Monitoring the Surface Temperature of Lake Victoria Using Modis Imagery

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Abstract:
The temperature cycle of Lake Victoria is not well documented as only a limited number of in-situ measurements are available. Hence they cannot account for the spatial distribution of the temperature pattern within a lake and more importantly they are not monitored regularly because of the high costs involved. Satellite technology has improved the ability to measure Lake Surface Temperature (LST) by enabling frequent coverage. The satellite-measured LST provides both the synoptic view of the lake and a high frequency of repeated views allowing the examination of basin-wide upper lake dynamics that is not possible with conventional methods. This paper demonstrates the use of MODIS Level 2 imagery of Lake Victoria to monitor LST. The MODIS data available was for the year 2009. LST was extracted from the MODIS imagery using the Long Wave algorithm developed by the National Aeronautics and Space Administration (NASA). From the results, it is evident that there was irregular variation of LST over Lake Victoria. It was characterized by high LSTs from April to May and October to November and low LST values in June to September. It was observed that these high LST coincided with the rainy season, high Inter Tropical Convergence Zone (ITCZ) and low wind speeds. Conversely, low LST coincided with the dry seasons, low ITCZ and high wind speeds. The algorithms implemented in this study are generic and ocean water based, therefore unique and site specific bio-optical algorithms or models need to be developed specifically for monitoring LST on Lake Victoria. This paper furthermore recommends the exploration of a bigger dataset to improve the understanding long term LST variations.

Keywords: MODIS, Remote Sensing, Lake Surface Temperature, Bio-Optical Algorithms**.**

1. Introduction

The ability to determine the spatial and temporal distribution of surface temperature over Lake Victoria offers an opportunity to obtain vital information about the nature and extent of the existing thermal structure, and also aids in locating upwelling areas in the lake where primary productivity might be taking place. Such areas are considered ideal for the development of the fisheries industry. In a country like Uganda where 70% of the animal protein uptake by its people is derived from fish, such information is crucial (Ochumba, 1987). On the operational side, the study of temperature and evaporation from saline solutions is important for designing, constructing and operating saline and hyper saline shallow lakes for mineral extraction and energy production (Oroud, 1994). In the past, Lake Surface Temperature (LST) could only be measured by ships and buoys, whose ranges were, limited (Wick *et al*, 1992). In Uganda, in-situ measurements of temperature are taken by organisations such as the National Water and Sewerage Corporation. This involves sending boats monthly to the lake to collect water quality parameters. Unfortunately this is a tedious and expensive venture, and does not give a synoptic perspective of the basin wide temperature variation. This has led to the interest in exploring the use of Satellite imagery in monitoring LST on Lake Victoria. Satellite imagery brings with it the advantage of regular synoptic views of the lake allowing the examination of basin-wide upper lake dynamics not possible with conventional methods (Corlett *et al.*, 2006). This paper explores the use of MODIS satellite imagery to monitor LST on Lake Victoria for the year 2009. This paper gives an overview of monitoring Lake Surface Temperature, the methodology developed results, discussion and conclusions.

2. Monitoring Lake Surface Temperature

The first attempts at monitoring Sea and Lake surface temperature date back to the 1960's. Initially LST was determined using sailing vessels and ships (Emery *et al.*, 2000), and later on using drifting or moored buoys (Wick *et al*, 1992). Based on these LST measurements, the standard dataset used to calculate the algorithm coefficients in today's calculation of LST from satellite infrared radiances was determined (Emery et al., 2001). The traditional measurement of LST is based on in situ sampling, which is a costly and time-consuming effort. Because of these limitations, it is impractical to cover the whole water body or obtain frequent repeat sampling at a site. This difficulty in achieving successive LST sampling becomes a barrier to water quality monitoring and forecasting (Senay *et al.,* 2001). Remote sensing techniques have the potential to overcome these limitations by providing an alternative means of studying and monitoring water quality over a wide range of both temporal and spatial scales.

2.1 Historical Perspective of Ocean Color Sensors

The first sensor to be used in the monitoring of ocean geophysical parameters was the Coastal Zone Colour Scanner (CZCS) that had six spectral bands, four of which were used primarily for ocean colour. These had a 20 μm bandwidth centred at 443, 520, 550 and 670 μm. This was followed by the Ocean Colour and Temperature Scanner (OCTS) which had an optical radiometer with 12 bands covering the visible, near infrared and thermal infrared regions. Eight of these bands were located in the Visible/Near Infrared portion of the electromagnetic spectrum and they were the only bands calibrated and processed by the Ocean Biology Processing Group (OBPG) of the National Aeronautic Space Administration (NASA). OCTS had a swath width of approximately 1400 km, and a nominal nadir resolution of 700 m. The instrument operated at three tilt states (20 degrees aft, nadir and 20 degrees fore) (IOCCG, 1998).

The success of these early sensors led to the development of more sophisticated sensors like Medium Resolution Imaging Spectrometer (MERIS). MERIS is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range. Fifteen spectral bands can be selected by ground command. The instrument scans the Earth's surface by "push-broom" method. Linear Charge-Coupled Device (CCD) arrays provide spatial sampling in the across-track direction, while the satellite's motion provides scanning in the along-track direction. The instrument's 68.5° field of view around nadir covers a swath width of 1150 km (European Space Agency, 2000 – 2011) ((IOCCG,1998).

Another of the newer generation ocean color sensors was the Sea-viewing Wide Field-of-viewSensor (SeaWiFS) which began scientific operations on 18 September 1997 and stopped collecting data on 11 December 2010·The sensor resolution had 1.1 km Local Area Coverage (LAC), 4.5 km Global Area Coverage (GAC). The sensor recorded information in 8 bands: 1(402-422nm), 2 (433-453nm) , 3(480-500nm), 4(500-520nm), 5(545-565nm), 6(660-680nm), 7(745-885nm), 8(845-885nm). The instrument was specifically designed to monitor ocean characteristics such as chlorophyll-a concentration and water clarity.

One of the longest serving sensors dedicated to monitoring ocean colour (as well as land based variables) is MODIS (Moderate Resolution Imaging Spectroradiometer). It is a key instrument aboard the Terraand Aqua satellites. Terra's orbit around the Earth is timed so that it passes from north to south and crosses the equator in the morning, while Aqua orbits south to north over the equator in the afternoon. It has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands and it acquires data at three spatial resolutions: 250-m, 500-m, and 1,000-m of land and ocean surface temperature, primary productivity, land surface cover, clouds, aerosols, water vapour, temperature profiles, and fires.

2.2 Related studies on monitoring LST

Several studies have confirmed that remote sensing can meet the demand for the large sample sizes required for water quality studies conducted on the watershed scale (Senay *et al*, 2001). Hence, it is not surprising that a significant amount of research has been conducted to develop remote sensing methods and indices that can aid in obtaining reliable estimates of these important hydrological variables. These methods range from semi-empirical techniques to analytical methods for estimating and producing quantitative LST maps. Satellite imagery has been used to understand spatial and temporal variation of LST of lakes like the Great Lakes (Plattner *et al.*, 2006), Great Slave and Great Bear Lakes (Bussieres and Schertzer, 2003), Lake Tahoe (Hook *et al.*, 2003), Lake Baikal (Mogilev and Gnatovsky, 2003), Wisconsin lakes (Becker and Daw, 2005), Salton Sea (Marti-Cardona *et al.*, 2008), and the hypersaline Lake Eyre in Australia (Barton and Takashima, 1986) and the Swedish lakes (Reinart and Reinhold, 2008). In these studies, different geophysical parameters have been the subject of interest e.g. Chlorophll-a, Secchi depth, Lake Surface Temperature, salinity etc.

3. Methodology

MODIS level 2 data was used to monitor LST on Lake Victoria for the year 2009. SeaDAS version 6.1software was used to visualise, process and analyse MODIS Level-2 (L2) data. The MODIS L2 images are corrected for both geometric and atmospheric errors during the image pre-processing stage. The long-wave SST algorithm makes use of MODIS bands 31 and 32 at 11 and 12 µm.The algorithm for computing long-wave LST from observed brightness temperatures is shown below (Franz, 2006):

For dBT <= 0.5

$$LST = a_{00} + a_{01}*BT11 + a_{02}*dBT*bLST + a_{03}*dBT*\left(\frac{1}{Cos(\o)-1}\right) \quad (1)$$

For dBT >= 0.9

$$LST = a_{10} + a_{11}*BT11 + a_{12}*dBT*bLST + a_{13}*dBT*\left(\frac{1}{Cos(\o)-1}\right) \quad (2)$$

For 0.5 < dBt < 0.9

$$LST(lo) = a_{00} + a_{01}*BT11 + a_{02}*dBT*bLST+ a_{03}*dBT*\left(\frac{1}{Cos(\o)-1}\right) \quad (3)$$

$$LST(hi) = a_{10} + a_{11}*BT11 + a_{12}*dBT*bLST + a_{13}*dBT*\left(\frac{1}{Cos(\o)-1}\right) \quad (4)$$

$$LST = LST(lo) + \frac{dBT-0.5}{(0.9-0.5)*(LST(hi)- LST(lo))} \quad (5)$$

Where:

BT11 = Brightness temperature at 11 µm, in deg-C (i.e. band 31)
BT12 = Brightness temperature at 12 µm, in deg-C (i.e. band 32)
dBT = BT11 - BT12
LST (lo)= Lake Surface Temperature when dBT >= 0.5
LST (hi) = High Lake Surface Temperature when dBT >= 0.9
bLST = Baseline Lake Surface Temperature
Cos(ø) = Cosine of sensor zenith angle

The coefficients a_{00}, a_{01}, a_{02}, and a_{03} and a_{10}, a_{11}, a_{12}, and $a_{13}$are based on match-ups between the satellite retrievals of brightness temperature and field measurements of sea surface temperature.

This algorithm was applied to the 365 images of the year 2009. Given the vastness of this dataset, temporal sampling was employed to evaluate the annual LST variation. Following this, only representative weekly images were used to portray LST variation. For purposes of illustration, this paper only shows sampled monthly images of the study area. Given that MODIS is an optical sensor its efficiency is compromised by cloud cover. Hence, all images plagued by cloud cover of over 50% were excluded from the analysis. Figure 1 shows an example of an image compromised by cloud cover.

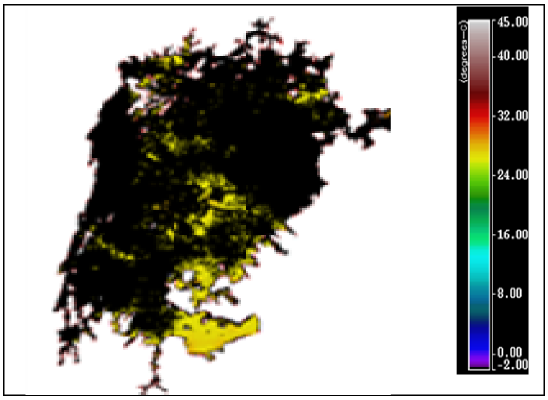

Figure 1: Cloud masked image

Further analysis was carried out by identifying two sampling points and observing the LST at the sampled points. These points were selected and are annotated as Stations 1 and 2 as shown in Figure 2. For each point, the annual LST was extracted and a time series curve derived.

Figure 2: Sampled Points. (Source; Google Earth)

4. Results and Discussion

Figure 3 presents the synoptic distribution of LST on Lake Victoria for the year 2009. Each image is a monthly extract for the month. Figures 4 and 5 depict the time series variation at the two sampled points for the year 2009. As can be observed the variation in LST implied that the surface of the lake can cool down or warm up as a whole at any time during the year, in an irregular pattern, without a uniform minimum temperature as shown. This could be explained by Lake Victoria being an eco-region with equatorial climate. In the North there are two rainy seasons; one during April/May (high LST), and the other during October/November (high LST), whereas the South experiences one long rainy season from December to March (Burgis and Symoens, 1987). LST is high in the rainy seasons and low in a dry season between June and September. During rainy seasons, lake surface temperatures are high because there is little evaporation from the water surface and little heat loss through radiation and consequently high temperatures and the reverse is true.

In general the results show that regions with largest response to LST anomalies during the short rains are correlated with the Inter-Tropical Convergence Zone (ITCZ). In October when the ITCZ is directly located over the lake, the largest response (maximum rainfall) is also located over the same region. As the season progresses and the ITCZ shifts out of the lake into northern Tanzania, the regions of rainfall maxima also shift with it. This explains an increase in LST in December in Northern Tanzania and also this could be a consequence of the enhanced convection to the south of the lake (over ITCZ) and the tendency of the system to conserve local moisture budget over the lake.

Wind speed is generally low during the wet season, due to the protection of the Ruwenzori Mountain in the north and the Rift escarpment to the east and south. Wind speeds increase during the dry season, between May and June (Spigel and Coulter, 1996). These strong southerly winds cause high evaporation rates, water mixing and a decrease of surface temperatures

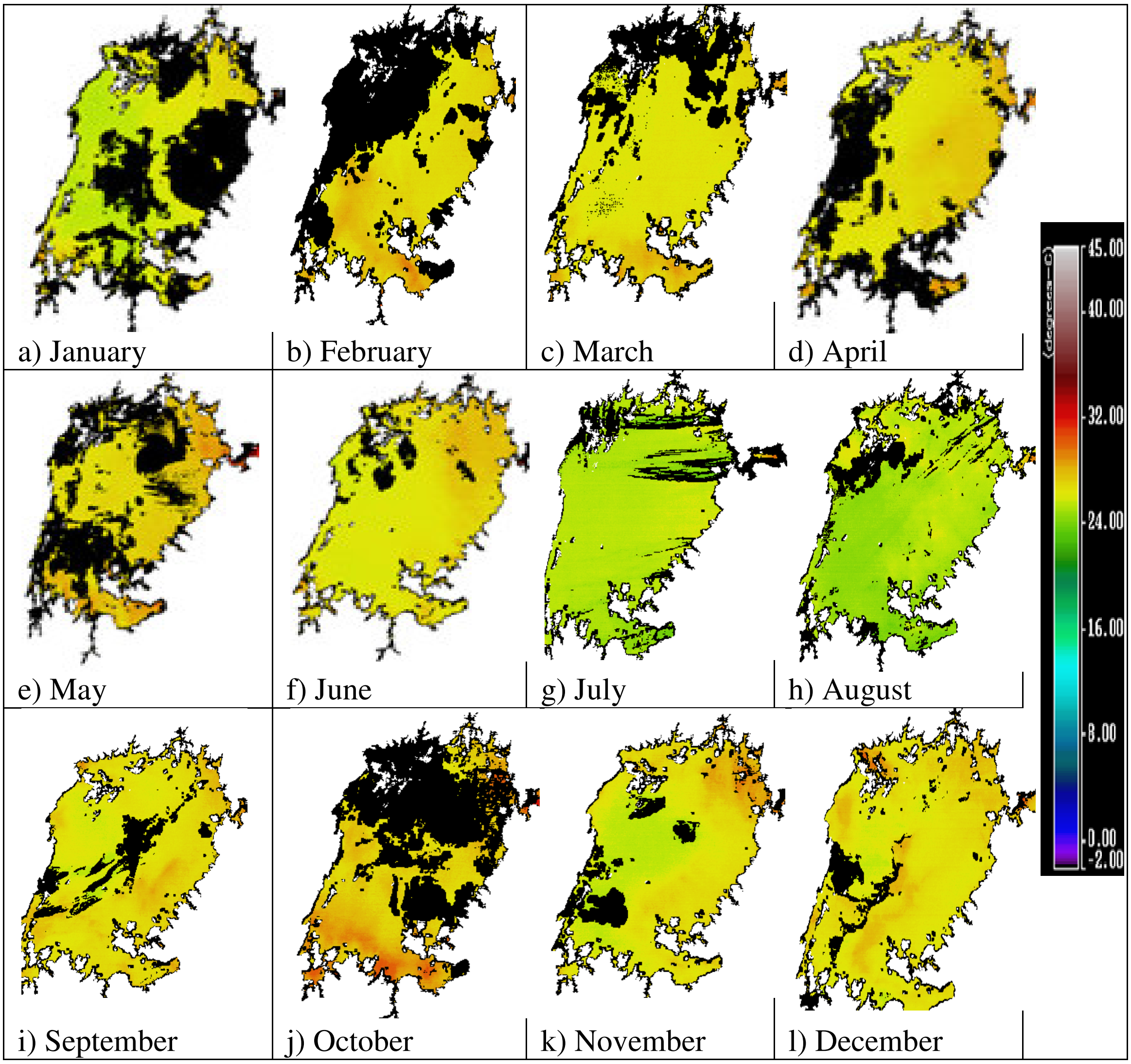

Figure 3: Monthly Mapped LST

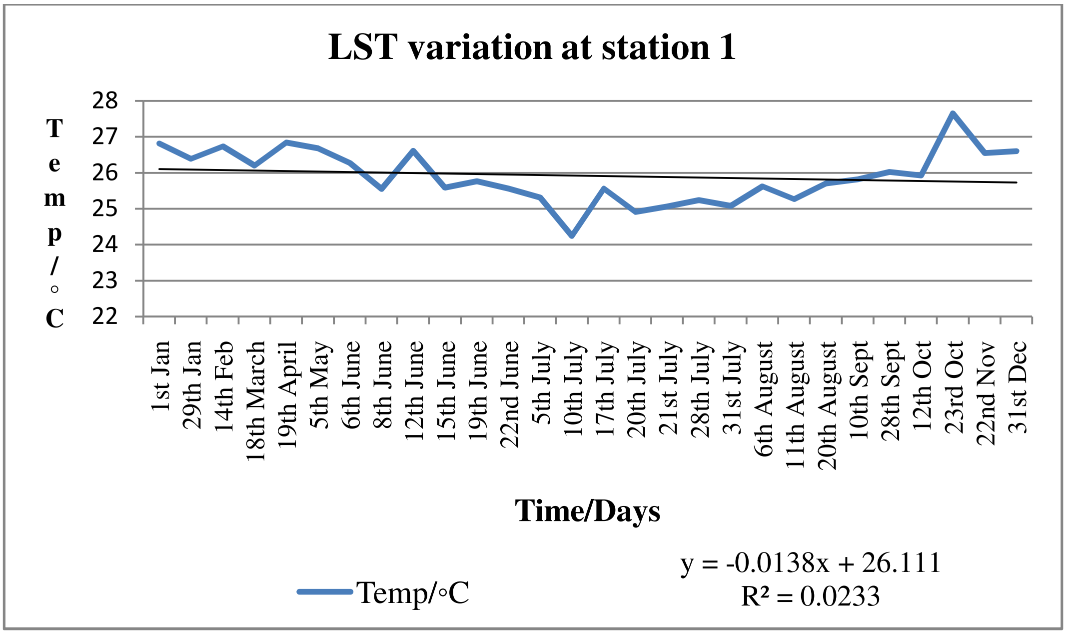

Figure 4: LST variation at station 1

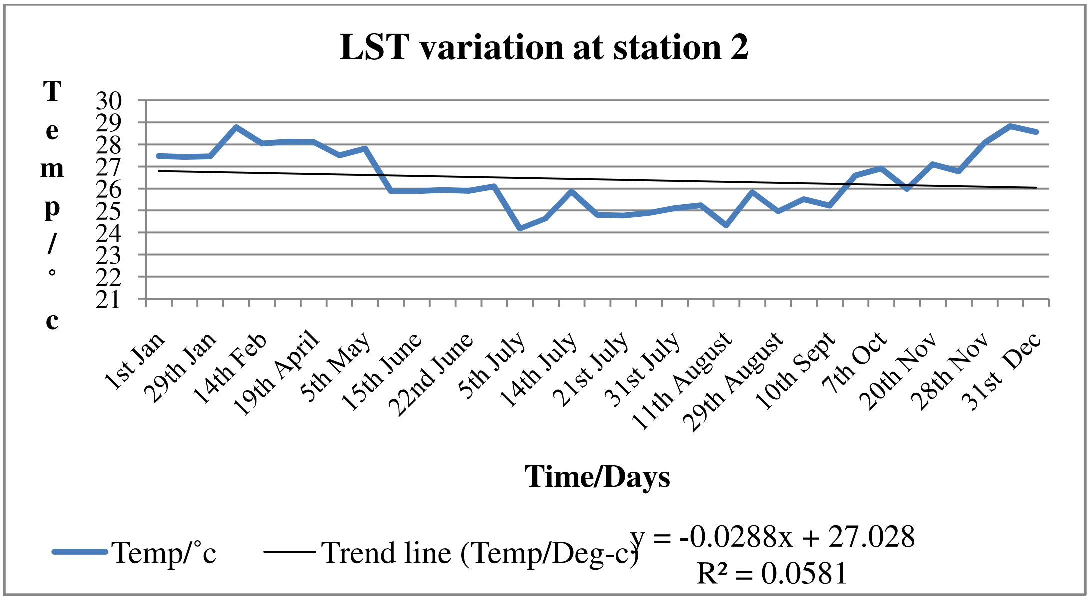

Figure 5: LST variation at station 2

5. Summary and Conclusions

LST is a determining factor in closed lakes especially inland and shallow lakes, as it controls many phenomena like evaporation, water quality and biological process. In large lakes, knowing the spatial pattern of the temperature as well as the temporal pattern is essential. However, as the long-term in-situ measurements are rarely available for such lakes, it is a difficult task. Mapped LST images were carefully studied for cloud masks so as to retrieve LST data at the sampled stations. In this paper, the retrieval of LST from satellite imagery has been demonstrated from which synoptic and site specific values extracted. The paper has also demonstrated the limitation of MODIS data by cloud cover. The algorithms used in this research are generic ocean based algorithms. This technique can be further improved by developing algorithms specific to Lake Victoria.

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