ESTIMATION OF LOW CLOUD BASE HEIGHTS AT NIGHT FROM SATELLITE INFRARED AND SURFACE TEMPERATURE DATA

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Abstract

A nighttime low cloud image product that highlights areas of the lowest cloud base heights has been developed by combining brightness temperature data from the Geostationary Operational Environmental Satellite (GOES) Imager InfraRed (IR) bands centered at 3.9 μm and 10.7 μm, with hourly temperatures from surface observing sites and offshore marine buoys. A dependent data sample collected during the Summer of 1997 showed a fairly strong correlation between the surface minus cloud top IR temperature differences versus measured cloud base heights. Histogram analysis indicated that a temperature difference of less than 4 °C related to a > 50% probability of ceilings below 1000 ft above ground level, the threshold for Instrument Flight Rules (IFR). Using the Man-computer Interactive Data Analysis System (McIDAS) software, an experimental Low Cloud Base (LCB) image product was developed that highlights regions of likely IFR ceilings. The image product is routinely available from GOES-8 and GOES-10 hourly at night for six regions in the Continental United States via a Web site (orbit-net.nesdis.noaa.gov/arad/fpdt/fog.html). Validation of the LCB product for two separate periods resulted in Probabilities of Detection of 67% and 72% and False Alarm Rates of 6% and 11%. Some regional variation was observed that could be related to the frequency of multi-layered overcast conditions. The biggest factor leading to under-detection of IFR ceilings by the GOES LCB is the presence of overlying clouds, including thin cirrus contamination. Although further improvements are planned, the prototype GOES LCB product shows potential for use as guidance for aviation meteorologists over both continental and marine areas.

1. Introduction

Detection of fog and low clouds at night with meteorological satellite data can be accomplished using brightness temperature differences (BTD) between the 3.9 μm short wave (T2) and 10.7 μm window (T4) infrared (IR) channels such as those available from the Geostationary Operational Environmental Satellite (GOES) Imagers (Ellrod 1995; Lee et al. 1997), and the polar orbiting National Oceanic and Atmospheric Administration (NOAA) series (Eyre et al. 1984). This derived imagery, sometimes referred to as the "fog product," clearly shows low-level water clouds (fog and stratus) that may often go undetected using only a single IR channel. Unfortunately, low clouds are only detectable if they are sufficiently thick (i.e., > 50-100 m) and not overlain by higher cloud layers. Additionally, the current nighttime low cloud product cannot easily distinguish clouds that may result in low ceilings[1] and/or reduced surface visibilities from higher-based stratus, stratocumulus and altostratus that do not represent significant hazards to aviation or marine interests.

The likelihood that fog is present may be assessed by means of empirical rules based on satellite image features such as: brightness, texture, growth or movement. However, these rules require some expertise and experience for proper application. A more objective, easily interpreted product that estimates the likelihood of very low ceilings and/or visibilities is desired.

Efforts to produce an experimental, enhanced GOES fog product began in 1997 with the collection of surface-based ceiling and visibility data from Meteorological Aviation Reports (METAR) from observing sites in the United States, along with co-located GOES IR brightness temperature data. Analysis of the data was completed in 1999, and plans for generating an experimental prototype product for ceilings were recently described (Ellrod 2000). This paper will discuss: (1) the preliminary research, (2) image processing procedures, (3) product examples, and (4) verification results.

2. Data Analysis

During the summer of 1997, cloud base ceiling heights (ft), surface visibilities (nm), and GOES IR cloud top temperatures (CTT) (°K) were collected for a large number of cases (N = 592) of nighttime low clouds over the Continental United States (CONUS). For cases in which the GOES fog product detected low clouds (when T4 - T2 ≥2 °K),[2] two hypotheses were tested. The first hypothesis assumed that low ceilings and visibilities were accompa-

[1] A ceiling exists when there is 5/8 or greater cloud cover.

[2] Brightness temperatures are typically several degrees cooler in IR Channel 2 than in Channel 4 at night for opaque clouds consisting of liquid droplets, due to lower emissivity at 3.9 μm. During the day, this technique cannot be used due to solar reflectance in the short wave channel.

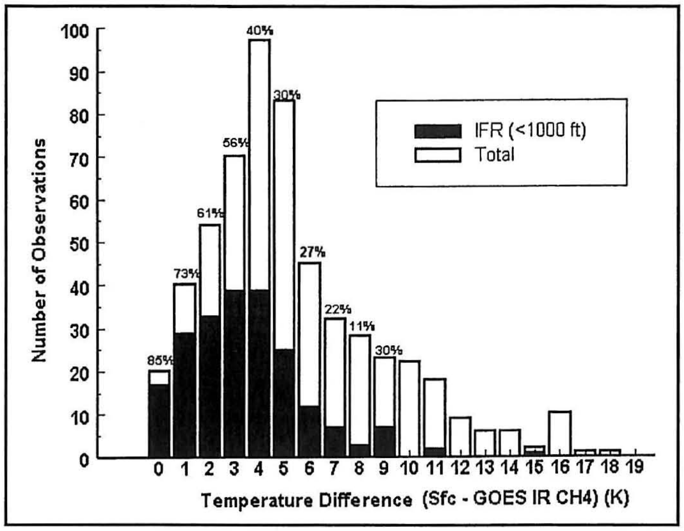

Fig. 1. Frequency distribution of ceilings <1000 ft (IFR) (solid) and all ceilings (open) vs. surface temperature minus GOES IR CH4 brightness temperature difference (°K). Numbers at the tops of bars represent the percentages of all ceilings that are in the IFR category.

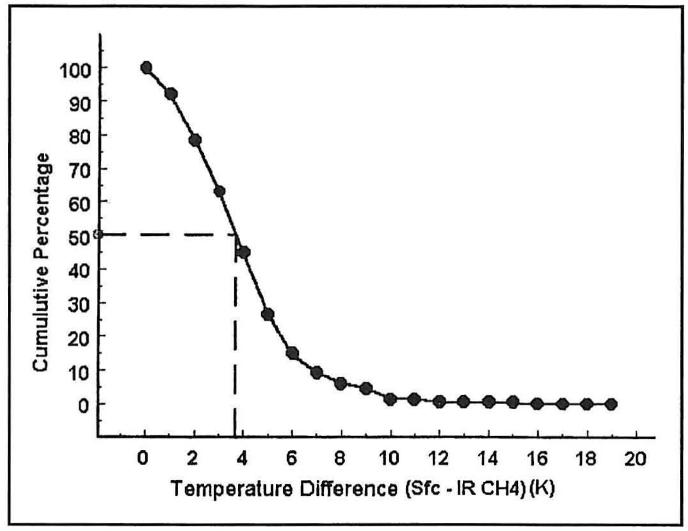

Fig. 2. Cumulative frequency distribution of IFR (<1000 ft) ceilings vs. surface temperature minus GOES IR CH4 brightness temperature difference (°K).

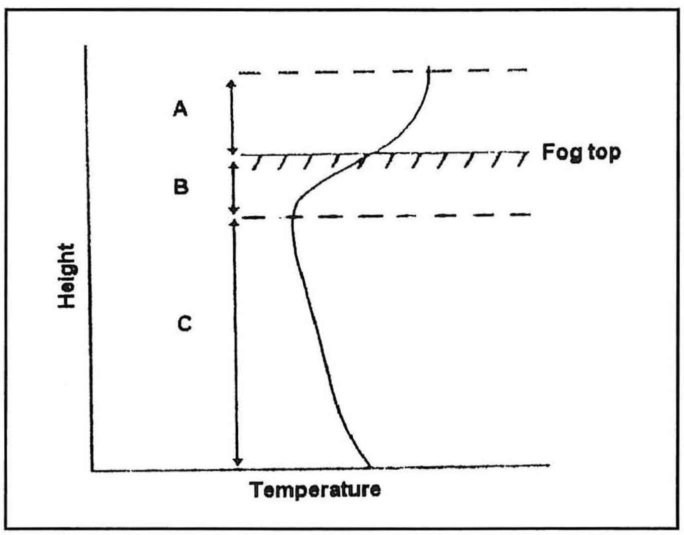

Fig. 3. Idealized model of radiation fog thermal profile (Brown 1987). Layer A is dry and stable above the fog. Layer B is the portion of the inversion containing the fog, and layer C is the well-mixed layer formed by weak convection, with warming at the surface and radiative cooling at the top.

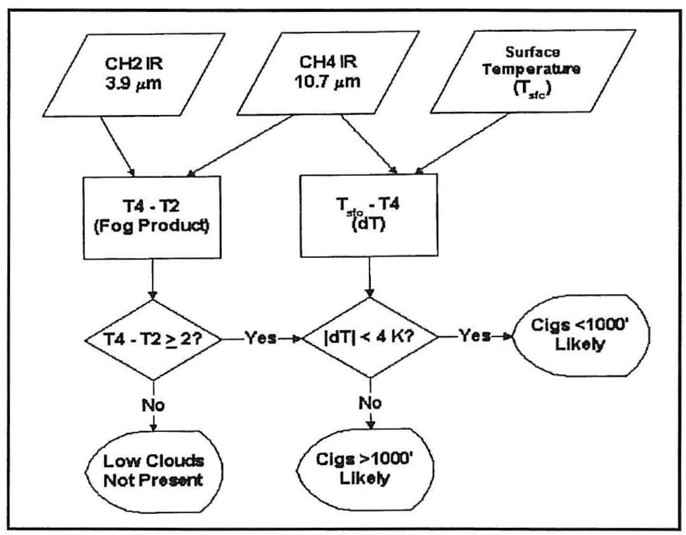

Fig. 4. Flow chart showing an experimental procedure for estimating cloud base conditions at night using a GOES bi-spectral IR technique and surface temperatures from METAR sites. T_{sfc} is surface temperature, T4 is GOES Channel 4 IR temperature, and T2 is GOES Channel 2 IR temperature.

nied by relatively smooth appearance in the GOES fog product, resulting in a low standard deviation (less spatial variation) of observed brightness temperatures near the surface reporting station. The second assumed that low ceilings and visibilities were accompanied by a relatively small temperature difference between the 10.7 μm window IR CTT (T4) and the METAR-observed surface temperature (T_{sfc}) (one of the empirical rules that is often used to check for the presence of very low clouds). This small temperature difference results in poor discrimination of low clouds in single band IR imagery (Eyre et al. 1984; Bader et al. 1995). In many cases, the IR CTT may actually be warmer than T_{sfc} due to pronounced low-level thermal inversions.

After statistical analysis of each of these two approaches, the first was rejected due to the relatively weak correlation ($r = 0.4457$) between the standard deviation of brightness temperature to observed ceilings and visibilities. One of the complicating issues with the first approach is that instrument noise increases with colder temperatures, resulting in poor detection capability during winter and thus, a seasonal variation in reliability. The second approach ($dT = T_{sfc} - T4$) resulted in a higher correlation ($r = 0.5915$), so it was decided to utilize the GOES-surface temperature difference technique to improve the low cloud product.

Evaluation of similar data for visibilities resulted in lower skill due to the complex effects resulting in reduced visibility. The correlation coefficient between dT and visibility was only 0.3147, so a product that only estimates the likelihood of low ceilings has been developed and evaluated initially here.

A frequency distribution of the cloud base height data was also completed for each 1 degree C interval of dT, to determine if there were any trends in the occurrence of low ceilings. The cloud base threshold selected was < 1000 ft (0.32 km) Above Ground Level (AGL), the height designated for Instrument Flight Rules (IFR). In IFR conditions, pilots must be instrument qualified and file a flight plan before departure. Figure 1 shows a histogram of both IFR ceilings (solid bars) and all ceilings (open bars) versus dT. The values plotted at the top of most bars show the percentage of all ceilings that are IFR. Figure 1 indicates that as dT decreased, the likelihood of low ceilings increased, further supporting the second hypothesis. For dT of ≤3 °K, IFR ceilings accounted for more than half of all ceilings. For dT ≤1 °K, 85% of all ceilings were IFR. A cumulative frequency distribution curve (Fig. 2) shows a rapid rise in IFR ceiling occurrence at about 4 °K, increasing to ~80% near 2 °K.

These results are consistent with an idealized vertical temperature profile (Fig. 3) of a fog bank in which there is a well-mixed sub-cloud layer, with a nearly moist adiabatic (1-2 °K / 1000 ft) lapse rate, capped by a thermal inversion (Findlater 1985; Brown 1987). The top of the fog bank is embedded in layer B, an average of 25 m above the inversion (Fig. 3). Elevated stratus can be more complex, due to the possibility of multiple cloud layers and inversions in advection situations. Assuming a single layer of stratus, the cloud base is likely to be located near the base of the inversion, with a nearly dry adiabatic lapse rate (2 - 3 °K / 1000 ft) below. Since GOES IR is observing the top of the stratus cloud, the IR temperature is often warmer than the inversion base, and possibly even the surface as well. The current technique does not consider negative dT values (CTT > T_{sfc}), and sets them to zero.

3. Product Generation

Based on results described in section 2, a simple algorithm (shown by the flow diagram in Fig. 4) has been developed to show how an enhanced GOES low cloud product (hereafter referred to as the Low Cloud Base (LCB) product) may be generated to display areas of possible IFR ceilings. The images are generated on a workstation using Man-computer Interactive Data Access (McIDAS) software. The first step involves the creation of a bi-spectral low cloud product based on the 10.7 - 3.9 μm IR BTD. Surface temperatures are then plotted, and a temperature grid is created using a Barnes interpolation technique. The grid is then converted to a gray scale image that is re-mapped into the native GOES projection, and calibrated the same as GOES IR, so that a given 8-bit brightness value (0 to 255 range) represents the same brightness temperature in each image. Once a temperature difference (dT) image has been created, areas representing the lowest dT values (< 4 °K) replace those portions of the image where stratus is present with an artificially high brightness value. This IFR output is displayed as a red-colored area, while other areas of low clouds are colored variable shades of green, and cirrus is shaded black or blue. Darker green shades indicate transition zones where dT is ~ 4-6 °K, and IFR conditions could exist.

Evaluation of early versions of the experimental LCB images indicated there was little apparent skill in assigning "good chance" and "likely" categories due to lack of precision in the processed McIDAS data. An increase in output image data precision is expected in McIDAS upgrades, and regional stratification of the data set could allow further refinement of the cloud base height thresholds.

The LCB images are currently produced in real time each hour at night at the World Weather Building in Camp Springs, Maryland for all CONUS regions. Six sectors are available: two over the western United States from GOES-10, and four covering the eastern United States from GOES-8. The sectors were originally produced in native GOES projection, but are now re-mapped into Lambert Conformal, true at 30 N and 50 N. Observed cloud ceilings (ft) at METAR sites are plotted on the image for comparison. Images are saved in CompuServe ".GIF" format, and sent to a Web server.

The LCB images may be accessed on Web site: orbit-net.nesdis.noaa.gov/arad/fpdt/fog.html

Certain problems associated with interpretation of the original fog images, such as the presence of obscuring higher cloud layers, and false signatures due to low-emissivity soils such as coarse sands will also affect the new product. The latter effect is chiefly a problem in western North American deserts, especially in the "Gran Desierto" north of the Gulf of California. Additional problems may occur in mountainous areas where METAR stations are sparse, leading to possible errors in cloud height category due to interpolation of low elevation temperature data into higher terrain.

4. Examples

a. Ohio Valley - 30 May 2000

Early in the morning of 30 May 2000, low clouds and fog developed in the eastern part of the Ohio Valley, with a large area of IFR ceilings over southern Ohio, eastern Kentucky and parts of West Virginia. Visibilities were also < 1 nm at many of these locations. The GOES LCB product at 1015 UTC (Fig. 5) showed good agreement with observed conditions. The area where the product performed poorly, such as in western Ohio near Dayton (DAY) is likely due to thin cirrus contamination. A "skew-T" plot for the Wilmington, Ohio (ILN) radiosonde at 1200 UTC (Fig. 6) shows the strong thermal inversion near 850 hPa associated with the top of the stratus layer. The GOES CH4 IR CTT from the image (star) was around 8 °C, similar to the radiosonde temperature. The surface temperatures at sites reporting IFR conditions (such as Cincinnati, Ohio (CVG)) were 10 to 11 °C. Thus, dT values were < 4 °C at those locations.

b. High Plains - 5 March 2001

On the morning of 5 March 2001, a surface ridge of

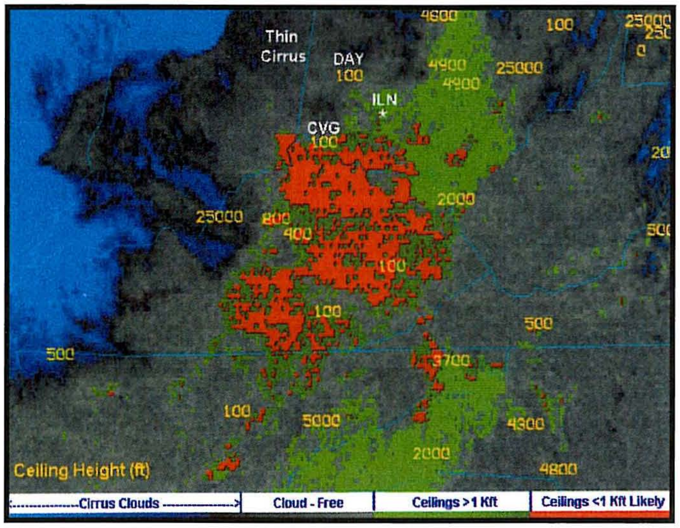

Fig. 5. Experimental GOES Low Cloud Base product for 1015 UTC 30 May 2000 with observed ceiling heights (ft) superimposed. Legend relates colors to various cloud categories as described.

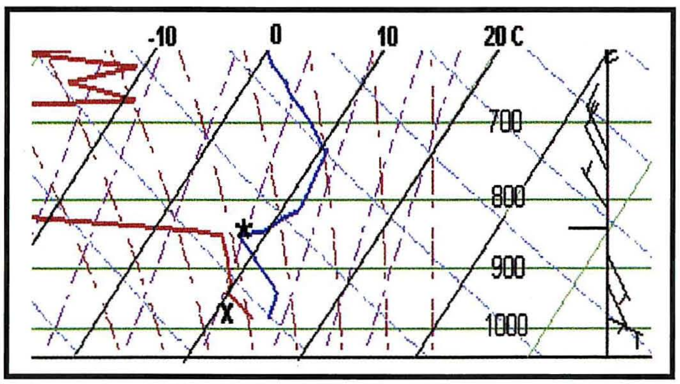

Fig. 6. Low-level portion of Skew-t plot for Wilmington, Ohio (ILN) radiosonde data valid at 1200 UTC 30 May 2000. GOES IR Channel 4 cloud top temperature is shown by the star (⋆), a representative surface temperature at IFR locations is shown by an X. (Skew-t plot from National Center for Atmospheric Research).

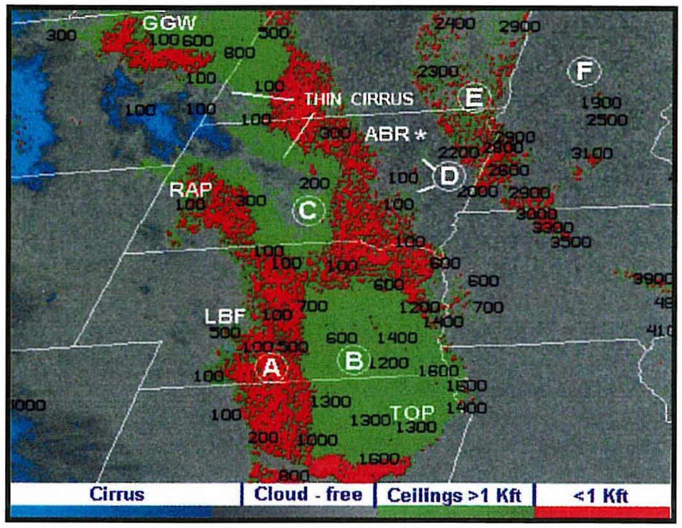

Fig. 7. GOES-8 Low Cloud Base product at 1115 UTC 5 March 2001. Three letter identifiers mark the locations of radiosonde sites described in the text (ABR location is at ★).

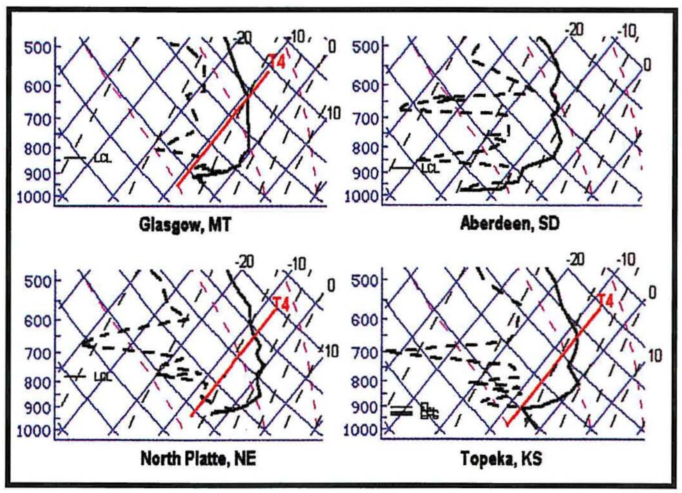

Fig. 8. Radiosonde profiles valid at 1200 UTC 5 March 2001. Line marked T4 represents the observed GOES Channel 4 IR temperature at the respective location.

high pressure extended from Manitoba province southward across the northern Plains states to north central Texas. On the west side of the ridge, light east to southeast flow resulted in upslope conditions in the northern High Plains, leading to the formation of extensive fog and stratus. Radiational cooling under the ridge axis also resulted in some shallow fog in the James River Valley of South Dakota. The LCB image at 1115 UTC (Fig. 7) shows two separate areas of low clouds, one large region from northeast Montana southeastward to northeastern Kansas, and a narrow band from eastern North Dakota to central Iowa.

The LCB product correctly showed IFR ceilings over most of the northern and western parts of the larger upslope stratus region (A) west of the surface ridge axis, and ceilings > 1,000 ft in southeast Nebraska and northeast Kansas (B) east of the ridge axis. The green areas in western North Dakota and west central South Dakota (C) appear to be contaminated by thin cirrus (thicker patches are shown as black and blue areas in southeast Montana), leading to slightly colder IR CTTs. Valley fog in east central South Dakota (D) was poorly depicted, probably because it was very shallow. In the easternmost stratus band (E), the LCB product incorrectly showed much of this region to have IFR conditions, when ceilings were actually quite a bit higher (>2000 ft). The speckling observed in the clear regions (F) is from instrument noise in IR band 2 caused by surface temperatures in single digits Fahrenheit.

Radiosonde data was available to help explain some of these conditions. Figure 8 shows four radiosonde profiles valid at 1200 UTC 5 March 2001 for Glasgow, Montana (GGW), Aberdeen, South Dakota (ABR), North Platte, Nebraska (LBF) and Topeka, Kansas (TOP). The GOES IR CTTs (T4) are indicated for GGW, LBF, and TOP. At GGW, the CTT (-9.5 °C) was slightly more than 4 °C colder than the surface temperature (- 4 °C), resulting in a misclassification of the ceiling conditions. The dT value was < 4 °C at LBF, although the GOES CTT is a few degrees C colder than indicated by the radiosonde. At TOP, subcloud mixing in northerly flow was evident by the adiabatic layer, leading to an elevated cloud base. The CTT (-8 °C) at TOP was more than 5 °C colder than the surface reading (-1 °C). At ABR, sky conditions were clear, but the sounding reveals an elevated moist layer that is likely related to the higher based stratus just to the east.

c. California Coast - 19 October 2000

The final example is for 19 October 2000 along the Pacific Coast of California. A ridge of high pressure centered just offshore and extending into the Pacific Northwest brought stable conditions near the coast with light northerly flow, an ideal situation for Pacific marine fog and stratus (see Leipper 1994). The GOES LCB image at 1200 UTC (Fig. 9) shows extensive low cloudiness with IFR cloud bases extending from near Los Angeles (LAX) up the coast to north of San Francisco (SFO) (red area A). Somewhat higher cloud bases (1000-1500 ft) were prevalent south of LAX to the Mexican border (green area B).

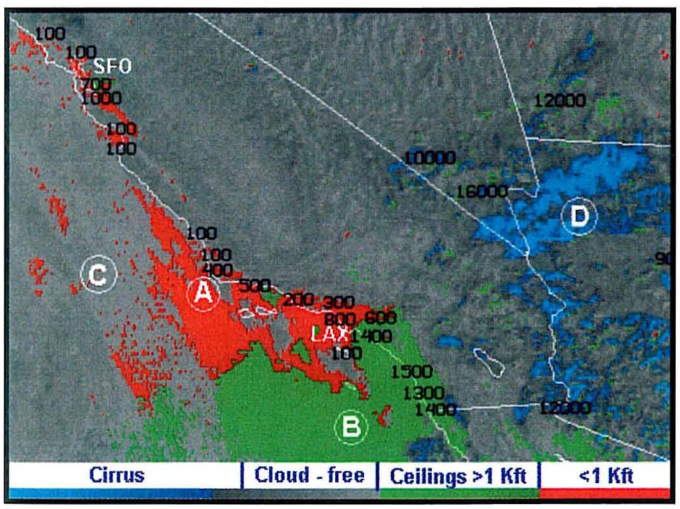

Fig. 9. GOES Low Cloud Base product for 1200 UTC 19 October 2000.

Conditions offshore are based on extrapolation of coastal station and buoy temperatures. The only verification is San Clemente Island, which indicated a 100 ft ceiling, in agreement with the GOES LCB. Much of the offshore stratus is not highlighted in the low cloud products (gray portions of area C), due to smaller bi-spectral temperature differences in the GOES IR data. This smaller BTD is commonly observed, and is due to the larger droplet sizes found in marine stratus (Lee et al. 1997). This problem can be corrected in coastal regions by assigning a lower temperature difference threshold to the cloud product, at the risk of increasing the area of false low clouds over land.

A 1000 ft ceiling south of SFO supports variable cloud base heights shown near SFO. Further inland, the patchy blue and green areas over the Desert Southwest (D) were an indication of variable middle and high cloudiness. Overall, the GOES LCB was quite representative of actual conditions on this morning.

5. Verification

Verification was completed from 30 May to 20 August 2000 for fog and low clouds occurring over the northern and western United States. Since there was very little low cloud occurrence in the southeast and south central states during this period, a separate verification was conducted for those regions from 10 to 26 January 2001. The color-coded images were compared at each location where a cloud ceiling was observed at a METAR station. Only two categories were evaluated: <1000 ft (IFR), and ≥1000 ft. A ceiling in either category that was observed at a boundary in the satellite product was scored as a "hit." Areas where thin cirrus was suspected to be a factor were not included in the validation due to the likelihood that the cloud base height estimates were corrupted. The performance was evaluated using Probability of Detection (POD) and False Alarm Rate (FAR) (Weiss 1977), which are defined as:

$$POD = x / (x + y) \quad (1)$$

$$FAR = z / (x + z) \quad (2)$$

where x is the number of correct IFR ceiling assignments as determined by GOES, y is the number of IFR events observed but not assigned and z is the number of IFR events assigned but not observed.

Table 1 is a contingency table showing how the satellite product compared with co-located METAR ceiling observations for 1551 comparisons over the northern and western United States during May - August 2000. There was a good correlation between

Table 1. GOES derived Cloud Base Height vs. METAR ceilings over locations in the northern and western United States, 30 May - 20 August 2000.

GOES Ceilings	METAR < 1 kft	METAR ≥1 kft	Totals	Bias
< 1 kft	587	70	657	.80
≥1 kft	230	664	894	1.22
Totals	817	734	1551	

Table 2. GOES derived Cloud Base Height vs. METAR ceilings over locations in the southern United States, 10-26 January 2001.

GOES Ceilings	METAR < 1 kft	METAR ≥1 kft	Totals	Bias
< 1 kft	261	16	277	.72
≥1 kft	126	427	553	1.25
Totals	387	443	830	

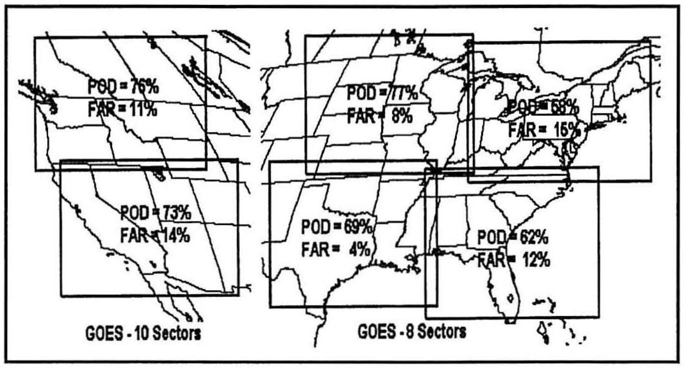

Fig. 10. Area coverage for the six regional sectors and the corresponding Probability of Detection (POD) and False Alarm Rate (FAR) verification statistics discussed in the text.

the satellite-estimated and observed ceilings, especially considering the simplicity of the technique. The POD of IFR ceilings for the entire sample was 72% and the FAR was 11%. There was a bias toward underforecasting IFR ceilings, most likely due to the presence of multiple cloud layers.

Verification data for 830 comparisons during January 2001 over the southern United States is shown in Table 2. Similar results were obtained, with a POD of 67%, a FAR of 6%, and a low bias with respect to the analysis of IFR conditions. Most of these cases involved stratus and fog that developed as a result of both advection and radiation processes.

The verification data were also stratified to determine if there were any regional tendencies. Figure 10 shows the area coverage for each regional sector and the corresponding POD and FAR values. Product performance was generally best in the western and central United States, and worst in the northeast. During the summer of 2000, there were numerous cases of multi-layered low- or middle-level clouds in the northeast due to the presence of a persistent upper-level trough.

6. Summary and Conclusions

GOES bi-spectral fog and low cloud images, based on the difference of two infrared channels centered at 3.9 and 10.7 μm, have been improved to show likely areas of low ceilings significant for aviation operations. The improvement is based on a technique that uses surface temperatures from METAR stations in combination with the satellite data. If differences between the surface temperatures and GOES 10.7 μm IR cloud top brightness temperatures are ≤ 3 °K, cloud bases below 1000 ft AGL, a criterion for Instrument Flight Rules (IFR), are likely to exist. Verification based on co-located, measured ceiling heights and GOES-derived ceiling estimates indicate that the product detects IFR conditions ~ 70% of the time, with a FAR ~ 10%. False alarms are most likely due to multiple cloud layers. Under-detection usually occurs when thin cirrus overlies the stratus clouds. Further experimentation is planned to improve the detection of low ceilings, reduce false alarms, and to extend the product into offshore marine areas. The experimental, enhanced low cloud base product has shown great potential for aviation use over both continental and oceanic areas.

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