DETECTION AND MASKING OF CLOUD CONTAMINATION IN HIGH-RESOLUTION SST IMAGERY: A PRACTICAL AND EFFECTIVE METHOD FOR AUTOMATION

Chuanmin Hu,[1] Frank Muller-Karger,[1] Brock Murch,[1] Douglas Myhre,[1] Judd Taylor,[1] Remy Luerssen,[1] Christopher Moses,[1] Caiyun Zhang[2]

[1]Institute for Marine Remote Sensing, College of Marine Science, University of South Florida
140 Seventh Avenue, South, St. Petersburg, FL 33701, USA. Email: hu@marine.usf.edu
[2]Department of Oceanography, College of Oceanography and Environmental Sciences, Xiamen University
Xiamen, Fujian 361005, China

ABSTRACT. Coarse resolution (9 – 50 km pixels) Sea Surface Temperature satellite data are frequently considered adequate for open ocean research. However, coastal regions, including coral reef, estuarine and mesoscale upwelling regions require high-resolution (1-km pixel) SST data. The AVHRR SST data often suffer from navigation errors of several kilometres and still require manual navigation adjustments. The second serious problem is faulty and ineffective cloud-detection algorithms used operationally; many of these are based on radiance thresholds and moving window tests. With these methods, increasing sensitivity leads to masking of valid pixels. These errors lead to significant cold pixel biases and hamper image compositing, anomaly detection, and time-series analysis. Here, after manual navigation of over 40,000 AVHRR images, we implemented a new cloud filter that differs from other published methods. The filter first compares a pixel value with a climatological value built from the historical database, and then tests it against a time-based median value derived for that pixel from all satellite passes collected within ±3 days. If the difference is larger than a predefined threshold, the pixel is flagged as cloud. We tested the method and compared to in situ SST from several shallow water buoys in the Florida Keys. Cloud statistics from all satellite sensors (AVHRR, MODIS) shows that a climatology filter with a 4°C threshold and a median filter threshold of 2°C are effective and accurate to filter clouds without masking good data. RMS difference between concurrent *in situ* and satellite SST data for the shallow waters (< 10 m bottom depth) is < 1°C, with only a small bias. The filter has been applied to the entire series of high-resolution SST data since1993 (including MODIS SST data since 2003), and a climatology is constructed to serve as the baseline to detect anomaly events.

KEY WORDS: Sea Surface Temperature, Cloud Filter, Remote Sensing, Climatology

1. INTRODUCTION

Sea surface temperature (SST) is an important parameter to study climate change at global scales and to indicate environmental health at local scales. Since the early 80's, the series of NOAA polar-orbiting satellites provided synoptic estimates of SST of the global ocean, critical in a variety of earth-science disciplines. More recently, NASA's MODIS sensors also provide global and local SST near-daily observations.

One particular application is to use SST anomaly as an index to predict coral bleaching. This concept has been implemented and operated by the NOAA/NESDIS Coral Reef Watch team (Liu et al., 2003; references therein). However, when applying the same concept to a small, coastal region, for example the Florida Keys National Marine Sanctuary (FKNMS), two major issues arise:

1. Due to the lack of onboard GPS, AVHRR data are auto-navigated by matching the image to the known coastline. Frequently there is residual error in the navigation in the order of several pixels (1-km resolution) but occasionally can reach to >10 pixels. This will induce large errors for time-series analysis in a small, heterogeneous region such as the FKNMS;
2. Although numerous cloud-detection algorithms have been proposed, mainly based on radiance thresholds and statistics of the multi-channel signals, frequently there are residual errors. One can visually identify these errors, but they can lead to significant SST bias in defining the "mean" state (i.e., climatology) and detecting anomaly events.

Based on continuous *in situ* data from several stations near the FKNMS and on cloud statistics, we developed a cloud filter to remove these residual errors. The "cleaned" individual images (> 47000 since 1993) form the basis to construct the long-term climatology, to detect anomaly events, as well as to facilitate time-series analysis.

2. DATA SOURCES

The University of South Florida started to collect AVHRR data through an L-band antenna since late 1993, and processed and archived all polar-orbiting series from n11 to n18. These data have been recently reprocessed to incorporate algorithm updates and new calibration coefficients. Briefly, we used SeaSpace's TeraScan software (version 3.2) to process the raw data. Pre-launch calibration was performed using a cold target, an external blackbody (representing the earth), and an internal warm blackbody. In-orbit calibration was performed using the internal warmbody and cold space. The calibration coefficients were updated routinely by SeaSpace.

SST was derived using the multi-channel sea-surface temperature (MCSST) algorithm (Strong and McClain, 1984; others). The approximate root mean square (rms) error of the AVHRR SST retrievals for the open ocean deep waters is of the order of 0.5°C (Brown et al., 1985; Minnett, 1991).

The cloud detection used by the TeraScan software uses a variety of methods, including threshold values, homogeneity, and band-ratio tests. A moving window of 3x3 pixels was used to screen for cloud, and a center pixel failing any of the tests was masked as "cloud".

Since summer 2003 USF has also collected MODIS/Terra and MODIS/Aqua data. These have been processed using the Miami/RSMAS codes. More recent data have been processed using SeaDAS4.8 (NASA code). Because of accurate onboard GPS there is no major navigation error with MODIS SST data. However, night-time data are not screened for clouds by SeaDAS.

3. METHODS

Each of the >40,000 AVHRR images was manually navigated to correct for auto-navigation errors.

Most published cloud-detection algorithms are based on the individual image only (Simpson et al., 2001; Chen et al., 2002). Here, however, we implemented a median filter based on temporal changes under the assumption that SST should change gradually within a short period, For any given pixel in the image, all satellite data for the same location within ±X days were queried. A median value was computed, excluding those already flagged as clouds. Then, the current pixel was compared with the median value, and if the difference was larger than Y°C the pixel was flagged as clouds. The median was used instead of the mean to minimize the effect of "outliers" due to cloud contamination.

To minimize bias in the temporal median calculation, for a given pixel each SST value from the ±X day pool was first screened against a pre-computed climatology value. If the difference was larger than 4°C, the value was discarded and not used in the median calculation.

To determine the number of days (X) and temperature threshold (Y) we performed statistical analysis using the SST data collected by several marine stations about 0.5-1 m below surface in the FKNMS (Table 1). Data were collected every hour. By iteration (trial-and-error) we found that X=3 days and Y=2°C were appropriate for this region. The ±3 days assures sufficient number of satellite passes (about 15 passes per day) to perform the statistics even after cloud cover is taken into account (see below). The ±2°C was the smallest threshold value in the trial-and-error that could retain nearly all (>99%) *in situ* data.

The entire scheme was implemented using IDL6.2, and then used to process the >47000 AVHRR+MODIS computers files.

Table 1. Station location and bottom depth.

Station	Location	Bottom	Time range
DRYF1	24.64N, 82.86W	6 m	1993-2005
LONF1	24.84N, 80.86W	2 m	1993-2005
NFBF1	25.08N, 81.09W	3.5 m	2004-2005

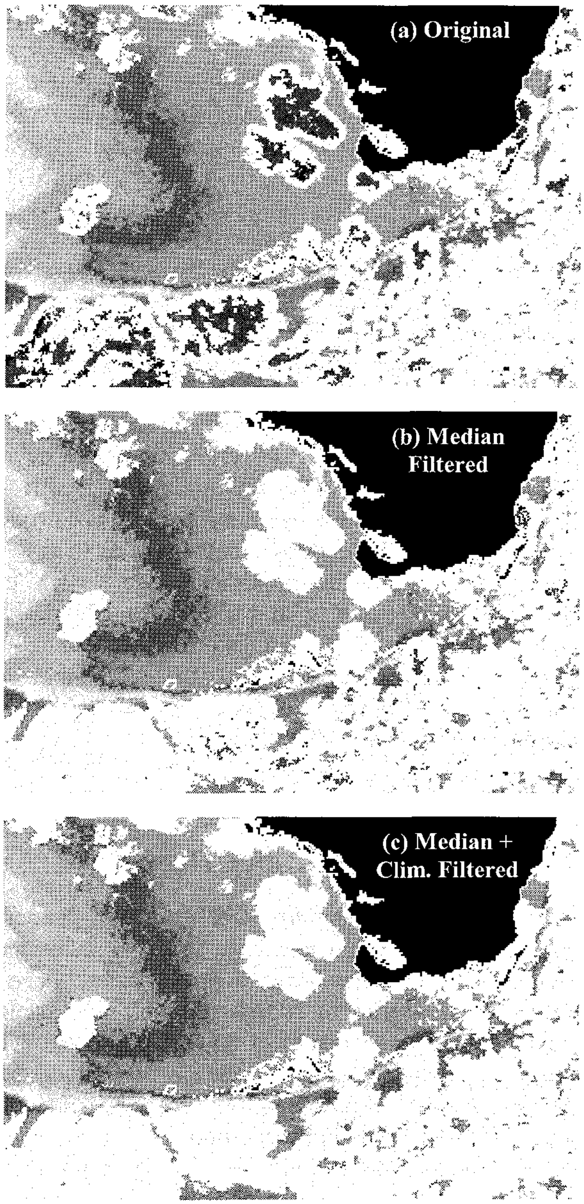

Fig. 1. An example of the filtering result for cloud-contaminated image. (a). Original image from the Terascan software after initial cloud filtering. Note the contaminated pixels adjacent to and on clouds (gray color); (b) The same image after a temporal (±3 days) median filter (threshold: ±2°C); (c) The same image after a weekly climatology filter (threshold: ±4°C) and the temporal median filter.

4. RESULTS

Fig. 1 shows the SST images from the n12 AVHRR sensor on 31 December 2004 at 10:37 GMT (local time: 5:37am). The median filter alone greatly improved the cloud filtering (Fig. 1b), but there were still some residual errors. A combination of the climatology and median filter yielded the best result (Fig. 1c).

The accuracy of the filtered SST data was evaluated against continuous field measurements. Fig. 2 shows that for the DRYF1 station, RMS difference between the 4066 satellite measurements and 4066 concurrent (within 2 hours) field measurements from 1993 to 2005 is about 0.83°C. This is slightly worse than that for the open ocean where RMS difference is typically about 0.5°C. However, because of the inherent difference between satellite (~ 1 km^2/pixel from the water "skin", i.e., sub-millimeter layer) and *in situ* (point measurement at about 0.5-1 m depth) measurements, and because of the small bias (mean_diff in the figure) and spatial heterogeneity of the shallow areas, we consider that the accuracy of the satellite data is satisfactory.

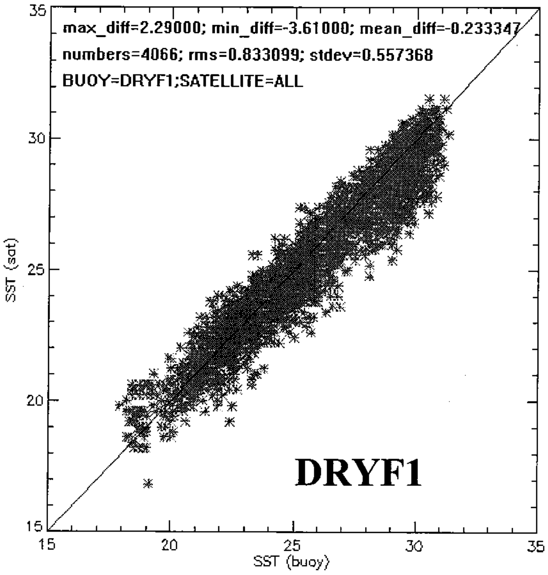

Fig. 2. Comparison between satellite and *in situ* SST. DRYF1 is the NDBC buoy at Dry Tortugas (Fig. 1a).

The cloud-filtered individual SST images from both AVHRR and MODIS sensors were used to generate daily, weekly, and monthly composite images as well as the weekly and monthly climatology. Fig. 3 shows the cloud-free probability of all four seasons between 2004 and 2005, based on the daily composite images. For any given pixel, 50% means that every two days (1/0.5 = 2) there is one cloud-free SST value for that pixel. Clearly, in all seasons and on average, there is at least one valid (cloud-free measurement) within two days. This validates that there should be sufficient number of valid measurements from ±3 days to construct the median filter.

In order to equalize the weighting of different times, weekly and monthly climatology images were composited from the daily composites instead of the >47,000 individual files. This is because that more data were collected (MODIS collection started in 2003) in recent years. Fig. 4 shows monthly climatology for January and July. For all seasons, there is a sharp contrast between the shallow and deep water SST to the south of the Florida Keys. Further, the full-resolution images show the heterogeneity within the shallow waters. Clearly, the coarse resolution SST data (e.g., 50-km or 20-km) cannot resolve these small-scale details that are important for this region.

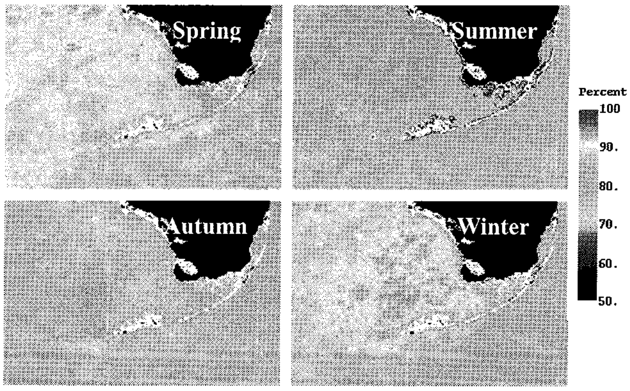

Fig. 3. Cloud-free probability for 2004-2005 near the Florida Keys. The statistics is from daily composite images from all AVHRR and MODIS passes.

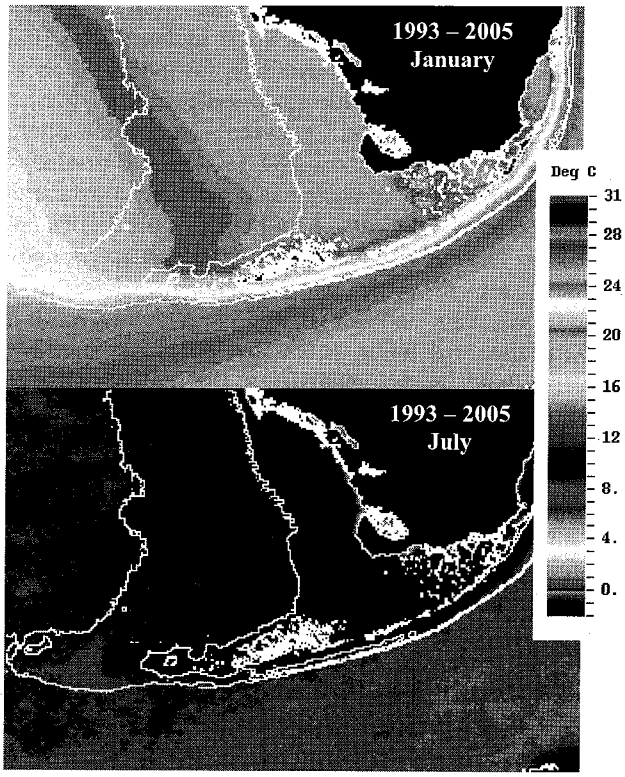

Fig. 4. Monthly SST climatology. Annotated on the images are the 10-m and 30-m bathymetry isobath lines.

Fig. 5 shows the SST anomaly (SSTA) for August 2005, defined as the difference between the current SST and the climatology SST..The shallow shelf, in particular the Florida Bay and the along the Florida reef tract, is about 0.5 – 1°C warmer than usual. Coincidently, there was some degree of coral bleaching in some spots in this region. Although other factors, such as UV penetration (modulated by the amount of CDOM in the water), may also play a role, the high-resolution SST anomaly, after rigorous quality control, provides an useful index to monitor the environmental health

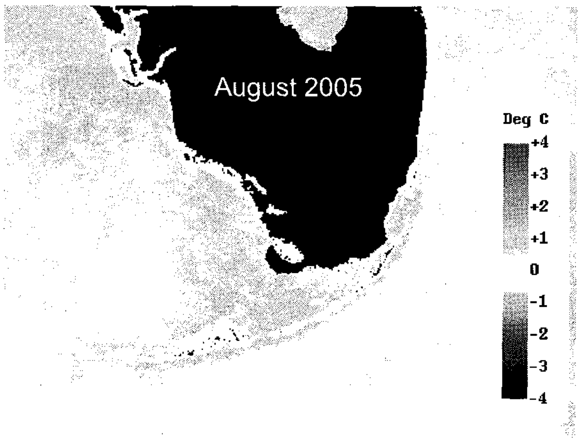

Fig. 5. SST anomaly (SSTA) for August 2005.

5. DISCUSSION

Although low-resolution SST data from microwave sensors (e.g., TRIM) or from some global efforts (e.g., NOAA SST products) are available for the world ocean, they are not adequate for small-scale studies. Further, preliminary comparison between our cloud-filtered products and the pathfinder SST (4- to 9-km resolution) found that the latter contains much more noise, where the exact reason is not clear. The 4-km GOES-R SST is only available recently (Walker et al., 2003) and covers only a limited region. The interpolation or merging of microwave SST and AVHRR SST can only result in intermediate resolution (note that for most nearshore waters there is no data from the coarse-resolution microwave sensors). Therefore, the current 1-km, cloud-filtered data products may be the best SST data for the region.

Can the same filter scheme (i.e., climatology + median) be applied to other regions? There are numerous ground stations around the world that capture data from the NOAA polar-orbiting series and from the MODIS sensors. In theory, the scheme should work for other regions. In practice, however, due to the different cloud-cover probability and different ocean dynamics, the threshold values for the climatology and median filters and for the time period of the median filter need to adjusted. In the worse scenario when a region is constantly experiencing cloud cover for days to weeks, the scheme will simply fail.

The filter is currently operational in near real-time at the Institute for Marine Remote Sensing (IMaRS) at the University of South Florida (http://imars.usf.edu). Because that in real-time operations there is no image *after* the current one, the filter is slightly relaxed to include previous 4 days to estimate the median. Visual examination of the results between June 2006 (when the filter started) and the present suggests that they are satisfactory.

6. CONCLUSION

From statistics of both *in situ* and satellite data we developed a filter to mask the cloud-contaminated pixels in SST imagery from both AVHRR and MODIS sensors. The published methods rely on spatial statistics and multi-channel relationships from the individual image alone, yet this new filter is based on historical and recent data. Results show that for shallow waters (bottom depth < 10 m) the RMS difference between satellite and *in situ* SST measurements is always < 1°C with bias < 0.4°C for all seasons. We believe that this new dataset will greatly facilitate the coastal monitoring effort in detecting anomaly events and studying climate-related coastal changes, and therefore recommended that such a filter be implemented for other coastal regions worldwide.

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