Microwave satellite data to quantify effects of global climate change on arctic rivers

Dr. Zsofia Kugler*[a], Dr. Robert Brakenridge [b], Dr. Tom De Groeve[c]

[a] Department of Photogrammetry and Geoinformatics, Budapest University of Technology and Economics H-1111 Budapest, Muegyetem rkp. 3, Hungary, Phone: +36 1 463 1454, Fax: +36 1 463 3084, zsofia.kugler@mail.bme.hu;
[b] Dartmouth Flood Observatory, Department of Geography, Dartmouth College,Hanover, New Hampshire USA 03755, Fax: (603) 646-1601
[c] DG-Joint Research Centre, European Comission, Via E. Fermi 2749, I-21027, Ispra, Italy

ABSTRACT

Research was conducted to monitor arctic river ice conditions in Siberia. The lack of traditional hydrological measurements in those remote inaccessible regions makes the use of satellite data a key technique in obtaining information on their hydrological cycle. The Global Flood Detection System (GFDS) based on microwave satellite data of AMSR-E system was used to observe river ice conditions in the polar region. The orbital gauging observations are serving the basis of artic river monitoring. The ice break-up in spring is a significant change in the river condition well detectable by the GFDS system. Variations in the time-series of several years can be mean to quantify effects of global climate change. Results show more significant change in the spring melting than in the freezing period. The ice-break up is showing more variation in Siberian rivers than in those of North-America. For this reason only the break-up period in the Siberian rivers was investigated. Limitation of the system is the length of the time-series still the trend shows that the period of ice-break up in the rivers are moving towards early spring.

Keywords: GFDS, river ice break-up, microwave satellite data, global climate change, arctic rivers

1. INTRODUCTION

In late September 2009, for the first time two German cargo ships successfully completed the crossing the Nothern See Route from Asia to Europe without the help of icebreakers. The route trims 4,000 nautical miles off the usual 11,000-mile journey via the Suez .The stunning transit is an effect of arctic see ice shrinking due to global climate change. For this reason several Earth Observation satellite systems are in operation to monitor polar see ice condition in the arctic region. Yet there are no regular observations carried out on continental arctic rivers even though their annual ice break-up and freezing period would also be a notable sign of climate change processes.

The Global Flood Detection System (GFDS) to observe river flow conditions from space [1] was developed at Dartmouth Flood Observatory (DFO)/US and operationally implemented at the Joint Research Centre (JRC)/Italy of the European Commission [2]. It provides a near-real time systematic detection of river floods around the world using AMSR-E passive microwave observations. The aim is to monitor river sites and detect flooding by using the radiation difference of land and water. Yet the satellite based flood detection tool works on an automatic signal processing providing operational information on river hydrology. The technique uses microwave remote sensing data of the descending orbit, H polarization, 36 GHz band which is sensitive to water surface changes. The sensor revisits river observation locations once a day and can therefore provide a daily temporal resolution. Sensor data is available 24 hours after acquisition. The GFDS is capable to monitor river ice condition too [1] using the time series of orbital river gauging.

Remote Sensing of the Ocean, Sea Ice, and Large Water Regions 2010, edited by Charles R. Bostater Jr.,
Stelios P. Mertikas, Xavier Neyt, Miguel Velez-Reyes, Proc. of SPIE Vol. 7825, 782508 · © 2010 SPIE
CCC code: 0277-786X/10/$18 · doi: 10.1117/12.866021

2. METHODOLOGY

2.1 The Global Flood Detection Tool

The Global Flood Detection System (GFDS) aims to provide a systematic detection of riverine flooding around the world. The techniques modifies the methodology first developed at the Dartmouth Flood Observatory (DFO) [1] to monitor river sites and detect flooding by using the microwave radiation difference of land and water. Brackenridge developed a method for daily monitoring of river systems around the globe based on AMSR-E data. They demonstrate that, using a methodology first developed for wide-area optical sensors AMSR-E can measure river discharge changes and river ice status.

The modified methodology [2] uses the 36GHz H-polarization band of the descending (nightly) orbit of AMSR-E with a footprint size of approximately 8x12km, available in the level 2A product. Night time radiation is more stable than day time, for this reason only descending swaths of the sensor were used.

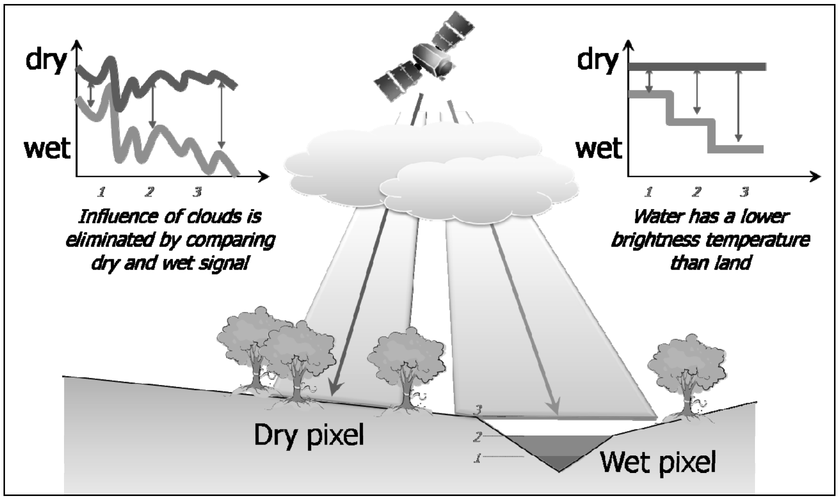

Figure 1. Methodology of the Global Flood Detection System (GFDS). Lower line in time is related to the wet/measurement pixel received over the river channel (M), upper line is related to the dry/calibration (C) pixel not affected by the riverine flooding.figures.

However, in spite of the great radiation dissimilarity of water and land, the raw brightness temperature observations are too noisy to reliably detect changes in surface water area (Figure 1). This is because brightness temperature measures are influenced by other factors such as physical temperature, permittivity, surface roughness and atmospheric moisture. While the relative contribution of these factors cannot be measured, they are assumed to be constant over a larger area. Therefore, by comparing a “wet signal” received over a river channel of a potential inundation location (M: measurement pixel) with a “dry signal” (C: calibration pixel) without water cover the mentioned noise factors can be minimized. Thus normalisation of the wet signal by the dry observation was implemented where the brightness temperature values of the measurement/wet signal (Tbm) were divided by the calibration/dry observations (Tbc), referred to as M/C ratio (1).

$$\frac{M}{C}\,ratio = \frac{Tb_m}{Tb_c} \qquad (1)$$

Results from this kind of calibration eliminates daily and seasonal temperature changes, soil moisture, vegetation influences in its time series by assuming that the wet and the dry location has the same properties except for the river condition changes.

The time series of the M/C Ratio provides the basis of space borne river gauging measurements. During normal flow conditions water stays in-bank, dry and wet signals have nearly the same trend over time from space. As soon as the river floods and water goes over-bank, the proportion of water in the wet pixel greatly increases. The radiation received over the wet pixel lowers due to the lower emission of water while the dry pixel stays with minor variations constant. Consequently, there is a strong response in the M/C ratio in case of an inundation event.

The same happens in case of river ice condition changes. During the winter time the river surface freezes and in early summer the ice breaks and melts. This periodical variation is well detectable using the same method owing to the fact that in winter the river surface has comparable emission properties than land having ice or/and snow cover. Thus the wet measurement pixel and the dry calibration pixel has alike Tb values. As a consequence the calculated signal (MC ratio) remains around the average in time. In spring the river ice breaks and starts to melt so that the Tb value observed over the river site decreases dramatically resulting in peak signal values. This rapid change allows detecting the exact time of the river ice break measured in a temporal resolution of days. As a result we obtain a temporal evolution of the phenomenon for several years.

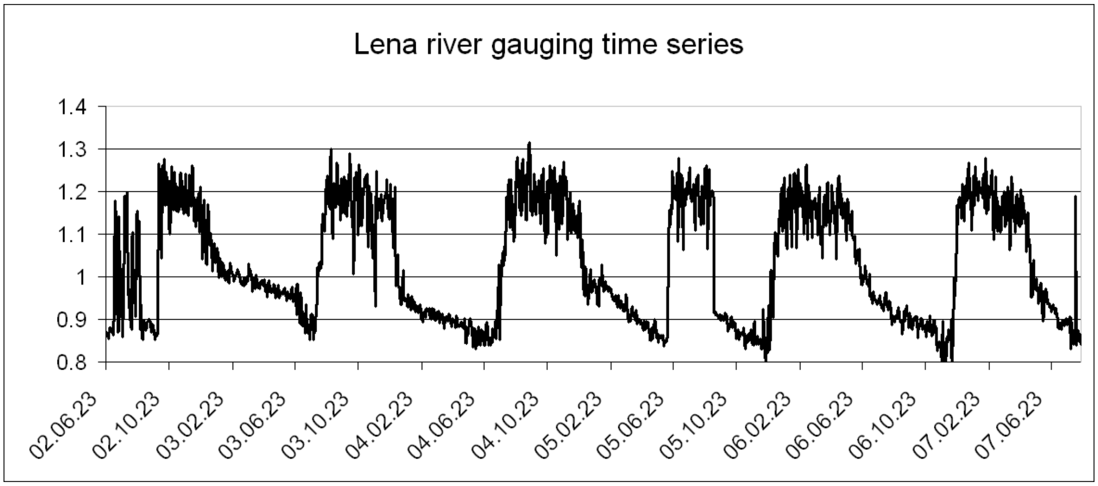

Figure 2. Time series of Lena River in Siberia observed by Global Flood Detection System (GFDS). Periodical changes are due to river ice freezing and melting.

2.2 Study area

Using the Global Flood Detection System (GFDS) a daily observation of arctic and subarctic river ice changes was carried out. The method based on microwave satellite observation was providing a good basis for analysing remote regions in Siberia.

To detect river flow condition changes observation sites over river channels were set around the globe. Location of the wet and dry pixel was selected manually based on mapped historical flood events. Their prime criteria were to be sensitive to river surface changes. Selection was made manually at DFO based on historical flood events detected in MODIS low resolution images mounted on the same satellite platform Aqua. Applying the same technique new observation sites were set along arctic and subarctic river channels in Russia. The selection of the orbital gauging sites was automated by defining observation pixels every 50 km along the river channel. Therefore the measurements could serve the basis for investigating upstream downstream relations in selected river valleys.

Four River valleys the Ob, the Yenisey, the Lena and the Kolyma in Siberia were chosen for detailed investigation (Figure 3). These rivers are the four largest rivers of the continent flowing into the Arctic Ocean. They generally flow from south to north being joined by several tributary on their way to the Ocean. The length of the selected rivers reach from 5540 km (Yenisey) to 2129 km (Kolyma) which enables to carry out studied of ice condition from upstream to downstream. Further to this to it allows to detect possible ice jam locations in the melting period. In general river ice starts to break in late spring while it starts to freeze in the autumn. The process generally starts on lower latitudes in the upstream regions and progressively follows in the downstream river sites.

The river valleys are more inhabited in the southern upstream areas as in the downstream subpolar, polar areas. The valleys cross several climate zones as well as expand through different vegetation zones. The climatic features of the basins reaches upper course well inside the continent and its lower course in the arctic zone. Mean annual precipitation averages 250-500 mm across their drainage basins. Their hydrograph rises quickly during snow melting time and floods over the low Siberian Plain and Highland in late spring and in early summer. In case the ice break-up is not absolutely progressive from upstream to downstream the river is facing ice jams.

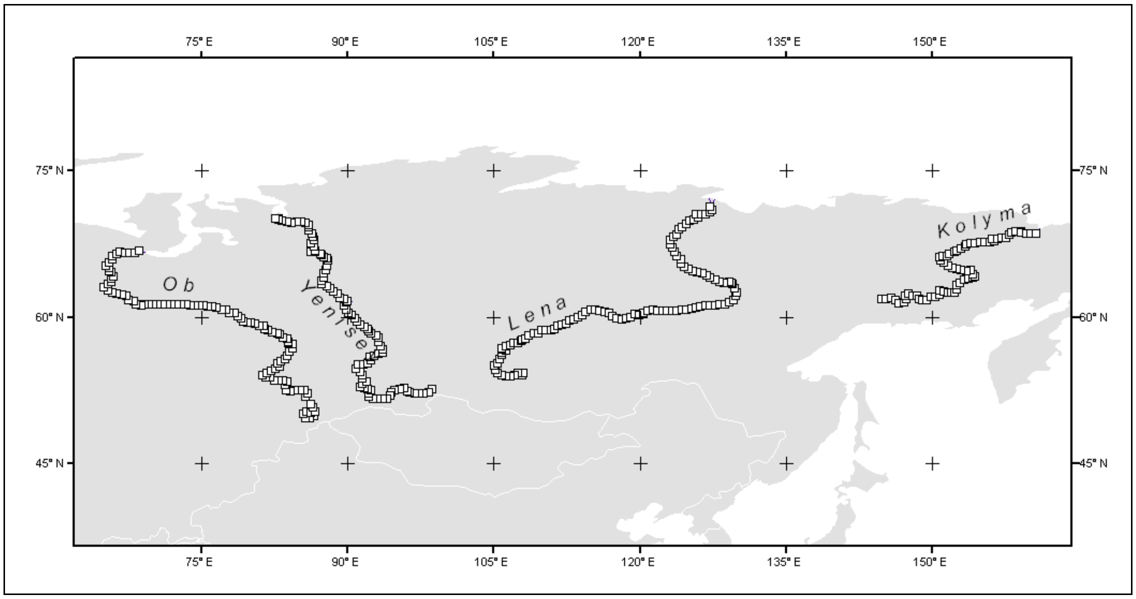

Figure 3. Study area for ice break-up investigation in Siberia. Four selected river are the Ob, the Yenisey, the Lena and the Kolyma

2.3 Ice break-up

The Flood Detection Tool was used observe the temporal and spatial evolution of river ice break-up in the spring time time. The spatial resolution of the monitoring system was 50 km along each river reach. A daily imagery was provided by the National Ice and Snow Center /US. Images were downloaded and processed at the JRC calculating the signal for the selected river sites.

Similar to the methodology of the flood detection ice break-up was defined as a threshold of standard deviation from the average. If the calculated signal in the spring time gets over the threshold of 1 standard deviation and stays for more than 5 days continuously than ice break-up is defined. By means of this simple rule information was extracted from the complete database resulting in exact days and locations for the studied river site. It allows to study the upstream downstream relations and to monitor any anomaly or trends in the seasonal river condition changes. In summary it allows to carry out full spatial and temporal investigation of the phenomenon. Results of the study will be described in the next section.

3. RESULTS

The ice break-up dates were analysed both from temporal and spatial aspect. Investigations were carried out in three steps as follows:

1. Maping ice break-up for each river site in the selected river valleys
2. Analyse relation in upstream – downstream ice conditions, detect possible ice jam locations
3. Extract time series of break-up at particula sites for different rivers in several years

3.1 Spatial analysis of ice break-up

Mapping the river ice break-up in the selected valleys was performed for each year. Consequences were drawn both from spatial and temporal aspect. The rivers generally run from South to North crossing different climate zones. For this reason melting in spring starts in the lower latitudes and propagates downstream with time. Further to the south-north relation a strong east-west spatial variation of the melting time was found. Yet in the upstream part of the Yenisei and the Ob the signal was very unstable. For this reason the first 20-30 sites from the source had to be taken out from consideration. Further to this there is a strong trend from the most west river of Ob to the most east river of Kolyma where ice break-up is generally later in the east than in the west. On the Ob ice break-up starts in early May, whereas on the Lena and Kolyma it dates to late May. The fact can be explained by the different climate zones the rivers are crossing.

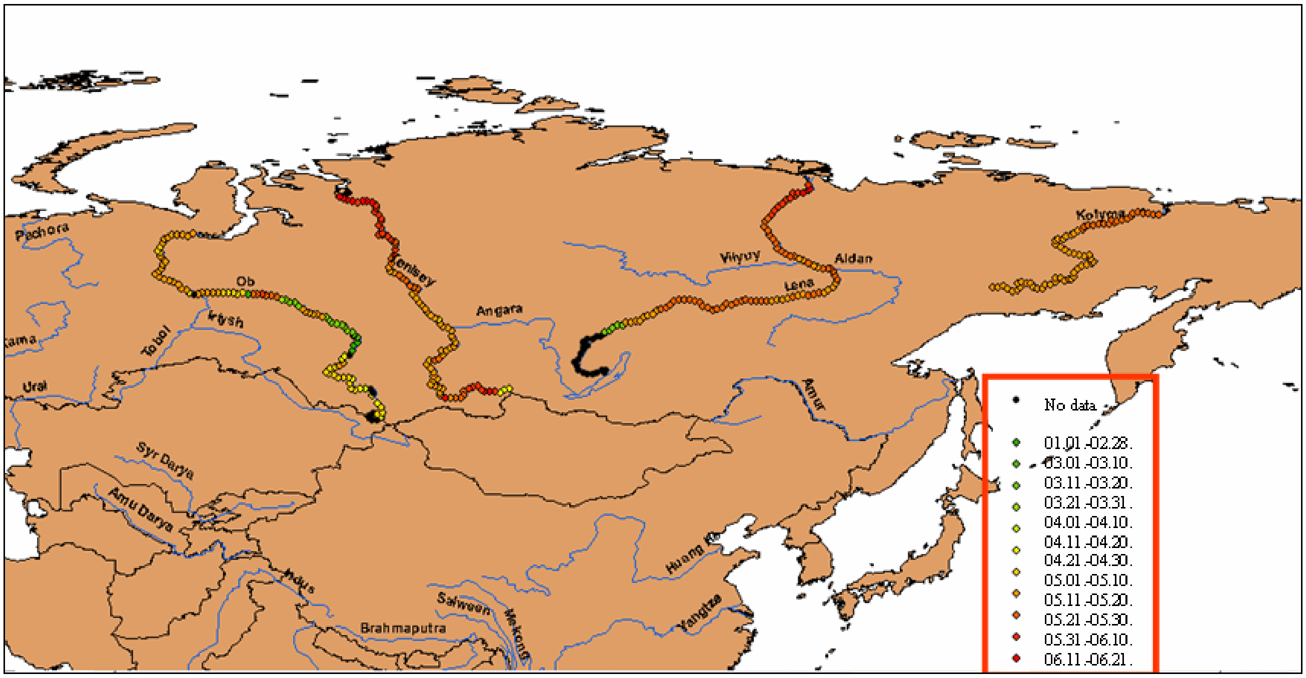

Figure 4. Dates for ice break-up in the study area for the year 2006 in a spatial context based on microwave satellite observations of GFDS.

The upstream-downstream relations analysis allows to extract possible locations of ice jamming. It appears in case the upstream area is melted while downstream ice is still present blocking normal flowing of the river. In this case extreme inundation might occur since water can only flow limited in the river channel as a consequence it is forced to go overbank.

In the monitored years the Ob has faced the most reoccurring ice jams in the upstream area along the river. Starting at around 1250 km from the source to 1700 and from 3200 to 3500 km observations detected river ice over the mentioned gauging sites. At the same time downstream and upstream from it river ice was already melting causing a local ice jam.

Ice jam along the further monitored rivers was less significant. On the River Yenisey the ice starts melting around the 10th May in the upstream area and propagates downstream reaching its downstream end in about one month. On the River Lena the ice starts to break around the 20th May. No rapid progress is detected downstream except for last 700 km where the river takes up an approximately south-north direction. On the River Kolyma the ice breaks around mid of May and runs progressively to the downstream end.

3.2 Temporal analysis of ice break-up

For each selected river ice-breakup was analysed site by site too. To mitigate upstream-downstream variation of break-up dates an average was calculated for each river valley. Plots were generated for ice break-up dates along particula site showing the exact days in the given year for the process. Average for ice break-up for each river was computed. Trend was considered for the mean of each river in form of linear trend lines to average yearly changes and extract tendencies. Apart from generating an average of ice break-up dates for each river, particular sites were analysed individually too. The majority of the sites were showing a negative trend. Consequently year by year the day of the ice break-up is shifting towards early spring.

Similar to the River Lena (Figure 5.) most of the sites' trend line equation – in general $m*x+y$ – showed a negative m value reaching from around -4.5 to -0.1. At the same time R^2 values were resulting to be between 0.001 – 0.5. For the River Lena the trend line for the calculated average for each year had an m value of -1.54 and a R^2 value of 0.2403. From the four studied rivers the Lena was showing the highest correlation coefficient. All other rivers had less correlation for this reason their resulting trend have to be considered with attention.

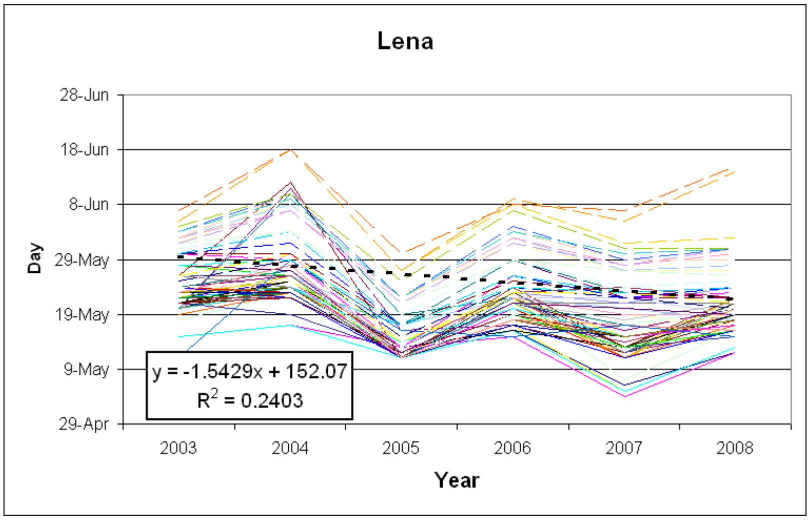

Figure 5. Ice break-up days for each site along the River Lena. Trend line of the average is shown with dashed line. Correlation is illustrated by the R^2 value.

In a next step river sites at a particular latitude, 62,8° were selected for detailed analysis. In case of the Ob it is around the upstream area of the river, on the Yenisey and the Lena it runs about the mid section of the stream and for the Kolyma it means the upstream part of the river (Figure 6).

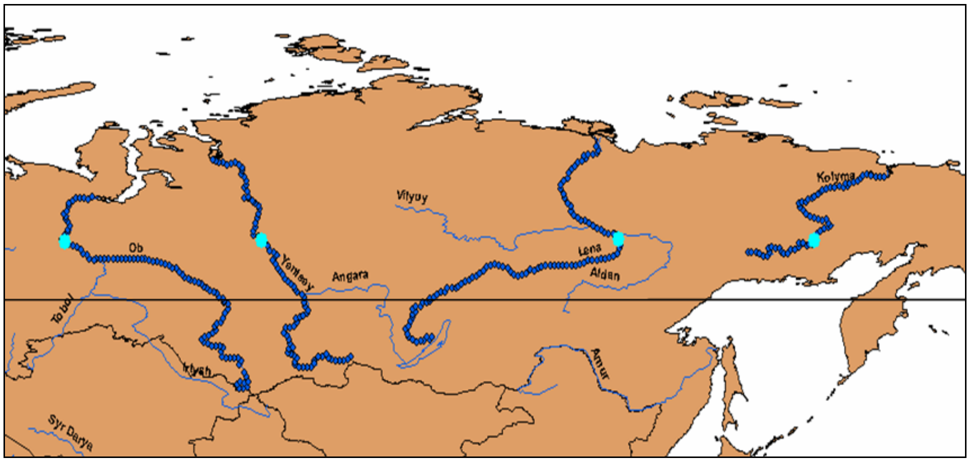

Figure 6. River sites selected for detailed study around 62,8° latitude. Selected locations are marked with large dot.

Ice break-up was extracted for the selected river sites and linear plots were generated from dates for the studied years. Graphs revealed similar conclusions described in the previous subchapter investigating west-east spatial relations of the phenomenon (Figure 7). In general the most west River Ob proves to be the first river where ice break-up takes place. It is followed by the Yenisey, the Lena and similar to the two previous the Kolyma. It starts around the end of April and the major part of the process follows in May. As mentioned in the previous subchapter the downstream area of the rivers only melts in early June. These statements have general validity to go beyond quantitative analysis was done.

Figure 7. Yearly dates of ice break-up for the selected river valleys.

Ice break-up was plotted for the selected river site in a single figure showing the process for studied years (figure 8.). Most of the rivers had a negative trend line except for the Kolyma which showed a positive increase due to an extreme value in 2003 and 2004. All remaining three rivers had a negative trend accounting for an early break-up year by year. The correlation of the trend lines remains low between 0.13 and 0.27. and have *an* m value from -1.14 to -1.85. Graphs assume to have a negative trend in the ice break-up period of the arctic rivers. The trend can be a consequence of global climate change however to prove the theory further investigation is needed. On the other hand the analysed time scale is very short compared to studies conducted in the field of hydrology or meteorology. For this reason to obtain more reliable results the time line has to be extended by processing data from further microwave satellite sensors.

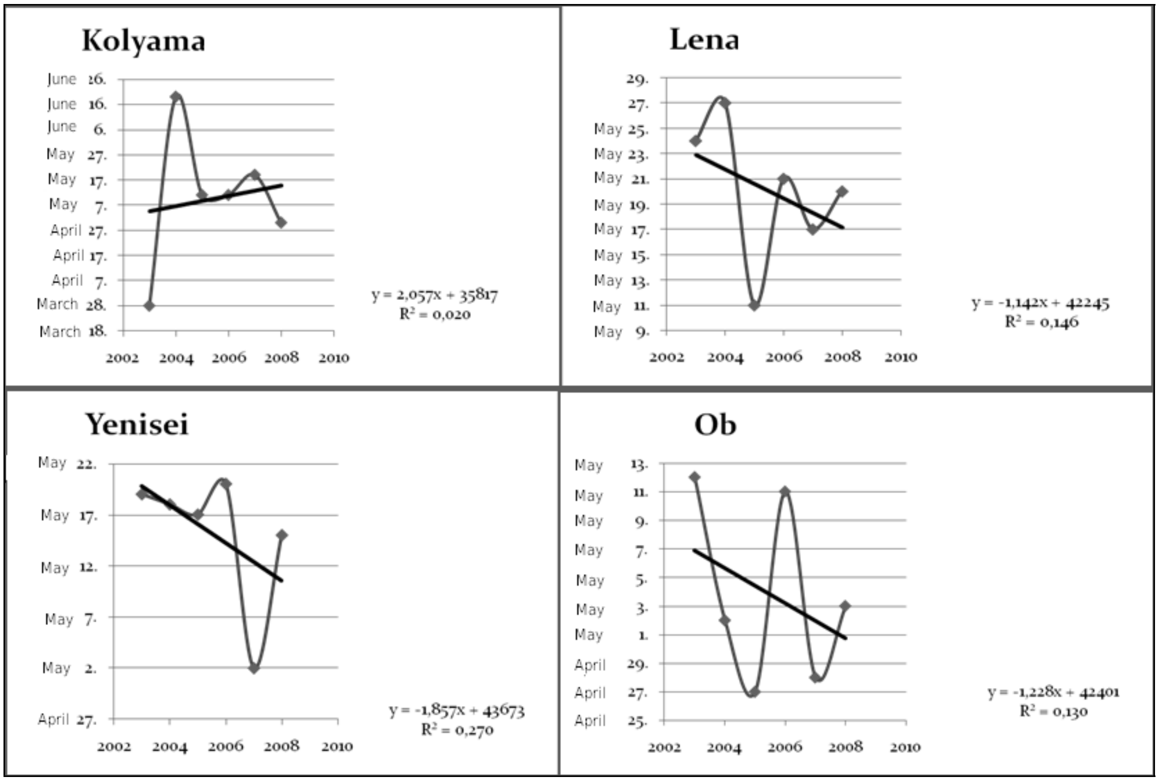

Figure 8. Yearly dates of ice break-up for the selected river sites and calculated trends.

4. CONCLUSIONS

Study was performed to investigate river ice break-up in arctic rivers of Siberia. Based on the Global Flood Detection Tool analysis was carried out to obtain information about remote inaccessible areas in the polar and subpolar region. Using microwave satellite data time serious was extracted for selected river sites and orbital gauging was used to detect trends during the investigated years. Analysis was carried out both in a spatial and a temporal context.

Results revealed a negative trend in the majority of investigated gauging sites thus river ice appears to break earlier every year. In addition there is an obvious trend from south to north and from east to west. Analysed rivers first melt in the southern, upstream region around the end of April begin of May and melt in the northern end around the end of the month or in early June. If it is not the case ice jams form in the river valley. Reoccurring ice jam formation was found in the valley of Ob in the upstream and mid reach of the river.

The negative trend in the ice break-up was found by using linear trend lines. Best correlation of the values was found along the river Lena when calculating the trend for the average of all sites in the valley. Comparable results were reported by Pavelsky&Smith [3]. Nevertheless their time series is based on optical remote sensing tools like MODIS and AVHRR. Yet the time series obtain by those optical sensors has a longer history. For this reason to obtain more reliable and stable source of information the current AMSR-E data set is planned to be extended by other microwave sensors dating back to longer history like SSM/I. Moreover results should be compared with ground trouth data and climate or weather observations to investigate the effects of global climate change in the arctic and sub arctic region.

5. ACKNOLEDGEMENT

At this point the author would like to express her gratitude to her students who made an excellent work on the topic. In project work they carried out investigations on ice break-up with the supervision of the first author. In alphabetic order they were Gyurászik Gábor, Fekete Nagy Ádám, Kovács Ádám, Nagy Veronika,Pethő László, Takács Bálint.

REFERENCES

[1] Brakenridge, G. R., S. V. Nghiem, E. Anderson, R. Mic., “Orbital Microwave Measurement of River Discharge and Ice Status”, Water Resources Research VOL. 43, W04405, (2007).

[2] Zs. Kugler, T. De Groeve, G. R. Brakenridge, E. Anderson, “Towards Near-real Time Global Flood Detection System”, International archives of photogrammetry and remote sensing volume XXXVI:(PART 7/C50),(2007).

[3] T. M. Pavelsky, L.C.Smith, “Spatial and temporal patterns in Arctic river ice breakup observed with MODIS and AVHRR time series”, Remote Sensing of Environment, 93, 328-338, (2004)