Advances in satellite radiometry for the surveillance of surface temperatures, ocean eddies and upwelling processes in the Gulf of Mexico using GOES-8 measurements during summer

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[1] GOES-8 satellite infrared (IR) measurements have been under-utilized in oceanographic research, although they provide several advantages over measurements from other sensors such as the NOAA AVHRR. Frequent coverage (48 times/day) over large regions, low noise in the mid-IR channel, and sole use of nighttime data have enabled the development of improved techniques for producing “de-clouded” images and calculating accurate SSTs (with RMS errors <0.5°C), over cloudy and humid regions such as the Gulf of Mexico. Animations of SST composite images reveal movements of the Loop Current, its frontal eddies and coastal upwelling even during summer months. GOES-12 and future GOES imagers for the next decade are missing the 12μm channel; however, this study demonstrates that the mid-IR channel is even more useful than previously thought. INDEX TERMS: 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4520 Oceanography: Physical: Eddies and mesoscale processes; 4279 Oceanography: General: Upwelling and convergences; 4504 Oceanography: Physical: Air/sea interactions (0312); 4243 Oceanography: General: Marginal and semienclosed seas. Citation: Walker, N., S. Myint, A. Babin, and A. Haag, Advances in satellite radiometry for the surveillance of surface temperatures, ocean eddies and upwelling processes in the Gulf of Mexico using GOES-8 measurements during summer, Geophys. Res. Lett., 30(16), 1854, doi:10.1029/2003GL017555, 2003.

1. Introduction

[2] Monumental improvements in the understanding of ocean circulation and, in particular, Loop Current (LC) and eddy circulations in the Gulf of Mexico (GOM) have been made over the past three decades using satellite-derived sea surface temperatures (SSTs) from the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA satellites [Vukovich et al., 1979; Vukovich and Maul, 1985; Muller-Karger et al., 1991]. Temperature measurements from two or more of the IR channels (3.7, 11, 12μm) are usually combined to estimate SST [McClain et al., 1985]. Limitations of AVHRR data for ocean research include poor temporal resolution (2 images/day per satellite), cloud contamination and a noisy or inoperable mid-IR channel.

The mid-IR channel is needed in tropical/subtropical regions where high atmospheric humidity renders the thermal IR channels useless [Bernstein, 1982; May et al., 1993].

[3] In 1994, with the launch of GOES-8 (Geostationary Operational Environmental Satellite), high quality radiometric measurements in similar IR channels became available every 30 minutes, from 30°W to 110°W [Menzel and Purdom, 1994]. GOES-8, fixed in position over 75°W, was replaced by GOES-12 on 1 April 2003. The frequent image coverage enables cloud removal, which reveals SST gradients, fronts and ocean features, previously undetectable for days and weeks [Legeckis et al., 1999]. The GOES-8 imager has IR channels similar in wavelength to the AVHRR sensors [Menzel and Purdom, 1994]. Spatial resolution of the GOES-8 IR ocean channels is 4 km, much better than its predecessor, but not as good as the AVHRR sensor with 1.1 km pixels. Future GOES-R imagers (2012 onwards) may have spatial resolutions of 0.5–2 km [NOAA NESDIS, 2001], a change that would greatly benefit coastal surveillance and research.

[4] This paper describes the development of regional GOM SST algorithms and new techniques for removing cloud and water vapor contamination. These techniques, combined with animation software, provide a powerful tool for ocean feature detection in cloudy and humid regions of the globe. Daily surveillance of circulation changes associated with the LC (an integral part of the Gulf Stream system) and its attached and detached eddies is now possible. These features require real-time monitoring for safe oil and gas operations and for the understanding of marine fisheries in the GOM. The new GOES SST composites and animations also provide more frequent coverage of coastal upwelling regions to advance studies of air-sea and physical-biological interactions on short time scales.

2. Data and Methods

2.1. Removal of Atmospheric Effects

[5] GOES-8 data were received via antenna and processed at the Earth Scan Laboratory (ESL), Louisiana State University, using SeaSpace Terascan® software. Since SSTs are higher than cloud top temperatures, clouds were removed by retaining the warmest pixels, from 10-hour sequences of co-registered nighttime (NT) images. The mid-IR channel (Ch 2) was used to improve SST gradient detection when atmospheric water vapor loads were high over the GOM, usually from May through September [May et al., 1993]. Since Ch 2 daytime data are contaminated by solar reflections, only NT data were used. Generation of GOES composites at the ESL was initiated in January 1996, now yielding a 7-year archive. Figure 1 shows Ch 2 and
Ch 4 composite images during summer to demonstrate the superiority of Ch 2 for detecting SSTs. Ch 2 temperatures revealed SST gradients across the GOM. In contrast, Ch 4 temperatures were lowered by water vapor in several regions of the GOM. A wide zonal band of cool temperatures was particularly apparent crossing the GOM south of 25°N (Figure 1, bottom). Figure 2 shows the extracted temperature values from all three channels along 25°N, as well as calculated SSTs. The relatively low temperatures in Ch 4 and Ch 5 indicate absorption and re-transmission of energy by water vapor [Robinson, 1994].

2.2. Development of SST Algorithms

SST algorithms were developed using measurements from 21 relatively clear-sky NT images (not composites), obtained between January and July 2001, and coincident measurements of SST from 10 National Data Buoy Center (NDBC) buoys (Locations, Figure 3). Visual inspection of the NT composite imagery was performed to identify large areas of cloud, which were excluded from the analysis. At each clear-sky buoy location, the two highest Ch 2 temperatures were extracted from the sequence of NT images. This procedure further minimized the possibility of including cloud-contaminated pixels. The Ch 2 temperatures were then matched with simultaneous data acquired in Ch 4, Ch 5 and the NDBC SSTs. Three algorithms were developed: equation 1 uses all channels; equation 2 uses Ch 2 and 4; and equation 3 uses only Ch 2. Temperatures are in degrees Celsius. All models yielded RMS errors less than 0.5°C and biases near 0°C (Table 1). GOES-8 SSTs were computed using equation 1, as it exhibited a slightly lower RMS value. Equation 2 is now being used to compute SSTs since Ch 5 was eliminated on GOES-12.

\[
Y = 1.513 + 1.035(\text{Ch 2}) + 0.393(\text{Ch 4} - \text{Ch 5}) \quad (1)
\]
\[
Y = 1.746 + 1.179(\text{Ch 2}) + (-0.133)(\text{Ch 4}) \quad (2)
\]
\[
Y = 1.062(\text{Ch 2}) + 1.513 \quad (3)
\]

3. Results and Discussion

3.1. Improvement in SST Retrievals

The new GOM SST algorithms are more accurate than previous algorithms reported in the literature [May and...
3.2. Advances in Ocean Feature Detection

[8] The warmest pixel compositing process provided a "clear sky" image on a nearly daily basis, and animations of composites greatly aided the surveillance and interpretation of circulation processes. Although researchers have discussed difficulties in resolving SST gradients in the GOM during summer [Vukovich and Maul, 1985; Sturges and Leben, 2000; Legeckis et al., 2002], SST variations of 8°C were detected across the GOM during July 2000 (Figure 3) with gradients of 1°C defining the LC and its eddies (Figure 2). In mid-July, water temperatures ranged from 23°C in coastal upwelling regions to 30–31°C along the Louisiana coastline and in Florida Bay. Two main coastal upwelling regions were identified. During spring and summer, a continuous band of cool water was often observed on the Campeche Bank, north of the Yucatan Peninsula, Mexico. During summer, the cool upwelled water (23–26°C) contrasted markedly in temperature with the warmer bank water and extended 150 km alongshore and 50 km offshore, driven westward by the prevailing trade winds [Walker et al., 1999].

[9] Persistent upwelling along the S. Texas and N. Mexico coasts (from 24°N to 28°N) occurred during summer when northward winds increased in strength and persistence [Walker, 2001]. Warm core eddies, detached from the LC, were often detectable in the northwest GOM, since they advect cooler coastal waters in a clockwise motion around their northern and eastern flanks (Figure 3).

Table 1. Statistical Details for the Three Nighttime SST Algorithms

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R²</th>
<th>RMS Error</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.99</td>
<td>0.98</td>
<td>0.45</td>
<td>−0.003</td>
</tr>
<tr>
<td>2</td>
<td>0.99</td>
<td>0.98</td>
<td>0.47</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.98</td>
<td>0.48</td>
<td>0.003</td>
</tr>
</tbody>
</table>

[10] The July 2000 image animation demonstrates circulation changes of the LC, its eddies, and coastal upwelling during summer 2000. On 12 July 2000, the LC was observed to be 0.5–1.0°C cooler than surrounding Gulf waters (Figures 2 and 3) whereas five days later, the LC was clearly identifiable as a 50 to 60 km wide stream of water with 1°C gradients along both inner and outer flanks. Cyclonic frontal eddies (FE) appear as wave-like perturbations along the outer edge of the LC [Vukovich and Maul, 1985]. Two cyclonic frontal eddies were best observed on July 17 and 18 along the northern margin of the LC. Multi-year satellite observations have demonstrated that, during non-summer months, the LC is relatively warm with SSTs about 10°C higher than winter-cooled continental shelf waters. However, during mid-summer, surface waters of the LC become a little cooler than ambient GOM waters. The transition periods, usually in June and August, are the most challenging times to detect the LC. The northward advection of cool waters from the Yucatan region can aid in the detection of the LC front during summer [Legeckis et al., 2002].

[11] During May 1999, four FEs traveled around the periphery of the LC. Their motion is depicted in Figure 4 and in a movie supplement. Although much research has focused on LC variability and the separation of warm core rings, less is known about the behavior of cyclonic FEs due to their rapid motion. The FEs advect warm LC water around their centers of circulation and, therefore, are detectable as warm wave-like features (Figure 4) although below the surface they have cold cores [Vukovich and Maul, 1985]. During May 1999, the four FEs traveled at variable speeds, moving 5 to 36 km/day in the along-current direction with...
diameters of 64 to 224 km. A detailed examination of FE movement during all months of 2000 and 2001 revealed that three FEs flanked the LC, on average. Many of the FEs were first observed along the eastern edge of the Campeche Bank, an observation in concurrence with Zavala-Hidalgo et al. [2003]. They usually grew in size as they traveled northwards, reaching maximum dimensions north and east of the LC.

The surface manifestation of FEs in the SST images were compared with contours of sea surface height (SSH) http://www-ccar.colorado.edu/~realtime/welcome). In many cases, these eddies were not revealed at all in the SSH data or were geographically offset. This observation was not unexpected, since the SSH data is confined to narrow tracks (2–4 km wide) that are widely spaced (60 to 300 km depending upon sensor) and only repeated every 10–35 days [Leben et al., 2002]. The lag in SSH updates does not always enable tracking of these rapidly moving features; however, this situation may improve as the number of altimeters increases. These cyclonic FEs may play an important role in the separation process for warm core rings from the LC [Vukovich and Maul, 1985], a process that appears imminent in late May 1999 (Figures 4c, 4d), but was not complete for several months [Sturges and Leben, 2000; Legeckis et al., 2002]. The FEs may contribute to the development of strong sub-surface currents when they interact with shoaling topography along the continental rise and slope from Louisiana to Florida. They may also play important roles in the life history of bluefin tuna, as tuna catches improve in proximity to the LC [Maul et al., 1984], where the upwelling of cool nutrient rich water concentrates food [Bakun, 1996].

4. Summary and Conclusions

The GOES SST composites and image animations provide oceanographers with a powerful new capability for detecting circulation changes in the GOM, a cloudy and humid ocean region. Much of the cloud contamination was removed by compositing NT images, obtained every 30 minutes over 10 hour periods. The extensive use of the mid-IR channel and sole use of NT data yielded improved techniques for quantifying SST and detecting ocean features during summer when atmospheric water vapor levels were extremely high. Multi-channel and single channel SST algorithms were developed with RMS errors <0.5°C. Although the 12 μm channel (Ch 5) was eliminated on GOES-12 and will not be available for about a decade, this study demonstrates that SST can be accurately estimated with the 3.7 μm channel alone or with a combination of the 3.7 and 11 μm channels.

The improved capability for tracking rapidly moving FEs offers exciting possibilities for understanding high velocity currents that impact oil and gas operations, for skill assessing numerical circulation models, and for the study of physical-biological interactions pertinent to fishery research. GOES SST composite images and animations also reveal coastal upwelling in two main regions of the GOM, providing measurements essential to the study of air-sea and physical-biological interactions on short time-scales. It is hoped that the spatial resolution of the ocean IR channels on future GOES-R radiometers can be improved to at least 1 km, a step that would further advance surveillance and research in coastal ocean regions.

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