# Surface Temperature Dynamics of Lake Baikal Observed from AVHRR Images

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## Abstract

*Satellite data are important in understanding the relationship between hydrodynamics and biological productivity in a large lake ecosystem. This was demonstrated using* NOAA AVHRR, *and* in situ *temperature and chlorophyll fluorescence data to describe the seasonal temperature cycle and distribution of algal biomass in Lake Baikal (Russia). Features such as ice cover, thermal fronts, and the dispersion of river water were described in a series of images from 1990 and 1991. The northern basin retained ice cover until the end of May. In June, thermal fronts extending <10 km from shore were observed to be associated with shallows, bays, and rivers. Offshore surface temperatures in the northern basin did not exceed 4°C until late June-early July. The southern and middle basins warmed more quickly than the northern basin. In* situ *data showed phytoplankton concentrations to be low offshore and high near thermal fronts. The Selenga River, the largest tributary of Lake Baikal, supplied warm water and nutrients which contributed to localized increases in chlorophyll fluorescence.*

## Introduction

Satellite data, in conjunction with field data, can be used to describe the seasonal temperature cycle, thermal fronts, upwelling, and the dispersion of river water in large lakes (Mortimer, 1988; Lathrop *et al.*, 1990; Bolgrien and Brooks, 1992). These features are important because they represent mechanisms by which heat, nutrients, and pollutants are distributed. The horizontal and vertical distributions of plankton are also highly dependent on thermal features. Because it is not feasible to synoptically sample large lakes using ships, data collected by satellites can be used to enhance our understanding of large lake ecosystems. The objective of this paper is to use satellite-derived surface temperatures to describe the hydrodynamics of Lake Baikal and to relate these properties to patterns of biological activity in the lake.

Lake Baikal, located in southeastern Siberian Russia, is the deepest and most voluminous lake on Earth (Figure 1; Table 1). Morphometric characteristics of Lake Superior and Lake Michigan are listed on Table 1 for comparison. Lake Baikal is oligotrophic. Offshore chlorophyll *a* concentrations in summer are typically <1.0 mg·m$^{-3}$. In shallow bays, near river mouths, and during under-ice algal blooms, however, chlorophyll *a* concentrations can exceed 10 mg·m$^{-3}$ (Kozhova *et al.*, 1985). The extraordinary bathymetry of Lake Baikal is an important factor influencing the seasonal temperature dynamics. The lake is divided into three basins with maximum depths of 1416 m, 1638 m, and 890 m (southern, middle, and northern, respectively). The southern and middle basins are separated by the Selenga River delta. The middle and northern basins are separated by the Academician Mountain

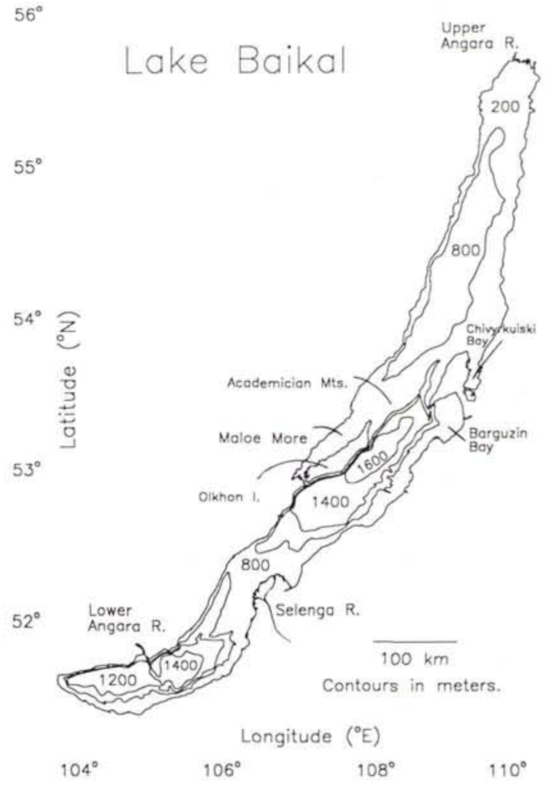

Figure 1. Bathymetry map of Lake Baikal. Contours are in metres.

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TABLE 1. MORPHOMETRIC CHARACTERISTICS OF SELECTED LARGE LAKES (FROM HUTCHINSON, 1957).

| Lake | Baikal | Michigan | Superior |
|---|---|---|---|
| Location | 53°N 108°E | 44°N 87°W | 47°N 89°W |
| Origin | Tectonic graben | Glacial corrasion | Glacial corrasion |
| Volume (km$^3$) | 23,000* | 5,760 | 12,221 |
| Max Depth (m) | 1,638 | 265 | 307 |
| Mean Depth (m) | 730 | 99 | 145 |
| Area (km$^2$) | 31,500 | 57,850 | 82,367 |
| Shoreline (km) | 2,200 | 2,210 | 3,000 |
| Max length (km) | 674 | 494 | 563 |
| Max width (km) | 74 | 190 | 257 |
| Catchment (km$^2$) | 540,000 | 118,000 | 124,800 |

*Total volume of Laurentian Great Lakes = 24,600 km$^3$

range (Figure 1). The basins are steep-sided, especially along the western shore. Lake Baikal has three large bays (Barguzin Bay, Chivyrkuiski Bay, and Maloe More) and three main tributaries (Selenga River, Barguzin River, and the Upper Angara). Littoral zones are restricted to river deltas, shallow bays, and "sores," i.e., isolated coastal wetlands. The northward-flowing Lower Angara River is the sole outlet (Figure 1).

The seasonal temperature cycle of Lake Baikal was described using satellite data from the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. To our knowledge, AVHRR data have not been previously used to describe this lake. Lake Baikal is a rift lake located between 51° and 56° N latitude and is surrounded by high mountains. This combination permits an ice cover of up to one m thick to form over the entire lake (Kozhov, 1963). Complete ice cover is atypical of large deep lakes because long fetches usually result in continuous wind mixing. Sitnikova *et al.* (1984) used both aircraft and satellite imagery to detail ice break-up in 1981. They found that the majority of the lake was ice covered in early April. Shore-bound ice in the southern and middle basins, and broken pack-ice in the northern basin, remained through the middle of May. Ice accumulated along the eastern shore because of the prevailing westerly winds. The entire lake was ice-free at the end of May. Although shore-based ice observations have been made for most of this century, Sitnikova *et al.* (1984) appear to be the only reported use of remote sensing techniques on the lake.

Vernal thermal fronts are common features in large north-temperate lakes. Fronts form in coastal regions through a combination of solar warming and spring runoff. They separate the thermally stratified inshore region where surface temperatures are >4°C from the isothermal or inversely stratified offshore region where surface temperature are <4°C. Fronts move offshore until the 4°C isotherm disappears across the lake (Mortimer, 1971; Bolgrien and Brooks, 1992). Convection currents and wind-mixing are the primary mechanisms responsible for deep-water mixing (Granin *et al.*, 1991; Shimaraev *et al.*, 1993; Weise *et al.*, 1992). Surface temperature is a good method of delineating the temporal and spatial dynamics of thermal fronts (Bolgrien and Brooks, 1992).

## Methods

Surface temperature and fluorescence data have been collected from Lake Baikal for more than 10 years by joint expeditions of the Limnological Institute (Irkutsk) and the Institute of Biophysics (Krasnoyarsk). Since 1988, foreign investigators have participated in expeditions under the auspices of the Baikal International Center for Ecological Research (Maddox, 1989). Transect data were collected using a flow-through thermistor and fluorometer interfaced to a microcomputer. Chlorophyll fluorescence, calibrated with extracted chlorophyll *a* samples, provided an estimate of phytoplankton concentration. The position and depth (2.5 m) of the intake pipe, flow rate, instrument response time, and ship speed defined a minimum detectable "patch" size of 200 m (Granin *et al.*, 1988). The temperature recorded by the ship was considered to be a "bulk" surface temperature as opposed to the "skin" surface temperature measured by the AVHRR. The location of transect points were estimated by dead-reckoning from navigational fixes.

Local Area Coverage (LAC) AVHRR images from the NOAA National Environmental Satellite Data Center were selected based on available *in situ* data, characterization of specific thermal features, and minimal cloudiness. Mountainous terrain surrounding the lake exacerbated the problem of cloud contamination of satellite images. Sitnikova *et al.* (1984) found surface evaporation and fog in fall and winter to obscure aerial observations more than in the spring and summer.

Sea surface temperatures (SST) were derived from AVHRR band 4 (1030 to 1130 nm) brightness temperatures (Kidwell, 1991). Ice cover was identified from AVHRR band 2 (720 to 1100 nm). Data were not corrected for atmospheric effects or sun angle differences, nor were the images geo-rectified. The spatial resolution of the AVHRR at nadir is approximately 1.1 km. AVHRR data (band 2 for Figure 3, and band 4 for Figures 3 to 6 and 8 to 10) were classified using a sequential clustering technique to create a "landmask," and enhance particular features in each scene.

## Results and Discussion

Satellite remote sensing research depends on the availability of data at spatial and temporal scales relevant to the feature investigated. Further, the feature of interest must be spectrally evident in the image. For large lakes, the AVHRR generally satisfies these criteria. The visible bands are useful for detecting ice cover on lakes (Harrison and Lucas, 1989). The approximate 1.1-km resolution of the thermal bands of the AVHRR has proven sufficient to describe salient physical features of the Laurentian Great Lakes (Bolgrien and Brooks, 1992). The availability of U.S. satellite imagery for the Lake Baikal region is summarized in Table 2. Review of image quality, including cloud cover, revealed that <50 percent of the images listed would be useful for limnological research. The increased availability of AVHRR images for Lake Baikal in recent years makes this sensor a very useful tool for the systematic monitoring of thermal features of this remote lake.

TABLE 2. NUMBER OF IMAGES AVAILABLE FROM U.S. SATELLITES FOR THE LAKE BAIKAL REGION (51°-56°N × 103°-110°E. DATA ARE FROM THE USGS GLOBAL LAND INFORMATION SYSTEM (GLIS), NOAA NESDIS, AND EOSAT (AS OF 15 SEPTEMBER 1993)

| Year | <1988 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 |
|---|---|---|---|---|---|---|---|
| AVHRR | ? | 0 | 3 | 32 | 22 | 129 | 51 |
| Landsat TM | 0 | 20 | 170 | 51 | 14 | 1 | 1 |
| Landsat MSS | 125 | 0 | 31 | 11 | 12 | 0 | 0 |
| CZCS | 40 | (no further data collected) | | | | | |

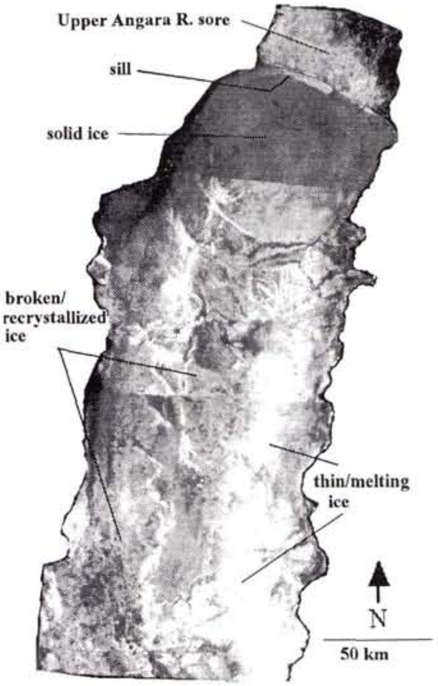

Figure 2. Photograph taken from the Space Shuttle of the northern end of Lake Baikal in late April, 1991 (photographs STS039-73-88, -89, -90). Ice conditions interpreted by Evans *et al.* (1992).

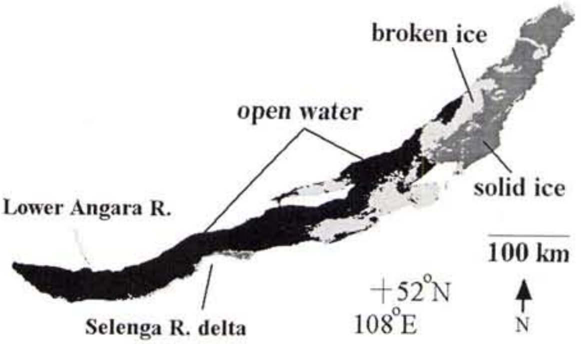

Figure 3. Distribution of ice on northern Lake Baikal derived from AVHRR band 2 from 15 May 1991.

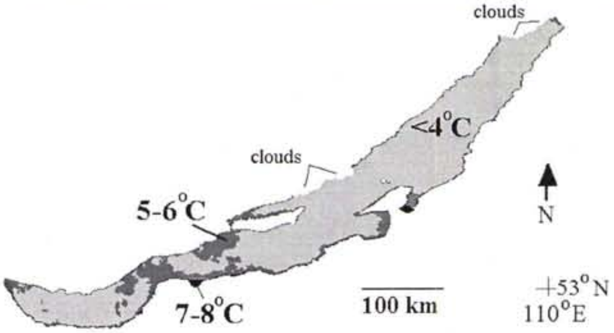

Figure 4. SST (°C) map of Lake Baikal derived from AVHRR band 4 from 09 June 1990.

The availability of Russian satellite data for the Lake Baikal region is not known.

A scheme of the seasonal temperature cycle of Lake Baikal was created using images from 1990 and 1991. Figure 2 is a photographic mosaic taken from the U.S. Space Shuttle (STS-39) in late April 1991 (photographs STS039-73-88, -89, -90). The northern end of Lake Baikal was covered by a mixture of ice types (Evans *et al.*, 1992). The sill isolating the Upper Angara sore from the main lake basin is noted. An AVHRR image (band 2) acquired on 15 May 1991 showed a similar situation for the entire lake (Figure 3). Broken ice filled Barguzin Bay and Maloe More and some shore-ice remained near the Selenga River delta. The majority of the southern and middle basins were completely free of ice. The northern basin was still ice covered although the ice appeared thicker along the eastern shore. Surface water temperatures were <4° (band 4 data not shown). The distribution of ice shown in Figures 2 and 3 was consistent with the description of Sitnikova *et al.* (1984). Variations in the timing of ice-out in different parts of Lake Baikal drive large-scale patterns of thermal stratification and, therefore, the patterns of biological productivity (Goldman *et al.*, 1993).

Ice was absent on 9 June 1990 (Figure 4) and thermal fronts were observed as <10-km wide bands of 5 to 6°C water bordering much of the southern and middle basins. Both *in situ* and AVHRR data showed offshore temperatures were <4°C. Temperatures >6°C indicated the onset of stratification in Chivyrkuiski Bay and near the Selenga River. Water 5 to 6°C between the Olkhon Island and the Selenga River delta may have originated on the shallow delta and/or been "leaked" from Maloe More through the straits south of Olkhon Island.

By 29 June 1990, the offshore SST was approximately 4°C and the thermal front had progressed 10 to 30 km offshore in the middle basin (Figure 5). Clouds obscured both ends of the lake on this date. The observed SST was consistent with transect data collected on 3-5 July 1990 (Granin *et al.*, 1991). The offshore surface temperatures in the middle basin were approximately 4°C. The warm water inputs (13°C) of the Selenga River, seen also in Figure 4, contributed to the warming in the middle basin.

The AVHRR scene from 8 July 1990 (Figure 6) coincided with a field expedition to measure thermal stratification, nutrient utilization, and phytoplankton productivity throughout the lake (Granin *et al.*, 1991; Goldman *et al.*, 1993). These studies found surface nutrient depletion and phytoplankton productivity were directly related to the degree of thermal stratification. Warm surface temperatures indicative of stratification were most pronounced in the southern and middle basins (Figure 6). Data collected along a transect running normal to shore in the northern basin showed a thermal front was located about 8 km from shore where surface temperature rapidly increased from approximately 4°C to >8°C (transect **a - a'** in Figure 6; Figure 7a). This front was also apparent in the AVHRR SST data. Chlorophyll fluorescence

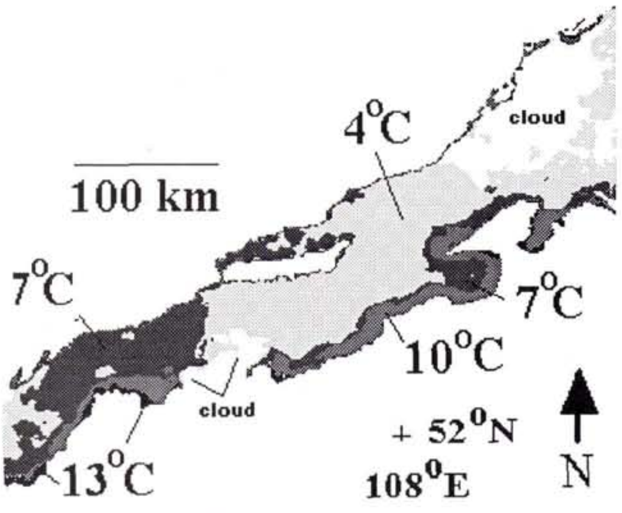

Figure 5. SST (°C) map of central Lake Baikal derived from AVHRR band 4 from 29 June 1990.

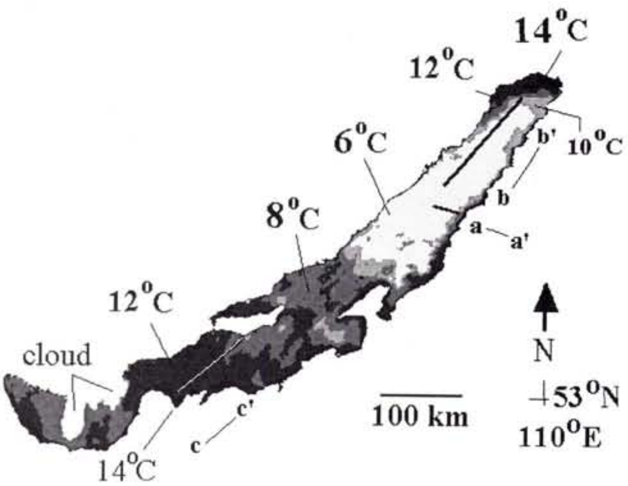

Figure 6. SST (°C) map of Lake Baikal derived from AVHRR band 4 from 08 July 1990. Transect lines for Figure 7 are labeled by lines running parallel on shore.

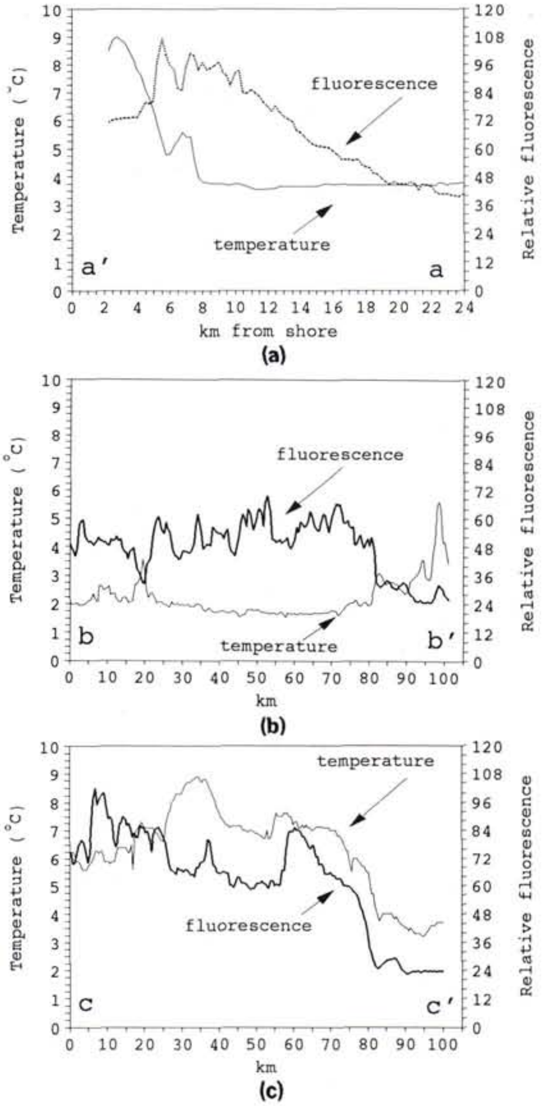

Figure 7. (a) Surface temperature and chlorophyll fluorescence data collected along transect line **a** in Figure 6. Chlorophyll fluorescence values are in relative units. Data are from Granin *et al.* (1991). (b) as in Figure 7a except data were collected along transect line **b** in Figure 6. (c) as in Figure 7a except data were collected along transect line **c** in Figure 6.

gradually increased from offshore to nearshore. Because phytoplankton growth in unstratified waters is constrained by light, resulting from deep vertical mixing, rather than external nutrient supply (Goldman *et al.*, 1993), this increase in chlorophyll fluorescence may reflect decreasing mixing depth along the transect.

A transect toward the north end of the lake (transect **b** - **b**' in Figure 6) showed several temperature and chlorophyll fluorescence fronts (Figure 7b). There was a significant decrease in fluorescence as temperatures increased from 2 to 4°C at the north end of the transect. While the AVHRR SST data show similar temperature patterns, there is a 2 to 4°C overestimation of bulk temperature by SST. This may indicate daytime heating of the surface skin during an extended calm and sunny period. The warm water near the north end of the lake, especially near the Upper Angara sore, resulted from the input of warm river waters and limited circulation in this relatively shallow region.

A transect from the Selenga River delta to Olkhon Island (transect **c** - **c**' in Figure 6; Figure 7c) showed higher temperatures and chlorophyll fluorescence in the middle basin as compared to the northern basin. High phytoplankton concentrations likely reflected the high nutrient supply of the Selenga River. There was a 25-km wide region near Olkhon Island where *in situ* temperatures decreased to about 4°C and fluorescence decreased by >50 percent. This cold-water re-

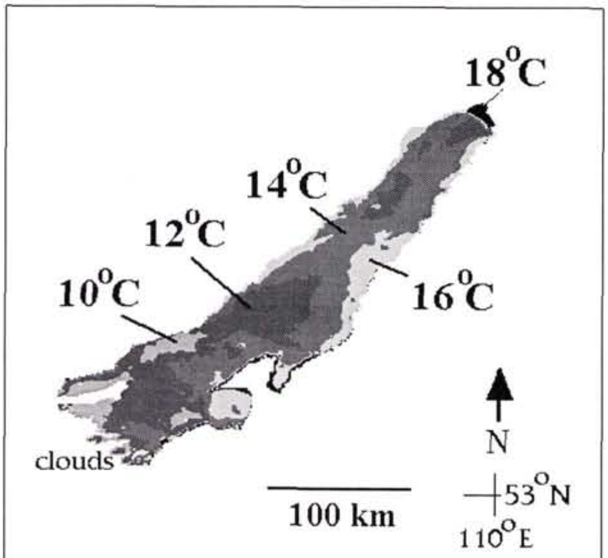

Figure 8. SST (°C) map of northern Lake Baikal derived from AVHRR band 4 from 25 July 1990.

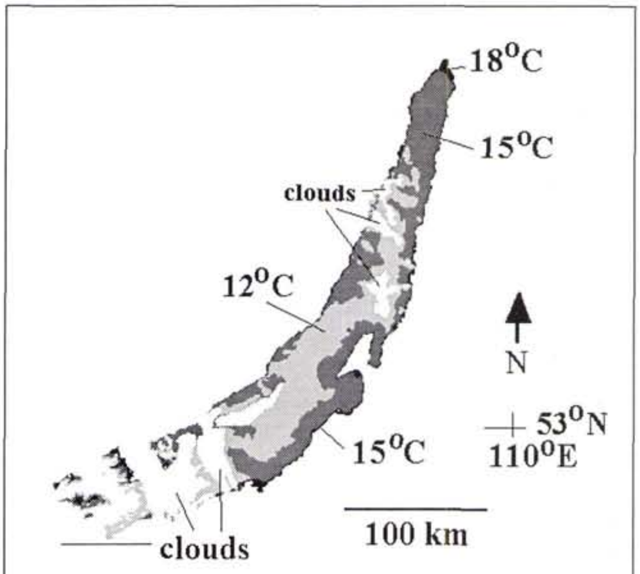

Figure 9. SST (°C) map of northern Lake Baikal derived from AVHRR band 4 from 07 August 1991.

gion was not observed in the AVHRR image (Figure 6). This difference may be explained by the surface heating phenomena or by the five days between *in situ* measurements and the AVHRR image acquisition. The temperature difference between these dates may represent an ephemeral upwelling event along the south shore of the island. Upwelling results from the upward displacement of the thermocline by internal waves or the horizontal displacement of the epilimnion by wind. Both situations result in the transient lowering of nearshore surface temperatures. Upwelling is common in Lake Baikal (Granin *et al.*, 1988) but was not well illustrated in the available AVHRR imagery.

Thermal features seen on 25 July 1990 and 7 August 1991 were consistent with the scheme constructed from the earlier AVHRR scenes (Figures 8 and 9). The southern basin was obscured by clouds in both scenes. Typical vertical temperature profiles in late July and August showed thermocline depths ranged from <1 to 15 m. A chlorophyll fluorescence maximum was often located at or slightly above the thermocline (summer vertical profile data not shown). Surface temperature heterogeneities ("patches") observed in Lake Baikal by Gitel'zon *et al.* (1991) may be discernible using the AVHRR. Typical patches in the relatively productive southern and middle basins of Lake Baikal are 0.7 to 1.5 km in size, while they are 3 to 7 km in the less productive northern basin. The lifetime of a typical patch is 2 to 16 days. Significantly, Gitel'zon *et al.* (1991) found no systematic relationship between surface temperature and chlorophyll fluorescence when measured simultaneously. There is a several day lag between a cold water (hence increased nutrient concentration) intrusion and the chlorophyll fluorescence increase resulting from phytoplankton growth. Factors such as adaptation by phytoplankton to low light may also be important. Because the heterogeneous distributions of energy and material are important to the functioning of the entire ecosystem, the capacity to monitor these processes utilizing satellite sensors is advantageous.

The short Siberian summer was evident in the decrease of surface temperature from August to September (Figures 9 and 10). Thermal stratification typically lasts from early July until early November (Shimaraev, 1977). In a fashion analogous to vernal warming, autumnal cooling appeared to commence nearshore and progress offshore (Figure 10). Surface waters cool until thermal stratification breaks down and deep vertical mixing occurs. The upper layer of the lake typically becomes isothermal in November and begins to freeze in January (Kozhov, 1963; Shimaraev, 1977).

## Conclusions

The seasonal thermal cycle of Lake Baikal was constructed using NOAA AVHRR images. Satellite-derived surface temperatures clearly depicted important thermal features such as ice break-up, thermal fronts, and autumnal cooling. Ship transect data described surface thermal features similar to those described by satellite data but at a much finer spatial scale. Surface chlorophyll fluorescence was found to be higher nearshore, presumably because of nutrients supplied by river runoff and restricted vertical mixing.

Hydrodynamic conditions (light availability, mixing, temperature) of large lakes, such as Lake Baikal, dominate biological productivity, especially during the spring. These conditions can be deduced through the systematic analysis of satellite SST data. Satellite remote sensing, therefore, plays an important role in the study of these expansive and remote ecosystems.

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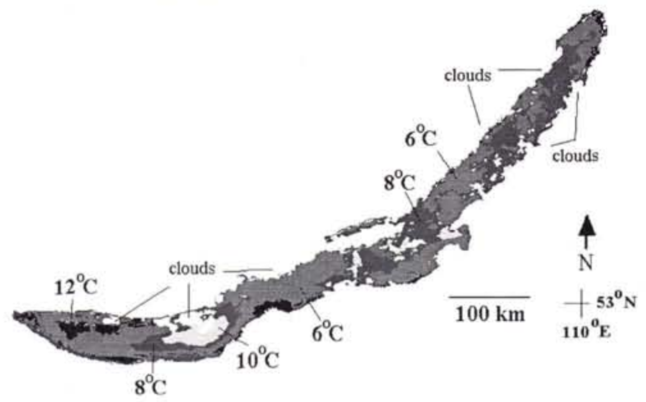

Figure 10. SST (°C) map of Lake Baikal derived from AVHRR band 4 from 04 September 1991.

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