LAKE SURFACE TEMPERATURE AND ICE COVER

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ABSTRACT

Lakes are a vital component of the Earth's fresh water resources, and are of fundamental importance for terrestrial life. Lake water temperature is one of the key parameters determining ecological conditions within a lake, as it influences both chemical and biological processes. In addition to the impact on lake ecology, lake water temperatures determine air-water heat and moisture exchanges, and are therefore vital for understanding the hydrological cycle. Lake surface temperature (Lake ST) and lake ice cover (LIC) observations therefore have potential environmental and meteorological applications for inland water management and numerical weather prediction (NWP).

The series of (Advanced) Along Track Scanning Radiometers, (A)ATSRs provide exceptional radiometric qualities and dual-view scanning capability, making them suitable instruments for providing observations of Lake ST and LIC globally. The (A)ATSRs have previously been exploited for sea surface temperature (SST) observations in the ATSR Reprocessing for Climate (ARC) project. However, attempts to deliver Lake ST as a by-product of SST retrieval or land surface temperature (LandST) retrieval have not delivered sufficiently convincing results from ATSRs or other satellite borne instruments. The ARC-Lake project aims to unlock the potential of the ATSRs for observations of Lake ST and LIC, and demonstrate the usefulness of these observations to climate science.

Phase one of the ARC-Lake project focuses on large natural lakes, with surface area greater than 500 km². A global database of over 250 such lakes has been constructed and the ARC SST retrieval scheme developed to provide improved observations of Lake ST and LIC for these lakes, over the ATSR-2/AATSR lifetime of 1995 to present day. A number of these lakes have been the subject of in situ measurement campaigns, over varying time periods, and of varying measurement type (buoy, ship, and radiometer). These in situ observations are used in validation studies of the new ARC-Lake observations of Lake ST and LIC. Further assessment of the new observations is carried out through comparisons with alternative satellite retrieval schemes. In this presentation, we demonstrate the quality of the new observations through results from these comparisons with in situ and alternative satellite observations.

1. INTRODUCTION

Lakes are a vital component of Earth’s fresh water resources, and are of fundamental importance for terrestrial life. Lake water temperature is one of the key parameters determining ecological conditions within a lake, as it influences both chemical and biological processes. In addition to the impact on lake ecology, lake water temperatures determine air-water heat and moisture exchanges, and are therefore vital for understanding the hydrological cycle. Lake surface temperatures (Lake ST) and lake ice cover (LIC) observations therefore have potential environmental and meteorological applications for inland water management and numerical weather prediction.

The series of Along Track Scanning Radiometers (ATSRs) provide excellent radiometric qualities and dual-view scanning capability, making them suitable instruments for providing observations of Lake ST globally. The ATSRs have previously been exploited for sea surface temperature observations in the ATSR Reprocessing for Climate (ARC) project [1]. But Lake ST retrieval is a separate, and in many ways, more challenging problem, not always tractable by application of SST or Land ST retrieval schemes.

The European Space Agency (ESA) have established the ARC-Lake project (www.geos.ed.ac.uk/arclake) to adapt SST techniques for cloud and ice detection and for surface temperature retrieval to the problem of lakes. The project started in mid 2009 with a phase one study of Lake ST estimation for large lakes globally. This paper gives a description of the approach taken, validation results obtained, and proposes potential science applications of the ARC-Lake data.

2. GLOBAL LAKES

The ARC-Lake project considers, in phase one, world’s “large” natural lakes, conventionally taken to be those in excess of 500 km² in surface area [2, 3]. In addition, some lakes slightly smaller have been included because they are of scientific interest and/or have validation data available. Three reservoirs have been added also, at the
request of one of the ARC-Lake User Group (Environment Canada).

Fig. 1 shows the locations of the phase one lakes, and their size distribution. The distribution can be interpreted as a joint consequence of hydrological factors (availability of surface water) and geological factors (presence or absence of a history of glaciation, rifting, etc.). The lakes where in situ observations are available are also marked in Fig. 1. The number of such lakes is small but in situ observation campaigns have been identified for additional lakes and efforts to obtain further in situ data are ongoing. The unique identification and naming of lakes is in itself not a trivial undertaking. The full list of target lakes, with their Global Lakes and Wetland Database ID [3] and their latitude and longitude, is available at www.geos.ed.ac.uk/arclake/target_lakes.html.

![Figure 1. Location and area of 263 large target lakes in phase one of ARC-Lake. Lakes where in situ observations are available to ARC-Lake are marked with the + symbol.](image)

3. LAKE MASK

Lake retrievals are made for locations defined by a lake mask. For a few cases, most famously the Aral Sea, this fixed approach is problematic (Fig. 2). Moreover, the need to attribute observations to a corresponding lake ID introduces complexities (e.g., where does an inflow end and the lake start? what about water bodies that are traditionally separately named, but have some connecting filament of water?).

The data sets available to define the ARC-Lake lake ID mask were: the Envisat binary land/water $1^\circ \times 1^\circ$ global gridded mask from envisat.esa.int/services/auxiliary_data/common/; the NAVOCEANO $1^\circ \times 1^\circ$ gridded mask (only covers up to 83° latitude) from www.ghrsst.org/GHRSST-PP-NAVO-Land-and-sea-Mask.html; and level 1 polygons from the GLWD from www.worldwildlife.org/science/data/item1877.html. Reconciling these data sets, cross-checking against Google Earth (which was used as the source of names for lakes in GLWD lacking a name) and LakeNet (www.worldlakes.org/searchlakes.asp) was a considerable effort, one which was not wholly foreseen.

![Figure 2. Mask (red) for Aral Sea (left) based on GLWD polygons and the NAVOCEANO mask compared to Google Earth image (right).](image)
represented, as demonstrated in Fig. 3. Here the mask is able to associate multiple separate groups of water cells correctly as belonging to the same lake.

Figure 3. Lake Astray in the consolidated NAVOCEANO/GLWD land/water mask. White: land cells in mask. Black: water cells in mask. Red: polygon from GLWD. White cells within the red polygon contain both water and land, so are masked as land.

4. FORWARD MODELLING

As discussed below, the approach to both cloud detection and Lake ST retrieval depends on forward modelling of clear-sky infra-red observations of the ATSRs. The radiative transfer model used is RTTOV8.7, driven by the nearest numerical weather prediction (NWP) profile for the state of the atmosphere from the European Centre for Medium-range Weather Forecasting (ECMWF).

A major motivation for ARC-Lake is the relatively inadequate observational information available to NWP systems on lake water temperature, which is becoming more important as lake dynamics are increasingly included in land-atmosphere interactions schemes. A corollary of this is that NWP is not a good source of surface temperature for forward modelling of the infra-red satellite observations. Alternatives are a monthly climatology from MODIS observations [4], and lake-mean temperature climatology by simulations using the lake model “FLake” http://www.flake.igb-berlin.de/ [5]. A further alternative is to use empirical orthogonal function (EOF) techniques [6] to reconstruct a spatially complete time series from the sparse ATSR observations and use an iteratively updated version of this as source of prior surface temperature.

Brightness temperatures (BTs) seen for lakes by imagers such as the ATSRs are generally less than the true surface temperature. Although this difference is known as the “atmospheric correction” it is a deficit caused by net absorption of IR radiance by the atmosphere (to a degree depending on the column water vapour present) and by the surface emissivity being less than unity. The BT-Lake ST relationships therefore depend on the altitude (affecting atmospheric impact) and salinity (affecting emissivity) of the lakes. These variables are captured in the RTTOV8.7 forward model, which is a big motivation for using forward modelling-based cloud detection and retrieval. Altitude and salinity distributions are shown in Fig. 4.

Figure 4. Salinity class (colours) and elevation (symbol size) of phase one lakes.
5. CLOUD DETECTION

Cloud detection is a key element of surface temperature retrieval, and inadequacies in detection are linked to significant uncertainties. Typical threshold based cloud detection schemes for SST [7] rely on ranges for BTs and differences between BTs at different wavelengths in order to distinguish clear and cloudy skies. The ideal range thresholds would depend on the surface temperature, atmospheric profiles and satellite zenith angle (at least), and pre-specifying thresholds that are successful across a wide set of circumstances is challenging. Spatial coherence information is also used to distinguish clouds and sea, and similar comments apply to determining these thresholds also.

Applying cloud detection for SST to lake bodies gives a useful result in some cases – particularly for the largest lakes with altitudes near sea level. It also helps if they are saline and are at a temperature no too different from SSTs for their latitude. Thus, SST schemes often give sensible results for the Great Lakes, Caspian Sea, etc, at least for some seasons.

However, more modest lakes can display greater spatial variability than is typical for the ocean, because of the effects of depth variations and thermal barring. This can trip tests for spatial coherence, leading to false detection of cloud.

The BT-Lake ST relationships are also changed by high elevation (less intervening atmosphere to affect IR radiance) and by continentality of air-mass. This can lead to false detection, and also failure to detect. Failures to detect cloud can cause large errors in retrieved Lake ST.

For cloud detection in ARC-Lake, we use a Bayesian approach [8, 9, 10] informed by the forward modelling discussed above in Section 4. This compares the expected (modelled) and observed BTs, and calculates in the context of various relevant uncertainties the probability the observation being clear-sky. The only threshold in the scheme is the threshold in the probability of clear sky above which Lake ST retrievals are made.

Fig. 5 shows a case study of the Bayesian cloud detection. Although the Bayesian approach adapts to the atmospheric conditions automatically (to the degree these are represented in NWP), the spatial coherence statistics currently used are still those developed for ARC SST work, and thus the results are preliminary.

6. TEMPERATURE RETRIEVAL

Earlier work [11] established that Lake ST retrieval using standard ATSR SST retrieval coefficients is prone, for some lakes, to retrieval biases of 0.5 K. (By retrieval bias, we mean the systematic offset between satellite and true Lake ST that arises from imperfection in the retrieval algorithm. Occasional “biases” from failures in cloud detection can be larger.) This contrasts with a level of SST retrieval bias for ATSR that is generally <0.2 K. One solution could be to specify lake-specific retrieval coefficients. But this is not really a scalable solution as we look forward to later phases of the project, where more lakes will be tackled.

The Lake ST retrieval is therefore done by optimal estimation (OE). We use a simplified formulation of the inverse problem originally developed for SST observations from the Advanced Very High Resolution Radiometer (AVHRR) [12]. This formulation includes only Lake ST and total column water vapour as retrieved (state) variables (all though full profile forward modelling is of course used). No radiance bias correction is yet derived for ATSR BTs, so the RTTOV8.7-simulated BTs are used “as is”.

7. TEMPERATURE VALIDATION

Lake temperature validation data are relatively sparse. Here we present a validation of OE Lake STs against moored buoys placed in 16 phase one lakes. The existence of suitable observations in a further 8 lakes has been identified from the literature, but data have not yet been forthcoming. Most of the available validation data are from the Great Lakes, with some from Canadian lakes and Scandinavian lakes. The locations of lakes with validation data so far is shown as Fig. 1.

Within this set of 16 lakes there are 52 observation sites. Most sites provide hourly observations over time periods of years; however in some cases observations are only daily and/or more short lived or sporadic in their temporal coverage. At sites where the lake is frozen for considerable lengths of time, in situ observations are unavailable during the frozen period.

Lake STs retrieved from ARC-Lake are validated against the in situ observations and also compared to equivalent validation of Lake STs from the operational cloud screening (SADIST) and retrieval scheme. Such assessment has been carried out for retrievals using the various standard channel combinations for both day and night time observations. Results for day time D2 (dual view, 11 µm and 12 µm channels) and night time D3 (dual view, 3.7 µm, 11 µm and 12 µm channels), using the Bayesian maximum channel-set cloud
Figure 5. Case study of cloud detection, and retrieval. Left: reflectance imagery reveals clear skies over northern portion (towards top of image, low reflectance areas). Right: ARC-Lake ST retrieval (black areas are masked as cloud). Lake STs are retrieved for most clear-sky areas of the lake, although testing of spatial coherence leads to several areas of false detection (near coasts and around thermal fronts within the lake).

screening, are presented for AATSR in Fig. 6. Corresponding statistics are provided in Tab. 1.

![Image](image_url)

Figure 6. Lake ST-Buoy differences against buoy temperature for AATSR. (a) and (b) operational SADIST day and night, (c) and (d) ARC-Lake day and night.

<table>
<thead>
<tr>
<th>Retrieval</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>RSD</th>
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<tr>
<td>(a) SADIST / Day / D2</td>
<td>1520</td>
<td>0.12</td>
<td>1.03</td>
<td>0.55</td>
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<td>(b) SADIST / Night / D3</td>
<td>1496</td>
<td>-0.41</td>
<td>1.20</td>
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<tr>
<td>(c) Bayes / Day / D2</td>
<td>2539</td>
<td>0.37</td>
<td>0.89</td>
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<td>(d) Bayes / Night / D3</td>
<td>2653</td>
<td>-0.28</td>
<td>0.78</td>
<td>0.53</td>
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</table>

Table 1. Lake ST-Buoy validation statistics for AATSR, corresponding to Fig. 6.

The results in Fig. 6 and Tab. 1 are for direct comparison of satellite and buoy observations; no adjustment is made for the skin-bulk effect. Biases from the operational and ARC-Lake retrievals are of the order expected for skin-bulk comparisons. RSDs are also comparable across the retrieval schemes. However, the Bayesian cloud screening used in ARC-Lake returns a greater number of observations than the operational SADIST method. This increased number of observations coupled with no increase in retrieval uncertainty gives us confidence that the Bayesian cloud screening offers consistently improved cloud masking. A further benefit of the ARC-Lake retrievals is the reduction of trends in Lake ST-buoy biases with temperature (Fig. 6).

Consistent biases (within 0.2 K compared to 0.7 K for the operational retrievals) are observed across OE retrievals using various possible channel combinations (not presented). Retrieval uncertainty is also consistent across these channel combinations. Biases and RSDs...
are also comparable between retrievals using Bayesian maximum and minimum channel-set cloud screening (i.e. with and without the 3.7 μm channel). This is of particular importance for extending the ARC-Lake project to include ATSR-1, due to the failure of the 3.7 μm channel on this instrument. Very similar results are observed for ATSR-2. Numerical results are presented in Tab. 2.

<table>
<thead>
<tr>
<th>Retrieval</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>RSD</th>
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<tbody>
<tr>
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<td>(b) SADIST / Night / D3</td>
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<td>(c) Bayes / Day / D2</td>
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<td>(d) Bayes / Night / D3</td>
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<td>-0.14</td>
<td>0.79</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 2. Lake ST-Buoy validation statistics for ATSR-2.

8. Ice Detection

The ARC-Lake project also provides observations of lake ice cover (LIC). This is based on the Normalized Snow Difference Index (NSDI) [13] and is limited to daytime observations (as it uses visible reflectance channels). The LIC product is preliminary and has yet to be validated for ARC-Lake. As a demonstration of the potential of the LIC product we present an example of the ice mask for a case study of lakes Onega and Beloye, in Russia (Fig. 7). In this example ice is correctly masked over the whole of Lake Beloye, and the northern section of Lake Onega, while Lake STs are retrieved over the ice-free region in the south of Lake Onega.

9. Science Applications

The ARC-Lake project produces Lake ST (and associated uncertainty) and LIC products on a 1/20° latitude-longitude grid. These are available for each day with potential ATSR observations, with day-time and night-time considered separately. ARC-Lake data may be downloaded from www.geos.ed.ac.uk/arclake. Spatially complete reconstructions [6], as used as the prior Lake ST field, are also available. Some of the potential science applications of the ARC-Lake data are explored in this section.
Perhaps the most obvious application of the ARC-Lake data products is in improving our knowledge of basic lake climatological information. As shown in Fig. 1, most lakes are poorly monitored in situ, therefore ARC-Lake offers a potentially far more globally complete picture of lake climatology, since 1991. Figures 8 and 9 provide examples of the type of climatological information that can be determined from ARC-Lake output. Fig. 8 shows the lake-mean seasonal Lake ST range for all phase one lakes and illustrates the global nature of the coverage provided. Low temperature ranges are observed in the tropics, with the peak temperature ranges occurring at around 45° N. Moving to higher latitudes the temperature range generally decreases again as the lakes do not receive sufficient heating following the frozen period to reach such high temperatures. Fig. 9 shows the lake-mean seasonal trend in Lake ST for Lake Vattern (Sweden) and compares ARC-Lake climatology to that from MODIS and from the online lake model, Flake [5]. Broadly good agreement is observed for this case but for some other lakes ARC-Lake provides a more reasonable seasonal climatology than MODIS.

Recent work [14] has found dramatic warming trends in Lake surface temperatures over a number of North American lakes. For Lake Tahoe, warming trends of >1 K decade⁻¹ are shown over the ATSR lifetime (Fig. 11). Unfortunately the data available to this study [14] did not include the overlap periods between ATSR instruments and was also missing ATSR-2 data in the late 90s. In ARC-Lake, ATSR-1 has not yet been processed but the ARC-Lake observations for ATSR-2 and AATSR (Fig. 11) do not yield the same dramatic warming trend as found in [14]. Neither set of results in Fig. 11 accounts for differences between the ATSR sensors or observation times and therefore both results should be interpreted with caution.

Lake ST observations of the form available from ARC-Lake, if made operational, have potential to improve NWP, through assimilation. This is demonstrated in Fig. 12, where ARC-Lake observations are compared with NWP data and in situ observations for Lake Nyasa. A climatological cycle is represented in the NWP data but the magnitude of the NWP temperatures are significantly different to those observed in ARC-Lake. There is good agreement between ARC-Lake and in situ observations, giving confidence that the ARC-Lake observation provide accurate Lake STs.
Figure 12. Comparison surface temperatures from NWP and ARC-Lake observations for Lake Nyasa. NWP data are ECMWF ERA-40 from 1995-2002 and ECMWF operational from 2002-2010. In situ observations are shown in orange.

10. Future Work

Phase two of ARC-Lake will see the time series of observations extended back to 1991, through application of the methodology defined to ATSR-1. Efforts will also be made to homogenize the observations from the difference sensors through analysis of the overlap periods. This will provide a stable time series suitable for climate analysis. Finally, the existing ice detection methods with be developed. In Phase three, the techniques developed and validated for large lakes will be applied to smaller lakes. The size threshold for this work has yet to be defined. Beyond the time-frame of the ARC-Lake project, it is hoped that Lake ST products can be delivered operationally in Sentinel-3.

11. References


