6.6 VALIDATION OF ECMWF GLOBAL FORECAST MODEL PARAMETERS USING THE GEOSCIENCE LASER ALTIMETER SYSTEM (GLAS) ATMOSPHERIC CHANNEL MEASUREMENTS

Stephen P. Palm[1] and David Miller
Science Systems and Applications Inc. Lanham, Md.
Angela Benedetti
European Center for Medium Range Weather Forecasts Shinfield Park, Reading, Berkshire RG2 9AX, UK
James Spinhirne
Goddard Space Flight Center, Greenbelt, Md.

1. INTRODUCTION

In January 2003 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 altimetry channel, GLAS contains both 1064 and 532 nm atmospheric backscatter lidar channels. The photon counting 532 channel has been operating since fall of 2003 providing incredible views of the vertical structure of atmospheric aerosol, cloud layers and the depth and structure of the planetary boundary layer (PBL) (Spinhirne et al., 2004). The high vertical and horizontal resolution of the GLAS data provide very accurate measurements of cloud height and vertical structure, tropopause height and PBL height. These measurements constitute a unique and valuable data set for the validation of global weather forecast and climate model output. The accurate representation of clouds in these models is extremely important. 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 European Center for Medium-range Weather Forecasts (ECMWF) model contains a sophisticated cloud scheme that is highly regarded within the scientific community (Jakob, 2003). However, it is very difficult if not impossible to verify the forecasts of cloud extent and coverage, especially in the vertical. In fact, the direct verification of the vertical distribution of cloud cover simply cannot be done. Verification at scattered points can be made with ground based instruments such as radar (Mace et al. 1998) or satellite observations of cloud cover can be used to ascertain the presence of cloud at a particular location (Lau and Crane, 1995). However, none of these methods can unambiguously verify cloud height and vertical extent on a global basis. Space borne lidar such as GLAS represents a unique opportunity to obtain the vertical distribution of global cloud cover thus providing the ability to verify cloud field forecasts of various models such as ECMWF.

The ECMWF model produces output fields of boundary layer height, cloud height and others that can be directly validated by comparison with the GLAS data. This type of forecast model verification has been used by Randall et al. (1998) to validate ECMWF model output of boundary layer height and Miller et al. (1999) to validate cloud height and coverage using data from the Lidar In-space Technology Experiment (LITE). In this paper we demonstrate the utility of GLAS data for the verification of global ECMWF output fields of cloud height and PBL height. As orbiting lidars such as GLAS and CALIPSO (2005 launch) and those to follow become more commonplace, the value of their data for not only model validation but assimilation will greatly increase.

2. METHOD

The GLAS data utilized for this study are the vertical cross sections of calibrated attenuated backscatter along the orbit track. The data are first averaged to a 5 second horizontal resolution (35 km) and the orbital position data are supplied to ECMWF personnel for a number of GLAS orbits. ECMWF 6, 24 and 48 hour global forecasts were run such that the verification times are within 1 hour of the given GLAS orbit. The ECMWF forecast fields were extracted from the output grid points that intersect with the GLAS orbit. Since the horizontal resolution of the ECMWF output grid is roughly 40 x 40 km, occasionally two of the GLAS orbit track points can fall within the same ECMWF grid box. In this case, the two points are assigned the same ECMWF values. The ECMWF data consist of vertical profiles of the prognostic fields at each of 60 model levels ranging from the surface to the 0.1 mb level (roughly 60 km). These data are then vertically interpolated from the ECMWF model levels to the vertical grid defined by the GLAS data which is every 76 meters starting at sea level and extending to an altitude of 20 km. After this process is complete, an image of the GLAS data is made for a portion of an orbit and the corresponding ECMWF data are contoured and overlain on top of the image. This approach is somewhat different than Miller, who degraded both the horizontal and vertical resolution of

[1] Corresponding author address: Stephen P. Palm, Code 912 Goddard Space Flight Center, Greenbelt, MD 20771 email: spp@virl.gsfc.nasa.gov

the lidar data to match that of the ECMWF forecast data. However, for the qualitative comparisons shown here this additional complexity is not necessary.

An example of the GLAS and ECMWF data is shown in figure 1. This image is a GLAS transect from October 1, 2003 beginning near New Zealand, crossing over Antarctica, and ending in the South Atlantic. The GLAS backscatter data are color coded such that the largest scattering is white, decreasing through purple, green, light blue with dark blue indicating the least scattering. The contoured ECMWF field shown on the image is relative humidity from a 48 hour forecast. The GLAS data reveal considerable cloud cover over the South Pacific and an extremely large cloud complex covering much of Antarctica. This cloud complex, extending some 3000 km across, is truly remarkable in its own right. Parts of the cloud extend up to 20 km, well above the tropopause which is roughly at 12 km. The temperatures in this region (12-18 km above Antarctica) are as low as 185 K which leads to the conclusion that the cloud, or at least the portion of it above 12 km, is a Polar Stratospheric Cloud (PSC). The contoured ECMWF relative humidity field shows extremely good correspondence with the GLAS cloud structure, even in this remote part of the world where observations are sparse.

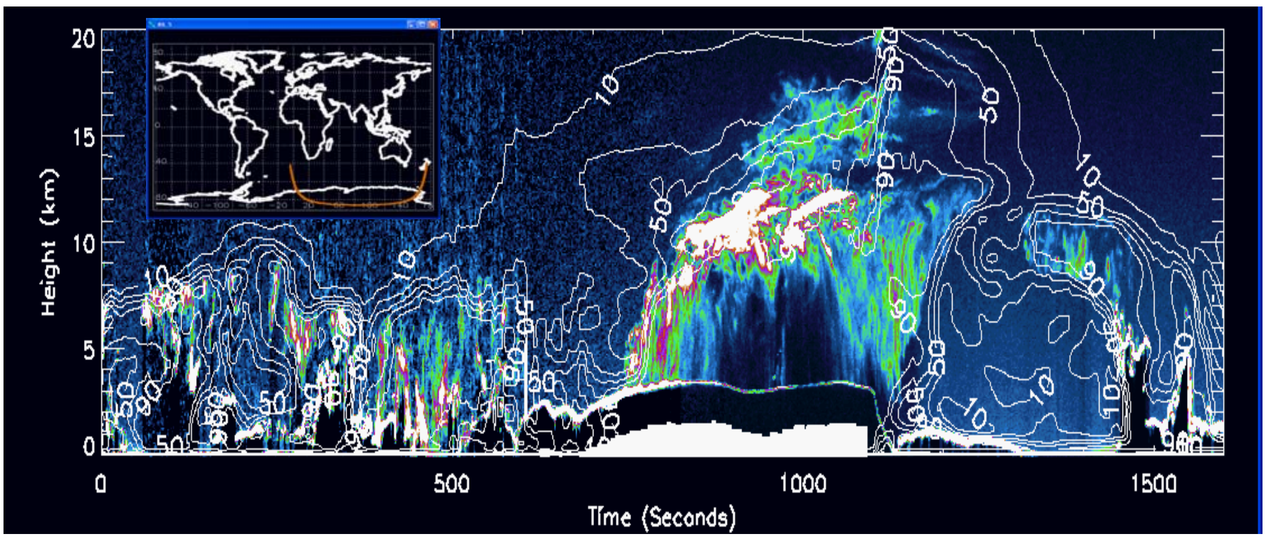

Figure 1. GLAS calibrated, attenuated backscatter with corresponding contoured field of relative humidity from an ECMWF 48 hour forecast. The track begins over New Zealand, crosses Antarctica and ends in the South Atlantic. The data are from September 30, 2003 and span from 20:25 to 20:50 GMT

3. CLOUD HEIGHT AND FRACTION

One of the most straightforward comparisons to make is that of cloud height and vertical and horizontal extent. Simple visual inspection of the images produced from the GLAS calibrated backscatter data will give unambiguous knowledge of the vertical and horizontal locations of clouds. The height to which clouds can accurately be determined from GLAS is roughly 75 meters. This is a much higher vertical resolution than the model output can attain. An example of ECMWF cloud fraction superimposed on the corresponding GLAS backscatter data is shown in figure 2. This is an orbit segment starting just north of the Antarctic coast in the South Atlantic and ending a few hundred km west of Spain. There are a wide variety of cloud types in this region ranging from marine stratus and stratocumulus to cumulonimbus and cirrus. The ECMWF cloud fraction (48 hour forecast) is contoured at the 0.3, 0.6 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 at roughly 10 km altitude and 400 seconds along the x axis. ECMWF has missed the horizontal location of these clouds by roughly 500 km (every 100 seconds along the x axis is 700 km). The large thunderstorm complex between 1050 and 1250 seconds is well predicted by the model, though cloud thickness is too small. Also in this region there are portions of the cloud where either the ECMWF does not report clouds (upper left of cloud complex) or reports clear (lower right side of cloud complex). However, the top height of this convective complex is well forecast. Clearly there are problems with ECMWF cloud forecast for this case, but overall the agreement is good.

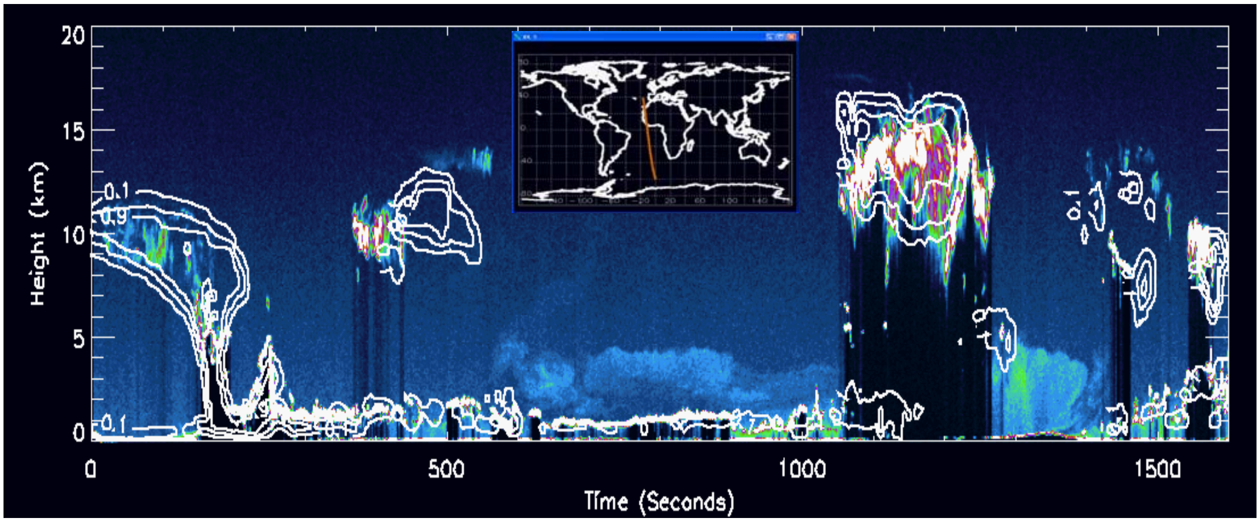

Figure 2. GLAS calibrated, attenuated backscatter with corresponding contoured field of cloud fraction from an ECMWF 48 hour forecast. The track begins just north of Antarctica and ends roughly 500 km west of Spain. The data are from September 30, 2003 and span from 20:45 to 21:10 GMT.

4. BOUNDARY LAYER HEIGHT

Comparison of PBL height derived from orbiting lidar and model forecasts of PBL height was performed by Randall et al. using data from LITE (Lidar In-space Technology Experiment). The algorithm used to derive the PBL height from the LITE data is similar to what is used for GLAS. Both algorithms look for the first gradient 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. Thus, the definition of PBL top as being the location of maximum aerosol scattering gradient is analogous to the more conventional thermodynamic definition. Randall et al. (1998) compared the LITE measurements with the output of two boundary layer models (unrelated to ECMWF) and found that generally the model overestimates the boundary layer depth over the ocean by some 200 – 500 m. Daytime cases were not included in the study because of the poor signal quality of the LITE data in the presence of solar background. . Since we are comparing the GLAS derived PBL height with the ECMWF output, it is important to state how the PBL height is defined within that model.

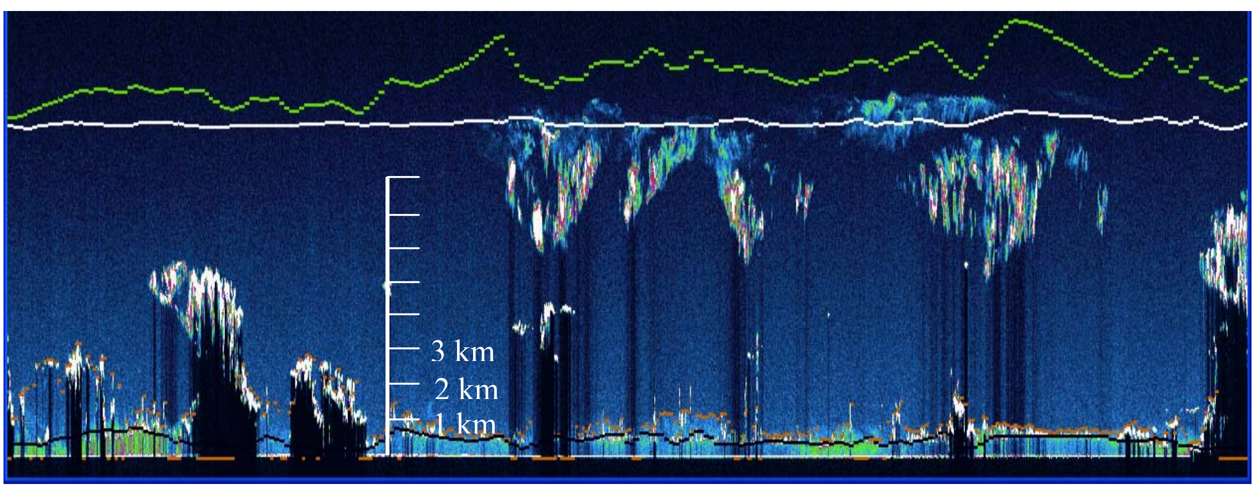

Figure 3. GLAS calibrated, attenuated backscatter with corresponding ECMWF boundary layer height (black line) and the boundary layer height obtained from the GLAS processing algorithms (red) for a typical data segment over the tropical Pacific Ocean. Also shown is the relative magnitude of the surface latent heat flux (green line at top) and sensible heat flux (white line) from an ECMWF 6 hour forecast.

The ECMWF 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.

An example of the comparison of ECMWF PBL height (black line) with GLAS (red points) for a 10,000 km long segment of data over the tropical Pacific Ocean is shown in figure 3. The image of backscatter clearly reveals a layer of enhanced aerosol scattering generally below 1 km. This is the marine boundary layer. Occasionally this layer contains small broken cumulus clouds at its top. Sometimes stratus clouds above this layer attenuate the lidar return so as to block the signal from within the PBL. It can be seen from figure 3 that the GLAS estimate of PBL top is problematic in the presence of these stratus clouds. In such cases, the PBL top jumps way up to values in the 3-6 km range. Conversely the ECMWF data is more consistent in the 500 – 1000 m range. Comparing the GLAS retrieval with ECMWF in those regions where stratus clouds are not affecting the GLAS PBL height, we see a striking correlation of the GLAS and ECMWF values but the later are on average 200 – 300 m lower. This is unlike the findings of Randall who found model PBL heights to be larger than the lidar derived heights, though he was using a different model for the comparison.

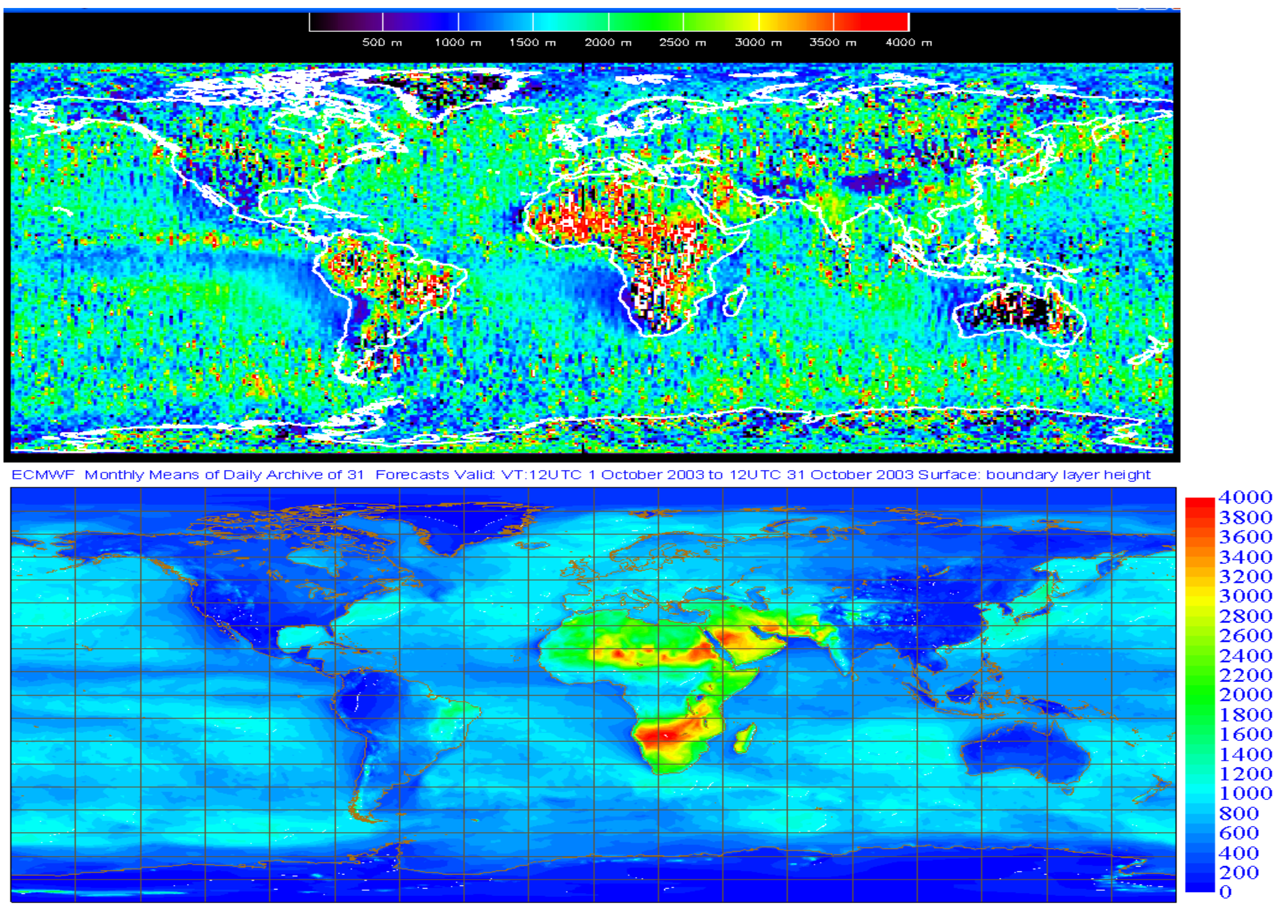

Figure 4. GLAS PBL height observations for the period October 3 – November 15, 2003 (upper panel) and the average of ECMWF 12 hour forecasts of PBL height valid 12 GMT for each day of the month of October, 2003.

Six weeks of GLAS PBL height data from October 3rd through November 15th, 2003 were used to generate a global map of the distribution of PBL height. Since GLAS is providing the first global measurements of PBL height, there are no other data sets with which it can be compared. Instead, ECMWF 12 hour forecasts of PBL height were made for each day of the month of October and then averaged to produce a global map of average PBL height for the month. The results are seen in figure 4. The upper panel shows the gridded GLAS PBL height data for the period October 3rd to November 15th, 2003. The lower panel shows the average ECMWF PBL height for the month of October, 2003. It should be noted that the GLAS PBL height retrievals over land at night will generally result in the height of the residual boundary layer from the day before. This is a direct consequence of the definition that GLAS uses for PBL top – i.e. the location of the first large scattering gradient seen when searching from the ground upwards. Over land at night this is often the residual layer from the day before. On the other hand, the model definition of PBL height uses actual prognostic meteorological variables to define the PBL top (Richardson number). Under this definition, once solar insolation is removed, the boundary layer collapses to near zero values. Thus, the only PBL values over land that can be compared are those values over Africa, Europe and the Middle East, since it was daytime there in the model runs. Over the oceans, the boundary layer height does not exhibit a diurnal cycle and the PBL heights can be compared at all times. Referring to the GLAS PBL height over oceans in figure 4, 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 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 appears to be 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 the west coast of Europe, with somewhat lower values in the central Atlantic. Also, note the region of higher PBL height southwest of Chile.

Randall et al. (1998) note that the LITE PBL height data show a minimum in the tropics between 0 and 25 deg North, and maxima in the subtropics just poleward of 30 degrees. They suggest that the minimum may be the result of moist convection. In the GLAS data we see the minima very close to the equator, with a band of maximum height just to the north of that (roughly 10-20 N)

5. SUMMARY AND CONCLUSION

Orbiting lidars such as GLAS provide the capability of obtaining high resolution 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. Important as these measurements are in their own right, they are also 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 48 hour ECMWF forecast output of cloud fraction. It was discovered that the ECMWF does a reasonably good job for low and middle clouds but often misses the location of high cirrus clouds. Since only one comparison of cloud extent utilizing less than ¼ of a GLAS orbit was performed, it is a little difficult to draw definitive conclusions. Instead, the work presented here demonstrates the utility of GLAS data for model verification and points to the need for further work that uses additional data to generate more substantial and quantitative results.

The boundary layer height comparison revealed that in general the model PBL height is 200 – 400 meters 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 model defines PBL top (using Richarson number). Regardless, it was seen that the relative changes of PBL height seem 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 if the ECMWF is ingesting these surface wind speeds, it could explain this correlation. In addition, six weeks of GLAS PBL measurements were mapped to a global grid and compared with a one month average of ECMWF PBL height. Striking similarity was seen in the overall PBL height pattern over oceans. Daytime values over land agreed well, but it was noted that the nighttime values over land could not be compared due to the nature of the GLAS PBL height retrieval. The PBL height measurements from GLAS represent the first first such measurement obtained globally from a space borne remote sensing instrument.

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