OPERATIONAL MAPPING OF LAKE SURFACE TEMPERATURE IN THE ALPS USING NOAA – AVHRR DATA:

INTERCOMPARISON OF DIFFERENT LAKES

D. Oesch, A. Hauser and S. Wunderle

Remote Sensing Research Group, Department of Geography
University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland
oesch@giub.unibe.ch, http://saturn.unibe.ch/rsbern

ABSTRACT

Continental lakes, such as those in the alpine region, contain a sufficient large volume and areal extent of water. In this case, lake surface water temperatures (LSWT) can exert a significant influence on local weather patterns. In addition, monitoring of climatological temperature conditions, temporal and spatial distribution of the lake surface temperature can be extremely valuable for different applications. Up to now, there is no area-wide consistent temperature data set for the alpine lakes available, especially not in real-time as it is required for several applications such as for the assimilation in numerical weather prediction models (NWP). Also, in situ measurements can not take into account the high LSWT variability in near shore zones and their limited spatial coverage are not adequate for resolving the spatial distribution of temperature in the lakes.

An operational real-time processing chain for NOAA-AVHRR data is used, from which LSWT measurements based on a non-linear SST algorithm are derived. The method used has been widely examined and the bias of the algorithm is around 0.5-1 K. Results show on the one hand the wide variety of annual mean LSWT for the different lakes in the Alpine environment, as one would expect. The different morphological features of the lakes, such as average lake depth can explain this behaviour. On the other hand strong surface temperature pattern variations over one year within lakes can be observed, such as shown for Lake Constance.

Knowledge of this fact gives new insights and possibilities for modelling 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 with grid sizes of a few kilometres.

1. INTRODUCTION

In the alpine region a substantial amount of lakes can be found with different morphology, size and geographic location. In Switzerland alone, there are more than twenty lakes with an area greater than $1km^2$. In general, water bodies have a significant influence on ecosystems on local and regional scale and are therefore sensitive to human activities. Most lakes contain a sufficient large volume and areal extent of water to exert a significant influence on local weather patterns [Livingstone and Dokulil, 2001]. Spatial and temporal LSWT 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 for assimilation in numerical weather prediction (NWP) models [Hasager *et al.*, 2002; Hasse and Smith, 1997; Lofgren and Zhu, 2000]. The spatial resolution of NWP's, such as the *Alpine Local Model* (aLMo) run by the MeteoSwiss, are dealing with scales in which meteorological processes related to lake parameters become important. LSWT is also useful for monitoring climatological temperature conditions, since they have a high spatial and temporal heterogeneity [Schwab *et al.*, 1992; Schwab *et al.*, 1999]. The accuracy required for assimilation of LSWT in NWP's is 0.5°C [Li *et al.*, 2001; Walton *et al.*, 1998].

Up to now, there is no area-wide consistent temperature data set for the alpine lakes available. Only a few in situ measurements at points of opportunity are available, which are not suitable to derive the temperature pattern properties of the entire lake surface. This infrared imaging sensor was found to be an excellent tool to obtain consistent temperature distribution pattern information for large water bodies [Schwab *et al.*, 1992].
The purpose of this paper is to proof the feasibility of the NOAA - AVHRR sensor to provide in a heterogeneous topography on an operational basis for small water bodies consistent LSWT data sets. The results in this paper show the heterogeneity of the annual mean LSWT amplitudes of the different lakes located in the Alps. In a second example, the LSWT variations within a lake during one year are discussed.

2. DATA

Full resolution AVHRR data are read out in High Resolution Picture Transmission (HRPT) format at the receiving station of the University of Bern. These data are the starting point for the LSWT processing. The derived Level-1B data are then further radiometrically-corrected and calibrated in physical units at full instrument resolution as acquired. 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. To detect and estimate the LSWT of small lakes with a spatial extent of a few square kilometres, a feature-matching algorithm is used to geocode the satellite imagery with subpixel accuracy. The rectification process is carried out by using piecewise linear mapping functions throughout the whole image. 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.

3. METHOD

In this paper the NOAA-16 sensor counts of noon passes in channels 4 (10.3-11.3µm) and 5 (11.5-12.5µm) are transformed to units of "brightness temperature", using the Planck black body function. The LSWT algorithm used is essentially the nonlinear SST (NLSST) according to [Walton *et al.*, 1998], as based on [Li *et al.*, 2001] and described in [Oesch *et al.*, 2003]:

$$NLSST = a_1(ch4) + a_2(ch4 - ch5)(MCSST) + a_3(ch4 - ch5)(q) - a_4$$
$$MCSST = b_1(ch4) + b_2(ch4 - ch5) + b_3(ch4 - ch5)(q) - b_4$$

Equation 1: Lake Surface Water Temperature (LSWT) algorithm based on NLSST

where NLSST,MCSST= non-linear and multichannel SST
ch4,ch5= Channel 4 and 5 brightness temperatures in K
a_1-a_4, b_1-b_4=coefficients according to NOAA's National Environmental Satellite Data and Information Service
q=((secant of satellite zenith angle) –1)

A lake - land mask according to the Pan - European Land Use and Land Cover Monitoring (PELCOM) [Mücher *et al.*, 2000] 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.

To maintain high accuracy of the LSWT algorithm, Pixel viewed with a satellite zenith angle greater than 53° are omitted, since larger atmospheric path lengths lead 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 additionally to the cloud mask as defined by CASPR [Key, 2002]. 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 [Schwab *et al.*, 1999] suggested, pixel representing a standard deviation greater 3°C of the neighbouring pixel and completely surrounded pixel by non valid data are rejected. The result is filtered with a 9x9 average filter to smooth any high frequency noise in the image. To reduce no data pixels, the data sets used in this study consist of a mean composite map from the previous eight days for each satellite image.

A validation study of the method discussed above for lakes located the alpine region shows good agreement between in situ data and the AVHRR data set [Oesch *et al.*, 2003].

4. RESULTS

For 22 lakes of different size and varying morphological properties (Table 1) the mean average temperature for each day have been derived. The size of the lakes ranges from 23 to 587km^2, the volume from 0.5 to 89km^3 and the average depth from 5 to 171m.

Name,	**geographical location**	**Volume [km^3]**	**Area [km^2]**	**Average depth [m]**
Lake Geneva	(46N,6E)	89.9	586.9	153
Lake Murten	(46N,7E)	0.6	23.0	26
Lake Neuchatel	(46N,6E)	13.8	217.9	63
Lake Biel	(46N,7E)	1.3	39.3	32
Lake Thun	(46N,7E)	6.5	48.4	134
Lake Brienz	(46N,7E)	5.2	29.8	170
Lake Lucerne	(46N,8E)	4.2	55.9	74
Lake Zug	(47N,8E)	3.2	38.2	84
Lake Zurich	(47N,8E)	4.3	88.2	48
Lake Constance	(47N,9E)	48.4	538.5	90
Lake Ammer	(48N,11E)	1.7	46.6	37
Lake Starnberg	(48N,11E)	2.9	56.4	53
Lake Chiem	(48N,12E)	1.9	79.9	25
Lake Atter	(48N,13E)	3.8	46.0	84
Lake Bourget	(45N,5E)	3.8	44.5	85
Lake Maggiore	(45N,8E)	37.1	212.5	171
Lake Como	(45N,9E)	22.9	145.9	153
Lake Iseo	(45N,10E)	7.6	60.9	124
Lake Garda	(45N,10E)	49.0	370.0	136
Lake Trasimeno	(43N,12E)	0.6	124.0	5
Lake Bolsena	(42N,11E)	9.2	113.0	81
Lake Bracciano	(42N,12E)	5.1	57.0	89

Table 1. Properties and location of the lakes covered in this study.

These waterbodies cover a wide variety of geographic locations. Some lakes are located on the north rim (e.g. Lake Ammer, Lake Chiem, Lake Atter) and on the south rim (e.g. Lake Como, Lake Iseo, Lake Garda) of the Alps. Central alpine lakes are for example Lake Brienz and Lake Lucerne, whereas Lake Trasimeno, Bolsena and Bracciano are located in the southern parts of the Apennine Mountains.

For all these lakes, the seasonal fluctuation of the mean average lake temperature has been determined for the year 2002 (Figure 1). The mean range of LSWT over the year between the different lakes mentioned above is 8°C. This is due to the different limnological regimes, which are determined by the morphology, geographic location, catchment area properties etc. Therefore the annual mean LSWT amplitude curve for each lake is different. Most lakes show a strong warming up period in May and a temperature peak in mid June, besides that common pattern in the annual temperature amplitude curve can not easily identified.

Comparing Lake Chiem from north rim of the Alps, Lake Brienz from the central part and Lake Como from the south rim, some typical features related to the geographical location and the morphological properties can be observed. Both, Lake Como and Lake Brienz have an average depth of about 150m and also a similar annual LSWT amplitude, whereas of its southern location Lake Como has warmer LSWT during the summer months. Lake Brienz has the coldest LSWT of these three lakes during the summer period of the year 2002. On the one hand, located within the rather steep Aare valley, the amount of incoming solar radiation is reduced by the topography. On the other hand, the catchment basin includes a substantial amount of glaciers. During summertime, snow and glacier melting rate has a peak resulting in cold discharge of rivers into the lake. Lake Chiem, a shallow (25m average depth) and rather small (1.9km^3 volume) waterbody, heats up faster and stronger during spring time, respectively cools out on a higher rate during fall time.

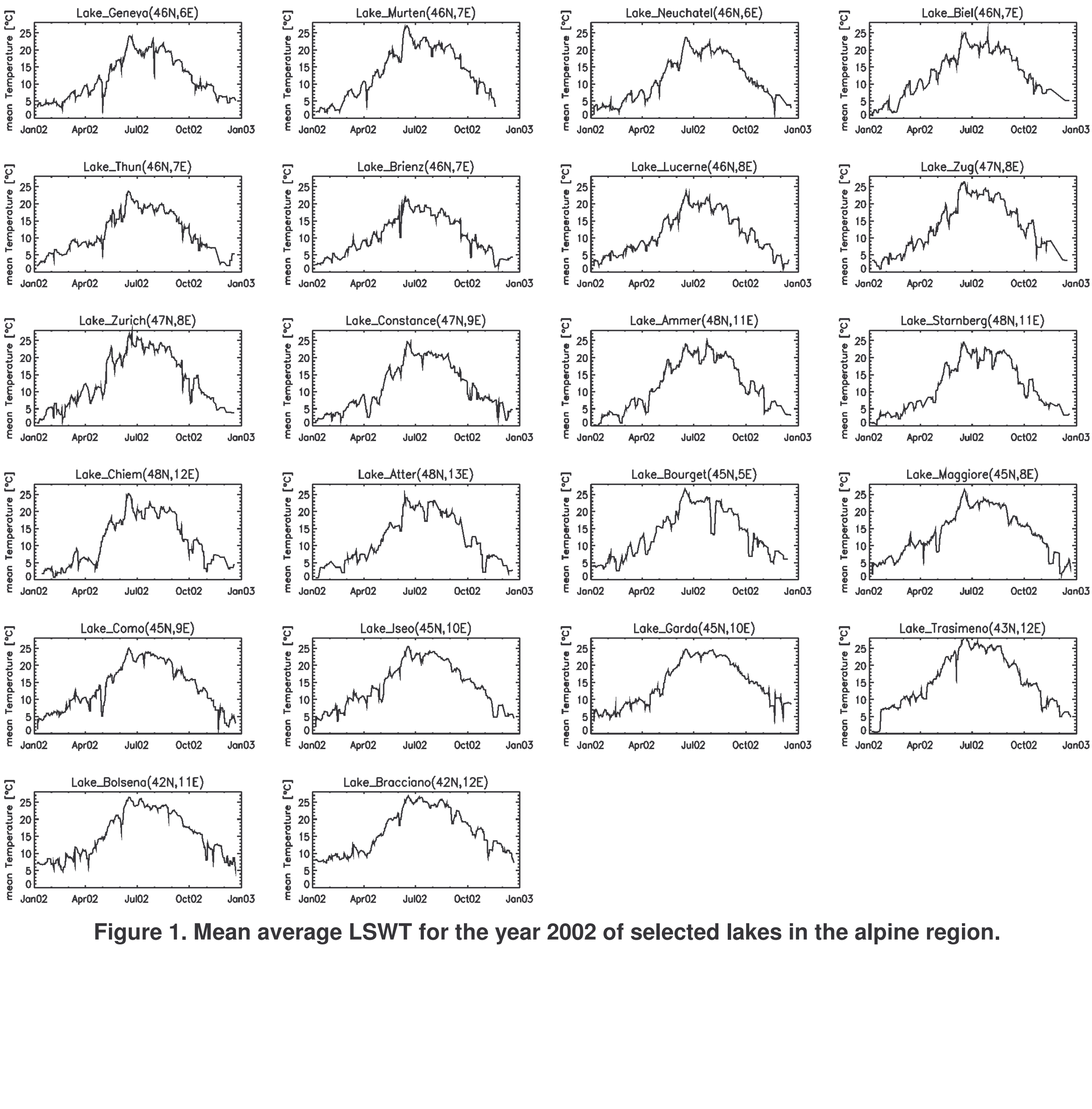

Figure 1. Mean average LSWT for the year 2002 of selected lakes in the alpine region.

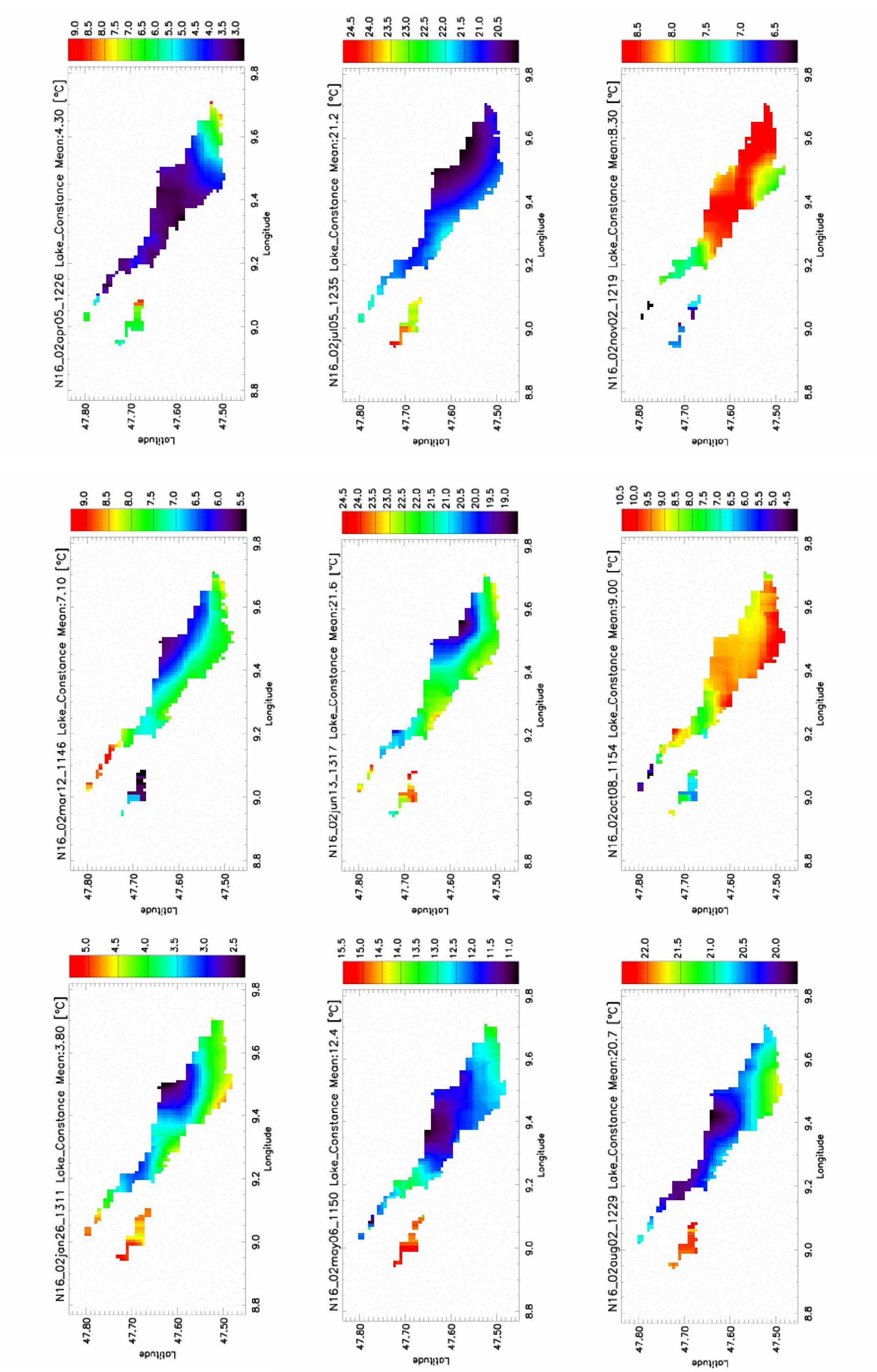

Figure 2. LSWT variation within Lake Constance for selected days of the year 2002.

Temperature variations within lakes need also be taken into account, as they can exceed several degrees Celsius. For the year 2002, nine different data set for Lake Constance have been chosen to discuss this fact, as can be seen in Figure 2. The warmer parts of the waterbody are coloured in red (bright) the colder in dark blue (dark), respectively.

The LSWT variation within Lake Constance ranges from 2° - 5℃. The different temperature pattern is due to complex internal circulation of the lake related to bathymteric, meteorological, limnological and seasonal parameters. The colder parts of the lake can be found on the north shore, whereas the southern part and the basin in the northwest tend to have warmer LSWT. Strong non - uniform temperature distribution can be observed during spring (April-June) and fall (October): The various parts of the lake react different to the changing solar irradiation and the different wind systems. This results in LSWT variation of up to 5℃ within the lake.

5. RESULTS

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 for lakes. As discussed and shown above, concerning the spatial and temporal coverage and the consistency of AVHRR data, satellite image offer new possibilities to monitor LSWT phenomena of lakes within a complex topography such as the Alps.

Average LSWT ranges of 8℃ between the different lakes have a substantial impact on NWP model on local scale: taking temperature amplitude of a single lake as representative for the whole alpine region will not yield accurate results. From the comparison between Lake Como, Brienz and Chiem, we can conclude that the LSWT variations between the lakes are the outcome of the combination of geographic location and morphological properties of the lakes. The spatial LSWT variation within a lake is not negligible. It can be assumed that in situ measurements at a single point of opportunity can not represent the LSWT distribution pattern of a whole lake.

The derivation of climatological LSWT for lakes covering areas greater than a few km^2 can be done using AVHRR imagery. Taking advantage of the real-time capabilities of the processing scheme, an implementation for assimilation in NWP and lake current models for the alpine region is possible.

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