OPERATIONAL WATER QUALITY MONITORING OVER LAKE WINNIPEG USING SATELLITE REMOTE SENSING DATA

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ABSTRACT

Lake Winnipeg is the 10th largest freshwater body in the world by area and its water quality is declining rapidly, apparently due to human and agricultural activity in the watershed. Spatially distributed water quality maps are useful for studies on the sustainability of the lake ecosystem and as a means of tracking the lake's response to nutrient and land use management strategies. A collaborative project was initiated between Noetix Research, the Department of Fisheries and Oceans and the Centre for Earth Observations Science, University of Manitoba to generate satellite remote sensing products for water quality monitoring over Lake Winnipeg. The project complements existing in-situ monitoring programs, and will assist in the development and validation of a water quality model for the lake, as well as informing the public. Total suspended solids, surface temperature, chlorophyll-*a* and surface algal bloom maps have been generated from AVHRR and MODIS imagery. This paper describes the approaches and procedures developed to generate these products as an operational service for inland water quality monitoring, including atmospheric correction and surface reflectance retrieval, image re-projection, algorithm calibration based on in-situ measurements, production and web publication. Potential improvements to the water quality service using MERIS images are also discussed.

INTRODUCTION

Remote sensing systems are acquiring information about the earth surface with increasing spatial and temporal coverage. Remotely sensed optical imagery over water bodies have been used as a cost effective way for water quality monitoring. In the visible and near infrared domain, solar radiation penetrates into water, interacts with different components while it travels within the water column (Jerlov, 1976). The interaction changes the spectral composition of the up-welling radiative flux. Thus, water colour information recorded by a remote sensing system reveals information about the bio-optical properties of a water body. The oceanic waters, referred to as Case I waters, are optically simple since generally only substances related with phytoplankton are present in the water. The optical properties of Case II waters (i.e., coastal and inland water bodies), are influenced not only by phytoplankton related substances, but also by a few other kinds of particulates, therefore are much more complicated. The concentrations of these particulates are indicators of water quality, which include total suspended solids (TSS), dissolved organic carbon (DOC), and chlorophyll-*a*. Various approaches have been developed to retrieve these parameters from remote sensing data. In addition to these bio-optical components of water, temperature is another critical water quality indicator and environmental parameter. It governs the kinds and types of aquatic life, regulates the maximum dissolved oxygen concentration, and influences the metabolic rates of aquatic organisms and the sensitivity of these organisms to pollution, parasites and disease. Water surface temperature can be measured with remote sensing in the thermal infrared domain.

Retrieval of inland water quality parameters using remote sensing data has been a research focus around the world for many years; however, there are few cases to implement such a service on an operational basis. With the support from the Canadian Space Agency (CSA), a collaborative project, Water Resource Development Project (WRDP), was initiated between Noetix Research Inc., the Department of Fisheries and Oceans (DFO) and the Centre for Earth Observations Science (CEOS) in the University of Manitoba, to generate satellite remote sensing products for water quality monitoring over Lake Winnipeg. This paper introduces the approaches and implementation of the system.

PROJECT BACKGROUNDS

Lake Winnipeg is the 10th largest freshwater body in the world by area. It is 436 km long, 111 km across, and has an average depth of 12 m. The total watershed area is about 1 million square km, supporting over 5 million people from four provinces in Canada and four states in the United States. It is important for commercial fisheries and tourism, and serves as a storage reservoir for downstream hydroelectric power generation. The shallow lake is fed by several rivers, including the Red River, the Saskatchewan River, and the Winnipeg River, and drains into the Hudson Bay by the Nelson River. Its western lakeshore is well forested, and southeastern and southwestern shores are a popular summer resort area.

Figure 1 shows the geographic location of Lake Winnipeg and a remote sensing image acquired on August 15, 2006 by the Moderate-Resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite. The lake consists of the North Basin and the South Basin, with the Narrows in between these two basins. To the west of Lake Winnipeg, three smaller lakes, Lake Manitoba, Lake Winnipegosis, and Cedar Lake are also shown in the figure. These lakes were also included in the monitoring system.

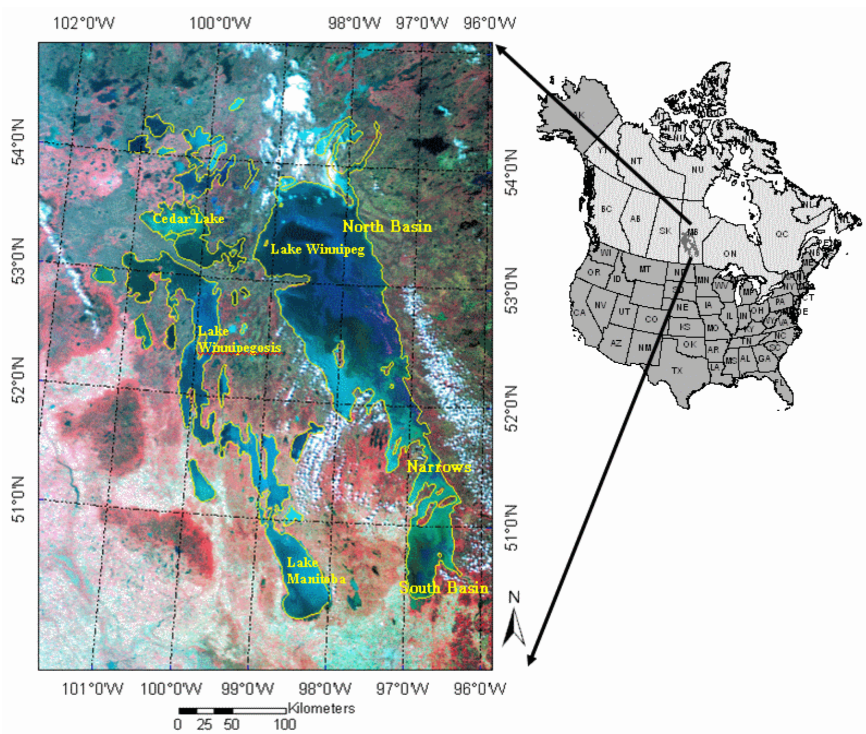

Figure 1. Lake Winnipeg study site.

In the past decades, water quality in Lake Winnipeg experienced a serious degradation. Factors that have caused the deterioration include agricultural practices, sewage effluent, cottage and recreational activities, logging and hydroelectric dams. Enhanced nutrient concentrations in runoff due to agricultural activity in the sustaining watershed are the major contributor. Furthermore, the control dam at the outlet stores summer peak flows, releasing them in winter when much of the lake's nutrient load has settled out of the water column, so that more nutrients are stored and recycled in subsequent years.

The degradation of water quality has attracted wide attention. Plans have been initiated to reverse the situation. DFO and CEOS have developed algorithms for the retrieval of TSS and the extent and intensity of surface algal blooms from the Advanced Very High Resolution Radiometer (AVHRR) images (McCullough et al., 2001). This was part of a Canadian Space Agency-funded study designed to develop remote sensing tools to enhance in-situ data collection, and to inventory primary production and productivity capacity of the lake.

It is desirable to provide research communities, governmental departments and the public with water quality products on an operational basis. Under the financial support from the CSA, the WRDP project was initialized to integrate expertise of DFO and CEOS in water quality monitoring, and expertise of Noetix Research Inc. in earth observation data processing and application, geo-spatial information integration and Internet based services, to develop an operational water quality monitoring service in Canada. Other objectives of the project were to improve AVHRR-based water quality products; to develop algorithms and generate enhanced products based on the more advanced sensors, namely MODIS and the Medium Resolution Imaging Spectrometer (MERIS). An operational system was established in this project to provide remote sensing images and remotely sensed water quality products over Lake Winnipeg on weekly basis. The products include colour composite images and maps of TSS, surface algal blooms, and water surface temperature.

SENSOR CAPABILITY

Optical remote sensing data is required for water quality monitoring. Due to the highly dynamic nature of water, an operational monitoring system demands that data is collected at a high frequency. Many medium resolution sensors offering daily global coverage can be used for this purpose. A few optical sensors currently in operation are specifically designed for water colour monitoring. Among these are COCTS (Chinese Ocean Colour and Temperature Scanner) on HY-1B, MERIS on ENVISAT, MODIS onboard Terra and Aqua, and SeaWiFS (Sea-viewing Wide Field-of-View Sensors) on OrbView-2. Although it was not designed for ocean colour monitoring, the AVHRR sensor records broad band red and near infrared (NIR) light that is useful for quantitative TSS determination and detection of surface algal blooms. Due to its long period of record and consistent operation, AVHRR was selected as the primary sensor to acquire optical imagery for retrospective water quality studies in Lake Winnipeg. The earliest AVHRR sensor (AVHRR/1) was a 4-channel radiometer, with two channels in the visible-NIR region, and two in the thermal infrared region. Starting from NOAA-7 (June 1981), it was upgraded to a 5 channel instrument (AVHRR/2), with a middle infrared channel centred at 3.75 μm. Starting from NOAA-15 (May 1998), the instrument was further upgraded to AVHRR/3, with an additional middle infrared channel centred around 1.6 μm. The specifications of AVHRR/3 are given in Table 1. It acquires 1 km surface reflectance information in the first three channels, and thermal information in the other three channels.

Table 1. AVHRR/3 sensor specifications

Channel	Resolution (km)	Wavelength (μm)	Application
1	1.09	0.58 ~ 0.68	Daytime cloud/Surface mapping
2	1.09	0.725 ~ 1.0	Land-water boundaries
3A	1.09	1.58 ~ 1.64	Snow and ice detection
3B	1.09	3.55 ~ 3.93	Night cloud mapping, sea surface temperature
4	1.09	10.3 ~ 11.3	Night cloud mapping, sea surface temperature
5	1.09	11.5 ~ 12.5	Sea surface temperature

In contrast to AVHRR, the MODIS sensor acquires images with three different spatial resolutions in 36 relatively narrower channels, ranging from visible to thermal infrared. The first two channels have a pixel resolution of 250 m, and reside in the red and NIR ranges. The next five channels have a pixel resolution of 500 m, and cover the spectral range from visible to middle infrared. The other channels have a 1 km pixel resolution. This configuration makes MODIS the most versatile sensor in a wide range of applications over land, water, atmosphere and cloud. For instance, there are nine channels (band 8 to 16) in the visible-NIR region dedicated to the study of ocean colour, phytoplankton and biogeochemistry (Table 2). A summary of MODIS specifications are listed in Table 2. Channels are grouped according to their applications and spectral ranges.

The MERIS sensor acquires images in 15 programmable narrow channels in the visible-near infrared region. This feature is especially advantageous for detection of chlorophyll-*a* fluorescence, for which the peak location is close to 680 nm. Pixel resolution is 300 m for full resolution (FR) and 1200 m for reduced resolution (RR) data. The MERIS data are not routinely accessible in Canada; thus, the work related with MERIS remains at the prototyping stage. Detailed sensor specifications are not given here.

Water temperature can be retrieved from the paired thermal channels of AVHRR and MODIS data. The thermal channels can also be used to generate a cloud mask, and used as a quality control measure. TSS and algal blooms are retrieved from the visible and NIR channels. The configuration of MODIS and MERIS sensors with more channels in the visible-near infrared range and finer spectral resolution not only provides a mechanism for improved water quality parameter retrieval, but also allows for improvement of correction of atmospheric influence, a major problem in remote sensing of water.

Table 2. MODIS sensor specifications

Channel	Resolution (km)	Wavelength (μm)	Application
1		0.62 – 0.67	
2	0.25	0.841 – 0.876	Land / Cloud / Aerosols Boundaries
3		0.459 –0.479	
4		0.545 –0.565	
5	0.50	1.23 – 1.25	Land / Cloud /Aerosols Properties
6		1.628 – 1.652	
7		2.105 – 2.155	
8-16	1.0	0.405 – 0.877	Ocean Color / Phytoplankton / Biogeochemistry
17-19	1.0	0.890 – 0.965	Atmospheric Water Vapor
20-23		3.660 – 4.080	Surface / Cloud / Temperature
24-25	1.0	4.433 – 4.549	Atmospheric temperature
26		1.360 – 1.390	
27-28	1.0	6.535 – 7.475	Cirrus Clouds / Water Vapor
29	1.0	8.400 – 8.700	Cloud Properties
30	1.0	9.580 – 9.880	Ozone
31-32	1.0	10.780 – 12.27	Surface / Cloud Temperature
33-36	1.0	13.185 – 14.385	Cloud Top, Altitude

PRODUCT DEVELOPMENT

In-situ Data

Water quality data were collected by CEOS and DFO on Lake Winnipeg during the summer of 2002, 2003 and 2004. Water samples were analysed to determine the concentrations of chlorophyll-*a*, TSS, tripton and DOC. Results from multiple missions showed a maximum content of 283 μg L^{-1} for chlorophyll-*a* in mid-summer, and a maximum content of 90 mg L^{-1} for TSS. Secchi depths ranged between 0.2 m to 3.1 m. High suspended solids were confined to the South Basin and the Narrows regions; tripton levels were up to 105 mg L^{-1}. DOC ranged from 412 to 1310 μg L^{-1}, with the higher values confined to regions near the mouths of Shield Rivers along the east shore of the lake. Algorithms were developed using data collected in 2002 and 2003, and were validated using data collected in 2004. Details can be found in McCullough (2006). In-situ water temperature was measured by three buoys on the lake, and was obtained from Environment Canada for the summer period in 2005 and 2006. This data was used to validate the temperature algorithm.

Theoretical Background of Water Quality Algorithms

The theoretical basis for retrieving chlorophyll-*a* and TSS in this study was based on a family of well-established semi-analytical models by Gordon et al. (1988). In this model, the irradiance reflectance at a given wavelength λ is expressed as a function of the total absorption coefficient α and the total backscatter coefficient b_b:

$$R(\lambda) = f b_b(\lambda)/(\alpha(\lambda) + b_b(\lambda)) \qquad (1)$$

where *f* is an empirical factor that is related with the incident light field and the volumetric-scattering function of the water. It is assumed to be a constant over a limited spectral range. Following the approximation by Stumpf and Tyler (1988, 1989), Equation (1) can be written as:

$$R(\lambda) = 0.33 b_{bs}^*(\lambda) / (s^*(\lambda) + \alpha_x(\lambda) / n_s) \quad (2)$$

where n_s is the concentration of suspended particulates; α_x is the absorption by materials other than the suspended sediment; b_{bs}^* is the specific backscatter of the particulates; S^* is the sum of specific backscatter and absorption coefficients of the sediment. The coefficients in Equation (2) can be determined through data modeling using in-situ data, and the relationship between the concentration of TSS and the reflectance R can be established.

Two channels are required for retrieving chlorophyll-*a* concentration. One channel is located in the red region where chlorophyll-*a* absorption reaches a peak value, and another is located in the NIR region. Following the approximation by Ruddick et al. (2001), chlorophyll-*a* concentration, *Chl*, can be written as a function of a two-band ratio:

$$Chl = \alpha / \alpha^* = (kR_2 / R_1 + b) / \alpha^* \quad (3)$$

where α^* is the specific absorption coefficient; R_1 and R_2 are the reflectance in the red and NIR regions, respectively. k, b and α^* can be determined using in-situ data. The algorithms were developed and validated by McCullough at CEOS (2001).

Surface Temperature Algorithm

The retrieval of water temperature with remote sensing is generally achieved using split-window techniques from two thermal channels. The split-window techniques reduce atmospheric effects using the difference of brightness temperature measured at paired thermal channels, e.g., two channels in the 10-12 µm range. Formula for surface temperature (*Ts*) estimation from the 11 µm and 12 µm thermal channels can be written as (Li et al., 2001):

$$T_s = A_1 + A_2 * BT_{11} + A_3 * (BT_{11} - BT_{12}) + A_4 * (BT_{11} - BT_{12}) * (1/\cos(\theta_s) - 1) \quad (4)$$

where A_1~A_4 are constant coefficients; BT_{11} and BT_{12} are brightness temperature at 11 and 12 µm, respectively; θs is the solar incidence angle. The brightness temperature is estimated from the at sensor radiance using Plank's law of black body radiation, assuming a unit emissivity for water. The same algorithm is applicable for both MODIS and AVHRR thermal channels (Brown and Minnett, 1999).

The buoy temperature data for 2005 and 2006 were used to validate this algorithm. Twenty-six MODIS images were acquired for the summer of these two years. The images were radiance calibrated, re-projected, then the water surface temperature was calculated from channel 31 (11 µm) and channel 32 (12 µm). Samples covered with cloud were identified and excluded. Of the remaining 54 cloud-free samples, the correlation between temperature estimated by MODIS data and that measured by buoy had an R^2 of 0.98 and RMSE of 0.43, with a 0.026 ºC bias. Figure 2 shows the comparison between temperature estimated from MODIS data and that measured by buoys.

Colour Composite Image

Composite colour images are very useful tools for visual interpretation in many applications. Composite colour images are generated from three channels. Since there are many channels available in MODIS images, both true colour and pseudo colour images can be generated. The first two channels have the highest spatial resolution, so that they are usually used to capture finer spatial features. The additional channel can be any of the 500 m or 1 km channel that is bi-linearly interpolated to 250 m. The third channel can also be generated from the 500 m channels using the novel downscaling approach developed by Trishchenko et al. (2006).

Product Specification

The remote sensing data are downloaded and processed operationally on a weekly basis, with minor manual interaction. All the image products are provided in Geotiff format with projection and geo-reference metadata information. The products can be used not only as visual material, but also as thematic layers that are easily loaded into a GIS environment and integrated with other information layers directly. The Colour composite images are three channel pseudo colour or true colour images; while maps of surface temperature, TSS, chlorophyll-*a* concentration and surface bloom distribution are single channel images with colour keys.

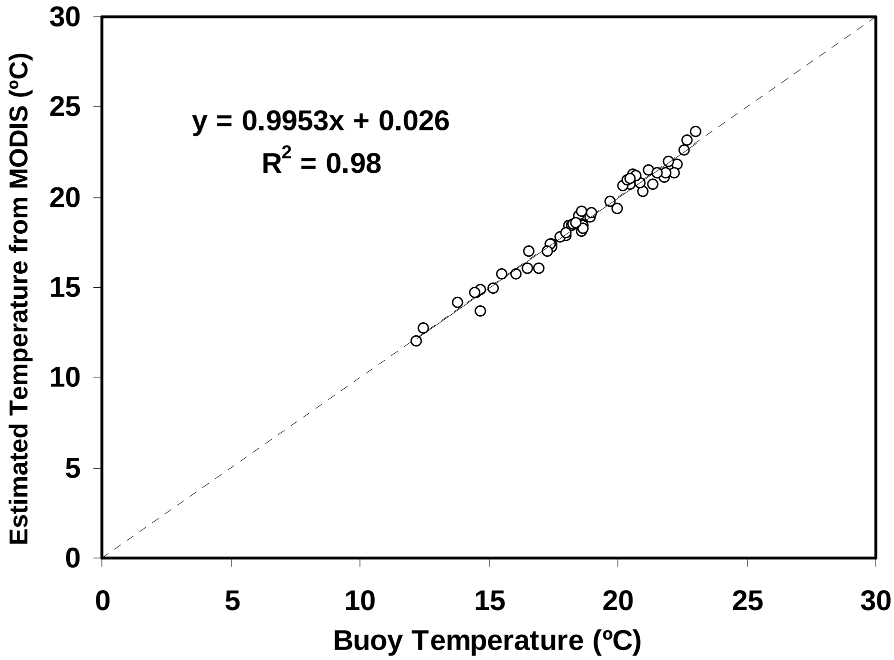

Figure 2. Comparison of estimated water temperature with buoy measured temperature. Dash line is the 1:1 line.

IMPLEMENTATION OF THE SERVICE

Figure 3 shows the data flow for the operational water quality monitoring service. Production consists of the following procedures: data query and order from the Internet, data pre-processing, product generation and rendering, and Internet post. Users or clients can be partners in the sense that, by working cooperatively, their in-situ data can be used to calibrate the products and improve the water quality service. IDL program and PCI scripts have been written to control the whole processing procedure.

Data Query and Order

AVHRR and MODIS image can be searched and ordered manually on the Internet. The advantage of this mode is, only data that meet quality requirement are ordered and downloaded. An alterative mode is to build up a connection with data provider, so that data can be transmitted automatically according to user defined region-of-interest (ROI). Auxiliary data, which include atmospheric parameters and meteorological data, are usually required for atmospheric correction. For processing of MODIS level 1B data, level-2 compound atmospheric products are available for atmospheric correction. Water vapor thickness, pressure, ozone content and aerosol thickness need to be collected to process AVHRR data.

Data Pre-processing

The pre-processing step generates atmospherically corrected, geo-referenced remote sensing data to be used in the next step. Under the technical transfer agreement between Noetix Research and the Canadian Centre for Remote Sensing, two software, the EODM (Earth Observation Data Manager) for AVHRR data processing and MODIS software for MODIS level-1B data processing, were obtained and used at this stage. The two software systems have similar structure and functionality: radiance calibration, atmospheric correction, geometric correction and geo-referencing. The Simple Model for Atmospheric Correction (SMAC; Rahman and Dedieu, 1994) is employed by both systems. After data pre-processing, the following data are available: calibrated radiance images for each channel, top of atmosphere and surface reflectance for the reflectance channels, brightness temperature for the thermal channels, and the solar/view angles for the region of interest. These images are used to generate products in the next step.

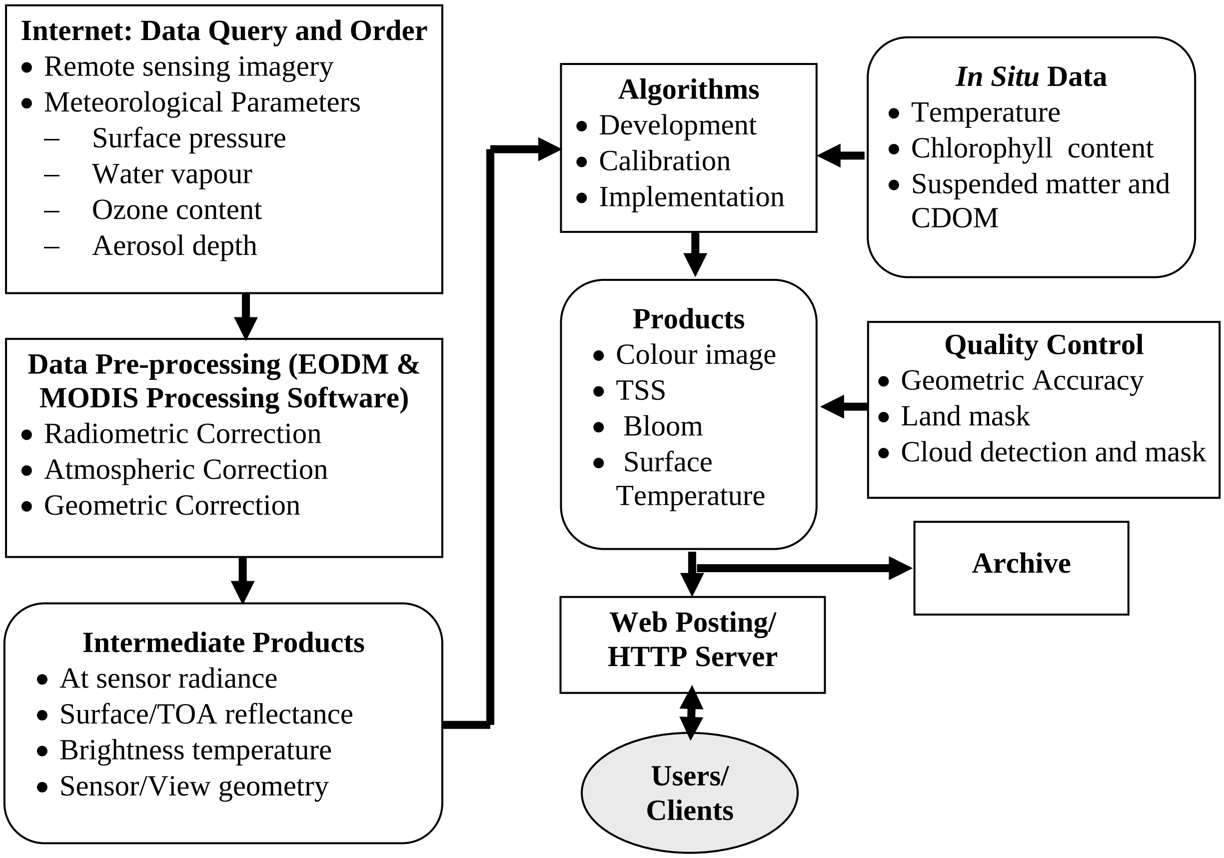

Figure 3. System structure and control flow.

Products

Algorithms have been implemented to generate water quality products, namely, water temperature, concentrations of TSS, chlorophyll-*a* and surface algal bloom distribution. Users contribute at this stage by developing and proving their own site-specific algorithms, collecting in-situ data for real time validation, calibration and product improvement.

Quality Control

Because algorithms for temperature, TSS and chlorophyll-*a* concentration are valid only for water bodies, a land mask is generated for each service area. The land mask has less meaning for a composite colour image, but helps to improve the interpretation of the other products. Another advantage of this operation is that the accuracy of geometric correction and geo-referencing can be visually evaluated.

In addition to the land mask, it is necessary to generate and apply a cloud mask. A classification approach is employed for AVHRR data. An unsupervised classification is performed first, and the classes representing cloud was visually identified to generate a cloud mask (McCullough, 2001). The MODIS data offers the opportunity for multispectral approaches to cloud detection (Ackerman et al., 2006). A few simple criteria are available to generate the cloud mask from MODIS data over water bodies. These include: 1) simple brightness temperature threshold test, using brightness temperature at 11 μm (channel 31) and/or 6.7 μm (channel 27); 2) difference between brightness temperature test; 3) near infrared cirrus test using the reflectance at 1.38 μm (channel 26); 4) visible reflectance test, using reflectance at 0.86 μm (channel 2) and/or 0.66 μm (channel 1); and 5) reflectance ratio test, using the ratio of reflectance measured in 0.86 μm and 0.66 μm bands. Due to the complexity of the cloud properties and the highly variable background of water, the best criteria are hard to achieve for all the situations. For instance, while reflectance at 0.86 μm is powerful for cloud detection, it sometimes mistakenly identifies surface algal blooms as cloud, since the reflectance from blooms in this channel is rather high. This situation can be easily identified from the generated water temperature map. An example is shown in Figure 5c. In the North Basin where the middle portion of the cloud was correctly detected and masked, the cloud edge was not masked, and demonstrated with an unusual low temperature compared to its neighbour areas. The criteria based on brightness temperatures were used to generate the cloud mask in this study.

Web-based User Service and Archiving

The products generated above are properly rendered in easily accepted formats and are posted on a web server that can be accessed by users and clients. Data and product archive are also implemented at this stage.

Although the system is established for Lake Winnipeg, the processing mode can be easily adapted to other study sites, or other applications. Lake of the Woods (south east of Lake Winnipeg), a lake with similar optical properties and an equally serious deterioration of water quality across the boundary between Canada and the US, is an example where this system could be applied. The MODIS processing streamline has also been used to generate composite colour image and water surface temperature maps for an arctic region, providing products that are complementary to the current standard SAR products. Although cloud cover limits the chances of successful optical images acquisition, the cloud free images offer very appealing visual products for the ice conditions interpretation.

RESULTS AND FUTURE PERSPECTIVES

Products are generated weekly, and are posted when cloud cover is not severe. AVHRR based water quality parameters are routinely generated starts from summer of 2005. The products include colour images, maps of total suspended solids concentration and surface algal bloom distribution. Algorithms based on MODIS imagery have been developed and are currently being validated. In addition to the previous three products, water surface temperature has been generated from AVHRR and MODIS data, and is under service from 2007. Examples of MODIS derived TSS and surface bloom distribution maps are shown in Figure 4 a and b, respectively. As can be seen from Fig. 3a, the retrieved TSS for May 17, 2006 is higher than 20 mg L^{-1} at the southern tip near a river estuary, and below 10 mg L^{-1} for most part up to the North Basin. On September 20, 2006, large patches of surface blooms formed along the eastern coast of the northern basin.

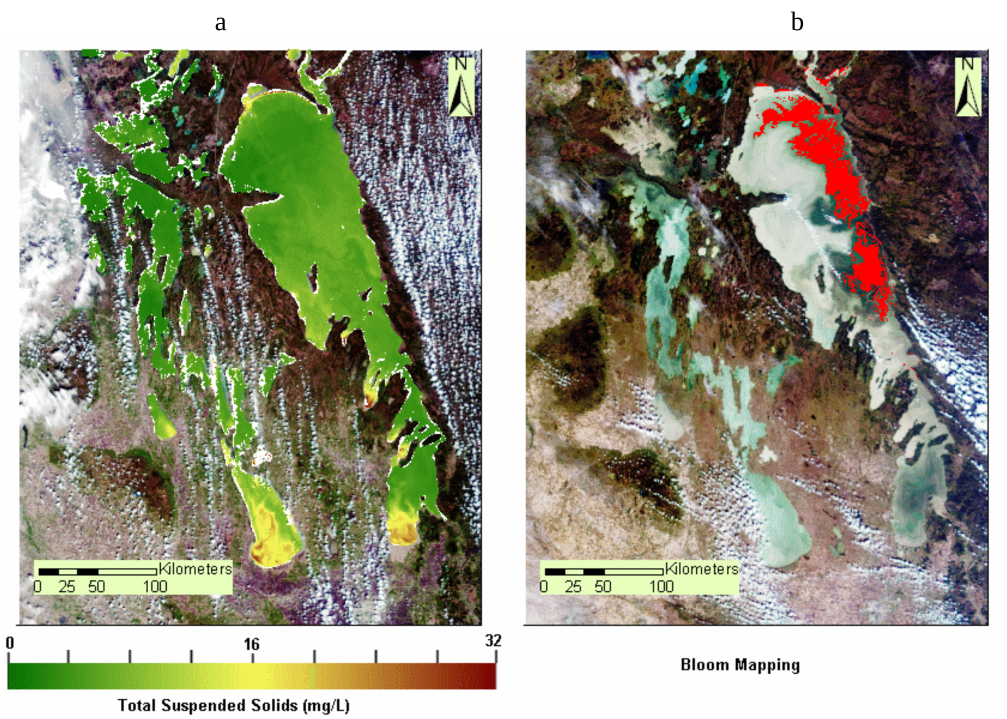

Figure 4. Products generated from MODIS data: a) total suspended solids concentration for May 17, 2006, and b) surface algal bloom distribution for September 20, 2006. The background is the composite true colour images; the TSS is colour coded; cloud over water body is masked with white colour.

Figure 5 shows examples of water temperature maps derived from MODIS data for 4 days in 2007. The maps represent temperature for May 27, June 21, July 12 and July 30, sequentially. Water temperature increases continuously during this period across the lake. The North Basin is generally a few degrees cooler than the South Basin.

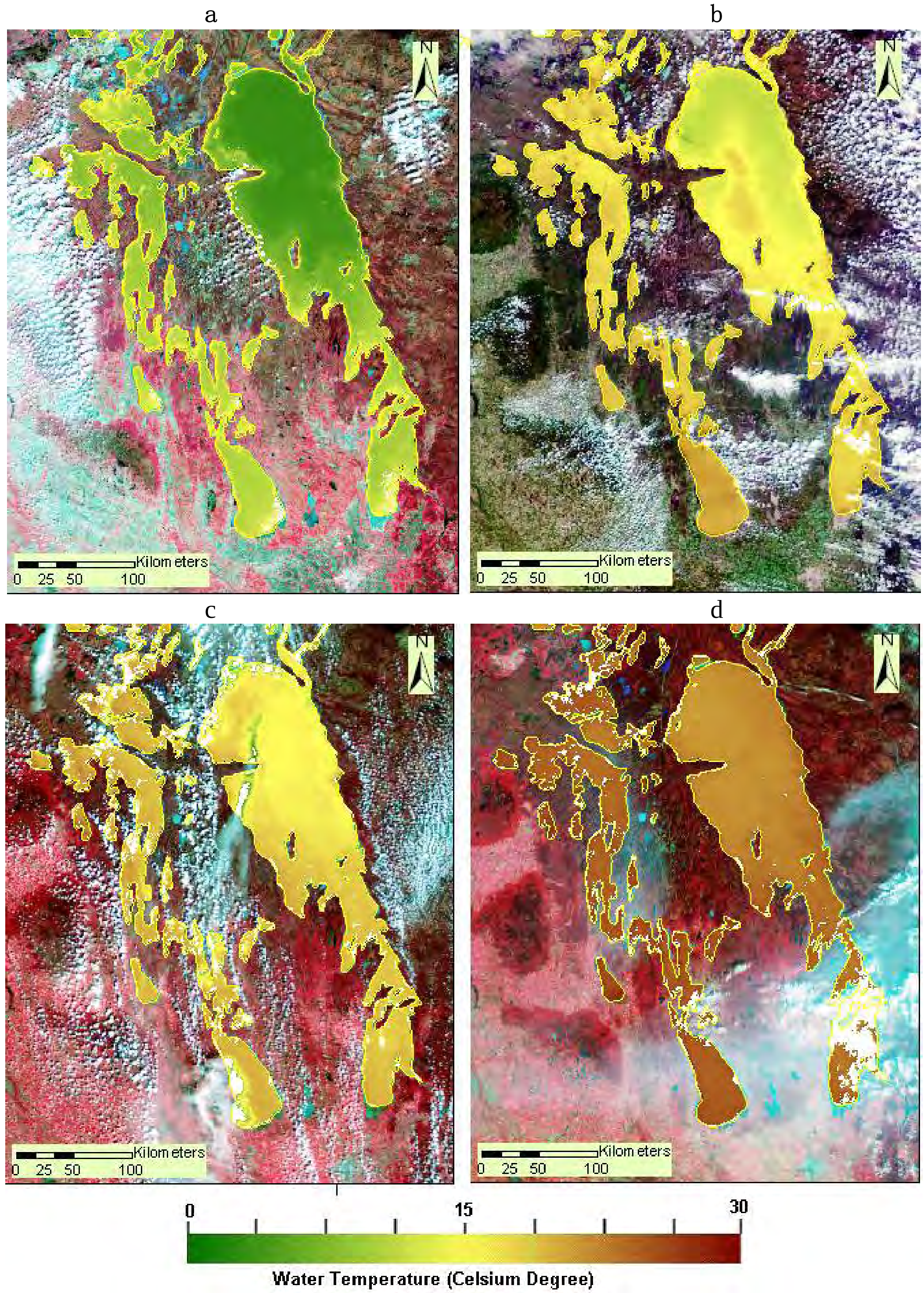

Figure 5. MODIS derived water surface temperature for 2007: a) May 27, b) June 21, c) July 12 and July 30. The retrieved water temperature is colour coded; where cloud is detected over water, the area is illustrated with white colour; the land surface is illustrated with colour composite image.

Future Activities

Currently, Noetix Research is prototyping MERIS data access and pre-processing streams. Algorithms are under development at DFO and CEOS for retrieving water quality parameters using MERIS data. Products will be available once MERIS data are routinely accessible to Canadian users. Products from different streamlines back-up each other, and are complementary. For instance, AVHRR data provides baseline products, due to its consistent and stable operation, while improved products can be generated from MODIS and MERIS. Multiple near infrared channels are available for MODIS and MERIS data. This will improve the atmospheric correction by evaluate aerosol properties using aerosol models and the reflectance in the near infrared channels (Ruddick et al., 2000).

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