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2 Observations of changes in surface water over the western Siberia 3 lowland

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7 [1] We analyse the evolution of the fraction of water
8 surface (FWS), derived by SSM/I between 1988 and 2002
9 over the Western Siberia Lowland. This whole region
10 exhibits an increase in the amount of FWS that is in
11 agreement with the observed trends of the Ob river
12 discharge and precipitation. However, a similar increasing
13 trend is not found over the most important wetland area of
14 Sibirskie Uvaly Hills located in a region of sporadic
15 permafrost. These observations support the hypothesis that
16 climate warming in discontinuous permafrost environments
17 may lead to a reduction of small lakes and wetland areas.

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23 1. Introduction

24 [2] Global warming is deeply affecting the Arctic regions
25 that are witnessing significant perturbations to the water and
26 carbon cycle [Serreze *et al.*, 2003; Wu *et al.*, 2005]. The
27 increase in air temperature and in atmosphere greenhouse
28 gases concentration is expected to intensify the Arctic
29 hydrological cycle and accelerate permafrost thawing
30 [Houghton *et al.*, 2001; Stocker and Raible, 2005]. In
31 particular, important modifications to the terrestrial water
32 cycle have been observed in Siberia. An increased trend in
33 the discharge of the major Siberian rivers over the last
34 decades has been reported by Peterson *et al.* [2002]. This
35 has been related to an increase in precipitation but not all the
36 precipitation data sets seem to agree with the magnitude of
37 the observed trend [Pavel'sky and Smith, 2006] and it
38 remains difficult to identify the mechanisms responsible
39 for it [McClelland *et al.*, 2004; Berezovskaya *et al.*, 2004].
40 For the period 1988–2001 [Mialon *et al.*, 2005], using
41 passive microwave remote sensing, observed an augmenta-
42 tion in the wetland area over the Ob river basin. However,
43 an analysis of optical remote sensing images by Smith *et al.*
44 [2005] showed a reduction in the number of Arctic lakes in
45 West Siberia that could be related to permafrost thawing.
46 According to Smith *et al.* [2005] climate warming in
47 discontinuous permafrost environment may well lead to a
48 decrease in the number of lakes and wetlands.

49 [3] The behaviour of wetland and inundated surface and
50 the role of permafrost on the water cycle under the impact of
51 climate change remain unclear, especially for Siberia where

in-situ observations are scarce. Reaching a better under- 52
standing of these phenomena is extremely important since 53
changes in peatland and wetland areas will alter the water 54
and carbon cycle and change the amount of carbon released 55
to the atmosphere [Oechel *et al.*, 1993]. Feedback mecha- 56
nisms between the biosphere, the cryosphere and the atmo- 57
sphere may further accelerate these processes [Freeman *et al.* 58
et al., 2001]. 59

[4] The aim of this paper is to provide further insights on 60
the evolution of wetland, small lakes and inundated surfaces 61
and its relation to permafrost in the western Siberia lowland 62
by analysing trends in the fraction of water surface (FWS) 63
derived by SSM/I between 1988 and 2002. 64

2. Study Area 65

[5] The Western Siberian Lowland contains a large 66
percentage of the northern wetland and shallow lakes that 67
are both net sinks for atmospheric carbon dioxide and 68
source for methane [Sheng *et al.*, 2004]. The study area 69
(Figure 1), that includes most of the lower Ob river basin, is 70
in a region of permafrost transition (Figure 2). Within this 71
area we further selected three test regions (Figures 2 and 3): 72
the first one (a) along the Ob river, the second one (b) in the 73
wetland bogs area of Sibirskie Uvaly Hills on the Siberian 74
Ridge in a region of sporadic permafrost (located North of 75
the Ob at 63°N) and the third one (c) in the Khanty- 76
Mansiysk region in a permafrost free zone (South of the 77
Ob and West of the Irtysh rivers at about 60°N) in swamped 78
taiga containing more than 25,000 lakes [Sheng *et al.*, 2004; 79
Frey and Smith, 2003]. 80

3. Water Fraction Estimation by Passive 81 Microwave Satellite Measurements 82

[6] Passive microwave sensors are very sensitive to the 83
amount of surface water on their footprint and they have 84
been successfully employed to derive the fraction of water 85
surface (FWS) corresponding to small lakes and reservoir, 86
inundated surfaces and natural wetland areas [Fily *et al.*, 87
2003; Mialon *et al.*, 2005]. FWS derived from SSM/I has 88
been also used to improve flood forecasting over the 89
Mackenzie river basin [Temimi *et al.*, 2005]. The SSM/I 90
brightness temperatures at 37 Ghz provided by National 91
Snow and Ice Data Center (NSIDC) with 625 km² resolu- 92
tion have been used to compute the FWS area present in the 93
satellite pixel. To minimise the spatial gaps resulting from 94
the swath width the daily data have been averaged over 95
pentads (5-day averages). The methodology, fully described 96
by Fily *et al.* [2003], is based on the estimation of the 97
emissivity ϵ_p from the measured brightness temperature 98
using linear relationships (that are site dependent) between 99

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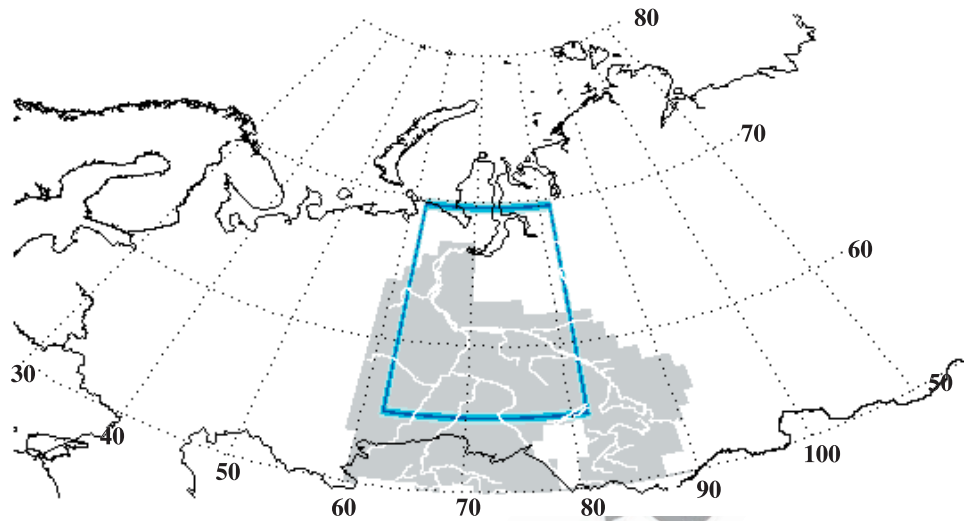


Figure 1. Location of the study area and the Ob river basin (shadow area in gray).

100 surface emissivity at vertical and horizontal polarisation. We
 101 used the global emissivities data set by Prigent *et al.* [1998]
 102 to derive the coefficients of this linear relationship for the
 103 study area. The FWS is then derived from the retrieved
 104 emissivity ϵ_p at polarisation p by the following equation:

$$\epsilon_p = \epsilon_{water} \times FWS + \epsilon_{dry} \times (1 - FWS) \quad (1)$$

106 where ϵ_{water} is the water emissivity and ϵ_{dry} is the emissivity
 107 of a dry surface at 37 GHz. Following [Mialon *et al.*, 2005]
 108 ϵ_{water} and ϵ_{dry} have been set respectively equal to 0.664 and
 109 0.965. The derived FWS values correspond to a combina-
 110 tion of different surface contributions including lakes and
 111 reservoirs smaller than the SSM/I EASE-Grid pixel, shallow
 112 open water, saturated wet surfaces, flooded surfaces,
 113 swamps, ponds, marshes, fens, bogs or pits. To a lesser
 114 extent they are also sensitive to the soil moisture in the first

few centimeters. For this analysis we only consider the
 115 summer values of FWS (July and August) when snow and
 116 ice are absent.
 117

4. Analysis Results 118

4.1. Comparison With Discharge Over the Ob River Basin 119

[7] We found significantly high correlations between the
 121 interannual variation of the FWS (spatially averaged over
 122 the part of the study area within the Ob river basin shown in
 123 Figure 1) and the Ob river discharge measured at the station
 124 of Salekhard at the Ob river estuary in summer (the
 125 discharge values were obtained by A Regional, Integrated
 126 Hydrological Monitoring System for the Pan-Arctic Land
 127 Mass (ArcticRIMS), <http://rims.unh.edu/>, 2003). An exam-
 128 ple of the interannual evolution of the FWS and the
 129

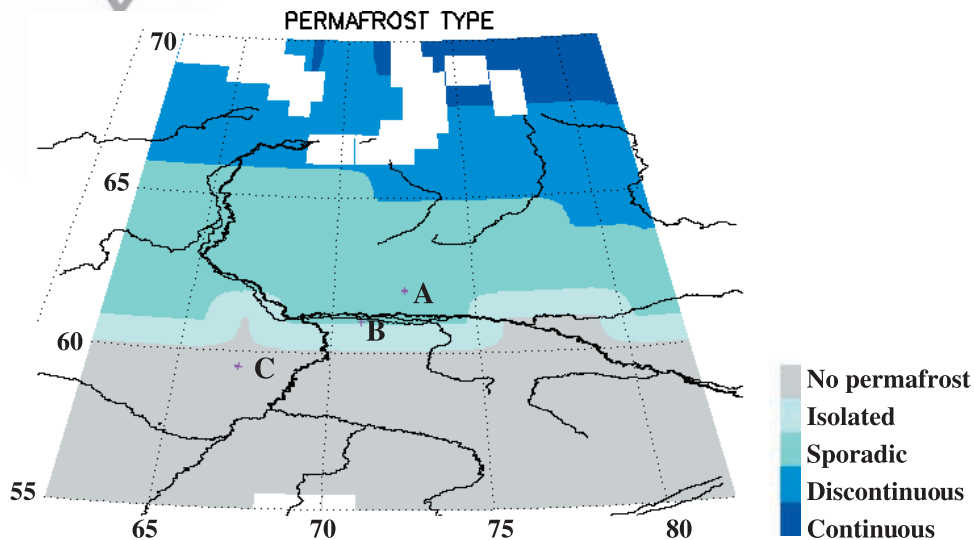


Figure 2. Map of permafrost types for the study area [Brown *et al.*, 1998]).

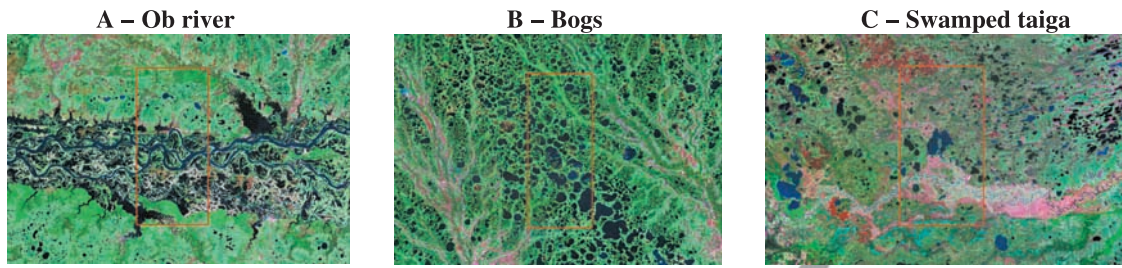


Figure 3. Landsat images showing part of the three selected test regions (red boxes show the SSM/I footprint) within the study area: (a) along the Ob river, (b) in the Sibirskie Uvaly Hills bogs area and (c) in the Khanty-Mansiysk swamped taiga. The geographical location of these test sites is shown in Figure 2.

130 discharge in July and August is shown in Figure 4
 131 (the correlation R- value is in this case equal to 0.87).
 132 The consistency between the FWS and discharge independ-
 133 ent data sets provides a further validation of the capability
 134 of SSM/I for monitoring the interannual variations of FWS.
 135 No correlation was instead found between precipitation
 136 (also shown in Figure 4, CRU data set by *Mitchell et al.*
 137 [2003]) and discharge or water fraction. Regarding trends,
 138 FWS, precipitation and discharge data are all consistent and
 139 they show a significant increase over the period 1988–2002
 140 (Table 1).

141 **4.2. FWS Trends**

142 [8] Figure 5 shows the spatial distribution of FWS
 143 (August) and precipitation (July and August) temporally
 144 averaged over the 1988–2002 time period and their trends
 145 over the same period (we average precipitation over a two
 146 month period to also take into account the rain events that
 147 occurred in the month preceding the FWS observations).
 148 Averaged high values of FWS are found along the lower
 149 part of the Ob river and over the two main wetland regions
 150 of Sibirskie Uvaly Hills and Khanty-Mansiysk. A signifi-
 151 cant positive FWS trend is evident along the Ob river and
 152 over its major affluents. This trend is consistent with the
 153 discharge increase measured at the Ob estuary and the
 154 significant augmentation in the summertime inundations’
 155 extent on its floodplain. A positive FWS trend is also

observed over the Khanty-Mansiysk area (C) but this is 156
 not the case for the Sibirskie Uvaly Hills (B), the zone 157
 where the averaged values of FWS are highest, despite the 158
 precipitation positive trends over the whole region. This is 159
 quite surprising since the Sibirskie Uvaly Hills area is 160
 characterized by bogs, a wetland system entirely fed by 161
 precipitation. A similar behaviour is observed for the FWS 162
 in July (not shown). 163

[9] More details on the behaviour of these three regions 164
 are provided in Figure 6, that shows the interannual varia- 165
 tions of FWS (August) and precipitation (July and August) 166
 at three selected $0.5^\circ \times 0.5^\circ$ test points (shown in Figure 3) 167
 and in Table 2 that reports the corresponding trends in FWS 168
 and precipitation during summer. 169

171 **5. Conclusions and Perspectives**

[10] The western Siberia lowland region analysed here 172
 extends across the transition zone between sporadic perma- 173
 frost in the Sibirskie Uvaly Hills, and the permafrost free 174
 region of Khanty-Mansiysk. This whole region exhibits an 175
 increasing trend in the amount of summer precipitation, in 176
 the average amount of water surface and in the discharge 177
 measured at the Ob’s estuary. When the location of the FWS 178
 trend is mapped, it becomes evident that the main region 179
 affected by the FWS increase is along the Ob river. The 180
 wetland located in the permafrost free region yields also a 181
 significant but lower increase in water surface whereas the 182
 wetland in the Sibirskie Uvaly Hills does not exhibit any 183
 significant trend despite the increase in precipitation that 184
 is the largest over this area. 185

[11] These observations could confirm the hypothesis by 186
Smith et al. [2005] that disappearing Arctic lakes could 187
 represent a diffuse lake drainage front where warming 188
 permafrost first experiences widespread degradation. 189

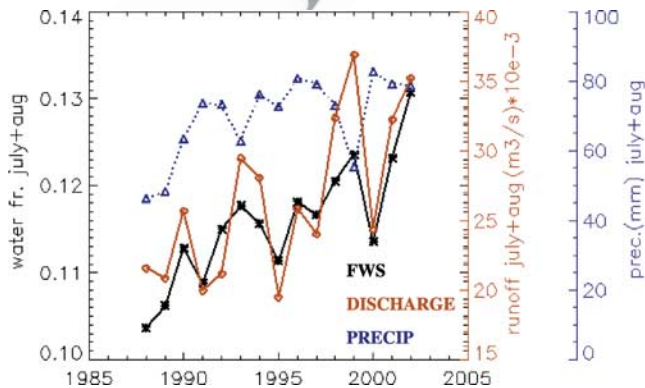


Figure 4. Comparison between the interannual variability of summer (July and August) FWS and precipitation spatially averaged over the Ob river basin (above 55°N) and of the Ob river discharge measured at Salehard.

Table 1. Trends in FWS and Precipitation Averaged Over the Ob River Basin (Above 55°N) and Trends in the Ob River Runoff Measured at Salehard^a

| Months | Trends FWS | Trends Precip. | Trends Discharge |
|-------------|------------|----------------|------------------|
| July | +18% | +15% | +14% |
| August | +12% | +48% | +97% |
| July+August | +15% | +32% | +44% |

^aPercentage trends are calculated as the change over the period 1988–2002 divided by the mean over the same period.

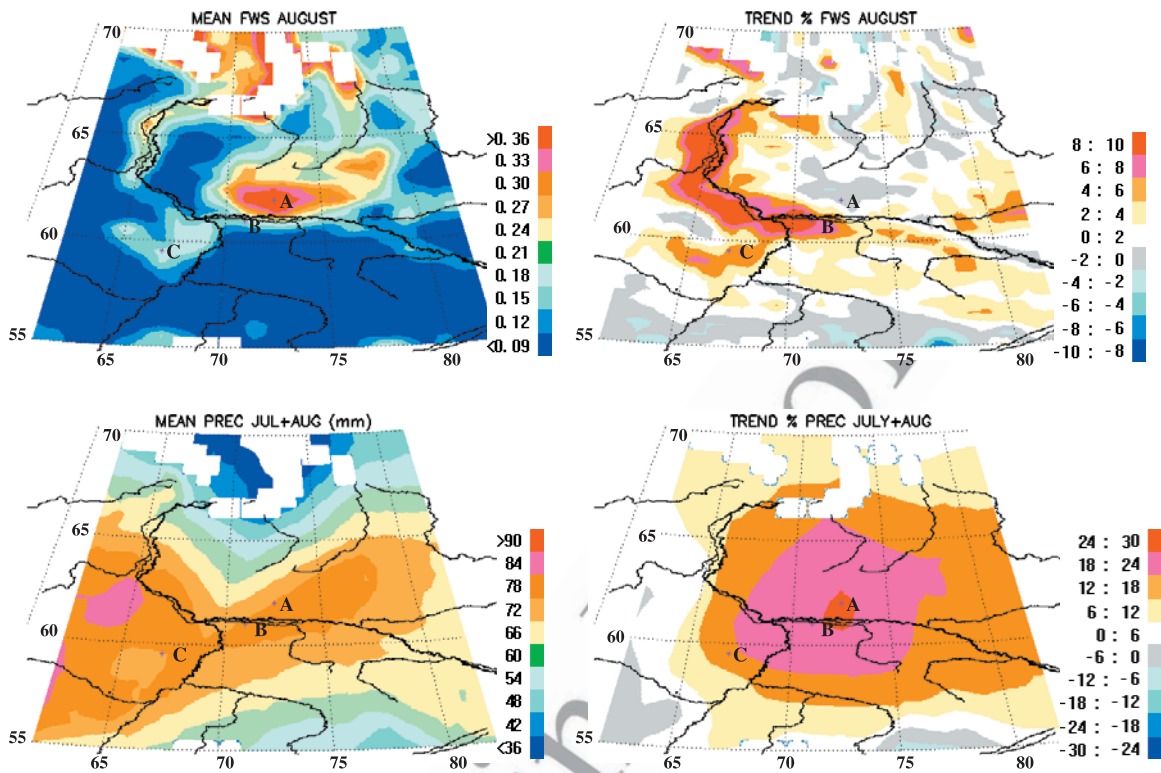


Figure 5. (top) Water fraction surface in August and (bottom) precipitation in July and August: (left) mean values over the period 1988–2002 and (right) trends over the same period.

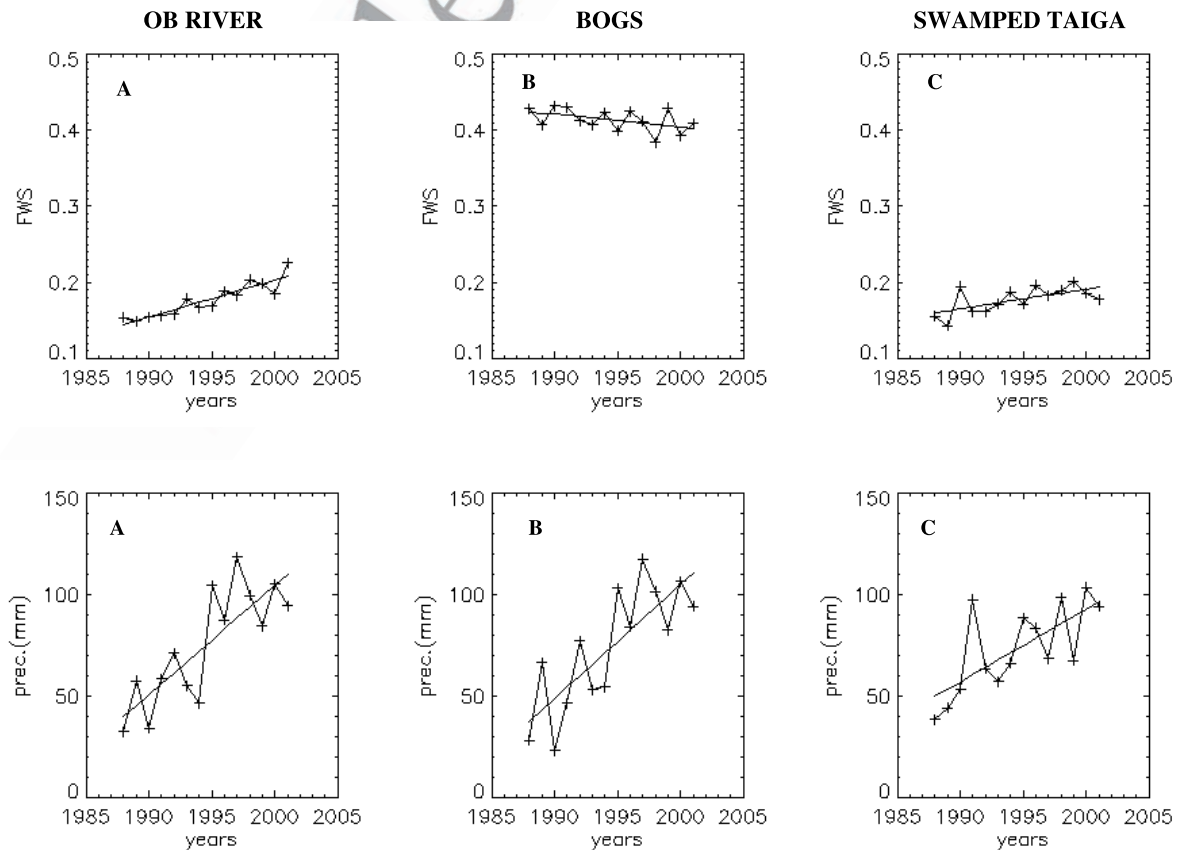


Figure 6. (top) Temporal evolution of the FWS in August and (bottom) precipitation in July and August for three selected sites.

t2.1 **Table 2.** Trends in FWS and Precipitation for the Three Selected Test Sites in Figure 6^a

| t2.2 | Test point | FWS Jul | FWS Aug | Precip Jun+Jul | Precip Jul+Aug |
|------|------------|---------|---------|----------------|----------------|
| t2.3 | A | 8.9% | 12.5% | 12.6% | 23.4% |
| t2.4 | B | 0.3% | -1.3% | 13.5% | 24.7% |
| t2.5 | C | 6.9% | 4.7% | 19.8% | 15.9% |

t2.6 ^aSee caption of Table 1.

190 However, further work needs to be done to understand the
191 reasons for the observed trends that could be also due to
192 changes in surface evaporation or to differences in the
193 hydrological conditions of the three sites analysed, such
194 as differences in soil permeability, groundwater outflows
195 and soil characteristics.

196 [12] Reaching a deeper understanding of the Western
197 Siberia hydrology is extremely important because this
198 region contains a large percentage of the worlds peatlands
199 and contributes for a significant portion to the total terres-
200 trial freshwater flux to the Arctic Ocean. These recent
201 climatic trends may, therefore, have globally significant
202 repercussions.

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