

Operational processing of NOAA - AVHRR data for mapping lake surface temperatures in an alpine environment: feasibility and validation

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ABSTRACT

Lake surface water temperature (LSWT) are operationally derived from the National Oceanic and Atmospheric Administration operated Advanced Very High Resolution Radiometer (NOAA - AVHRR) data using a nonlinear sea surface temperature (NLSST) algorithm. The adapted method has been widely examined with the bias of the algorithm around 0.5°C or better. Preliminary analysis shows good agreement between satellite derived LSWT and in - situ measurements at two different lakes. A comparison of LSWT at noon (mean local time) for three lakes is presented. Surface water temperature variations are dominating the annual cycle, however, the varying geospatial attributes of each lake result in specific surface temperature characteristics. Lakes located close to each other can display considerable differences in average surface temperatures by as much as 3°C. Knowledge of this fact gives new insights and possibilities for modeling local scale meteorological phenomena like heat flux, energy budget and evapotranspiration. Using operational satellite-derived lake surface temperature can also improve numerical weather prediction models on local scales.

Keywords: Sea surface temperature, operational application, NOAA - AVHRR, thermal remote sensing

1. INTRODUCTION

LSWT has a strong influence on the entire lacustrine ecosystem, including the human activities located around the water bodies. Lakes of sufficient volume and areal extent affect regional weather patterns more than any other lake parameter.¹ Spatial and temporal variations in waterbodies play an important role in those processes. Possible applications of lake temperature are the derivation of energy fluxes / budget, studies of lake current models and input for assimilation in numerical weather prediction (NWP) models.²⁻⁴ Lake surface temperatures can also be used to monitor climatological temperature conditions, since they have a high spatial and temporal heterogeneity.^{5,6} The accuracy required for global change studies is about 0.3°C, whereas as for the NWP 0.5°C is sufficient.^{7,8}

Infrared imaging sensors on weather satellites, such as from the NOAA - AVHRR were found to be an excellent tool to obtain consistent temperature distribution pattern information for large water bodies.⁶ Schwab⁵ has successfully established an automatic mapping technique for the Great Lakes in North America. In Switzerland alone, 24 lakes with an area greater than 1km² exist. For those lakes, no consistent lake wide climatological data - set is available. Satellite data of the alpine region has been used to map and analyze LSWT and other features for a case study for Lake Constance by Schneider⁹ using NOAA - AVHRR and LANDSAT - TM data.

The purpose of this paper is to investigate the suitability of the NOAA - AVHRR sensor for an operational monitoring of LSWT of small water bodies in a topographic complex terrain such as the Alps. A new combination

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of geocoding and orthorectification procedure has been implemented for operational processing resulting in high spatial accuracy.

This paper describes the characteristics of the satellite data including the image mapping parameters. The technique uses a near-real time processing scheme including LSWT algorithm based on the sea surface temperature (SST) approach introduced by McClain¹⁰ as modified by Schwab.⁵ Radiative transfer theory is used to correct for the effects of the atmosphere on the observations by utilizing "windows" of the electromagnetic spectrum where little or no atmospheric absorption occurs. Channel radiances are transformed through the use of the Planck function to units of temperature, then compared to a-priori temperatures measured at the surface. This comparison yields coefficients which, when applied to the AVHRR data, give estimates of lake surface temperature which have been nominally accurate with an bias of 0.3°C or better depending on the satellite platform.⁸ Additionally, a cloud mask using CASPR¹¹ is derived, so that automated maps can be produced in near real-time. An accurate cloud mask is essential for the alpine region, because with its topography and location in the mid latitudes, blocking situations of air masses occur, causing a wide variety of cloud types.

The year 2002 was chosen for a comparison with in - situ data. This study uses local point data from three different sites situated in two lakes (Lake Geneva and Lake Neuchâtel) in Western Switzerland for validation, as shown in Fig.1.

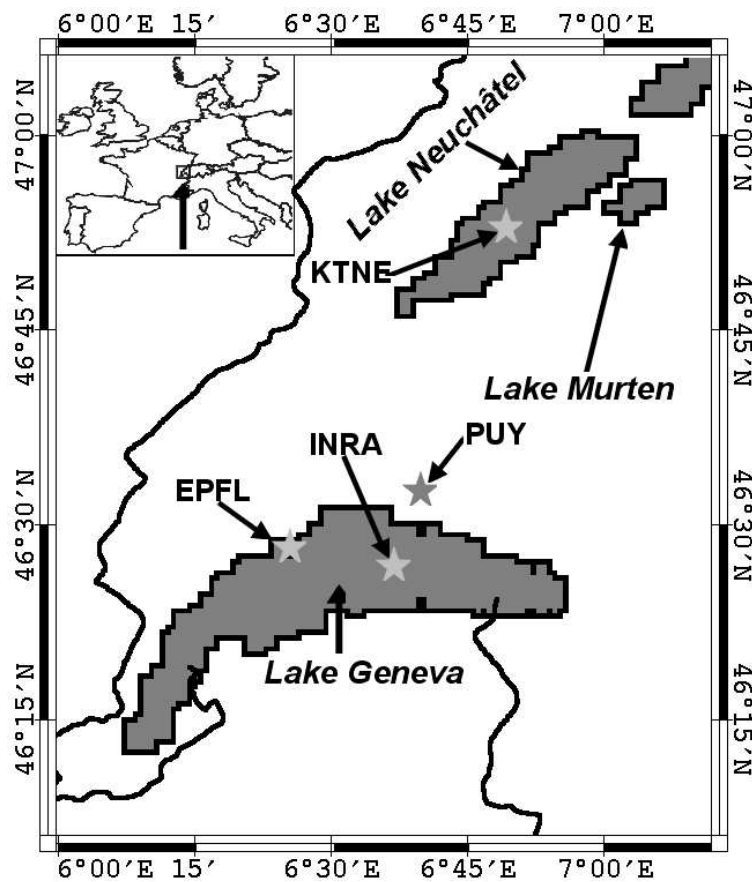


Figure 1. The area of interest located in Western Switzerland with the different positions of the in - situ measurements (INRA, KTNE, EPFL) and the position of the meteorological station from MeteoSwiss at Pully (PUY).

2. METHOD

2.1. Data

2.1.1. AVHRR imagery

The data presented in this paper uses observations from the 5-channel AVHRR (AVHRR-2 and AVHRR-3 instruments) on board the operational NOAA polar satellites. These satellites are in sun-synchronous orbits, with nominal ascending equatorial crossings at 7:30 AM and 2:00 PM. The instruments measure emitted and reflected radiances in the following bands: 0.58-0.68 (channel 1), 0.725-1.10 (channel 2), 3.55-3.93 (channel 3), 10.3-11.3 (channel 4), and 11.5-12.5 micrometers (channel 5). The nominal instrument spatial resolution is 1.1 km.

The high resolution picture transmission (HRPT) data are ingested by the receiving station located in Bern, Switzerland (46° 55' 42"N / 7° 28' 41"E). Since August 2001, we are in an operational status to receive and process all data covering the European Alps in near - real time. Thermal calibration is done according to Goodrum¹² and SHARP Level-2 User Guide.¹³ The nonlinear modification to this calibration for the thermal channels is achieved at the time of postprocessing, and takes into account sensor nonlinearities, measurement of internal target temperature, calculation of target radiance, internal reflections and emissions as discussed by Rao¹⁴ and applied by Ouaidrari.¹⁵ This radiance-based correction procedure results in a single correction algorithm applicable over the entire range of AVHRR operating temperatures, representing a significant improvement over the use of myriad tables to look up temperature corrections.

To detect and estimate the LSWT of small lakes with a spatial extent of a few square kilometers, a feature matching algorithm is used to geocode the satellite imagery with sub-pixel accuracy. The rectification process is carried out by using piecewise linear mapping functions throughout the whole image. Input and output images are partitioned into patches defined by closest grid points. An affine transformation function is evaluated at every pixel on the output image (i.e. on the rectified image) by using three closest georeferenced points on the grid and their respective image coordinates. Image geocoding includes four steps. Firstly, an image is approximately rectified using the control point grid that was generated from the image file. Secondly, ground control points are defined. The method uses two images, a reference map and the image to be rectified. This method is based on sub-window correlation between two images, and it automatically finds control points. A ground control points file will be produced. Thirdly, the grid will be corrected by using previously defined ground control points. This includes re-computing the grid coordinate locations. After this, we have a control points grid with correct geographic values. Fourthly, the original image will be rectified again. The benefit of the grid-rectification method compared with the more conventional approaches, is that it will carry out the re-mapping process only once, from original coordinates to final coordinates without any intermediate steps. The geometric accuracy of the original grid is normally within few kilometers. The accuracy of the corrected grid is in most cases less than a pixel. The process of mapping the image to geometrical coordinate system is actually a single phase process. No system corrections are required in advance.

An orthorectification of the imagery is essential in an alpine region to overcome the displacement errors introduced by the topography. An automated procedure which uses a terrain model based on the GTOPO30 was developed and implemented. The resulting data - set is subset to a latitude - longitude grid on the WGS84 ellipsoid with the dimension of 1700x1357 pixels, covering the alpine region from 0°E - 17°E and 40° 30'N - 50°N. The pixel size in longitude dimension was defined as 0.007 degrees, in the latitude dimension 0.01 degrees.

2.1.2. In - Situ Data

A few temperature data - sets at locations of opportunity (Fig.1) are available, such as the measurements from the Institut National de la Recherche Agronomique (INRA) site in the center of Lake Geneva, monthly measurements from the Service de la protection de l'environnement de Neuchâtel (KTNE) site in the center of Lake Neuchâtel and the hourly measurements of the École polytechnique fédérale de Lausanne (EPFL) at their meteorological weather station located at the shore. Unfortunately, these point measurements are not adequate for resolving the spatial temperature distribution of the lake, because of the high spatial and temporal variability of water temperature near the shore zones and their in some cases limited temporal coverage.

The thirteen in - situ measurements for central Lake Neuchâtel (46° 54' 48.4" N / 6° 50' 38.1" E) were made in the year 2002 by a KTNE operated boat. Unfortunately, the exact time and the depth below the water surface of the data take are not known. For central Lake Geneva (46° 27' 09.7" N / 6° 35' 19.4" E), seven measurement were made in the same year by INRA. Here also, exact time and the depth of the data measured are not known. The EPFL pylon is equipped with meteorological sensors and a water temperature sensor at approximately 1m depth (not a floating device), and records an hourly average. The station is located in a water depth of 3 - 4m, 100m off shore (46° 27' 30.1" N / 6° 23' 58.5" E).

2.2. Algorithm

Since the nineties, satellite imagery has been used for LSWT derivation as described by Schwab.⁶ The procedure used is essentially the nonlinear SST split-window algorithm (NLSST) (Walton⁷). The history and development of SST computation from NOAA - AVHRR radiances is explained at length by McClain¹⁰ and Li.⁸ Radiative transfer theory is applied to correct for the effects of the atmosphere on the observations in the two thermal channels of the electromagnetic spectrum where little or no atmospheric absorption occurs. A slight but not negligible distortion of the infrared channels in this spectrum are due to the effect of water vapor. The "split window technique" utilizes the difference between channel 4 and channel 5 to correct this effect: The temperature difference between these two channels is proportional to the amount of water vapor in the atmosphere, because infrared radiation undergoes a stronger absorption due to atmospheric moisture within channel 5 than within channel 4. Another advantage of the split window approach is the fact, that it takes into account the varying atmospheric path length variations with the satellite viewing angle. Also, the method takes into account the 'skin' effect of radiometric temperatures, so they can be compared with 'bulk' temperatures, like in - situ measured data.^{16, 17}

The more advanced NLSST uses the multi-channel sea surface temperature algorithm (MCSST) as a first estimate of sea surface temperature for the non linear term of the equation. For night and day passes, different coefficients for the equations are applied, which are provided by NOAA's National Environmental Satellite Data and Information Service (NESDIS) as described by Walton.⁷ The coefficients are independent of season, geographic location or atmospheric moisture content. Adjustments are necessary if spacecraft instruments calibration changed or background aerosol content in the stratosphere is affected by volcanic eruption. When applying this method to continental lakes, such as the North American Great Lakes, accuracy of LSWT estimation comes up with a bias of 0.5°C, or better depending on the satellite platform.⁵ The root mean square differences range from 1.10 to 1.76°C.

The form of the LSWT retrieval algorithms used in this paper is suggested by Li⁸ as

$$NLSST = A1(T11) + A2(T11 - T12)(MCSST) + A3(T11 - T12)(Secq - 1) - A4 \quad (1)$$

$$MCSST = B1(T11) + B2(T11 - T12) + B3(T11 - T12)(Secq - 1) - B4. \quad (2)$$

T11 and T12 are channel 4 and 5 temperatures in Kelvin; Secq is the secant of the satellite zenith angle q; NLSST and MCSST are the nonlinear and linear multi-channel SST, respectively, in degrees centigrade; A1-A4 and B1-B4 are the coefficients according to NESDIS. The valid range of the NLSST approach ranges from -5°C to 30°C.

A lake - land mask according to the Pan-European Land Use and Land Cover Monitoring (PELCOM)¹⁸ data - set is used to determine the water bodies. To avoid mixed land and water pixel, an additional buffer distance of the size of one AVHRR pixel is applied to the shoreline, as shown as black border in Fig.1. To maintain high accuracy of LSWT algorithm, pixel viewed with an satellite zenith angle greater than 53° are omitted, since larger atmospheric path lengths leads to greater attenuation of surface emitted radiance.

A day (sun zenith less than 75°) and night (sun zenith greater than 75°) threshold scheme is used to mask out cloud contaminated pixel, which are not detected by CASPR. During daytime, a gross IR test and visible cloud threshold test is performed: Pixels with channel 4 temperatures lower than 0°C or if the corrected albedo (albedo value divided by the cosine of the solar zenith angle) is greater than 10 percent are considered as cloud contaminated. The gross IR test is also used for night satellite imagery together with a test for low stratus

clouds: The difference obtained when subtracting channel 3 temperature from channel 5 temperature must be less or equal -0.6°C . Finally, as Schwab⁵ suggested, pixels with a standard deviation greater than 3°C computed of the neighboring pixels and pixels completely surrounded by non - valid data are rejected. Finally the the image is filtered with a 9×9 simple average filter to smooth any high frequency noise in the image.

3. RESULTS

Three lakes of different size and with varying geomorphological properties, as shown in Fig.1 and Table 1, are used for validation and comparison. The size of the lakes vary from 23.0km^2 for Lake Murten up to 583.1km^2 for Lake Geneva. The limnological regime of the three lakes are completely different, since their depths vary from 46 to 310m. The development of the diurnal and annual thermocline is directly related to the lake depth. All three lakes are situated within $100\times 100\text{km}^2$ area at the foot of the Jura mountain range, however they are subject to different local meteorological influences: Lake Neuchâtel is often influenced by postfrontal cloud systems, which tend deepen over the hills of the Jura mountain range while the eastern parts of Lake Geneva are often affected by local meteorological processes related to the valley of Valais.

The different lake sizes are not only a challenge for the LSWT algorithm itself but also for the feature matching algorithm: While Lake Geneva is represented by up to 824 LSWT pixel, Lake Murten LSWT is sampled with only 10 pixels in cloud free situations. Also, the southeast shore of Lake Geneva is surrounded by a mountain range with altitudes up to 2200 m.a.s.l., the orthorectification has to be accurate.

Table 1. Hydrological properties of the lakes (Fig.1) used in this study.

| Name | Average spatial coverage [km ²] | Average lakelevel [m.a.s.l.] | Total volume [10 ⁶ m ³] | Maximum depth [m] | Maximum number of map pixels covering lake |
|----------------|---|------------------------------|--|-------------------|--|
| Lake Geneva | 581.3 | 372 | 89'900 | 310 | 824 |
| Lake Neuchâtel | 217.0 | 429 | 14'170 | 153 | 244 |
| Lake Murten | 23.0 | 429 | 600 | 46 | 10 |

Fig.2 shows the time series for the thirteen in - situ temperatures made at KTNE and the AVHRR derived LSWT. For the sake of simplicity and because an accurate time of in - situ measurements is not known, the in - situ data of KTNE in Fig.2 is compared with AVHRR derived LSWT ranging from 11-15 UTC (NOAA-16 noon passes). The AVHRR LSWT for cloud free conditions at the pixel location of KTNE is smoothed with a boxcar average of 9. The overall characteristics of the two data sets are the same, considering the few data points available by KTNE. During the period of July and August, no in - situ measurements were taken: so the temperature variations shown by the AVHRR LSWT in this period can not be detected by the KTNE due to the limited temporal resolution of the in - situ data - set. Generally, the temperature curves for this data point show good agreement in Spring, whereas during Autumn / Winter time, LSWT is about 2°C cooler.

Examining the comparisons for the larger and deeper Lake Geneva in Fig.3 between EPFL and AVHRR LSWT shore temperatures (bottom) and INRA for central lake (top) respectively, reveals a similar behavior to the intercomparison at the KTNE site in Fig.2. The EPFL pole is situated within the additional buffer shore zone of the AVHRR imagery, so for the pixel covering the position of the pole no LSWT is available. To overcome this, the mean of adjacent 3×3 pixels is compared with the point measurement. Considering the fact that EPFL is representing temperatures of a waterbody of 3 - 4m in depth and AVHRR LSWT pixels are located at depths of about 100m, the agreement is good. The seven data points of INRA are of limited use for intercomparison with corresponding AVHRR LSWT since the exact time and depth of the measurement were not available.

Fig.3 and Fig.2 show that the AVHRR LSWT from Autumn to Spring has a cool bias. This discrepancy in the surface layer can be explained with two different, but connected processes. First, LSWT at the top skin layer of the waterbody reacts stronger to changes in solar irradiation input than the deeper measured in - situ data, as

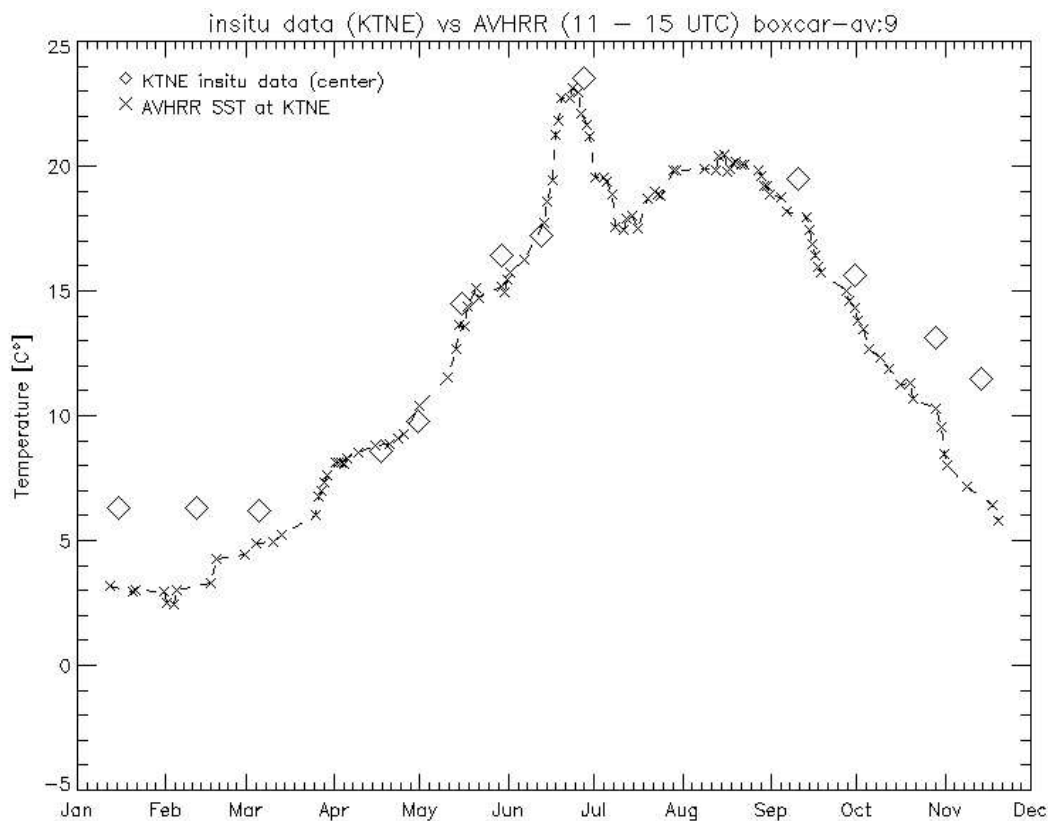


Figure 2. Lake Neuchâtel: Comparison of in - situ measurements by KTNE (diamonds) with AVHRR LSWT (× connected with a dashed line) at central lake Neuchâtel for the year 2002. The AVHRR LSWT temperature is representing the pixels at KTNE location at cloudfree condition. The satellite data is smoothed with a boxcar average of 9.

can be seen from the global radiation data from meteorological station located at Pully (PUY) in Fig.3. This is evident during the April to June period in Lake Geneva: pixels located in the deeper center react stronger than the littoral LSWT AVHRR. As soon as the input from solar energy decreases to account for latent heat loss in Autumn, the upper water layer is cooling down faster than the underlying parts. The other process assumed to influence this temperature pattern is related to the internal annual circulation pattern, which is inherent to each lake. Both lakes, are situated in a temperate climatic zone and have a dimictic behavior: they usually mix twice annually in the Spring and in the Autumn. This mixing process, partly driven by global radiation and strong winds, alters the energy transfer process in the uppermost layer of the waterbodies, and can explain in this case the increasing bias between in - situ and AVHRR LSWT data - set.

4. DISCUSSION AND CONCLUSION

One purpose of the implementation of a LSWT algorithm for NOAA - AVHRR imagery is to gather information about the annual cycle of the water surface temperature as function of lake size. The intercomparison with in - situ data shows that the temporal coverage of AVHRR data result in a new dimension of information density on LSWT. The comparison with in - situ data shows good agreement in most cases. In a first approach, a comparison of mean noon (11-15 UTC) LSWT for three different sized lakes in Western Switzerland was performed, as shown in Fig.4. LSWT is derived from AVHRR imagery if 80 percent of the corresponding lake surface was cloud free. This condition was fulfilled in 79 cases for Lake Geneva, 72 for Lake Neuchâtel and 48 for Lake Murten respectively. The data has been filtered with a boxcar average with the size of 9. As expected

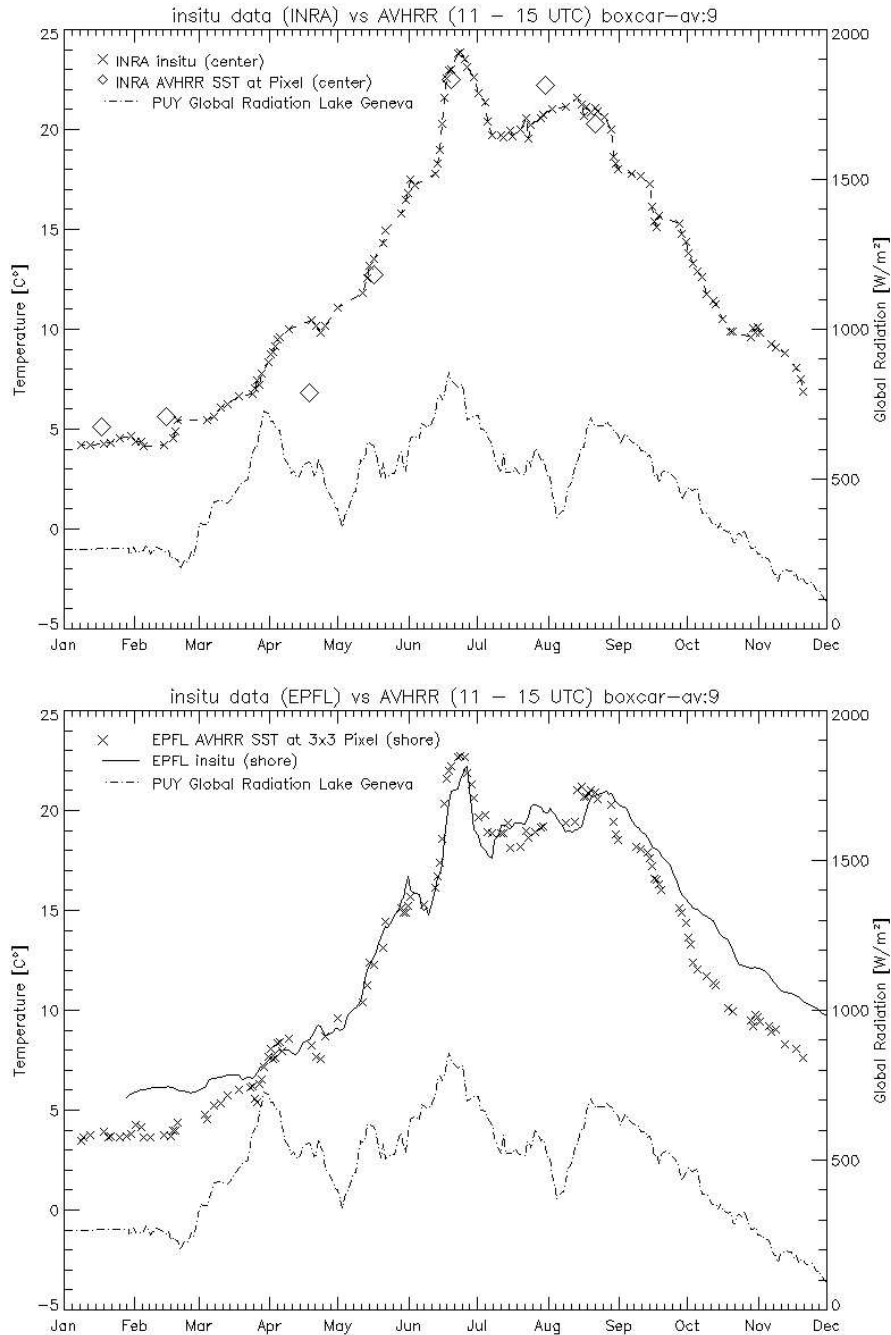


Figure 3. Lake Geneva, top: Central Lake Geneva temperatures at INRA (diamonds) are compared with AVHRR LSWT (\times connected with a dashed line) at INRA position for the year 2002. Bottom: Comparison of in - situ measurements by EPFL (solid line) with AVHRR LSWT (\times) at the shore of Lake Geneva, representing a 3×3 pixel area surrounding the EPFL point measurements, for the year 2002. In both plots, satellite data is smoothed with a boxcar average of 9 and the mean global radiation for 11-15 UTC at the meteorological station located at Pully (PUY) is plotted as a dash dotted line.

Lake Murten shows a more prominent annual cycle. Because of its small water volume, its heat diffusivity is higher than the bigger sized lakes. During Winter it is evident that the size of the lake determines the average temperature, while in Spring, at the beginning of April, within days Lake Murten turns from the coldest lake into the warmest, highlighting the effect of lake size and high global radiation (Fig.3). Temperature differences between the lakes can be as high as 3°C.

Additional and more exact in - situ data from more lakes is necessary to complete the validation and determine the quantitative quality of the AVHRR LSWT measurements. A more thorough understanding of LSWT variability, and in particular the Winter bias, can only be achieved with knowledge of the diurnal variations of the lake thermocline. A satellite image composite technique needs to be established to provide a continuous data - set throughout the year, so LSWT estimation for cloudy conditions are available. The processing scheme discussed in this paper has shown a certain reliability in a challenging environment such as the European Alps. The feasibility of the AVHRR sensor to detect LSWT of lakes with the size as small as 23km² in an operational manner has been proved. Based on this, the derivation of climatological LSWT for lakes covering areas greater than several km² can be done using AVHRR imagery. Taking advantage of the near realtime capabilities of the processing scheme, assimilation in NWP is possible.

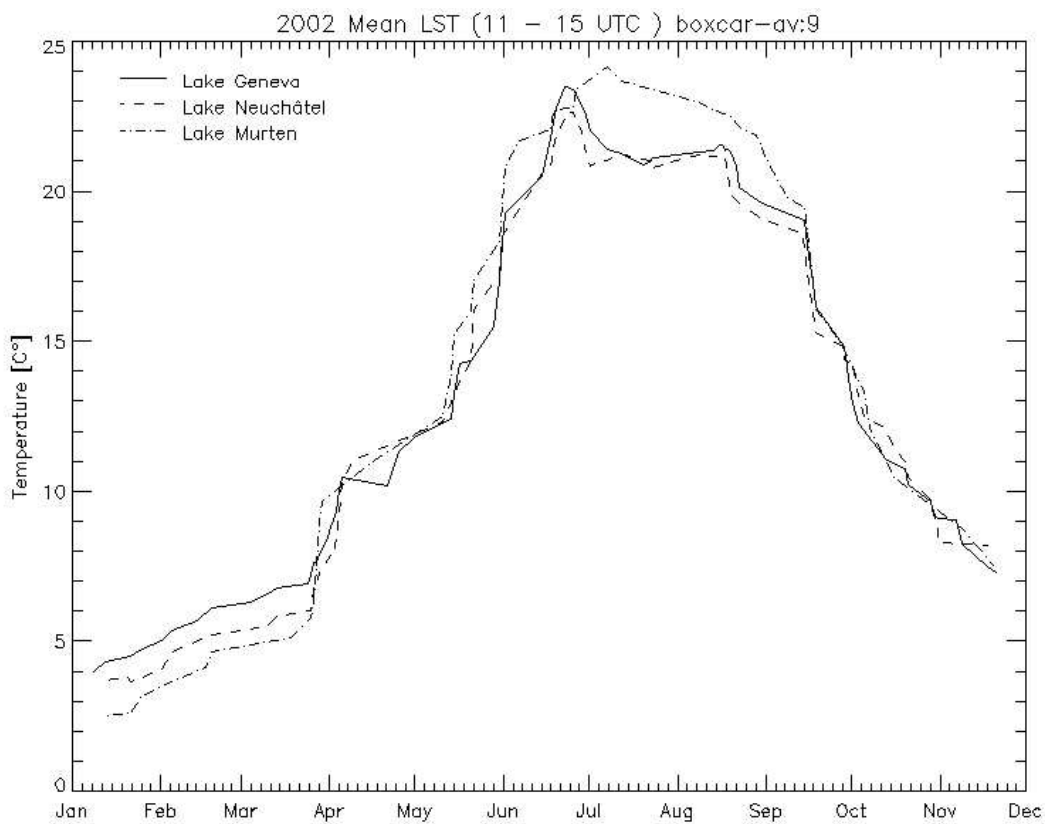


Figure 4. Mean noon (11-15 UTC) LSWT for three different sized lakes in Western Switzerland for the year 2002. LSWT is calculated from AVHRR imagery if 80 percent of the lake surface is cloud free. The result is filtered with a boxcar filter with the size of 9.

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