Global monitoring of wetlands – the value of ENVISAT ASAR Global mode

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Abstract

This paper elaborates on recent advances in the use of ScanSAR technologies for wetland-related research. Applications of active satellite radar systems include the monitoring of inundation dynamics as well as time series analyses of surface soil wetness. For management purposes many wetlands, especially those in dry regions, need to be monitored for short and long-term changes. Another application of these technologies is monitoring the impact of climate change in permafrost transition zones where peatlands form one of the major land cover types. Therefore, examples from boreal and subtropical environments are presented using the analysed ENVISAT ASAR Global mode (GM, 1 km resolution) data acquired in 2005 and 2006. In the case of the ENVISAT ASAR instrument, data availability of the rather coarse Global Mode depends on request priorities of other competing modes, but acquisition frequency may still be on average fortnightly to monthly depending on latitude. Peatland types covering varying permafrost regimes of the West Siberian Lowlands can be distinguished from each other and other land cover by multi-temporal analyses. Up to 75% of oligotrophic bogs can be identified in the seasonal permafrost zone in both years. The high seasonal and inter-annual dynamics of the subtropic Okavango Delta can also be captured by GM time series. Response to increased precipitation in 2006 differs from flood propagation patterns. In addition, relative soil moisture maps may provide a valuable data source in order to account for external hydrological factors of such complex wetland ecosystems.

1. Introduction

Specific mechanisms of water supply and storage are essential for maintaining the particular character of a wetland. Any change, directly by, e.g. water abstraction or indirectly through climate variation, can have a considerable impact on a wetland ecosystem. Disturbance can impede their role as natural habitats, cultural landscapes and alter greenhouse gas cycling (Mitra et al., 2005). In addition, shallow lakes and streams that undergo seasonal and long term drying (e.g. Stulina and Sektimenko, 2004) are major sources of atmospheric mineral dust. The extent and biophysical properties of wetlands are variable in space and time. Information on the extent of wetland areas—in particular the temporal dynamics—is lacking at a global scale (Finlayson et al., 1999). In recent years, active radar (microwave) remote sensing has been proven a useful technique for monitoring components of the hydrosphere and has a high application potential for wetlands (e.g. Oldak et al., 2002; Alvarez-Mozos et al., 2005; Frappart et al., 2005; Wagner et al., 2007a). Active radar sensors can be grouped into SAR, ScanSAR and scatterometer systems. SARs have good spatial sampling characteristics (e.g. European remote sensing satellites (ERS) with 25 m) but the lowest temporal sampling (approx. monthly) and have mainly been used for inundation mapping. Scatterometer on the other hand can provide several measurements per day depending on latitude. The footprint, however, is in the range of several

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tens of kilometres. These data are used for global derivation of relative soil moisture (Wagner et al., 2003). ScanSAR systems are characterized by sampling in between SARs and scatterometers. It is proposed that they are suitable for both inundation and soil moisture mapping. The ENVISAT ASAR is a ScanSAR system and when operating in Global mode (GM) several images per week can be acquired with varying incidence angles and 1 km resolution (500 m pixel spacing).

Radar signals are strongly dependent on hydrological conditions in addition to surface roughness and vegetation structure. Thus, multi-temporal approaches allow the detection of environmental processes that are important for the functioning of terrestrial biota, in particular inundation dynamics, soil moisture (Wagner et al., 2007b) and freeze–thaw changes (Bartsch et al., 2007).

The objective of this paper is to discuss the capabilities of medium resolution satellite microwave data for global monitoring of wetlands. The major advantage of these data is the comparably short revisit intervals. The global availability and usefulness of such data is analysed from the viewpoint of providing information on wetland types and their distribution. The parameters which can be derived are inundation extent and duration and potentially also relative soil moisture. This study concentrates on the first two parameters. Two examples are shown which represent different wetland types and environments. Both subtropic and subarctic regions are environments which are highly sensitive to climate change. The subtropical Okavango Delta is a wetland with pronounced seasonal dynamics. The boreal peatlands of the West Siberian Lowlands are characterized by permafrost features and seasonal snowmelt patterns. Advantages and disadvantages of ENVISAT ASAR GM data are discussed for the two selected sites.

2. Data and processing

ENVISAT was launched by the European Space Agency (ESA) in February 2002 into a sun synchronous orbit at about 800 km altitude and an inclination of 98.55°. The Advanced Synthetic Aperture Radar (ASAR) instrument is one of the instruments installed on board. It provides radar data in different modes with varying spatial and temporal resolution and alternating polarization at C-Band ($\sim$5.6 cm wavelength). The following case studies utilize ASAR data acquired in the Global Monitoring (GM) mode. GM data for our studies are available in C-HH polarization with 1 km resolution.

ENVISAT ASAR Image and Wide Swath modes are acquired on request. GM mode serves as backup mode if no other is ordered. The image data provided represent swaths with a 405 km width (Desnos et al., 2000). For further processing these data require georeferencing with respect to the curvature of the earth and terrain (Meier et al., 1993). Digital elevation data of sufficient resolution are only available below 60°N from the Shuttle Radar Topography Mission (SRTM, 100 m × 100 m, USGS). Since wetlands occupy mostly flat regions and the terrain in the study area is moderate in higher latitudes the GTOPO30 (USGS)-based correction is sufficient. The effects on the backscatter due to varying incidence angle and distance from sensor (near and far range) are removed (Roth et al., 1993; van Zyl et al., 1993) within the normalization step of the analyses. The resulting backscatter images show the backscatter coefficient at the reference angle of 30 ° expressed in decibels. A processing chain has been developed for ENVISAT ASAR which allows the analysis of GM (1 km) as well as Wide Swath (WS, 150 m) mode data over large regions (Bartsch et al., 2004).

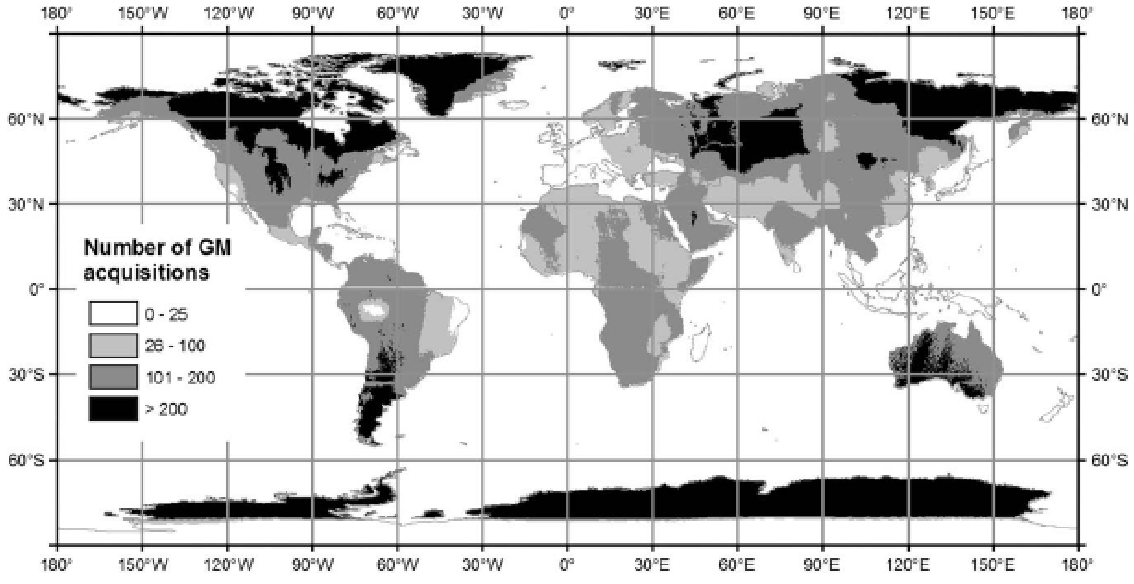

Fig. 1. ENVISAT ASAR GM coverage December 2004–October 2006.

Whereas ASAR WS data are suitable for wetland analyses on a regional scale (Bartsch et al., in press), GM offers a much wider perspective. Coverage varies due to acquisition mode priorities and latitude. Frequency is highest at northern latitudes and over Antarctica. Europe and northern Africa have low GM coverage due to high demand for other modes (Fig. 1). Average numbers of acquisitions for different wetland types have been derived for the wetland types outlined in the Global Lakes and Wetland Database (GLWD; Lehner and Döll, 2004, Table 1).

Data from northern peatlands (ID 1 for Asia and 2 for North America in Table 1), however, have been acquired weekly on average during the first 22 months (starting December 2004). Fortnightly to monthly data acquisition intervals are available for subtropical floodplains. Both estimates depend on size and acquisition mode priorities for the sensor. Coverage at the pixel level even exceeds these estimates, adding up to two per week in high latitudes and weekly intervals in the subtropics.

3. Example 1: boreal peatlands

Both Wide Swath and Global modes have been used for the identification of boreal peatlands in central Siberia (Bartsch et al., in press). ASAR WS data for central Siberia are available for this study for summer 2003 and GM for summer 2005 and 2006. The Wide Swath data have been analysed within the framework of the Siberia II project (Schmullius et al., 2003). The mapping approach is transferred to the West Siberian Lowlands for ASAR GM. A validation of the GM classification results has been carried out using the West Siberian Lowland (WSL) database (Sheng et al., 2004) which was compiled using topographic maps.

3.1. Study site

The peatlands initially investigated are located at approximately 60°N at the eastern rim of the West Siberian peat basin (Bartsch et al., in press). The basin still features sporadic permafrost (Stolbovoi and McCallum, 2002) although it is located at relatively low latitudes. The study site is located west of the Yenisey River. Open bogs are an important land cover in this region, albeit not dominating. These peat bogs are characteristic of the eastern portion of Western Siberia (Botch and Masing, 1983) and play an important role in establishing the geochemistry, sedimentology and flow pattern of the Yenisey River (Kremenetski et al., 2003). The mapping approach was then applied to the southern part of the West Siberian peat basin which stretches from approximately 60° to 90°E and 56° to 64°N. The area of interest within this boundary covers approximately 1,000,000 km^2. Peatland within the West Siberian Lowlands are estimated to cover 600,000 km^2 and thus contribute a considerable share of the global terrestrial carbon pool (Sheng et al., 2004). This also includes the region north of the chosen study area. The Ob River flows through this region from SE to NW.

Table 1
Number of data acquisitions by wetland category for December 2004–October 2006 (source: Global Lakes and Wetland Database, Lehner and Döll, 2004)

ID	Wetland category	Mean	STD
1	Peatland	231	75
2	50–100%	224	58
3	25–50%	200	62
4	Freshwater marsh, floodplain	163	67
5	Intermittent	146	66
6	Pan, brackish/saline	138	58
7	Swamp	122	52
8	Coastal	129	91
9	Complex (0–25%)	99	27

3.2. Open peatlands

The previous study (Bartsch et al., in press) showed that ASAR WS data are suitable for mapping open peatland in

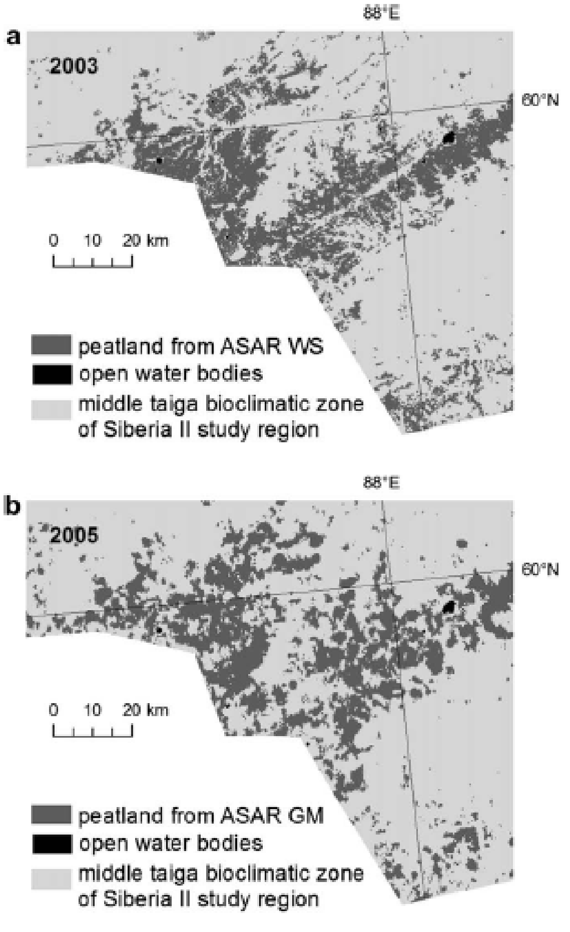

Fig. 2. Peatland classification results: (a) ASAR WS data from 2003, 150 m resolution; (b) ASAR GM data from 2005, 1 km resolution. The area of interest is limited by the administrative boundary of Krasnoyarsk Kray (part of Siberia II study region; Bartsch et al., in press).

the boreal environment. Although the GM data has a much coarser spatial resolution it is expected that it can be useful across large peatland areas. A direct comparison between GM and WS images, however, is not possible since they cannot be acquired at the same time. At the initial test site, autumn data have been found most suitable for detection of all peatland types when using ASAR WS data. Such data were only available for the year 2003. Since GM data distribution started after December 2004, the earliest possible summer and autumn season that can be investigated is 2005. Fig. 2 shows a comparison between the ASAR WS results from 2003 and the classification result for GM data in 2005.

Discrepancies are introduced by scale differences and possible intra-annual variations in surface soil wetness. These changes in relative surface soil wetness could be monitored with ASAR GM data with a suitable temporal resolution. A database was established which comprises all available GM data for June−September 2005 and 2006. The threshold-based classification developed for WS data was applied to this data set for the mapping of peatland extent. GM coverage varied from 0 to 46 in 2005 and 11 to 45 in 2006 (Fig. 3). This variation over the area of interest needs to be considered for the classification. Specific thresholds have been determined with the use of the West Siberian Lowland database (Sheng et al., 2004). All regions with high summer and autumn backscatter (>-3.5 dB) in more than 20% of available acquisitions are classified as peatland.

A comparison with the WSL database (Sheng et al., 2004) shows that oligotrophic to mixed peatlands with an approximate minimum carbon density of 150 kg C/m^2 can be identified with this method. Such high density values can be found south of the Ob River. Peatlands cannot be distinguished from other land cover to the north, between 70 and 77°E (Fig. 4, northern area), where carbon density is lower than 100 kg C/m^2. This is a permafrost transition area (Stolbovoi and McCallum, 2002) with a large number of lakes, which can only be monitored using the ASAR GM data starting from a size of 2 km^2 depending on their shape. Smaller lakes, which are abundant in this region, contribute to the backscatter signal in such a way that these peatlands cannot be distinguished from surrounding forests and other land cover (Fig. 4, northern area). In comparison with the peatland map by Sheng et al. (2004) only 8% can be identified in 2005 and 18% in 2006. In the southern area with seasonal permafrost about 76% of the extent (mainly oligotropic peatland) can be determined correctly (Table 2).

In this case a further step is necessary during which interseasonal backscatter behaviour is analysed. Data representing the late winter and spring period (April−June) have been added to the database. The entire time series of normalized backscatter for different land cover types is shown in Fig. 5. Open peatlands as found south of the Ob River are characterized by on average -8 dB during winter. Values increase to more than -4 dB within approximately 3 weeks after snowmelt. Surrounding forest has higher backscatter in winter ranging between -6 and -7 dB. During snowmelt values drop to -10 dB and rise afterwards to on average -5 dB. Peatlands with a high amount of open water surfaces below GM resolution have comparably lower backscatter values during winter (-10 dB) and show similar mean values to those for forest during the summer although variation is higher and it does not result from volume scattering but from a mixture of high

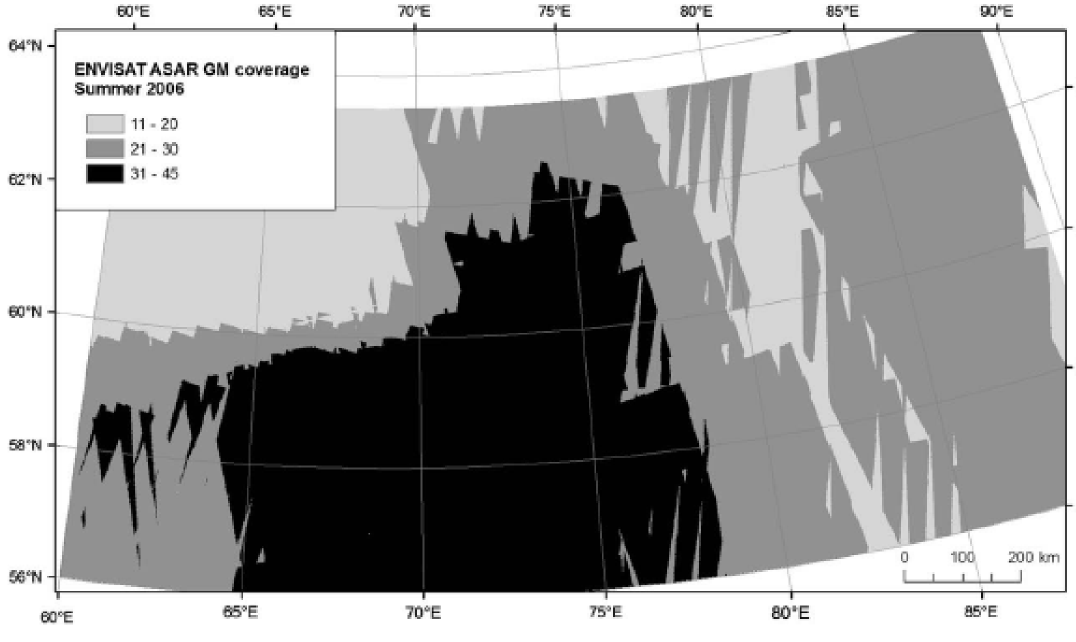

Fig. 3. ASAR Global mode coverage 2006 for the southern part of the West Siberian Lowlands.

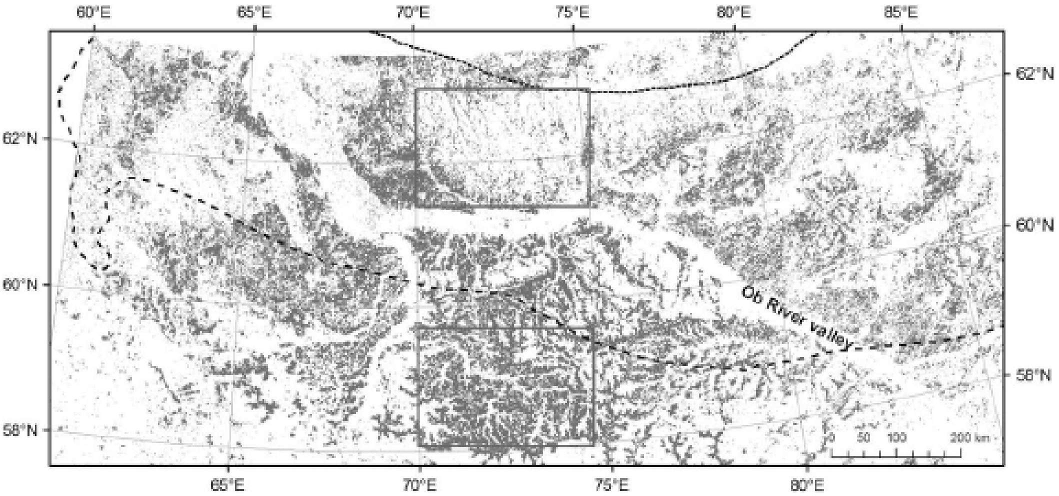

Fig. 4. ASAR Global mode 2006 classification result: open peatlands. Rectangles indicate the northern and southern area of interest. Area south of long dashes, seasonal permafrost; area between long and short dashed lines, 25−50% frozen ground; area to the north has up to 75% permafrost (source: Stolbovoi and McCallum, 2002).

surface soil moisture and specular reflection from the water surface. After the onset of snowmelt backscatter stays low for about a month until the snow cover disappears and melt water has drained. With global mode data, this delay in backscatter increase can be determined and may also be used for discrimination of this wetland type from other peatland.

4. Example 2: subtropical floodplain

A time series including all GM data available since December 2004 has been established for the semiarid, subtropical Okavango Delta. Due to the large size of the wetland (12,000 km^2), its entire area is covered by GM images only at approximately monthly intervals (Bartsch et al., 2006). This limits the application of the radar images for detailed system-wide studies, however, it extends and complements previous flood dynamics analyses which have been carried out using optical satellite data (Gumbricht et al., 2004; Wolski and Murray-Hudson, 2006a). On the other hand, parts of the system are covered at least once a week, which forms a good base for monitoring relative soil moisture patterns.

Table 2
Agreement between GM classification results and the peatland map produced by Sheng et al. (2004) for the northern and southern areas of interest (for location see Fig. 4) by peatland type: proportion of peatland type with respect to entire land cover and percentage of correctly identified peatland in 2005 and 2006

Peatland type	Northern site			Southern site		
	Proportion of land cover	Identified as peat		Proportion of land cover	Identified as peat	
		2005	2006		2005	2006
Oligotrophic	41	6	14	32	76	77
Transitional	7	10	25	2	74	70
Eutrophic	1	17	30	1	68	75
Mixed	6	13	33	13	71	74
All types	55	8	18	48	74	76
Non-peatland	45	5	16	52	13	17

4.1. Study site

The Okavango Delta is located in a semi-arid region with rainfall of 460 mm/year and evaporation four times higher (Ringrose et al., 2005). The wetland is strongly flood-pulsed, with a single annual flood event caused by inflow along the Okavango River that arises in the high rainfall zone of central Angola, and to a lesser extent by local rainfall. Inundation of the Delta is at its maximum in September, 5−6 months after the end of rainy season, due to the slow movement of the flood wave. The dynamics of flooding within the Okavango Delta depend on internal as well as external factors (Gumbricht et al., 2004; Wolski and Savenije, 2006). The wetland area varies at decadal, multi-decadal and millennial time scales, in response to variation in regional climate (McCarthy et al., 2000). Additionally, aggradation and tectonic processes cause episodic and gradual changes in the timing and spatial pattern of inundation within the delta (Wolski and Murray-Hudson, 2006a). Monitoring of flood size and distribution is therefore a necessary prerequisite for short and long term management of the wetland.

4.2. Wet area extent

The total local precipitation in the 2006 rainy season (720 mm) exceeded that of the previous year (380 mm). The extent of inundated and saturated soil at the end of the rainy season was therefore larger in 2006 than in 2005. In June 2006 it was 7060 km^2, which is comparable with the maximum wetland extent observed in 2005 (7090 km^2, Fig. 6).

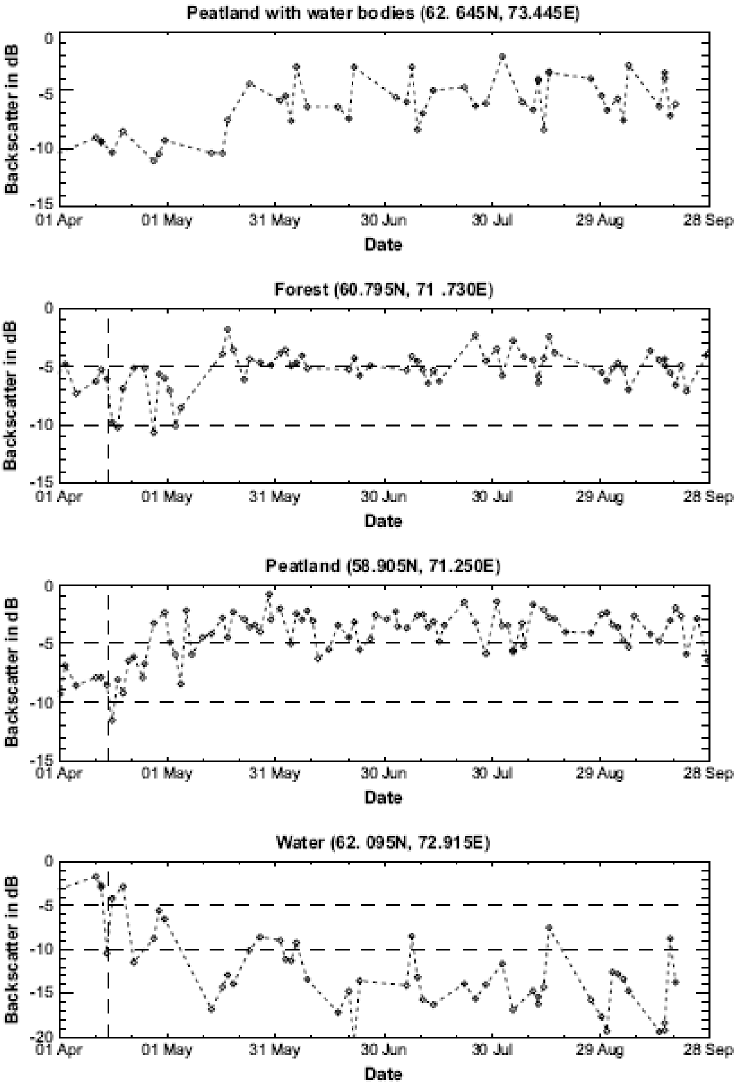

Fig. 5. Normalized backscatter time series for peatland with small ponds, forest, peatland without ponds and open water from spring and summer 2006. The onset of snowmelt is indicated by the vertical dashed line.

The maximum inundation and wet area extent of 2006 reached approximately 8200 km^2 since the 2006 inflow to the system was relatively low. This corresponds to a 10% increase within 3 months for the 2006 dry season compared to a 27% increase in 2005 for the same time period. In the end of September 2006, 70% was determined as wet area. The overlap of inundated and high surface soil moisture area in September of the two consecutive years was 40%.

Complex interactions between internal and external parameters cause the pattern of inundation to differ between the two years analysed. The flood in the eastern branch is known to be triggered by local rainfall (Wolski and Murray-Hudson, 2006b) and the inundation is more extensive there at the end of the wet season in 2006 than in 2005. The effects of the Okavango River flood pulse are not strongly accentuated, thus the inundation there does not expand towards September, but remains stable, or even reduces slightly. The western part, in turn, responds strongly to the flood pulse of the Okavango River, and much less to local rainfall. Thus, there is a strong increase in inundated area between April and September in both years.

5. Discussion

ENVISAT ASAR GM coverage is highly variable but could allow, at a minimum, weekly observations at single points. The lack of data over large areas such as western Europe impedes

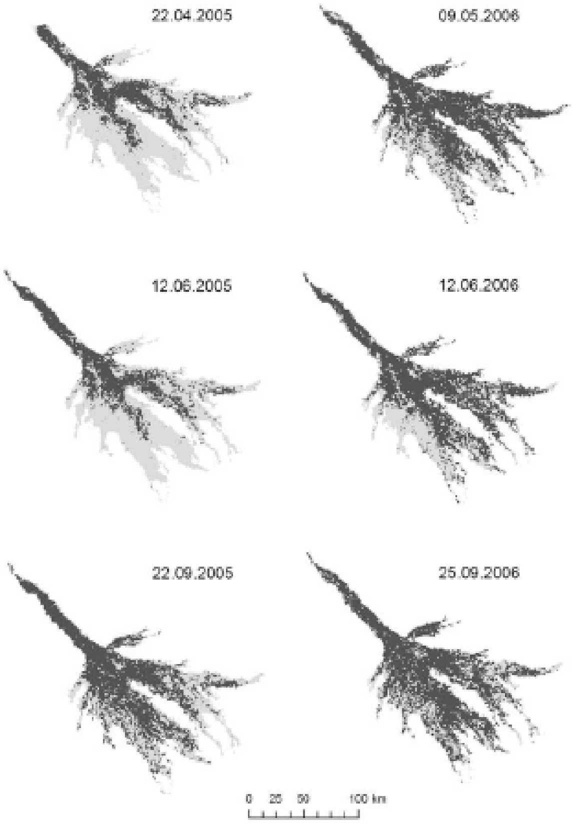

Fig. 6. Comparison of the ASAR GM derived wet area in 2005 and 2006: (a) April — end of rain season; (b) June — dry season; (c) September — maximum inundation extent.

global monitoring capabilities that relies on this data. Additionally, the size of the area of interest is important as this affects the sampling interval at which the entire area can be covered. Despite these limitations, GM data can be used to map some peatland types and to monitor dynamics on a monthly basis for areas of up to 200 × 200 km.

Apart from data coverage, the size of the objects being investigated influences the monitoring capabilities due to the swath width (405 km). High numbers of small lakes below the resolution of the GM do not support a straightforward identification (threshold method) of boreal peatland. By use of the high temporal sampling rate of less than a week, a time series analysis can be carried out and thus specific characteristics during the snow melt period determined.

Inundated area with emergent vegetation can be confused with high soil moisture land area. This restricts the comparability to other fine resolution maps from, e.g. optical satellite sensors. In comparison to such data, radar images allow identification of the extent of wet areas due to its sensitivity to near surface soil moisture.

The irregular timing of acquisitions prohibits the provision of a regular time series. Some differences in the intra-annual comparison for the Okavango Delta, for example, may occur due to the fact that the exact date of maximum flood extent cannot be determined and/or covered with the available dataset.

Apart from monitoring the Okavango Delta itself it would be of great value to monitor the soil moisture of the upper catchment. It has been shown in previous analyses for the Zambesi River (Scipal et al., 2005), that even coarse resolution scatterometer-derived soil moisture time series relate well to river discharge measurements in sub-tropical environments. Regular measurements of global soil moisture are available from scatterometer data (Wagner et al., 2003) at 25—50 km resolution. The retrieval approach relies on high temporal sampling. Since ENVISAT ASAR GM features a comparably high sampling rate it could similarly be used for the derivation of relative soil moisture maps with 1 km resolution. Estimates from fewer ScanSAR measurements may be possible by combining with optical satellite data, as demonstrated by Yang et al. (2006) for Radarsat. The incorporation of a spatially improved soil moisture product from the upper catchment of the Okavango may, for example, improve prediction models for the wetland region. Additionally, the amount of GM data is less than any high resolution product and thus makes operational processing feasible on global scale.

6. Conclusions

The two case studies show that although ASAR Global mode data has a 1 km resolution it is capable of capturing not only the extent but also the dynamics of wetland areas. Data availability is restricted, especially in Europe, but it is sufficient for most boreal and also sub-tropical environments which are susceptible to climate change and thus require regular monitoring. Relative soil moisture maps at 1 km resolution from C-band ScanSAR systems may enhance and complement existing coarse scale products.

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