A Comparison of Cloud Cover Statistics from the GLAS Lidar with HIRS

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ABSTRACT

The cloud dataset from the Geoscience Laser Altimeter System (GLAS) lidar on the Ice, Cloud, and Land Elevation Satellite (ICESat) spacecraft is compared to the cloud analysis of the Wisconsin NOAA High Resolution Infrared Radiation Sounder (HIRS) Pathfinder. This is the first global lidar dataset from a spacecraft of extended duration that can be compared to the HIRS climatology. It provides an excellent source of cloud information because it is more sensitive to clouds that are difficult to detect, namely, thin cirrus and small boundary layer clouds. The second GLAS data collection period from 1 October to 16 November 2003 was used for this comparison, and a companion dataset of the same days were analyzed with HIRS. GLAS reported cloud cover of 0.70 while HIRS reported slightly higher cloud cover of 0.75 for this period. The locations where HIRS overreported cloud cover were mainly in the Arctic and Antarctic Oceans and parts of the Tropics.

GLAS also confirms that upper-tropospheric clouds (above 6.6 km) cover about 0.33 of the earth, similar to the reports from HIRS data. Generally, the altitude of the cloud tops reported by GLAS is, on average, higher than HIRS by 0.4 to 4.5 km. The largest differences were found in the Tropics, over 4 km, while in midlatitudes average differences ranged from 0.4 to 2 km. Part of this difference in averaged cloud heights comes from GLAS finding more high cloud coverage in the Tropics, 5% on average but >13% in some areas, which weights its cloud top average more toward the high clouds than the HIRS. The diffuse character of the upper parts of high clouds over tropical oceans is also a cause for the difference in reported cloud heights.

Statistics on cloud sizes also were computed from GLAS data to estimate the errors in cloud cover reported by HIRS from its 20-km field-of-view (FOV) size. Smaller clouds are very common with one-half of all clouds being <41 km in horizontal size. But, clouds <41 km cover only 5% of the earth. Cloud coverage is dominated by larger clouds with one-half of the coverage coming from clouds >1000 km. GLAS cloud size statistics also show that HIRS possibly overreports some cloud forms by 2%–3%. Looking at groups of GLAS data 21 km long to simulate the HIRS FOV, the authors found that ~5% are partially filled with cloud. Since HIRS does not account for the part of the FOV without cloud, it will overreport the coverage of these clouds. However, low-altitude and optically thin clouds will not be reported by HIRS if they are so small that they do not affect the upwelling radiation in the HIRS FOV enough to trigger the threshold for cloud detection. These errors are partially offing.

1. Introduction

Cloud climatologies have been compiled from spacecraft sensors for the purpose of understanding climate and how clouds affect radiative transfer in the earth's heat budget. Four studies that have produced global cloud data over multiple years are the International Satellite Cloud Climatology Project (ISCCP; see Rossow and Schiffer 1999; Schiffer and Rossow 1983), the Wisconsin NOAA Pathfinder (Wylie et al. 2005), the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder (Jacobowitz et al. 2003), and the Stratospheric Aerosol and Gas Experiment (SAGE; see Wang et al. 1996). Different cloud frequencies are reported from these datasets because of different sensitivity to cloud density and size. For example, Jin et al. (1996) noted that a Wisconsin analysis from the National

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Oceanic and Atmospheric Administration (NOAA) High Resolution Radiometer Sounder (HIRS; Wylie and Menzel 1999; Wylie et al. 1994) reported 10%–15% more cloud cover than the ISCCP because of its sensitivity to optically thin upper-tropospheric cirrus. The SAGE, with its higher sensitivity and large field of view (FOV), reported even higher values of cloud cover than the ISCCP and the Wisconsin HIRS (Liao et al. 1995). These differences have led to some confusion as to the frequency of clouds since no single system or sensor is capable of accurately detecting all forms of clouds.

We have an opportunity to reduce some of this confusion with observations from a new sensor with higher sensitivity and spatial resolution than the sensors used in the previous studies. The Geosciences Laser Altimeter System (GLAS) was launched on the Ice Cloud and Land Elevation Satellite (ICESat) in January 2003. This is a lidar on a polar-orbiting spacecraft collecting global cloud data. The GLAS observations were designed for multidisciplinary earth science research specifically including very high performance cloud and aerosol profiling (Spinhirne et al. 2005).

The GLAS measurements were intended to operate continuously for a 5-yr time span. As a result of reliability problems on orbit with the three lasers, the system has been run in data collection periods four to six weeks in length, three to four times per year. This study concentrated on the second data collection period from 1 October until 16 November 2003. This dataset is significant because it spans over 1.5 months and we need at least one month of global data to make meaningful statistical comparisons to the HIRS cloud climatology. The HIRS climatology of Wylie and Menzel (1999) samples the cloud population similar to most other global cloud climatologies. This climatology is designed for measuring monthly averages of global cloud cover and poorly represents shorter records where the variability of local weather systems affect the statistical averages.

A brief description of the instruments is given in the following section. Global cloud coverage statistics are discussed in section 3. The vertical profiles of the cloud reports are discussed in section 4. Statistics on cloud size frequencies are discussed in section 5. With its smaller FOV, GLAS provides an opportunity to estimate the influence of clouds below the FOV resolution of the HIRS sensor on its climatological statistics. A summary and implications of the GLAS statistics to the HIRS cloud climatology are discussed in section 6.

2. The satellite instruments

A description of the ICESat mission and the GLAS atmospheric measurements can be found in Schutz (1998) and Spinhirne et al. (2005) (and online at http://nsidc.org/daac/icesat/ and http://glo.gsfc.nasa.gov/). The GLAS laser operates at 1064 ($\sim$1 μm) and 532 nm with a pulse repetition frequency of 40 hz. The two wavelengths are used in separate receiver channels. The 532-nm channel (green) is designed specifically for high-performance cloud and aerosol detection through photon counting signal acquisition. The 1064-nm channel is in the near-infrared part of the spectrum, while the 532-nm channel is visible as green light. The ability to detect clouds differs between these channels. Practical detectors at 1064 nm were inherently not as good as those available for 532 nm. The 1064-nm channel employs analog detection and has worse dark noise than the 532-nm channel. As a result, the detection sensitivity of the 532-nm channel for atmospheric scattering layers is approximately an order of magnitude better than for the 1064-nm channel (Spinhirne et al. 2005). The difference in the amount of cloud cover reported by the two channels reflects the ability of each to detect the optically thinnest clouds.

The first GLAS data were collected using only the 1064-nm channel from 19 February to 28 March 2003. The on-orbit laser reliability problem resulted in a failure of the first of three lasers at this time (Abshire et al. 2005). After a review of the laser problem, as stated above, it was decided to operate the instrument in 4 to 6 week periods every 3–4 months. The second laser was initially started at the end September 2003 and used through mid-November 2003, which is the focus of this study because of the availability of the higher-quality 532-nm channel.

The GLAS lasers have pulse repetition frequencies of 40 Hz, and each pulse illuminates an approximately 70-m footprint on the earth's surface. Pulses are spaced at $\sim$176 m along the ICESat orbit track. The instrument operates in a single direction and is normally pointed to 5 mrad off nadir. The data are processed with algorithms developed by the science team, including cloud and aerosol applications (Spinhirne et al. 2005; Hart et al. 2005; Hlavka et al. 2005). The primary data products applied here are the detection of the presence of one or more cloud layers and the height of the layers. The cloud detection is presented at the full 40 Hz and with averaging over 0.2, 1, and 4 s with the retrievals linked in sequence from most averaging to least in order to increase the detection the thinnest layers. This study used the 1-s-averaged data, so we assumed that each cloud reported represents a field of view that is long and narrow, nominally 7.1 km along a 70-m-wide orbit track.

This effective lidar FOV is much smaller than any of the HIRS data, which have a 20-km diameter FOV without sampling and averaging. About three GLAS

1-s-averaged FOVs describe one dimension of a HIRS FOV.

The GLAS sensitivity to clouds is also far greater than the other datasets. Clouds are diagnosed from an algorithm that examines the strength and vertical gradient of the backscatter profile. This is a multiparameter analysis that employs several tests on the backscatter profile and is discussed in Hart et al. (2005) and Palm et al. (2002). Distinct increases in the backscatter profile indicate cloud layers. An issue is the classification of these scattering layers as either cloud or aerosol. Aerosols tend to have lesser gradients in the vertical profile than clouds and the algorithm has been tuned based on extensive experimental experience and visual inspection of backscatter data (Palm et al. 2002). The GLAS cloud product is produced at Goddard Space Flight Center (GSFC) and is available from its Distributed Active Archive Center (DAAC; online at http://nsidc.org/daac/icesat/).

The 532-nm channel reliably detects clouds down to optical depths of ~0.02. Validation experiments have shown sensitivity to much lower optical-depth clouds. Hlavka et al. (2005) and Spinhirne et al. (2005) summarize the results of extensive airborne comparison experiments to GLAS. Using 1-s-averaged data, backscatter cross sections down to 10^{-7} are reliably detected. For typical cirrus cloud, with a physical thickness around 2 km, the corresponding optical depth for a backscatter cross section of 10^{-7} is about 0.004. The HIRS will not detect these thin clouds and has a higher minimum detection level from 0.1 to 0.3 (visible optical depth).

ICESat also is not in a sun synchronous orbit, which differs from the orbits used by the NOAA satellites. The 94° inclination of the ICESat orbit was chosen primarily to maximize coverage of the polar ice caps and precesses at a rate close to 0.5° day^{-1} relative to a sun synchronous orbit. The NOAA satellites carrying the HIRS fly in synchronous orbits, which cause some bias where there are large diurnal cycles in clouds. However, the Wisconsin NOAA Pathfinder analysis from HIRS used both ascending and descending passes of the NOAA satellites, 12 h apart, to reduce the affects of diurnal cycles. An advantage of the precessing orbit plane of GLAS for cloud observations is that in a year's time period, the lidar measurements will have moved through the observational swath of all existing cloud imagers, permitting direct comparison of retrievals on a pixel-to-pixel basis (Mahesh et al. 2004).

The cloud analysis from HIRS is described by Wylie et al. (1994, 2005) and Wylie and Menzel (1999). The first two describe the basic technique. The third paper is a reanalysis of HIRS data using many of the principals employed in the first two studies and extended back to the first HIRS-2 sensor flown in 1979. Similar values of cloud frequency were found in the reanalysis as the previous work. For this comparison we used the last NOAA satellite of the series used in Wylie et al. (2005), *NOAA-14*, which crossed the equator at 0530 and 1730 LT. The crossing time for GLAS data moves from 0810/2010 to 0658/1858 LT for the 1 October–16 November data period.

The Wisconsin NOAA HIRS Pathfinder analysis uses passive radiative measurements from five HIRS channels from 11- to 15-μm wavelength. The primary use of these channels is for making temperature soundings in the troposphere. They also allow detection of optically thin cirrus clouds and an estimation of the magnitude of the IR transmission through these clouds. The purpose of the HIRS cloud analysis is to compliment the ISCCP taking advantage of sensors not used by the ISCCP. It has the advantage of detecting more of the optically thin upper-tropospheric cirrus clouds, as previously mentioned. However, it also uses a larger FOV sensor than the ISCCP, which contributes to higher cloud frequency reports. The HIRS cloud analysis technique cannot distinguish radiative transmission through thin clouds from radiation passing through holes between clouds when the size of the holes is below the resolution of the sensor.

The HIRS analysis also suffered from a problem common to all cloud studies—distinguishing clouds from the earth's background when clouds are at low altitudes and broken. All satellite studies compare the radiation from a pixel thought to be cloudy with the radiation expected from a clear pixel and make a decision to call that pixel either cloudy or cloud free. The quality of the clear or cloud decision is determined by scientists visually inspecting satellite images since more quantitative data are illusive. The Wisconsin NOAA HIRS Pathfinder system requires a cloudy pixel to have a signal of 1 mW m^{-2} str^{-1} cm^{-1} in radiance colder than the estimated clear (FOV) radiance on at least two of the four partially absorbing CO_2 channels from 13 to 15 μm (HIRS channel numbers 4–7). This implies that the cloudy pixel has to be at least 1 K colder in radiance than the estimation of clear radiance on two of these channels. For low clouds below the altitude that the CO_2 channels can see (>700 hPa), the 11-μm window channel (8) is used and the clouds have to be at least 2 K colder than the surface. These are quantitative decisions made in the cloud analysis algorithm that depend on estimating the radiance of clear FOVs from the temperature soundings of the NCEP–NCAR reanalysis. The GLAS cloud analysis does not depend on an estimate of the clear FOV radiance, which is one of the

TABLE 1. The frequency of clouds and high clouds reported by GLAS and HIRS (*NOAA-14*) from 1 Oct to 16 Nov 2003.

	GLAS	HIRS
	All clouds	
20°–60°N	0.67	0.69
20°S–20°N	0.68	0.73
20°–60°S	0.78	0.78
	High clouds (<440 hPa or >6.6 km)	
20°–60°N	0.35	0.29
20°S–20°N	0.45	0.40
20°–60°S	0.30	0.28

reasons why it was chosen for evaluating the HIRS cloud data.

3. The frequency of clouds

For comparison to HIRS only the highest cloud top level reported by GLAS was used. A second cloud level was reported in 27% of the GLAS data. However, the Wisconsin NOAA HIRS Pathfinder analysis reports only one cloud level in each pixel, so only the highest cloud level reported by GLAS was used for consistency.

The HIRS reports slightly more cloud cover than GLAS; see Table 1. The largest difference was in the Tropics where the HIRS reported 73% cloud coverage and the GLAS reported 68%. These differences are small and less than the geographical variances of cloud cover shown in Fig. 1.

The geographical distributions of cloud cover show general agreement between both GLAS channels and HIRS. All systems report numerous clouds in the Tropics, the North Pacific, North Atlantic, and Antarctic Oceans. Tropical clouds were most frequent over southern Brazil, the southern Congo in Africa, and the Indonesian islands and western Pacific Ocean. These areas are the intertropical convergence zone (ITCZ) where most tropical convection is found. Latitudes of lesser cloud cover occur north and south of the ITCZ—the subtropical high pressure centers over oceans and the subtropical deserts (including the Sahara). The midlatitude regions of cloudiness are the storm belts where baroclinic fronts are common. Cloud frequencies range from ~0.20 to ~0.95.

The largest difference between GLAS and HIRS was found at the poles north and south of 70° latitude. In the Arctic Ocean HIRS reported cloud frequencies of 0.88, while GLAS found only 0.78. HIRS was suspected of overreporting cloud cover from an unpublished comparison of part of Wylie et al. (2005) to the Pathfinder analysis of the Arctic by Wang and Key (2005). Wang and Key report 10% less cloud coverage than the HIRS poleward of 60°N. A comparison of GLAS to Wang and Key (2005) is not possible because they did not analyze data from 2003 when GLAS became available.

We suspect that HIRS overreports cloud cover in the Arctic because of the strong lower-atmosphere temperature inversion that is usually present. Clouds with their tops in this inversion appear warmer than the surface and are the warmest objects seen by the HIRS. These warm clouds are mistakenly called clear FOVs and are used to establish the clear radiance. All other HIRS FOVs, whether they are cloudy or clear, are colder, and the analysis system then labels them as clouds. The analysis algorithm used on the HIRS data did not account for clouds being in strong low-level inversions. Cirrus clouds that are above the temperature inversion are colder and correctly identified.

HIRS also reported more cloud cover than GLAS over the tropical western Pacific Ocean and in three continental areas: northern Africa, southern Asia, and the southeastern United States. These differences were smaller than the poles and appear to come from HIRS overreporting low-altitude clouds.

High cloud frequencies have better agreement (see Fig. 2). For consistency we used the ISCCP definition that high clouds have their tops above 440 hPa, which is 6.6 km for these data. In Fig. 2 both systems show the ITCZ, its southern extension in the southwest Pacific, and the frequent high clouds in the storm belts of midlatitude oceans. The largest differences with GLAS were north of 50° latitude over northern Asia, Scandinavia, and North America where the 532-nm channel reported 10%–15% more high cloud cover than the HIRS. This difference comes from two sources—greater sensitivity to optically thinner clouds, as discussed earlier, and GLAS reporting higher cloud tops than the HIRS.

4. Frequency of semitransparent clouds

Semitransparent clouds are very important for energy budget studies because they can heat the earth. Clouds are normally expected to cool the earth through solar reflection, but clouds that are semitransparent can have the opposite affect (Hobbs 1993) because they can capture more terrestrial radiation than their solar reflection. Clouds in the upper troposphere are better able to attenuate the terrestrial radiation than low-altitude clouds because of their colder temperatures and larger temperature contrast with the earth's surface

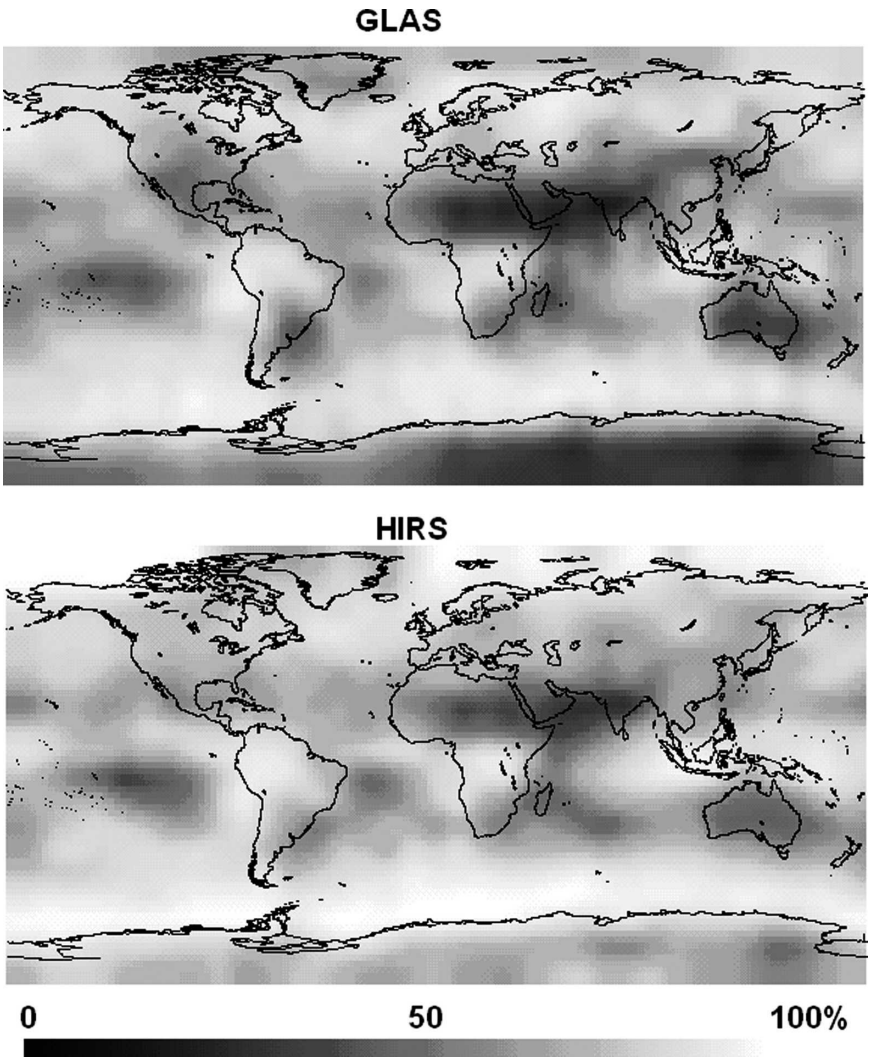

FIG. 1. Frequency of clouds reported by GLAS and HIRS (*NOAA-14*) from 1 Oct to 16 Nov 2003.

below. The HIRS data are better suited to detecting semitransparent upper-tropospheric clouds than the ISCCP, which is the reason a HIRS cloud analysis was made as an appendage to the ISCCP, as previously mentioned (Wylie et al. 2005). Since the GLAS lidar is more capable of detecting these clouds and determining their transparency than either the ISCCP or HIRS, a comparison of semitransparent cloud statistics is included in Table 2.

The definition of a semitransparent cloud in the HIRS data is a cloud in which 5% or more of the upwelling 11-μm radiation passes through. These clouds are 1 K or more colder than the earth background in the 11-μm HIRS channel. The emissivity calculated in the cloud retrieval algorithm is $\leq$0.95. If infrared scattering is ignored, then a cloud with an IR transmissivity of 0.05 and emissivity of 0.95 has a visible optical depth of 6.0 [see Wylie et al. (1995) for the details of the calculation].

In the GLAS cloud product we can identify semitransparent clouds when a second cloud layer is reported or the altitude of the earth's surface is reported below the cloud. To detect a second layer or the earth's surface some lidar energy has to pass both ways through the cloud and be reflected off the lower surface. Sufficiently optically dense clouds in GLAS data do not show either lower cloud layers or the surface in the backscatter profile. The loss of subsequent signal as a definition for optically dense clouds is straightforward in terms of processing but ambiguous in terms of definition. The signal returned from a bright surface or cloud can be as high as several thousand photons, or as

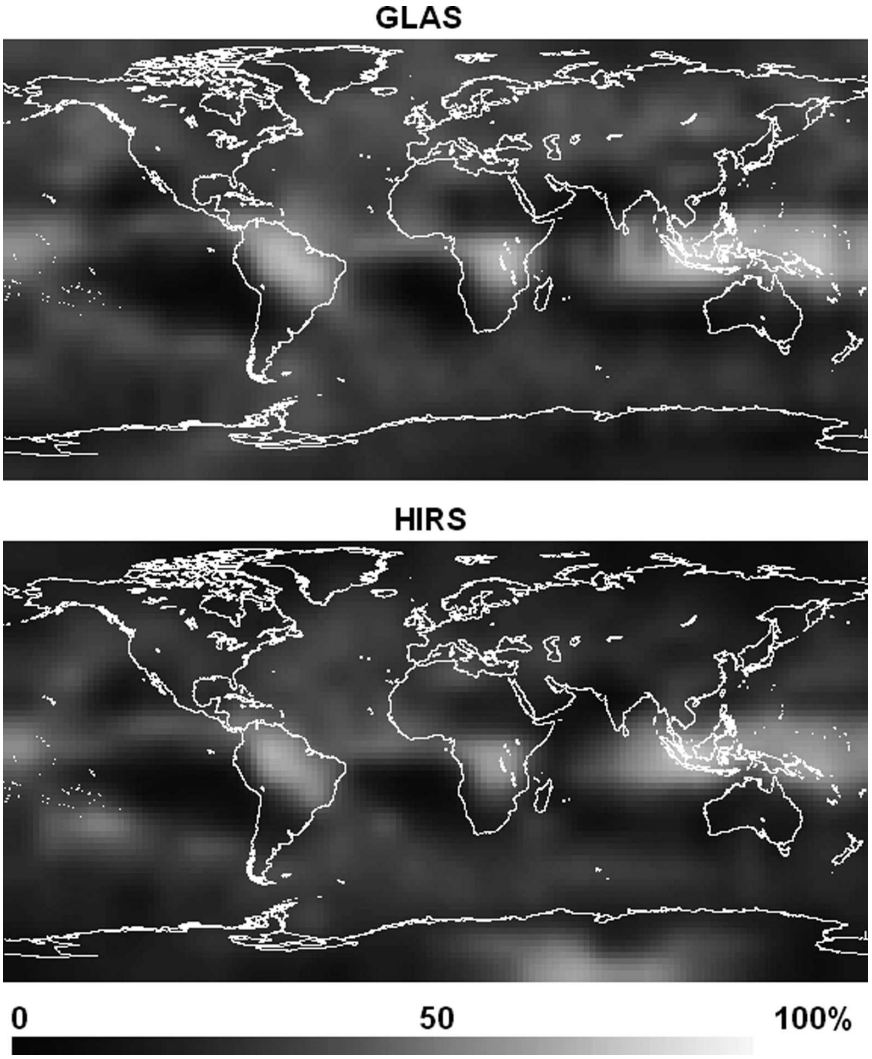

FIG. 2. As in Fig. 1 but for high clouds above 440 hPa.

low as a couple photons, due to signal attenuation from clouds and poor reflection from the surface. Complicating the definition is forward-scatter transmission. Forward scattering increases the signal through and below clouds by a factor of 2–3 in optical depth (OD) typically—meaning clouds as thick as OD 10 could be below this dense definition. Also, the surface albedo is generally low and variable. Over the ocean it is a function of wind speed and can be lower than 0.1 for strong winds and 10 times higher where seas are calm. The cloud optical thickness to block a lower surface return can thus range from 2 to 10, but more typically it would be in the range of 3–5. Considering the strength of the laser and the sensitivity of the detection system in the lidar, we estimate that clouds <3.0 OD will allow detectable signal transmission to happen consistently. The

TABLE 2. The coverage of semitransparent clouds measured by each system with visible optical depth <3.

	Coverage of		Semitransparent clouds		
	All clouds	High clouds	All	All ($\tau_\upsilon < 3$)*	High ($\tau_\upsilon < 3$)*
			Global		
GLAS	0.70	0.33	0.44	0.26	0.14
HIRS	0.75	0.32	0.45	0.34	0.23
			Tropics		
GLAS	0.68	0.45	0.49	0.35	0.25
HIRS	0.73	0.40	0.47	0.38	0.30

* GLAS clouds with optical depth <3 are clouds in which the ground was seen through the cloud. For HIRS these are clouds with IR transmissivity <0.23.

transmission of 0.67% for a cloud of optical thickness 5 is still sufficient for the surface pulse reflectance to be detected by the 532-nm channel in many cases. But using the consistent estimate of 3.0 as the lidar value, this is one-half of the optical density for which HIRS defines clouds as being semitransparent.

Using either the existence of a second cloud layer or a reflection from the earth's surface through a cloud, we found that semitransparent clouds covered 0.44 of the earth. sINCE the average cloud coverage was 0.70, this implies that almost two-thirds of the clouds (62%) were semitransparent or at least had an upper layer that was semitransparent (see Table 2). In the Tropics semitransparent clouds were more frequent, appearing in 70% of the cloudy data. The HIRS found similar values of semitransparent cloud coverage—0.45 globally and 0.47 in the Tropics, which were 60%–64% of the cloud cover reported by HIRS.

Our definition of semitransparent clouds in the GLAS data can include situations where an optically thin cloud layer has a denser layer below it. In this situation, the total optical depth of all cloud layers could be large. Thus, a more simple definition of semitransparent clouds is desired. The transmissivity and optical depth reported by HIRS is for all clouds of all levels, and to be consistent with HIRS we will only consider GLAS cloud reports in which the earth's surface altitude also was reported underneath the cloud as being semitransparent and OD < 3. A corresponding statistic for the HIRS data is all clouds with 11-μm IR transmissivity >0.78, which would have an equivalent visible OD < 3.

The global coverage of clouds with OD < 3 is 0.26 according to GLAS and 0.34 according to HIRS (Table 2). HIRS found 8% more semitransparent cloud coverage of this density than GLAS. A large part of this difference is from HIRS reporting 5% more cloud coverage of all forms than GLAS. HIRS also overreports cloud cover in broken cloud fields because of its larger FOV, and these clouds will also be classified as semitransparent since the radiation passing through holes in the cloud field below FOV resolution cannot be distinguished from radiation passing through the clouds. A second possible cause of this difference is that the GLAS data depend on the reflectivity of the lidar energy by the earth's surface. Some semitransparent clouds over poor reflecting surfaces may have been missed. In the Tropics better agreement was found with GLAS reporting 0.35 coverage compared to 0.38 from HIRS.

The same sensor disagreement is found in the coverage of high clouds of OD < 3, where GLAS reported coverage of 0.14 and HIRS reported 0.23 (Table 2, a 9% difference). In the Tropics a closer relationship (0.25 coverage reported by GLAS and 0.30 coverage reported by HIRS) was found. Clouds of OD < 3 comprise 42%–53% of the high clouds reported by GLAS and 72%–75% of the high clouds reported by HIRS.

5. Vertical distribution of cloud height reports

To understand the differences in how these two systems see clouds we show a small sample of cloud view nearly simultaneously by both the GLAS and HIRS. The *NOAA-15* HIRS had to be used because its orbit was closer to the ICESat. Both *NOAA-15* and ICESat crossed over the western continental United Sates (CONUS) within one hour on 15 November 2003 (GLAS at 1437 UTC and *NOAA-15c*at 1533 UTC, see Fig. 3). The dots show the locations of HIRS observations while the dark line is the GLAS observations. Both satellites are descending over this region. The center of the *NOAA-15* orbit track is where the HIRS observations are tightly packed.

The vertical profile of GLAS lidar backscatter over this track is shown in Fig. 4. Backscatter returns from clouds are gray and black areas indicate no backscatter returns. The cloud tops indicated by HIRS are the white bars in the image. For most of the track, the bright return in the lower part of the image indicates lidar returns from the ground. On the right side ground returns are absent, indicating dense clouds.

The HIRS reported cloud heights are generally beneath the cloud tops and above the cloud bases reported by GLAS. Some of the HIRS cloud retrievals are in the black area where GLAS did not measure backscatter, on the right side of Fig. 4. These clouds are difficult to understand since their tops have variable heights and the backscatter returns are strong in small patches. We suspect the GLAS was attenuated in these clouds and the cloud bases were not seen. We assume it is below the cloud heights reported by HIRS.

The HIRS analysis algorithm also has difficulty dealing with multiple cloud layers since it has to assume that all of the infrared radiative attenuation occurs at one level in the vertical. A vertical structure of clouds cannot be assumed as there are an infinite variety of possibilities. The single cloud level assumption is made by all algorithms that retrieve cloud heights from passive radiative data. When thin semitransmissive clouds overlay more dense clouds, the retrieval solution often has to be underneath the upper thin cloud and can end up in between cloud layers. This is extensively discussed in Wylie et al. (1994) and Wylie and Menzel (1999). In general, Holz et al. (2006) found the cloud heights derived from this method to be at the level

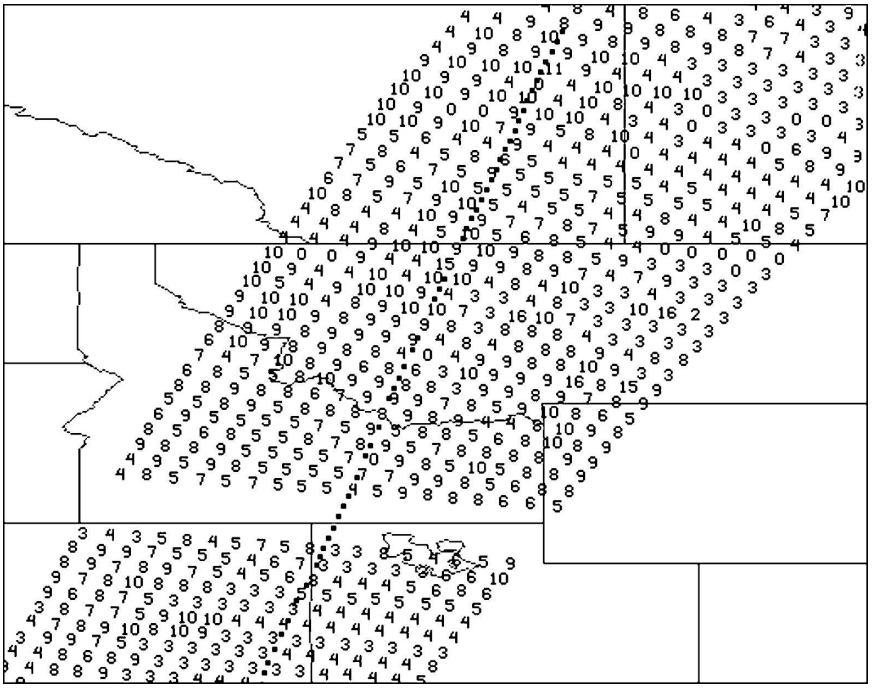

FIG. 3. Location of GLAS and HIRS (*NOAA-15*) observations from 1023 to 1033 UTC 27 Feb 2003. GLAS observations are the black line.

where visible optical depth integrated from the cloud top downward into the cloud reached a value of 1.0.

The GLAS reports both cloud top and base heights. A summary of average top and base heights reports from GLAS and HIRS is shown in Table 3. The base reported in lidar data differs from the physical cloud base height for dense clouds through which the lidar cannot penetrate. We assume these clouds have OD > 3,

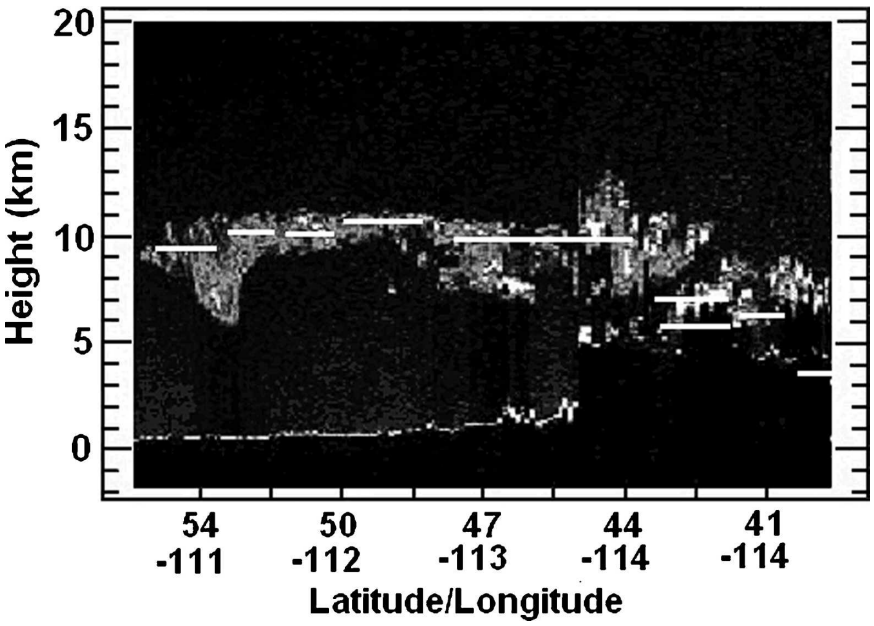

FIG. 4. Backscatter profile from GLAS for the orbit track shown in Fig. 3: 532-nm CAB, 1435–1440 UTC 15 Nov 2003. White rectangle boxes are the cloud levels reported from the *NOAA-15* HIRS.

TABLE 3. Comparison of the average cloud heights in meters.

	Top	Base	Average
		Land	
20°–60°N			
GLAS	7.3	4.4	5.9
HIRS			5.4
20°S–20°N			
GLAS	12.3	7.9	10.1
HIRS			7.7
20°–60°S			
GLAS	7.7	5.4	6.7
HIRS			5.3
		Sea	
20°–60°N			
GLAS	6.5	3.4	5.0
HIRS			5.1
20°S–20°N			
GLAS	9.4	5.6	7.5
HIRS			5.5
20°–60°S			
GLAS	5.1	2.6	3.8
HIRS			4.7

as previously mentioned. Stubenrauch et al. (2005) suggested that lidar cloud-base height reports be regarded as "the apparent cloud bases" for the denser clouds. While they do not represent the physical cloud base, they are an indication that the upper part of the cloud is semitransparent and that this transparency extends down to at least the apparent cloud base reported by the lidar.

The coverage of clouds through which the lidar has penetrated entirely are indicated in Table 2 as clouds with $\tau_\upsilon < 3$. They cover 0.26 of the earth, which is 37% of the global cloud cover. In the Tropics $\tau_\upsilon < 3$ clouds are more common and are found in 51% of the cloud cover.

The cloud heights reported by HIRS averaged from 0.4 to 1.9 km below the cloud tops reported by GLAS (Table 3) outside of the Tropics while inside the Tropics the differences were greater, averaging 4 km over oceans to 4.6 km over land. The cloud top differences in most areas are similar to the HIRS–SAGE cloud studies reported in Wylie (1997) and Wylie and Wang (1999) and the earlier comparison to ground-based lidars (Wylie et al. 1994; Wylie and Menzel 1989). However, the previous comparisons had very little tropical ocean data, so this area of large difference was not identified. The tropical oceans have a lot of very high semitransparent clouds that are very diffuse in their upper layers. The cloud levels reported by HIRS tend to be weighted toward the denser clouds at lower altitudes.

Stubenrauch et al. (2005) found that infrared cloud heights from HIRS agreed better with the average of the cloud top and base heights reported by the Lidar In-Space Technology Experiment (LITE) lidar than the cloud top data by itself. This situation also is present in this GLAS–HIRS comparison, where the HIRS-reported cloud levels are within 0.8 km of the GLAS cloud top/base average everywhere except the Tropics. This agreement occurs because the cloud level reported by HIRS for semitransparent clouds is a mean level of radiative attenuation, as discussed in section 2, and should be inside the semitransparent region of the cloud. It approaches the physical cloud top only when the upper part of the cloud is optically dense.

The vertical profiles of the cloud height reports by the GLAS and HIRS are similar (Fig. 5). Both have maxima in the upper troposphere above 440 hPa and a secondary maxima in the lower troposphere. The high cloud maximum is more obvious in the GLAS data than the HIRS and generally is 100 hPa higher in the GLAS data.

The vertical profiles of GLAS cloud top data also clearly show that low-level clouds are very common. The profiles in Fig. 5 do not account for the fact that, when a high cloud was detected, the lower troposphere was not observed since in this analysis we are only applying the top of the highest layer reported by GLAS. The HIRS algorithm also only reports one cloud height and does not define the structure below this height. The simplest method of reporting vertical profiles is to count the number of cloud observations in layers. However, this does not represent the true frequency of clouds in the lower troposphere because it is observed less when high clouds are present. This is a common problem to most papers reporting cloud frequencies. If a correction were made for the true number of observations in the lower troposphere, it would show that low-altitude and boundary layer clouds are more common than high clouds. However, correcting for this characteristic of the observing system tends to confuse readers, so it was not done here. Wylie et al. (2005), in discussing their climatology of clouds, has included this correction.

6. Cloud sizes and coverage

An analysis of the GLAS 1-s cloud data was made looking at the length of continuous cloud or clear events along the orbit track of ICESat. The highly elongated FOV of GLAS does not allow an analysis of the area covered by clouds since it samples only in the direction of the orbit without side scanning. The data were analyzed for continuity of cloud and clear events along the ICESat orbit track. The cloud size statistics are summarized in Fig. 6. This is a sum of cloud fre-

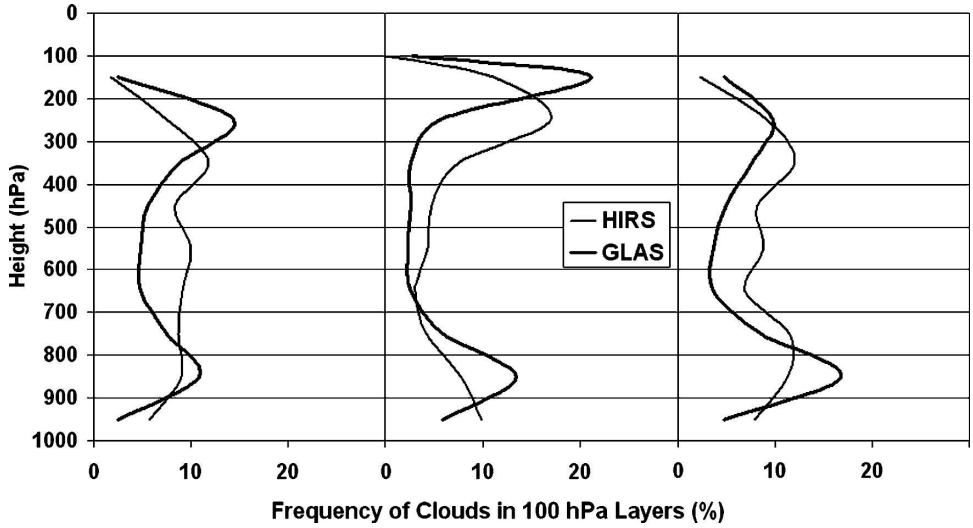

FIG. 5. Vertical profile of cloud top reports from GLAS and HIRS (*NOAA-14*) from 1 Oct to 16 Nov 2003. All frequencies include both clear and cloudy observations. No correction was made to lower layers for high cloud blockage.

quencies by size from the smallest to largest. The rapid increase in accumulated frequency indicates a predominance of small clouds.

The HIRS sensor is thought to overreport the cloud coverage because it cannot resolve small holes in cloud fields. The GLAS data can be used to estimate the magnitude of this FOV problem since it has higher spatial resolution. To simulate the FOV of HIRS in one dimension, we looked at groups of three 1-s GLAS pixels and counted how many of these groups contained solid cloud cover as opposed to how many had mixed clear and cloudy reports. Groups of three GLAS 1-s pixels represent 21 km along the orbit track, which is similar to one dimension of a HIRS FOV. In these three pixels groups, 68% were fully cloud covered and 27% were fully clear, while 5% were mixed with only one or two pixels in the group having clouds. This implies that about 7% (5/68) of the cloud cover reported by HIRS is from partially covered FOVs.

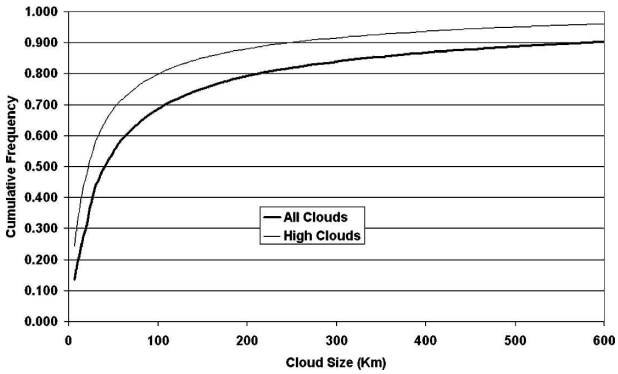

FIG. 6. Frequency of clouds by size, accumulated from the smallest to largest.

For high clouds, the contribution of partially covered FOVs is larger because high cloud coverage is less than total cloud coverage. For high clouds (>6.6 km in GLAS data) 30% of the GLAS three-pixel groups were totally covered with clouds while 7% were mixed and 63% were cloud free (above 6.6 km). The partial FOVs account for 18% of the GLAS three-pixel groups.

The FOV coverage problem was previously evaluated by Wylie and Menzel (1999) using the higher-resolution AVHRR instrument flown on the same NOAA satellites as HIRS. This study found that 17% of HIRS cloud reports contained broken clouds. They occurred mainly in low-altitude clouds and optically thin upper-tropospheric clouds. This agrees with the GLAS statistics for high clouds, but is larger than GLAS for total cloud coverage.

The HIRS analysis algorithm accounts for the radiation passing through holes in high cloud fields with its estimation of cloud emissivity and transmissivity. Holes smaller than the HIRS FOV have the same effect as transmission through the high clouds and thus are part of the cloud emissivity/transmissivity estimate.

The GLAS data imply that adjustments for sub-FOV-size clouds and holes should be made to HIRS data. We have estimated these adjustments and they are summarized in Table 4. The HIRS-reported cloud cover of 0.75 should be adjusted downward by a multiplication factor of 0.97 to 0.73 and high clouds should be adjusted by a factor of 0.96 from a measurement of 0.32 to 0.31.

TABLE 4. Summary of cloud frequency adjustments for partial FOV coverage.

	Reported frequency of clouds	% of FOVs partially covered	Adjustment factor	Corrected frequency of clouds
All clouds	0.75	7%	0.97	0.73
High clouds	0.32	19%	0.96	0.31

The large HIRS FOV size also affects its ability to detect small clouds. Since the radiation measured by HIRS is a combination of FOV coverage and cloud transmission, some clouds will not be detected because the HIRS FOV does not have enough contrast from a clear FOV. Altitude also affects cloud detection as higher-altitude clouds have a larger thermal contrast from the ground or ocean below them, which improves their ability to be detected. The combination of these three factors—altitude, FOV coverage, and cloud density—was simulated for a tropical atmosphere and is shown in Fig. 7. Clouds that are in the upper-right part of Fig. 7 have sufficient thermal contrast to be detected, while clouds on the lower-left sides of the lines cannot be detected.

This simulation shows that all optical dense clouds of OD > 6 will be detected down to 0.5-km altitude if they cover $\geq 40\%$ of the HIRS FOV. If they cover less of the FOV, then they have to be at higher altitudes for HIRS to detect them. For example, clouds covering only 20% of the HIRS FOV have to be at least 2 km high to be detected and smaller clouds will not be detected. Most cumulus and clouds with water phase particles have OD > 6 but vary in size. GLAS found ~3% of clouds only cover 1/3 of the HIRS FOV in the Tropics. Previously, we stated that the HIRS incorrectly interprets these small clouds as the full HIRS FOV size, which leads to an overreporting of cloud cover by ~3%. However, if the small clouds reported by GLAS are actually <7 km wide, then our previous estimate of HIRS overreporting clouds is incorrect. Clouds <7 km wide may be able to trigger the GLAS detection system because of its high sensitivity, but they are not detectable by HIRS. This leads to an underreporting of clouds by HIRS.

GLAS found that 2% of the clouds <3.0 km high were ≤7 km wide (the smallest cloud object diagnosed in the GLAS 1-Hz data product); these clouds covered 1% of the Tropics. This implies that HIRS may have missed small low-altitude clouds by as much as 1%. Thus, the overreporting error of HIRS of 3% previously discussed could be offset by up to 1% of low-altitude small clouds that HIRS will miss.

Optically thinner clouds have to be at higher altitudes to be detected by HIRS. Clouds of OD ~1.0 have

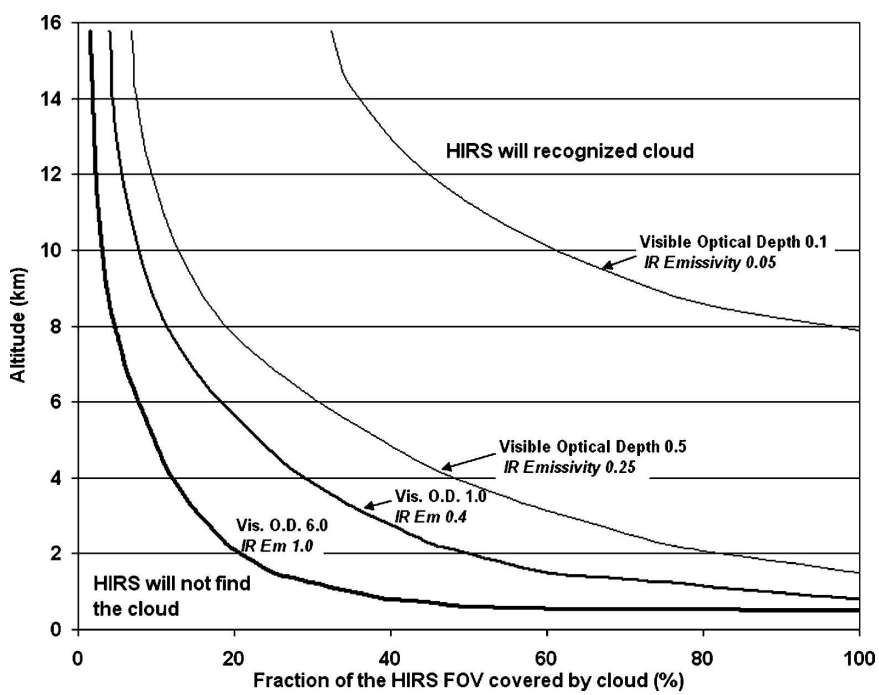

FIG. 7. An estimation of the combination of cloud altitude, density, and FOV coverage required for HIRS to recognize a cloud using a standard tropical atmosphere.

to be >4 km high and cover 33% of the HIRS FOV to be detected. The vertical profile of cloud reports from GLAS in Fig. 5 indicates that 71% of the clouds in the Tropics are above this altitude and size. Very thin cirrus of OD 0.5 have to be 5.8 km high to be detected, and GLAS indicates that 66% satisfy these detection conditions.

For the definition of high clouds, we used the ISCCP's definition of 440 hPa, which is 6.8 km in the Tropics. A broken cloud at this altitude covering only 33% of the HIRS FOV has to have OD $\geq$ 0.4 to be detected. GLAS found 7% of the high clouds $\geq$6.8 km covered only 33% of the HIRS FOV. For the GLAS data an optical thickness is derived up to a limit of approximately OD ~3. However, we do not know what part of the small and optically diffuse (OD < 0.4) high clouds were missed by HIRS. Breon et al. (2005) found that optically thin clouds of OD < 0.2 occurred in 3%–4% of the GLAS data with a tropical maximum of 7.4%. The underreporting of small diffuse high clouds partially offsets the overreporting of high clouds (4%) owing to the large FOV size previously discussed. This is slightly less than our previous estimate of overreporting of high-altitude clouds by HIRS. The net result is that HIRS probably overreports high-altitude clouds by 2%–3%.

The SAGE FOV is much larger than for HIRS—1 km wide by 200 km long. GLAS found that 80% of clouds are <200 km. Liao et al. (1995) estimated the average size of clouds in the SAGE FOVs to be 75 km based on what adjustment for partial FOV coverage was needed to make SAGE's reported cloud frequency equal to the ISCCP. To adjust the SAGE data to the HIRS, which reports higher cloud frequencies, the size of clouds in the SAGE FOVs would have to be around 129 km following Liao et al.'s reasoning (Wylie and Wang 1997). The GLAS data confirm Liao et al.'s assumption that the cloud frequencies reported by SAGE are excessive. But, GLAS also indicates that mean cloud size is far smaller than the 75-km estimate of Liao et al. (1995) or the 129 km estimated by Wylie and Wang (1997).

The total coverage of clouds is more important to earth radiation budget studies than the frequency distribution of cloud sizes. To estimate what part of the total cloud cover comes from small versus large clouds, we looked at a statistic of the cloud dimension multiplied by its frequency. The cloud dimension is used as a surrogate for cloud area because the GLAS FOV is so narrow and does not sample across the orbit track. It samples continuously only in one dimension. The cloud dimension × frequency statistic indicates that one-half of the cloud coverage comes from clouds <1000 km in one dimension and one-half of the coverage is from the few clouds >1000 km (Fig. 8). While only 6% of the clouds are >1000 km, they account for one-half of the cloud coverage. For clouds above 6.6-km altitude, smaller clouds are more prevalent. One-half of the coverage coming from clouds <500 km (not shown).

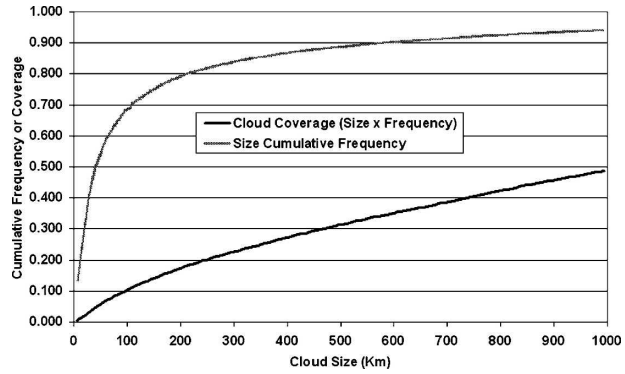

FIG. 8. A surrogate of the contribution of clouds by size to areal coverage.

7. Summary and conclusions

GLAS cloud observations show that the Wisconsin NOAA HIRS Pathfinder cloud analysis (Wylie et al. 2005) overreports cloud cover by 5%–10% in some geographic regions. Most of this error is overreporting of clouds in the lower troposphere and it is caused by both the characteristics of the HIRS sensor and the algorithm used to analyze the data. In the Arctic HIRS overreported clouds because of the strong low-level temperature inversion. The analysis algorithm incorrectly classified warm clouds in this inversion as being cloud free. The truey cloud free areas appear colder than these clouds and were incorrectly classified. The other source of error is the large FOV of the HIRS sensor. The GLAS data indicate that 7% of the HIRS data contain broken clouds below the HIRS FOV resolution, causing an overestimation of cloud cover by 3%. However, GLAS also reveals that very small and low-altitude clouds are missed by HIRS, which partially compensates for this adjustment by $\leq$1%.

For upper-tropospheric clouds the GLAS data mostly agreed with the HIRS. The GLAS found slightly more high cloud cover than HIRS by 4%–5%. The GLAS supports the primary purpose for running the Wisconsin NOAA HIRS Pathfinder analysis, which was detection and monitoring of upper-tropospheric clouds.

An additional comparison also was made of the coverage of semitransparent high clouds. In the GLAS data semitransparent clouds can be identified where

multiple cloud layers are reported and where ground also can be detected under clouds. HIRS identifies semitransparent clouds as having cloud-level temperatures colder than the blackbody radiances measured in the 11-μm window channel. Both systems found semitransparent clouds to be very frequent, covering 0.44 of the earth. This includes multiple-level clouds, which were 0.27 of the data (clear and cloudy combined), and situations in which the ground or ocean was seen through clouds, also occurring in 0.26 of the data. The more transparent clouds of optical depth <3 covered at least 0.26 of the earth globally and 0.35 of the Tropics.

The frequency of multilevel clouds reported by GLAS (0.27 coverage) is lower than the analysis of the LITE lidar data by Stubenrauch et al. (2005), which found 0.45 coverage. A study of radiosonde data by Wang et al. (2000) also reported multilevel coverage of 0.42, indicating that the GLAS statistic is low. This may due to its high spatial resolution.

Since both GLAS and HIRS can detect radiative transmission through clouds with visible optical depth roughly <3, we compared the coverage of these thinner semitransparent clouds reported by each system. GLAS found a coverage of 0.26 globally with a higher 0.35 coverage of the Tropics. HIRS reported higher values of 0.34 globally and 0.38 in the Tropics. While there is near agreement in the Tropics, there is a 33% disagreement in the global coverage. We cannot definitely describe the cause of the disagreement since our definition of OD < 3 as GLAS seeing the earth's surface through the cloud is only very approximate. For HIRS, some overreporting of transparent clouds comes from small holes below the FOV resolution of the sensor, which was previously discussed. Statistics on cloud sizes from GLAS estimate that HIRS overreports cloud cover by 3% and these clouds would be reported as semitransparent cloud cover in the HIRS data.

Upper-tropospheric semitransparent clouds, which have the greatest potential for causing warming similar to greenhouse gasses, were found to cover at least 0.14 of the earth and 0.25 of the Tropics by GLAS. HIRS overestimated the coverage of these clouds by 9%.

The average cloud heights reported by HIRS are below the cloud tops reported by GLAS, from 0.4 to 4.6 km. The largest differences are in the Tropics, 4.0 to 4.6 km, while smaller average differences of 0.4 to 1.9 km were found in midlatitudes. The GLAS also reported 5% more high cloud cover than HIRS over tropical oceans, which influenced the average cloud height statistic. In very cloudy regions of tropical oceans, the difference in reported high cloud cover is even higher: ~13%. HIRS is probably missing some of the thin high clouds, which are exceptionally high, and reporting cloud levels from denser clouds below them.

The average of the cloud top and base reported by GLAS has better agreement with the HIRS cloud level reports similar to the study of Stubenrauch et al. (2005). This is to be expected as the GLAS lidar cloud base report is not always the true cloud base where clouds are optically dense. It becomes an indication of the depth of the diffuse upper part of the cloud. The cloud level retrieved from the passive IR HIRS data is also sensitive to the same part of the cloud.

GLAS also shows that most clouds are small in the horizontal dimension. One-half are <42 km. But, considering their contribution to total cloud cover, small clouds have a lesser contribution than larger clouds. One-half of the cloud coverage comes from clouds >1000 km in size. Statistics on upper–tropospheric clouds show slightly smaller cloud sizes with one-half of the coverage coming from clouds >500 km.

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