GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L22402, doi:10.1029/2009GL040846, 2009

Satellite observations indicate rapid warming trend for lakes in California and Nevada

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Received 10 September 2009; revised 21 October 2009; accepted 26 October 2009; published 25 November 2009.

[1] Large lake temperatures are excellent indicators of climate change; however, their usefulness is limited by the paucity of in situ measurements and lack of long-term data records. Thermal infrared satellite imagery has the potential to provide frequent and accurate retrievals of lake surface temperatures spanning several decades on a global scale. Analysis of seventeen years of data from the Along-Track Scanning Radiometer series of sensors and data from the Moderate Resolution Imaging Spectroradiometer shows that six lakes situated in California and Nevada have exhibited average summer nighttime warming trends of $0.11 \pm 0.02°\mathrm{C}\ \mathrm{yr}^{-1}$ ($p < 0.002$) since 1992. A comparison with air temperature observations suggests that the lake surface temperature is warming approximately twice as fast as the average minimum surface air temperature.

Citation: Schneider, P., S. J. Hook, R. G. Radocinski, G. K. Corlett, G. C. Hulley, S. G. Schladow, and T. E. Steissberg (2009), Satellite observations indicate rapid warming trend for lakes in California and Nevada, *Geophys. Res. Lett.*, *36*, L22402, doi:10.1029/2009GL040846.

1. Introduction

[2] Global climate change is increasingly evident from a wide variety of observations. The characterization of temperature change over land is primarily based on measurements at meteorological stations [*Hansen et al.*, 2006]. However, research has shown that inland lakes and water bodies have the potential to serve as excellent indicators of climate change [*Coats et al.*, 2006; *Quayle et al.*, 2002; *Verburg et al.*, 2003]. Lakes act as integrators of the physical parameters affecting their temperature, and like the oceans, their high heat capacity dampens short-term temperature variability and highlights longer-term variations. Furthermore, they integrate over an abundance of additional factors related to climate, such as snow accumulation, snow melt timing, stream runoff, etc.

[3] Several authors have evaluated the impact of climate change on the thermal behavior of lakes and have reported an increase in lake water temperature in recent decades. *Coats et al.* [2006] studied the effects of climate on the thermal variability with depth of Lake Tahoe since 1970 and found a warming trend of the volume-weighted mean temperature of $0.015°\mathrm{C}\ \mathrm{yr}^{-1}$ with the highest rate occurring at the surface. *Livingstone* [2003] used a 52-year-long record of monthly temperature profiles at Lake Zurich to show a significant warming trend in the uppermost 20 m of the lake at a rate of $0.024°\mathrm{C}\ \mathrm{yr}^{-1}$. Antarctic lakes have also been found to exhibit warming rates of $0.06°\mathrm{C}\ \mathrm{yr}^{-1}$ between 1980 and 1995 [*Quayle et al.*, 2002]. *Austin and Colman* [2007] have found warming rates of $0.11°\mathrm{C}\ \mathrm{yr}^{-1}$ for Lake Superior between 1979 and 2006.

[4] All these studies were based on in situ data and were limited to the few lakes and locations on those lakes for which long-term temperature records were available. On a global scale, such records are very rare. By contrast, thermal infrared (TIR) imagery from spaceborne satellites has provided a global archive of Earth surface temperatures since the early 1980s, often with several passes per day, and allows for near-daily observations of lake skin temperature depending on the availability of cloud-free scenes.

[5] Studies have indicated that sea surface temperature (SST) can be derived from TIR data with a high degree of accuracy, typically to within a few tenths of a degree [*Corlett et al.*, 2006]. Satellite data have been used to assess climate variability in the oceans, where increases in SST between 0.009 and $0.018°\mathrm{C}\ \mathrm{yr}^{-1}$ have been observed [*Good et al.*, 2007; *Lawrence et al.*, 2004]. Several authors have used remotely sensed TIR imagery to assess spatial and temporal thermal behavior of lakes [*Crosman and Horel*, 2009; *Hook et al.*, 2003; *Hook et al.*, 2007; *Reinart and Reinhold*, 2008], yet few studies have used these data to evaluate the impact of climate change on lakes which has the potential to offer a regional context to globally observed trends.

[6] We have utilized an archive of satellite thermal infrared imagery from the Along Track Scanning Radiometer (ATSR) series of sensors (beginning in 1991) in conjunction with Moderate Resolution Imaging Spectrometer (MODIS) imagery (beginning in 2000) to identify trends in the long-term thermal behavior of several lakes in California and Nevada.

2. Data and Methodology

2.1. Study Sites

[7] Six lakes in California and Nevada were studied, namely Lake Tahoe (39.13°N, 120.05°W), Mono Lake (38.01°N, 118.97°W), Pyramid Lake (40.11°N, 119.59°W), Walker Lake (38.72°N, 118.71°W), Lake Almanor (40.23°N, 121.11°W), and Clear Lake (39.07°N, 122.84°W). The lakes range from fresh (Lake Tahoe) to salty (Mono Lake), and none of the lakes freeze in winter.

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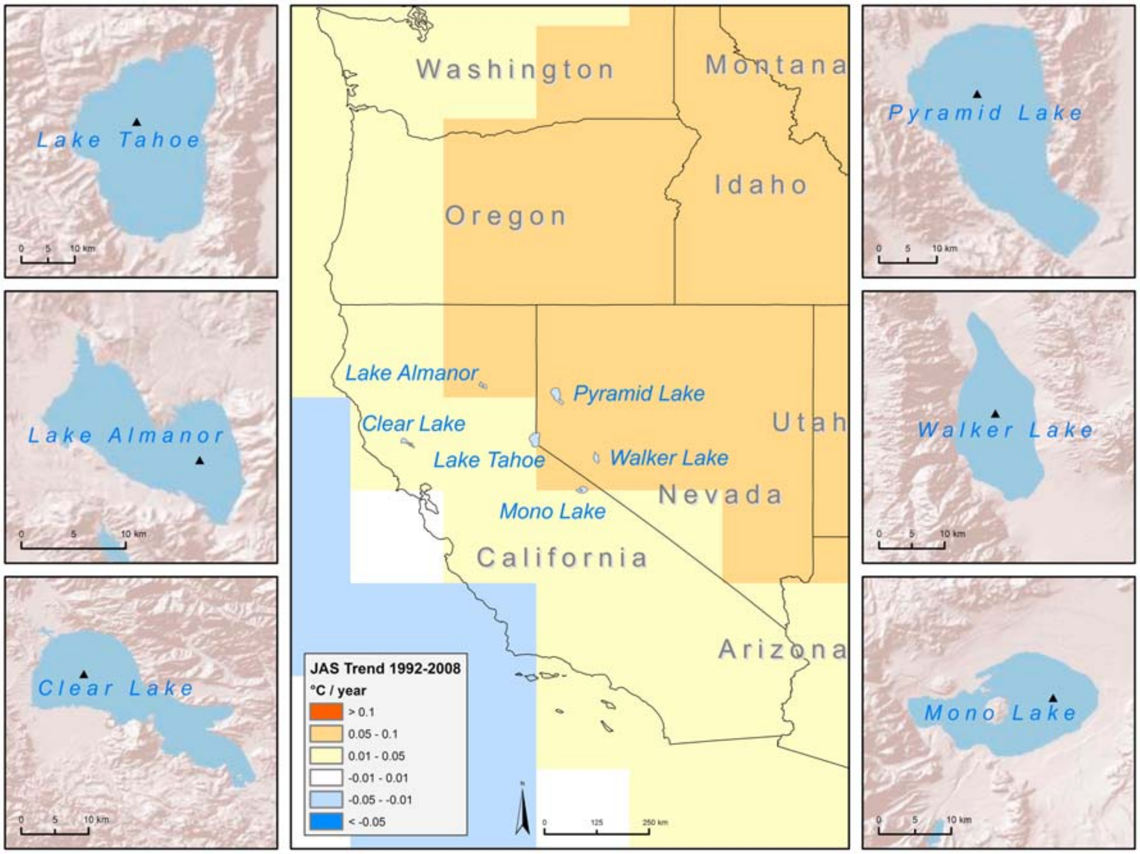

Figure 1. (middle) Overview of the study sites with (left and right) detailed maps of the water bodies. Black triangles indicate the location at which the temperature time series were extracted from the satellite imagery. The overview further shows the mean JAS air temperature trends from 1992 to 2008 as computed by the GISTEMP Analysis [*Hansen et al.*, 1999] for reference. Topography data by the Environmental Systems Research Institute (ESRI), Redlands, CA.

Except for Clear Lake, which is polymictic, all the lakes are monomictic. The lakes used in this study were primarily selected based on the possibility of extracting a clear temperature signal over the lake. Therefore, the surface area and shape of the lakes were the primary selection criteria. Figure 1 gives an overview map and detailed maps of all study sites. It further shows the 1992 to 2008 air temperature trends as computed by the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) for reference [*Hansen et al.*, 1999].

2.2. Data

[8] TIR data from the ATSR series and MODIS series of sensors were used. The ATSR series includes ATSR-1 on the ERS-1 satellite (1991 through 1997), ATSR-2 on the ERS-2 satellite (1995 through 2003) and the Advanced ATSR (AATSR), onboard the Envisat satellite which was launched in 2002 and continues to operate today. In the remainder of the paper, the term ATSR refers to all three sensors. A total of 5,486 ATSR scenes covering the selected lakes from 1991 through 2008 were available, providing an 18-year record of lake surface temperature. Only nighttime imagery was used for this study as previous research has shown that nighttime skin temperature retrievals provide a significantly better accuracy than daytime data due to absence of differential solar heating [*Hook et al.*, 2003]. Due to issues with the European ATSR processing system only a limited number of nighttime ATSR-2 scenes were available for the years 1996 to 1999. A 9-year archive of MODIS Terra LST imagery from the MOD-11 standard product [*Wan*, 1999] was used to supplement and corroborate the results derived from the ATSR data. No MODIS data were available for Lake Almanor and Clear Lake.

[9] In situ data were available for Lake Tahoe from the Lake Tahoe Automated Validation Site which was established in 1999. This site has been described in detail previously [*Hook et al.*, 2003, 2007]. The site includes four buoys that provide highly accurate observations of both skin and bulk temperature at intervals of two minutes. Additional less frequent in situ data of bulk water surface temperatures sampled from a boat approximately every two weeks since 1979 are also available.

2.3. Processing

[10] Initially the average skin temperature of 3 × 3 arrays of ~1 km^2 pixels in the center of each lake was extracted from each available ATSR image, except for Lake Almanor and Clear Lake where only the center pixel was used due the size and shape of these lakes. The ~9 km^2 area was chosen to provide a balance between sampling a large area and conservatively avoiding any potential bias by including shoreline pixels. For validation with in situ data at Lake Tahoe the pixel arrays were extracted directly over the buoy location. The resulting time series of top-of-atmosphere brightness temperatures were masked for cloud contamination using a technique based on the cloud masking proce-

dure applied operationally for the ATSR SST product [*Zavody et al.*, 2000]. This operational cloud mask was designed for open ocean and includes tests for spatial homogeneity that are not applicable for inland water bodies and were thus excluded in this study. They were substituted by testing if the standard deviation within a 3 × 3 extraction window lies above a threshold of 0.2°C, in which case the window is flagged as cloudy and not used in the analysis. The cloud masking procedure was validated against a visual inspection of all available AATSR images between April 2002 and September 2003. The results indicate that the automated cloud masking agrees with the visual inspection. Lake skin temperatures were subsequently computed from the brightness temperatures using two sets of coefficients. The first set of coefficients used in this study was derived by *Hook et al.* [2003] for Lake Tahoe using ATSR-2 data between March and August 2000. All matchups between in situ data and ATSR-2 that were used for deriving these coefficients were removed before any subsequent analysis of these coefficients at Lake Tahoe to avoid any possible bias. The second set of coefficients consists of the operational ATSR Standard SST coefficients (SSST). They were derived from radiative transfer calculations [*Zavody et al.*, 1995] and optimized with respect to sensor type, sensor temperature, latitude, scan angle, and stratospheric aerosol loads [*Merchant et al.*, 1999]. ATSR SST retrievals using these coefficients have been validated extensively [*Corlett et al.*, 2006; *Merchant and Harris*, 1999; *Noyes et al.*, 2006]. Dual-view retrievals using two channels were used. Since the *Hook et al.* [2003] coefficients were derived specifically for lakes they were used for both ATSR-2 and AATSR, which is functionally identical to ATSR-2. Due to different sensor characteristics the SSST coefficients were used for ATSR-1.

[11] An equivalent procedure was used for the MODIS data. A 3 × 3 pixel array of the LST product MOD11 was extracted at the specified coordinates over each lake for all available images. The resulting time series were then subject to cloud screening using the algorithm described by *Hulley* [2009] with an additional spatial homogeneity test. In order to avoid a sampling bias due to the different repeat interval of MODIS and ATSR, short gaps in the retrieved ATSR lake temperature time series were filled using cubic interpolation, therefore ensuring the same number of samples from both sensors for each averaging period. Comparisons of the interpolated data with in situ data showed very good agreement, indicating that this technique does not introduce any noticeable error.

3. Results and Discussion

3.1. Validation of Satellite Derived Surface Temperatures

[12] In order to investigate if the skin temperatures obtained from ATSR and MODIS can reliably reproduce the actual skin temperatures at the lake, a validation against in situ data was carried out at Lake Tahoe. All available skin temperatures from cloud-free ATSR and MODIS extracts for Lake Tahoe were matched with the corresponding in situ measurements. Only matchups with less than five minutes difference between the observation times of both data sets were considered.

[13] Figure 2a shows a scatterplot of all available matchups of skin temperatures from ATSR-2 and AATSR, using the *Hook et al.* [2003] coefficients, and MODIS Terra MOD11 retrievals with in situ measurements of skin temperature for Lake Tahoe. The plot indicates that the retrievals obtained from all three sensors agree very well with the in situ observations over the entire range of temperatures and do not exhibit any significant biases. Bias (computed as in situ minus satellite retrieval) and standard error for MODIS were found to be −0.007°C and 0.32°C respectively. The equivalent values for AATSR were −0.082°C, and 0.30°C. Finally, for ATSR-2, the bias was found to be 0.001°C while the standard error was 0.19°C. The R^2 values for all three sensors were found to be greater than 0.99. In order to better resolve the errors on the vertical axis, Figure 2b shows the differences between satellite retrievals against in situ skin temperature.

[14] In order to assess the inter-sensor bias for the ATSR platform, retrievals from the overlap periods between ATSR-1 and ATSR-2 (July 1995 to June 1996) as well as ATSR-2 and AATSR (July 2002 to June 2003) were assessed over Lake Tahoe by pairing the temporally closest retrievals. The time difference between samples was ∼24 hours for ATSR-1/ATSR-2 and ∼30 minutes for ATSR-2/AATSR. The bias for ATSR-1/ATSR-2 was found to be −0.008°C with a standard deviation of 1.2°C while that for ATSR-2/AATSR was found to be −0.081°C with a standard deviation of 0.23°C. The larger standard deviation is primarily related to the 24 hour time difference between matchups compared to the other sensors. The biases for both overlap periods are very low. Long-term in situ data at Lake Tahoe was used to investigate the temporal stability of the ATSR sensors. An analysis over all 18 years of day-time data showed no significant trend in the errors indicating any systematic drift. Further, no abnormal uncertainty levels due to aerosols after the Mt. Pinatubo eruption in 1991 were detected. These results indicate that the sensor platform delivers stable retrievals of lake surface temperature in the absence of real changes. Uncertainty (including both inter-sensor bias and standard error) estimates for each sensor computed from both in situ data sets were subsequently propagated through the weighted linear regression analysis to obtain trend uncertainty estimates.

3.2. Assessment of Warming Trends

[15] In order to assess the change in surface temperature over time, an index was developed which was calculated as the average of all nighttime summertime temperatures for the 3-month period from July through September (JAS). This index was based on a visual analysis of the data which suggested that the summertime nighttime temperatures were increasing. This analysis agrees with recent findings indicating that the strongest warming occurs in lakes during late summer and fall [*Arhonditsis et al.*, 2004; *Coats et al.*, 2006]. The index captures the annual temperature peak around August, allows for a reasonable large sample size, and eliminates diurnal heating by using nighttime data. *Austin and Colman* [2007] showed for Lake Superior that the JAS surface water temperatures were increasing more rapidly than regional air temperatures. Further, research at Lake Zurich suggests that processes responsible for long-term changes in lake water temperature act primarily at

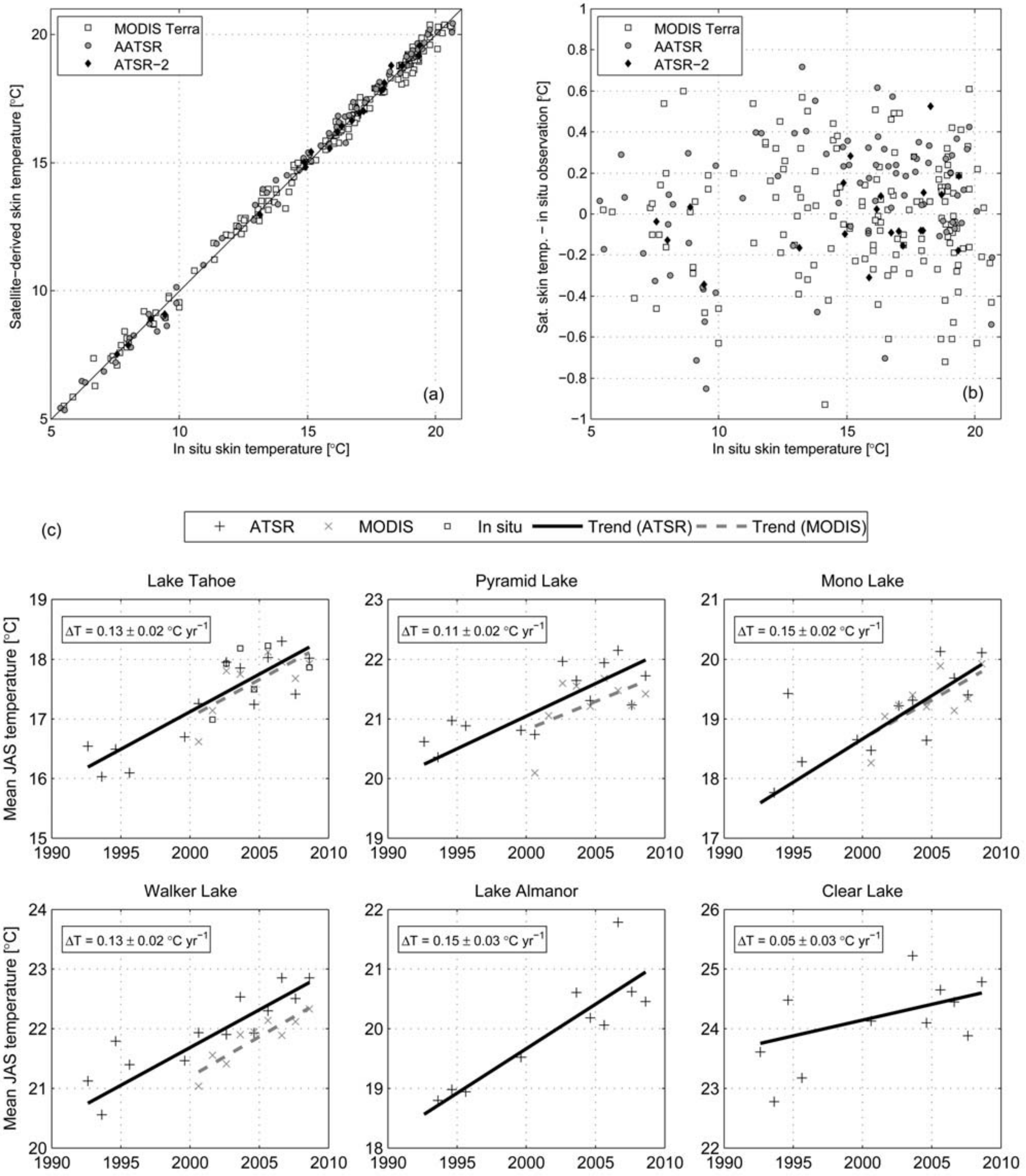

Figure 2. (a) and (b) Validation of MODIS, AATSR, and ATSR-2 retrievals at Lake Tahoe. Scatterplot of satellite-derived skin temperatures against in situ measurements (Figure 2a) and differences between satellite retrievals and in situ data dependent on skin temperature (Figure 2b). (c) Weighted linear regression analysis for July through September nighttime averages. MODIS data were not available for Lake Almanor and Clear Lake. In situ data were available for Lake Tahoe between 2001 and 2008. All linear trend lines derived from ATSR are significant at the $p < 0.05$ level. Rates of temperature change computed from ATSR trend. Vertical axes all show the same relative range. For detailed regression results, see Table 1.

Table 1. Statistics of Weighted Linear Regression Analysis for Mean Summer Nighttime Temperatures Between 1992 and 2008 From ATSR and MODIS Data[a]

Lake	ATSR					MODIS				
	N	Intercept	ΔT yr^{-1} [°C yr^{-1}]	R^2	p	N	Intercept	ΔT yr^{-1} [°C yr^{-1}]	R^2	p
Lake Tahoe	13	16.2 ± 0.2	0.13 ± 0.02	0.77	0.000	9	16.1 ± 0.5	0.13 ± 0.04	0.54	0.025
Pyramid Lake	13	20.2 ± 0.2	0.11 ± 0.02	0.62	0.001	9	20.1 ± 0.5	0.10 ± 0.04	0.29	0.133
Mono Lake	12	17.6 ± 0.2	0.15 ± 0.02	0.52	0.008	9	17.7 ± 0.5	0.13 ± 0.04	0.53	0.026
Walker Lake	13	20.7 ± 0.2	0.13 ± 0.02	0.79	0.000	9	20.2 ± 0.5	0.13 ± 0.04	0.81	0.001
Lake Almanor	11	18.6 ± 0.3	0.15 ± 0.03	0.75	0.001	-	-	-	-	-
Clear Lake	11	23.8 ± 0.3	0.05 ± 0.03	0.40	0.037	-	-	-	-	-
Mean	11	19.5 ± 0.3	0.11 ± 0.02	0.76	0.002	9	18.5 ± 0.5	0.12 ± 0.04	0.59	0.016

[a] N represents the number of observations, p gives the p-value, and uncertainties are given as standard errors.

night [*Livingstone*, 2003]. As a result, for this study, we analyzed the mean nighttime skin temperatures for the JAS period. A weighted linear regression approach was applied to analyze trends in the JAS means, allowing weighting of data points based on their associated uncertainty and providing a corresponding uncertainty estimate for the derived trend. The trend was modeled in all cases as $T_s = \beta_0 + \beta_1 * (\text{Year} - 1992) + \varepsilon$, where β_0 and β_1 are the regression coefficients and ε is the residual error.

[16] Figure 2c shows the trends in summer nighttime temperature found for the study sites. All sites show a significant warming trend since 1992. Although the length of the time series differs significantly for ATSR and MODIS, the derived trends from the two independent sensors are remarkably similar. For both Lake Tahoe and Mono Lake, the trend lines are nearly identical. At Lake Tahoe, the retrievals from both sensors further agree quite closely with the in situ observations acquired at the lake surface. For Pyramid Lake and Walker Lake, the trend lines from both sensors exhibit a similar slope but show an offset of approximately 0.3°C to 0.5°C. Table 1 lists the linear regression coefficients including the estimated uncertainties, R^2 values, and p-values.

[17] The data sets confirm that all studied lakes in California and Nevada exhibit a significant warming trend with respect to summer nighttime temperatures at the lake surface. At Lake Tahoe, data from three independent sources (in situ, ATSR and MODIS) agree with each other, thus rendering the possibility of an instrument artifact highly unlikely. The annual warming rates were found to range from 0.05 ± 0.03°C yr^{-1} for Clear Lake to 0.15 ± 0.03°C yr^{-1} for Lake Almanor and Mono Lake. The increasing surface water temperatures at Lake Tahoe confirm the warming found by *Coats et al.* [2006], though the absolute rates are not comparable due to significant differences in methodology. All lakes exhibit a fairly similar rate of change with the mean warming rate being 0.11 ± 0.02°C yr^{-1}. This rate is equal to the mean surface warming rate found for Lake Superior by *Austin and Colman* [2007] and an order of magnitude higher than recently found rates of global ocean surface temperature increase of 0.009 ± 0.003°C yr^{-1} to 0.018 ± 0.004°C yr^{-1} [*Good et al.*, 2007; *Lawrence et al.*, 2004].

[18] An analysis of data from the Tahoe City meteorological station at Lake Tahoe (located at 39.17°N, 120.14°W) shows significant increases in average minimum air temperature. JAS means computed from bias-corrected monthly station data exhibit a linear warming trend of 0.03°C yr^{-1} since 1910 and a more rapid increase of 0.06°C yr^{-1} for the time period considered in this study. Lake Tahoe nighttime skin temperature warmed by 0.13°C yr^{-1} and thus warmed more rapidly than minimum air temperature - an effect that mirrors the results reported by *Quayle et al.* [2002] for Antarctic lakes and by *Austin and Colman* [2007] for Lake Superior. Data from the GISTEMP analysis [*Hansen et al.*, 1999] identifies 1992–2008 mean JAS air temperature warming trends for the study region as ranging from 0.01 to 0.06°C yr^{-1} (Figure 1) – less than the nighttime warming rates found for all the lakes studied here, and indicating that the lake surface temperatures may be warming more rapidly than the mean surface air temperature.

4. Summary and Conclusions

[19] Validation of the ATSR and MODIS skin temperatures against in situ data at Lake Tahoe showed that nighttime surface water temperatures can be estimated with an absolute bias of less than 0.1°C and standard errors of around 0.2 to 0.3°C. These results, together with an assessment of inter-sensor bias between all ATSR sensors of less than 0.1°C and the lack of any systematic drift when compared against long-term in situ data, indicates that accurate and stable time series of lake surface temperature can be retrieved from ATSR and MODIS data.

[20] All lakes studied here show a strong warming trend of summer nighttime temperatures since 1992, with rates of temperature increase ranging between 0.05 ± 0.03°C yr^{-1} (Clear Lake) and 0.15 ± 0.03°C yr^{-1} (Lake Almanor/Mono Lake), with all trends highly significant at $p < 0.05$. The average trend over all lakes and its associated standard error was found to be 0.11 ± 0.02°C yr^{-1} with $p < 0.002$. These rates of change are an order of magnitude higher than trends observed for global sea surface temperature and about twice as high as regional trends in air temperature, suggesting that summertime nighttime lake surface temperatures may be warming more rapidly than surface air temperatures. These increased warming rates in the near surface euphotic zone will likely impact the associated ecosystems and further work is required to characterize, understand and if necessary mitigate any impacts. The methods used in this study can be readily extended to a global scale in order to produce accurate temperature time series at the vast majority of lakes where no in situ data is available for quantifying climate change and characterizing its regional variability.

[21] **Acknowledgments.** The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Admin-

istration. The authors wish to acknowledge funding by the NASA Earth Observing System and support from ESA in acquiring the ATSR data. Numerous people have contributed to this work. In particular we would like to thank Fred Prata and Duane Waliser for valuable discussions.

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