SATELLITE-BASED STUDY OF WATER QUALITY OF CHILKO LAKE (BRITISH COLUMBIA, CANADA): IMPACT ON SOCKEYE SALMON

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ABSTRACT

Chilko Lake sockeye constitute one of the largest salmon stocks in the Pacific Northwest, for which Fisheries and Oceans Canada has maintained a 55-year record, including partitioned freshwater and marine survival. The lake was also the site of fertilization experiments in the 1970s-1990s. This paper examined the use of spaceborne data from MERIS and LANDSAT collected over the Chilko Lake watershed for the purpose of generating long time series of lake chlorophyll and water temperature, testing and validating standard chlorophyll algorithms against *in situ* measurements, comparing Sockeye survival with lake variables, and assessing the state of glaciers in the watershed.

Index Terms— Chilko, Sockeye, MERIS, LANDSAT, glaciers.

1. INTRODUCTION

The success of Pacific salmonids, and in particular the Fraser River Sockeye, is a major concern of Fisheries and Oceans Canada (DFO Pacific), and was the subject of the recent "Cohen Commission" [1]. Current predictive models of Sockeye production are based primarily on the size of parental stocks, but the factors underlying variability in mortality rates, in both freshwater and marine phases of their life cycle are not well understood. A large research effort is aimed at improving the understanding of the relationships between environmental conditions and salmonid production and mortality.

Chilko Lake hosts one of the most important Fraser River Sockeye stocks. It is one of few stocks for which partitioned freshwater and marine survival data have been recorded; for Chilko, these data are available from 1949 to present. However, like many lakes, environmental data for Chilko are limited, particularly for primary production. In order to expand upon the existing *in situ* dataset for use in retrospective analysis of the environment on salmon population dynamics, DFO are looking to the use of satellite Earth Observation (EO) to provide quasi-continuous, archival records of lake chlorophyll and surface temperature. The existing *in situ* data can provide validation for satellite-based estimates of environmental variables.

There are a number of challenges to the use of EO products, particularly water colour, for Chilko Lake. First, although it is one of the largest lakes in BC, it is long and narrow (5 km wide at its widest point). This effectively limits the use of water colour sensors to MERIS FR, with 300 m spatial resolution. Secondly, the lake is considered oligotrophic to ultraoligotrophic [2], yet it is subject to high glacial turbidity in the southern half of the lake. This means that standard algorithms may not accurately retrieve chlorophyll concentrations, and the development of a local algorithm may be required.

The approach taken to this project was to (1) test standard chlorophyll algorithms against available *in situ* measurements, (2) explore a local chlorophyll algorithm and to compare it with standard algorithms, (3) develop time series of EO-based chlorophyll and water temperature, the latter using LANDSAT, and (4) perform a preliminary fisheries analysis comparing Sockeye freshwater survival with lake variables. Finally, since the lake is surrounded by glaciers that may affect its productivity, a history of glaciation in the Chilko watershed was compiled, based on LANDSAT imagery.

2. METHODS

The entire MERIS (from EOLI for 2002-07 and CEOCAT for 2008-12) and LANDSAT (USGS, 1979-2011) archives were searched, and available Chilko Lake imagery downloaded. MERIS swaths were subset to the Chilko Lake area and chlorophyll products generated in BEAM for the FUB, C2R, and Boreal Lakes standard algorithms, as well as

FLH. The BEAM Cloud Probability Processor was also used to provide a standard estimate of cloud cover. Products were navigated and clouds masked based on the cloud probability flag "2" (probability of cloud less than 0.2). Chlorophyll concentration estimates were extracted from nine locations matching DFO field sampling conducted between 2009 and 2011, and validated using 16 scenes that were acquired within four days of *in situ* sampling. LANDSAT data were subset to the Chilko Lake area and thermal band 6 was calibrated to surface temperature using PCI Geomatica's ATCOR2T. Temperature estimates were extracted from the DFO sampling locations and validated against *in situ* measurements acquired between 1984 and 2011.

In July 2012, *in situ* field data were collected in support of the development of a local algorithm for chlorophyll. Hyperspectral measurements of apparent optical properties (AOPs) were made using Satlantic HyperPRO and HyperSAS sensors, and inherent optical properties (IOPs) using WET Labs ac-S sensor. Water samples were collected simultaneously for laboratory analysis of CDOM absorption, photosynthetic pigment concentration, and suspended organic and inorganic sediment concentrations. HYDROLIGHT radiative transfer model was later used to generate further AOPs from *in situ* IOPs. These modelled AOPs were then compared with the *in situ* AOPs to assess the accuracy and validity of the model. The validated model was subsequently used to generate a lookup table from which concentrations of chlorophyll and inorganic sediments, and CDOM absorption could be estimated from reflectance. Validation of predicted concentrations was performed using monthly measurements of surface reflectance collected with and ASD handheld spectrometer and *in situ* water sampling between May and October, 2012.

In the original project plan, the local chlorophyll algorithm calculated from HYDROLIGHT modeling was to be applied to MERIS imagery for which a local atmospheric correction had also been applied. The development of the atmospheric correction algorithm was to be based on MERIS overpass(es) close in time to the May-October sampling. Due to unfortunate demise of the MERIS instrument in April 2012, this was not possible; so instead, a variety of standard atmospheric correction algorithms were applied to the 16 archive MERIS scenes for which *in situ* chlorophyll estimates were available. The local chlorophyll algorithm was applied to the suite of atmospherically corrected scenes, and the chlorophyll predictions compared with the *in situ* concentrations.

For the fisheries analysis, the best chlorophyll product from the local and standard validation analysis was compiled into a time series spanning June 2002 to April 2012. Data were binned from daily to 8-day and monthly temporal resolutions and a number of metrics derived, including the timing of bloom initiation and peak annual chlorophyll.

A glacier time series was built from the LANDSAT optical data based on the algorithm of Bolch *et al.* [3] for snow and ice. As this algorithm does not differentiate between seasonal snow/ice and glacier, the glacier extent was expressed as the minimum snow/ice extent in late summer. Time series were constructed for three areas of the watershed with different slope aspects and drainage.

3. RESULTS

3.1. Algorithm

Of the standard and local chlorophyll algorithms tested, the best match to *in situ* concentration estimates was obtained using the C2R algorithm version 1.3.2 (3 versions of the C2R algorithm were tested), with an overall r^2 of 0.55. This algorithm performed very well given the low chlorophyll concentrations (0 to 1.2 mg m^{-3} chlorophyll *a*), even in water of moderately high turbidity (up to 6 mg l^{-1} suspended minerals). The local algorithm consistently overestimated chlorophyll calculated from both field measurements and MERIS imagery, suggesting a miscalibration of the IOP. LANDSAT-based water temperature estimates were on average correct, but with a rather large RMS error of 2.5° C. Seasonality played a role in the error, with LANDSAT temperatures generally warmer than *in situ* measurements in the summer and cooler in spring and fall (no *in situ* measurements were made in the winter). Variability of the temperature gradients between the surface microlayer observed by LANDSAT and the subsurface measurements made *in situ* may be responsible for this discrepancy.

3.2. Chlorophyll time series

Figure 1 shows the 8-day, C2R chlorophyll time series averaged over the entire lake. An average canonical cycle fitted to the time series shows an annual minimum in mid-April and a maximum in early September. The magnitude of the seasonal maximum is only 0.7 mg m^{-3}, consistent with the lake's oligotrophic status, with an absolute 8-day maximum of 1.7 mg m^{-3} recorded in 2002. The timing of phytoplankton bloom initiation appears to be remarkably consistent from year to year, with slightly earlier than average blooms in 2009 and 2010, and a late bloom in 2011.

An analysis of the linkages between lake chlorophyll and Chilko sockeye freshwater production showed that:

- early blooms in the freshwater phase seemed to produce larger smolts;
- freshwater survival is higher with early blooms in the north end of the lake;
- early spring primary production was associated with larger smolts but worse freshwater and smolt survival;
- strong summer primary production improves growth, freshwater survival and smolt survival (exact timing varies);

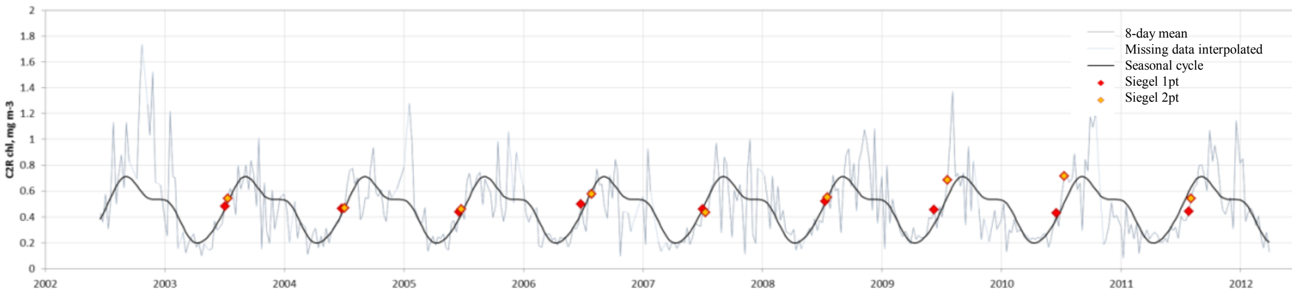

Figure 1. 8-day C2R chlorophyll time series for Chilko Lake derived from MERIS, showing the calculated average seasonal cycle (black line) and timing estimates for phytoplankton bloom initiation, based on two variants of the algorithm of Siegel *et al.* [4] (red and yellow circles).

- strong early spring primary production in smolt year yielded better smolt survival;
- there was no significant relationship between annual chlorophyll and freshwater survival or smolt size; and
- cumulative chlorophyll relationships echoed other findings: smolt size and smolt survival tied to total chlorophyll biomass during main growing season.

3.3. Glacier time series

Glacier analysis revealed significant recession in all three areas studied, over the period 1985-2010. Based on LANDSAT, the average rate of retreat was 0.46% per year in Franklin Arm, 0.47% per year in South Arm East and 0.24% per year in South Arm West (Figure 2).

4. CONCLUSIONS

Results are in general agreement with the findings of the lake fertilization experiment in the late 1980s and early 1990s: that nutrient enrichment and the subsequent increase in primary productivity led to increased smolt size and increased adult returns. Spatial patterns of the observed correlations are also consistent with what is known about Chilko Sockeye biology – that they spawn at the north end of the lake and subsequently distribute southward during their freshwater year. Many of the relationships were stronger at the north end of the lake and weaker in Franklyn Arm and the south end.

The glacier analysis showed a significant recession in three glaciers in the last 25 years.

This project has successfully demonstrated the use of satellite EO data to produce data-dense time-series for remote, sparsely-sampled locations.

5. ACKNOWLEDGEMENTS

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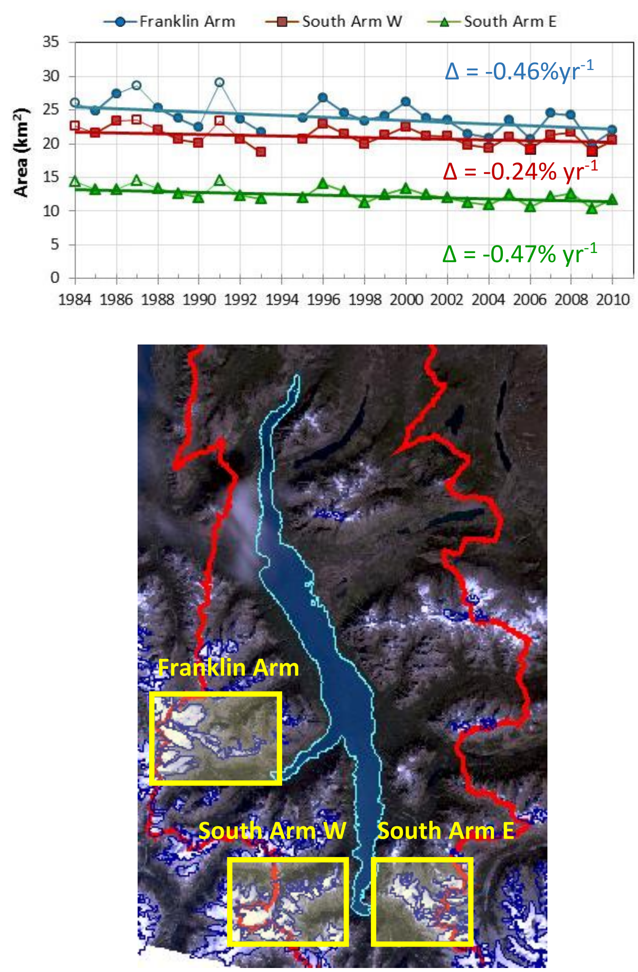

Figure 2. Time series of glacier extent for three areas in the Chilko watershed, estimated from LANDSAT, for Franklin Arm, South Arm West, and South Arm East glaciers.

5. REFERENCES

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