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Moderate Resolution Imaging Spectroradiometer (MODIS) Observations of Cyanobacteria Blooms in Taihu Lake, China

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Moderate Resolution Imaging Spectroradiometer (MODIS) observations of cyanobacteria blooms in Taihu Lake, China

Chuanmin Hu,[1] Zhongping Lee,[2] Ronghua Ma,[3] Kun Yu,[1,4] Daqiu Li,[1,5] and Shaoling Shang[6]

[1] A novel approach was used with data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to characterize the intense blooms of cyanobacteria (primarily *Microcystis aeruginosa*) in Taihu Lake, China's third largest freshwater lake. The approach involves first deriving a floating algae index (FAI) based on the medium-resolution (250 and 500 m) MODIS reflectance data at 645, 859, and 1240 nm after correction of the ozone/gaseous absorption and Rayleigh scattering effects and then objectively determining the FAI threshold value (−0.004) to separate the bloom and nonbloom waters. By definition, the term "bloom" or "floating algae" refers to bloom where cyanobacteria form floating scums on the water surface. The 9 year MODIS time series data showed bloom characteristics (annual occurrence frequency, timing, and duration) between 2000 and 2008. Assuming 25% area coverage as a gauge for significance, significant bloom events rarely occurred between 2000 and 2004 for the entire lake (excluding East Bay) or several lake segments (Northwest Lake, Southwest Lake, and Central Lake). In most lake segments, the annual frequency of significant blooms increased from 2000–2004 to 2006–2008, when they started earlier and had a longer duration. The year 2007 showed unique bloom characteristics due to conditions highly favorable for bloom development and proliferation. The results suggest that the long-term bloom patterns are driven by both nutrients and climatic factors. The multiyear series of consistent MODIS FAI data products provide baseline information to monitor the lake's bloom condition, one of the critical water quality indicators, on a weekly basis, as well as to evaluate its future water quality trends.

Citation: Hu, C., Z. Lee, R. Ma, K. Yu, D. Li, and S. Shang (2010), Moderate Resolution Imaging Spectroradiometer (MODIS) observations of cyanobacteria blooms in Taihu Lake, China, *J. Geophys. Res.*, *115*, C04002, doi:10.1029/2009JC005511.

1. Introduction

[2] Coastal eutrophication is a serious global problem, especially in developing countries where excessive nutrients and other pollutants from rapidly growing agriculture, aquaculture, and industries are delivered to lakes, estuaries, and other coastal waters. As a result, coastal resources are under perceptible stress, with significant degradation in water quality, biodiversity, and fish abundance. For example, since the late 1990s, the number, size, and diversity of toxic algae blooms have increased significantly in Chinese coastal waters [*Zhou and Zhu*, 2006]. Likewise, *Brand and Compton* [2007] found an increasing trend in both bloom frequency and intensity for *Karenia brevis* from the 1950s through the 2000s on the central West Florida Shelf, although whether the trend is biased by the subjective sampling is being debated.

[3] Satellite remote sensing provides rapid, synoptic, and repeated information on water state variables (physical and biogeochemical) that avoids interpretive problems associated with undersampling. Indeed, over the last three decades, there have been significant advances in technology and algorithm development allowing satellite ocean color measurements to be used for studying coastal ocean water quality. Most of these advancements have focused on turbidity, water clarity, or other bio-optical properties [e.g., *Dekker*, 1993; *Hu et al.*, 2004; *Chen et al.*, 2007a, 2007b; *Lee et al.*, 2007]. Some algorithms and case studies have been developed for algal blooms [e.g., *Kahru*, 1997; *Kahru et al.*, 2000; *D'Sa and Miller*, 2003; *Kutser*, 2004; *Kutser et al.*, 2006], and long-term bloom patterns have also been established using multisatellite data in some marginal seas

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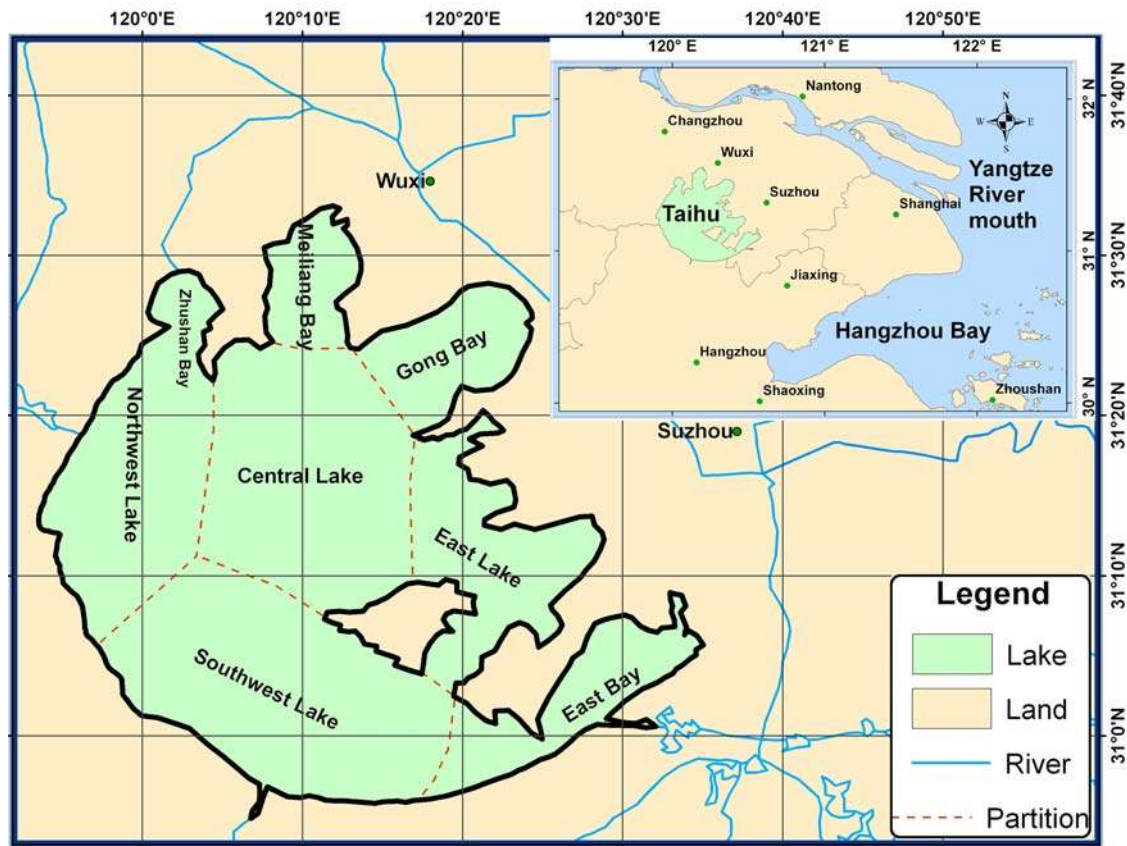
Figure 1. Location of Taihu Lake, China. The inset shows that the lake is close to the Yangtze River mouth and Hangzhou Bay. By convention, the lake is divided into several lake segments. The cities of Wuxi and Suzhou are located to the northeast and east of the lake, respectively.

(e.g., the Baltic Sea [*Kahru et al.*, 2007]). Algorithms using hyperspectral data to detect cyanobacteria from the chlorophyll and phycocyanin pigments have also been proposed [*Randolph et al.*, 2008], and some of the published algorithms have been evaluated recently [*Ruiz-Verdu et al.*, 2008]. However, there has been little published work on establishing a long-term, reliable record of phytoplankton blooms in any estuaries based on satellite data alone. This is due to the inherent problems in atmospheric correction and bio-optical inversion algorithms for estuarine and inland waters, where variable aerosols, suspended sediments, and other nonliving constituents (e.g., tripton, colored dissolved organic matter (CDOM), and shallow bottom) can significantly affect the remote sensing signal. This is particularly true for the case of Taihu Lake, a medium-sized eutrophic lake in eastern China (see area description below), where cyanobacteria blooms occur every year.

[4] Unlike other phytoplankton species, cyanobacteria can rapidly alter their buoyancy, and in calm weather they can form surface or subsurface scums, giving them the appearance of land surface vegetation instead of being uniformly mixed with water [*Paerl and Ustach*, 1982; *Sellner*, 1997]. Therefore, simple methods using the normalized difference vegetation index (NDVI) or the enhanced vegetation index (EVI) have been proposed to detect intense surface cyanobacteria blooms from limited field and satellite data for Taihu Lake [*Chen and Dai*, 2008; *Xu et al.*, 2008]. How-

ever, *Hu* [2009] showed that both NDVI and EVI are too sensitive to interference from changing aerosols (type and thickness), sun glint, and solar viewing geometry. Therefore, it is difficult to derive a consistent time series using these algorithms. In a few cases, several other studies have used band ratios between near-IR and red bands [*Duan et al.*, 2008; *Peng et al.*, 2008] to detect intense blooms. *Ma et al.* [2008a] applied a band-ratio method (859 versus 555 nm) to MODIS 250 m resolution data to separate bloom and nonbloom waters and then used multisatellite data and similar methods to derive long-term bloom distribution patterns in Taihu Lake. Due to inadequate atmospheric correction, these band-ratio methods face the same limitations as NDVI and EVI. In one case study, *Li et al.* [2008] used the atmospheric correction module (Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes) from the software ENVI version 4.1 (ITT Visual Information Solutions) before applying the NDVI classification. Due to the inherent limitations of the module (e.g., aerosol type and thickness must be known a priori), its general applicability is unknown. *Wang and Shi* [2008] used the shortwave-IR data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to remove the atmospheric effects by assuming that water-leaving radiances at these wavelengths were negligible. However, over thick blooms, surface reflectance at these wavelengths can be considerably higher than zero (see below). Clearly, an improved method is required to establish a
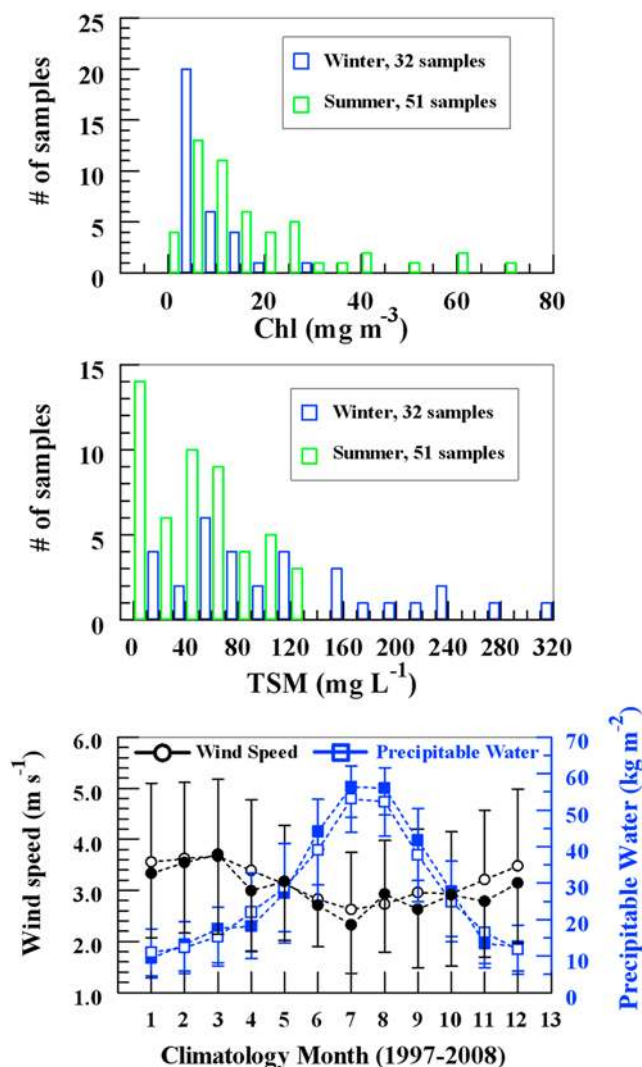
Figure 2. Seasonality of two water quality parameters and environmental conditions (wind and precipitable water) for Taihu Lake. The two water quality parameters are concentrations of (top) chlorophyll a (Chl, milligrams per cubic meter) and (middle) total suspended matter (TSM, milligrams per liter) determined from regular and irregular in situ surveys from July 2002 to November 2007 for the entire lake. (bottom) The monthly climatology of wind speed and precipitable water for Taihu Lake obtained from the National Centers for Environmental Prediction data. The solid symbols represent the year 2007.

consistent long-term record of cyanobacteria blooms in the lake.

[5] In this paper, using a novel method and 9 year MODIS data at 250 and 500 m resolution, we establish a long-term record of intense cyanobacteria blooms (where they form floating scums on the water surface) for Taihu Lake. There are four objectives:

[6] 1. To demonstrate a practical method for monitoring Taihu Lake's water quality, which may be applicable for similar water bodies where algae form surface scums.

[7] 2. To provide reliable statistics of intense blooms of Taihu Lake to help understand factors controlling blooms

and affecting water quality of this socioeconomically important lake.

[8] 3. To provide baseline data for future evaluations of the lake's water quality state. (Indeed, despite coordinated efforts in monitoring and management in the last decade, a reliable record of bloom statistics is lacking.)

[9] 4. To better understand the dynamics of the 2007 bloom event that caused significant economic loss and public impact.

[10] We first introduce our study area and describe our approach to quantifying intense cyanobacteria blooms. Then we present and discuss detailed statistical analyses of the bloom patterns between 2000 and 2008 (with particular focus on the 2007 bloom event). Finally, we discuss the implications of these findings for long-term water quality assessment in Taihu Lake and in similar water bodies.

2. Study Area

[11] Taihu Lake (30°5′N–32°8′N, 119°8′E–121°55′E) is the third-largest freshwater lake in China. It has a surface area of 2338 km^2 and an average water depth of 1.9 m (Figure 1). It is influenced by a semitropical monsoon climate with high wind during winter and more precipitation during summer (Figure 2). Average annual precipitation is about 1100 mm, with the average water temperature falling between 15°C and 17°C [*Jia et al.*, 2001]. The lake is characterized by seven major segments, including four embayments: Zhushan Bay, Meiliang Bay, Gong Bay, and East Bay [*Mao et al.*, 2008] (Figure 1).

[12] During the 1980s the lake became more and more eutrophic [*Jiang et al.*, 2001; *Ding et al.*, 2007]. By the end of 1998, local government enforced strict management practices (the "Zero Action" plan), which set up nutrient criteria for all wastewater discharged into the lake. However, it has been shown that the plan had little effect in reducing the lake's long-term eutrophic state [*Huang et al.*, 2002], possibly due to a lack of wastewater treatment and recycled nutrients in the lake. Between 1991 and 2007, several discrete monitoring stations showed increasing levels of total phosphorus and suspended solids and decreasing water clarity, especially from 2001 to 2007 [*Zhu*, 2008]. Concentrations of chlorophyll a (Chl) and total suspended matter (TSM) show clear seasonal patterns, where Chl is higher in summer and TSM is higher in winter due to strong winds (Figure 2).

[13] The lake's most eutrophic region is Meiliang Bay [*Ma and Dai*, 2005a], which serves as a source of drinking water for more than two million people in nearby Wuxi City. Of particular concern is the lake's blue-green algae or cyanobacteria (mainly *Microcystis aeruginosa*), which, if ingested, produces toxins that can damage the liver, intestines, and nervous system. During May–June 2007, extensive algae blooms were reported, followed by contaminated tap water in Wuxi City [*Duan et al.*, 2008; *Guo*, 2008; *Wang and Shi*, 2008; *Yang et al.*, 2008]. This event was reported extensively by the local, national, and international news media. Preliminary studies [*Kong et al.*, 2007; *Ren et al.*, 2008] suggested that the event resulted from a combination of several factors, including an earlier than usual algae bloom due to a warm winter, low water levels,
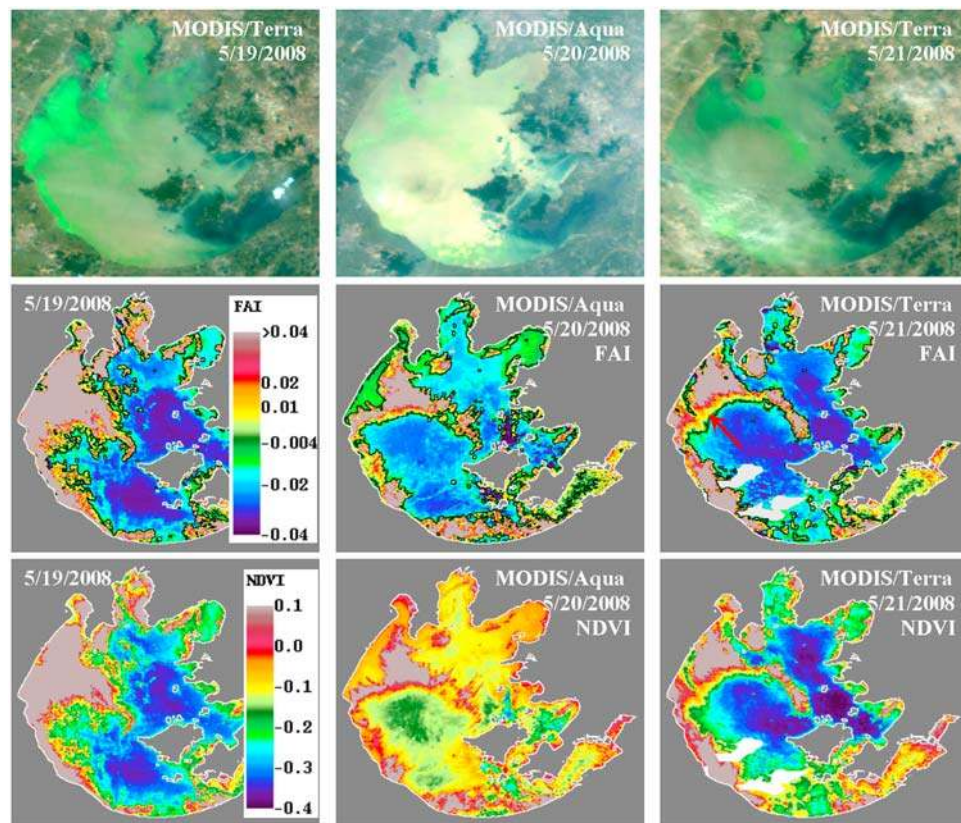
Figure 3. An example of the advantage of the Moderate Resolution Imaging Spectroradiometer (MODIS) floating algae index (FAI) against the MODIS normalized difference vegetation index (NDVI). FAI is less sensitive to changes in observing and environmental conditions such as aerosol type, thickness, sun glint, and solar viewing geometry, and therefore it serves as a better index for estimating floating algae (i.e., cyanobacteria blooms in Taihu Lake when they form surface mats). The black outlines in the FAI images distinguish FAI = −0.004, above which algae bloom is defined. For the three consecutive days, $R_{rc}(1640)$ in the lake center was 0.022, 0.139, and 0.020, respectively, while glint reflectance (L_g) was estimated as 1.7×10^{-5}, 0.05, and 0.0 sr^{-1}, respectively. The sevenfold higher $R_{rc}(1640)$ on 20 May 2008 was a result of combined effects from sun glint and thick aerosols. In ocean color remote sensing, $L_g > 0.01^{-1}$ is considered as significant and not correctable [*Wang and Bailey*, 2001]. Here the accuracy of FAI in distinguishing floating algae can tolerate values to at least $L_g = 0.05$ sr^{-1}. In contrast, NDVI is much more prone to errors [*Hu*, 2009].

and favorable wind conditions. However, there is no information on where the bloom initiated or how it evolved.

[14] A water quality monitoring network has been in place for nearly two decades. Water samples at 32 predefined, fixed stations have been collected and analyzed monthly or seasonally since 1991 [*Zhu*, 2008]. Routine ship surveys have also been used since 2002 [*Ma and Dai*, 2005b]. Both methods have provided water quality data regarding nitrogen, phosphorous, dissolved oxygen, Chl, TSM, temperature, and other pollutants. Several regional remote-sensing algorithms have been proposed from limited field data for Taihu Lake [*Ma and Dai*, 2005a, 2005b; *Ma et al.*, 2006; *Wen et al.*, 2006; *Yang et al.*, 2006; *Zhu et al.*, 2006; *Zhou et al.*, 2008], but their applicability in deriving consistent long-term time series has not been tested.

3. Data Sources

[15] This work relied mainly on the MODIS 250 and 500 m resolution data. Less frequent Landsat 7 Enhanced Thematic

Mapper Plus (ETM+) data at 30 m resolution were used to validate the MODIS observations.

[16] MODIS level 0 (raw digital counts) data from both Terra and Aqua satellites since February 2000 and June 2002, respectively, were obtained from the U.S. NASA Goddard Flight Space Center. As of 31 December 2008 there were more than 7000 data granules covering Taihu Lake. Each 5 min granule consists of scanned multispectral data (about 2300 km east–west) along the satellite track (north–south). The online quick-look images were first visually examined, and those with minimal cloud cover were chosen and processed. Between February 2000 and December 2008, about 600 near-cloud-free level 0 granules were obtained and used in this study.

[17] Landsat 7 ETM+ data (30 m resolution) were obtained from the U.S. Geological Survey. These are the level 1 georeferenced total radiance data at seven wavelengths (spectral bands), with the first five centered at 483, 565, 660, 825, and 1650 nm. The online browse images were first examined, and those with minimal cloud cover were also
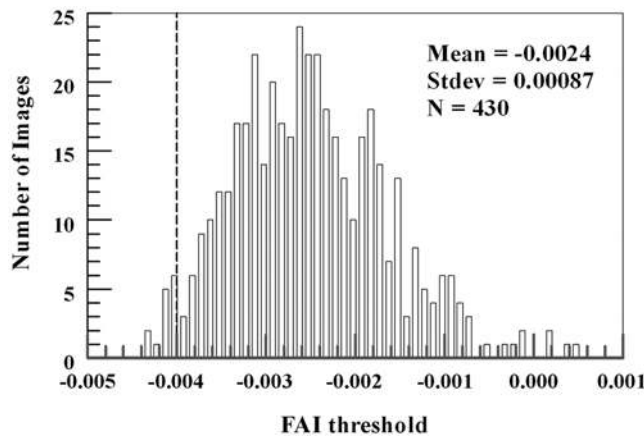
Figure 4. Statistics of FAI thresholds in all individual images for distinguishing floating algae (cyanobacteria bloom in Taihu Lake). The threshold from each individual image was determined as the mean FAI value over pixels where maximum FAI gradient was found. The dashed line denotes the mean minus two standard deviations, which is approximately −0.004. This value was chosen as a time-independent threshold value for distinguishing cyanobacteria bloom for the entire MODIS time series.

obtained. Due to the 16 day revisit frequency, only several Landsat scenes per year were found with minimal cloud cover.

4. MODIS Data Products Development

4.1. FAI (Floating Algae Index) Product

[18] MODIS level 0 data were converted to calibrated radiance data using the software package SeaDAS (version 5.1). Then, gaseous absorption and Rayleigh scattering effects were corrected using computer software provided by the MODIS rapid response team, based mainly on the radiative transfer calculations from Second Simulation of the Satellite Signal in the Solar Spectrum [Vermote et al., 1997]. The resulting reflectance data (dimensionless), $R_{rc}(\lambda)$, where λ is the center wavelength of the MODIS bands (469, 555, 645, 859, 1240, 1640, and 2430 nm), were georeferenced to a cylindrical equidistance (rectangular) projection using computer programs developed in-house. The georeference errors were less than 0.5 pixel [Wolfe et al., 2002].

[19] Three types of imagery were generated from the georeferenced $R_{rc}(\lambda)$. The first was the red-green-blue (RGB) "true-color" composite, using 645, 555, and 469 nm as the red, green, and blue channels, respectively. The 500 m resolution data at 555 and 469 nm were resampled to 250 m resolution (to match the resolution at 645 nm) using a "sharpening" scheme similar to that used for Landsat data. The second was the NDVI image, derived as NDVI = $[R_{rc}(859) - R_{rc}(645)]/[R_{rc}(859) + R_{rc}(645)]$. The purpose was to provide a simple image set for quick examination, although it has been shown that NDVI suffers from aerosol and sun glint effects [Hu, 2009].

[20] The last image type was a floating algae index (FAI), introduced by Hu [2009] for MODIS data, defined as follows:

$$FAI = R_{rc}(859) - R'_{rc}(859), \qquad (1)$$

with

$$R'_{rc}(859) = R_{rc}(645) + [R_{rc}(1240) - R_{rc}(645)]$$
$$\cdot (859 - 645)/(1240 - 645).$$

[21] Note that the design of FAI is the same as that of the MODIS fluorescence line height [Letelier and Abott, 1996] and the Medium-Resolution Imaging Spectrometer (MERIS) maximum chlorophyll index [Gower et al., 2005], except that longer wavelengths are used. Indeed, use of wavelengths in the red and near-IR can avoid atmospheric correction and CDOM interference problems at the blue and green wavelengths, and this technique has been shown to be useful for detecting blooms in coastal and inland waters [e.g., Ruddick et al., 2001; Hu et al., 2005; Gitelson et al., 2007; Gilerson et al., 2008; Yang et al., 2009].

[22] Using model simulations and MODIS measurements, Hu [2009] showed that compared with NDVI and EVI, FAI was less sensitive to changes in observing and environmental conditions (aerosol type and thickness, sun glint, solar viewing geometry). Although the index was designed to detect floating algae in the open oceans, these characteristics suggest that FAI may be a useful index for deriving long-term bloom patterns and trends for Taihu Lake.

[23] Examples of the two image types are shown in Figure 3, where images from three consecutive days (19–21 May 2008) are presented. The RGB images suggest that the atmospheric conditions on 19 and 21 May 2008 were similar, but hazy atmosphere and sun glint were present on 20 May 2008. On the basis of the Cox and Munk [1954] surface roughness model and National Centers for Environmental Prediction wind data, sun glint reflectance L_g [Wang and Bailey, 2001] was estimated as 1.7×10^{-5}, 0.05, and 0.0 sr^{-1} for the 3 days, respectively. Even under the extreme condition on 20 May 2008 ($L_g = 0.05$ sr^{-1} and $R_{rc}(1640) = 0.139$), floating algae could still be clearly distinguished from the nonbloom waters (see below for the method), and the results were consistent with the results obtained from two adjacent days. Note that $L_g = 0.01$ sr^{-1} is regarded as significant in ocean color data (too large to be correctable), and $R_{rc}(1640) > 0.0215$ would be classified as clouds by a relaxed cloud-masking method [Wang and Shi, 2006]. Therefore, the FAI method is robust for virtually all conditions in this region (thick aerosol, frequent sun glint during summer). In contrast, because of the higher sensitivity of NDVI to aerosol and sun glint influence (NDVI image on 20 May 2008), NDVI time series are more prone to errors.

4.2. Land Masking

[24] Land pixels show high FAI values and can be falsely recognized as floating algae. Therefore, a reliable land mask is required to exclude these pixels in our statistics. There are some global land cover databases that might be used. However, to ensure self-consistency, a land mask was
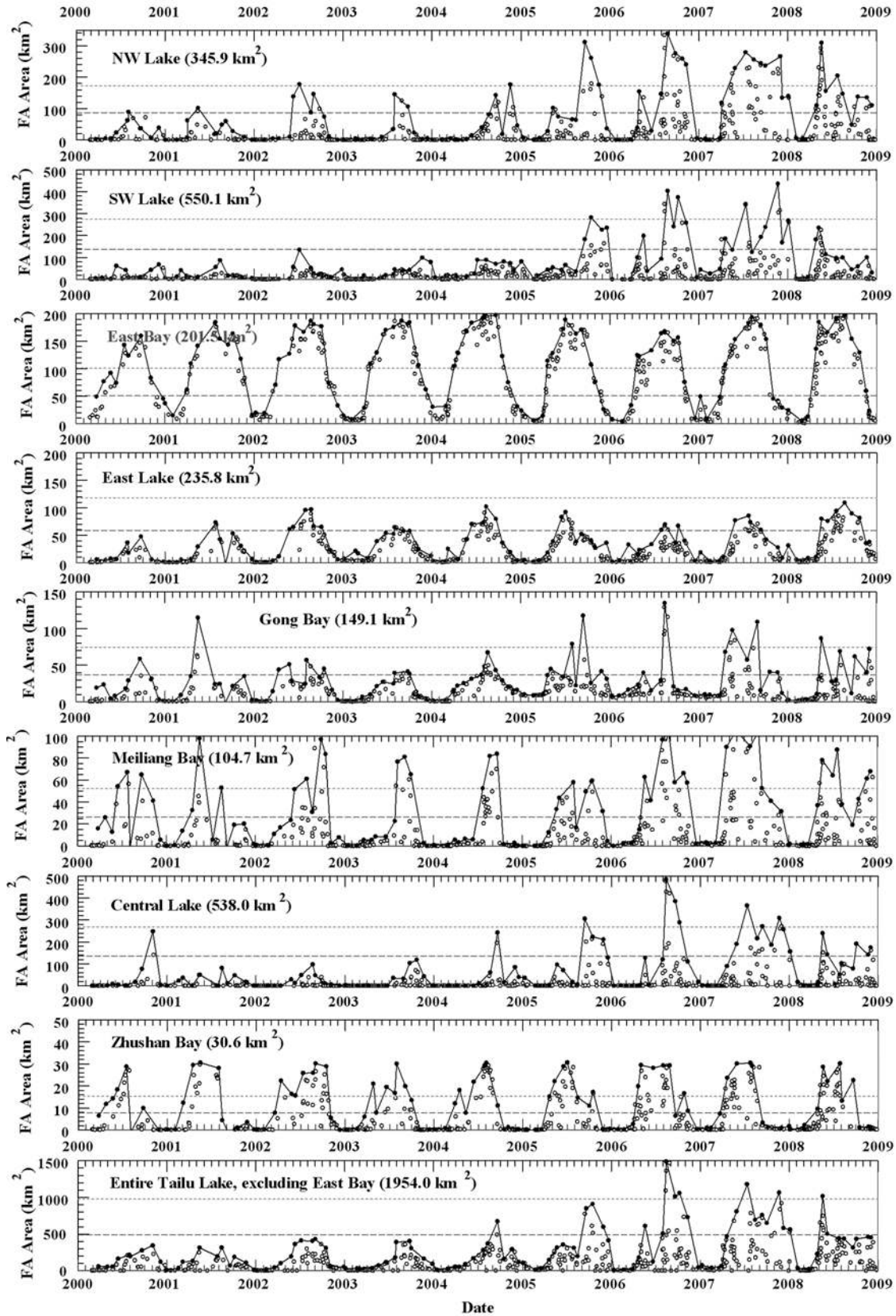
Figure 5

generated using MODIS FAI data. A composite FAI image was first created by averaging all valid MODIS measurements from 2000 to 2008 (578 images in total). The maximum gradient in the composite FAI image near the land-water interface was determined, and the pixels associated with the maximum gradient were chosen as the land-water interface. The polygons of these interface pixels were filled to yield a land mask. To compensate for navigation errors (about 150 m [*Wolfe et al.*, 2002]) and to avoid mixed land-water pixels during different seasons, the land-water interface pixels were dilated 1 pixel (250 m) toward the water, resulting in slightly less total water area (40,319 pixels or 2160 km^2) than commonly reported. The land-water interface could change slightly between different seasons or different years, but the 1 pixel dilation yielded a static land mask that was applied to the entire MODIS series.

4.3. Cloud Masking

[25] Similar to land pixels, cloud pixels also show high FAI values and therefore need to be identified and excluded. There exist several cloud detection algorithms. However, application of a recently developed algorithm [*Wang and Shi*, 2006] that uses a threshold value of $R_{rc}(1640) = 0.0215$ to differentiate cloud over turbid coastal waters did not lead to satisfying results: our analysis showed that for the lake center, most cloud-free images had $R_{rc}(1640) > 0.0215$ ($R_{rc}(1640) = 0.031 \pm 0.029$, minimum = 0.004, maximum = 0.193, $n = 557$ images). This is due to hazy atmosphere (thick aerosols), sun glint, and/or floating algae. Indeed, floating algae can cause significant reflectance in the near-IR and shortwave-IR wavelengths. A new method to differentiate clouds under the three circumstances is required.

[26] A trial-and-error analysis of the spectral shapes of various features did not lead to a robust, automatic cloud detection algorithm. Although this work is ongoing, because of the limited number of images used in our work, a semi-objective delineation was used to mask the clouds. The 578 images were first visually examined; 269 were associated with clouds and 309 were completely cloud-free. Each of the 269 images was analyzed with ENVI, and the regions where clouds occurred were first manually and crudely outlined. Then, the pixels within the outlined areas and with $R_{rc}(1640) > 0.03$ were considered as clouds and excluded from further analysis. Overall, the cloud cover percentage is small over the entire lake ($11.9 \pm 13.5\%$, $n = 269$).

4.4. FAI Threshold

[27] The most critical task in distinguishing intense blooms from other waters was to determine the threshold

value in the FAI imagery. One could use trial and error together with visual analysis, but this would be subjective and therefore arbitrary. Instead, we used FAI gradients and statistics to determine this critical value.

[28] For each FAI image (with land and cloud masked), a gradient image was generated. A pixel's gradient was defined as the FAI difference from the adjacent pixels in a 3 × 3 window. A threshold of FAI < −0.01 was used to exclude all pixels associated with high concentrations of submersed particles (either algae or sediments), and a threshold of FAI > 0.02 was used to exclude all pixels associated with thick algae scums. A histogram of the remaining pixels in the gradient image was generated and the mode of the maximum gradient determined. It was found that the pixels associated with the mode could separate floating algae from other nonbloom waters very well. This is understandable because at the bloom-nonbloom boundary there should be a sharp change (large gradient) in the FAI values. Although waters with high concentrations of submersed particles can also have high FAI gradient values, these pixels were not used in the histogram statistics. The mean value of all pixels in the FAI image associated with the gradient mode was used to represent the threshold value (FAI$_{thresh}$) to distinguish floating algae (i.e., intense bloom).

[29] The method was applied to the entire image series, and it worked well for most of the images (from visual examination), especially when extensive blooms were found. However, in images where bloom patches are small, the method failed due to there being fewer pixels pooled in the histogram. Therefore, instead of using a different FAI threshold value for each image, all FAI threshold values (after excluding those with none or small bloom patches) were pooled together to compute the histogram as well as the mean and standard deviation (Figure 4). From this, a universal FAI threshold was determined as the mean minus twice the standard deviation, which was approximately −0.004. This value was chosen as a time−independent FAI threshold to distinguish intense algae blooms from background waters. A sensitivity analysis (not shown here) suggested that using FAI$_{thresh}$ = −0.004 and FAI$_{thresh}$ = 0.0 would result in nearly identical statistics and spatial/temporal patterns, except that the former typically led to 5%–10% larger bloom area coverage. Therefore, FAI$_{thresh}$ = −0.004 was used in our study.

[30] Note that although high FAI values (> −0.004) are used to indicate floating algae (FA), in the context of this work and in the following, "FA" and "cyanobacteria bloom" are used interchangeably (see section 7.1 for accuracy assessment). In areas where known aquatic vegetation exists (e.g., weed, reed, and other macrophytes in East Bay; see

Figure 5. Daily area coverage of floating algae (i.e., cyanobacteria bloom) for each lake segment and for the entire Taihu Lake. The dashed and dotted lines represent 25% and 50% of the lake segment area, respectively. A pixel in MODIS FAI imagery is defined as cyanobacteria bloom if its FAI value is > −0.004. The solid circles represent the monthly maxima in floating algae coverage, which are connected by the lines. Annual statistics are presented in Tables 1–3. The marked dates start from 1 January of each year. Note that the results for East Bay indicate the temporal patterns of aquatic vegetation and not algae bloom. Likewise, in East Lake and Gong Bay the results may be mixed by algae bloom and aquatic vegetation [*Ma et al.*, 2008b].

Table 1. Frequency of Significant Cyanobacteria Blooms in Each Lake Segment[a]

Year	Northwest Lake Number of Images	Northwest Lake Percent of Images	Southwest Lake Number of Images	Southwest Lake Percent of Images	East Bay[b] Number of Images	East Bay[b] Percent of Images	East Lake[c] Number of Images	East Lake[c] Percent of Images	Gong Bay[c] Number of Images	Gong Bay[c] Percent of Images	Meiliang Bay Number of Images	Meiliang Bay Percent of Images	Central Lake Number of Images	Central Lake Percent of Images	Zhushan Bay Number of Images	Zhushan Bay Percent of Images	Taihu Lake[d] Number of Images	Taihu Lake[d] Percent of Images
2000	1	3	0	0	17	59	0	0	1	3	7	23	2	6	12	36	0	0
2001	2	5	0	0	26	74	3	9	4	11	5	14	0	0	13	36	9	9
2002	5	10	0	0	35	71	14	29	6	13	11	23	0	0	25	51	0	0
2003	3	5	0	0	35	60	3	5	4	7	7	12	2	3	13	24	0	0
2004	5	8	0	0	40	66	16	25	12	19	16	26	6	9	22	37	2	3
2005	9	14	6	10	42	63	6	9	6	9	13	20	6	9	23	35	6	9
2006	20	29	9	14	41	69	5	7	6	10	21	33	8	12	30	47	12	18
2007	31	45	11	16	41	59	8	12	15	22	22	33	14	19	30	43	16	23
2008	30	34	8	9	47	58	21	24	9	11	23	28	9	9	26	33	10	10

[a]The values shown represent the number and percentage of images where significant algae blooms were found from the Moderate Resolution Imaging Spectroradiometer (MODIS) floating algae index (FAI) imagery. "Significant" was defined as when the bloom area (FAI ≥ −0.004) exceeded 25% of the total surface area of the lake segment. For example, for Meiliang Bay, during 2007 there are 22 images (33%) where algae blooms covered an area of >26 km² (25% of 104.7 km² in Meiliang Bay).

[b]Results in East Bay are mainly from aquatic vegetation, not cyanobacteria.

[c]In these lake segments the results come from both cyanobacteria blooms and some aquatic vegetation [Ma et al., 2008b].

[d]Taihu Lake is defined as the entire lake excluding East Bay because of its prevailing aquatic vegetation.

below), FA is actually an indicator of other vegetation instead of cyanobacteria bloom.

5. Landsat Data Products Development

[31] Landsat 7 ETM+ data were processed in a similar fashion as with MODIS. The georeferenced data were first corrected for gaseous absorption and Rayleigh scattering effects to generate the spectral R_{rc} (dimensionless). The R_{rc} data at 660, 565, and 483 nm were used as the red-green-blue channels to compose the "true-color" images, and those at 660, 825, and 1650 nm were used to generate the Landsat FAI images (equation (1)). Due to the sporadic nature of Landsat measurements, these products were not used to study the spatial-temporal bloom patterns but were only used to validate the concurrent MODIS observations. Note that we did not use Landsat FAI to validate MODIS FAI but visually examined Landsat FAI and RGB images to determine the bloom extent for MODIS validation because at 30 m resolution the surface algae scums can be easily recognized by their spatial texture. Although water plants such as macrophytes can also show some spatial texture, they mainly occur in East Bay, which was excluded from our statistics for cyanobacteria blooms.

6. Results

6.1. Spatial and Temporal Distributions of Cyanobacteria Blooms

[32] Figure 5 shows the temporal distributions of cyanobacteria blooms (FAI > −0.004) in each Taihu Lake segment from MODIS observations. To avoid cloud-induced bias in the area coverage statistics, only when the lake segment contained at least 75% cloud-free data were those data extracted and analyzed. Several lake segments (Gong Bay and East Lake) are known to have seasonal water plants (e.g., weed, reed, and other macrophytes [Ma et al., 2008b]) and therefore their patterns should not be viewed as cyanobacteria blooms only but rather as a mixture of plants and algae blooms. East Bay presents an extreme case, where the clear seasonal cycle is almost purely from water plants. Therefore, in the following, unless otherwise noted, "entire lake" means the entire Taihu Lake excluding East Bay. Note that these water plants cannot be advected to other lake segments, and therefore they did not affect our interpretations for other segments.

[33] For most lake segments (Northwest Lake, Southwest Lake, and Central Lake), as well as for the entire lake, there is an apparent difference between the 2000–2004 and 2006–2008 periods, with 2005 being the transition year. Assuming that 25% FA coverage represents the level of significance, between 2000 and 2004 significant blooms rarely occurred in these waters. They occurred much more often between 2006 and 2008, especially during summer months. The statistics in Table 1 also show that the occurrence frequency of significant blooms (as measured by the available MODIS FAI imagery; see below) in these lake segments increased dramatically from 2000–2004 to 2006–2008.

[34] Of particular interest is Meiliang Bay, which provides freshwater to more than two million people in nearby Wuxi City. Significant blooms (>25% area coverage) occurred in all years, but more frequent blooms were observed between

Table 2. Mean and Standard Deviation of Annual Coverage of Cyanobacteria Blooms in Each Lake Segment[a]

	Northwest Lake	Southwest Lake	East Bay[b]	East Lake[c]	Gong Bay[c]	Meiliang Bay	Central Lake	Zhushan Bay	Taihu Lake[d]
Total Area (km²)	346	550	202	236	149	105	538	31	1954
2000	30 (30)	28 (26)	94 (40)	15 (16)	22 (17)	32 (26)	40 (82)	11 (10)	165 (103)
2001	31 (33)	25 (26)	104 (61)	22 (25)	24 (33)	22 (30)	24 (26)	9 (13)	136 (108)
2002	54 (67)	30 (39)	112 (67)	41 (37)	26 (20)	32 (33)	21 (30)	15 (12)	199 (173)
2003	28 (47)	33 (30)	113 (70)	35 (22)	19 (15)	23 (32)	28 (42)	11 (10)	154 (140)
2004	44 (59)	46 (32)	122 (67)	39 (35)	26 (18)	20 (32)	38 (70)	11 (12)	191 (190)
2005	94 (103)	106 (97)	99 (68)	36 (29)	38 (32)	26 (23)	91 (104)	12 (12)	354 (297)
2006	124 (127)	143 (148)	96 (66)	32 (24)	28 (35)	42 (38)	129 (168)	14 (13)	483 (502)
2007	161 (113)	176 (127)	104 (70)	37 (32)	43 (37)	52 (43)	172 (130)	13 (14)	581 (391)
2008	126 (84)	104 (85)	106 (76)	54 (37)	35 (31)	39 (32)	109 (77)	10 (12)	408 (259)

[a]This is based on the assumption that the monthly maxima (solid circles in Figure 5) can represent the monthly bloom conditions after interference from the wind mixing is removed. For reference, the size (total area) of each lake segment is given. Annual coverage is given in km² and the standard deviation is given in parentheses.
[b]Results in East Bay are mainly from aquatic vegetation, not cyanobacteria.
[c]In these lake segments the results come from both cyanobacteria blooms and some aquatic vegetation [*Ma et al.*, 2008b].
[d]Taihu Lake is defined as the entire lake excluding East Bay because of its prevailing aquatic vegetation.

2006 and 2008 (28%–33% of the images; Table 1). While the annual bloom frequency (in percentage of the available images) shown in Table 1 does not distinguish seasons, Figure 5 reveals that most blooms occurred in the summer and fall months. During these seasons, the bloom frequency was significantly higher than listed in Table 1. Indeed, if the monthly maximum points are connected, blooms persisted in Meiliang Bay between mid spring and late fall in 2007. This was the worst bloom year for the entire MODIS series (2000–2008).

[35] Because of the effect of wind on the formation of the surface mats, the monthly bloom coverage may be better represented by the monthly maxima than by the monthly mean (see below for details of the wind effect). On the basis of this argument, mean and standard deviation of the annual bloom coverage for each lake segment were estimated from the monthly maxima, and results are presented in Table 2. Similar to Table 1, for Northwest Lake, Southwest Lake, Meiliang Bay, Central Lake, and Taihu Lake, there is significant increase in the bloom coverage from 2000–2004 to 2006–2008.
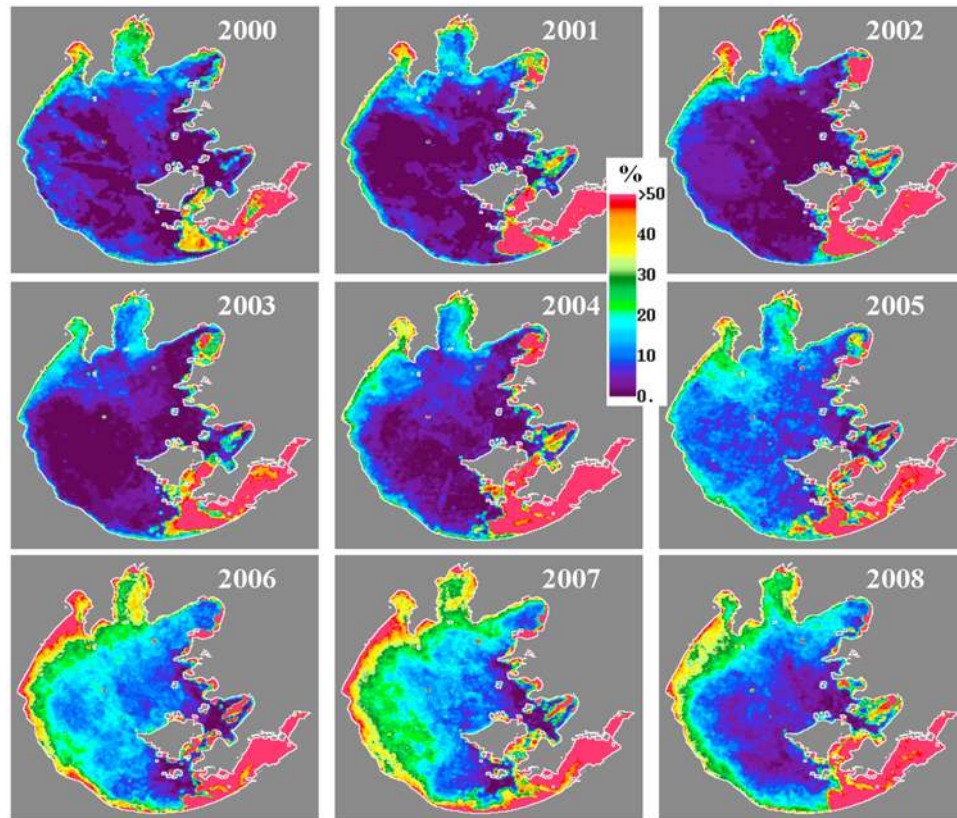

Figure 6. Percentage of MODIS measurements when cyanobacteria blooms (FAI > −0.004) were found from MODIS FAI imagery.
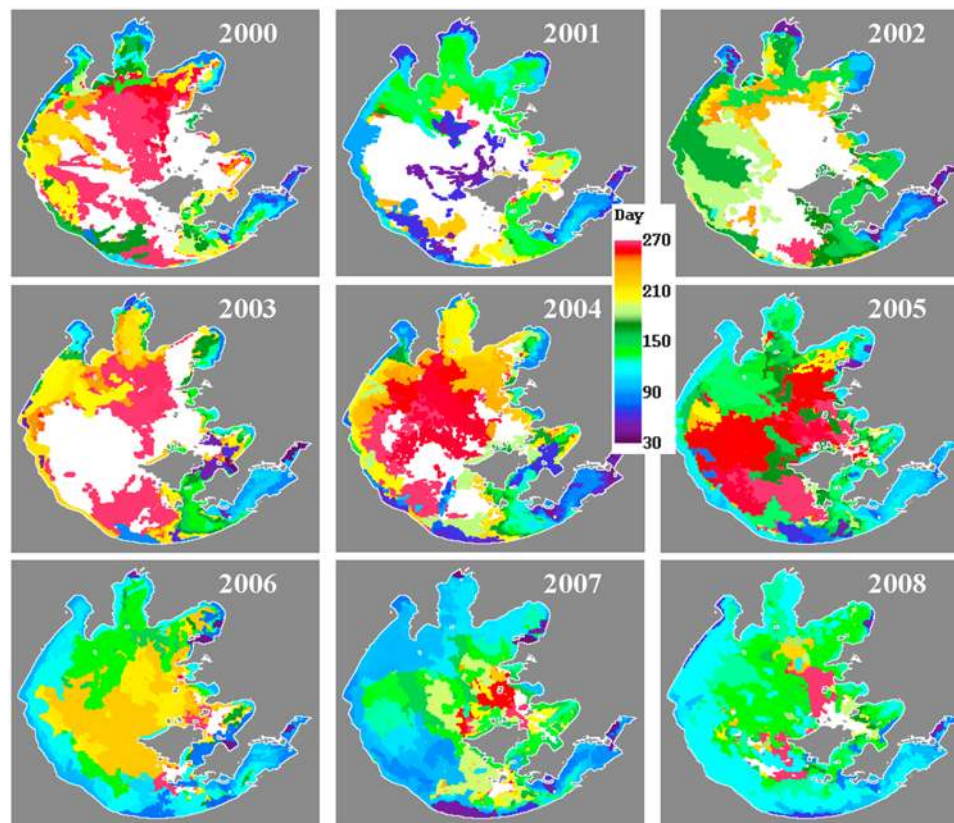
Figure 7. Timing of cyanobacteria blooms during each year after January. For each location (pixel), the first day when cyanobacteria bloom (FAI > −0.004) appeared was color-coded. White represents no bloom for the entire year.

[36] The bloom frequency for each location can be clearly visualized and compared in Figure 6 for every year between 2000 and 2008. The western lake segments (Northwest Lake, Southwest Lake, and western part of Central Lake) experienced more frequent blooms between 2006 and 2008 than between 2000 and 2004, with 2005 as a transition year. There is also apparent disparity in the bloom locations, with few or no blooms in the eastern part of the lake. Consistent with the time series data in Figure 5, 2007 appears to be the worst year. Before 2005, blooms rarely occurred in most regions of the lake, suggesting that the lake was relatively healthy (in terms of bloom frequency), especially away from the coastline. Some of the high-frequency values are found near the coast of Gong Bay and East Lake. Field surveys showed that some of them were from water plants instead of algae blooms [*Ma et al.*, 2008b]. Nevertheless, these annual distribution maps clearly show the bloom distributions and their 9 year trend. Whether this trend continues in the future should be closely monitored. Indeed, after 2007, there was a noticeable decrease in the bloom frequency in the lake center.

6.2. Timing and Duration of Cyanobacteria Blooms

[37] The timing of algae blooms can affect fish abundance [e.g., *Platt et al.*, 2003] and lake ecology [e.g., *Ren et al.*, 2008]. Figure 7 shows the date (day of the year) when a bloom first appeared in MODIS FAI imagery. Due to the noncontinuous nature of the available cloud-free MODIS

data (on average, about one image is available per week), the spatial distributions of the bloom timing are rather patchy. However, there appears to be a trend suggesting that the western lake blooms occurred earlier during 2006–2008 than during 2000–2004. The early bloom is particularly apparent in 2007, with extensive bloom patches first appearing in Northwest Lake in MODIS imagery on 4 April 2007. This early bloom played an important role in the magnitude of the 2007 bloom event that caused significant social and economic impacts (see section 6.3).

[38] Although for most of the lake the bloom frequency is lower in 2008 than in 2006, the blooms occurred earlier in 2008. The similarity of bloom timing between 2007 and 2008 did not lead to similar bloom impacts in the two years. This is thought to be due to the differences in meteorological conditions (wind, rain, etc. [*Ren et al.*, 2008]) and nutrient availability.

[39] The bloom duration in each year is defined as the difference between the first and last day that a bloom is present in MODIS FAI imagery. Figure 8 shows the spatial distributions of bloom durations between 2000 and 2008. For most of the western lake, 2006–2008 showed longer bloom durations than 2000–2004. The trend actually began in 2005, with 2007 being the worst bloom year. Indeed, more than half of the entire lake had blooms lasting for >7 months during 2007. Similar long-lasting blooms were also found in Meiliang Bay during 2007 and 2008.
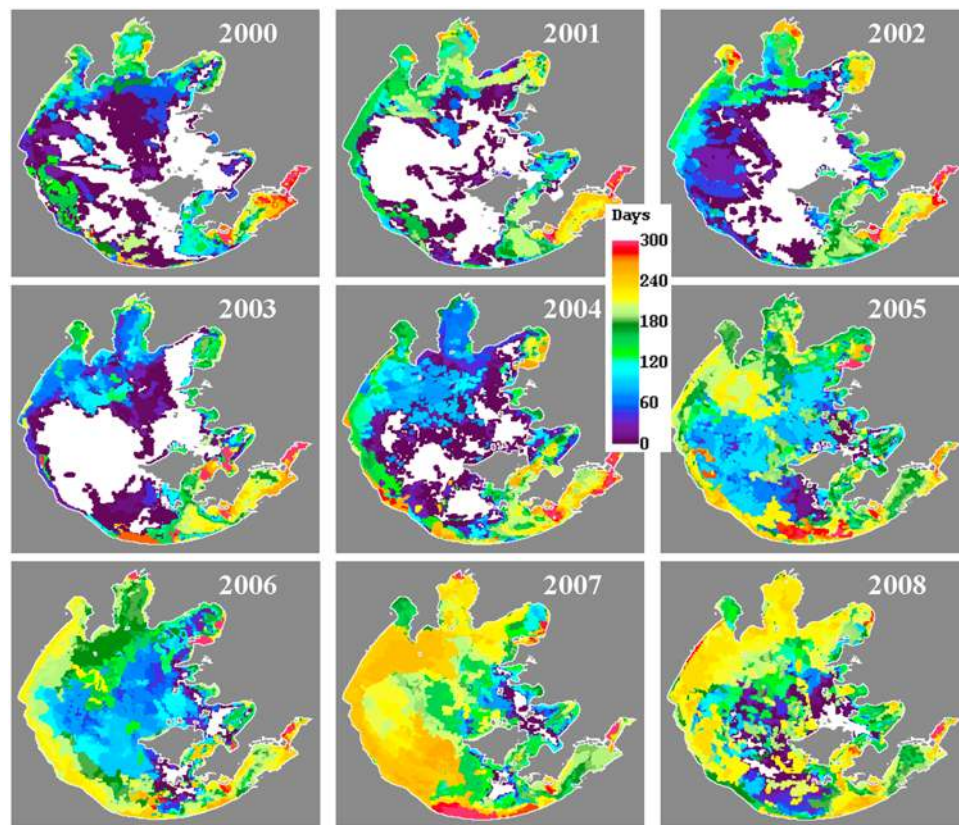
Figure 8. Duration of cyanobacteria blooms, defined as the difference between the last day and first day when blooms (FAI > −0.004) were found from MODIS FAI imagery. White represents no bloom for the entire year.

[40] The timing and duration of blooms in each lake segment are summarized in Table 3. Note that in Tables 1–3, East Bay statistics represent water plants rather than algae blooms. Gong Bay and East Lake contain water plants as well, and thus the data for these lake segments should be interpreted with caution. However, for the rest of the lake segments, these data should be valid. On the basis of 25% bloom area coverage as a measure of significance, these tabular data provide a quantitative measure of the bloom timing and duration for their visual counterparts in Figures 6–8. The earlier bloom occurrence and longer duration between 2006 and 2008 are apparent for Northwest Lake, Southwest Lake, Central Lake, and the entire lake. Indeed, bloom coverage never exceeded 25% of the entire lake area between 2000 and 2003 and exceeded 25% of the entire lake area only twice during 2004. This suggests that the lake was relatively healthy (i.e., devoid of blooms) between 2000 and 2004. This observation is also consistent with Table 1 and Figure 6.

[41] The findings from the statistics discussed above can be summarized as follows. Most of the lake was healthier during 2000–2004 than during 2006–2008, with less frequent blooms, later blooms, and shorter blooms. This is apparent for Northwest Lake, Southwest Lake, Central Lake, and Meiliang Bay. There is significant disparity in the spatial distributions of blooms even during the 2006–2008 bloom years, with most blooms having occurred in the western part of the lake. This observation agrees with those

obtained from periodic field surveys. The year 2007 experienced the worst blooms since MODIS data became available in 2000. This event is presented and discussed below.

6.3. The 2007 Bloom Event

[42] The extensive and long-lasting bloom in Taihu Lake and particularly in Meiliang Bay during spring–summer 2007 has been studied by several groups through analyzing in situ and remote-sensing data as well as meteorological conditions [*Kong et al.*, 2007; *Duan et al.*, 2008; *Guo*, 2008; *Ren et al.*, 2008; *Wang and Shi*, 2008; *Yang et al.*, 2008]. The earliest bloom in Taihu Lake was reported to start in late April [*Yang et al.*, 2008], and by 25 April an extensive bloom was found in Meiliang Bay [*Kong et al.*, 2007]. However, the MODIS FAI image series showed that an extensive bloom first appeared on 4 April in Northwest Lake and Southwest Lake (Figure 9), 3 weeks earlier than reported by *Yang et al.* [2008]. By 18 April (1 week earlier than reported by *Kong et al.* [2007]), an extensive bloom occurred in Meiliang Bay. Between 20 April and 30 August, the bloom occupied almost the entire Meiliang Bay. On 11 July and 21 November, more than half of the entire lake was covered by the intense bloom, some of which even lasted until at least 5 January 2008, making it the longest bloom event evidenced in all MODIS data and possibly the longest bloom event in history. Although at least 6000 tons of algae were collected in June 2007 in an attempt to reduce the

Table 3. Timing and Duration of Significant Cyanobacteria Blooms in Each Lake Segment[a]

Year	Northwest Lake Starting Days	Northwest Lake Duration	Southwest Lake Starting Days	Southwest Lake Duration	East Bay[b] Starting Days	East Bay[b] Duration	East Lake[c] Starting Days	East Lake[c] Duration	Gong Bay[c] Starting Days	Gong Bay[c] Duration	Meiliang Bay Starting Days	Meiliang Bay Duration	Central Lake Starting Days	Central Lake Duration	Zhushan Bay Starting Days	Zhushan Bay Duration	Taihu Lake[d] Starting Days	Taihu Lake[d] Duration
2000	214	1	−1	0	114	197	−1	0	262	1	159	152	308	3	114	154	−1	0
2001	132	3	−1	0	88	241	202	10	123	14	106	120	−1	0	65	147	−1	0
2002	162	108	−1	0	78	254	146	131	103	187	162	127	−1	0	78	220	−1	0
2003	213	55	−1	0	105	243	213	30	213	62	213	62	−1	0	116	159	−1	0
2004	261	74	−1	0	86	242	163	100	215	48	204	59	261	2	86	177	261	2
2005	132	202	262	92	104	228	167	45	123	209	142	190	257	77	110	181	257	77
2006	122	192	139	175	109	204	212	69	139	101	139	175	224	57	97	217	139	175
2007	94	274	94	274	94	200	149	106	110	216	108	227	149	194	94	149	139	204
2008	116	230	115	27	109	215	138	158	138	208	119	227	138	200	116	148	128	30

[a]The values shown represent the starting days (0–366) and durations (in days) of significant algae bloom. "Significant" was defined as when the bloom algae area (FAI > −0.004) exceeded 25% of the total surface area of the lake segment. Duration was defined as the difference between the last and first days when significant bloom occurred. The notation −1 indicates that significant bloom never occurred during the year.
[b]Results in East Bay are mainly from aquatic vegetation, not cyanobacteria.
[c]In these lake segments the results come from both cyanobacteria blooms and some aquatic vegetation [Ma et al., 2008b].
[d]Taihu Lake is defined as the entire lake excluding East Bay for its prevailing aquatic vegetation.

bloom [*Guo*, 2008], the results here suggest that the effort was compromised by sustained reproduction of cyanobacteria.

[43] Clearly, the bloom characteristics distinguish the 2007 event from all previous years. This is in contrast to the conclusion that "The algal bloom in Taihu Lake in 2007 was in fact not much different from those in previous years" [*Yang et al.*, 2008]. This is possibly because that the sporadic field surveys used in previous studies missed the early April bloom detected in MODIS imagery. The example here provides strong evidence that operational remote sensing, such as MODIS observations, can provide unique information on bloom characteristics that are difficult or impossible to obtain using in situ surveys. Indeed, the MODIS FAI image series (Figure 9) clearly revealed that the bloom in Meiliang Bay followed the bloom in Northwest Lake and Zhushan Bay. Following the dominant wind from the south [*Ren et al.*, 2008], the bloom was advected to Meiliang Bay and further developed and lasted for at least 4 months, making it the worst bloom event in history in this small bay and causing serious ecological and environmental problems [*Guo*, 2008]. The event suggests that despite significant efforts and resources used in the water quality management during the last decade, a long-term, continuous, and persistent management plan is required to bring the lake's water quality back to 2000–2004 levels, not to mention the levels found before the industry boom era in the 1970s.

6.4. Environmental Forcing

[44] Algae respond to changes in environmental conditions very quickly [*Coesel et al.*, 1978], and algae growth in Taihu Lake is influenced by both algal physiology and external factors, including light, temperature, and nutrients [*Ding et al.*, 2007]. For the 2007 bloom event, several studies [*Kong et al.*, 2007; *Ren et al.*, 2008] showed that meteorological and other environmental conditions (warm winter, favorable wind direction, low water level, ambient light, etc.) favored algae growth. Our analysis shows that although MODIS sea surface temperature (SST) in March and April 2007 was higher than multiyear averages, the difference was not significant (ANOVA test $p = 0.063$ and 0.34, respectively). Average surface photosynthetically available radiation (in einsteins per square meter per day), estimated from measurements by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), was slightly lower in March 2007 and slightly higher in April 2007 than its multiyear average. Wind speed in April 2007 was significantly lower than the multiyear average, but in March 2007 it was the same as the average. It is possible that during March 2007 higher than usual temperatures favored algae growth, and in April 2007 the lower than usual wind helped the algae to form surface scums (see below). However, similar meteorological conditions also occurred in history without significant bloom events, and there is no clear trend evident in Figure 10 that could explain the observed contrast between 2000–2004 and 2006–2008 bloom characteristics (Figures 5–8 and Tables 1–3).

[45] Due to nutrient inputs from a variety of sources (sewage, industry discharge, agricultural fertilizer, and other point and nonpoint runoff), *Zhu* [2008] reported that between 2002 and 2006, total N and P in both the lake center and Meiliang Bay showed a continuous increasing trend
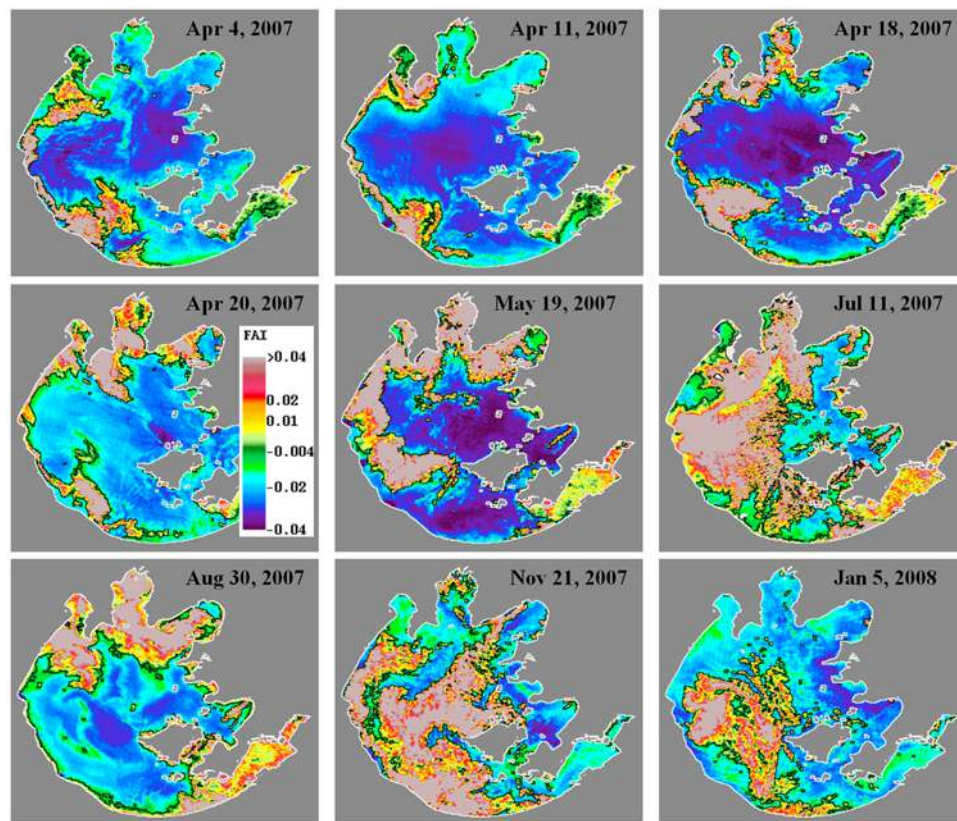
Figure 9. Evolution of the 2007 cyanobacteria bloom event in Taihu Lake. The bloom is indicated by FAI > −0.004.

(Figure 11). More recent data showed that total nutrients in 2007 and 2008 were not higher than in 2006 (Figure 11), but they were all significantly higher than in previous years (2000–2004). Hence, the apparent difference in bloom characteristics between 2006 and 2008 and 2000–2004 (Figures 5–8 and Tables 1–3) is very likely due to increased nutrients in the latter years, during which the favorable meteorological conditions in 2007 triggered the largest bloom event. However, continuous increases in nutrient concentrations between 2000 and 2004 were not accompanied by increased blooms even when favorable meteorological conditions existed. We hypothesize that there might exist some nutrient threshold levels below which significant blooms rarely occur (as between 2000 and 2004). If this is the case, nutrient criteria for the lake might be established from the mean nutrient levels between 2000 and 2004. The continuous measurements from MODIS and other planned satellite sensors may add additional data to test our hypothesis.

7. Discussion

[46] From the comprehensive analyses of bloom characteristics and environmental conditions, we believe that cyanobacteria blooms in Taihu Lake are primarily driven by nutrient levels but are also modulated by meteorological conditions. In particular, the 2007 bloom event appears to have resulted from both anthropogenic and climatic influences. Clearly, the FAI approach is useful in making these

ecologically important observations. However, before the approach is used for general water quality monitoring in this lake and similar water bodies, its strengths and limitations need to be addressed.

7.1. Accuracy

[47] FAI was designed to measure algae floating on the water surface, and for Taihu Lake, FAI > −0.004 refers to cyanobacteria blooms (except East Bay and some of the nearshore areas in the east) when cyanobacteria form surface scums. Therefore, the term "bloom" in this context differs from that used traditionally when algae particles are suspended in the water column, For example, the method will not be useful for blooms where algae do not form floating scums. However, with fast-changing wind conditions and relatively frequent MODIS measurements (on average, once per week after removing cloud cover), our results below show that it is unlikely that an intense bloom will be missed using FAI.

[48] The accuracy of our observations depends on two aspects: (1) Is the bloom size accurately quantified for each image? (2) Are the observed temporal patterns valid without significant bias due to infrequent sampling (e.g., one image per week)?

[49] Ideally, the bloom size should be validated by concurrent ground truth data. Unfortunately, in practice this is very difficult; for instance, a field survey platform (boat or aircraft) would strongly disturb the surface algae scums [*Kutser*, 2004]. Local news reported that 600,000 tons of algae
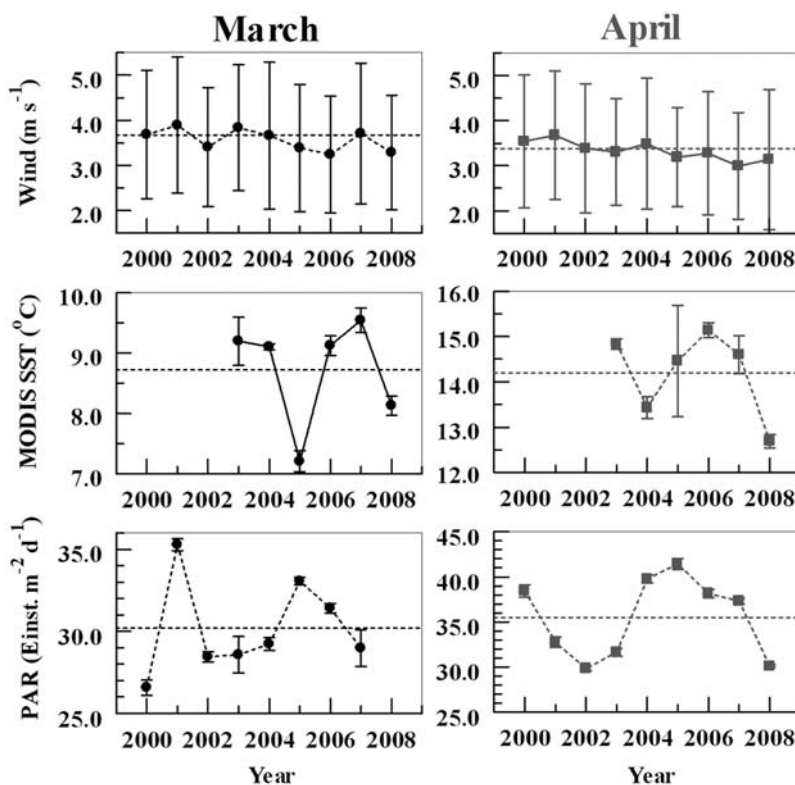
Figure 10. Average wind speed, sea surface temperature (SST), and photosynthetically available radiation (PAR) for March and April 2000–2008. Note that the units of the SeaWiFS PAR data follow the convention of the ocean color research community. For the year 2007 and the three environmental variables, only wind in April was significantly lower ($p = 0.0015$) and SST in March was nearly significantly higher ($p = 0.063$) than their multiyear averages (plotted as dotted lines).

were collected during 2008 (http://paper.people.com.cn/rmrbhwb/html/2009-07/25/content_304637.htm). Assuming that they were collected from 300 km^2 of the surface water (corresponding to one third of the Northwest and Southwest lake segments), we could derive an area concentration of 2 kg wet algae m^{-2}. With an average water depth of 2 m and conservative assumption of 1 g chlorophyll a kg^{-1} wet algae, Chl would be >1 g m^{-3}, which is at least 10 times higher than the maximum Chl from the in situ samples (Figure 2). The assumption of 1 g chlorophyll a kg^{-1} wet algae is similar to that used to estimate biomass of floating *Sargassum* in the Gulf of Mexico [*Gower et al.*, 2006]. Clearly, this conservative estimate suggests that none of the samples were collected from the algae scums, attesting to the difficulty of taking measurements with a boat. Also, the algae scums are formed under calm conditions, and they may be submersed or dissipated (not dead, however) under strong wind or storm conditions, making a "snapshot" field survey very difficult. Indeed, the bloom size in adjacent days can be significantly different for this reason (Figure 5). Figure 12 shows two examples where bloom size appears to be strongly controlled by wind. During several consecutive days in both September 2005 and November 2007, bloom size oscillated between >770 km^2 for wind speed ~<2 m s^{-1} and <140 km^2 for wind speed >3 m s^{-1}. It is impossible for an extensive algae bloom to die in 1 day and grow to the previous bloom state immediately thereafter. Therefore, the observed oscillating bloom size in consecutive days must be due to changes in physical

conditions (primarily wind forcing) and not due to changes in the total algae biomass. For the same reason, the odds of not detecting the algae bloom from the weekly MODIS measurements (after removing cloud cover) are very small because algae scums can form on the surface almost immediately after the wind subsides (points 1 and 3 in Figure 12a and point 3 in Figure 12b). For this reason, the maximum bloom size in each month in the 9 year period is highlighted in Figure 5. We believe that these monthly maxima should represent the monthly bloom status better than the monthly mean.

[50] Although it is difficult to validate the bloom distributions using field data, the accuracy can still be evaluated in the following three ways: (1) comparison with concurrent higher-resolution Landsat 7 ETM+ observations, (2) examination of the reflectance spectra of the identified bloom, and (3) evaluation of the observed patterns against existing knowledge from historical field surveys.

[51] First, the FAI threshold (-0.004) was validated using Landsat 7 ETM+ data. Because of the higher resolution, the algae bloom in Landsat imagery often shows spatial texture that can be clearly visualized (Figure 13). Therefore, the bloom can be manually outlined and used to validate the MODIS observations. The manually derived bloom outlines from the Landsat RGB image (red lines in Figure 13b) and the objectively derived bloom outlines from the contemporaneous MODIS FAI image (blue lines in Figure 13b) are nearly identical, suggesting the validity of the FAI threshold
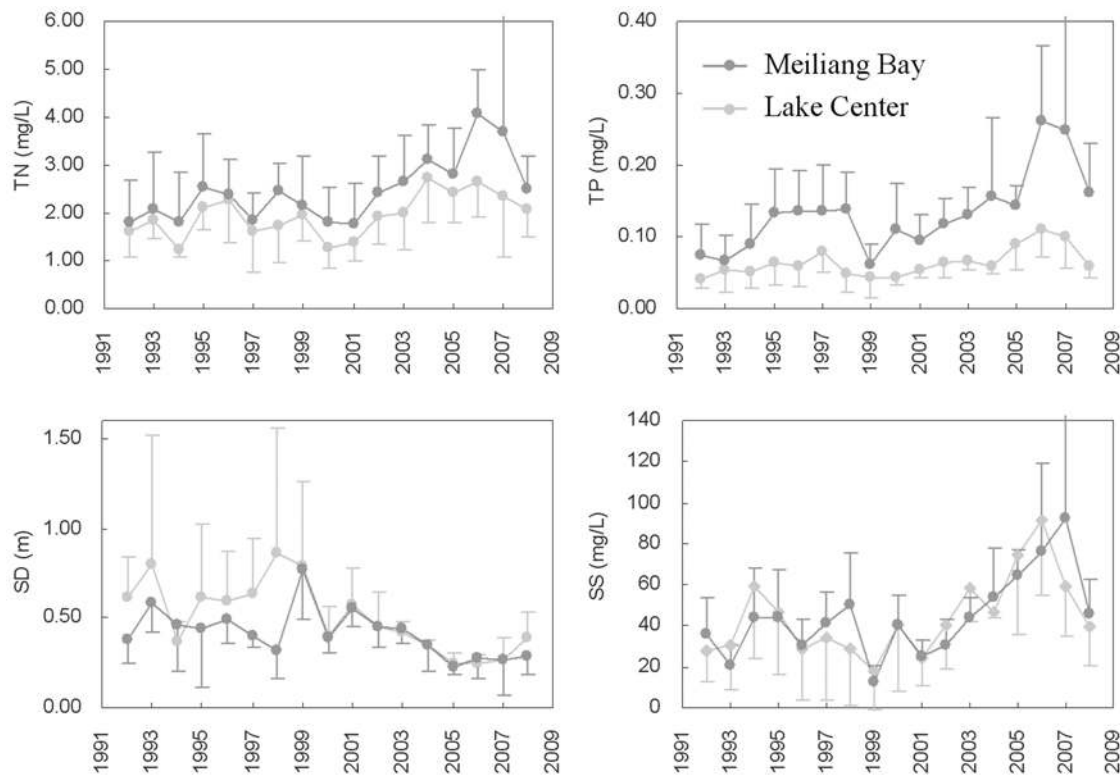
Figure 11. Total nitrogen (TN), total phosphorus (TP), transparency (Sechi disk depth (SD)), and suspended solids (SS) in the lake center and Meiliang Bay during summer 1991–2008. Adapted from *Zhu* [2008], but with more recent data for 2007 and 2008.

method. Even where algae are submersed in water due to wind and current and appear only in Landsat RGB images and not in MODIS FAI images (once the algae are below the water surface their signal in the 859 nm band decreases rapidly), these areas and their associated errors are small. Further comparison using other Landsat-MODIS image pairs when both were cloud-free showed very similar results (within ±10% in area coverage) between the two different measurements (Table 4). Clearly, the FAI threshold of −0.004 was a reasonable choice to generate the MODIS time series.

[52] The MODIS R_{rc} spectra of the identified blooms were also examined. Figure 14 shows several examples from the 21 May 2008 MODIS image in Figure 3 where the corresponding FAI values are −0.0025, 0.015, and 0.051, respectively. Comparison with the R_{rc} spectrum from the nearby water pixel (free of algae bloom scums) shows a clear difference in the 859 nm band. The difference spectra show a local peak at 859 nm, confirming the presence of an algae bloom even when FAI is negative (−0.0025), also suggesting that FAI threshold of −0.004 was a reasonable choice. Note that if the criterion of $R_{rc}(859)/R_{rc}(555) > 1$ was used to detect blooms [*Ma et al.*, 2008a], none of the pixels would be regarded as bloom. Therefore, the results of *Ma et al.* [2008a] should be regarded as very conservative estimates (i.e., very thick algae scums). It is possible that low FAI values result from pixels only partially covered by the surface algae. In this case, the bloom sizes in Figure 5 and Tables 1–3 are overestimated. Indeed, assuming that FAI = 0.02 represents 100% bloom coverage (this value was

obtained from land surface immediately adjacent to the coastline) and using a linear mixing model, we find that bloom size for >100 km^2 is reduced by 10%–30% in Figure 5, where the higher the coverage, the lower is the relative reduction. We believe that while it is necessary to obtain the absolute bloom size after taking into account the partial coverage, it is equally or even more important to know which pixels contain the algae bloom, even with partial coverage. The latter could provide better early warning of the bloom condition. Therefore, the results presented here should be interpreted as MODIS pixels with both 100% and partial algae bloom coverage, where for large bloom size (>100 km^2) the relative errors are smaller (<10%–30%).

[53] The observed patterns can also be validated using East Bay data where aquatic vegetation prevails and algae bloom is rare [*Ma et al.*, 2008b]. The seasonal cycle of the vegetation, with little interannual variability, is clearly revealed by the temporal patterns in Figure 5 for this lake segment. This provides additional validation of our approach. Certainly, some a priori knowledge is required to correctly interpret these FAI-derived results. For example, along the coast of East Lake, there is some aquatic vegetation [*Ma et al.*, 2008], and the results for this lake segment presented in Figure 5 cannot be interpreted as algae blooms only. For most lake waters (e.g., the western lake, Zhushan Bay, and Meiliang Bay), however, the results are truly an indication of algae bloom coverage.

[54] There are two limitations in using FAI to monitor algae blooms in a more general sense. Since FAI was designed to detect surface algae scums, it is not useful for
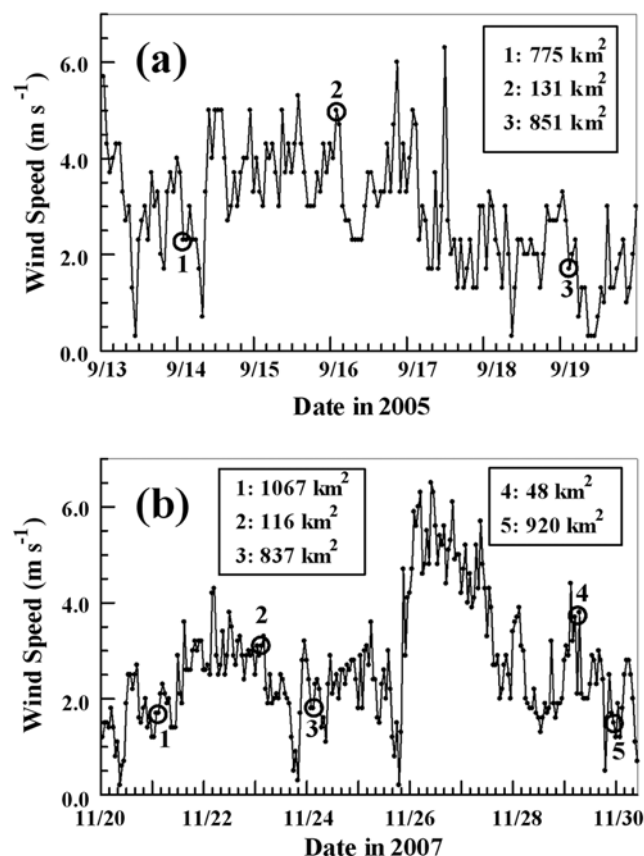
Figure 12. Hourly wind speed from a Taihu Lake monitoring station. The marked dates start from 0000 UT. MODIS measurements are marked with circles and numbers. The bloom size is given in square kilometers.

studying cyanobacteria blooms with biomass concentrations too low to form surface scums or algae blooms of non-cyanobacterial taxa, where the algae particles are mixed with the water molecules. The low detection limit for cyanobacteria blooms is difficult to determine because there has been no study on when (i.e., under what concentrations) cyanobacteria fail to form surface scums even under calm conditions. Local management reports used Chl of 40 mg m^{-3} as a threshold for significant blooms (http://www.tiaozhan.com/shijian08/file/200809071442171.doc). Thus, the low detection limit of our method may be comparable to this value. On the other hand, since FAI was designed to estimate the algae scum area and not the thickness, once the surface scums are thick enough (e.g., ~1 cm) to block all sunlight, FAI will be saturated and insensitive to increased thickness (i.e., increased area concentration). Therefore, there is also a high detection limit for biomass concentration estimates. This limit may be comparable to 2 kg algae m^{-2} or 2 g chlorophyll a m^{-2} derived in the analysis above. The exact detection limits (for both low and high ends), however, can only be determined through carefully designed field sampling in the future.

7.2. Long-Term Monitoring

[55] Our results show that although under certain conditions (e.g., high winds) the algae scums are dissipated and not observable, FAI is a reliable indicator of long-term bloom conditions. Indeed, the image series revealed earlier blooms than reported previously, suggesting the validity of this approach in providing early warning and long-term trend analysis. In contrast, traditional methods using water sampling or flowthrough instrumentation may incorrectly determine chlorophyll concentrations from the intense blooms because the water sample is often taken from a fixed depth below the surface bloom or the bloom patch pattern is altered by the ship [*Kutser*, 2004]. Therefore, satellite remote sensing, particularly with the FAI approach to remove most of the atmospheric effects, provides a better means to characterize intense cyanobacteria blooms in Taihu Lake.

[56] Conventional approaches in ocean color research often rely on the near-IR bands to remove the atmospheric effects to obtain the surface reflectance in the visible wavelengths and then use a band-ratio or similar bio-optical inversion algorithm to estimate Chl. For a number of reasons, these approaches may not work for this turbid lake. For example, similar to land vegetation, the algae scums can have significant reflectance in the near-IR and shortwave-IR wavelengths (e.g., $R_{rc}(1640)$ from the bloom pixels can often reach 0.1–0.2), making traditional atmospheric correction difficult. Bio-optical inversion using blue-green bands is also problematic because of the interference from high sediment concentrations and occasionally from the shallow bottom. The baseline subtraction in the FAI algorithm is essentially a simple but effective atmospheric correction after which the local R_{rc} peak at 859 nm is a robust indicator of the presence of floating algae (i.e., intense cyanobacterial bloom in Taihu Lake). FAI performance is stable over time (see East Bay results in Figure 5) and between MODIS-Terra and MODIS-Aqua results. In addition, many future sensors will be equipped with similar spectral bands, assuring long-term continuity. Therefore, the FAI approach provides a practical means for long-term monitoring of cyanobacteria blooms in the lake.

[57] Since FAI was designed to detect algae blooms when they form scums, future efforts will be required to develop an improved algorithm focusing on the visible bands to quantify biomass at low algal concentrations. These visible bands penetrate much deeper than the red-near IR-shortwave IR bands and will enhance remote sensing by improving bloom initiation detection. For example, MERIS is equipped with a band at 625 nm, which is potentially useful for detecting the cyanobacterial pigment phycocyanin [*Ruiz-Verdu et al.*, 2008]. It is desirable to test MERIS data in this eutrophic lake for its ability to separate phycocyanin pigment from suspended sediments and shallow bottom in the near future.

7.3. Global Applicability

[58] Because blooms often form surface scums in Taihu Lake, the proposed FAI approach is robust in establishing both long-term series and baseline conditions, as well as providing early warning. Whether the same approach is applicable in other lakes, estuaries, and coastal waters, however, remains to be tested. In general, accurate remote-sensing estimation of Chl for estuaries and inland waters is still a challenge for the remote-sensing community [*Zimba and Gitelson*, 2006; *Gons et al.*, 2008].
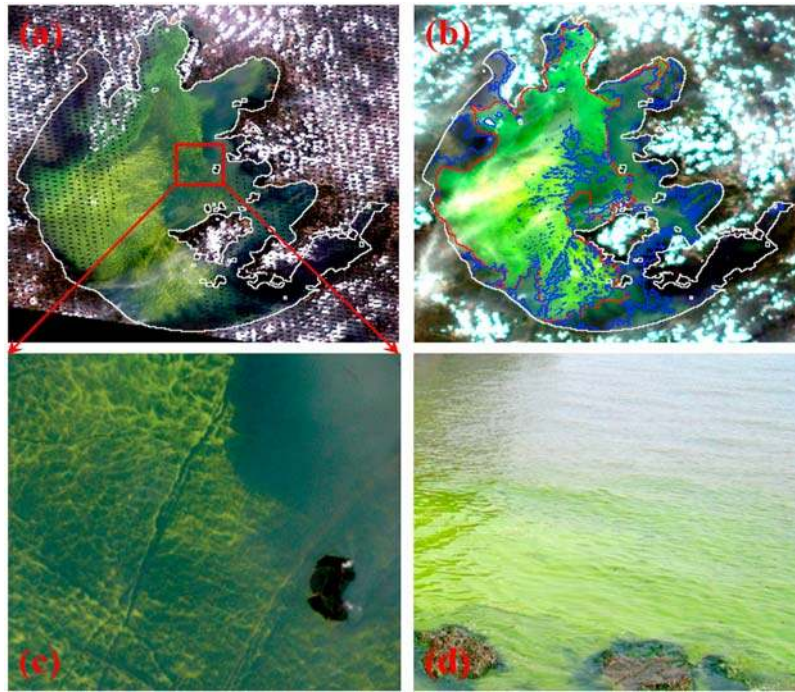
Figure 13. Validation of the MODIS FAI threshold in distinguishing cyanobacteria blooms in Taihu Lake. (a) Landsat 7 Enhanced Thematic Mapper Plus (ETM+) red-green-blue (RGB) imagery on 11 July 2007 showing the algae bloom (the black dots are due to errors in the sensor's scan line corrector). The RGB channels are from the 660, 565, and 483 nm ETM+ bands, respectively. (b) Concurrent MODIS/Terra RGB image from the 645, 555, and 469 nm MODIS bands. The red outline shows the bloom-nonbloom boundary visually determined from the Landsat image, while the blue outline shows the bloom-nonbloom boundary determined by FAI = −0.004 from the MODIS image (see text). (c) Enlargement of a small area in the Landsat image, where the bloom texture can be clearly visualized and therefore distinguished. (d) A photo of the cyanobacteria bloom during spring 2007 in Taihu Lake.

[59] Cyanobacteria and other phytoplankton blooms have been reported in many coastal waters and marginal seas, such as in the Gulf of Finland and the Baltic Sea [*Bianchi et al.*, 2000; *Hansson and Hakansson*, 2007], Lake Erie [*Vincent et al.*, 2004], the Bay of Bengal [*Hegde et al.*, 2008], and Moreton Bay, Australia [*Roelfsema et al.*, 2006]. The West Florida Shelf in the eastern Gulf of Mexico is also known to experience periodic occurrence of cyanobacteria (*Trichodesmium* spp.) blooms, which fix N_2 from the air and may fuel the toxic dinoflagellate *Karenia brevis* [*Walsh et al.*, 2006]. Many other coastal cyanobacteria blooms and their potential connections with climate change and human impact have been presented and discussed by *Paerl* [2007]. If these blooms form similar surface scums to those in Taihu Lake, they should be observable in FAI imagery.

[60] Specific algorithms using blue-green bands have been proposed to detect cyanobacteria blooms of *Trichodesmium* in the open-ocean environment [*Subramaniam et al.*, 2002]. *Vincent et al.* [2004] used Landsat data and multiband empirical regression to estimate phycocyanin pigment (specific to cyanobacteria), but it is unknown whether the approach is applicable for long-term time series studies. *Kahru et al.* [2007] used several sensors and green-red bands to establish a long-term time series (1979–1984, 1998–2006) of cyanobacteria blooms in the Baltic Sea. The method is useful for offshore waters but may not be applicable in coastal waters where suspended sediment concentrations are high. Our study region (Taihu Lake) is rich in suspended sediments, where TSM concentrations can often exceed 100 mg L^{-1} (Figure 2). To our knowledge, no one has been able to quantify long-term changes in bloom characteristics using a reliable method (i.e., immune to both

Table 4. Area Coverage of Cyanobacteria Blooms in Taihu Lake[a]

	21 Mar 2007	6 May 2007	11 Jul 2007	3 Jan 2008	20 Feb 2008	23 Mar 2008	18 Nov 2008
Landsat	0.0	330.2	1224.4	538.8	0.0	0.0	296.2
MODIS	0.0	315.0	1180.0	530.6	0.0	0.0	316.0
Diff%	−	−5	−4	−2	−	−	7

[a]Area coverage is given in km^2 and is determined from Concurrent Landsat 7 Enhanced Thematic Mapper Plus and MODIS imagery by visual interpretation of Landsat red-green-blue imagery and MODIS FAI thresholding (> −0.004), respectively. Diff% is defined as the percentage difference between Landsat and MODIS results.
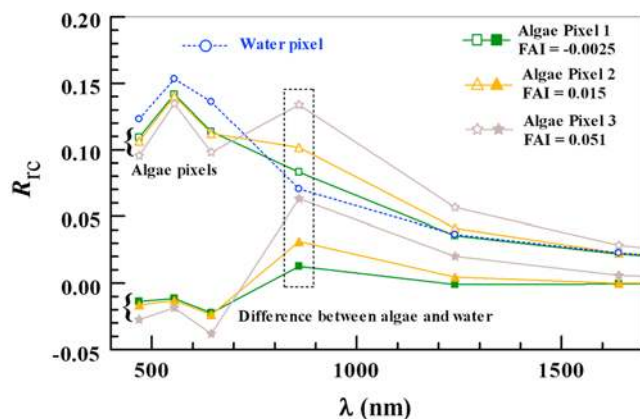
Figure 14. Sample spectra of Rayleigh-corrected reflectance (R_{rc}, dimensionless) of "algae" pixels (open squares, triangles, and stars) and a nearby reference "water" pixel (open circles) along a FAI gradient on the 21 May 2008 FAI image (shown by a red arrow in Figure 3). Their difference spectra (solid symbols) clearly show the local peak at 859 nm, even when FAI is negative (-0.0025), suggesting the validity of the FAI approach in detecting cyanobacteria blooms.

atmospheric and water constituent interference) for such case 2 waters. The FAI approach is immune to sediment interference; in such waters the high signal in the red band, $R_{rc}(645)$, will increase the baseline (i.e., R'_{rc} (859) of the FAI calculation in equation (1)), leading to lower FAI values. This is similar to the method of *Gitelson et al.* [1995], where the sum of reflectance above the baseline from 670 to 950 nm was used to estimate biomass. However, as discussed earlier, if the algae do not form surface scums but rather are mixed in the water column, the FAI approach is simply not applicable. In this regard, the Taihu Lake case is special, and whether the approach can be generalized for other waters with known cyanobacteria blooms should be tested. We speculate that where and when the algae are mixed in the water column, FAI might be inversely proportional to chlorophyll a concentrations because the increased concentrations will lead to increased reflectance baseline in equation (1), thus reducing the FAI values. For the same reasons, when suspended sediments dominate the optical signal, FAI might also be used as an effective index for turbidity.

8. Conclusion

[61] Several major findings can be summarized from this work. The FAI approach, originally designed to identify floating macroalgae in the open-ocean environment, can be applied to study cyanobacteria blooms in Taihu Lake, where the algae often form surface scums under calm weather. Such blooms are otherwise hard to quantify in a consistent manner due to inherent limitations in field techniques and due to imperfect algorithms in remote-sensing techniques (e.g., interference from the atmosphere, suspended sediments, and/or shallow bottom). On the basis of MODIS FAI imagery, the long-term spatial/temporal distributions of cyanobacteria blooms in Taihu Lake have been addressed in

detail. The most striking results are the disparity in bloom statistics between western and eastern parts of the lake and the contrast between the 2000–2004 and 2006–2008 periods. The temporal bloom patterns do not follow exactly the temporal patterns of nutrient availability even after meteorological conditions are taken into account. This suggests that certain threshold nutrient levels may exist below which blooms rarely occur. Further, the results show unique bloom characteristics for the year of 2007, including timing, duration, and location. These observations differ from those reported earlier using field surveys. Finally, because of the data continuity from MODIS as well as from other existing and planned satellite missions, the results can be used as baseline data to evaluate the lake's bloom conditions and also eutrophic status in the future.

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