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VALIDATION OF LAKE SURFACE WATER TEMPERATURES DERIVED FROM NOAA AVHRR AND MODIS DATA

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1. INTRODUCTION

Numerous lakes in the European Alps contain a sufficient large volume and areal extent of water to influence significantly local weather patterns with their surface temperature (Livingstone et al., 2001). Monitoring of climatological temperature conditions and temporal and spatial distribution of the lake surface water temperature (LSWT) can be valuable for many applications (Alsdorf et al., 2003).

Up to now, there is no area wide consistent temperature data set for the alpine lakes available. The in situ measurements at points of opportunity can not take into account the high spatial variability of water in near shore zones and their limited spatial coverage is not adequate for resolving the spatial distribution of temperature in lakes. Data derived from imaging sensors such as AVHRR and MODIS can provide an area wide operational lakes surface water temperature (LSWT) information. The feasibility of the AVHRR for LSWT retrieval of continental water bodies has been shown so far for the Great Lakes and Lake Constance (Schwab et al., 1999: Thiemann et al., 2003) but not for lakes with a spatial extent of a few square kilometers.

In this study, an operational near real time processing scheme for AVHRR data was developed from which LSWT measurements based on the multi channel sea surface temperature (MCSST as described in Li et al., 2001) and the nonlinear sea surface temperature (NLSST, Walton et al., 1998) algorithm are derived.

For the years 2002 and 2003, day and night data from NOAA-12, -15, -16 and -17 and from MODIS on board TERRA and AQUA have been compared with in situ data of three different sized lakes in the Alps. The validation revealed a bias around 0.5 - 1.5 °C and standard deviation (scatter) of 0.9 - 1.9°C for AVHRR, depending on the lake and sensor. For the different quality levels of MODIS LSWT values of 0.6 – 2.4 for the bias and 0.6 –2. 9°C for the scatter were found.

Here we focus on the derivation and validation of the different algorithms of the two sensors. On the poster we examine the dependence of the bias on wind speed and insolation.

2. AVHRR DATA

Approximately 4000 HRPT AVHRR data sets from AVHRR/2 (N12) and AVHRR/3 (N15, N16, and N17) have been read out at the receiving station of the University of Bern during 2002 and 2003. The level1b data were radiometrically corrected and calibrated in physical units, accounting for sensor nonlinearity of the AVHRR/2 as suggested by Rao et al., 1993. To derive LSWT from lakes with a size of a few square kilometers, a georeferencing with sub pixel accuracy is necessary. This was achieved through an automated feature matching algorithm. An orthorectification based on the terrain model GTOPO30 of the imagery is essential in a mountainous area to overcome the displacement introduced by the topography. The resulting data set was subset to a latitude – longitude grid on the WGS84 ellipsoid, covering the alpine region from 0°E -17°E and 40°30'N – 50°N. The pixel size was defined as 0.007° in the longitude dimension and 0.01° for the latitude respectively.

LSWT has been determined for both, MCSST and NLSST, at day (sun zenith less than 75°) and night (sun zenith greater than 75°) using the coefficients as provided by NOAA NESDIS:

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

Equation 1: NLSST and MCSST: ch4, ch5 = Channel 4 and 5 brightness temperatures in K, a_1-a_4, b_1-b_4 = coefficients according to NOAA NESDIS, q = ((secant of satellite zenith angle) –1)

A land mask according to the global self-consistent hierarchical high-resolution shoreline database (Wessel et al., 1996) is used to determine the pixel covered by water bodies. Clouds were masked using the CASPR algorithm (Key, 2002). During daytime, an additional gross IR test and visible could threshold test was 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) were greater than ten percent were assigned as cloud contaminated. The gross IR test was also used for night data together with a test for low stratus clouds: The difference obtained when subtracting channel 3 temperature from channel 5 temperature had to be less or equal -0.6°C. To maintain high accuracy of the retrieved LSWT, pixel viewed with a satellite viewing zenith angle greater than 53° are omitted, since larger atmospheric path lengths lead to greater attenuation of surface emitted radiance. Finally, as Schwab et al., 1999 suggested, pixel representing a standard deviation greater than 3°C of the neighboring pixels and completely surrounded pixel by

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Lake	Latitude	Longitude	Altitude (m.a.s.l.)	Max Depth (m)	Volume ($10^6 * m^3$)	Surface ($10^6 * m^2$)	Catchment Area ($10^6 m^2$)
Geneva	46°20'N	6°40'E	372	310	88900	584	7975
Constance	47°40'N	9°20'E	400	252	48530	539	10900
Mond	47°50'N	13°23'E	527	68	510	14	247

Table 1: Lake Properties.

non valid pixel have been rejected. To smooth high frequency noise in the LSWT data, a 9x9 average filter was applied.

3. MODIS DATA

The MODIS SST algorithm as described in Minnett et al., 2002 is based on the AVHRR Pathfinder SST split window method (nonlinear SST method) Kilpatrick et al., 2001. The final thermal infrared algorithm (10-12 µm) for day and nighttime used in this study was formulated as:

$$MODIS_{SST} = c1 + c2(T31) + c3(T32 - T31)(SST_{guess}) + c4(Secq - 1)(T32 - T31)$$

Equation 2: $MODIS_{SST}$. Where T31 and T32 are bands 31 and 32 BT, SST_{guess} is the first guess SST,c1-c4 coefficients and q is the satellite zenith angle.

Unlike the AVHRR LSWT algorithm, the MODIS SST distinguishes between high and low atmospheric water vapor content by using two pairs of coefficients sets, depending on the brightness temperature difference of channel 31 and channel 32. During daytime, Reynolds weekly OI SST (Reynolds et al., 1994) are used as SST_{guess} and the mid-infrared SST product during nighttime, respectively.

In this study, we used all available MODIS/Terra Sea Surface Temperature Products 5-Min L2 Swath 1km (MOD28L2) and MODIS/Aqua Sea Surface Temperature Products 5-Min L2 Swath 1km (MYD28L2) for the year 2002/2003. The data were provided by the NASA/Goddard Earth Sciences Distributed Active Archive Center (GES DAAC) at http://daac.gsfc.nasa.gov/. The SST products were available in its third release (Collection 4). These datasets are considered as validated products. AQUA SST of this collection was only available for the period from end of July 2002 to end of November 2003.

All data sets covering the area of 0°E –17°E and 40° 30'N – 50°N were subset and resampled to the same dimension as the AVHRR data sets. The data were screened using the quality flags supplied with the SST data. Quality flag 0 (good), flag 1 (questionable) and flag 2 (probably cloud) were used in this study. For more information on the quality flags see: http://modis-ocean.gsfc.nasa.gov/qa/terra/data qualsum/sst_qualsum.V4.pdf

4. LAKES AND IN SITU MEASUREMENTS

Three lakes located at the north rim of the European Alps offer in situ data with a temporal resolution of at least 60min (Table 1).

Lake Geneva is the largest lake in the pre - alpine region. The Rhone River discharges at the east part and flows southward from the west end of the lake to the Mediterranean Sea. The lake is deep and has a comparatively large water volume for its surface area.

The in situ water temperature was recorded at the north shore of the lake, on a pylon 100m offshore (46° 27' 30. 1"N / 6° 23' 58.5"E) in a water depth of 3 - 4m. The pylon is equipped with meteorological sensors and a water temperature sensor at approximately 1m depth (not a floating device). The measurements are sampled to hourly averages. A continuous data set from 1/31/2002 to 12/31/2003 is available.

Lake Constance is the second largest (to Lake Geneva) European pre-alpine lake. The lake is divided into two parts, the deep "upper lake" (maximum depth 252 m) including the fjord-like Lake Ueberlingen and the shallow "lower lake" (maximum depth 46m). A thermistor chain at a moored buoy (47° 45' 37. 8"N / 9° 7' 53. 22"E) in Lake Ueberlingen measures the water temperature at 0.9m depth in 20min intervals. The data set for 2002 - 2003 has gaps for 3/24/2002 - 5/28/2002, 8/12/2002 -8/27/2002 and 4/7/2003 - 4/28/2003.

Lake Mond (527 m.a.s.l) in the eastern part of the Alps is approximately 175 times smaller than Lake Geneva and with its surface area of $14km^2$ and a length of 12km a challenge for the resolution of the AVHRR and MODIS sensor. With its size and surrounded by two high mountain ranges, it represents a typical Alpine Lake. A moored buoy (47° 50' 14.5''N / 13° 22' 06.9''E) measures the water temperature in 1m depth using a Yellow Springs Multisonde 6920. The data sampling was done in 60 minutes intervals. The data set 2002 –2003 was continuously available except a data gap from 1/25/2002 – 5/16/2002.

Both, the Lake Constance and the Lake Geneva in situ data are located near the shore and do not fall within the water mask used by the MODIS SST product. Therefore, the closest pure water pixel was chosen. For Lake Geneva, the validation was done at (46° 26' 38. 0"N /6° 23' 58.5"E) whereas for Lake Constance in the "Lower Lake" at (47° 41' 2.7"N /9° 14' 18.3"E). One could assume that due to internal seiches, there might be temperature differences between the actual in situ measurements and the validation location, however the validation of AVHRR LSWT at both locations showed similar results. Only the number of coincident data points was different since the near shore and data in the Lake Ueberlingen is more affected by land contamination.

At all the three locations, for a given satellite pass the corresponding pixel LSWT was compared to the in situ temperature closest to the satellite overpass, not exceeding the time difference of 30 min.

5. VALIDATION: AVHRR

The performance of the MCSST and NLSST algorithms were tested using the matchup database as described above. The scatter plots of the satellite versus the in situ for the NOAA operated satellites can be found in fig. 1 for Lake Geneva, fig. 2 Lake Constance and fig. 3 for Lake Mond.

An analysis of the outliers in figs. 1-3 revealed that the AVHRR LSWT data colder than the in situ measurement can be related to cloud contamination. Especially sub pixel cirrus clouds at day and night time introduce a significant cold bias. The AVHRR LSWT data with a warm bias has different sources. As described by Khattak et al., 1991, sun glint can introduce a bias up to 2K. For several warm biased outliers of NOAA-12 and NOAA-15 day passes, sun glint could be identified over the water bodies (fig. 1). Low wind speed conditions can exert a strong gradient between bulk and skin temperature (Minnett, 2003). This can be observed for the outliers of NOAA-16 and NOAA-17 day data around 10°C AVHRR LSWT at Lake Geneva.

The in situ measured wind speed is as low as 1.2 m/s for these data points. Effects like traces of internal waves that extent until shallow water where the in situ measurement was taken can explain other differences at higher temperature ranges.

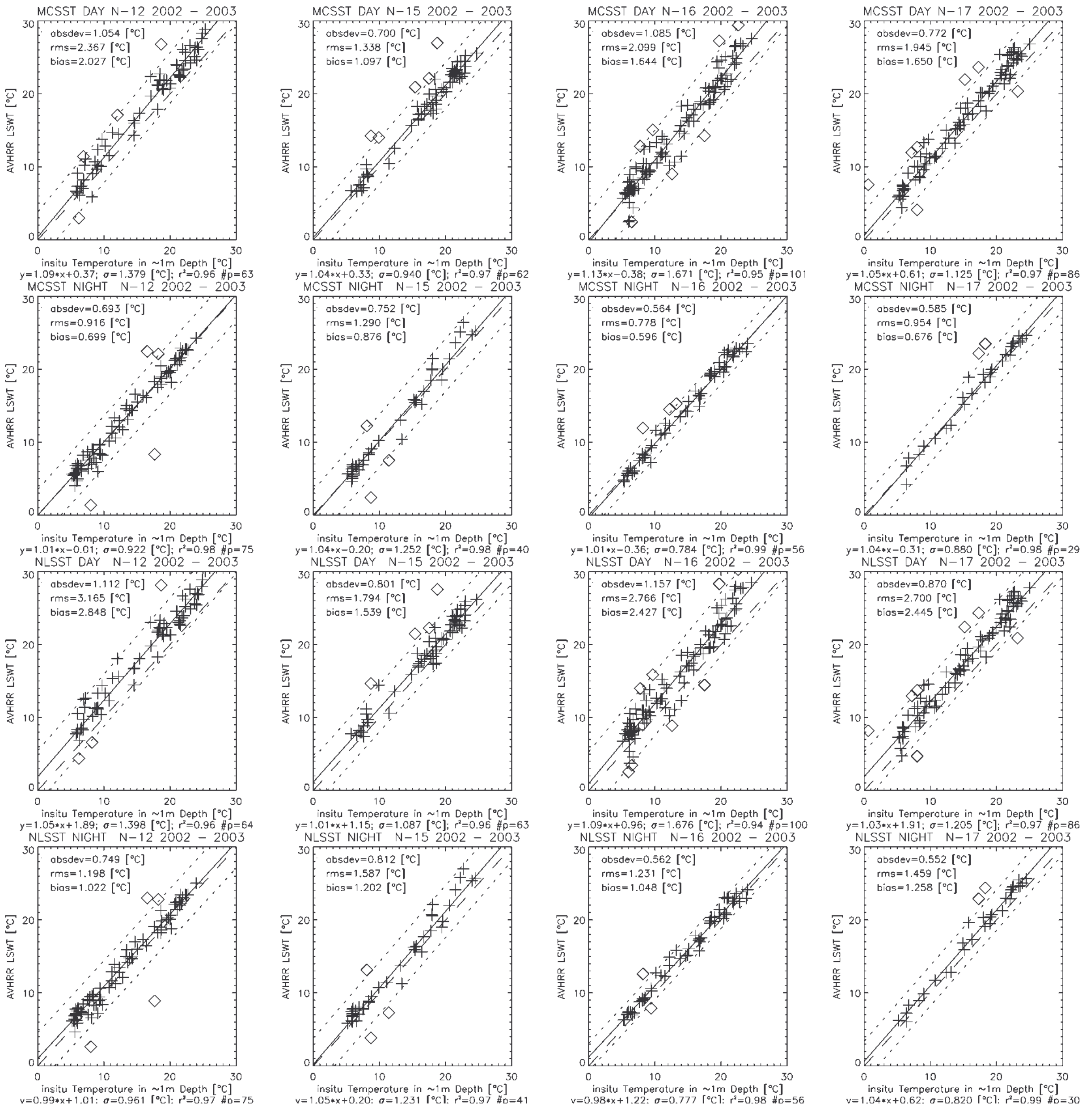

Figure 1: Scatter plots of satellite (MCSST, NLSST) vs. in situ SST measurements for Lake Geneva. Diamonds: outliers, dashed line: 1:1 line, solid line: fitted data line, dotted line: ±2 standard deviation.

To identify outliers in the matchup database, data points beyond 2 standard deviations (dotted line) compared to the rest of the data set, were not included in the validation, but plotted as diamonds in the corresponding figures. Using this method, we excluded only about 6% of the original matchup data set. The use of the difference between the center pixel and the 3x3 pixel array was found not to be appropriate to remove erroneous data points, since a strong surface heterogeneity within lakes is quite common.

The performance of the MCSST is slightly better than of the NLSST while on the other hand nighttime data are of better-quality than day time data, independent of the satellite sensor. The bias and standard deviation for Lake Geneva and Lake Constance data are quite the same, the scatter and offset of Lake Mond is higher.

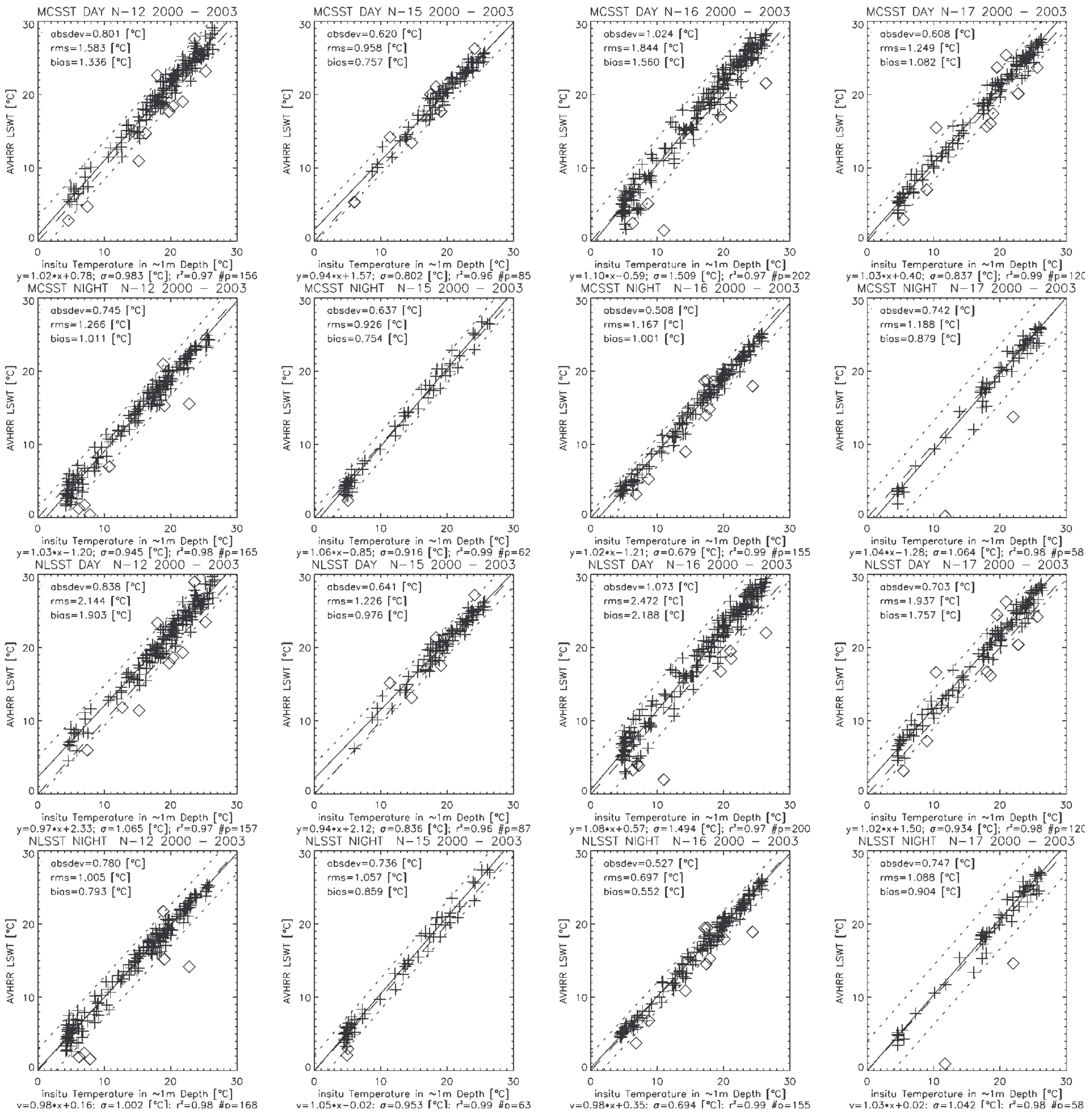

Figure 2: Scatter plots of satellite (MCSST, NLSST) vs. in situ SST measurements for Lake Constance. Diamonds: outliers, dashed line: 1:1 line, solid line: fitted data line, dotted line: ±2 standard deviation..

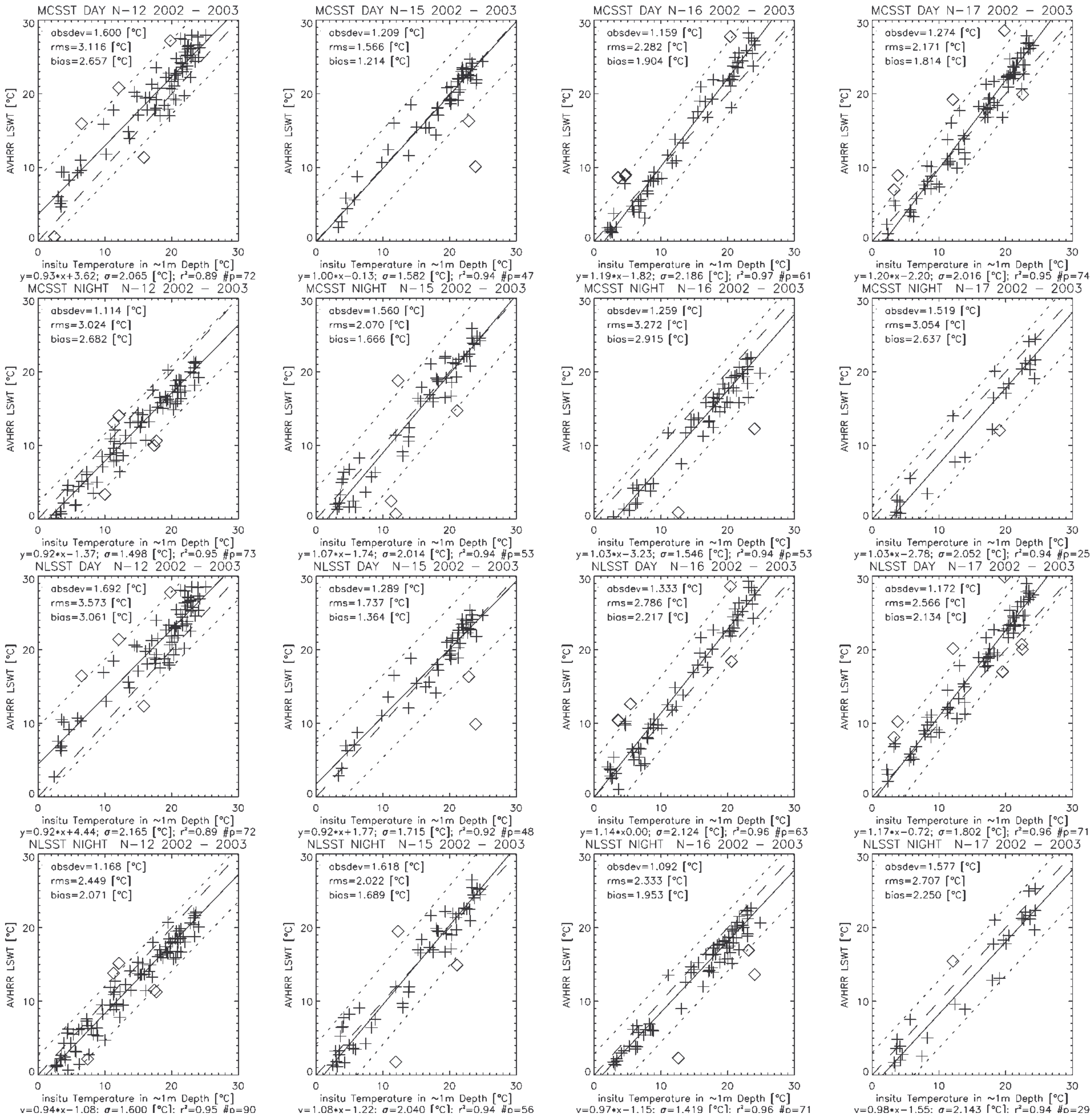

Figure 3: Scatter plots of satellite (MCSST, NLSST) vs. in situ SST measurements for Lake Mond. Diamonds: outliers, dashed line: 1:1 line, solid line: fitted data line, dotted line: ±2 standard deviation.

The performance of the different algorithms for the different satellites is ambiguous. During daytime the bias is ranging for the MCSST from 0.94 (NOAA-15) to 2.66 (NOAA-12) and 1.17 (NOAA-15) to 3.10 (NOAA-12) for the NLSST, respectively. For nighttime MCSST: 0.60 (NOAA-16) – 2.92 (NOAA-16) and for NLSST: 0.55 (NOAA-16) – 2.25 (NOAA-17).

The range of the standard deviation is similar: MCSST daytime data has a scatter ranging from 0.94 (NOAA-15) to 2.07 (NOAA-12) and for NLSST: 0.91 (NOAA-15) to 2.17 (NOAA-12). During nighttime, a minimum of 0.78 (NOAA-16) for MCSST and NLSST was found, while the maximum is in the NOAA-12 data with 2.07 and 2.17, respectively.

Comparing the scatter plots, Lake Mond has the biggest scatter and NOAA-12 data the maximum offset (solid line) during nighttime and daytime data.

6. VALIDATION: MODIS

Since the MODIS retrieved LSWT follow a more sophisticated scheme, less data was included in the matchup database but with a smaller offset (bias) and less scatter (standard deviation) than the AVHRR data.

Day and night data for Lake Geneva can be found in fig. 4, for Lake Constance in fig. 5. Lake Mond was obviously too small and the constraints stringent to get any daytime data and a significant amount of daytime data.

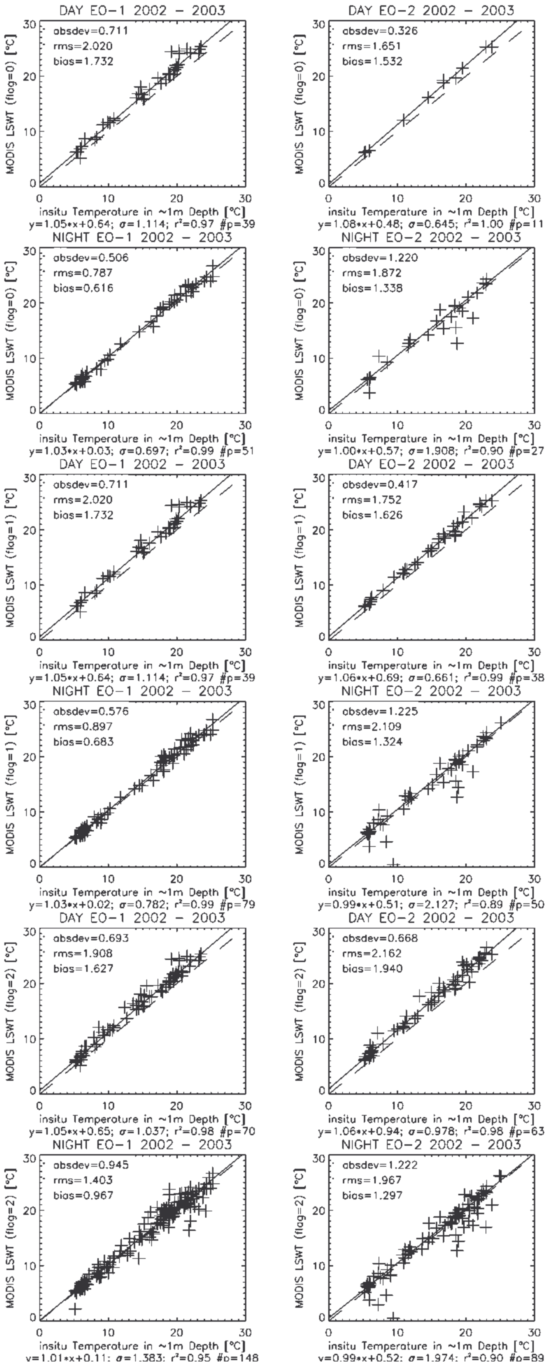

Figure 4: Scatter plots of satellite (TERRA (EO-1), AQUA (EO-2), quality 0,1 and 2) vs. in situ data SST measurements for Lake Geneva.

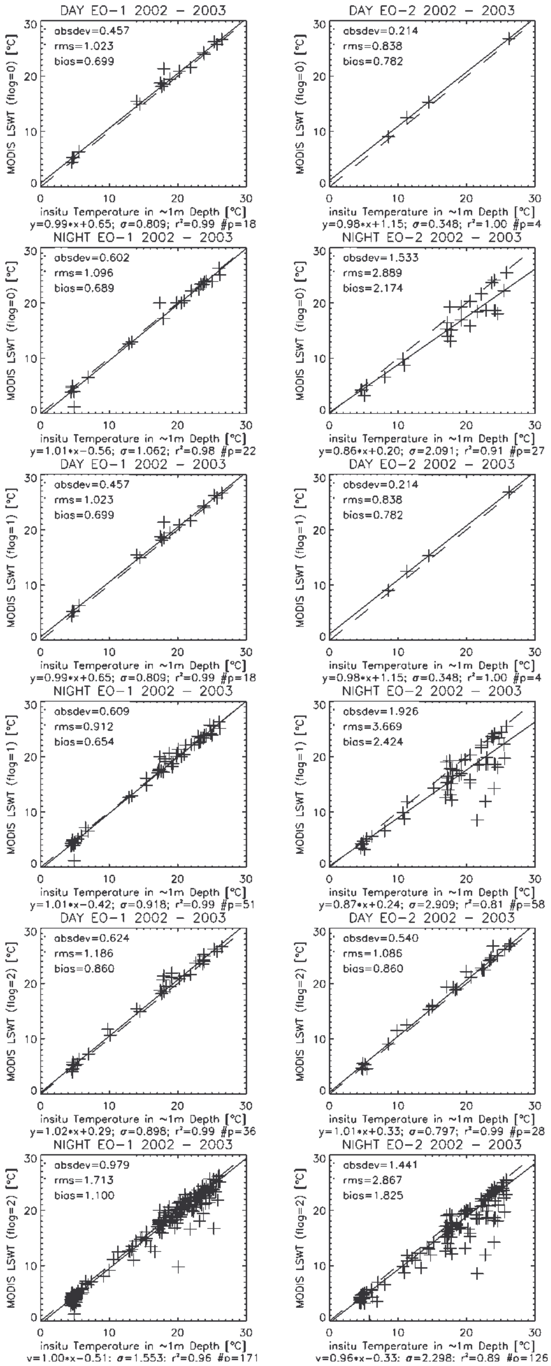

Figure 5: Scatter plots of satellite (TERRA (EO-1), AQUA (EO-2), quality 0,1 and 2) vs. in situ data SST measurements for Lake Constance.

For the sake of completeness, the night time data is shown in fig. 6, but only for quality flag 2 enough data was available with a large bias and standard deviation for both TERRA and AQUA data.
Matchup data sets with less than 30 data points have not been taken into the statistical analysis discussed in this study. Daytime MODIS LSWT show a bias ranging from 0.8 -1.9℃ and scatter from 0.6 - 1.1℃. During night time, the performance of TERRA LSWT (bias 0.6 - 1.1℃, standard deviation: 0.6 - 1.5℃) is better than during daytime and better than nocturnal AQUA LSWT (bias: 1.2 - 2.4℃, standard deviation: 1.9 - 2.9℃). Nighttime AQUA LSWT are less accurate than daytime, this might be due to a higher amount of not discriminated cloud pixel which introduce a cold bias into the matchup database.

As expected, in the possible cloud contaminated data (flag 2) we can find more cold outliers than in flagged 1 data. Unfortunately, a matchup database with a significant amount of best quality data (flag 0) was only available for Lake Geneva TERRA data (fig 4). The difference of the results in this case between flag 0 and flag 1 data is not significant.

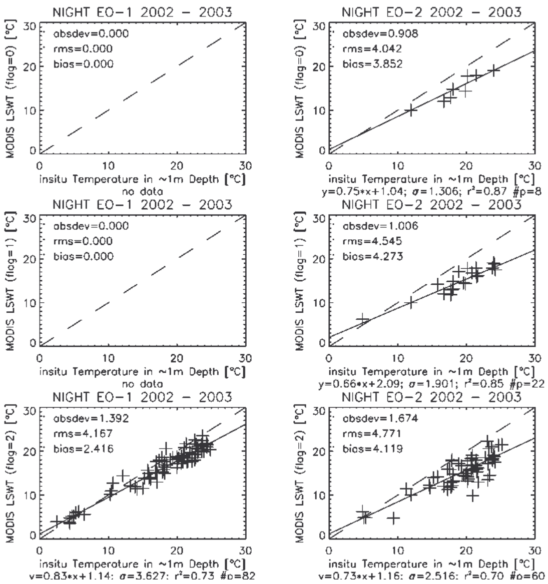

Figure 6: Scatter plots of satellite (TERRA (EO-1), AQUA (EO-2), quality 0,1 and 2) vs. in situ SST measurements for Lake Mond.

7. DISCUSSION

Overall, the variability of the surface temperature within a pixel in a lake can be of a strong heterogeneity, especially at the shore or near shore region, where most in situ measurements were made. Even more, the larger scatter in the Lake Mond data is due to the fact, that since the lake is of a small size the AVHRR / MODIS pixel represent quite a heterogeneous pixel, whereas at the other lakes, the temperature within the pixel is more homogenous. In addition, the satellite retrieved LSWT represents the average temperature within a pixel, whereas the in situ measurements only a point within 1kmx1km.

Due to the near shore location of both in situ measurements at Lake Mond and Lake Geneva, their number of data sets in the matchup database is only half the numbers as the one of Lake Constance, so the size of the lake is, as expected, no limitations for the retrieval of LSWT.

The performance of the MCSST for the retrieval of LSWT is overall better than NLSST, especially for the daytime data. A bias of 1.5℃ and a standard deviation of 1.3℃ has to be expected when retrieving LSWT using MCSST algorithm, which are similar to other studies such as for the Great Lakes (Li et al., 2001).

MODIS SST products can be used for LSWT derivation of water bodies of substantial size, whereas for lakes with the size of Lake Mond they are not feasible. As expected, MODIS quality 0 and 1 show less scatter than quality 2. Using MODIS data for LSWT for lakes of the size similar to Lake Geneva or Lake Constance a bias and scatter starting at 0.7℃ can be expected.

The relatively small amount of flag 0 data in coastal and upwelling areas is a known problem (http://modis-ocean.gsfc.nasa.gov/qual.html/terra/knownprobs/knownprobs.V3.html). The use of lower quality data is recommended for these areas, and as shown here, gives reasonable results.

Overall, this study shows the feasibility of the AVHRR LSWT processing scheme and MODIS data for different application, such as LSWT monitoring and assimilation for numerical weather prediction models, on water bodies of a few square kilometer extent for AVHRR and greater lakes for MODIS

8. ACKNOWLEDGEMENT

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