Thermal bar studies in the Krasnoyarsk Reservoir based on remote sensing datasets

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Abstract. We study a possibility of using remote sensing datasets to identify a thermal bar in the Krasnoyarsk Reservoir. MODIS thermal band data have been used to produce sets of images showing temporal and spatial temperature distribution across the Krasnoyarsk Reservoir. Thematic maps of temperature distribution across the reservoir have been derived for the spring period of 2016-2019, which show the thermal bar period to commence and end up within about one and the same time interval.

1. Introduction

In springtime, when the air temperature is permanently above zero, the ice starts melting. It is the time when direct stratification is observed, i.e. the water temperature drops with increasing depth. The highest water density occurs at 4°C. When the surface layer warms up to this temperature, stratification in the reservoir becomes unstable and there appears a thermal bar. A thermal bar is a frontal interface between warm water with the temperature above 4°C and cold water with the temperature below 4°C. Waters separated by a thermal bar differ not just in their temperature but in the transparency color and elemental composition as well. Thermal bar studies are important as they provide essential information on the overall hydrothermal picture of a reservoir and on the river regime after construction of a hydroelectric power plant. A thermal bar in the Krasnoyarsk reservoir was described by Kosmakov I.V. in [1], where this was shown to be the primary factor of internal water exchange affecting the movement of water masses. Hydrological monitoring of the reservoir is carried out by ground gauging stations, their data being in open access [2]. However these data cannot provide sufficient information on the overall picture of the hydrothermal regime. In particular, they are not helping in detecting such a phenomenon as a thermal bar. Water temperature studies may employ long-term MODIS datasets on the land surface temperature.

Our aim is to check up if remote sensing data can be used to identify a thermal bar in the spring period and to trace its travel across the Krasnoyarsk reservoir.

2. Object of study

The Krasnoyarsk Reservoir is one of the largest in Russia and in the world. It has a maximum capacity of 73.3 km\textsuperscript{3} and a navigable length of 334 km. The reservoir resulted from construction of the Krasnoyarsk HPP. It is a piedmont reservoir of a valley type as far as the morphological structure of its bed is concerned. The reservoir is located in the southern forest-steppe and mountain-taiga landscape.
zones. Based on the shape and structure of its basins and shores there are five lake-like reaches distinguished in the Krasnoyarsk Reservoir: Shchetinkinsky, Primorsky, Novoselovsky, Krasnoturansky, and Ust-Abakansky interconnected by narrow corridors of mountain ridges (Proplotinny, Belysky, and Buzunovsky).

Creation of water storage reservoirs involves technogenic interference of humans in nature, which entails environmental impact and promotes climate changes. Water temperature in a reservoir is an essential indicator of the state of the water ecosystem. In terms of thermal regime, water reservoirs resemble deep-water lakes, which is particularly obvious in the slow-flow zones of a reservoir where temperature stratification occurs [4].

Depending on the water masses movement and seasonal changes in downwelling solar radiation on the water surface, the thermal regime of the Krasnoyarsk Reservoir is divided into four periods: spring warming up, summer warming up, autumn cooling down, and winter cooling down. Herein we dwell on the spring and summer warming periods of the reservoir. The spring water warming and ice thinning period starts once daily air temperatures remain permanently above 0°C. This happens around the first decade in April in the central and southern parts of the reservoir.

3. Research methods and instruments

Ground-based observation instruments (gauging stations) are capable of acquiring data under almost any weather conditions, including fog and cloudiness; yet they can provide only limited information on the spatial and temporal distribution of water temperature. Data on the surface water temperature from the gauging stations located on the Krasnoyarsk Reservoir turn out to be incomplete and often not available for the time span under study. Therefore we have to resort to remote sensing methods to derive temperature data. The land surface temperature can be obtained from thermal spectral channels of the sensor, i.e. the channels that take images of the land surface in the Thermal Infrared Radiation band (10-15 µm). The so obtained data are then substituted into the Plank formula yielding the surface temperature [5]:

\[ T = \frac{T_B}{1 + \left(\frac{\lambda T_B}{c_2}\right) \ln(e)} \]  

where \( T_B \) is the radiation brightness temperature (K); \( \lambda \) is the wavelength, \( c_2 = 14388 \times 10^{-2} mK \); \( e \) is the emission coefficient. For water, the emission coefficient \( e \approx 0.98 \) [6].

Our thermal bar studies in the Krasnoyarsk Reservoir employed MODIS (Moderate Resolution Imaging Spectroradiometer) data acquired over the period from April to June in 2016-2019. The remote sensor aboard the Terra satellite has 36 spectral bands in the visible, near, middle, and thermal infrared ranges and a spatial resolution at nadir of 250 m for bands 1-2; 500 m for bands 3-7, and 1000 m for bands 8-36. MODIS takes images every 4 hours in a 12 bit/pixel dynamic range and over a 2330 km swath at nadir. Satellite remote sensing data are available in open access [7].

To tackle specific problems, there are available customized products (cloud, snow cover, ice cover, vegetation index temperature masks) that are essentially algorithms of data processing for specific bands. We applied the MOD11A2 product, being an 8-day average of the MOD11A1 product. The daily MOD11A1 LST product uses the results obtained in the MOD11_L2 products within a day and is a linear multiplication of all pixel temperatures. The product data are provided in a Hierarchal Data Format (HDF) and contain datasets on day- and night-time land surface temperatures, quality control assessments, observation times, clear-sky view and swath zenith angles. The only thing missing to be able to solve the problem is information on day-time land surface temperatures. These data are exported from a dataset as a 1-km grid. Data processing was performed in an open-source cross-platform geographic information system QGIS 2.10 [8]. The polygonal boundary layer of the Krasnoyarsk Reservoir was derived from an open-access dataset of the OpenStreetMap Project distributed under an ODbL license [9]. To map temperature distribution across the reservoir, we cut the edges of the obtained scenes at the reservoir layer and used the OpenStreetMap data as an underlayer.
4. Results
In the first decade of April the air temperature goes above 0°C, the ice on the reservoir starts melting and the period of spring warming of water sets in. Therefore, to study a possibility of tracking the thermal bar, we downloaded MOD11A2 scenes from the first decade of April through to mid-June 2016-2019. Thematic maps have been built of temperature distribution across the reservoir surface in order to visually assess variability of the day-time temperature over the period from April to June. Thematic maps illustrating the location of the assumed frontal interface are shown in figures 1-4.

Figure 1. Movement of the temperature front in April to June 2016.

Figure 2. Movement of the temperature front in April to June 2017.

Figure 3. Movement of the temperature front in April to June 2018.

Figure 4. Movement of the temperature front in April to June 2019.
Every year in early April, a frontal interface separating warm and cold water can be observed in the vicinity of the Ust-Abakansky reach. In 2016, this zone emerged by the 14th of April. The earliest warming of the reservoir (starting early in the first decade of April) in the review period occurred in 2017. In 2019, the frontal zone emerged in the second decade of April, which was later than in any other year under review. It is attributed to the fact that the air temperature in the Ust-Abakan area in 2019 was the lowest and in 2016 – the highest. Monthly average temperatures in April to June 2016-2019 for various areas, as per [11], are given in table 1.

**Table 1.** Monthly average air temperature.

| Year/month | April  | May  | June  |
|------------|--------|------|-------|
|            | Ust-Abakan | Krasnoyarsk | Ust-Abakan | Krasnoyarsk | Ust-Abakan | Krasnoyarsk |
| 2016       | 8.0    | 4.1  | 11.2  | 8.5  | 18.2 | 17.9 |
| 2017       | 6.9    | 5.2  | 9.7   | 11.0 | 18.0 | 19.3 |
| 2018       | 5.8    | 4.0  | 8.3   | 5.0  | 18.0 | 18.0 |
| 2019       | 5.0    | 2.2  | 10.9  | 8.4  | 17.9 | 17.1 |

In late April, warming of the Krasnoturansky reach is complete and the warm water starts moving through the narrow section of the reservoir forcing out cold water while the Shchetinkinsky reach of the reservoir is still covered in ice. By mid-May, warm water has advanced as far as Novoselovo settlement and the reservoir has become completely ice-free. Since late May, as the water temperature in the reservoir increases, movement of the thermal bar in the region of the Primorsky and Shchetinkinsky reaches follows the lake pattern: the warm near-shore water and the warm downstream flow displace the cold water towards the center of the Shchetinkinsky reach. The water temperature across the entire reservoir levels off by the 10th of June. Commencement of the water warming period depends on weather conditions, which is obvious from the temperature maps of early April 2016-2019; yet by the 10th of June water warming was complete in all the years under review.

The obtained images can be used to assess the rate of movement of warm waters. Along the narrow zone towards the center of the reservoir, the frontal interface advances an average of 161 km in 44 days. A rough estimate of the front speed along the reservoir, ignoring the wind velocity, would be 0.15 km/h.

A comparative analysis of the 2016-2019 data leads us to conclude that movement of warm water starts and the water reaches the highest density temperature approximately within one and the same time interval.

### 5. Conclusion

The aim of this paper is to study a possibility of identifying a thermal bar in the Krasnoyarsk Reservoir based on land thermal remote sensing data. Out of the archive data on weather in the region of the Reservoir we selected the dates of the assumed emergence of the thermal barrier and acquired MODIS-based products for those dates. These datasets were used to build thematic maps of the thermal bar movement in the years 2016-2019. The results obtained prove that the frontal interface can be readily identified using remote sensing datasets. It is shown that movement of warm water differs in various parts of the reservoir. Water warming starts from the Abakansky reach in the first or second decade of April, depending on the weather conditions. Through the narrow section of the reservoir, the warm waters force out cold water as far as Novoselovo settlement. By late May, the reservoir is completely free of ice and waters at the shoreline start getting warmer. Once the warm water has advanced as far as the large lake-like reaches, the cold water is displaced towards the center due to the warm shoreline waters. By the end of the first decade in June, the surface water temperature of the reservoir levels off. The 2016-2019 data suggest that the temperature interface period starts and ends up within approximately one and the same time interval. The results obtained have proved the remote sensing methods to be suitable for identifying a thermal bar and monitoring its movement across the Krasnoyarsk Reservoir.
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