ASSIGNING HEIGHTS TO CLOUD MOTION VECTORS

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ABSTRACT

Satellite derived cloud motion vector (CMV) production has been troubled by inaccurate height assignment of cloud tracers, especially in thin semi-transparent clouds. This paper presents the results of an intercomparison of operational height assignment techniques. Heights are assigned by one of three techniques when the appropriate spectral radiance measurements are available: the infrared window (IRW) technique, the carbon dioxide (CO_2) ratio technique, and the water vapor (H_2O) intercept technique. The results presented in Nieman et al. (1993) suggest that the H_2O technique is a viable alternative to the CO_2 technique for inferring the heights of semi-transparent cloud elements. For the several days studied, the heights from the two approaches compare to within 60 to 110 hPa rms; drier atmospheric conditions tend to reduce the effectiveness of the H_2O intercept technique. Problems associated with determinations of cloud free radiances in both the CO_2 and H_2O techniques have been largely overcome. Difficulties remain when more than one layer of cloud is present; progress in assigning heights to cirrus over lower opaque clouds is being made.

1. INTRODUCTION

In the current operational use of four geostationary satellites (the United States Geostationary Operational Environmental Satellite, GOES, the European Meteorological Satellite, METEOSAT, the Japanese Geostationary Meteorological Satellite, GMS, and the Indian Geostationary Satellite, INSAT), there continues to be considerable emphasis on improving height assignment of cloud tracers used for inferring cloud motion vectors (CMV), especially in thin semi-transparent clouds. The last Workshop on Wind Extraction from Operational Meteorological Satellite Data (EUMETSAT, 1991) concluded that the present techniques for height assignment needed further review and that greater commonality in techniques should be encouraged. This paper presents a comparison of operational cloud height assignment techniques and discusses of some possible improvements. The work has been done at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) in collaboration with the NESDIS Advanced Satellite Products Project.

Presently heights are assigned by any of three techniques when the appropriate spectral radiance measurements are available. In opaque clouds, infrared window (IRW) brightness temperatures are compared to forecast temperature profiles to infer the level of best agreement which is taken to be the level of the cloud. In semi-transparent clouds or sub-pixel clouds, since the observed radiance contains conributions from below the cloud, this IRW technique assigns the cloud to too low a level. Corrections for the semi-transparency of the cloud are possible with the carbon dioxide (CO_2) slicing technique (Menzel et al., 1983) where radiances from different layers of the atmosphere are ratioed to infer the correct height. A similar concept is used in the water vapor (H_2O) intercept technique (Szejwach, 1982; Schmetz et al., 1993), where the fact that radiances influenced by upper tropospheric moisture (H_2O) and IRW radiances exhibit a linear relationship as a function of cloud amount is used to extrapolate the correct height. The H_2O intercept technique offers the hope of international commonality of height assignment, as GOES-I, Meteosat-6, and GMS-5 will all provide the necessary spectral measurements.

2. ALGORITHM DESCRIPTION

a. The Window Channel Estimate

A window channel (IRW) estimate of the cloud height is made by comparing infrared window (11.2 microns) brightness temperatures to numerical model forecast temperature profiles to infer the level of best agreement. For opaque clouds, this level is a good representation of the level of the cloud. However, movement of opaque clouds is not usually very representative of atmospheric flow. For semi-transparent clouds (such as cirrus) or sub-pixel clouds (small clouds not filling the sensor field of view), this level is consistently too low. While these are often the best tracers for estimating cloud motion vectors, the brightness temperature (T_b) in the infrared window is usually not representative of the cloud temperature nor its height.

In the operational production of wind fields at NESDIS, the window channel estimate averages the infrared window brightness temperatures, T_b, of the coldest 25 % of pixels in the tracer selection area of about 100 km on a side (Merrill, 1989). A six hour forecast model is the source of the temperature profile. The window channel estimate is used for low clouds (below 600 hPa) and when other techniques experience problems.

b. The CO_2/IRW Ratio Algorithm

The CO_2/IRW ratio technique calculates the spectral radiative transfer in an atmosphere with a single high cloud layer; it accounts for any semi-transparency of tha cloud. For a given cloud element in a field of view (FOV) the radiance observed, $R(\nu)$, is given by

$$R(\nu) = (1 - nE)\{B(\nu, T(P_s))\, t(\nu, P_s) + \int_{P_s}^{P_c} [B(\nu, T(P)) dt/dP]\, dP\}$$

$$+ nE\{B(\nu, T(P_c))\, t(\nu, P_c)\} + \int_{P_c}^{0} [B(\nu, T(P)) dt/dP]\, dP, \qquad (1)$$

where $t(\nu,P)$ the transmittance through the atmosphere for band ν, nE the effective emittance considering FOV coverage, and $B(\nu,T(P))$ the Planck function for band ν and temperature T which is function of pressure level P. P_s is the surface pressure while P_c is the cloud level pressure. The four terms in Equation (1) are the radiation emitted from the surface, the contribution from the atmosphere below the cloud, the cloud contribution and the contribution from the atmosphere above the cloud. In Equation (1) for a given radiance observation, when the emissivity is overestimated, the cloud top pressure is also overestimated (putting the cloud too low in the atmosphere).

Determination of a cloud top pressure proceeds as follows. The radiance difference in two and cloudy FOVs is measured with VAS for the infrared window (11.2 microns, VAS band 8) and the CO_2 band (13.3 microns, VAS band 5). It is also calculated in a radiative transfer formulation. Equating the measured and calculated ratios of IRW and C02 channel radiance differences yields (after integration by parts)

$$\frac{R(CO_2) - R'(CO_2)}{R(IRW) - R'(IRW)} = \frac{(n - n')E(CO_2)\int_{P_s}^{P_c}[t(CO_2, P)\, dB(CO_2, T(P))]}{(n - n')E(IRW)\int_{P_s}^{P_c}[t(IRW, P)\, dB(IRW, T(P))]}. \qquad (2)$$

If the emissivities of the clouds are roughly the same, the cloud top pressure of the cloud can be specified. The left hand side of the equation is evaluated using measured radiances for IRW and CO_2 channels for two observations of the same cloud covering the FOV by differing amounts. The right hand side is calculated as a function of cloud pressure for the same two channels the first guess sounding and analyzed surface temperatures interpolated to the site of the cloud. The cloud tracer is assigned that pressure which best satisfies the equation.

If one of the FOVs is clear (eg. n′=0), then this expression is the same as the current operational algorithm, where the clear FOV radiances are calculated from the first guess sounding (Nieman et al., 1993). However to eliminate the effects of radiance bias on a calculated clear FOV radiance,or cloud contamination on a measured clear FOV radiance, the difference of two measured cloudy FOV radiances is preferred in Equation (2). The assumption is that the same cloud layer is viewed in both FOVs and that the radiance difference is large enough to be measured (greater than instrument noise).

The 11.2 and 13.3 micron channels have been suggested in the work of Eyre and Menzel (1989) because the 13.3 micron channel is sensitive to radiation emitted from most tropospheric features, yet the transmittance through the atmosphere is different enough from the 11 micron channel to produce a noticeable contrast. And most importantly, the emissivity of thin cirrus clouds in these two spectral bands is very similar (Ackerman and Smith, 1989).

The observed radiances used in the above calculation are obtained using a cold and warm sampling procedure. Data are taken from an area roughly 100 km on a side, centered on the target point, and a histogram of the infrared window brightness temperatures is calculated. Radiances for both channels are averaged for the coldest and warmest 25% of the pixels in the window channel. The histogram is also used to modify the surface (skin) temperature that appears in the computation of the clear column radiance; the warmer of the 90th percentile T_b and the analyzed surface temperature (using model forecast and surface reports) is used in the forward calculation.

The CO_2/IRW ratio fails when the difference between the observed radiances in either channel is less than the instrument noise (.2 mW/m2/ster/cm-l for 11.2 micron and 1.5 mW/m2/ster/cm-l for 13.3 micron). This happens for low broken cloud or very thin cirrus. Another difficulty occurs in two cloud layer situations; the CO_2/IRW ratio yields a height somewhere between the two cloud layers (Menzel et al., 1992). Tracer selection for CMVs attempts to avoid multiple cloud layers. The CO_2/IRW ratio also experiences problems with very high opaque clouds, where the radiance differences between the channels are nearly identical and the ratio is almost invariant with pressure above a certain altitude. In this situation the window channel estimate is adequate.

c. The H_2O/IRW Intercept Method

The H_2O/IRW intercept height assignment is predicated on the fact that radiances in one spectral band observing a single cloud layer will vary linearly with the radiances in another spectral band as a function of cloud amount in the FOV. Thus a plot of H_2O (6.7 microns) radiances versus IRW (11.2 microns) radiances in a scene of varying cloud amount will be nearly linear. These radiance measurements are used in conjunction with radiative transfer calculations for both spectral channels; Equation (1) is used to calculate the radiance at the top of the atmosphere emanating from opaque clouds at different levels in an atmosphere whose temperature and humidity are specified by a numerical weather prediction model. The intersection of measured and calculated radiances will occur at clear sky (cloud amount of zero) and opaque cloud radiances (cloud amount of one). The cloud top temperature (and hence the pressure) is extracted from the cloud radiance intersection. More details are presented in Nieman et al. (1993). Since the H_2O radiances are primarily emanating from the upper troposphere, height determinations below 600 hPa are screened out.

The linear relationship of the radiances in the IRW and H_2O channels can be seen in Equation (2) by substituting H_2O for CO_2. The radiance change in H_2O over the radiance change in IRW is independent of cloud fraction difference, n-n′, indicating constant slope for single level clouds. Thus all radiance measurement pairs, R(H_2O) and R(IRW), viewing different amounts of a single layer cloud at pressure P_c, lie on a straight line. The H_2O/IRW intercept method requires two cloudy sky radiance measurements with different cloud amounts in both the IRW and H_2O spectral channels.

The measured radiances used to infer the linear relationship between H_2O and IRW radiances are the average radiances for the cluster of clearest (warmest) fields of view and the cluster of the cloudiest (coldest) fields of view within the observational area. Radiances from an area roughly 100 km on a side, centered on the target point, are plotted and grouped into several clusters with differing cloud amounts. When the calculated H_2O radiances for clear sky are less than the measured H_2O radiances, the calculated H_2O radiances are adjusted to agree with the measured clear sky H_2O radiances; the difference is attributed to an inaccurate guess profile (especially over the oceans) used in the computation of the clear column radiance. Calculated warm radiances that are greater than the measured radiances are not adjusted, since the low measurement may be the result of cloud contamination.

3. INTERCOMPARISON RESULTS

Many of the intercomparisons were performed in the overlap region of GOES-7 and Meteosat-3 mostly for single cloud layer tracers from the north Atlantic region from 20 to 50 N latitude and from 50 to 100 W longitude. As ground and aircraft observations of cloud height are sparse in this region, the CO_2/IRW ratio pressure estimates were used as a reference. The accuracy of the CO_2 estimates is well documented (Menzel et al., 1992). While the comparisons reported here do not yield a measure of absolute accuracy, they do provide insight on the relative performance of the various height estimation algorithms.

a. Comparison of VAS CO_2/IRW and H_2O/IRW Heights

Initial comparison of these three height assignment techniques was accomplished with data from the Visible Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) in January 1992 (Nieman et al., 1993). The multispectral imaging from VAS measures IRW (11.2 micron) radiances from 8 km FOVs and H_2O (6.7 micron) and CO_2 (13.3 micron) radiances from 16 km FOVs. Cloud elements were selected by the autowindco procedure (Merrill et al., 1991) which divides the entire image into cells (roughly 100 km on a side) and selects targets based on the overall brightness and contrast of the scene. Height assignments were made with all three methods described in the previous section. Table 1 presents the results corresponding to 200 targets in mid-latitudes (20 to 50N latitude, 50 to 100W longitude) for 29, 30, and 31 January 1992.

The H_2O height assignment is on the average 30 hPa higher in the atmosphere than the CO_2 height assignment. The IRW heights, without benefit of any semi-transparency correction are about 70 hPa lower in the atmosphere than the CO_2 height assignment on the average. The H_2O/IRW and CO_2/IRW cloud top pressures show good similarity; agreement is within 50 hPa rms for the top of the troposphere and drops off to 100 hPa rms near 600 hPa. Both techniques show more skill higher in the troposphere. The IRW cloud top pressures are noticeably lower in the atmosphere, some unrealistically low due to the semi-transparency of the high cloud tracers selected. IRW versus H_2O/IRW and CO_2/IRW estimates show larger disagreement near the top of the troposphere (about 150 hPa rms) than at 600 hPa (about 100 hPa rms).

Better comparisons of CO_2 and H_2O heights are seen on days where the upper troposphere was moister. In a drier atmosphere, clouds will exhibit lower emissivity in the infrared window and so the IRW channel measures warmer radiances; however the water vapor attenuation in the H_2O channel remains disporportionately high (the H_2O channel is sensitive to only the first few tenths of a millimeter of water vapor). This combination of less sensitive IRW and more sensitive H_2O will produce large slopes between cloudy and clear sky clusters and yield H_2O/IRW intercept estimates that are too high in the atmosphere (Schmetz et al., 1992).

Table 1. IRW, CO_2/IRW, and H_2O/IRW height assignments for cloud tracers using VAS radiances from 20 to 50N and 50 to 100W for 29-31 January 1992.

All 3 days (199 tracers)	Mean Cloud Top Pressure (hPa)	Scatter wrt Mean (hPa)	RMS Deviation (hPa) wrt CO_2/IRW	wrt H_2O/IRW
IRW	416	102	109	141
CO_2/IRW	344	87	--	85
H_2O/IRW	314	65	85	--

b. Comparison of VAS H_2O/IRW and Meteosat-3 H_2O/IRW Heights

Height assignments using the same technique but different sensors were compared next. VAS H_2O/IRW intercept estimates of cloud top pressure were compared to Meteosat-3 H_2O/IRW intercept estimates for the same three days, 29-31 January 1992. The Meteosat-3 measures IRW (10.7 to 12.4 microns) radiances and H_2O (5.8 to 7.3 microns) radiances from 5 km FOVs. As with VAS, the Meteosat-3 cloud tracer elements were selected by the autowindco procedure. Table 2 presents the comparison of the cloud top pressures for close to 100 cloud elements collocated in the Meteosat-3 and GOES-7 VAS 1130 UTC images from these three days; collocation was within 50 km. The mean cloud top pressures agree to within 9 hPa and both show rms scatter about the mean of about 80 to 90 hPa; rms deviation between the two data sets is 94 hPa. Some of the differences in the cloud heights may be attributed to the different sized FOVs and the different spectral response functions.

Table 2. Collocated Meteosat-3 (M-3) and GOES-7 (G-7) H_2O height assignments for cloud tracers on 29-31 January 1992.

All 3 days (hPa) (97 tracers)	Mean Cloud Top Pressure (hPa)	Scatter wrt Mean (hPa)	RMS Deviation wrt G-7 H_2O
G-7 H_2O	285	80	--
M-3 H_2O	294	89	94

c. Comparison of CIMSS H_2O/IRW and Operational ESOC Heights with Meteosat-4

Finally, height assignment from CIMSS and ESOC using the same sensor were compared in an attempt to verify that future NESDIS operational height assignments with Meteosat-3 or GOES-I will have comparable quality to those generated operationally by ESOC. The H_2O/IRW intercept algorithm was applied to the Meteosat-4 data and the cloud height results were compared to the heights of the operational ESOC cloud motion winds (Schmetz et al., 1992). ESOC also estimates cloud heights with an H_2O/IRW intercept approach. Table 3 shows the comparison of CIMSS and ESOC height assignments for upper level (between 150 and 600 hPa) cloud tracers collocated to within 50 km for 21 March, 27 April, and 30 April 1992; it is in the upper levels where the semi-transparency correction of the H_2O/IRW intercept method is most important. The ESOC and CIMSS mean cloud top pressures agree to within 25 hPa and both show scatter of about 100 hPa; rms error between the two height data sets is about 77 hPa. To put this agreement in perspective, recall that the skill of the CO2 technique has been shown to be about 50 hPa (Wylie and Menzel, 1989).

Table 3. Collocated CIMSS and ESOC Meteosat-4 (M-4) H_2O height assignments for upper level (150-600 hPa) cloud tracers on 21 March, 27 April, 30 April 1992.

Both days (hPa) (136 tracers)	Mean Cloud Top Pressure (hPa)	Scatter wrt Mean (hPa)	RMS Deviation wrt CIMSS M-4 H_2O
CIMSS M-4 H_2O	272	97	--
ESOC M-4 H_2O	297	100	77

d. Comparison of CIMSS and NESDIS Operational CO_2/IRW Heights

Recent tests with the CO_2/IRW height algorithm have focussed on the influence of the radiance bias between observed and calculated clear radiances on the cloud top pressure. As mentioned earlier, the current NESDIS operational height algorithm calculates the clear radiances used in the left side of Equation (2); these forward calculations are generally biased with respect to the satellite observed clear radiances. For the VAS bands at 13.3 and 11.2 microns, observed minus calculated mean biases are .4 and -.6 C respectively for typical winter scenes (biases are adjusted seasonally). At a given FOV, the bias will vary depending on noise and moisture in the atmospheric column. If these biases are not corrected, then the CO_2/IRW heights are too low in the atmosphere. Table 4 shows the pressure biases as a function of cloud fraction for a typical October scene; cloud top pressure estimates can be off by more than 200 hPa for thin tracers.

Table 4. Cloud top pressure errors caused by calculated clear radiance biases as a function of effective cloud amount nE for a cloud scene in October 1990. Clouds were determined to be at 300 hPa from aircraft reports. The CO_2/IRW height using nearby observed clear radiances correctly assigned the cloud at 300 hPa.

nE	1.0	0.8	0.6	0.4	0.2
bias (hPa)	100	110	130	170	260

In the current NESDIS operational CO_2/IRW height algorithm the clear radiances are calculated from the NMC model six hour forecast; the resulting low height bias is mitigated by the autoeditor where height assignments are modified objectively as necessary after assimilation with other wind estimates (Hayden and Velden, 1991). In a modified version of the CO_2/IRW height algorithm the left side of Equation (2) is determined from observations of different cloud amount; the coldest and warmest 25% within the target area are differenced to determine cloud top pressure, assuming a single cloud layer in the target area. This avoids calculating the clear radiance, and hence any radiance bias. For a week in winter 1993, the operational and the modified versions of the CO_2/IRW ratio method were compared. Figure 1 shows the locations where the modified and operational CO_2/IRW algorithms were able to determine heights for CMV targets for 1 December 1993; the modified algorithm shows more success around thin tracers. In the mean the modified CO_2/IRW algorithm produced cloud top heights about 30 hPa higher in the atmosphere. Mean speed was about 5 m/s faster for high level winds in the modified than the operational wind fields; thin cirrus at high speeds is staying in the modified wind algorithm where it was rejected in the operational algorithm. On other days the differences were less remarkable; Table 5 details the daily comparison for 29 November through 3 December.

Table 5. Cloud top pressures (in hPa) and average speeds (in m/s) produced by the operational and the modified CO_2/IRW height algorithm. CMV indicates the acceptable cloud motion vectors that were produced from all targets (ALL). Sample size for each day is about 20.

day	modified CO_2/IRW			operational CO_2/IRW		
	ALL hPa	CMV hPa	SPD m/s	ALL hPa	CMV hPa	SPD m/s
29 Nov	475	342	25.0	483	350	26.4
30 Nov	459	366	20.2	464	373	20.6
01 Dec	413	368	23.5	445	413	18.4
02 Dec	418	368	23.8	439	378	19.2
03 Dec	422	361	30.2	447	391	29.2

e. Errors in CO_2/IRW Heights associated with the presence of a lower cloud layer

The CO_2 slicing algorithm assumes that there is only one cloud layer. However, for over 50% of satellite reports of upper tropospheric opaque cloud, the ground observer indicates additional cloud layers below (Menzel et al., 1991). When a lower cloud layer is present under the semi-transparent or cirrus cloud, some of the warmer surface is obscured by the colder cloud and the observed radiance is less than it would have been for a single cirrus layer. If the lower cloud layer is uniform throughout the target area, then the observed difference of the warmest and coldest 25% in the left side of Equation (2) will yield the correct cirrus height only if the integration in the right side of Equation (2) is peformed from the lower cloud pressure to the upper cloud pressure. Thus

$$\int_{P_s}^{P_c} \quad \text{must be replaced by} \quad \int_{P_{cl}}^{P_c}$$

To determine P_{cl}, cloud clusters in plots of CO_2 and IR window radiances within the target area are investigated. The lowest cloud cluster belongs to the largest radiances that are not representative of the earth surface. A CO_2 slicing height, using calculated clear radiances, is determined for this cluster. The highest cloud cluster belongs to the smallest radiances; a CO_2 height is determined for this cluster using the pressure of the lowest cloud cluster in the target area as the surface pressure in Equation (2). Testing with this two layer algorithm continues; it is not part of the NESDIS winds system yet.

5. CONCLUSIONS

The results presented in this paper suggest that the H_2O/IRW intercept technique is a viable alternative to the CO_2 slicing technique for inferring the heights of semi-transparent cloud elements. On a given day the heights from the two approaches compare to within 60 to 110 hPa rms; drier atmospheric conditions tend to reduce the effectiveness of the H_2O/IRW intercept technique. The results compare well with the validation of the CO_2 heights versus lidar and stereo cloud heights (Wylie and Menzel, 1989). The infrared window channel technique consistently places the semi-transparent cloud elements too low in the atmosphere by 100 hPa or more; only in more opaque clouds does it perform adequately. By inference one can conclude that the height algorithms used operationally at NESDIS (with the CO_2/IRW ratio technique) and ESOC (with their version of the H_2O/IRW intercept technique) provide similar results.

A modified CO_2/IRW ratio technique that does not rely on calculated clear radiances shows promise. It retains more fast tracers and places them higher in the atmosphere than the operational CO_2 technique.

The European Meteosat and the US GOES will be maintaining the H_2O and IRW imaging capability at least for the rest of this decade. The Japanese will be launching GMS-5 (probably in 1994), which will add a H_2O imaging capability to the existing IRW imaging capability. Thus, there is hope for international commonality in cloud motion vector height assignment.

6. ACKNOWLEDGEMENTS

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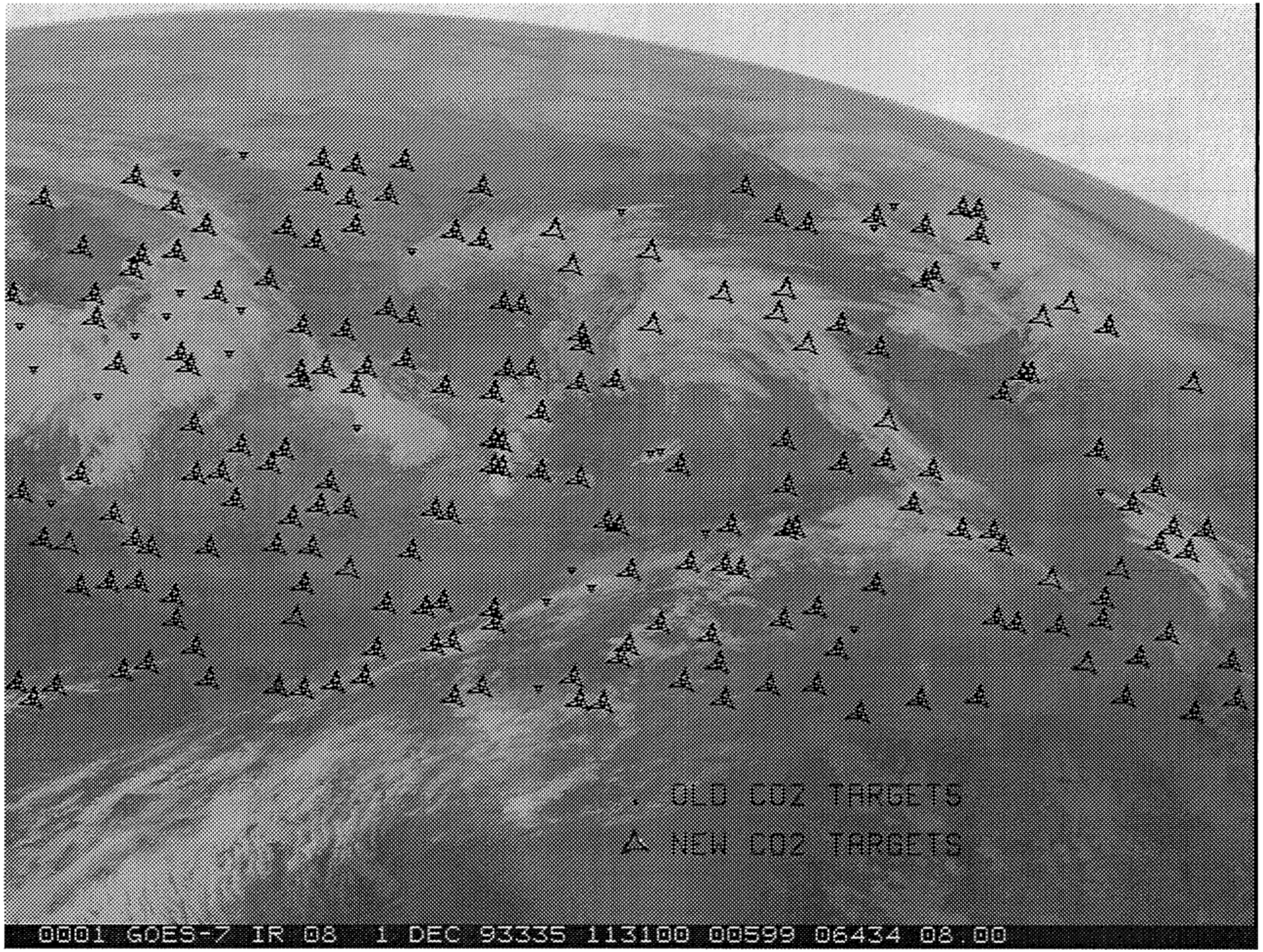

Figure 1. Locations where the modified (new) and operational (old) CO_2/IRW algorithms were able to determine heights for CMV targets for 1 December 1993; the modified algorithm shows more success around thin tracers.