Passive and active detection of clouds: Comparisons between MODIS and GLAS observations

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ABSTRACT

The Geoscience Laser Altimeter System (GLAS), launched on board the Ice, Cloud and Land Elevation Satellite in January 2003 provides space-borne laser observations of atmospheric layers. GLAS provides opportunities to validate passive observations of the atmosphere for the first time from space with an active optical instrument. Data from the Moderate Resolution Imaging Spectrometer aboard the Aqua satellite is examined along with GLAS observations of cloud layers. In more than three-quarters of the cases, MODIS scene identification from spectral radiances agrees with GLAS. Disagreement between the two platforms is most significant over snow-covered surfaces in the northern hemisphere. Daytime clouds detected by GLAS are also more easily seen in the MODIS data as well, compared to observations made at night. These comparisons illustrate the capabilities of active remote sensing to validate and assess passive measurements, and also to complement them in studies of atmospheric layers.

Introduction

Satellite observations of atmospheric layers have until recently relied solely on passive detection. The launch of the Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud and Land Elevation Satellite (ICESat) in January 2003 marks the advent of space-based laser profiling of the atmosphere and the planetary surface. Although primarily intended for altimetry studies of the polar ice sheets (Cohen *et al.*, 1987) ICESat data also provide a new atmospheric capability – in the form of continuous global measurements of vertical cloud structure and optical depth, planetary boundary layer height, and polar tropospheric and stratospheric clouds. These measurements have some advantages over passive data in detecting atmospheric layers that are either radiatively thin or comparable to the surfaces underlying them. These advantages are especially significant in the detection of cloud layers over snow- and ice-covered surfaces; the similarity of ice clouds to these surfaces at visible as well as infrared wavelengths constrains the usefulness of passive observations (Yamanouchi et al., 1987; King et al., 1992). Scattering of laser energy by air-borne particles leads to unambiguous detection of atmospheric layers; besides detecting layers that may be missed by passive sensors active detection also significantly reduces the uncertainties in the heights of atmospheric layers (Spinhirne, 1993). Passive detection techniques typically rely on reflectance variations at solar wavelengths and on temperature variations at infrared wavelengths (e.g. Ackerman et al., 1998, Smith and Frey, 1990, Han et al., 1999, Mahesh et al., 2001) – and uncertainties of hundreds of meters are typical, even in non-isothermal atmospheres. ICESat measurements of scattering layers, in contrast, are accurate to within 70 meters.

Spectral observations of clouds may also contain radiances from more than one atmospheric layer, leading to significant uncertainties in cloud properties obtained from them. Active profiling allows multiple layers to be distinguished from one another; when used together with spectral data, this allows radiance contributions from each layer to be separated.

The active observations made by GLAS are highly complementary to cloud studies based on spectral observations such as those made by MODIS. The unambiguous detection of atmospheric layers from coincident ICESat data presents significant opportunities, both for validation of passive measurements and for improved understanding of cloud layers using both types of data. In this paper, using measurements from a five-week period following the launch of ICESat we illustrate the potential for such comparisons, and suggest other avenues for similar research.

Data

Following ICESat's launch in January 2003 routine lidar measurements were available between February 21 and March 29. Orbiting at 600 km above the earth, ICESat's near-polar path (94° inclination) regularly passes under the sun-synchronous orbits of the Aqua and Terra satellites, both of which carry MODIS instrumentation and whose orbiting elevations are approximately 100 km higher. The MODIS footprint swath is 2500 km; in comparison the GLAS footprint – 60 meters each, 175 meters apart– is miniscule, and ICESat will typically remain within the MODIS swath for more than two minutes during each underpass. For this analysis, however, only those GLAS measurements were selected that were taken when ICESat was within 400 km of the direct nadir point of Aqua or Terra.

Figure 1 shows ICESat tracks during times of overlap with Aqua during the five-week period. Since both satellites are polar orbiters more numerous crossings occur nearer the poles; during the period crossings that met the selection criteria occurred at latitudes north of 35 N and south of 35 S. Because of this spread of latitudes, Aqua observations likely include data over several kinds of surfaces – land, ocean, snow and ice. Terra-ICESAT coincidences (not shown), on the other hand, occurred only at latitudes north of 70 N or south of 70 S, and are likely to be almost entirely over snow and ice surfaces.

In all, 99 periods of simultaneous GLAS-Aqua observations were available, and on average the two observing platforms remained within 400 km of each other for 40 seconds during such coincident times. The Terra-ICESat observations were fewer (24) in number but their coincident periods averaged 72 seconds, nearly twice the average period of coincidence between ICESat and Aqua. These periods of simultaneous observations from ICESat-Aqua and ICESat-Terra occur as the satellites travel in opposite directions (i.e. an ascending orbit coinciding with a descending one) as well as in similar directions (i.e. both ascending or descending orbits). The fewer incidences of ICESat-Terra crossings and the longer average period of coincident observations for this pair results from a higher proportion of crossings that occur as the two satellites are traveling in similar directions whereas more of the ICESat-Aqua coincidences occur as the two satellites pass each other in opposing orbits.

GLAS atmospheric measurements are available from an observing channel at 1064 nm that uses an Avalanche Photo Diode detector with a 0.1 nm band-pass filter and a 450 μrad field of view (Palm *et al.*, 2001). The technique used to locate the occurrence of clouds using the GLAS 1064 data is based on a simple threshold detection scheme. The raw GLAS data are first averaged to 5 Hz (the fundamental data collection frequency is 40 Hz below 10 km altitude and 5 Hz above that height) and threshold detection is applied to the profile, beginning at a height of 16 km and ending approximately 400 m above the surface. The 400 m cutoff in the search algorithm was used to ensure that a ground return would not be mistakenly identified as a cloud. If three consecutive bins show a backscatter cross section in excess of 5.0×10^{-6} m^{-1}-sr^{-1} then a cloud is considered to exist at that height. The vertical resolution of the GLAS data is 76.8 m; this technique would therefore not capture cloud layers geometrically thinner than about 230 m. For a cloud of this thickness with an average backscatter cross-section just above the threshold value, we can calculate the approximate minimum layer optical depth that can be detected with this algorithm. Using an extinction-to-backscatter ratio of 30, this minimum detectable optical depth is about 0.04. Also, this algorithm will miss clouds whose tops are below 400 m altitude.

For GLAS and MODIS coincident locations cloud observations are extracted from the Collection 4 MODIS Cloud Mask product (MOD35). The MODIS observations take the form of a percentage likelihood of a non-clear scene (Ackerman et al., 2002) While this usually indicates a cloud in the scene it is important to note that this is not necessarily the case; occasionally thick aerosol, dust and other contaminants can be the source of the non-clear determination of the cloud mask. Visual confirmation of the cloud comparisons is performed for a subset of cases by comparison with the high-resolution MODIS 250-meter and 500-meter visible reflectance observations.

Comparisons between the different observing techniques used with ICESat and MODIS data must first address the differences in the reported data themselves. GLAS, as noted above, reports layers wherever scattering of laser energy passes its threshold of detection. MODIS, on the other hand, reports a 'probability that a given scene of passive observations is of clear-sky conditions". Plainly, these are quite different quantities; for our comparisons we classified the MODIS and ICESat observations as follows to make them more easily comparable. Where MODIS reported a 95% or greater probability of clear-sky conditions, we assumed that the scenes observed were 'clear'; where MODIS reported a lower (66% or less) probability of clear skies, we assumed that the scenes included clouds. When at least one of the 5 observations (per second) from GLAS was of cloud, we assumed that GLAS observations were 'cloudy'; else (i.e. when the 5 Hz data recorded no scattering whatsoever) the data were classified as 'clear'.

Other classification schemes are possible; it can be argued, for instance, that only those cases where MODIS data are reported to be either 99% clear or 0% percent clear should be included in our analysis. Such extreme filters, however, would be less useful in evaluating the scene classification measures used in MODIS processing algorithms.

Comparisons

A histogram of the four possible combinations in our comparisons (see figure 2) shows that Aqua classifications of observed scenes largely agree (2a) with findings from ICESat. The two combinations that indicate agreement (clear-clear, and cloud-cloud) together account for 77% of the total. A number of the periods of overlap between the two platforms are from the coastal Antarctic region, which is among the cloudiest places on the planet. Understandably, therefore, the observations that agree are dominated by instances where both GLAS and Aqua detect clouds. In 15% of the cases, GLAS measurements indicate the presence of clouds whereas the Aqua observations do not, and in 8% of the cases, Aqua observations are found to be 'cloudy' whereas GLAS finds no atmospheric scattering layer.

The disagreement between observations from the two platforms is greater in the case of ICESat-Terra (2b). Here, in 56% of the cases, both ICESat and MODIS find similar conditions, whereas they disagree 44% of the time. Unlike the Aqua observations, which were made during a wide range of solar zenith angles, the data from Terra are nearly all taken from regions very close to the day-night termination. MODIS scene classifications for pixels were based on the local solar zenith angle. Values lower than 84^{o} were treated as sunlit; as a result of this 'night' bias nearly 2/3 of the Terra data were classified as nighttime observations, whereas the Aqua data were evenly split between day and night observations. MODIS scene classifications are more uncertain at night, since they must rely on fewer spectral channels of data; this could account for the higher disagreement between GLAS and Terra than is the case with Aqua.

Note also that the disagreement is dominated by instances where ICESat does not detect a 'cloud' reported by MODIS. Coincidences between ICESat and Terra during this period were confined to the extreme high latitudes, and over the snow and ice covered surfaces typical of these regions, MODIS scene identification algorithms can have difficulty distinguishing clouds from their underlying surfaces.

The effect of uncertainties resulting from surfaces spectrally similar to clouds can be studied using the Aqua observations; if we treat 'latitude' as a reasonable proxy for the presence of surface snow and/or ice, we should expect that scenes identified from the mid-latitude coincidences of ICESat-Aqua should show greater disagreement than scenes over the higher latitudes. Figure 3 shows the fraction of observations from each 1-degree latitude bin that was classified into the four combinations. Nearly all the observations from the southern mid-latitudes are of clouds; as a result comparisons of the two observations in this hemisphere do not show any significant dependence on latitude. In the northern hemisphere, however, there appears to be some sensitivity to latitude; a broad zone of disagreement (oranges and reds, indicating cloud-clear and clear-cloud combinations of ICESat-Aqua classifications respectively) is seen north of 50 N.

Also, MODIS scene classifications of sunlit observations are more robust than those of nighttime data. In the absence of solar radiation – and therefore, reflection by surfaces that receive it – scene classifications must rely wholly on the infrared channel on MODIS, leading to higher uncertainties. The distributions seen in figure 2 are separated into 'day' and 'night' observations in figure 4; the upper panels (a, d) are identical to figure2; this data is separated into its day (b, e) and night (c, f) constituents in the middle and lower panels. The benefit of additional spectral information in daytime observations is apparent; whereas under sunlit conditions 91% of the coincident ICESat-Aqua points show agreement (either cloud-cloud or clear-clear), at night nearly 37% of the observations show disagreement between the two platforms. Also, while mismatches of either kind (clear-cloud or cloud-clear) are just as common in daytime observations, at night MODIS reports of 'clouds' unseen by GLAS are twice as common as GLAS observations of clouds unreported by MODIS.

This difference is less evident in the ICESat-Terra coincident observations (about 60% of daytime data and 54% of night-time observations show agreement between the two satellites), but it is possible, as mentioned above, that MODIS scene classifications themselves are less reliable at the extreme high latitudes and 'near-night' conditions in this dataset.

Conclusions

Unambiguous layer detection by active sensing provides opportunities to validate MODIS algorithms used with passive observations. A comparison between scene identification algorithms used with Aqua spectral data and a threshold technique used to detect cloud layers in GLAS observations, agrees more than 75% of the time over a large range of latitudes. Disagreement is higher in nighttime observations than in day, and also over snow-covered latitudes in the northern hemisphere. Similar conclusions can also be drawn from coincidences between ICESat and Terra, but less forcefully; this may be partly due to the fact that these observations are limited to narrow high-latitude belts. These comparisons illustrate the potential for active atmospheric profiling to validate techniques used with passive observations, and to assess their performance under different conditions. With the expected availability of data from the higher resolution (532 nm) channel on ICESat beginning in the second half of 2003, these comparisons can be more closely studied for extremely optically thin clouds, which may be missed at 1064 nm. Similar to observations of cloud occurrence, other MODIS products such as cloud heights, optical depths, etc., as well as similar products from other platforms such as the Advanced Very High Resolution Radiometer [AVHRR] can be validated and complemented with ICESat measurements. When a longer time series of data from ICESat becomes available, as is expected beginning in the second half of 2003, such multi-platform studies will become possible.

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List of Figures

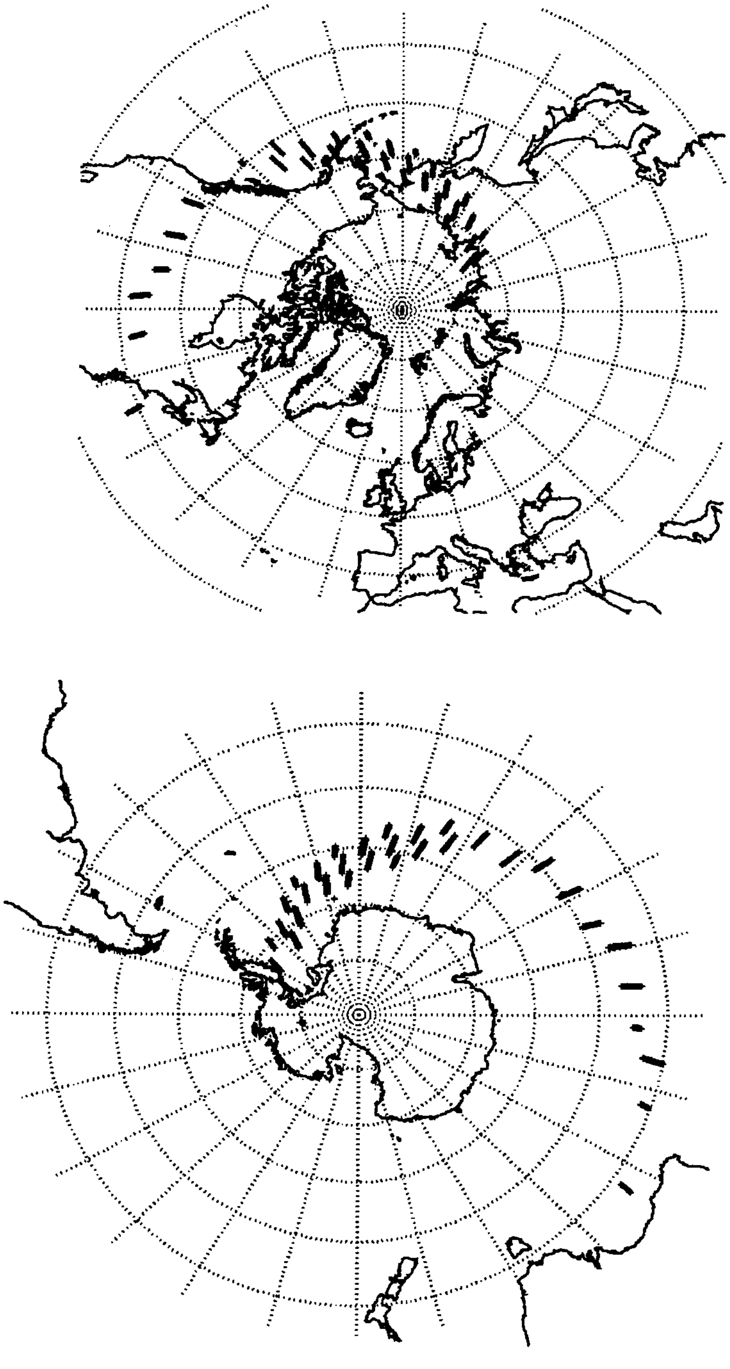


Figure 1

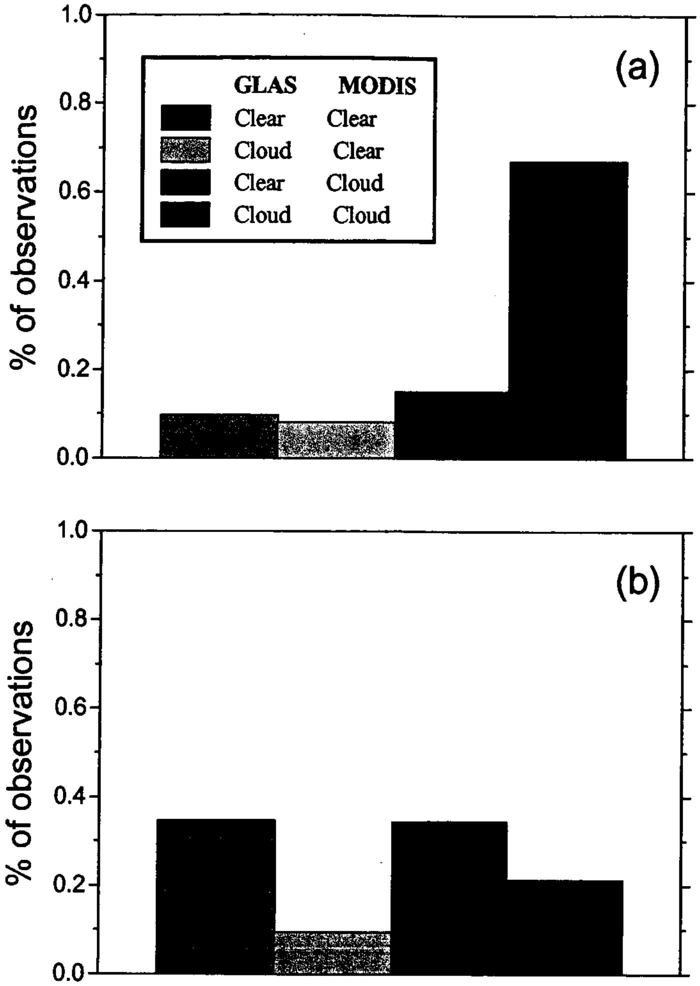

1.0
0.8
0.6
0.4
0.2
0.0
% of observations
(a)
GLAS
MODIS
Clear
Clear
Cloud
Clear
Clear
Cloud
Cloud
Cloud
(b)

Figure 2

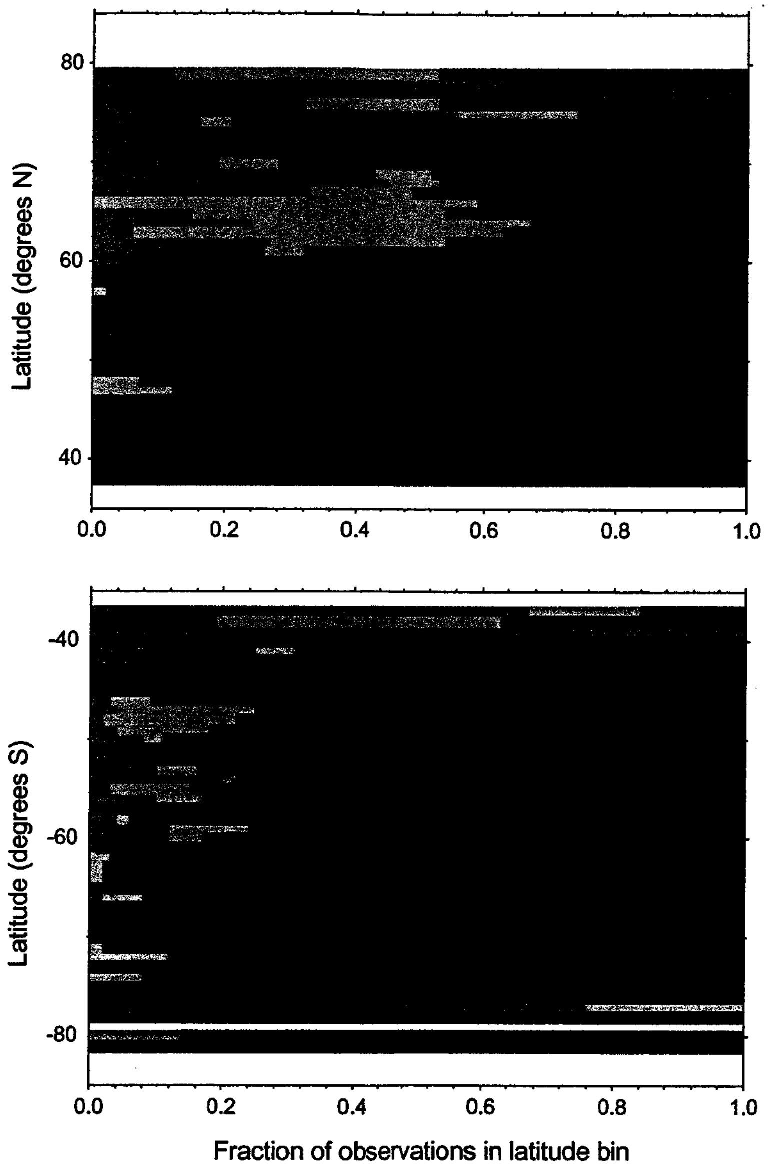
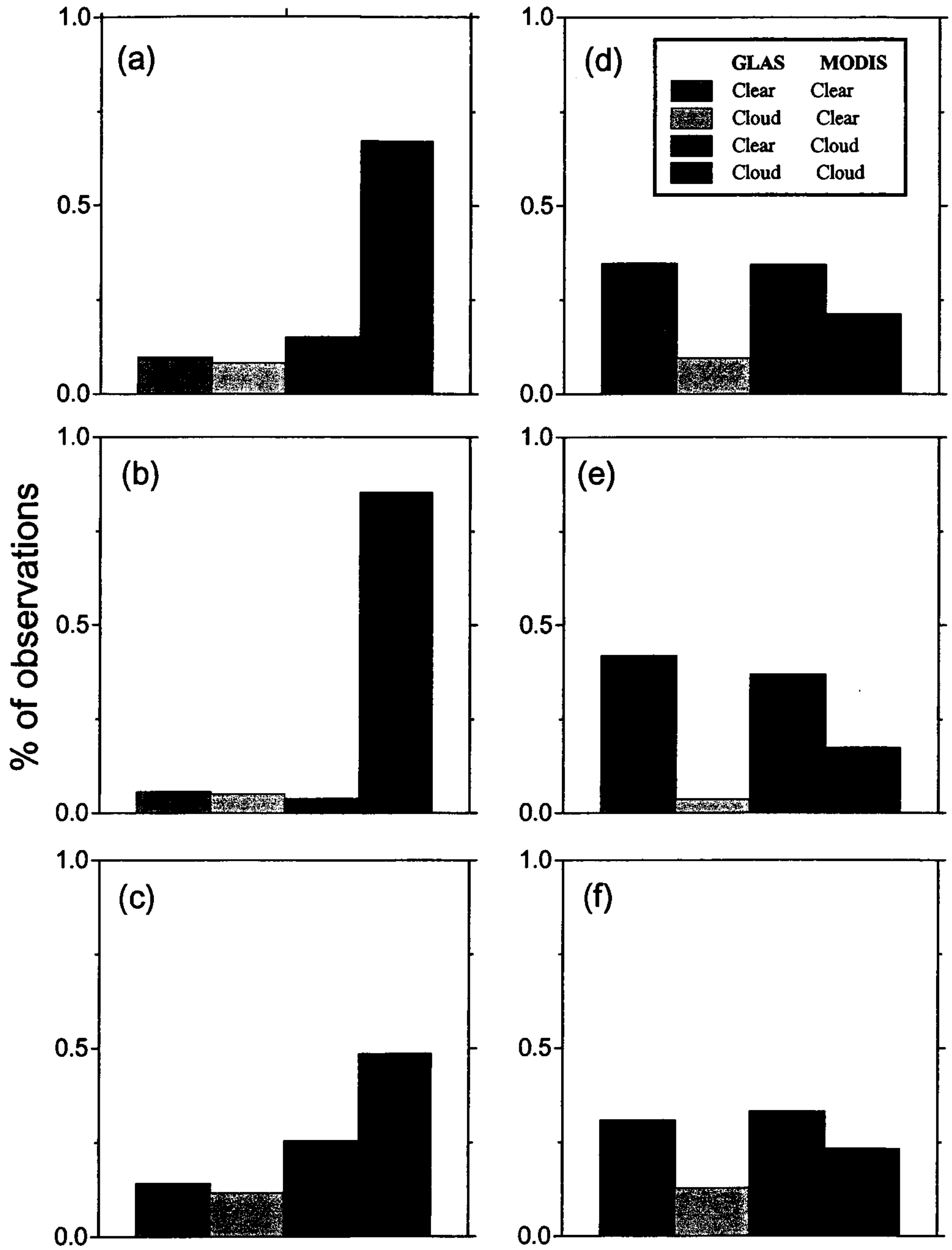

80
60
40
Latitude (degrees N)
0.0
0.2
0.4
0.6
0.8
1.0
-40
-60
-80
Latitude (degrees S)
0.0
0.2
0.4
0.6
0.8
1.0
Fraction of observations in latitude bin

Figure 3



% of observations
(a)
(b)
(c)
(d)
(e)
(f)
1.0
0.5
0.0
GLAS MODIS
Clear Clear
Cloud Clear
Clear Cloud
Cloud Cloud

Figure 4