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15 **Abstract-** In the context of the Surface Water and Ocean Topography mission (SWOT),
16 investigations are needed to refine the error budget for discharge estimations. This study
17 proposes to evaluate the uncertainties in the estimation of mean river discharge around the
18 seasonal peak flow due to the satellite temporal sampling intervals. The daily time series of *in*
19 *situ* river discharge measurements for 11 large rivers are used to analyze the uncertainties
20 associated with the sampling of four altimeter repeat cycles: the 35, 22 and 10-day repeat
21 cycles in the nadir-looking configuration of current altimeters and the 22-day repeat cycle in
22 the SWOT wide-swath configuration, where a given location is observed every cycle twice at
23 the equator and six times in higher latitudes. Results show that for boreal rivers, a sampling of
24 35 or 22 days from current nadir altimeters is too coarse to give an accurate estimate of the
25 average discharge around the seasonal peak flow, whereas, for all watersheds, the uncertainties
26 associated with a 10-day repeat cycle or the 22-day repeat cycle in the SWOT wide-swath
27 configuration are within the range of acceptable uncertainties (15-20%). In addition, the
28 absolute maximum mean discharge uncertainties associated with the SWOT time sampling
29 have a strong relationship with the variance of the river discharge. This suggests that, rather
30 than the commonly used basin area, the magnitude of the short-time-scale variance of the
31 discharge could be used as predictor of the uncertainties associated with temporal sampling
32 intervals when estimating average discharge around the seasonal peak flow.

33

34 **1. Introduction**

35 Continental freshwater runoff or discharge, as well as the spatial distribution and storage of
36 fresh water on land, is a key parameter of the global water cycle and play an important role in
37 driving the climate system [1]. Moreover, natural disasters of hydrological origin dramatically
38 affect human societies, with large economic losses during water-related extreme events such as
39 floods or droughts.

40 Despite a widespread recognition of the need for better observations at global scale, surface
41 freshwater measurements are still limited mostly to sparse *in situ* networks of gauges, the
42 number of which has dramatically decreased during the last two decades, especially in remote
43 areas [1]. In addition, public access to recent observations is generally restricted.

44 Over the last twenty years, satellite remote sensing techniques have become more useful for
45 hydrologic investigations [1], [2], [3]. In particular, satellite altimetry (TOPEX-Poseidon (T-P),
46 Jason-2, ERS-1/2, GFO and ENVISAT missions) has been used for systematic monitoring of
47 water levels in large rivers, lakes and floodplains [4] and several studies have demonstrated the
48 capability of using these sensors locally for estimating river discharge in large rivers (still
49 limited to rivers with a width of few kilometers), including the Ganges-Brahmaputra [5] or the
50 Ob River [6]. Indeed, the construction of empirical regression curves between altimetry-derived
51 river water heights in large river basins and *in situ* measurements of river discharge can provide
52 altimetry-based discharge estimates for times when *in situ* discharge observations are missing,
53 or even, to extend the time-series of river discharge forwards/backwards. This technique has
54 several limitations [1], [5], [7], such as, to name a few, the quality of the current altimetry data
55 themselves over continental water bodies, the current altimeter sampling frequency along track,
56 and the spatial coverage of current satellite altimetry missions which is not adequate for global
57 scale investigations due to their orbit track separation at the equator (few tens to hundreds of
58 kilometers). In addition, a major drawback in the use of current altimetric measurements to
59 monitor river stage and discharge is the temporal sampling rate at a given location, which is 10
60 days for T-P/Jason-2 and 35 days for ERS-1/2 and ENVISAT. With such space/time sampling
61 intervals, current satellite altimeters cannot compete with observations made daily or twice
62 daily by *in situ* gauges, a frequency required to study local hydrological processes, to evaluate
63 flood risk or for the management of water resources. Nevertheless, for studies related to
64 climate, the use of current radar altimetry is still extremely valuable as a complement to

65 ground-based observations [5].

66 The future wide swath altimetry measurements made by the Surface Water and Ocean
67 Topography (SWOT) satellite mission (to be launched in 2020) will provide high-resolution
68 characterization of water surface elevations with 2D global maps of terrestrial surface water
69 extent and storage changes and discharge estimates [1]. Previous studies [1], [7], [8], [9] have
70 reviewed the expected accuracy of the variables that will be measured and investigated the
71 different errors which will affect SWOT data and the derived discharge. Instantaneous
72 discharge estimated globally from SWOT are expected to have errors below 25%, even if
73 locally these errors might be higher for ungauged basins. These errors are primarily due to
74 errors on SWOT measurements (error on water elevation will be equal or below 10 cm, error on
75 the water mask will be around 20% of the true area and error on the river slope will be equal or
76 below 1cm/1km). Other anticipated sources of error come from ancillary data needed to
77 compute the discharge (bathymetry and friction coefficient). When estimating monthly or
78 average river discharge from instantaneous discharge estimates, the temporal resolution of the
79 satellite observations will also be a source of uncertainties.

80 In this paper, we focus on the evaluation of the uncertainties due to the temporal sampling
81 on the estimation of mean river discharge around the annual peak flow. Even though it is
82 important to accurately monitor low flow and high flow discharge, the hydrologic events
83 around the yearly peak flow are of particular importance as they are generally associated with
84 the flood waves.

85 The in situ measurement and observation of river discharge are in general well established
86 and, ideally, the goal for in situ discharge data accuracy is within $\pm 5\%$ of the true value.
87 However, given the difficulties to measure the depth and velocities (and consequently the true
88 discharge), especially in large and strong- flowing rivers, the community agrees that a 15-20%
89 accuracy is generally acceptable. When using radar altimetry, the accuracy of river discharge

90 estimates depends, among other factors, on the satellite temporal sampling: for instance, mean
91 discharge estimates will likely be more accurate for a river with several views per orbit than for
92 a river with one revisit. Former and current radar altimeters (T/P, Jason-2, ERS-1/2,
93 ENVISAT) view nadir along the orbit track, so a particular point is observed only once every
94 repeat cycle except at overpasses (ascending and descending views) where two measurements
95 are made. Given the inter-track interval (~300 km and ~80km at the equator respectively for T-
96 P/Jason-2 and ERS-1/2 and ENVISAT) most of continental water bodies that are monitored are
97 sampled only once and not always at an adequate location to measure river discharges. Unlike a
98 nadir-viewing instrument, wide-swath instrument might see the same location from adjacent
99 orbits, so a particular point might be observed several times every repeat cycle. With its wide
100 swath altimetry measurements, the SWOT mission will offer a global spatial coverage with the
101 number of views of a given location per cycle varying as function of latitude, and ranging from
102 twice at the equator to more than 6 times at high latitudes. At the time of writing, SWOT
103 nominal orbit will have a 22-day repeat period and a global coverage of the Earth up to the
104 latitudes 78° North and South.

105 Using T-P (10-day repeat cycle), ERS-2 and ENVISAT (35-day repeat cycle) altimeters, [5]
106 and [6] showed that the errors of the discharge estimated indirectly from altimetric
107 measurements (at 10 days, monthly or annual time scales) are on average well within the range
108 of acceptable errors (5 to 20%). However, the impact of the temporal sampling on the accuracy
109 of the river discharge estimates during the annual peak flow is still not well known. For
110 instance, if all overpasses occurred during flood stage, it leads to an overestimation of the
111 average discharge based on these observations whereas in other cases, the sensor may
112 completely miss the peak flow event. Over the Ganges-Brahmaputra river system, [5] showed
113 that even with a coarse 35 day interval sampling interval (ERS-2/ENVISAT), the
114 underestimation or overestimation of the *in situ* mean discharge in general never exceeds 20%.

115 Using a similar methodology, the goal of this study is to assess the effects that different
116 altimeter repeat cycles (10-day, 22-day, 35-day temporal sampling and with a “real” SWOT
117 repeat cycle in the wide-swath configuration) will have in estimating mean discharge around
118 the yearly peak flow. For this we will use daily *in situ* gauge measurements from 11 large rivers
119 around the world. Section 2 presents and discusses the datasets and the methodology. Section 3
120 presents and discusses the results. The conclusions are given in Section 4.

121

122 **2. Dataset and methodology**

123 We analyze the daily time series of *in situ* river discharge measurements for 11 large rivers
124 (Table 1), which represent a fair sample of different environments, from the Tropics to Boreal
125 regions. These time series are provided by 1) the HYBAM project (www.ore-hybam.org) for
126 the Amazon and Congo Rivers and 2) the Global Runoff Data Center [10] for the other rivers.
127 These 11 rivers were selected because of the availability of fairly long (more than a decade),
128 accurate (evaluated) and continuous measurements.

129 Using these datasets, we performed the following analysis for each of the 11 rivers, with T
130 representing the repeat cycle of the satellite (10, 22 or 35 days):

131 The date of the peak flow is identified for each year in the *in situ* record. A sliding window
132 of T days is applied to the record, starting T days before the peak flow and going to the peak
133 flow date in each year. The window moves with one-day steps; at each step, the average
134 discharge is calculated using all T days in the window (the true mean) and using only the two
135 end-points. The same calculation is done for all the years for which *in situ* discharge is
136 available (Table 1). The difference (in percent of true mean) between the two means at each
137 step is averaged over the years. The analysis is done for each of the 11 stations.

138 In parallel, “true” SWOT observation times were determined for each of the 11 gauge
139 locations by calculating the number of times each gauge location is viewed from the satellite

140 during a cycle using the relationship between the number of revisits and latitude [7]. The same
141 analysis is done as previously but instead of considering only the 2-end points of the 22-day
142 repeat cycle, we consider all observations of the target within the 22-day repeat cycle. The
143 numbers of revisits per cycle for each station is given in Table 1, but note that the SWOT
144 sampling is not uniformly distributed in time during one repeat cycle. Depending on the
145 location, a target may be observed twice on two consecutive days and then not be sampled
146 again for the next ten days. In our case, for the Amazon at Obidos, two observations are made
147 on the 16th and 17th day of the cycle whereas there are up to six observations for the Lena River
148 in Siberia, with irregular sampling on the 2nd, 5th, 8th, 11th, 18th and 21st days of the cycle.
149 Globally, the maximum time between two observations for a target is 13 days [7]. Note also,
150 that in this study, we have only considered the SWOT measurements that observe the gauge
151 location directly. However, because of its wide swath, SWOT will also measure water
152 elevations upstream and downstream of the gauge location, which could then be used to infer
153 water elevation at the gauge location using hydrodynamic models or statistical relationships
154 and therefore, increase the number of samples on the mean discharge estimate [11]. Thus, the
155 SWOT temporal sampling uncertainty computed in this study corresponds to the maximum
156 expected error.

157 Finally, in the present study, we are interested in the effect of temporal sampling only. It is
158 important to remind here that these uncertainties represent only a source of error among many
159 other uncertainties associated with the estimates of instantaneous and mean river discharge
160 from altimeter data. Indeed, as discussed in the introduction, the river water height needs to be
161 first converted into discharge and such retrieval errors [7, 9] will also largely impact the results.
162 These effects will not be discussed here.

163

164 **3. Results and Discussion.**

165 The results for the 35-day, 22-day and 10-day temporal sampling are plotted in Figure 1 for
166 the 11 stations. The x-axis values represent the lower endpoint of a T day sliding window. For
167 0, the lower end-point of the time window is at peak minus T days and the upper end-point is
168 on the day of the peak discharge. At 5, the lower end is at peak minus T plus 5 days and the
169 upper end is at peak plus 5 days and so on. The y-axis represents for each step the average
170 difference over the years between the average discharge calculated using only the two end-
171 points and the true mean discharge calculated using all days in the time window. The y-axis
172 values are expressed in percent of the true mean.

173 As expected, with the 35-day window (Figure 1a, the case of ERS/ENVISAT altimeters),
174 the uncertainties are the largest, with big differences from river to river. The largest differences
175 are found for the three basins in Siberia, the Ob, the Yenisey and the Lena, for which river
176 discharge is characterized by a sharp and rapid increase at the end of the snowmelt season when
177 the river ice breaks up. High river discharge values last only few weeks before a sharp
178 decrease. For instance, for the Lena River, when one of the end-points is within ± 5 days of the
179 date of the peak flow, the average overestimation can be more than 200% of the true mean.
180 When the two samples bracket the peak flow date (around day 14 to 25), the underestimation is
181 between 30 to more than 50%. The Yenisey and the Ob Rivers show the same patterns, but
182 with smaller over/underestimation, especially for the Ob River for which the flood season and
183 high peak flow last longer [12,13]. For mid-latitude and tropical watersheds, the results show
184 differences within the acceptable range of uncertainties for river discharges, i.e. around $\pm 20\%$.
185 In most tropical watersheds (Amazon, Niger, Orinoco...), when one of the end-points is on the
186 date of the peak flow (day=0 for instance), the mean discharge using the two end-points
187 overestimates the true 35-day mean river discharge by about 10%. Then the differences show
188 almost permanent underestimations of the 35-day mean discharge as soon as the peak flow is
189 missed by 3 to 4 days. Moving the window forward shows that the differences (underestimates)

190 are less than 5%, even with a 35-day sampling interval, and reach a maximum when the two
191 samples bracket the peak flow date. The differences are larger for mid-latitudes watersheds, but
192 the differences are generally less than 15% with a maximum underestimation of ~20% for the
193 Mississippi. Note that among the tropical watersheds, the Irrawaddy shows the largest
194 uncertainties (maximum and minimum underestimation above 20%) which might be explained
195 by sharp increases and variability of the river discharge value during the monsoon season. This
196 behavior is similar to the one found in [5] for two other large rivers of the region, the Ganges
197 and the Brahmaputra.

198 As also expected, a ten-day sampling (Figure 1b), which is the repeat cycle of Topex-
199 Poseidon and Jason-2 radar altimeters, leads to much smaller errors when estimating the
200 discharge around the peak flow. Tropical basins, such as the Amazon, the Orinoco or the
201 Congo, show almost no difference between the 10-day bracket and the true mean discharge
202 (uncertainties below 2%). With a 10-day sampling interval, all rivers except the Lena are within
203 $\pm 20\%$. The maximum error for the Lena is an underestimation (25%) when the two samples
204 bracket the peak flow date (day 5). Nevertheless, uncertainties for around day 0 for the Lena
205 are reduced from more than 200% with a 35-day repeat cycle to ~20%. For the Yenisey and the
206 Irrawaddy Rivers, the large uncertainties noticed with the 35-day sample are reduced to less
207 than 10% with a 10-day repeat cycle.

208 Figure 1c gives the results for a 22-day repeat cycle for the SWOT mission with only nadir
209 view, i.e. when the targets are visited only once every 22 days. As an intermediate case
210 between the 35 and 10-day sampling intervals, the results still show fairly good estimates of
211 mean discharge around the peak flow for most tropical basins (Amazon, Congo, Orinoco) and
212 uncertainties in mid-latitude basins on the order of 10%. The Irrawaddy and Yenisey have
213 largest errors but with maximum over/underestimations around 20%. For the Lena River, a
214 sampling at twenty-two days is still too coarse to give an accurate estimate of the peak flow

215 mean discharge with uncertainties ranging from ~100% to -40%.

216 However, as mentioned earlier, “true” SWOT observation times are more frequent per orbit
217 repeat cycle with each gauge location sampled at least twice within a 22-day repeat cycle.
218 Using the real SWOT orbit sampling (Table 1), Figure 2 shows that the errors on estimated
219 discharge around the peak flow are greatly reduced and well within the range of acceptable
220 uncertainties for all 11 rivers. For the boreal and mid-latitudes basins (Figure 2a), the
221 over/underestimation of mean discharges is always under 20%. The Lena, which is now
222 sampled up to 6 times in a cycle also shows uncertainties within this range. For the Ob River,
223 which already showed acceptable errors with a 22-day cycle (Figure 1c) is now sampled six
224 times in a true SWOT configuration, reducing uncertainties less than 5%.

225 For the tropical watersheds (Figure 2b, 2 revisits minimum as in Table 1), all associated
226 uncertainties are below 10%, except for the Irrawaddy, which still shows larger errors
227 (overestimation of ~10% and underestimation of ~20%) even when it is sampled twice. For the
228 Amazon, the Congo, the Mekong, the Orinoco, the uncertainties are on the order of a few
229 percent. Thus, these results show that for the 11 rivers considered here, the uncertainties
230 associated with SWOT temporal sampling when estimating mean discharge around the annual
231 peak flow are well within the range of acceptable errors.

232 Absolute maximum mean discharge errors for each river (as in Figure 2a and 2b) have been
233 plotted as a function of the percentage of river discharge variance for frequencies above 1/(20
234 days) (Figure 3). This percentage is computed as follows. For daily each discharge time-series
235 for the 11 rivers, a Fourier transform is calculated, and the integral of its variance (which is the
236 square of the Fourier transform amplitude) over all time scales less than 20 days computed as a
237 percentage of the total variance. This percentage gives the relative contribution of frequencies
238 above 1/(20 days) to the discharge variance, and is expected to be larger for rivers with
239 significant variability at shorter time scale. Figure 3 shows that the temporal sampling error is

240 associated with the short-time-scale variability of the river discharge time series. A regression
241 analysis gives a quantitatively estimate of the relationship between discharge variance and
242 SWOT temporal sampling errors in a form of a power law, statistically significant at 99%
243 confidence level ($R^2=0.87$ with 11 points, $p\text{-values}<0.01$ with $|R|>0.735$). Quite logically, for
244 rivers with large short-time-scale variance, typically the boreal rivers with freeze/thaw cycles
245 and the monsoon-affected Irrawaddy, the SWOT sampling error is larger. Usually, temporal
246 sampling errors on mean river discharge are parameterized as a function of the river catchments
247 area [7]. However, we show that in the case of estimates of the mean discharge around the
248 seasonal peak flow, the uncertainty has a strong relationship with the variance of the river
249 discharge. In the case of these 11 large rivers, the correlation between the absolute discharge
250 errors and the catchment's area is only $R^2=0.18$. Thus, the magnitude of the short-time-scale
251 variance is a stronger predictor of the peak discharge error than the basin area. Although this
252 analysis only had 11 samples, we suggest that the relationship with the variance could then be a
253 new tool to infer the quality of future SWOT measurements at other gauge locations, if some
254 past discharge time series is available to calibrate the relationship.

255

256 **4. Conclusion.**

257 This study reports a first effort to evaluate the uncertainties in the estimation of mean river
258 discharge around the seasonal peak flow due to satellite altimeters temporal sampling intervals.
259 Analyzing the daily time series of *in situ* river discharge measurements for 11 large rivers in
260 different environments, the results show that for high latitudes rivers, a sampling of 35 or 22
261 days in the nadir-looking configuration of current altimeter mission is too coarse to give an
262 accurate estimate of the average discharge around the seasonal peak flow. For tropical
263 watersheds however, such time sampling intervals lead to uncertainties that generally never
264 exceed 20% and thus are in the range of uncertainties acceptable for river discharge

265 estimations. On the other hand, the uncertainties associated with a 10-day repeat cycle are well
266 within the range of acceptable errors from Tropical to Siberian rivers. Thanks to its wide swath
267 altimetry technique, which will enable to observe a given location at least twice at the equator
268 and up to six times in high latitudes every repeat cycle, the uncertainty due to SWOT time
269 sampling on the average discharge around the seasonal peak flow is greatly reduced when
270 compared to a 22-day repeat cycle instrument with a nadir looking angle. We found that these
271 uncertainties are generally well within the range of acceptable errors for boreal watersheds
272 (absolute maximum mean discharge uncertainties from 5 to 20%), mid-latitudes watersheds
273 (absolute maximum mean discharge uncertainties ~10%) and tropical watersheds (absolute
274 maximum mean discharge uncertainties from 2 to ~20%). Moreover, we find that absolute
275 maximum mean discharge uncertainties around the seasonal peak flow have a strong
276 relationship with the variance of the river discharge. Thus, around the peak flow, we suggest
277 that the magnitude of the short-time-scale variance of the discharge could be used as predictor
278 of the uncertainties rather than the commonly used basin area.

279 The future launch of the SWOT mission in 2020 will represent a step increase for
280 continental hydrology and further studies are needed to refine the SWOT error budget for
281 discharge estimates. For instance, the uncertainties for smaller rivers (~100 m to ~1 km width)
282 have not been addressed here and require further investigations. Moreover, we address in this
283 study the source of errors due to the temporal sampling of the satellite only, but in reality it will
284 combined with other sources of uncertainty. These issues need to be addressed in future works.

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328

329

330 **Table 1:** Information on the daily *in situ* river discharge time series used in this study: River
331 name, Gauge station name and location, first and last year of the available time series,
332 catchment’s area, mean value and standard deviation (STD) for the entire daily discharge time
333 series and the number of views of the a given gauge station per SWOT cycle.

River Name	Station Name and locations	Time series	Catchment area (km ²)	Mean Discharge/ STD (m ³ /s)	Number of samples per SWOT cycle
Amazon	Obidos (1.92°S; 55.67°W)	1968-2008	4618000	172700 / 49840	2
Congo	Brazzaville (4.25°S; 15.28°E)	1968-2008	3500000	40500 / 9300	2

Danube	Ceatal Izmail (45.21°N; 28.72°E)	1954-2008	807000	6580 / 2550	2
Irrawaddy	Sagaing (21.98°N;96.10°E)	1978-1988	117900	8170 / 6820	2
Lena	Kusur (70.70°N; 127.65°E)	1954-2003	2430000	16950 / 23860	6
Mekong	Phnom Penh (11.58°N; 104.96°E)	1960-1973	663000	13305 / 13300	2
Mississippi	Vicksburg, MS (32.31°N; 90.95°W)	1954-1999	2964000	17370 / 9620	2
Niger	Lokoja (7.80°N; 6.77°E)	1970-1993	2077000	4830 / 4890	2
Ob	Shalekard (66.57°N;66.53°E)	1954-1999	2949000	12800 / 11190	6
Orinoco	Puente Angosta (8.15°N; 63.60°W)	1950-1989	836000	31650 / 21690	2
Yenisey	Igarka (67.48°N; 86.50°E)	1980-2003	2440000	19170 / 23180	3

334

335

336 **Figures Caption:**

337 **Figure 1:** Uncertainty of the 35-day (a) and 10-day (b) and 22-day (c) sampling intervals in the
338 estimation of mean river discharge around the yearly peak flow for 11 large rivers (see text for
339 details and the method): the Ob (black solid line), the Yenisey (black dotted line), the Lena
340 (black dashed line), the Orinoco (red solid line), the Amazon (red dashed line), the Congo
341 (green solid line), the Niger (green dashed line), the Irrawaddy (blue solid line), the Mekong
342 (Blue dashed line), the Danube (purple solid line), and the Mississippi (purple dashed line).

343

344

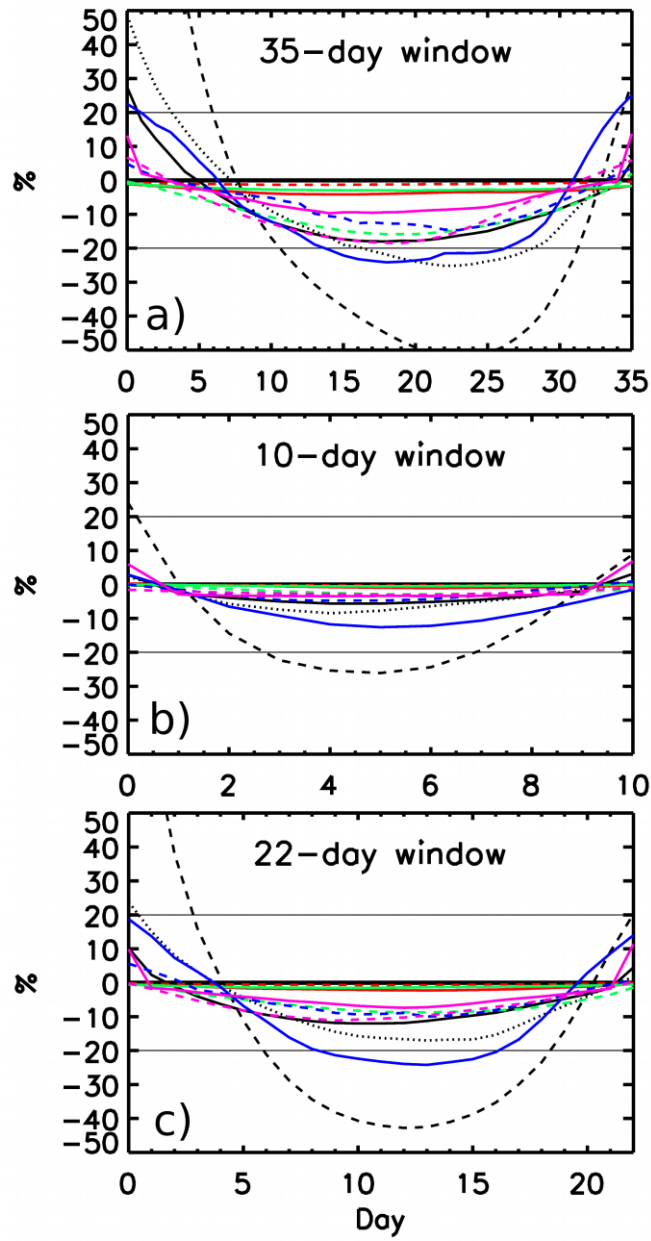
345 **Figure 2:** Same as Figure 1 with the SWOT 22-day repeat cycle but taking into account the
346 number of SWOT views per cycle. For clarity, we separate the rivers in boreal/mid-latitudes
347 environments (a) and the ones located in the Tropics (b)

348

349 **Figure 3:** Relationship between the uncertainties on the monthly discharge estimates around
350 the yearly peak flow in the context of SWOT 22-day repeat cycle versus the percentage of total
351 discharge variance for frequencies above 1/(20 days) estimated for the 11 stations.

352

353 **Figures:**



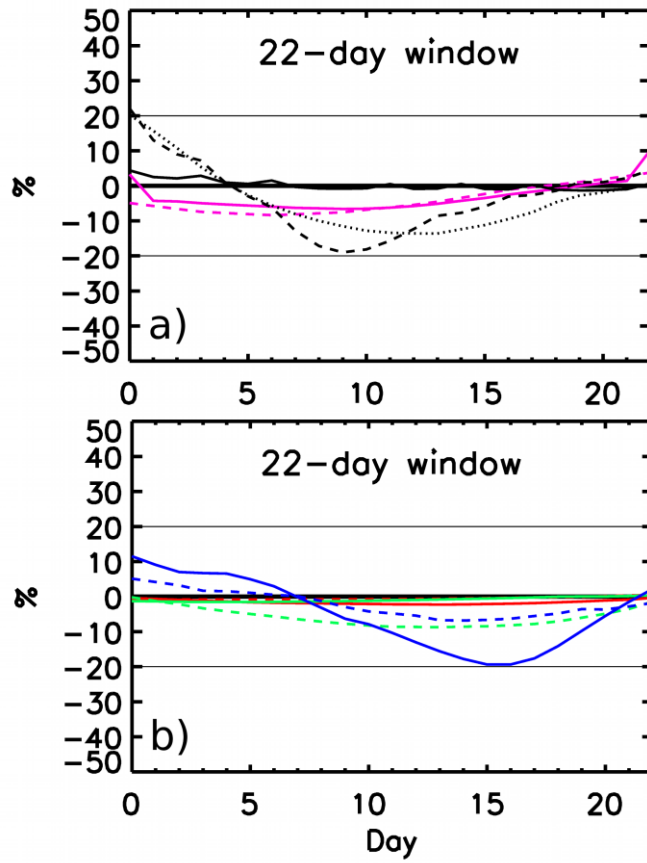
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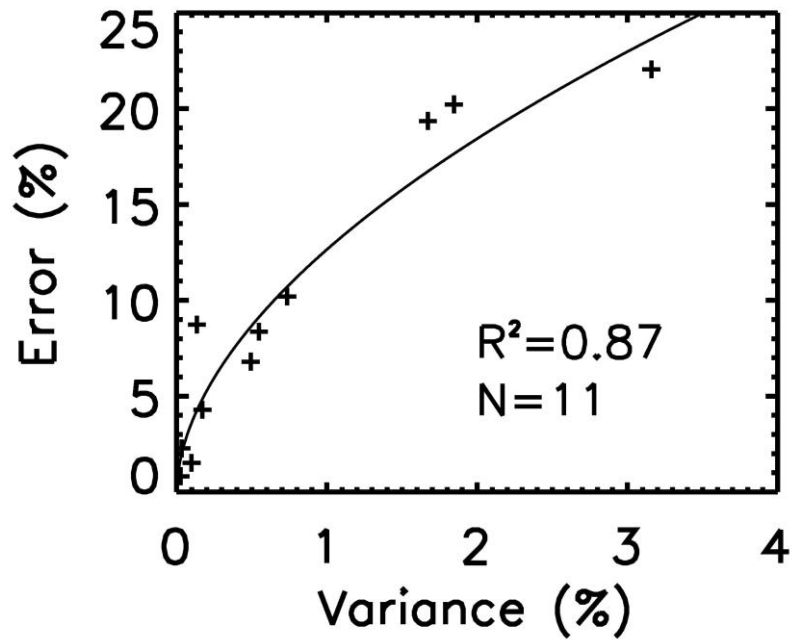
Figure 1.



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Figure 2.



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Figure 3.