFeeters 1996). Due to the limited data
204 availability, NDWI was computed starting from July 2002.

205 **3.4 Precipitation**

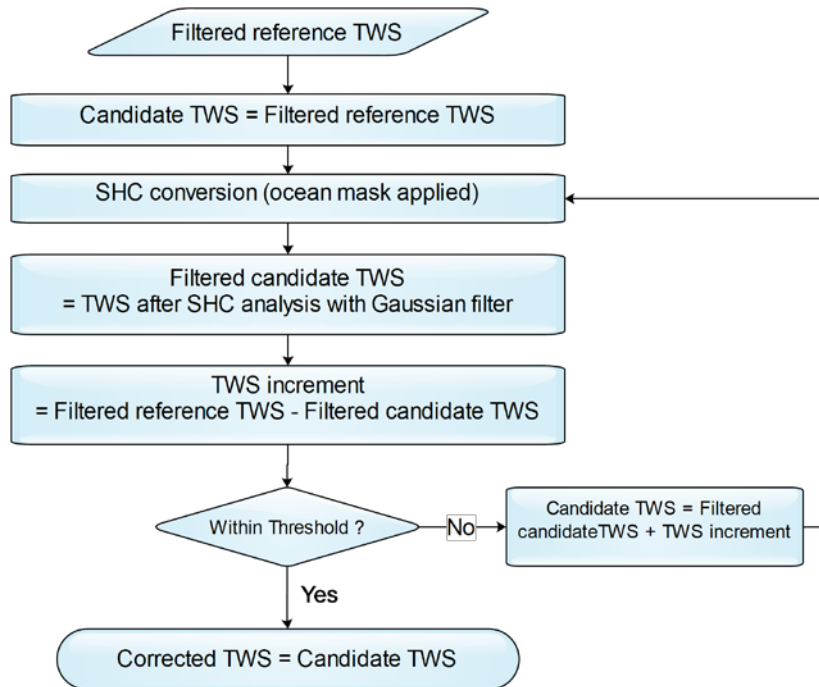
206 Precipitation data were obtained from TRMM (Kummerow et al., 1998), a joint NASA/JAXA mission.
207 Several sensors (e.g., radar, microwave, infrared) were used to collect the precipitation-related passive
208 microwave data, which contain the hydrometeor profiles information. In this study, the latest released
209 monthly precipitation data (TRMM 3B43 Version 7; Huffman et al., 2007) between April 2002 and
210 October 2014 were used. The product provides the rainfall estimates every 0.25 degree between 50° S and
211 50° N.

212

213 **4. GRACE signal restoration methodology**

214 The GRACE inter-satellite range observable does not measure TWS variations directly, and requires
215 processing to relate the absolute and relative accelerations of the twin satellites to variations in the gravity
216 field. The publicly available GRACE SHC products contain high-frequency errors that require the use of a
217 spatial filter to suppress them. As mentioned earlier, both signal and error are impacted by this filtering
218 step, making restoration of the leaked signal important for proper characterization of the full TWS
219 changes in the basin. Similar to the approach of Chen et al. (2014), the following signal restoration
220 scheme is applied (see also Fig. 2):

- 221 1. After de-striping and Gaussian filtering are applied to the GRACE SHC (result from Sect. 3.1),
222 the TWS variation in the form of Equivalent Water Height (EWH) is computed following Wahr
223 et al. (1998). The result is set as the filtered reference TWS.
- 224 2. A candidate TWS variation (i.e., the “candidate TWS”) is introduced and is set equal to the
225 filtered reference TWS.



226

227

Fig. 2: Flowchart of the GRACE signal restoration scheme

228

229

3. The candidate TWS is set equal to zero over the oceans. After that, it is converted to SHCs up to degree 60, with a Gaussian filter of radius $R=350$ km applied. Then, the SHCs are converted back to TWS variations. Note that, following the recommendation of Chen et al. (2014), the de-stripping filter is not applied. The result of this step is called the “filtered candidate TWS”.

230

231

232

233

4. The TWS increment is computed as the filtered reference TWS minus the filtered candidate TWS.

234

235

5. If the TWS increment satisfies a stopping criterion (e.g., if the difference in every grid cell is smaller than a pre-defined threshold), the candidate TWS is defined as the corrected TWS (the

236

final product). Otherwise, the candidate TWS is updated by adding the TWS increment and the

237

steps 3–5 are repeated.

238

It is emphasized here that the signal restoration process was applied to the TWS globally, but the stopping

239

criterion was locally defined. The stopping criterion was chosen empirically: the signal restoration process

240

was repeated until the increment TWS in every grid cell inside the Tonlé Sap basin became smaller than

241 0.5 cm EWH. Note that the selected value is 3–4 times smaller than the noise level of TWS variations
242 derived from GRACE (Wahr et al., 2006; Klees et al., 2008; Dahle et al., 2014). For all monthly solutions,
243 the criterion was met after about 30–40 iterations.

244 To study the sensitivity of the obtained results to the choice of the Gaussian filter radius, four more time
245 series of the corrected TWSs were computed using the same signal restoration procedure but with other
246 Gaussian filters radii R : 300, 400, 450, and 500 km. Every month, the error bounds were drawn based on
247 the minimum and maximum values taken from the 5 time series (including the case of $R=350$ km).

248 Furthermore, two more variants of the corrected TWS were produced for comparison.

249 1. To evaluate the sensitivity of the signal restoration method to the choice of the filter radius, the
250 filtered land mass data provided by the GRACE Tellus website were considered
251 (<http://grace.jpl.nasa.gov>; last access: 24 March 2015). Similar to this study, the land mass grid
252 data (CSR option) were also produced using the CSR RL05 product, but using different de-
253 striping parameters, and with the Gaussian smoothing radius set equal to 300 km (see
254 <http://grace.jpl.nasa.gov/data/gracemonthlymassgridsland>; last access: 24 March 2015). The filter
255 radius R in the signal restoration procedure was defined consistently. For clarity, the term
256 “GRACE TWS” is used below to represent the results of the processing from this study (Sect. 3.1)
257 while the term “GRACE TWS (Tellus)” is used to represent the results based on the data obtained
258 from the Tellus website.

259 2. To compare the performance of the signal restoration method and the scale parameter method
260 (Landerer and Swenson, 2012), the latter technique was used to post-process the filtered TWS
261 instead. The scale parameters were computed based on the three hydrological models considered
262 in our study. First, the original monthly TWS variations from each hydrological model were
263 converted to the SHCs, and the SHCs were Gaussian filtered using the same smoothing radius as
264 in the case of GRACE (350 km, see Sect. 3.1). The filtered SHCs were then converted to TWS
265 (called the filtered TWS). Second, the time-series of mean TWS over the Tonlé Sap basin was

266 computed from the filtered TWS and the original TWS, and the former was fit using least-squares
267 to the latter using one scale parameter. The scale parameters estimated from GLDAS-NOAH,
268 ERA-Interim, and PCR-GLOBWB hydrology models were 1.63, 1.27, and 1.67, respectively. The
269 difference in the estimated values was likely influenced by the model dependency. As indicated
270 by Landerer and Swenson (2012), the estimated scale parameter over the small river basin could
271 be biased toward the hydrology model applied. Therefore, instead of applying the scale parameter
272 individually, the mean value of 1.52 was used to scale the filtered TWS extracted from GRACE.

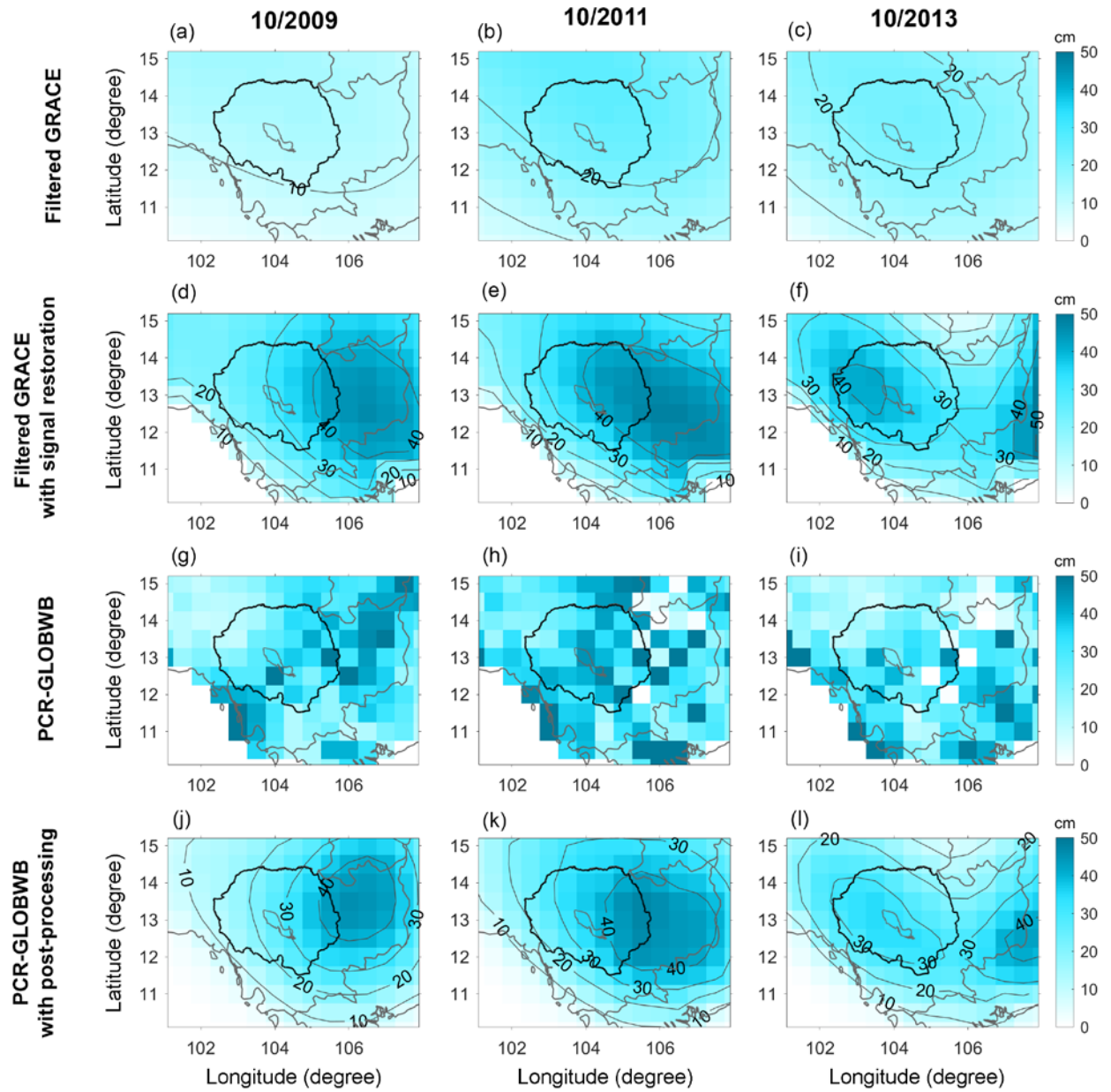
273

274 **5. Results**

275 **5.1 TWS variations estimated over the Tonlé Sap basin**

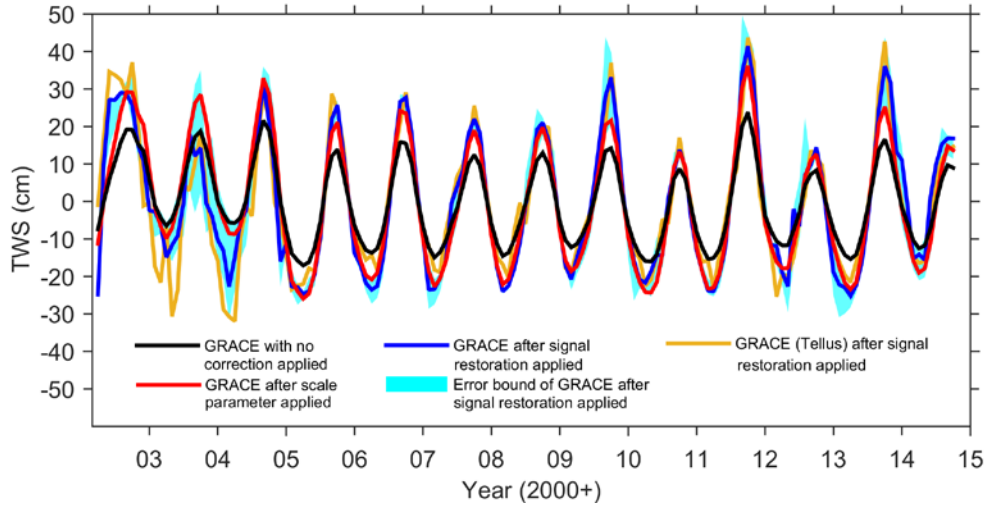
276 **5.1.1 Signal restoration from the filtered GRACE-based estimates**

277 The signal restoration method was applied to the filtered monthly GRACE TWS variations. The results
278 before and after the restoration are demonstrated in Fig. 3 for the flood months of October 2009, 2011, and
279 2013. Before the signal restoration, a single maximum was observed in the northern part of the basin with
280 the amplitude reaching approximately 10 – 20 cm EWH (Fig. 3 (a,b,c)). After the restoration, the TWS
281 variations between the Tonlé Sap basin and Central Highlands of Vietnam became apparent in all
282 solutions (see Fig. 3 (d,e,f)), and TWS amplitude reached approximately 40-45 cm EWH (see contours in
283 Fig. 3 (d,e,f)). As the signal restoration process was designed without any involvement of the hydrology
284 model or any other external data, the agreement with an independent hydrological model provides some
285 confidence in the GRACE TWS estimates. The TWSs derived from PCR-GLOBWB hydrological model
286 were shown in Fig. 3 (g,h,i). Although the spatial resolution mismatches between GRACE (Fig. 3 d,e,f)
287 and PCR-GLOBWB (Fig. 3 g,h,i) were presented, the signal location between them was relatively
288 consistent. To verify the consistency of the location,



289

290 **Fig. 3:** TWS variation over Tonlé Sap basin in October 2009, 2011, and 2013 derived from GRACE
 291 solution before (a,b,c) and after signal restoration applied (d,e,f). PCR-GLOBWB results of the same
 292 months are also shown (g,h,i). For the comparison with GRACE, the same post-processing procedures
 293 used for GRACE were applied to PCR-GLOBWB (see Sect. 3.1 and 4), and results were shown in the last
 294 row (j,k,l).

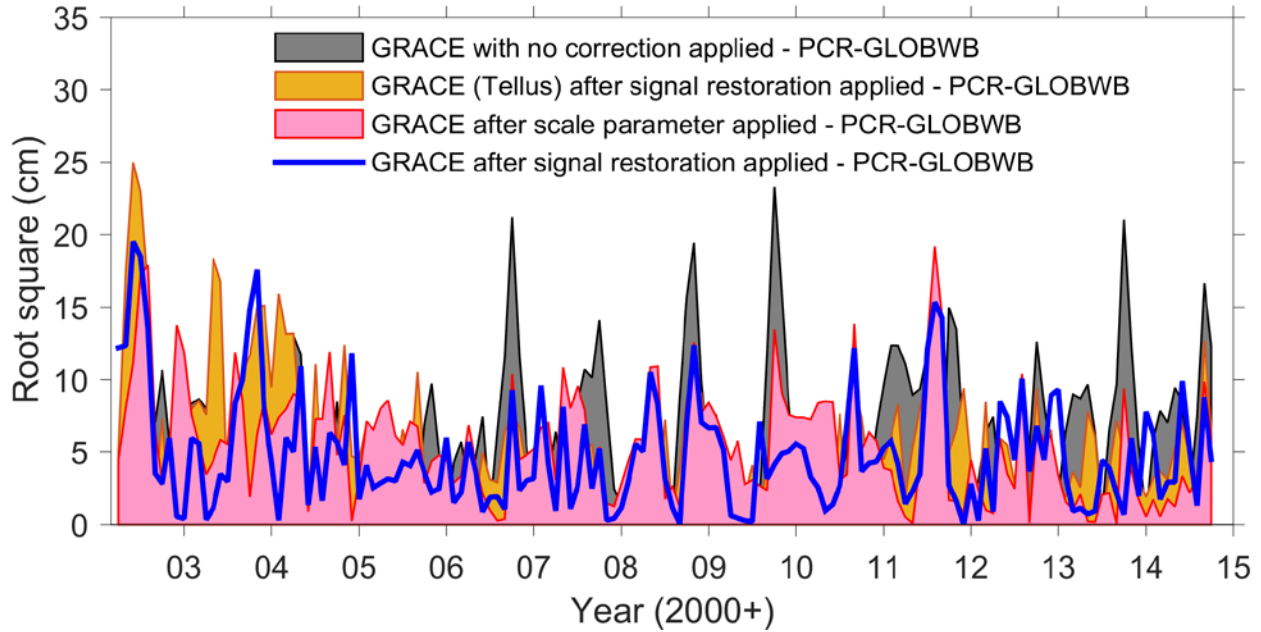


295

296 **Fig. 4:** TWS averaged over Tonlé Sap basin derived from different GRACE solutions and correction
 297 methods.

298 the same GRACE post-processing procedures (see Sect. 3.1 and 4) were applied to PCR-GLOBWB, and
 299 the results were shown in Fig. 3 (j,k,l). Again, although not identical, the spatial distribution was observed
 300 very close to GRACE signal restoration results. Note that the PCR-GLOBWB with post-processing was
 301 only used to illustrate the consistency of the TWS spatial distribution and was not used further in this
 302 study.

303 Fig. 4 presents the basin averaged TWS variations based on different GRACE solutions and correction
 304 methods. The filtered TWS without any correction applied is very smooth with a clear seasonal signal
 305 varying within the range of approximately ± 10 cm EWH. After applying the signal restoration method to
 306 the GRACE solutions, the amplitude of the TWS variations increases by approximately a factor of two.
 307 Note that the amplitude of the corrected TWS was always approximately 20 cm EWH, even though
 308 different R values were used (see Table 1). This indicates that, for the average signal amplitude estimated
 309 over a long time interval, the signal restoration is sufficiently insensitive to the choice of R . In some
 310 specific months, however, a difference is observed. This is likely due to the remaining error caused by the
 311 choice of an R value that was too small (i.e., stripes may still exist in that case).



312

313

Fig. 5: Absolute value of the root-square difference between TWS based on various GRACE solutions and TWS from PCR-GLOBWB ($\sqrt{(GRACE - PCRGLOBALWB)^2}$). A value closer to zero indicates a closer match to the PCR-GLOBWB.

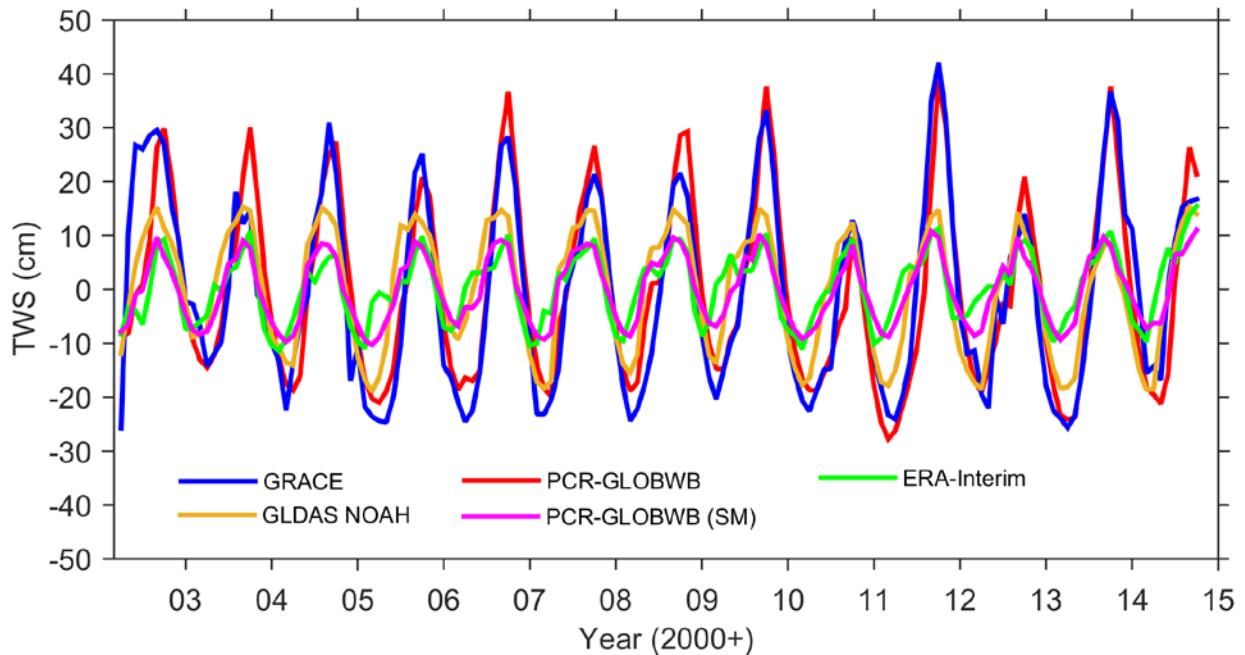
316

For the comparison, the corrected TWS was also computed from the GRACE solutions using the scale parameter method. Note that, in contrast to the signal restoration method, which computes a correction for each month individually, the scale parameter method uses the same scale parameter for all months. In this way, the annual amplitude increased to approximately 20 cm EWH. Although the resulting time series after the two correction methods show a similar pattern (see Fig. 4), the overall amplitude after the scale parameter method is smaller, particularly during the flood events, e.g., in October 2011 and October 2013. On the other hand, large differences can also be seen in October 2003, where the scale parameter method led to significantly larger TWS variation. To assess which technique might better characterize the true TWS in the region, the next section compares the results to the output from the hydrological models.

325

326 **Table 1:** Correlation coefficient and RMS difference between GRACE-based TWS and TWS from PCR-
327 GLOBWB. Annual amplitude and phase (estimated using Eqs. B1–B3) of TWS variations from various
328 GRACE solutions and hydrological models are also provided. The best performing correction method is
329 highlighted in bold.

	Correlation wrt PCR-GLOBWB	RMS difference wrt PCR-GLOBWB (cm)	Annual amplitude (cm EWH)	Annual phase (month)
No correction GRACE (350 km)	0.91	7.84	13.6 ± 0.4	5.70 ± 0.05
Scale parameter GRACE (350 km)	0.91	7.60	20.7 ± 0.7	5.70 ± 0.05
Signal restoration GRACE (300 km)	0.85	8.90	22.4 ± 1.4	5.51 ± 0.10
Signal restoration GRACE (350 km)	0.92	7.43	21.6 ± 1.0	5.77 ± 0.06
Signal restoration GRACE (400 km)	0.90	7.64	20.7 ± 0.9	5.56 ± 0.07
Signal restoration GRACE (450 km)	0.90	7.48	20.2 ± 0.8	5.67 ± 0.07
Signal restoration GRACE (500 km)	0.89	8.13	20.9 ± 0.8	5.55 ± 0.08
Signal restoration GRACE (Tellus)	0.91	7.54	20.7 ± 0.9	5.52 ± 0.09
PCR-GLOBWB	-	-	21.5 ± 0.7	5.81 ± 0.06
PCR-GLOBWB (SM)	-	-	8.3 ± 0.2	4.90 ± 0.05
GLDAS-NOAH	-	-	14.6 ± 0.4	4.84 ± 0.08
ERA-Interim	-	-	7.5 ± 0.3	4.48 ± 0.08



330

331 **Fig. 6:** TWS averaged over Tonlé Sap basin derived from GRACE solutions (with signal restoration
 332 applied), and hydrological models. PCR-GLOBWB includes soil moisture, groundwater, and surface
 333 water components. GLDAS-NOAH includes soil moisture and canopy water storage components. Only
 334 soil moisture component is covered by ERA-Interim and PCR-GLOBWB (SM).

335 **5.1.2 GRACE versus PCR-GLOBWB**

336 Because the TWS derived from the PCR-GLOBWB model covers all storage components, that model was
 337 used in the first instance as an additional comparison to the GRACE results. Fig. 5 shows differences
 338 between TWS based on various GRACE solutions and TWS from PCR-GLOBWB. The amplitude and
 339 phase were also estimated, based on Eqs. (B1–B3). Although not uniformly, the GRACE solutions after
 340 signal restoration (with $R=350$ km) show a closer match to PCR-GLOBWB, particularly after 2005, than
 341 the other solutions. Even though PCR-GLOBWB was used in the scale parameter estimation (see Sect. 4),
 342 the GRACE-based result after the scale parameter applied was not closer to the PCR-GLOBWB result
 343 than the result from the signal restoration method. Applying a uniform scale parameter to the entire time-
 344 series likely led to the insufficient flexibility of that correction.

345 Additionally, the statistical values given in Table 1 demonstrate that applying signal restoration with
346 different R led to similar results. The GRACE-based TWS after the signal restoration with $R=350$ km was
347 selected for further analysis, as it matches best to PCR-GLOBWB in terms of correlation coefficient and
348 RMS difference.

349 **5.1.3 Comparison of hydrological models**

350 The basin averaged TWS variations derived from GRACE solutions and three hydrological models are
351 shown in Fig. 6. As TWS variations derived from GLDAS and ECMWF lack surface water and
352 groundwater contributions (so that the primary signal there is related to soil moisture (SM)), PCR-
353 GLOBWB derived SM alone is also shown for a comparison (defined as PCR-GLOBWB (SM)). From
354 Fig. 6 and Table 1, one can see that PCR-GLOBWB matches GRACE better than the other models, in
355 terms of amplitude, phase and RMS difference. Such a good agreement justifies the primary usage of
356 PCR-GLOBWB for the cross-comparison of GRACE-based estimates presented in the previous section.
357 Furthermore, the similar performance of GLDAS, ERA-Interim, and PCR-GLOBWB (SM) models is
358 noteworthy, and suggests that the SM component is well characterized by all three models. To assess the
359 role of the individual storages in TWS variations, the contribution percentage of the store ($w_{\%}$) can be
360 simply computed as follows:

$$361 \quad w_{\%} = \left[\frac{1}{T} \sum_{t=1}^T \frac{w_t}{TWS_t} \right] \times 100 \quad (2)$$

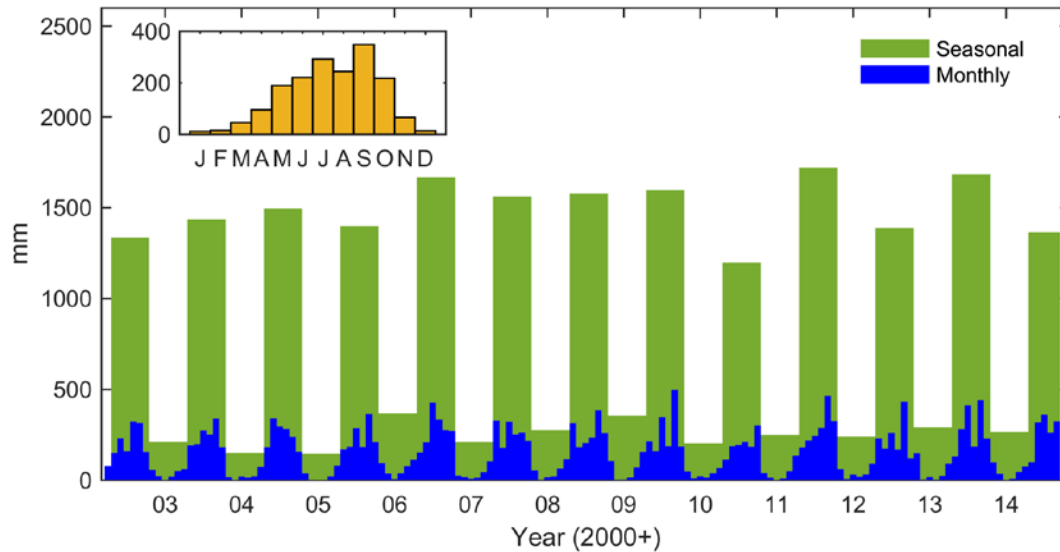
362 where w_t and TWS_t are the hydrological components and TWS variations estimated at time t and T is the
363 total time interval of the time series considered. A comparison of PCR-GLOBWB (SM) with PCR-
364 GLOBWB shows that SM contributes with only 24.5% to the TWS variation averaged over the entire
365 Tonlé Sap basin (see Fig. 6), while the groundwater storage (GWS) is the major contributor (71.1 %). The
366 remaining contribution is mostly provided by surface water (including reservoir, lake, irrigation paddy
367 storages, and river channel storages): approximately 4.4%. Interception storage variation contributes less

368 than 0.001%. Note that the percentage values were computed based on the entire time series. A phase lag
369 of approximately one month is observed between TWS and SM. This phase difference is explained mainly
370 by the GWS component: it takes water several weeks to transfer from upper to lower layers (e.g., from
371 surface to GWS).

372 Considering only the positive peak of every year, the lowest peak in the GRACE-derived TWS variations
373 is detected in October 2010: 12.6 cm EWH. This peak is 49 % lower than the mean peak value (computed
374 from all the peaks between 2002 and 2014). The second lowest peak is observed in October 2012: 44 %
375 lower than the mean peak value. These features are also seen in the PCR-GLOBWB results. Additionally,
376 the greatest flood event was seen as the highest TWS peak observed in October 2011 (by both GRACE
377 and PCR-GLOBWB), quantified as approximately 42 cm EWH, which is 40% higher than the mean peak
378 value. The second and the third largest flood events are observed in October 2013 as approximately 36 cm
379 EWH (~34% higher than the mean peak) and October 2009 as approximately 33 cm EWH (~31% higher),
380 respectively. The TWS variations constructed using only the SM component show much lower variations
381 in the peak value, approximately 10 cm EWH. The reason is that the SM storage is limited by a specific
382 field capacity with a particular maximum value, and therefore the similar peak value (corresponding to the
383 field capacity) is observed in both normal and flood years. This suggests that the inter-annual TWS
384 variability in the Tonlé Sap basin is driven by the GWS component and explains the relatively low peak
385 values of GLDAS and ERA-Interim models in that area.

386 **5.2 Precipitation**

387 Monthly total precipitation averaged over the Tonlé Sap basin was computed (Fig. 7) for a comparison
388 with the estimated TWS variations. In addition, the seasonal precipitation was computed by accumulating
389 the monthly data over 2 periods per year, May – October (monsoon season) and November – April (dry
390 season). The pattern of annual precipitation variations slightly changed after 2009 and, as seen in 2010,
391 2012 and 2014, a shortage of precipitation during the monsoon period was responsible for the low TWS



392

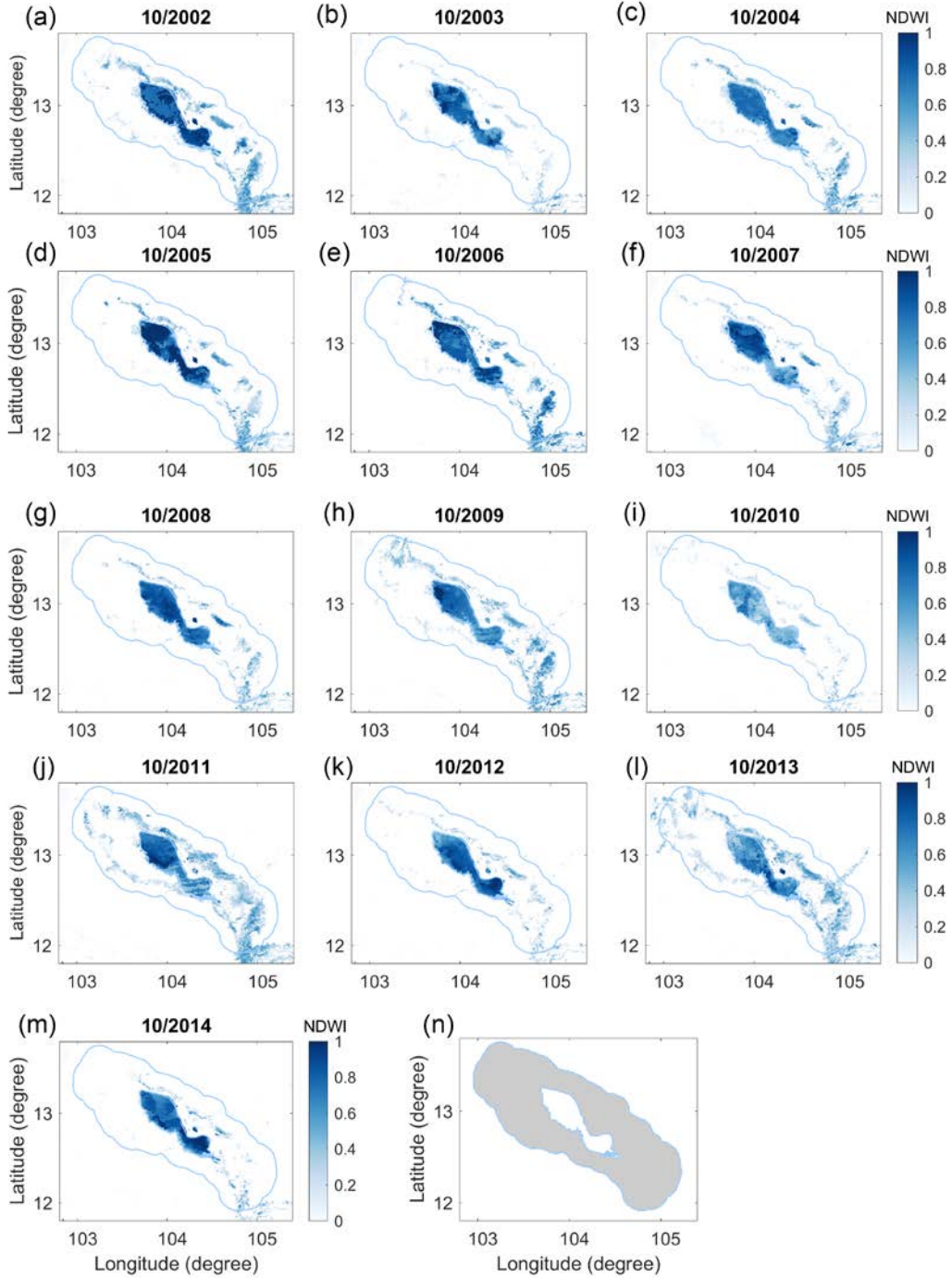
393 **Fig. 7.** Monthly and seasonal total precipitation over the Toulé Sap basin derived from TRMM 3B43.

394 Seasonal precipitation was computed by accumulating the monthly data in 2 periods per year, May –
 395 October and November – April. The mean value of a specific month is shown in the inset figure.

396 signatures seen in the GRACE TWS estimates. The largest amount of precipitation was recorded in 2011,
 397 when precipitation in all the months of the monsoon period was higher than the average. This was likely
 398 the reason for the greatest TWS observed in 2011 (see Fig. 6).

399 **5.3 Inundated area variations**

400 To observe variations of the inundated area, the monthly averaged NDWI values calculated from
 401 MYD09A1 data were analyzed (Fig. 8). Large flood extents are seen in October 2011 and October 2013.
 402 A limited inundated area is observed in October 2003, October 2012, and particularly in October 2010,
 403 where the average NDWI falls below 0.3. To estimate the inundated area, the positive NDWI pixels inside
 404 the maximum flood extent area (defined as a gray shaded area in Fig. 8 (n)) were counted. The maximum
 405 flood extent polygon (outermost blue boundary line) was drawn based on the fact that the NDWI outside
 406 the polygon (between July 2002 and October 2014) always has zero or negative values. Based on the
 407 resolution of the surface reflectance data, each positive NDWI pixel was counted as 0.25 km².



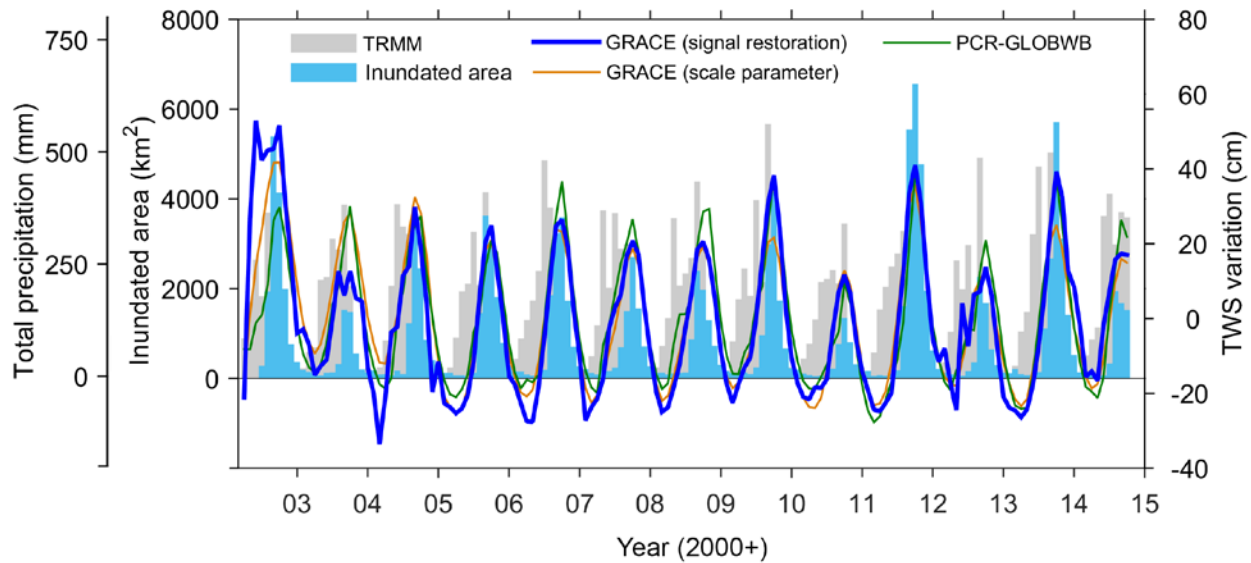
408

409 **Fig. 8.** Monthly mean NDWI [-] of October between 2002 and 2014. Zero and negative values are
 410 excluded. The maximum flood extent is defined by the blue polygon. For the inundated area calculation,
 411 only the NDWI values inside the gray shade area (see (n)) are used.

412 In contrast to the small proportion computed over the entire basin, the surface water estimated from PCR-
413 GLOBWB contributes approximately 61.3% to the TWS variation averaged inside the Tonlé Sap
414 floodplain. GWS is the second contributor (35.3%) while SM contributes only 3.4%. As the surface water
415 is the major contributor, it is reasonable to represent the TWS variations in terms of inundated area
416 variations. Therefore, the average TWS variation inside the Tonlé Sap floodplain (the shaded polygon in
417 Fig. 8 (n)) was computed from GRACE data to investigate whether it has the same temporal pattern as
418 MODIS-derived inundated area variations. The number of TWS pixels was 7 inside the floodplain,
419 compared to 28 over the entire basin.

420 The inundated area variations and TWS variations over the Tonlé Sap floodplain correspond well to each
421 other, with a correlation coefficient of 0.81 (Fig. 9). Note that the area within the maximum flood extent
422 area (see Fig. 8 (n)) is only 21,300 km² (equal to a linear resolution of ~146 km), which is 3.8 times
423 smaller than the total area of the Tonlé Sap basin. Due to a limited GRACE spatial resolution, the
424 GRACE-based estimates of TWS inside the floodplain area is close to the TWS estimates over the basin
425 (see also Fig. 6). Therefore, even though the GRACE TWS inside the floodplain area was used in this
426 section for the sake of consistency with the inundated area, the GRACE TWS estimate is rather a basin
427 average signal and not a signal inside the floodplain only. On the other hand, a high correlation between
428 GRACE TWS estimates and MODIS inundation area estimates implies a strong spatial correlation of mass
429 re-distribution processes in the area, let the TWS inside the floodplain area and over the basin be driven by
430 different hydrological processes, as described by PCR-GLOBWB.

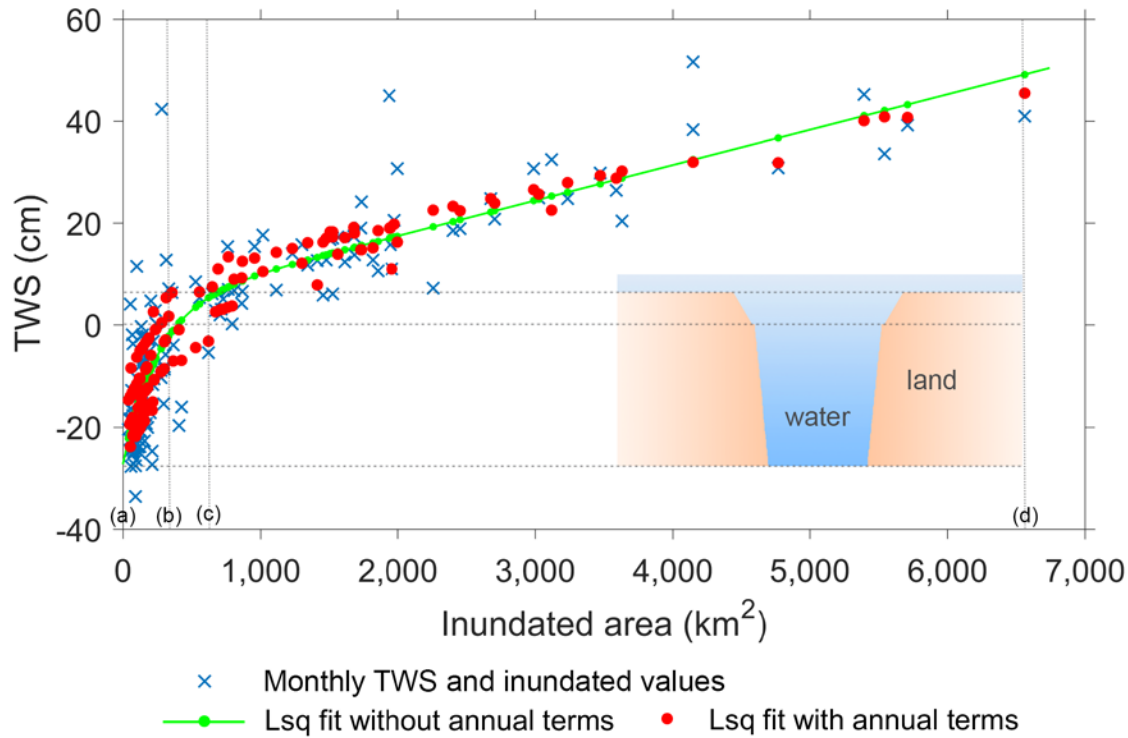
431 From Fig. 9, the phase difference between the two time series is only 0.13 months, or approximately 4
432 days. The phase shift is likely due to the different data interval used to calculate the monthly average of
433 the TWS and the inundated area variations. The mean peak inundated area, calculated by averaging all
434 yearly peak values between September 2002 and September 2014, is 3,436 km². The lowest peak
435 inundated area and lowest average TWS peak are observed in October 2010. The inundated area in that
436 month was 1,342 km², i.e., 2.6 times less than the mean value. The largest inundated areas of 6,561 km²



437

438 **Fig. 9:** Monthly inundated area and TWS variations (derived from GRACE solutions after signal
 439 restoration applied, GRACE solutions after scale parameter method applied, and PCR-GLOBWB)
 440 averaged inside the defined polygon (see Fig. 8 (n)). Total monthly precipitation (TRMM) is also provided.
 441 Note that the zero positions are different in the left and right vertical axes.

442 (91% above the mean peak value) and 5,710 km² (66% above) are seen in October 2011 and 2013,
 443 respectively. The similarity of the inundated area variations and the GRACE-derived TWS variations is
 444 also seen in the late 2003 monsoon period. Interestingly, in line with the small inundated area in late 2003,
 445 GRACE also observed the low TWS at the same period. This is in agreement with Kummu et al. (2014),
 446 who showed that in 2003 the Tonlé Sap Lake received the smallest amount of rainfall (69.1 km³/year;
 447 measured at Cambodian weather stations) since 1999. Remarkably, the aforementioned feature is not
 448 present in PCR-GLOBWB, GRACE data with the scale parameter correction, and the global precipitation
 449 data (see Fig. 9). According to Kummu et al. (2014), it is likely that the precipitation in the global dataset
 450 is overestimated during the late 2003 monsoon period. As PCR-GLOBWB was forced by this dataset,
 451 PCR-GLOBWB likely overestimated TWS in



452

453 **Fig. 10.** Scatter plot between TWS variation and inundated area before (original, blue crosses), and after
 454 applying a least-squares fit with (red dots) and without (green line) an annual variation term. Insert image
 455 explains schematically the relationship between the TWS and inundated area with respect to the
 456 topography of the inundation area.

457 this period. As far as the scale-corrected GRACE data are concerned, it is likely that the artifact in 2003 is
 458 caused by applying a uniform scale parameter to the entire time-series.

459 Next, a quantitative relationship between the inundated area and the TWS variation is investigated. The
 460 scatter plot of these two quantities shows a non-linear behavior (Fig. 10). A different slope is seen
 461 between, e.g., points (a) to (b) and points (c) to (d), which is presumably due to the topography of the
 462 inundation area. Water is firstly accumulated inside the deeper inundation bank (e.g., between points (a)
 463 and (c)), and therefore a large rise in TWS is not accompanied by a significant increase in inundated area.
 464 During the wet season, when the deeper inundation bank is filled, water forms a shallow layer over a large
 465 inundation area, and even a small change in TWS can lead to a large variation of the inundated area (e.g.,

466 between points (c) and (d)). From Fig. 10, a relationship between the inundated area and the TWS
 467 variation can be established, e.g., using a simple polynomial regression. It is found that the residual
 468 (between the fit and the target) was further reduced when the annual variation term was also used in the
 469 regression equation. The equation used to relate the inundated area to the TWS variation in this study was
 470 ultimately defined as

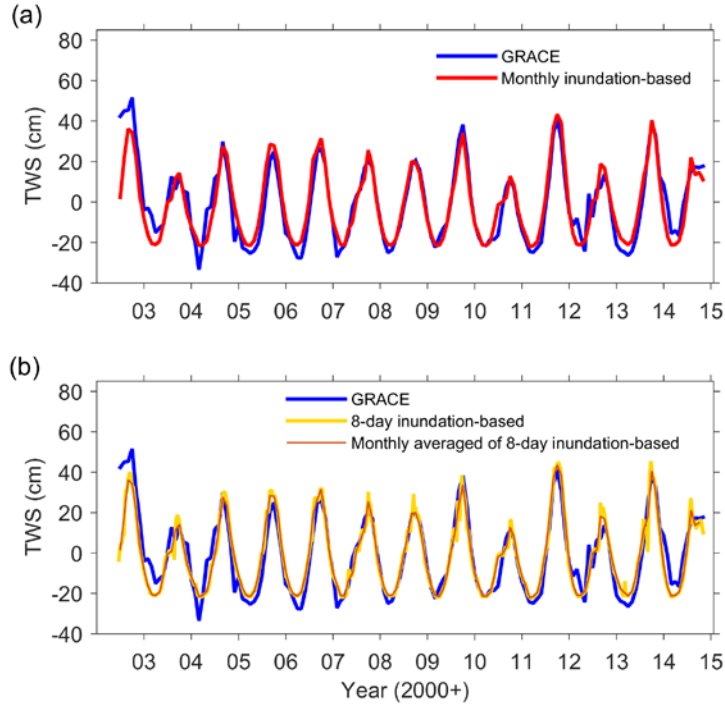
$$471 \quad y = a_0 + a_1x + a_2 \exp(b) + \overbrace{a_3 \cos(\omega t) + a_4 \sin(\omega t)}^{\text{annual variation}} \quad , \quad (2)$$

$$472 \quad b = \frac{-x}{1000 \text{ km}^2} \quad (3)$$

473 where y is a vector containing the TWS variations (m) derived from GRACE, and x is a vector containing
 474 the inundated area (km^2) estimates derived from NDWI. The fourth and fifth terms represent annual
 475 variations, where t is the observation time, and $\omega = 2\pi/T$ with T the annual period. Using least-squares
 476 adjustment, we estimated the coefficients in Eq. (2) and their values are given in Table 2. Fig. 11(a) and
 477 Table 3 show a good agreement between the TWS variations estimated on the basis of the MODIS-
 478 derived inundated area and the GRACE-based ones, with a correlation coefficient of 0.92 and a RMS
 479 difference of 7.65 cm EWH, when the annual variation term is included. The correlation coefficient
 480 reduces to 0.88 and the RMS difference increases by 14% when the annual variation term is not included.

481 The need of annual terms is explained by the presence of the stationary annual signal from the soil
 482 moisture component (see Fig. 6). This suggests that in order to ensure the consistency of results with the
 483 TWS signal properties, the annual variation should be included in the adjustment. To support our
 484 interpretation, the annual variation terms in Eq. (2) are replaced by the soil moisture signal from PCR-
 485 GLOBWB:

$$486 \quad y = a_0 + a_1x + a_2 \exp(b) + a_5 SM \quad (4)$$



487

488 **Fig. 11.** TWS averaged over the maximum flood extent area (see Fig. 9 (n)) derived from the mean
 489 monthly MODIS-derived inundated area (a), and from the 8-day mean MODIS-derived inundated area (b).
 490 In (b), the monthly averaged was computed from the 8-day result. GRACE-based TWS estimates are
 491 shown in both plots for a reference. The annual variation terms are included based on Eq. (2).

492 **Table 2:** Parameters estimated from least-squares adjustment using Eq. (2) – (4) with and without
 493 including annual variation terms.

	Without annual variation terms	With annual variation terms	With annual variation terms from SM
a_0 (m)	3.6 ± 0.7	$-5.4 \times 10^{-1} \pm 6.4 \times 10^{-1}$	1.2 ± 0.7
a_1 (m/km ²)	$1.7 \times 10^{-3} \pm 1.2 \times 10^{-4}$	$1.4 \times 10^{-3} \pm 1 \times 10^{-4}$	$1.4 \times 10^{-3} \pm 1 \times 10^{-4}$
a_2 (m)	-30.6 ± 1.6	-16.2 ± 1.4	-20.6 ± 1.4
a_3 (m)	0	-4.8 ± 0.9	0
a_4 (m)	0	-9.2 ± 0.9	0
a_5 (-)	0	0	0.9 ± 0.1

494

495 **Table 3:** Correlation coefficient and RMS difference between the MODIS-derived inundation-based TWS
 496 variations and the GRACE-based ones. In the former case, the estimation process made use of the mean
 497 monthly inundated area and the mean 8-day inundation area.

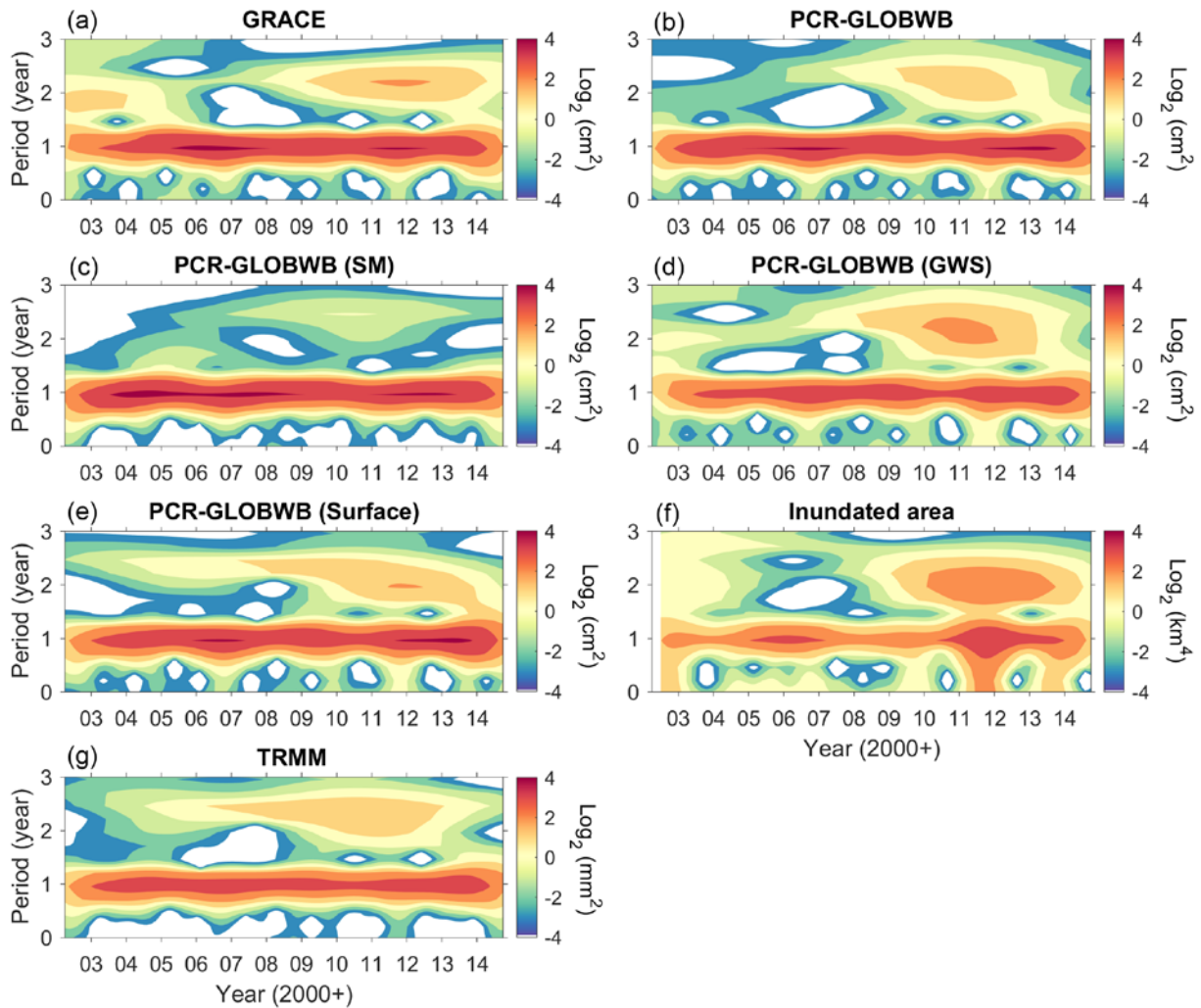
Monthly MODIS-derived inundation-based	Correlation coefficient	RMS difference (cm EWH)
No annual variation term	0.884	8.94
With annual variation term	0.921	7.65
With annual variation term from SM	0.908	7.98
8-Day MODIS-derived inundation-based		
No annual variation term	0.884	8.95
With annual variation term	0.920	7.70
With annual variation term from SM	0.911	7.87

498
 499 where SM is the soil moisture component (m). The coefficients estimated from Eq. (4) are also given in
 500 Table 2. Again, good agreement between the GRACE-based and MODIS-based values is observed with a
 501 similar correlation and RMSE values as obtained based on Eq. (2) (see Table 3). Importantly, the
 502 restoration of the annual variation (either from the mathematical fit or from SM component) is necessary
 503 to increase the accuracy of the adjustment.

504 The analysis above was based on the monthly data. Further investigation was conducted to determine
 505 whether the same relationship could be applied with a higher temporal sampling. The 8-day MODIS-
 506 derived inundated areas were firstly converted to TWS variations (using Eq. (2) with the same coefficients)
 507 and then averaged over monthly intervals (Fig. 11(b)). The TWS variations estimated this way are again
 508 compared to GRACE-based TWS variations (Fig. 11(b) and Table 3). For completeness, the adjustment
 509 based on Eq. (4) was also performed. The obtained correlations and RMS differences are very similar to
 510 those based on the mean monthly inundated areas. Such a good agreement is an indication that reflectance
 511 data can be employed to observe the sub-monthly (e.g., 8-day) TWS variations over the Tonlé Sap basin,
 512 and potentially at spatial scales higher than that GRACE data can reliably provide.

513 **5.4 Inter-annual variations**

514 To explore annual and inter-annual variations of hydrological activity over the Tonlé Sap basin, power
515 spectra were computed based on the Morlet wavelet with the software provided by Torrence and Compo
516 (1998). The wavelets are used to estimate the dominant time-frequencies (periods) for different time-series.
517 We analyzed the monthly averaged TWS estimates derived from GRACE and PCR-GLOBWB (Fig. 12
518 (a), (b)), the monthly averaged SM, GWS, and surface water storage derived from PCR-GLOBWB (Fig.
519 12 (c), (d), (e)), the monthly inundated area (over the defined flood extent; Fig. 12 (f)), as well as the
520 monthly averaged global precipitation (Fig. 12 (g)). As the precipitation is a derivative of water storage,
521 we integrated precipitation over time before computing its power spectrum to avoid mathematical artifacts
522 caused by the spectral inconsistency. In all spectra, annual variations are clearly observed throughout the
523 entire study interval. Starting from October 2010, inter-annual variations with an approximately 2-year
524 period are present in all spectra, except PCR-GLOBWB (SM), for which the limitation of the SM storage
525 capacity is likely the cause. The SM storage cannot exceed a certain amount and therefore only a regular
526 seasonal variation was observed from the SM spectrum. From Fig. 12 (d), it is clear that GWS has the
527 strongest 2-year cycle of the three considered PCR-GLOBWB components. In fact, the shown power
528 spectra of inter-annual variations reflect their relative amplitudes (compared to the total signal). The
529 amplitudes of GWS inter-annual variations seem to be larger simply because that signal is cleaned from
530 nearly all stationary soil moisture signal. Inter-annual variations of open water can also be observed from
531 the surface water storage (PCR-GLOBWB (Surface), Fig. 12 (e)) and the MODIS-derived inundated area
532 (Fig. 12 (f)). It is noted that although the power spectrum of surface water storage was computed over the
533 entire basin, the spectral pattern is identical when it was computed over the flood extent only (not shown).
534 This is explained by the fact that the surface water component was only situated inside the floodplain area.
535 Therefore, the comparison between the spectra of PCR-GLOBWB (Surface) and the MODIS-derived
536 inundated area based on Fig. 12 is reasonable. Due to the coarse spatial resolution of the remote sensing



537

538 **Fig. 12.** Power spectral distribution of (a) GRACE-derived TWS, (b) PCR-GLOBWB derived TWS, (c)
 539 PCR-GLOBWB derived soil moisture, (d) PCR-GLOBWB derived groundwater storage, (e) PCR-
 540 GLOBWB derived surface water storage, (f) MODIS-derived inundated area, and (g) TRMM monthly
 541 precipitation (integrated over study period). The power spectra are presented in the base-2 logarithmic
 542 scale.

543 observations, similar spectra patterns of TWS, SM, GWS, and TRMM as Fig. 12 were also observed even
 544 when only the signal inside the floodplain was considered (not shown). The inter-annual amplitude of the
 545 MODIS-derived inundated area (Fig. 12 (f)) is stronger than that of surface water storage (Fig. 12 (e)) and
 546 even of TWS (Fig. 12 (a), (b)). This can be explained by the non-linear relationship described earlier

547 between the inundated area and the TWS: small variations of TWS can cause large variations in the
548 inundated area during the flood period (see the discussion in Sect. 5.3). The 2011 and 2013 floods
549 apparently led to stronger inter-annual amplitude of the inundated area variations than of TWS variations.
550 Finally, it is not surprising that the TWS power spectra resemble that of precipitation (Fig. 12 (g)), since
551 the latter is the source of the observed TWS variations.

552

553 **6. Discussion and conclusions**

554 Satellite remote sensing data of several types as well as several hydrological models were used to study
555 the TWS variations and flood signatures over the Tonlé Sap basin between 2002 and 2014.

556 Among the satellite observations, the major focus was on GRACE, which observes the TWS variations
557 directly. Applying the signal restoration method to GRACE data improves the accuracy of the TWS
558 estimates. In contrast to the scale parameter method that applies the same scale parameter to all monthly
559 data, the signal restoration method treats TWS differently for different months. This improves the ability
560 of GRACE-based estimates to capture the irregularly low and high (e.g., flood) TWS signatures. Of course,
561 it is worth keeping in mind that only the signal over one particular basin was analyzed in this study, and
562 the performance of the signal restoration method may be different in other regions. Furthermore, the
563 optimal choice of implementation details (for example, Gaussian smoothing radius and stopping criterion)
564 may be different in other areas. Ideally, the choice of the stopping criterion should be such that additional
565 iterations do not significantly affect the final result, so that the total number of iterations can be very large.
566 However, in practice, each iteration introduces an additional error, e.g., due to the Gibbs phenomenon
567 (Swenson and Wahr, 2002) or the presence of North-South stripes in the filtered reference TWS.
568 Therefore, the iterations should be stopped before the errors become too large. Further sensitivity studies
569 on the impact of implementation details are recommended to facilitate the use of the signal restoration
570 method in various regions.

571 Using observations from more than one independent source was necessary to interpret and validate the
572 GRACE-based TWS estimations. Due to the absence of several important components (in particular,
573 groundwater) in some hydrological models, a mismatch in amplitude and phase was observed compared to
574 GRACE. The PCR-GLOBWB hydrological model, on the other hand, covers all the major contributors to
575 TWS (including groundwater and surface water), allowing the results to be directly compared to GRACE.
576 Furthermore, usage of the PCR-GLOBWB model allows the contributions of the different storage
577 components to be quantified, yielding an improved understanding of their dynamics. Irregular
578 precipitation variations between 2010 and 2014 observed from TRMM verify the low and high TWS
579 variation in the same period.

580 The inter-annual TWS variations between 2010 and 2014 were driven by the variability of the
581 precipitation seasonal amplitude that began from 2009. The inter-annual variations were mainly present in
582 the GWS and surface water storage components. The SM component lacks those variations due to its
583 limited storage capacity. Although the 2010-2014 inter-annual patterns were clearly visible, it is difficult
584 to verify their long-term continuity due to the limited understanding of the driving mechanisms. Longer
585 time series are needed for better understanding of the phenomenon.

586 It was shown that the inundated area variations derived from surface reflectance observations can also
587 provide valuable information for GRACE data validation. It was shown for the first time that the
588 reflectance data can be successfully used to estimate the total TWS variations. To that end, an empirical
589 non-linear relationship between the inundated area and GRACE-based TWS variations was established for
590 the Tonlé Sap basin. The non-linear relationship constructed can also be used to explain the topography of
591 the inundation area. The relationship reveals that only small change of the TWS can lead to a significant
592 variation of the inundated area in the wet season. It is also found that including the annual signal is
593 necessary in the adjustment process in order to reduce the RMS values. The source of the annual variation
594 is the soil moisture component, which does not correlate with the inundation area variation signal. Further
595 analysis showed a good agreement between the 8-day MODIS-derived TWS variations averaged over

596 monthly intervals and the GRACE TWS variations. This indicates that surface reflectance data can also be
597 used to estimate TWS at sub-monthly time scales, provided that monthly GRACE-based TWS variations
598 are used as a “training” phase. It is likely that the approach developed would have similar applications to
599 other areas that experience regular large-scale inundation where NDWI has strong correlation with TWS.
600 More case studies conducted over other regions are needed to confirm the performance of the approach.

601 Although this study made use of the state-of-the-art satellite data, higher accuracy of the data is still
602 welcome in order to achieve more accurate descriptions of flood events. This might be possible if data
603 from new satellite missions are used that are already operational or will become operational in the near
604 future. For example, the Sentinel-2 mission (Drusch et al., 2012) will provide surface reflectance data with
605 a temporal resolution of 5 days and a spatial resolution of 60 m or higher (Sentinel-2A was launched in
606 June 2015; Sentinel-2B is to be launched in the middle of 2016). The Global Precipitation Measurement
607 mission (GPM; Hou et al., 2014) has provided global near real-time rainfall data since March 2014 with a
608 spatial resolution of approximately 10 km. GPM data can be used to force the next version of PCR-
609 GLOBWB model, which will provide global near real-time TWS estimates with a similar spatial
610 resolution (Sutanudjaja et al., in prep.). Additionally, the variation of the Tonlé Sap Lake level could be
611 measured to a very high accuracy using future altimetry satellite observations, e.g., Sentinel-3 (Donlon et
612 al., 2012), ICESat-2 (Abdalati et al., 2010) and SWOT (Durand et al., 2010). Finally, the GRACE Follow-
613 On mission (Flechtner et al. 2014; launch scheduled in August 2017) is expected to continue delivering
614 monthly gravity field products well into the next decade. By utilizing these state-of-the-art satellite
615 observations and hydrological models, the monitoring of flood events and their impact will continue to
616 improve.

617

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624

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764

765 **Appendix A: PCR-GLOBWB description**

766 The state-of-the-art global hydrological model PCR-GLOBWB (van Beek, 2008; van Beek and Bierkens,
767 2009; van Beek et al., 2011; Sutanudjaja et al., 2011; Sutanudjaja et al., 2014; Sutanudjaja et al., in prep.)
768 basically simulates spatial and temporal continuous fields of fluxes and storages in various water storage
769 components (primarily, snow, soil moisture, surface water and groundwater) at a typical spatial resolution
770 of 30 arc minutes (approximately 50 km at the equator). In brief, for each grid cell and for each daily time
771 step, the model computes the storages of two vertically stacked soil layers and an underlying groundwater
772 store based on water balance equation. Above the surface, the model also includes interception and snow

773 storages. For each cell, the model computes the vertical water exchanges between the soil layers and
774 between the top layer and the atmosphere, i.e., rainfall and snowmelt, percolation and capillary rise, as
775 well as evaporation and transpiration. The groundwater store underlies the soil and is fed by net
776 groundwater recharge and exempt from direct influence of evaporation and transpiration fluxes. However,
777 capillary rise from the groundwater store can occur depending on the simulated groundwater storage,
778 surface elevation, and sustain soil moisture. Fluxes are simulated under various land cover types by
779 considering sub-grid variations in topography, vegetation phenology, and soil properties. The model
780 includes a physically-based scheme for infiltration and runoff, resulting in direct runoff, interflow, as well
781 as groundwater baseflow and recharge. River discharge is calculated by accumulating and routing the
782 specific runoff along the drainage network. In this study, the daily precipitation from the Tropical Rainfall
783 Measuring Mission (TRMM) 3B42 V7 (Huffman et al., 2007), the daily mean 2 meter air temperature
784 from ERA-Interim (Dee, 2011), and the daily reference potential evapotranspiration calculated based on
785 Hamon method (Lu et al., 2005) were used to force the model.

786

787 **Appendix B: Estimation of annual amplitude and phase**

788 The TWS time series are represented by

$$789 \quad L = f_0 + f_1 t + f_2 \sin(\omega t) + f_3 \cos(\omega t) + f_4 \sin(2\omega t) + f_5 \cos(2\omega t) \quad , \quad (B1)$$

790 where L is the vector containing monthly TWS estimates, t is the observation time, and $\omega = 2\pi/T$ with T

791 the annual period. The coefficients f_0, \dots, f_5 are estimated using least-squares adjustment. The annual

792 amplitude (A) is estimated as

$$793 \quad A = \sqrt{f_2^2 + f_3^2} \quad , \quad (B2)$$

794 and the phase (φ) is estimated as

795 $\varphi = \arctan_2(f_2, f_3).$ (B3)

796 Note that the function \arctan_2 is realized in many high-level computer languages (e.g., function `atan2` in
797 Matlab). The function always returns a value in the range $(-\pi, \pi]$.