Observations of Lower Tropospheric Water Vapor Structures in GOES-16 ABI Imagery

Lewis Grasso1, Dan Bikos1, and Steven Miller1

1Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA

Abstract During the afternoon of 16 April 2017 over Durango, Mexico, Geostationary Operational Environmental Satellite (GOES)-16 Advanced Baseline Imager (ABI) imagery near 1.38 and 7.34 μm exhibited nonstationary banded features. Alternating patterns of bright (dry) and dark (moist) bands were evident in images of 1.38-μm reflectance, while corresponding warm (dry) and cool (moist) bands were evident in images of 7.34-μm brightness temperatures. Based on observations, ambient southwesterly flow across the region is hypothesized to have channeled water vapor through major valleys over western Durango, followed by terrain lifting of water vapor over the plateau of central Durango. Due to lifting, moist bands appeared relatively cool in imagery near 7.34 μm. Similar bright and dark banded patterns were also evident in ABI imagery over Chihuahua, Mexico, on 8 May 2017. During the afternoon over Chihuahua, broken linear segments of cumulus formed within moist portions of the bands. Imagery from the 12.3- to 10.3-μm split window difference also supported the presence of moist bands. In the 8 May 2017 case, the banded features are hypothesized to be the result of horizontal convective rolls. Observations suggested that dark (moist) bands in imagery near 1.38 μm corresponded to the rising branch of horizontal rolls. Due to vertical motion, broken linear segments of cloud streets formed within the rolls. One consequence of newly identified features of the clear-sky water vapor field indicated the importance of new ABI measurements to aid forecasters in their interpretation of complex mesoscale dynamics.

Plain Language Summary Satellite imagery near 1.38 μm has the primary purpose of detecting cirrus clouds during the daytime. However, when skies are clear, water vapor contents are low, and terrain heights are high; imagery near 1.38 μm may capture detailed atmospheric motion within the first thousand feet above the ground. Two cases are presented in this manuscript: The first occurred on 16 April 2017, and the second occurred on 8 May 2017. Both cases occurred over elevated portions of northern Mexico: Durango and Chihuahua. Cirrus clouds are detected near 1.38 μm because of the interaction of energy from the Sun and water vapor in the air. If water vapor amounts are large, then the cirrus clouds appear bright while the ground appears black. However, if water vapor amounts are low, then the motion of water vapor near the ground can be captured.

1. Introduction

Cirrus clouds have long been recognized to participate in an important radiative feedback role in the global climate of the Earth (Liou, 1986; Stubenrauch et al., 2006). Detection of cirrus by satellites, over high-albedo, daytime surfaces, contains uncertainties, which limits (1) the global description of cirrus in terms of both space and time coverage and (2) the accuracy of spectral optical properties of cirrus clouds. Motivation to detect cirrus clouds came from the two limitations due to uncertainties just mentioned along with the impact cirrus clouds have on the global radiation budget. In response, a field experiment named the First International Satellite Cloud Climatology Project Regional Experiment Phase II Cirrus (Starr & Wylie, 1990) was conducted.

Examination and adoption of a spectral band dedicated to the remote sensing of cirrus clouds began about 20 years ago (Gao & Kaufman, 1995). As part of the First International Satellite Cloud Climatology Project Regional Experiment Phase II Cirrus experiment, the Airborne Visible Infrared Imaging Spectrometer (AVIRIS; Vane et al., 1993) was flown at altitudes of 20 km with the ability to detect radiant energy within 224 spectral bands ranging from 0.4 to 2.5 μm. One of the AVIRIS bands of interest for the purpose of cirrus detection was centered near 1.38 μm. A direct comparison of AVIRIS imagery near 0.55 μm with imagery near 1.38 μm demonstrated the skill of cirrus detection near 1.38 μm. One consequence of the field experiment
was the decision to include a spectral band with a spectral width from 1.36 to 1.39 μm on the Moderate-
resolution Imaging Spectroradiometer (MODIS).

MODIS, which has flown for nearly two decades on the National Aeronautics and Space Administration’s Terra
and Aqua satellites, has demonstrated an enhanced ability of measurements near 1.38 μm, which coincides
with an atmospheric water vapor absorption band, to detect cirrus during the day. Cirrus detection is enabled
by the suppression of surface reflectance contributions, owing to absorption of solar energy by lower tropo-
spheric water vapor. Reflection of sunlight by cirrus near 1.38 μm occurs in the upper troposphere, well above
most of the atmospheric water vapor; as a result, relatively bright cirrus clouds are readily discerned against a
darker background. Since both the Terra and Aqua satellites are in Sun-synchronous polar orbits, cirrus detec-
tion is limited to ~1030 and ~1330 local times, respectively.

Cirrus retrieval algorithms have been developed with the aid of MODIS imagery near 1.38 μm and radiative
transfer models. Due to significant absorption of solar energy near 1.38 μm by water vapor in the atmosphere
of the Earth, a noticeable contrast exists between values of reflectance of cirrus clouds and values of reflect-
ance in clear-sky scenes in MODIS imagery. Results from radiative transfer models have suggested that fea-
tures on the surface of the Earth are unlikely to be present in satellite imagery near 1.38 μm. In regions of the
atmosphere where values of total precipitable water (TPW) are less than about 0.5 cm, features on the surface
of the Earth may become noticeable (Gao & Kaufman, 1995; Gao et al., 2002, and references therein).

Keep in mind, however, that the ability of a satellite sensor to detect energy emitted from the surface of the
Earth is dependent on the vertical distribution of water vapor along with relatively large viewing angles, that
is, the limb, of a satellite. At times, new satellite observations reveal features that contribute to an improved
understanding of the complex environment of the Earth. Such is the motivation for this paper, which relates
structures that aid in the characterization of atmospheric composition and dynamics. New geostationary
observations near 1.38 μm, over portions of elevated terrain of the Sierra Madre Occidental in Mexico, con-
tained not only surface features but also banded, nonstationary atmospheric structures.

This paper is outlined as follows: section 2 provides an overview of the new geostationary satellite and the
principal sensor along with the instrument’s unique new perspective on cirrus. Sections 3 and 4 present
two case studies of satellite-observed banded structures that originated from different forcing mechanisms.
In section 5, a hypothesis is presented, based on observations, outlining a physical interpretation for the
observed banded structures. Section 6 concludes the paper.

2. GOES-16 ABI

The Geostationary Observational Environmental Satellite (GOES)-16 was launched from Kennedy Space
Center, Cape Canaveral, Florida, on 19 November 2016. Upon successfully reaching geostationary orbit in a
checkout position at 89.5°W, the satellite assumed the identification of GOES-16—the first of a new gener-
ation of satellites from the National Oceanic Atmospheric Administration operational geostationary satellite
program, which began with GOES-1 in 1975. This study took advantage of the principal sensor on GOES-
16: The Advanced Baseline Imager (ABI).

The ABI represents a significant advance in geostationary imaging of the surface and atmosphere of the Earth
compared with past satellites in the GOES series. The ABI images at 16 different spectral bands with a spec-
trally dependent nadir Instantaneous Geometric Field Of View (IGFOV) of 0.5, 1.0, and 2.0 km. By comparison,
GOES-15 images at five spectral bands with a spectrally dependent nadir IGFOV of 1.0 and 4.0 (Goodman
et al., 2012; Kalluri et al., 2018; Schmit et al., 2008).

Some of the new spectral bands on the ABI allow for the generation of true color imagery (Miller et al., 2017,
2016), determination of cloud optical and microphysical properties (Heidinger et al., 2015), cloud macrophy-
sical properties such as geometric thickness (Noh et al., 2017), and information about convection initiation
and severity (Cintineo et al., 2014; Lindsey et al., 2014; Walker et al., 2012). ABI also provides the first
geostationary-based 1.38-μm band and a unique new ability to characterize the spatially and temporally
resolved distribution and evolution of cirrus in the full disk view of the sensor over a portion of the
Western Hemisphere. One application of daytime imagery near 1.38 um is to screen out cirrus clouds for
improved clear-sky retrievals such as land surface temperatures and TPW. Additional advancements that
characterize ABI are the inclusion of three bands—6.19, 6.95, and 7.34 μm—dedicated to the sensing of
atmospheric water vapor. Each water vapor band provides information about water vapor in approximately the upper, middle, and lower troposphere, respectively. Other bands provide useful information about land/ocean surfaces, the cryosphere, atmospheric temperature and moisture structure, and atmospheric aerosol (Schmit et al., 2017, 2018).

Although GOES-R assumed the identification of GOES-16 and is now operational, imagery for this study was collected prior to the operational status of GOES-16. That is, ABI imagery presented in this paper was collected during a so-called checkout period. During a checkout period, many quality control steps are examined before data from GOES-16 are termed operational. As a result, there exists the possibility that imagery used herein contains some minor nonphysical characteristics. However, features of the imagery used herein are consistent with similar features of imagery from existing operational sensors. That is, imagery presented below contains prominent features that are consistent with motions and structures of the atmosphere of the Earth as opposed to minor nonphysical characteristics that may exist during the current checkout period.

All images herein have been produced from the Advanced Weather Interactive Processing System (AWIPS). One advantage of the AWIPS system is the ability of overlaying plots of model and surface observations on satellite imagery.

3. Case Study 1: 16 April 2017 Over Durango, Mexico

3.1. Overview

On the afternoon of 16 April 2017, weather conditions were generally clear over central Mexico. Figure 1 shows ABI imagery near 0.64 μm (IGFOV at nadir is 0.5 km) at 1757 UTC over the Mexican state of Durango under mostly clear-sky conditions. Cirrus clouds were evident over the Gulf of California, located in the upper left portion of Figure 1, while a few regions of marine stratocumulus were present over the waters offshore, located in the lower left portion of Figure 1.

Cumulus clouds had developed in association with land mass heating-induced convection over the Mexican interior, both to the northeast and southeast of Durango. Winds at a standard pressure level of 500 hPa, from Global Forecast System (GFS) reanalysis at 1800 UTC, were generally westerly at speeds between 5, in the southwestern portion of the figure, and 25 kt, in the northeast portion of the figure. Wind speeds at...
700 hPa (Figure 2) were, in general, less than those at 500 hPa with values between 5 and 10 kt; however, values of wind speeds were 20 kt along the southern portion (Figure 2).

Figure 2 also displays ABI imagery near 7.34 μm (IGFOV at nadir is 2.0 km). Brightness temperatures (Tbs) ranged between −4 and 1 °C, values that were representative of about 600 hPa in clear skies over Durango. Values of Tbs were the warmest over the state of Durango where Tb ~ +1 °C compared to 0 °C at 600 hPa from the 1800 UTC GFS analysis. Regions toward the southwest of Durango had Tb ~ −4 °C, while values of Tbs decrease over the upper left corner (Tb ~ −40 °C), which were associated with cold, optically thick cloud tops. Values of Tbs over the eastern third of Figure 2 were cooler near 7.34 μm as well, due to the presence of enhanced middle- to upper-level water vapor and additional clouds. The relatively warm Tbs over the region from Durango toward the southwest suggest lower values of TPW in this region.

Figure 3 shows surface observations at 1800 UTC, which were overlaid on imagery near 0.64 μm. At that time, surface temperatures were in the 80s °F (~29 °C) along the western coast with dew point temperatures ranging from the low 40s (~5 °C) to low 60s °F (~12 °C).

Surface wind speeds were generally light and variable. A few observations over Durango indicated temperatures in the middle 70s to upper 80s °F (~25–30 °C) with dew point temperatures in the middle to upper 10s (~−10 °C), indicative of relatively dry air. Further northeast of Durango, temperatures were near 80 °F (~27 °C) with dew point temperatures in the low 60s (~−12 °C). Both temperatures and dew point temperatures were lower to the southeast of Durango. Values of GFS derived TPW over Durango (0.25 cm ≤ TPW ≤ 0.62 cm) were the smallest for the region and increased westward. The largest values of TPW were found to the northeast (TPW ~ 2.54 cm) and southeast of Durango (1.24 cm ≤ TPW ≤ 1.86 cm). Another way to view water vapor in the atmosphere is through the use of a skew-T diagram. A skew-T from the GFS, at 1800 UTC, is shown in Figure 4 and also indicated a dry atmosphere with TPW values of 0.23 cm. As suggested by Gao and Kaufman (1995), surface features may be observable in imagery near 1.38 μm for regions where values of TPW are less than about 0.5 cm.

3.2. Notable Features

Little if any absorption of solar energy by atmospheric water vapor occurs near 0.64 and 0.87 μm; as a result, details of surface features appear prominently in imagery at these two bands for cloud-free conditions. A combination of both imagery from 0.64 to 0.87 μm can thus be used to highlight topographical features.
over and near Durango. Due to horizontal and spectral variations in values of the surface albedo, surface features may appear differently in various ABI reflective bands. For example, 0.64-μm imagery (Figure 5) over Durango shows two bodies of water, El Palmito and Santiaguillo, which are annotated in the figure. When comparing these two bodies of water to each other, El Palmito was darker than Santiaguillo. Further

![Figure 3](image)

**Figure 3.** Geostationary Operational Environmental Satellite-16 Advanced Baseline Imager 0.64-μm reflectance at 1757 UTC, 16 April 2017, over west central Mexico and the Gulf of California. Surface station observations at 1800 UTC are also plotted along with contours of total precipitable water (cm). The red plus sign indicates the location of a sounding to be shown in Figure 4.

![Figure 4](image)

**Figure 4.** Skew-T from the GFS at the location of the red plus sign in Figure 3 with TPW = 0.23 cm. In the yellow box, 170416 represents the year, month, and day, while 18(Sun) represents the hour, 1800 UTC, and day. Latitude and longitude of the GFS point are 24.86 and −105.37, respectively. GFS = Global Forecast System; TPW = total precipitable water; CONtinental United States.
to the west, regions of higher terrain are also denoted. Note the darker gray shades associated with surface features on higher terrain. (A word of caution is warranted to avoid misinterpretation: Darker gray shades appear as a result of surface characteristics as opposed to values of elevation. That is, darker gray shades appear as a result of absorption of solar energy near 0.64 µm by surface features, which coincidently were located atop elevated terrain.) Also in Figure 5, larger values of reflectance appear brighter due to increased reflection of solar energy near 0.64 µm. That is, El Palmito/Santiaguillo appeared dark/light due to less/more surface reflection of solar energy near 0.64 µm.

Appearances change, however, in ABI imagery near 0.87 µm (Figure 6) where the nadir IGFOV is 1.0 km, compared to 0.5 km for imagery at 0.64 µm. ABI data near 0.87 µm are used since the imagery contains information about green reflectances as opposed to imagery near 0.64 µm, which contains information about red reflectances (Cai et al., 2014; Turvey & McLaurin, 2012). An increase in footprint size will cause some blurring of details in imagery from 0.64 to 0.87 µm. In addition, valleys and canyons appeared darker along western portions of Durango (indicated by arrows).

In sharp contrast to the solar reflective bands shown in Figures 3, 5, and 6, Figure 7 shows the impacts of atmospheric water vapor in imagery near 1.38 µm in cloud-free conditions. At 1757 UTC (Figure 6a), reflectance values were relatively small with values ranging linearly from 0% to 5%. In addition to water vapor absorption, the IGFOV for imagery near 1.38 µm is 2.0 km, a factor of 4 and 2 compared to the IGFOV of the 0.64- and 0.87-µm bands, respectively, which causes additional blurring of surface features. Both bodies of water in central Durango, originally pointed out in Figure 5, remained evident along with two additional bodies of water just to the south of Santiaguillo. For clarity, all three bodies of water in close proximity to Santiaguillo will be referred to collectively as Santiaguillo. A topographical ridge line to the west of Santiaguillo is indicated within a white oval. In addition, valleys and canyons appeared dark over western Durango. Two hours later at 1957 UTC (Figure 7b), a series of bright (B) and dark (D) bands were evident in the imagery. An AWIPS terrain map with a resolution of 1.0 km is included (Figure 8) to aid in the identification of terrain features in Figures 5–7. In particular, the ridgeline west of Santiaguillo in Figure 8 is highlighted within an oval.

A topographical ridge line to the west of Santiaguillo is indicated within a white oval. In addition, valleys and canyons appeared dark over western Durango. Two hours later at 1957 UTC (Figure 7b), a series of bright (B) and dark (D) bands were evident in the imagery. An AWIPS terrain map with a resolution of 1.0 km is included (Figure 8) to aid in the identification of terrain features in Figures 5–7. In particular, the ridgeline west of Santiaguillo in Figure 8 is highlighted within an oval.

A comparison of the TPW contour of 0.62 cm in Figure 3 supports the findings of Gao and Kaufman (1995) that surface features may be evident in imagery near 1.38 µm in regions where values of TPW are less than about 0.5 cm. That is, when TPW increased above 0.62 cm, surface features in Figures 7a and 7b were
obscured by significant absorption by water vapor. In the region of Durango to the west of Santiaguillo and east of the western border of the state, bright and dark bands, oriented approximately southwest-northeast, were noted (Figure 7b).

Furthermore, there existed significant horizontal variations of values of reflectance over Durango. The various features and orientations would make their distinction a challenging task if limited to a single image, such as what would be available from conventional polar-orbiting satellite data. An important advantage of ABI is the relatively high temporal sampling: Every 5 min for the CONtinental United States sector. One benefit of the 5-min temporal sampling of ABI was to allow for the construction of an animation to aid in the discrimination of stationary and nonstationary features.

### 3.3. Analysis of Banded Structures

Animation of 5-min imagery near 1.38 μm on 16 April 2017 from 1707 to 1957 UTC is displayed in Figure 9. When viewing the animation, the eye may naturally be drawn to the bright bands that appeared to move toward the east-northeast and conclude incorrectly that the bright bands represented atmospheric motion.
related to elevated values of TPW. Although counterintuitive, motion in Figure 9 was due to the movement of the dark portions of the image. That is, dark bands represented atmospheric motion related to elevated values of TPW that drifted across a bright and dryer background.

Several surface features were also evident in the loop of Figure 9: (1) El Palmito, (2) three bodies of water associated with Santiaguillo, (3) a bright ridge line located immediately to the west of Santiaguillo, and (4) the valleys and canyons in the complex terrain along western portions of Durango. For clarity, the first three surface features were annotated in imagery near 1.38 μm at 1722 UTC in Figure 7a; feature (4) has been

**Figure 8.** Terrain elevation (km) in and around Durango. Note the similar pattern of terrain in western Durango within Figures 5–7.

**Figure 9.** Animation (click on image) of ABI imagery near 1.38 μm, collected on 16 April 2017 from 1707 to 1957 UTC over Durango, Mexico. ABI = Advanced Baseline Imager; GOES-16 = Geostationary Operational Environmental Satellite-16.
denoted in Figures 5–8. During the animation, prominent bright and dark bands, oriented from the southwest to the northeast, appeared to originate from the series of high terrain, valleys, and canyons along western portions of Durango. Furthermore, the perpendicular distance between two bright bands near 1.38 μm was approximately 30 km.

Over time, both the bright (dry) and the dark (moist) bands elongated toward the northeast. In addition, a dark linear feature of similar orientation to the topographical ridge, which was noted in Figure 8, expanded eastward from the east side of the ridge to the Santiaguillo water bodies. Over a 1-hr time period, the dark linear feature appeared at 1752 UTC and reached Santiaguillo at 1852 UTC. During the same time period, both the bright and dark bands, to the west of the topographical ridge, moved northeastward and reached the ridge line at ~1852 UTC. These filamentary structures subsequently passed over the ridge line and continued to drift to the northeast. By 1957 UTC, some of the bright (B) and dark (D) bands were quite prominent as indicated in Figure 7b. Since the elevation of the state of Durango, Mexico, attains values near 3 km (Figure 8), there existed the possibility that the banded structures may be evident in imagery near 7.34 μm.

Animation of imagery near 7.34 μm, for the same period Figure 9, is shown in Figure 10. In the beginning of the loop, at 1707 UTC, El Palmito and the three bodies of water of Santiaguillo appeared as relatively cool regions near the center of the imagery.

During the animation of the imagery near 7.34 μm, Tbs begin to decrease near and east of the ridgeline at 1752 UTC, just to the southwest of Santiaguillo. By 1812 UTC, the region of cooling expanded eastward toward Santiaguillo. At 1852 UTC, the cool region reached the southern two bodies of water of Santiaguillo. Further to the west, distinct bands of warmer and cooler Tbs originated over the region of valleys and canyons along western portions of Durango. Over time, the size of the bands of warmer Tbs (dry) decreased, while the size of the bands of cooler Tbs (moist) increased. During the loop, all of the distinct bands expanded toward the northeastward.

Figure 10 shows images near 1.38 and 7.34 μm at two distinct times near the beginning (1722 UTC) and end (1957 UTC) of the loops, which were shown in Figures 9 and 10. Locations of geographical features (Figure 11a) along with bright (B) and dark (D) bands (Figure 11b) in imagery near 1.38 μm are indicated in the top two panels of Figure 11, respectively. Similarly, geographical features (Figure 11c) along with warm
and cool (C) bands (Figure 11d) in imagery near 7.34 μm are displayed in the bottom two panels of Figure 11, respectively. Measurements of the distance between two warm bands near 7.34 μm yielded a perpendicular distance of approximately 30 km; consistent with values in imagery near 1.38 μm. As stated earlier, Tbs near 7.34 μm over central Durango were representative of temperatures near 600 hPa from the 1800 UTC GFS analysis fields. Furthermore, the height of the 600-hPa surface over Durango, extracted from the GFS 1800 UTC analysis fields, was about 2,100 m above ground level. Consequently, plumes that were evident in imagery near 7.34 μm reached a vertical depth of at least 2,100 m above ground. Since (1) banded structures appeared in imagery near 1.38 and 7.34 μm and (2) satellite measurements are sensitive principally to atmospheric water vapor in each band, a direct correlation was suggested between banded structures and atmospheric water vapor, which are discussed further in section 5 to follow.

4. Case Study 2: 8 May 2017 Over Chihuahua, Mexico

4.1. Overview

During the spring of 2017, observations of nonstationary banded features in ABI 1.38-μm imagery were a common occurrence over the elevated plateau of central Mexico. A second example comes from the state of Chihuahua, Mexico, observed on 8 May 2017. Similar to the format of Figure 3, Figure 12 shows GOES-16 ABI 0.64-μm imagery collected at 1800 UTC, along with surface observations and TPW from 1800 UTC GFS analysis fields. Values of surface dew point temperatures and TPW were the lowest over Chihuahua in this scene, similar to the Durango case (Figure 3).

4.2. Notable Features

Figure 13 shows an animation of imagery near 1.38 μm. Similar to the Durango case discussed above, nonstationary banded features existed and were oriented from the southwest to the northeast, with a series of adjacent bright and dark bands over west central Chihuahua. Unlike the perpendicular band separation distance of about 30 km determined for the 16 April 2017 case, the bands in the Chihuahuan case were separated by a distance of approximately 15 km. A body of water, Laguna de Bustillos, was also evident as
the larger dark oval slightly to the right of the center in the imagery. Unlike the Durango case, a field of broken cumulus formed in linear segments, oriented parallel to the bright and dark bands. The appearance of the cumulus field was reminiscent of cloud streets that form within horizontal convective rolls in the planetary boundary layer (Brown, 1980; Weckwerth, Horst, & Wilson, 1999; Weckwerth, Wilson, et al., 1999).

Another way that GOES-16 data can be used to identify water vapor in the boundary layer is through the use of the so-called split window difference (SWD), defined as values of $T_b(10.35 \, \mu m) - T_b(12.3 \, \mu m)$; e.g., Lindsey

**Figure 12.** Same as Figure 3, centered on Chihuahua, Mexico, on 8 May 2017 at 1800 UTC.

**Figure 13.** Animation (click on image) of Advanced Baseline Imager imagery near 1.38 $\mu m$ on 8 May 2017 from 1742 to 2257 UTC. As a point of reference, the larger dark oval, located slightly to the right of center, is Laguna de Bustillos. Note that this figure covers less area compared to Figure 12.
et al., 2014). Due to (1) enhanced absorption of upwelling energy, from the surface, by water vapor near 12.3 μm compared to near 10.35 μm and (2) the weighting functions of each band peaks near the surface (relatively clean atmospheric window bands), relatively small positive values of the SWD indicate where more water vapor existed in a vertical column, only in clear-sky regions, during the daytime, when temperatures decrease with height. An animation of values of the SWD for the Chihuahuan case study is presented in Figure 14.

Values of the SWD exhibited banded features, similar to banded features evident in imagery near 1.38 μm that are displayed in Figure 13. Based on the selected color table, more water vapor existed in bands enhanced in yellow compared to bands enhanced in red. Values of the SWD provided further evidence to the notion that the dark features that displayed 1.38 μm were directly related to the fine-scale variations of the water vapor field.

Upon close examination of the animations, clouds formed in linear segments, parallel to the bands, and coincident with the dark bands of Figure 13 and the yellow bands of Figure 14. Results just discussed suggested that the broken linear segments of clouds formed within portions of the bands characterized by larger values of water vapor.

Similar to Figure 11, a direct comparison between imagery near 1.38 μm and the SWD is presented in Figure 15 for two times: One at the beginning (1742 UTC) and one at the end (2047 UTC) of the animations shown in Figures 13 and 14. At 1742 UTC, two distinct regions have been denoted in the imagery near 1.38 μm and the SWD, which have been separated by a NW/SE oriented dashed line. Although some banded structures, reminiscent of internal buoyancy waves, were seen to be oriented approximately parallel to and northeast of the dashed line, our focus concentrated on the nonstationary bands that were somewhat orthogonal to and located southwest of the broken line segment (Figure 15, top left). Three hours later at 2047 UTC, the boundary between the structures, denoted by the dashed line, advected to the northeast so that the southwest to northeast oriented nonstationary bands occupied Chihuahua.

Two dark bands seen in 1.38-μm imagery were denoted by white arrows for reference. By 2222 UTC, a broken linearly oriented segment of clouds was evident in the SWD and colocated with the dark bands in imagery near 1.38 μm. A comparison of the animation of imagery near 1.38 μm and the SWD indicated that the broken linearly oriented segment of clouds formed within the dark bands. As a final comparison, and as
a way of highlighting the presence of cloud streets, Figure 16 exhibits imagery near 0.64 μm (Figure 16a) and the SWD (Figure 16b) after clouds had developed, approximately 2222 UTC. Due to the 2.0-km IGFOV of the infrared bands, which were used for the SWD, compared to the 0.5-km IGFOV of the 0.64-μm reflective band, clouds in the white oval at 0.64 μm appeared slightly blurred and subsequently larger in the SWD. On the eastern side of the clouds and within the white ovals, labeled 1 and 2, dark spots appeared in the 0.64-μm reflective band, corresponding to shadows cast by clouds upon the surface. Results above suggested the existence of horizontal convective rolls within cloud-free portions of the scene, which aid in the identification of vertical circulations and cloud formation in the planetary boundary layer.

Figure 16. Geostationary Operational Environmental Satellite-16 imagery at (a) 0.64 μm and (b) the SWD on 8 May 2017 at 2222 UTC. Ovals denote the location of clouds in each panel. Due to an increase of the IGFOV from 0.5 km at 0.64 μm to 2.0 km for the SWD, blurring causes clouds within the white ovals in (a) to appear larger within the black ovals (b). An additional feature was the existence of cloud shadows that were evident within and to the right of the clouds of the white ovals (a).
5. Physical Interpretation

ABI observations near 1.38, 7.34, and the SWD respond in a similar way to variations in values of atmospheric water vapor. Although full radiative transfer calculations of these cases are reserved for future work, some insight can be gained from plots of weighting functions of the infrared and cirrus bands used herein. Plots of weighting functions are produced from a standard atmosphere; one relatively dry and a second relatively moist. In addition, all plots begin at 800 hPa, which is the approximate surface of the interior of central Mexico; see Figure 4. Plots of the weighting functions for are shown in Figure 17; relatively dry/moist profiles are displayed in Figures 17a, 17c, and 17e/17b, 17d, and 17f, respectively. The region bounded by the weighting function curve and the pressure axis represents the total source of energy measured by ABI for each band. That is, near 7.3 μm a significant contribution to ABI measured energy comes from the surface, peaks near 700 hPa, then subsequently decreases near the tropopause Figures 17a and 17b. A comparison

![Figure 17. Weighting functions from a standard atmosphere at (a and b) 7.3 μm, (c and d) 10.4 μm, and (e and f) 12.4 μm. Panels (a), (c), and (e) represent a relatively dry standard atmosphere, while (b), (d), and (f) represent a relatively moist standard atmosphere. In each panel, the weighting function plots are terminated near the surface as indicated in Figure 4. Credit is given to the University of Wisconsin, Madison, for use of the publicly available interface to produce each panel.](image-url)
indicates that more energy from the surface contributes to ABI measured energy in the drier atmosphere than the moist atmosphere. The peak of the 7.3 μm near 700 hPa also explains the modification of Tbs in Figures 11c and 11d. Plots of the weighting function for the two infrared bands (Figures 17c and 17d and 17e and 17f) that were used for the SWD indicate that the main source of ABI measured energy is the lower troposphere and surface. Note that the location of the peaks of the weighting functions is coincident with the location of boundary layer rolls, thus enabling their appearance in Figures 15c and 15d. Similar to the plots of weighting functions in Figure 17, weighting functions near 1.38 μm are shown in Figure 18 for a standard atmosphere and for relatively dry and moist profiles. For the relatively dry standard atmosphere (Figure 18a), a significant contribution originates from the surface, which is in sharp contrast to the profile in a relatively moist standard atmosphere (Figure 18b).

Spatial correlations between banded structures observed in ABI imagery at both 1.38 and 7.34 μm on 16 April 2017 were, in hindsight, to be expected. However, the unusual structures observed over Durango, revealed for the first time by 5-min ABI 1.38-μm observations, lead to questions as to what could account for them. In this section, a physical interpretation is proposed to highlight possible dynamic processes responsible for the observed structures. For clear-sky conditions over the Durango region, solar energy reached the surface. A fraction of the incident radiation was absorbed by the surface and converted to internal energy; that is, the temperature of the surface increased. Subsequently, the surface transferred energy into the surface layer by way of conduction. In response to the warming of the surface layer, positively and negatively buoyant plumes developed, which influenced the circulation in the planetary boundary layer. Circulation patterns, in the boundary layer, have been documented extensively over the state of Colorado, USA (Banta, 1984, 1986, 1990; Banta & Barker-Schaaf, 1987).

In the specific case studies shown in section 3, thermally driven circulations formed within the windward valleys and ridges (see Figures 5–8) of the complex terrain over western Durango. The aforementioned thermally driven circulations, which arose from radiative heating of complex terrain, drove upward vertical motion and convergence of water vapor from lower elevations. Due to ambient wind, the convergent plumes of moisture were channeled and lifted upward through the valleys over western Durango. In response to absorption of solar energy near 1.38 μm, plumes of larger values of water vapor appeared as dark bands in imagery near 1.38 μm. Dark (moist) bands then advected northeastward over the brighter (dry) elevated surface of Durango.

Upward ascent of water vapor, which was subsequently advected by the mean southwesterly flow, provided a possible explanation for the darker shadow-like feature that was oriented along the noted ridgeline and moved toward Santiaguillo from 1752 to 1852 UTC. A sequence of bright (B) and dark (D) bands formed as moist plumes of air (dark bands) moved northeastward across the dryer (brighter) environment.
background. As stated earlier, imagery over Durango near 7.34 μm contained Tbs that were similar to temperatures at 600 hPa from the GFS. Due to the elevation of Durango and the vertical depth of the plumes of at least 2,100 m above ground level, Tbs near 7.34 μm were influenced by thermally driven circulation. In contrast, if the surface elevation of Durango was near sea level, the moist plumes would have existed at levels too low to influence Tbs near 7.34 μm. Within imagery near 7.34 μm, moist plumes would be characterized by cooler (C) bands within a warm (W) and dry environment. Coincident with the dark feature that moved from the ridgeline toward Santiaguito in imagery near 1.38 μm was a cooler region that expands eastward in imagery near 7.34 μm. The dark/bright bands (D/B) in Figure 11b were colocated with cool/warm bands (C/W) in Figure 11c. For the Durango case, banded features were not evident in SWD imagery.

Unlike observations for Durango on 16 April 2017, broken linear segments of cumulus clouds formed within the dark bands of 1.38 μm imagery over the state of Chihuahua. In addition, banded features were observed in animated loops of the SWD. Coincident with the banded features in the SWD was the development of broken linear segments of cumulus clouds, highlighted as yellow bands. Development of clouds in the dark/yellow bands of 1.38-μm imagery and the SWD was consistent with cloud development in an ascending branch of a circulation system in the planetary boundary layer. Features appeared consistent with horizontal convective rolls associated with the development of cloud streets. In a roll, upward/downward motion would have acted to increase/decrease values of vertically integrated water vapor within the depth of a roll. Consequently, upward/downward motion in a roll would be colocated with (1) increased/decreased water vapor, (2) local maximum/minimum in values of the SWD, (3) cloud streets/no cloud streets, and (4) dark/bright bands in imagery near 1.38 μm.

6. Summary and Conclusions

In order to gain more insight on the existence of cirrus clouds, environmental satellites have been designed to measure radiant energy near 1.38 μm. In addition, detection of cirrus clouds aid in the improvement of such products as sea and land surface temperatures. Owing to absorption of water vapor, transmission of energy through the atmosphere, both upward and downward, near 1.38 μm is small enough that reflection of incoming solar energy at this wavelength provides a significant contrast between cirrus and a surrounding clear-sky background. Previous experiments have shown enhanced skill in detecting cirrus when imagery near 1.38 μm compared to imagery near 0.67 μm with either aircraft or satellites. However, radiative transfer models have suggested that surface features may appear when values of TPW are less than about 0.5 cm—leading to occasional “unusual” effects in the appearance of 1.38-μm imagery, as presented herein.

GOES-16 ABI observations near 1.38 μm collected on 16 April 2017 for a relatively dry atmospheric column over Durango, Mexico, revealed moisture plumes that were visible against a highly reflective background surface. Values of TPW were less than 0.64 cm over most of Durango. As a result, horizontal variability of 1.38-μm reflectance at values between 0% and 5% was able to reveal surface bodies of water, a ridge line, and complex terrain over western Durango. In addition, animations of imagery near 1.38 μm contained distinct, southwest to northeast oriented, bright and dark plumes that moved with the mean flow from western Durango over the high plateau of central Durango. Since water vapor was the primary absorber of solar energy near 1.38 μm, satellite observations suggested that the dark and bright plumes were regions of larger and smaller values of TPW, respectively.

Animation of the ABI imagery provided a unique view of motion within the clear-sky boundary layer due to the inhomogeneous distribution of water vapor over Durango. Imagery near 7.34 μm also contained plumes formed by the topography of the Durango region. Dark and bright plume near 1.38 μm where colocated with cool and warm plumes of Tbs near 7.34 μm. Since water vapor was the primary absorbing gas at both wavelengths, satellite observations suggested that the dark and cool plumes were regions of elevated TPW while bright and warm plumes were regions of reduced TPW. Imagery also showed that the plumes originate over the complex terrain of western Durango. As a result, water vapor was likely transported upward within the rising branches of thermally driven circulation within the complex terrain.

GOES-16 ABI also observed nonstationary banded features on 8 May 2017 over the state of Chihuahua, Mexico. There were two distinct differences between the banded features over Durango and Chihuahua. First, the bands were separated about 30 km over Durango compared to approximately 15 km over Chihuahua. Perhaps, the difference was due to the dynamics responsible for creating the bands: thermally...
driven circulations within complex terrain (e.g., the spacing of the valley features) of western Durango versus horizontal convective rolls over Chihuahua. Second, only the bands over Chihuahua contained broken linear segments of cumulus clouds. Imagery of the SWD lends support for cloud development within the moist plumes, which implied enhanced upward motion within horizontal convective rolls versus a simple channeling of moisture by complex topography.

GOES-16 ABI contains a channel near 1.38 μm for the purpose of cirrus cloud detection. This study documented the existence of cloud-free vertical circulations within the boundary layer over central portions of the country of Mexico. Theoretical calculations have suggested that surface features may be evident in imagery near 1.38 μm if values of TWP are less than about 0.50 cm (Gao & Kaufman, 1995; Gao et al., 2002, and references therein). As a result, surface features may likely be evident over elevated land masses, such as central Mexico and other elevated plateau regions worldwide. Beneficiaries of features highlighted herein are forecasters, numerical modelers, and boundary layer meteorologists. Forecasters benefit by being able to pinpoint location where clouds may develop; numerical modelers benefit by being able to use satellite observations to validate simulations of complex motions in the boundary layer, and boundary layer meteorologists benefit by using satellite observations to aid in the progress of understanding of detailed boundary layer motions. Imagery from GOES-16 ABI was highlighted herein to illustrate detection of complex atmospheric motions, for the first time, from a geostationary sensor. Detection of new features, at improved temporal, spatial, and spectral resolutions, provides support for similar capabilities on future geostationary satellites.

Two important steps have been used in this paper. That is, GOES-16 imagery served as (1) observations of an event or process from which (2) hypothesis has been offered to explain the event or process. Future direction would then follow the next few steps of the so-called Scientific Method by using a predictive system to test and verify the hypothesis put forth herein. In connection with the work presented in this study, a predictive system could be a numerical weather predictive system combined with a radiative transfer model.

References


GRASSO ET AL.

Acknowledgments

The authors gratefully acknowledge that this research was primarily funded by the NOAA GOES-R Program Office. The views, opinions, and findings in this report are those of the authors and should not be construed as an official NOAA and or U.S. Government position, policy, or decision. Weighting functions are available at the following link: https://gfigshare.com/s/ebd378ff9e7b32083556. All the data used are listed in the references or archived in the figshare repository. Please use the following link: https://figshare.com/s/ebd378ff9e7b32083556. In addition, there are no restrictions to access the data.


