Validation of ECMWF global forecast model parameters using GLAS atmospheric channel measurements

Stephen P. Palm,[1] Angela Benedetti,[2] and James Spinhirne[3]

Received 17 May 2005; revised 14 July 2005; accepted 17 August 2005; published 20 September 2005.

[1] Satellite lidar (LIght Detection And Ranging) data from GLAS is used to ascertain the performance of the European Center for Medium Range Weather Forecasts model predictions of cloud fraction, cloud vertical distribution, and boundary layer height. Results show that the model is reasonably accurate for low and middle clouds, but often misses the location and amount of high cirrus clouds. The model tends to overestimate high cloud fraction and this error grows with forecast length. The GLAS-derived boundary layer height over the oceans is generally 200–400 m higher than the model predictions, but small-scale and global patterns of PBL height show similar features. **Citation:** Palm, S. P., A. Benedetti, and J. Spinhirne (2005), Validation of ECMWF global forecast model parameters using GLAS atmospheric channel measurements, *Geophys. Res. Lett.*, *32*, L22S09, doi:10.1029/2005GL023535.

1. Introduction

[2] In January 2003 the Geoscience Laser Altimeter System (GLAS) was launched into a near-polar orbit aboard the Ice Cloud and land Elevation Satellite (ICESat) [*Zwally et al.*, 2002]. In addition to a high resolution 1064 nm altimetry channel, GLAS contains both 1064 and 532 nm atmospheric backscatter lidar channels. The 532 nm atmospheric channel has been operating since September 25, 2003 providing unprecedented views of the vertical structure of atmospheric aerosol, cloud layers and the depth and structure of the planetary boundary layer (PBL) [*Spinhirne et al.*, 2005]. The high vertical (76 m) and horizontal (175 m) resolution of the GLAS data provide accurate measurements of cloud height and vertical structure, tropopause height and Planetary Boundary Layer (PBL) height. These measurements constitute a valuable data set for the validation of global weather forecast and climate models. Clouds play an integral role in the climate system, primarily through their role as modulators of radiative transfer and their contribution to diabatic heating. The accurate representation of clouds in these models is, therefore, extremely important. However, it is difficult, if not impossible, to verify its forecasts of cloud extent and coverage, especially in the vertical. Similarly, PBL height is an important model parameter that is difficult to validate due to a lack of global observations.

[3] GLAS represents a unique opportunity to verify cloud field forecasts of various models such as the European Center for Medium-range Weather Forecasts (ECMWF) forecast model. Using an approach similar to the method presented here, *Miller et al.* [1999] validated ECMWF model output of cloud height and coverage using limited data from the shuttle Lidar In-space Technology Experiment (LITE). *Randall et al.* [1998] compared boundary layer height derived from the LITE data with output from the Colorado State University atmospheric general circulation model as well as the National Center for Atmospheric Research (NCAR) Community Climate Model 3 (CCM3). In this paper we demonstrate the utility of GLAS data for the verification of global ECMWF output fields of cloud height, fraction and PBL height. As orbiting lidar data from the ICESat Mission, CALIPSO [*Winker et al.*, 2003] and The Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus) [*Duran et al.*, 2004] and those to follow become commonplace, the value for not only model validation but also for data assimilation will greatly increase.

2. Data and Methodology

[4] The ECMWF spectral model contains a sophisticated cloud scheme that is highly regarded within the scientific community [*Jakob*, 2003]. It uses triangular truncation at wave number 511 (roughly 40 km resolution) and has 60 model levels in the vertical. This is a slight increase in resolution compared to the version of the ECMWF model used by *Miller et al.* [1999] in their analyses (60 $\times$ 60 km horizontal with 31 vertical levels). The GLAS data utilized for this study are the vertical cross-sections of calibrated attenuated backscatter along the ICESat ground track (GLA07) [*Spinhirne et al.*, 2005]. The 5 Hz data were first averaged to a 5 second horizontal resolution (35 km), and the 5s orbital position data were then supplied to ECMWF for a number of ICESat orbits. ECMWF 6 and 48 hour global forecasts were run such that the verification times are within 3 hours of the given ICESat orbit. The ECMWF forecast fields were extracted from the output grid box that intersects with the ICESat orbit. The ECMWF data consist of vertical profiles of the prognostic fields at each of 60 model pressure levels ranging from the surface to the 0.1 mb level, where each pressure surface corresponds to a specific geometric height. Linear interpolation was then used to vertically interpolate the ECMWF cloud fraction from the model levels to the vertical grid defined by the GLAS data (every 76 m) starting at sea level and extending to an altitude of 20 km. After this process is completed, the two data sets are vertically aligned and can be compared in a number of ways. Note that in the analysis presented here, no consideration is being made for the fact that we are comparing a thin cross-section through the atmosphere with

[1]Science Systems and Applications Inc., Lanham, Maryland, USA.
[2]European Center for Medium Range Weather Forecasts, Reading, UK.
[3]Goddard Space Flight Center, Greenbelt, Maryland, USA.

0094-8276/05/2005GL023535$05.00

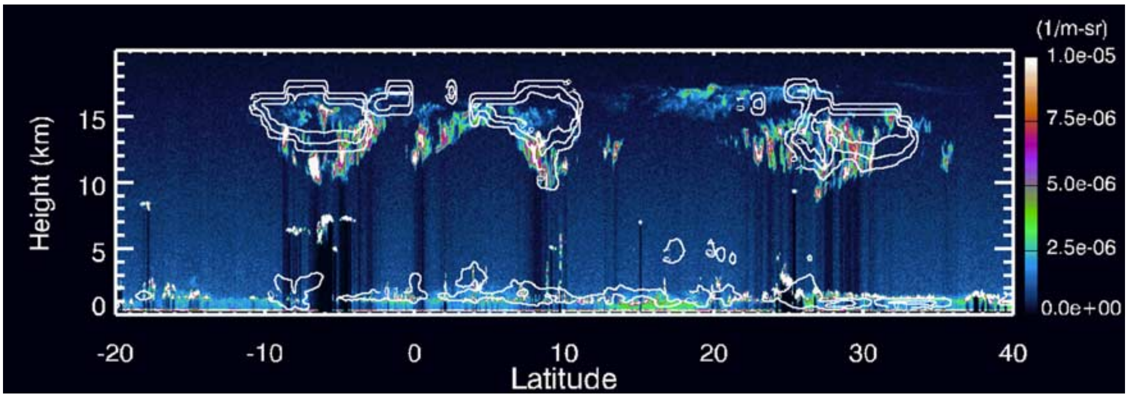

Figure 1. GLAS attenuated, calibrated backscatter data (GLA07, $m^{-1}sr^{-1}$), with the ECMWF 6-hour forecast contours of cloud fraction overlaid. The contour values are 0.9 (inner-most), 0.5 and 0.1. The data span about 7000 km along ICESat track number 52 over the tropical Pacific Ocean (near longitude 160E) on October 1, 2003 beginning at 08:10 UTC.

an ECMWF grid box, which represents a vertical column of the atmosphere with cross-sectional dimension of 40 km by 40 km.

3. Cloud Height and Fraction

[5] An example of the vertically interpolated ECMWF cloud fraction superimposed on the corresponding GLAS backscatter data is shown in Figure 1, which is an ICESat orbit segment over the tropical Pacific Ocean from track number 52. The figure shows the 532 nm attenuated backscatter cross-section ($m^{-1}sr^{-1}$) along the track. There are a wide variety of cloud types in this region ranging from marine stratus and stratocumulus to cumulonimbus and cirrus. Also shown in Figure 1 is the ECMWF cloud fraction (6-hour forecast) contoured at the 0.1, 0.5 and 0.9 levels. Thus, the inner contour (0.9) gives a good indication of where nearly solid cloud cover exists within the model. Some general observations are that the model does an excellent job of predicting low cloud location and extent, but has somewhat more trouble with the higher clouds. Note in particular the cirrus clouds between roughly 16–18 km altitude and 20N that are not present in the ECMWF forecast. A large area of clouds between 13 and 16 km near the equator is also not captured by the model forecast.

[6] A threshold algorithm has been applied to the GLAS data in Figure 1 to locate all cloudy pixels in the image. For each height level a cloud fraction is obtained by counting all cloudy pixels at that height and dividing by the total number of pixels in the image. The resulting cloud fraction as a function of height is shown in Figure 2 as the dark solid line. Also plotted is the ECMWF cloud fraction for the same time span for the ECMWF 6-hour (dashed line) and 48-hour forecasts. A number of things are evident from Figure 2. First, the forecasted cloud amount is much better for low clouds than for high clouds, regardless of the forecast length. However, it should be noted that in general, the GLAS retrievals will under-report the occurrence of low cloud because of those cases where the signal is totally attenuated by thick, higher clouds. In this particular example, total attenuation of the signal does not occur often, thus limiting the effect to less than10 percent. While the top height of the highest clouds is well forecast, the ECMWF high cloud amount tends to be too large for both forecasts, but especially so for the 48-hour forecast. This is similar to the results of *Beesley et al.* [2000], who compared radar-derived cloud amount with the ECMWF cloud fraction in the Arctic.

[7] To better assess the performance of the ECMWF model forecasts of cloud fraction, an objective skill score analogous to *Miller et al.* [1999] was developed. The cloud threshold algorithm is applied to a given segment of GLAS data (similar to that shown in Figure 1) to obtain the true cloud field distribution. For this segment we set all cloudy pixels to a value of 1 and all others to 0. For the ECMWF data, the pixels with cloud fraction > 0.50 are set to 1 and all others to 0. Where pixels match in value we call a hit, where they differ in value it is called a miss. The skill score is then defined as: Σ (hits-misses)/total pixels. The results of this procedure applied to half an orbit of data are listed in

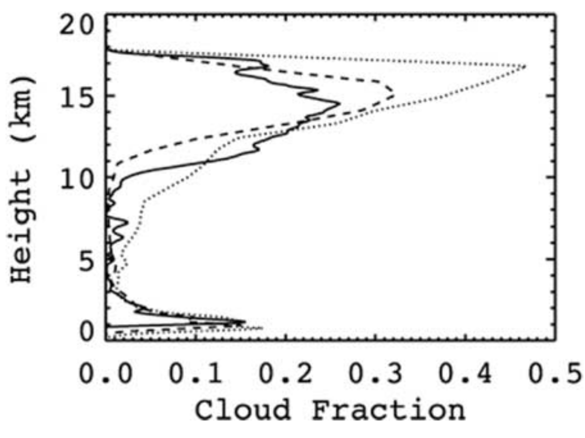

Figure 2. The GLAS measured (solid line) and ECMWF 6 and 48 hour forecasts (dashed and dotted lines, respectively) of cloud fraction as a function of height for a typical data segment (7000 km) over the tropical Pacific Ocean that is comprised mainly of cirrus and boundary layer clouds.

Table 1. The ECMWF 6 Hour (Middle Column) and 48 Hour Forecast Skill Scores for Data Comprising Half of an ICESat Orbit[a]

	6 Hour	48 Hour
GLAS Cloud ECMWF Cloud	3.0%	3.1%
GLAS Clear ECMWF Clear	87.0	84.0
GLAS Cloud ECMWF Clear	3.4	3.2
GLAS Clear ECMWF Cloud	6.6	9.7
Skill Score	80.0	74.2

[a]The numbers represent the percentage of time the condition listed in column one occurs and the skill score is described in the text.

Table 1 and show a decrease in cloud fraction skill score with length of forecast, as expected. The decrease in skill score is caused mainly by the model over-prediction of cloud amount in the 48-hour forecast.

4. Boundary Layer Height

[8] Another important output parameter from the ECMWF model that can be validated using the GLAS data is boundary layer height. The GLAS PBL height algorithm looks for the first gradient (decrease) of scattering, searching from the ground upwards. In general, the PBL is capped by a temperature inversion which tends to trap moisture and aerosol within the PBL. The gradient of backscatter seen by lidar is almost always associated with this temperature inversion and simultaneous decrease in moisture content [*Palm et al.*, 1998; *Melfi et al.*, 1985]. Thus, the definition of PBL top as being the location of maximum aerosol scattering gradient is analogous to the more conventional thermodynamic definition. The ECMWF model defines the top of the PBL as the level where the bulk Richardson number, based on the difference between quantities at that level and the lowest model level, reaches the critical value of 0.25. The bulk Richardson number is essentially the ratio of stability to vertical wind shear and may reach this critical value at a height somewhat below the PBL top as defined by other means.

[9] An example of the comparison of ECMWF PBL height (black line) with GLAS (yellow line) for a 7,000 km long segment of data over the tropical Pacific Ocean is shown in Figure 3. The data are from October 1, 2003, ICESat track number 52. The image of backscatter clearly reveals a layer of enhanced aerosol scattering generally below 1–2 km. This is the marine boundary layer. Occasionally this layer contains small, broken cumulus clouds at the top. Sometimes mid or higher level clouds attenuate the lidar return so as to block the signal from within the PBL. This makes retrieval of PBL height from the GLAS data in these regions impossible. The GLAS-derived PBL height is shown as the yellow line that generally follows the largest gradient of backscatter. There is considerable variability to the GLAS PBL heights, with an average and standard deviation of 1310 and 440 m, respectively. Conversely the ECMWF data shows much less variability with a mean of 862 m and standard deviation of 200 m. Comparison of the GLAS retrieval with the ECMWF model prediction reveals a noticeable correlation, but the latter are on average nearly 450 m lower. This is similar to the findings of *Randall et al.* [1998], who found that the CCM3 boundary layer heights were generally 300–400 m lower than LITE-derived PBL heights. However, a second model (Colorado State Atmospheric GCM) produced PBL heights very close to those derived from the LITE data.

[10] In Figure 4a we have used GLAS PBL height data for the month of October 2003 to generate a global map of the distribution of average PBL height over the oceans. In Figure 4b, ECMWF 6 -hour forecasts of PBL height for each day of October were averaged to produce a global map of ECMWF average PBL height for the month. Referring to the GLAS PBL height over oceans in Figure 4a, we can immediately see a number of prominent features. First, there are repeated and distinct minima in PBL height to the west of major continents, especially Africa and South and North America. These minima, which are also seen in the ECMWF data, are regions of persistent, low marine stratus clouds that occur over cool, upwelling waters. The minima to the west of South America extends further west close to the equator in a rather narrow band and then still further west, this minima seems to fan out and encompass a larger area of the far west Pacific, north of New Guinea. This pattern is also seen in the ECMWF data, but the minima appear to be

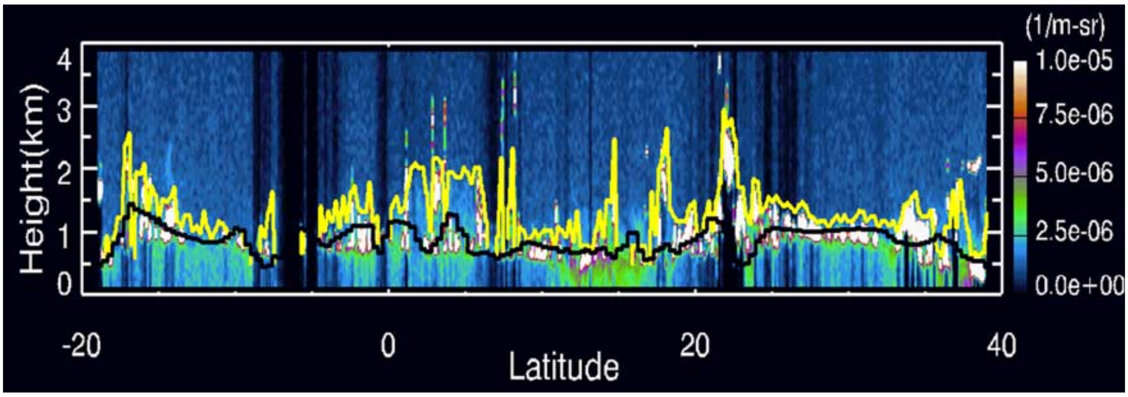

Figure 3. GLAS attenuated backscatter (GLA07) showing the PBL height derived from the GLAS standard processing algorithms (yellow) and the ECMWF model 6-hour PBL height forecast (black) for ICESat track number 52 over the Pacific Ocean on October 1, 2003 at roughly 08:00 UTC.

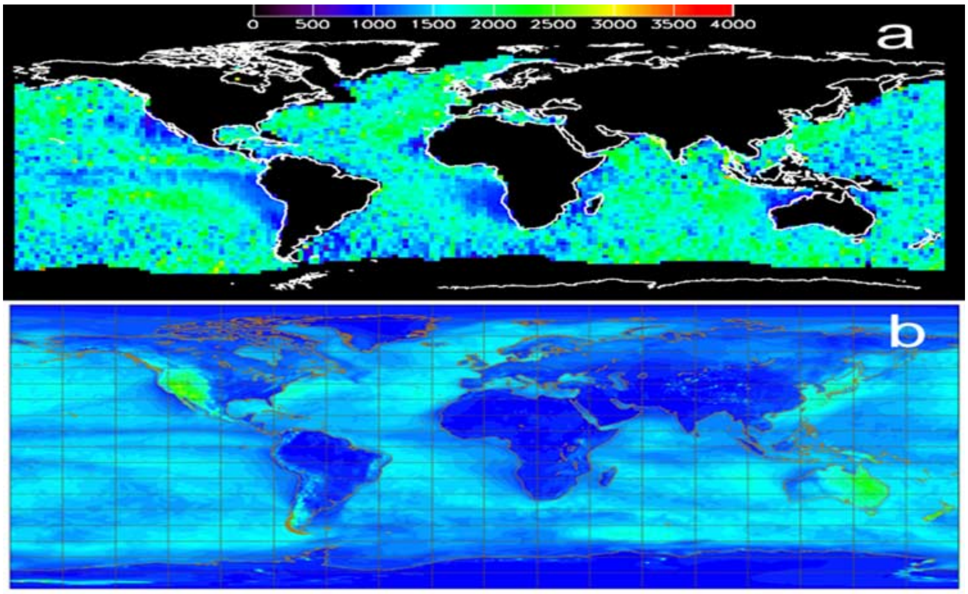

Figure 4. (a) The GLAS-derived boundary layer height for October 2003 and (b) the ECMWF model 6-hour PBL height forecast (valid 00 UTC) averaged over the month of October 2003. The height scale in meters, valid for both Figures 4a and 4b, is given at the top of Figure 4a.

centered at about 10 N. Other features can be seen in both data sets such as the relatively high PBL heights off the east coast of North America and Asia, and the west coast of Europe, with somewhat lower values in the central Atlantic. Also, note the region of higher PBL height southwest of Chile and west of Australia.

5. Summary and Conclusion

[11] Orbiting lidars such as GLAS provide the capability of obtaining high resolution vertical cross-sections of atmospheric structure. This ability enables the unambiguous global determination of cloud top height, cloud bottom height (for clouds of optical depth < 3–4), multi-layer cloud structure and PBL height. These measurements are valuable as verification measurements for general circulation and climate models that are difficult, if not impossible, to obtain otherwise. GLAS measured cloud height and extent was compared with 6- and 48-hour ECMWF forecast output of cloud fraction. From these preliminary and limited comparisons, it was discovered that the ECMWF does a reasonably good job for low and middle clouds but often misses the location and amount of high cirrus clouds. ECMWF overestimates high cloud fraction and this error grows with forecast length. However, it was found that ECMWF forecast of cloud top height for high clouds was very good and independent of forecast length. The work presented here demonstrates the utility of satellite lidar data for model verification and points to the need for further work that uses additional data to generate more substantial and quantitative results.

[12] The boundary layer height comparison revealed that in general the model PBL height is 200–500 m lower than the PBL height as discerned from GLAS data using the maximum scattering gradient as the definition of PBL top. This could be at least partly due to the way in which the ECMWF model defines PBL top (using Richardson number). Regardless, it was seen that the relative changes of PBL height seemed to be correlated with like changes in PBL depth as measured by GLAS. This phenomenon is very interesting and could be the result of the model assimilation of sea surface wind data from orbiting scatterometers. Wind speed is a primary driver of PBL height and structure over the ocean and since the ECMWF is ingesting these surface wind speeds, it could explain this correlation. In addition, GLAS average PBL height measurements for the month of October 2003 were mapped to a global grid and compared with ECMWF average PBL height for the same period. Striking similarity was seen in the overall PBL height pattern over oceans. The PBL height measurements from GLAS represent the first such measurement obtained globally from a space-borne remote-sensing instrument.

[13] **Acknowledgment.** We thank NASA's ICESat Science Project and the NSIDC for distribution of the ICESat data, see http://icesat.gsfc.nasa.gov and http://nsidc.org/data/icesat.

References

Beesley, J. A., C. S. Bretherton, C. Jakob, E. L. Andreas, J. M. Intrieri, and T. A. Uttal (2000), A comparison of cloud and boundary layer variables in the ECMWF forecast model with observations at the Surface Heat Budget of the Arctic Ocean (SHEBA) ice camp, *J. Geophys. Res.*, *105*, 12,337–12,349.

Duran, Y., S. J. Culoma, R. Meynart, D. Morancais, F. Didier, and F. Fabre (2004), Predevelopment of a direct detection Doppler wind lidar for ADM/AEOLUS mission, *Proc. SPIE Int. Soc. Opt. Eng.*, *5234*, 354–363.

Jakob, C. (2003), An improved strategy for the evaluation of cloud parameterizations in GCMS, *Bull. Am. Meteorol. Soc.*, *84*, 1387–1401.

Melfi, S. H., J. D. Spinhirne, S.-H. Chou, and S. P. Palm (1985), Lidar observations of vertically organized convection in the planetary boundary layer over the ocean, *J. Clim. Appl. Meteorol.*, *24*, 806–821.

Miller, S. D., G. L. Stephens, and A. C. M. Beljaars (1999), A validation survey of the ECMWF prognostic cloud scheme using LITE, *Geophys. Res. Lett.*, *26*, 1417–1420.

Palm, S. P., D. Hagan, G. Schwemmer, and S. H. Melfi (1998), Inference of marine atmospheric boundary layer moisture and temperature structure using airborne lidar and infrared radiometer data, *J. Appl. Meteorol.*, *37*, 308–324.

Randall, D. A., Q. Shao, and M. Branson (1998), Representation of clear and cloudy boundary layers in climate models, in *Clear and Cloudy Boundary Layers*, edited by A. A. M. Holtslag and P. G. Duynkerke, pp. 305–322, R. Neth. Acad. of Arts and Sci., Amsterdam.

Spinhirne, J. D., S. P. Palm, W. Hart, D. Hlavka, and E. J. Welton (2005), Cloud and aerosol measurements from the GLAS: Overview and initial results, *Geophys. Res. Lett.*, doi:10.1029/2005GL023507, in press.

Winker, D. M., J. Pelon, and P. M. McCormick (2003), The CALIPSO mission: Spaceborne lidar for the observation of aerosols and clouds, *Proc. SPIE Int. Soc. Opt. Eng.*, *4893*, 1–11.

Zwally, H. J., et al. (2002), ICESat's laser measurements of polar ice, atmosphere, ocean, and land, *J. Geodyn.*, *34*, 405–445.

S. P. Palm, Science Systems and Applications Inc., Lanham, MD 20706, USA. (spp@virl.gsfc.nasa.gov)

A. Benedetti, European Center for Medium Range Weather Forecasts, Shinfield Park, Reading, Berkshire RG2 9AX, UK. (angela.benedetti@ecmwf.int)

J. Spinhirne, Goddard Space Flight Center, Greenbelt, MD 20771, USA. (jspin@virl.gsfc.nasa.gov)