FLOOD MAPPING INFERRED FROM REMOTE SENSING DATA

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ABSTRACT

In ungauged basin, space-based information is essential for the monitoring of hydrological water cycle, in particular in regions undergoing large flood events where satellite data may be used as input to hydrodynamic models. A method for near 3D flood monitoring has been developed which uses synergies between radar altimetry and high temporal resolution multi-spectral satellite. Surface Reflectance from the MODIS Terra instrument are used to map areas of open water as well as aquatic vegetation on a weekly basis, while water level variations in the inundated areas are provided by the radar altimetry from the Topex / Poseidon (T/P) and Envisat satellites. We present this synergistic approach to three different regions: Niger Inner delta and Lake Tchad in Africa, and Ganga river delta in Asia. Based mainly on visible and Near Infra Red (NIR) imagery is suitable to the observation of inundation extent. This method is well adapted for arid and semi arid regions, but less for equatorial or boreal ones due to cloud coverage.

This work emphasizes the limitations of current remote sensing techniques for full 3D-description of water storage variability in ungauged basins, and provides a good introduction to the need and the potential use of the future SWOT (Surface Water and Ocean Topography) satellite mission.

Keywords:*radar altimetry, MODIS, Flood mapping, SWOT, Arid climate*

1. INTRODUCTION

The main purpose of this study is to provide space-based tool for the monitoring of inundated areas in large wetlands and floodplains located in arid and semi arid regions.

Space and airborne technologies are increasingly found to be a key and unique source of spatial information for wetlands' conservation and management as many of the World's wetlands have insufficient on-ground data partly due to their size, number and limited accessibility. Finding complementary and new methods to monitor inundation patterns for large wetlands and floodplains is consequently important with expectation to assimilate such space-based hydrological information into models (e.g.climate, land surface, water-management and eco-hydrological models)

Comprehensive time series of inundation are required from space observations to: i) investigate links between floods in remote areas and climate variability; ii) model the hydrodynamic of a floodplain at high spatio-temporal resolution; iii) understand the interaction among inter-annual and seasonal flood cycle and land use patterns in and around area of flooding; iv) to examine the vulnerability of an ecosystem to inundation; v) to develop alert systems for inundation in a given wetland.

In recent years, remote sensing techniques have clearly shown their capability to monitor components of the water balance of large river basins on time scales ranging from months to decades. Satellite altimetry, which has been developed and optimized for open oceans, was also widely used in different fields of continental hydrology based on coupled satellite altimetry / in-situ gauges measurements (Crétaux and Birkett [1]; Cretaux et al. [2], and Calmant et al. [3]). The global altimetry data set has now an 18 years-long lifetime and is intended to be continuously updated in the coming decade.

Moreover several authors have addressed the issue of water extent mapping over floodplain from Remote Sensing data. Toyra et al., [4], [5], have used a combination of Radarsat and Spot scenes to study extent of water in wetlands and produced multi-year map's time series of flooded area in the Peace-Athabasca delta in Canada with high spatial resolution. Frappart et al., [6], [7], have combined radar altimetry with SAR images onboard the Japanese Earth Resources Satellites (JERS-1) or visible images of the Vegetation instrument onboard the Spot Satellites in order to study floods over the Rio Negro (Amazon) and Mekong Basin. The ASAR instrument is also very effective sensor to detect flooded areas in the particular cases of cloud cover regions with high spatial resolution (Henry et al. [8]). Bartsch et al. [9] have also used ENVISAT ASAR data for mapping of fresh water ecosystems in Siberia, and their analysis have shown that numerous areas previously mapped as tundra are in fact covered by water. Peng et al, [10] have used the MODIS data to develop a method of water extent and level monitoring, which however depends on the knowledge of topographic map of the surface study or on a relation between surface and level of water. Over large flood regions, medium resolution multi-spectral imagery like MODIS is well suitable as demonstrated by Sakamoto et al. [11]. They have produced from this instrument weekly time series of inundation maps of the Mekong basin over a multi-year period. Synthetic Aperture Radar (SAR) Interferometry (Alsdorf and Lettenmaier, [12], Alsdorf et al. [13]) and passive and active microwave observations (Prigent et al. [14]) also offer important information on land surface waters, such as changing area extent of large wetlands. A common problem in remote sensing of wetlands inundation is the detection of water under aquatic vegetation. Leblanc et al. [15] used Meteosat thermal images to derive monthly flood maps of Lake Chad that captured water under aquatic vegetation and adequately reconstructed the drying of Lake Chad since the 1980's.

Current challenges remain especially in providing global mapping of inundation and estimates of water storage changes and this has driven the decision of CNES and NASA to propose a new concept satellite mission (Surface Water and Ocean Topography: SWOT).

2. METHODOLOGY OF FLOOD MAPPING

The Modis instrument is a multispectral imaging system installed onboard the Terra and Aqua satellites at sun-synchronous near polar orbit at an altitude of 705 km. It observes the whole Earth every day. The basic measurements used to classify earth surface are surface reflectance measured over 7 spectral bands from the visible to the middle Infrared. The surface reflectance product we used (MOD09GHK) is corrected for atmospheric effects.The Modis images are very useful because they offer high temporal and spectral resolution, with images free of charge, covering wide areas of few tens of thousands square kilometres. Spatial resolution is 500 meters for the images used in our study. Here, we used MODIS images to detect open water and aquatic vegetation in arid and semi arid regions.

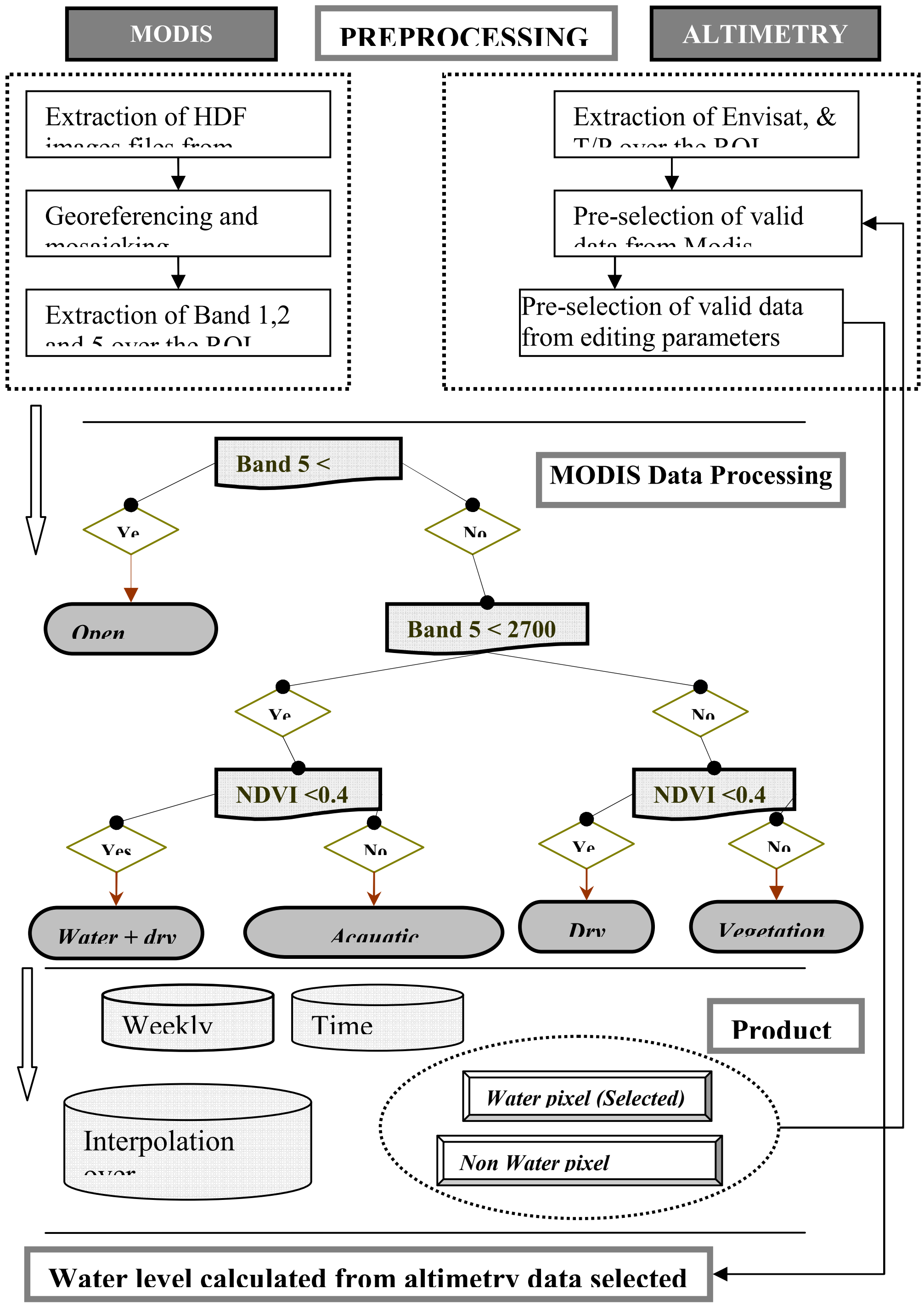


Fig. 1 Algorithm developed for the flood mapping from MODIS and water height determination from radar altimetry. Band Unit of reflectance is internal HDF-EOS data format specific to the Modis data and do not correspond to usual reflectance unit.

MODIS data also provided a means to select altimetry data along the tracks of T/P and Envisat satellites in order to estimate water level variations in different part of the inundation area. Designed to operate over ocean surface, the classical radar altimeters measurements that mainly consist on waveform or backscatter energy are much more complex over land surface. It can be affected by many radar echoes due to the presence of several reflectors under the footprint: water, vegetation, sand, etc … or inhibited by rapidly varying topography (Frappart et al. [16]).The radar altimetry is a profiling technique, which does not allow global view of the Earth surface, hence limits worldwide surveying as well spatial resolution in the cross-track satellite direction.

Despite those limitations the altimetry is a technique, which has a proven potential for hydrology science: the data are freely available on all the whole earth, and for a lot of remote areas it is the only source of information, as for the flood plain where in-situ data (when they exist) are limited to some points near main stream of the rivers. It however remains a significant limitation when using radar altimetry for flood monitoring. Due to revisit interval of several days (10 for T/P or Jason1 & 2, 35 for Envisat) the chance to collect altimetry data at the time of a flood peak is reduced, with very few measurements for quick inundation.

The methodology developed is illustrated by the Fig. 1. It is separated into 3 steps: a pre-processing phase of MODIS (georeferencing and mosaicking) and altimetry data, a processing of the MODIS data for pixel classification (to detect open water and aquatic vegetation in particular), and a processing of the radar altimetry for the measurements that have been classified as open water by MODIS. The MODIS data along each track of altimetry satellite above the area of study are interpolated in space and time, then, this information gives a criterion of selection for altimetry data. Below we present the main results obtained from this method over few case studies around the world

3. CASE STUDIES

3.1 Niger Inner Delta

The Inner Niger Delta (IND) is located in Central Mali in the semi-arid Sahelian zone, in the south of the Sahara Desert. It is a shallow area of about 70,000 km^2 constituted by channels, swamps and lakes, and its water extent varies seasonally from around 1000 to 12000 km^2 with large inter-annual changes (a factor of 1 to 5 has been observed according to Mahe et al. [17]). The IND is at the junction of 2 rivers, the Niger and the Bani which supply approximately 1490 m3/s of water to the delta (Mahe et al. [17]).The factor, generating this variability is the precipitation rate change, in time and with latitude. From October to May, the IND is hot and dry, and water balance is mainly driven by evaporation. From June to September, direct precipitation on the IND and in the upstream part of Niger and Bani Basins generate the seasonal flood. Precipitation over the IND are weak (~300mm/yr over the northern part of the IND) while they can between 1200 and 1500 mm/yr over the upstream parts of the Niger and Bani Basins, mainly occurring during the four months of the wet seasons (June to September). Interannual variability of rainfall is also marked as shown in Fig. 2. Therefore, the extent of water in the IND is changing year to year with very complex patterns depending on the topography of the river channels in the delta, or the presence of vegetation, and on the total amount of water filling the IND. During flood periods, the IND land is also subject to noticeable vegetation growth, mixed with water and dry soil. In that context, reliable frequent information on the water extent, spatial distribution and temporal variation of IND floodplain are vital for: i) water resources management, ii) a better understanding of the influence of climate change and the feedback of this floodplain on regional climate, iii) the monitoring of this important ecosystem and socio-economical resource. Moreover, our ability to measure, monitor, and forecast supplies of fresh water in the IND using in-situ methods is almost impossible because of limited access and the physics of water flow across vast lowlands. This reinforce the needs for methodologies based on space techniques, e.g., visible and radar satellite imagery to measure water extent over the wetlands and floodplains, and radar altimetry to measure the water level variations with time. The flood over the IND is a combination of high water in both Bani and Niger rivers but with changes in their role from one year to another one. This is a factor of complexity of understanding the flood over the IND as this implies to model both river basins hydrodynamic. Modis mapping of inundation every week over inter-annual period can therefore provide an invaluable source of information for both understanding the flood regime and to serve as external validation data for everyone who aim to develop model of the flood over the IND and more generally to model the Niger basin hydrodynamic.

We applied the synergistic mapping with radar altimetry and MODIS to the IND for the 2000-2008 period. From January to May, the IND and surrounding regions are drying out, and active vegetation is fully disappearing. In June, the permanent lake in the IND starts to grow and in July aquatic vegetation initiates its seasonal cycle. Until

August the aquatic vegetation is growing regularly and it covers the entire region. At end of August flood waters start to reach the IND and continue to rise during two months until a peak between mid and late of October. From November to January the water over the IND evaporates or flows downward and the only region which still presents some vegetation covers are the areas that just dried out, exclusively in the IND.

Precise correlations between flood sequence and precipitation patterns in the upstream part of the Niger and Bani river watershed and in the IND have been established over the period 2000-2010. Fig. 2a shows that open water maximum is shifted by one month and half from the maximum of rainfall over the Bani River (the same has been observed with Niger upstream watershed rainfall). Fig. 2b shows that a first apparition of open water is observed in August over the IND due to direct precipitation, which is however much weaker than the main inundation due to flow from Niger and Bani. Fig. 2c shows that vegetation starts growing immediately after the first rainfall occurring in the IND, in July, and also that vegetation covers over the IND presents a second smaller peak in end of November after the main inundation.

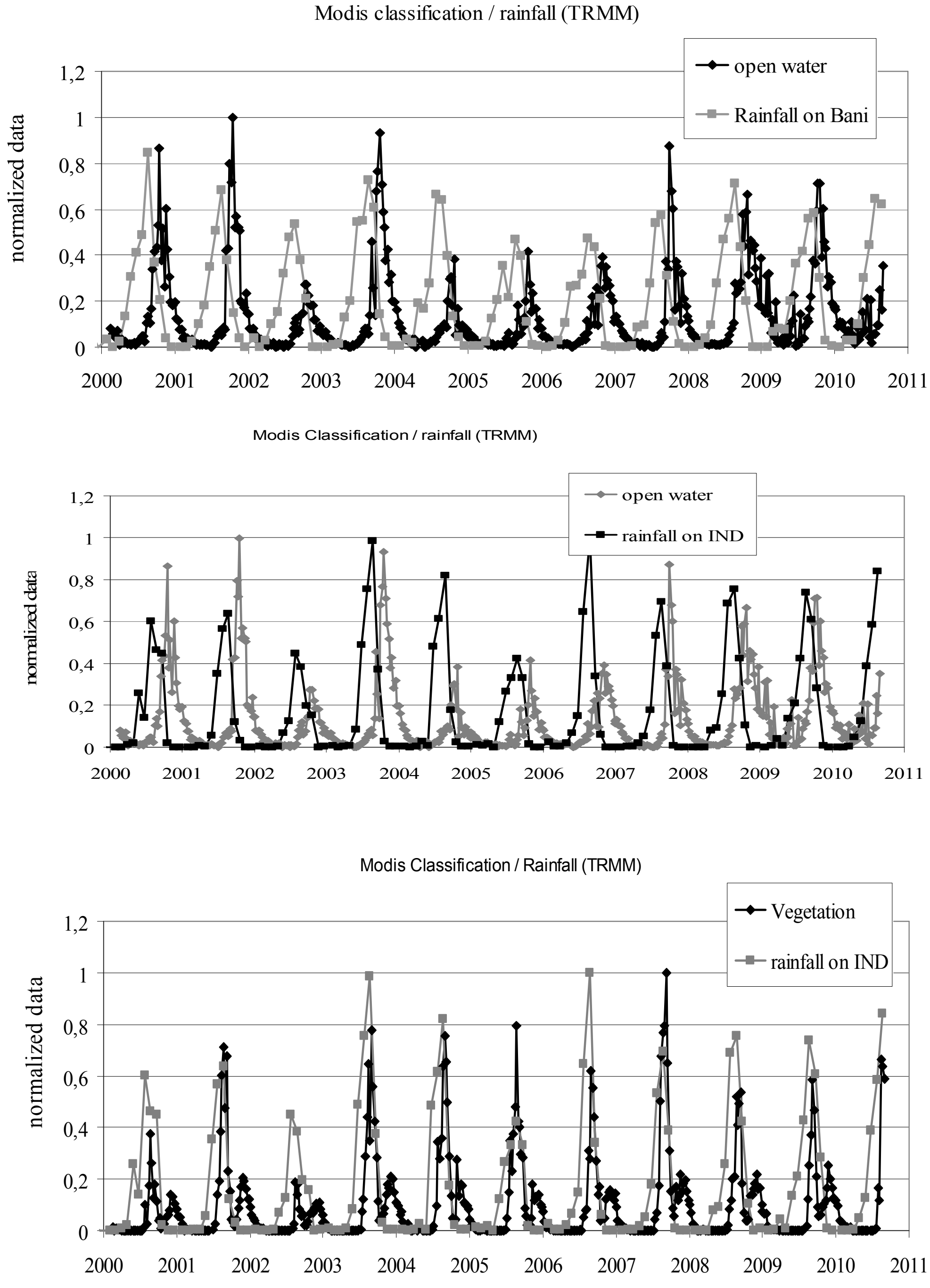


Fig. 2: Modis classification over the IND versus precipitation rate over the Bani River and the IND. (TRMM data set has been used for the computation of rainfall).

The 8-days mapping of flood and vegetation dynamic over the IND has also been done for the 10 years period, and one sees on figure 3 the high inter-annual variability of water extent from dry to wet years.

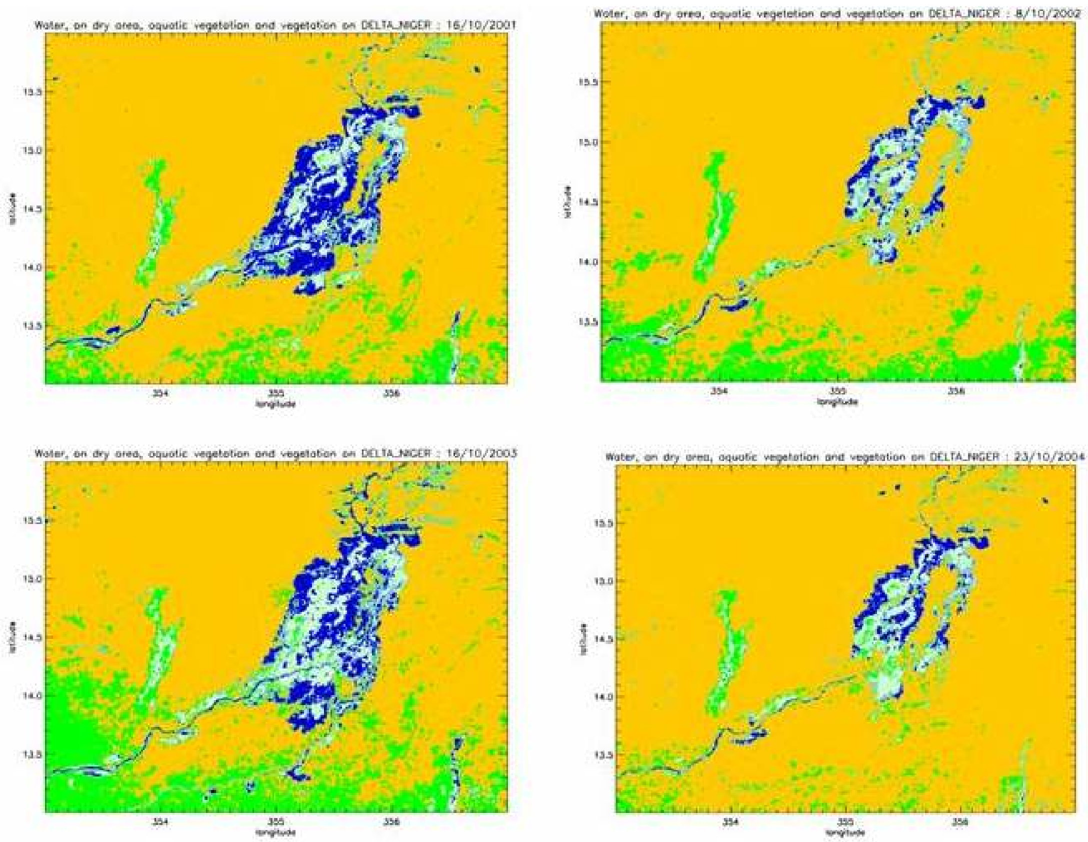
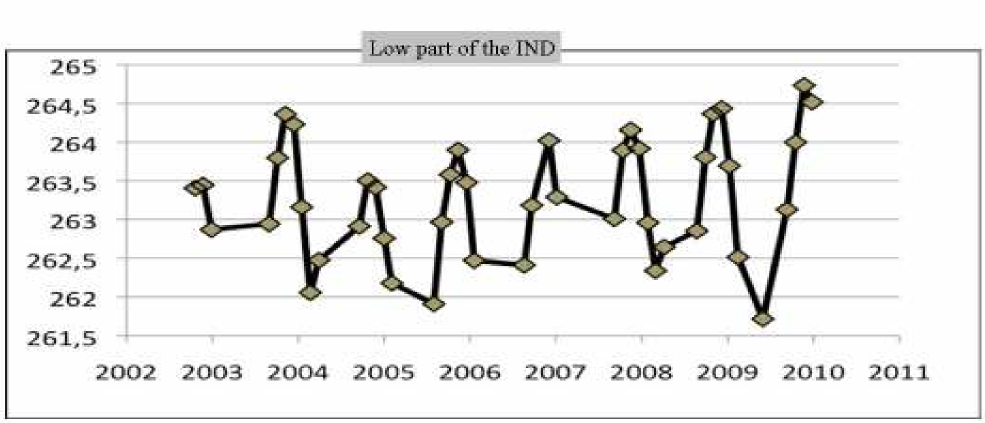


Fig. 3 maps of IND during the maximum of inundation of four different years, from dry years (2002, 2004) to a wet year (2001, 2005). Dark blue is representing free water, light blue: mixed water and dry land, light green: aquatic vegetation, dark green: vegetation on dry land, and yellow: the other type of surface.

To complete the information given by MODIS data, satellite radar altimetry measurements from T/P (one track) and Envisat (5 tracks) mission have been used. They have allowed calculating the water level variations over the IND, at the location where the satellite altimetry tracks are passing over open water's pixel as determined by the MODIS weekly. Fig. 4 shows some results obtained with Envisat satellite along a track which crosses the IND from South to North. The low temporal resolution of Envisat satellite is a clear limitation if one needs to monitor the exact water height variations from the beginning to the end of each inundation, but relative water height from upper part to lower part of the IND is measured, and it also can serve as control data of hydrodynamic model of the flood over the IND.



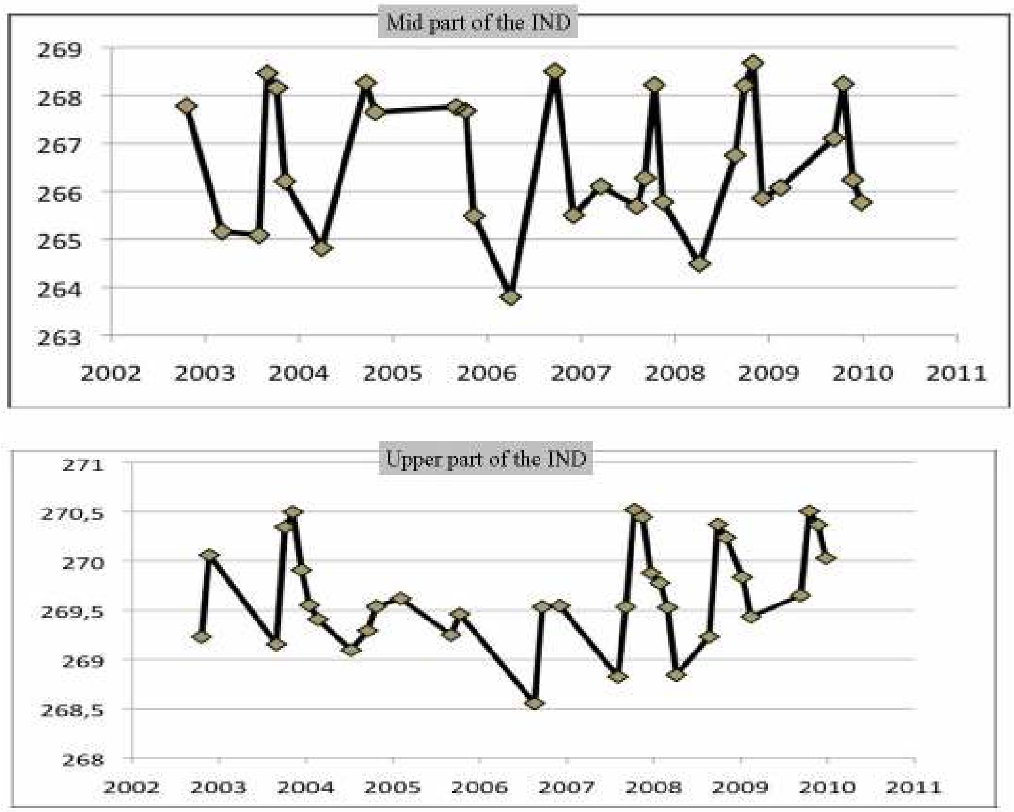


Fig. 4: level variations (m) over the IND from Envisat track n° 474

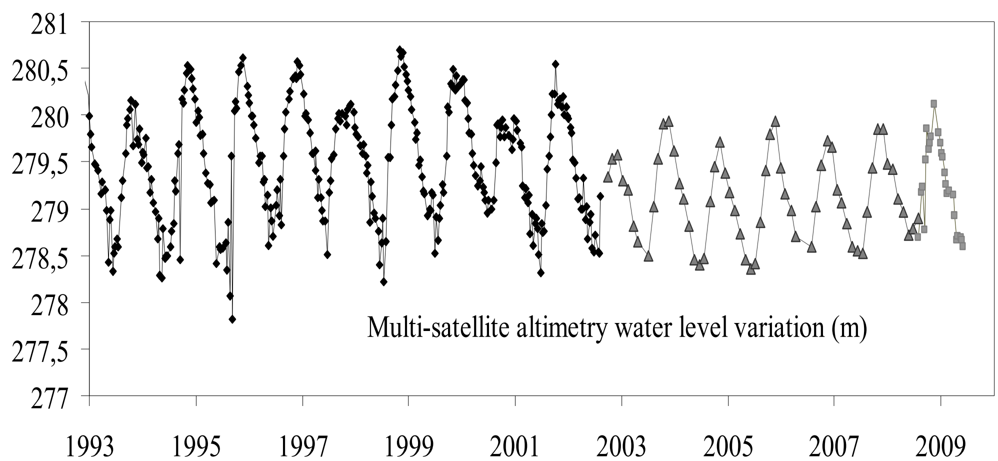
In summary, themonitoring of the flood inter-annual variability also offers an interesting feedback to the study of convective storms in the surrounding regions. It has been demonstrated in Taylor [18] that inundation over the IND influences convection which provokes rainfall over large regions in West Africa. They conclude that planned new dams in Guinea (upstream to the delta) could have enormous influence, both in the inundation in the IND and in rainfall patterns across hundreds of km^2.

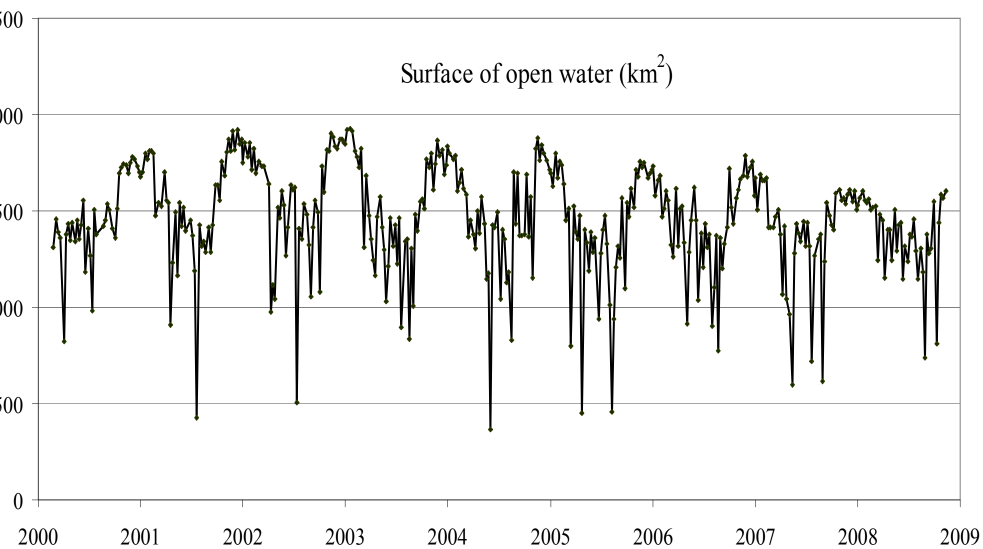
3.2 Lake Tchad

The Lake Chad Basin (LCB) is located in Central Africa, between latitudes 5°N and 25°N and longitudes 7°E and 27°E. It extends over 2. 5 Mkm^2 across the territory of Niger, Nigeria, Chad and Cameroon, and the borders of Algeria, Libya, Sudan and the Central African Republic, making it the largest endoreic basin in the world. Enclosed between mountain ranges (Tibesti, Darfour) and high plateaus (Adamoua), this entire drainage network converges on a central depression, in which Lake Chad is situated. The climate of this region is related to the movement of the Inter Tropical Convergence Zone (ITCZ) (Olivry *et al.* [19]). In the south, the monsoon flow brings heavy precipitation whereas in the north, the Harmattan produces a dry climate, at the latitude of Lake Chad, the climate is of Sudano Sahelian type because the ITCZ only reaches this zone between June and August, the rainy season during which total precipitation barely exceeds 300 mm.

The water balance of the lake is represented in Figure 5c. During the period preceding the 1970s drought, the Chari and Logone rivers supplied Lake Chad with, in average, nearly 85% of the total inflows. The other significant tributary into the lake is the intermittent Nigerian river the Komadougou Yobé which contribution to the lake is about 1 km^3/yr. Precipitation over the lake contributes 6 km^3/yr. Concerning losses, evaporation is the dominant process, accounting for an average annual volume of 43 km^3/yr. Losses due to infiltration are estimated at 3 km^3/yr. It should be noticed that due the recent droughts at the beginning of the 1970s and 1980s, these volumes have been divided by two, and that the total surface of the lake decreased from about 25 000 km^2 to about 5 000 km^2.

Lake Chad is of great ecological and socio-economical value for the region. This high hydrological variability and regional importance confirm the need for an effective monitoring of the lake. Unfortunately, in-situ observations of the lake are scarce. Only one staff gauge is currently operational (Bol station) and does not allow for the complexity of the inundation patterns to be captured. Specifically, as Lake Chad dries it can split into several isolated pools (Lemoalle et al. [20]). For these reasons, remote sensing data are the only means of gaining consistent hydrologic observations across the entire lake. These space observations are used to simulate the hydrology of Lake Chad (Delclaux et al. [21]; Lemoalle et al. [22]; Bader et al. [23]). Radar altimetry (Fig. 5a) provides water height time series over the Lake Chad since 1993, from multi satellite tracking (T/P from 1993 to 2002, then Envisat up to 2010 and Jason 2 from 2008), and Modis imagery allow the monitoring of flood water dynamic in the south and north basins since 2000 (Fig. 5b). Since 2001, a small decline in the south pool of Lake Chad is observed from both radar altimetry and Modis images analysis.





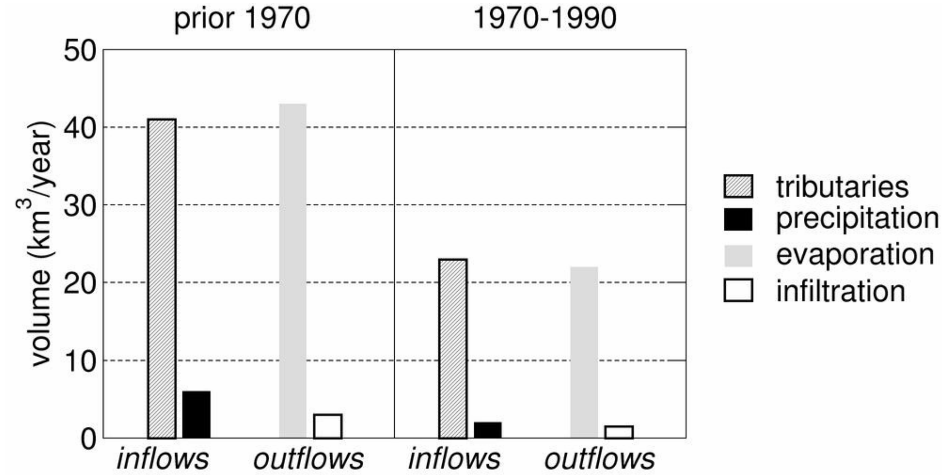


Fig. 5: (from up to low) Level variation of Lake Tchad from altimetry multi-mission (T/P (up to 2002), Envisat (up to 2008) and Jason-2(up to 2010)) (a), surface variations from Modis images (b) and water balance of the lake (c).

3.3 Ganga river basin

The Ganga River is continuously fed by the melting of ice on glaciers and other rivers originating in Himalaya. Rain water, during the period mid June to Sept, over the Gangetic plain is also a major contributor in the river water which is causing the flood in northern India and Bangladesh. Though the various rivers in India feed the water from glaciers it is also affected by the Indian Monsoon. The climate of India is classified in four categories: winter, pre-monsoon, monsoon and post- monsoon. Monsoon period, also known as the rainy season, lasting from June to September, causes the flood in most of the region if India. In pre-monsoon period, April to June is the driest season and this time river sink to its minimum.

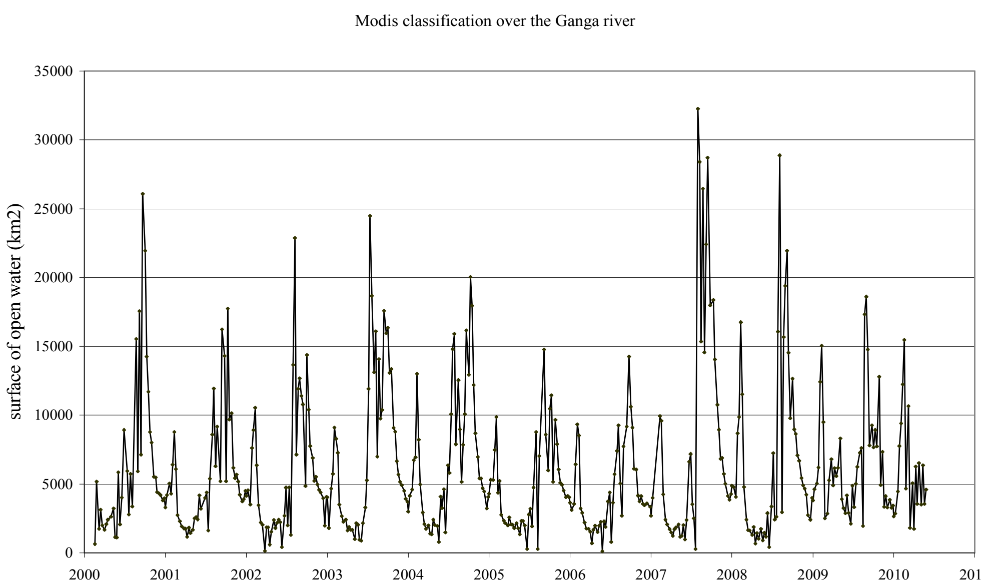


Fig. 6: Surface of open water detected from Modis classification for the down Ganga River.

Like the other rivers in India, the inundation along the river Ganga is also mostly depending upon the rain in catchments of the Ganga basin and its tributaries. The water drained to river from catchments is at his maximum in the middle of the rainy season.
Although the region is rather cloudy in rainy season, the Modis images provide an interesting view of phase of inundation over the Ganga delta with however a proportion of rejected images higher than what was observed in the other regions described in this study. One hence could estimate average water extent on the delta at inter-annual time scale.

For example the variation of water logging, Fig. 6, in lower Ganga basin shows a good annual repetition in rainy season (maximum in August-September). There is a high peak in 2007 (also 2008) which is because of the huge amount of water discharge in Kosi River, due to high rain, from Nepal. Large flood area south to the Ganga River is also observed from MODIS in Bihar in 2000 during which, the width of the Ganga River increases significantly, causing lateral overflow from the bank of the river. Analysis of images from 2000 to 2010 has also showed high inter-annual amplitudes of the inundation over the Ganga River, therefore over the delta in Bangladesh. Between the 2 dry years of 2005 and 2006, and the wet years of 2007 and 2008 there is a factor two of the inundated surface (Fig. 6).

4. DISCUSSION ON FUTURE MISSION AND CONCLUSIONS

What are the perspectives for the next decade on flood monitoring from space? Multispectral imagery from Modis has proven its ability to monitor water extent over large areas with continuous data at relatively high temporal resolution. Other sensors exist or are programmed for the coming years. The Meris instrument onboard the Envisat platform is based on the same measurement's principle. However the Envisat mission is at the end of its life and one would not be able to rely on this satellite in the near future for multi-spectral and radar altimetry data. In the frame of the establishment of new Global Monitoring for Environment and Security GMES capacities by the European Union, a panel of new satellites have been planned for the next decade, with dedicated missions in land monitoring from multispectral sensor (Sentinel-2), and radar altimetry in dual Ku-C bands (Sentinel-3). Sentinel-2 will provide multispectral imagery at high resolution (4 spectral band at 10m, 6 at 20m and 3 at 60m), with a full coverage of the Earth every 5 days. It will consist in pair of satellites, with initial launch in 2013. Sentinel-3, mission is dedicated to the measurements of sea surface topography but could also be used for water level estimation on continental water bodies, in the same way that Envisat is currently used. Sentinel-3 will also consist in a pair of satellites with expected first launch in 2013. In 2011, the Centre National d'Etudes Spatiales (CNES) and ISRO Indian Space Research Organisation (ISRO) will launch the Saral/Altika mission, which will be the first altimeter operating in Ka band which will have the main advantage of a better spatial resolution due to smaller footprint of the radar signal (150 m instead of few km), allowing a better discrimination of water in floodplains and anastomosed rivers with a large number of small channels. This mission will be placed on the same orbit than Envisat and should cover the needs for continental water level monitoring, for lakes, rivers, and floodplains. In 2013, the CNES, EUMETSAT, and NASA will continue the Jason program, with the launch of Jason-3 radar altimeter in Ku and C bands.
However, none of those missions is dedicated exclusively to continental hydrology. The future SWOT mission is the first satellite mission dedicated to the measurement of continental surface water. SWOT will provide a global inventory of all terrestrial water bodies whose surface area exceeds (250 m^2) and river whose width exceeds 100 m, at sub-monthly, seasonal and annual time scales (Biancamaria et al., [24]). The principal instrument of SWOT will be a Ka-band Radar Interferometer (KaRIN), which will provide heights and co-registered all weather imagery of water over 2 swaths, each 60 km wide, with an expected precision of 1cm/km for water slopes, and absolute height level precision of 10 cm / km^2 (Fig. 7). SWOT will provide an estimate of river discharge, and map floodplain topography and channel reaches. SWOT will allow us to better quantify the exchange between rivers and floodplains for improved prediction of inundations (Biancamaria et al., [25]). For floodplain mapping the improvement should be very significant since SWOT will have a global coverage with a resolution of 250 by 250m.
As shown above, the high spatio-temporal heterogeneity of inundations is a key limitation for actual remote sensing system. Combination of altimetry and imagery provide interesting control data to validate and assess quality of hydro dynamical model. They allow better understanding of the linkage with climate variability, changes due to monsoon or drought in Africa or India, impact of PDO or El Niño in South America and Central Australia, but the

spatial and temporal sampling of data actually does not allow having a global view of surface water elevation and storage variation at high spatio-temporal resolution. Additional information like precise topography of the floodplain inferred from digital elevation model for example, is still needed if one expects to determine water volume variation. Other very important information that SWOT will provide, is the water discharge at each river channel entering and leaving a floodplain like the IND for example. This information would be invaluable for assimilation in hydrodynamic model of inundation (Biancamaria et al. [26]) and to understand the role played by such floodplain in the regional water availability with high societal interest. The potential of SWOT measurements will be enhanced if coupling with other Remote Sensing data (SMOS-like, radar altimetry, imagery, gravimetry and meteorological satellite data sets) and it will considerably improve our understanding of flood process.

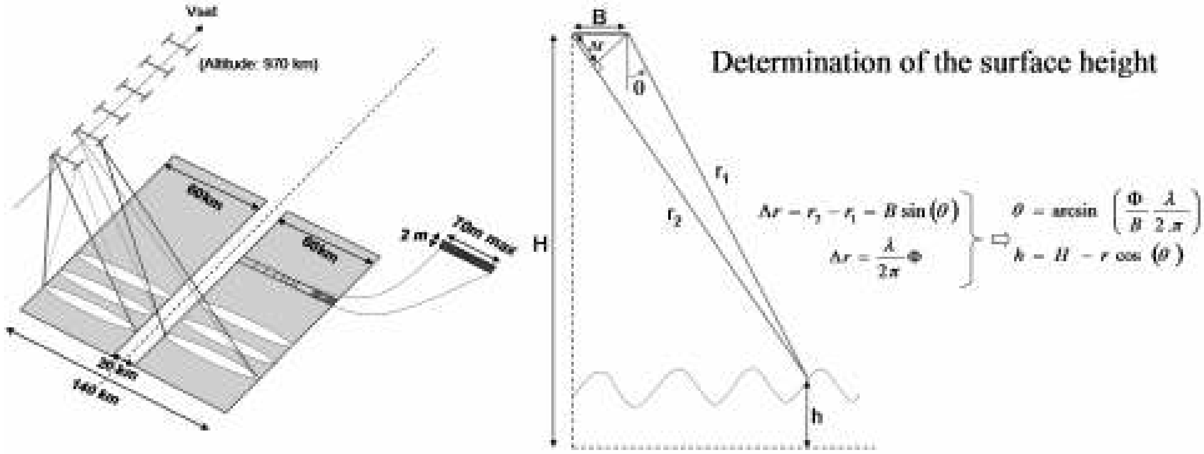


Fig. 7: SWOT mission. Radar Interferometry principle for the determination of water height over wide swath of 120 km along the orbital track of the satellite.

The combined radar and multispectral approach developed in this paper demonstrates our current capabilities for operational space monitoring of inundated extents and levels for three case studies across the World. It also raises serious limitations which could be overcome by future missions. By complementing in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in large river basins and their influence on climate variability, geodynamics and socio-economic life. It offers global geographical coverage, good spatio-temporal sampling, continuous monitoring with time, and capability of measuring water mass change occurring at or below the surface.

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