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

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ABSTRACT

Satellite lidar 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.

1. INTRODUCTION

The accurate representation of clouds and cloud processes in numerical weather prediction and climate models is vital, since clouds are both generators of precipitation and key modulators of surface and top-of-atmosphere radiative fluxes. Indeed, a proper parameterization of cloud behavior in general circulation models (GCMs) remains one of the most important challenges to prediction of future climate trends. At the same time, however, validation of model cloud height, vertical distribution and fractional coverage has so far been extremely difficult due to the lack of global observations with sufficient temporal and spatial resolution to adequately validate model output. Fortunately, this is now changing, as instruments such as MODIS, GLAS, CloudSat and CALIPSO provide new high quality and high resolution cloud datasets. These active sensors provide very accurate measurements of cloud height, vertical structure and optical depth with global coverage and high vertical and horizontal resolution and constitute a unique dataset for the validation of model cloud parameterizations.

In January 2003 GLAS was launched into a near polar orbit aboard the Ice Cloud and land Elevation Satellite (ICESat) [1]. In addition to a high resolution altimetry channel, GLAS contains both 1064 and 532 nm atmospheric backscatter lidar channels. Operating periodically since February, 2003, GLAS has provided global views of the vertical structure of atmospheric aerosol, cloud layers and the depth and structure of the planetary boundary layer (PBL) [2,3] (See also: http://glo.gsfc.nasa.gov). The high vertical and horizontal resolution of the GLAS data provide very accurate measurements of cloud height and vertical structure that can be used to validate the performance of cloud forecasts in climate and weather models such as the European Center for Medium-range Weather Forecasts (ECMWF) model. The ECMWF model contains a sophisticated cloud scheme [4] and 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 [5] to validate ECMWF model output of boundary layer height and [6] 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 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

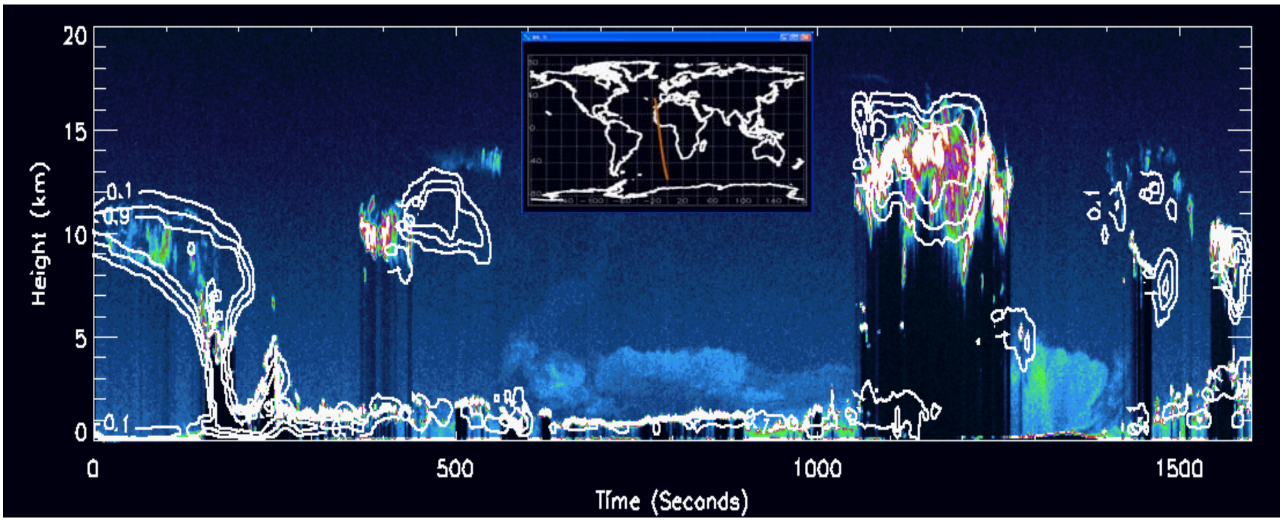

Fig. 1. GLAS calibrated, attenuated backscatter with corresponding contoured field of cloud fraction from an ECMWF 48 hour forecast. The track begins just north of Antarctica and ends roughly 500 km west of Spain. The data are from September 30, 2003 and span from 20:45 to 21:10 GMT.

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 the lidar data to match that of the ECMWF forecast data.

3. CLOUD HEIGHT AND FRACTION

Simple visual inspection of the images produced from the GLAS calibrated backscatter data give unambiguous knowledge of the vertical and horizontal locations of clouds. An example of ECMWF cloud fraction superimposed on the corresponding GLAS backscatter data is shown in Fig. 1. 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.

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. [5] 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. 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 (lowest line) with GLAS (red points) for a 10,000 km long segment of data over the tropical Pacific Ocean is shown in Fig. 2. 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

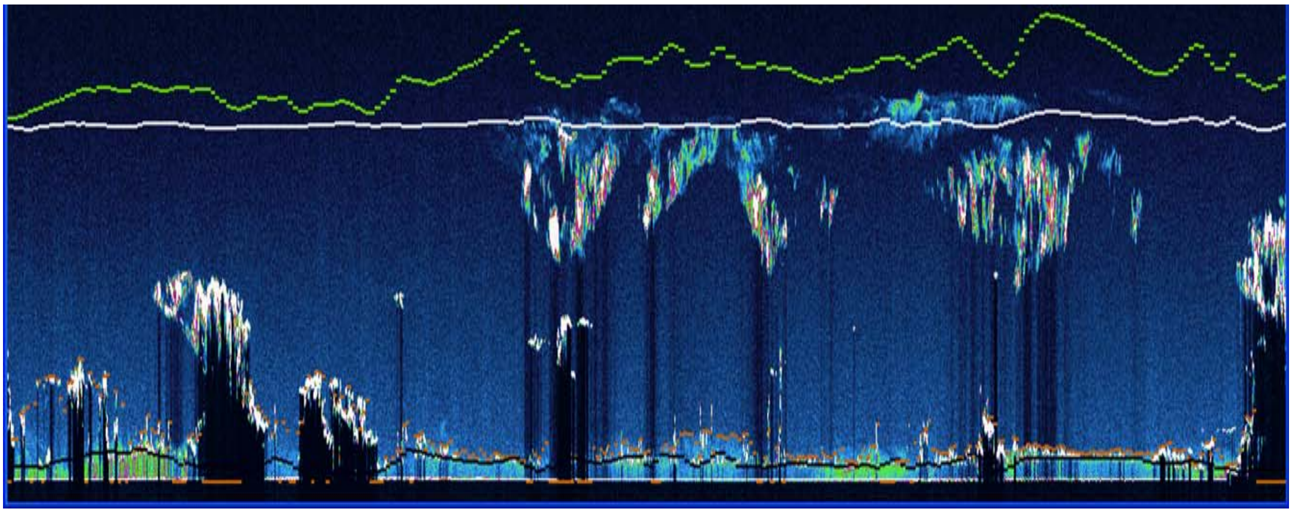

Fig. 2. GLAS calibrated, attenuated backscatter with corresponding ECMWF boundary layer height (lowest line) and the boundary layer height obtained from the GLAS processing algorithms (dots) for a typical data segment over the tropical Pacific Ocean. Also shown is the relative magnitude of the surface latent heat flux and sensible heat flux (two upper lines, respectively) from an ECMWF 6 hour forecast.

block the signal from within the PBL. It can be seen from Fig. 2 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.

The GLAS PBL height data were used to compile a global average for October, 2003. 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 shown in Fig. 3. In Fig. 3a, 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 a limited analysis was performed in this study, it is difficult to draw definitive conclusions. Instead, 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. The boundary layer height comparison revealed that in general the ECMWF model PBL height is 200 – 400 meters lower than the PBL height as discerned from the GLAS data using the maximum scattering gradient as the definition of PBL top. This could be due, at least in part,

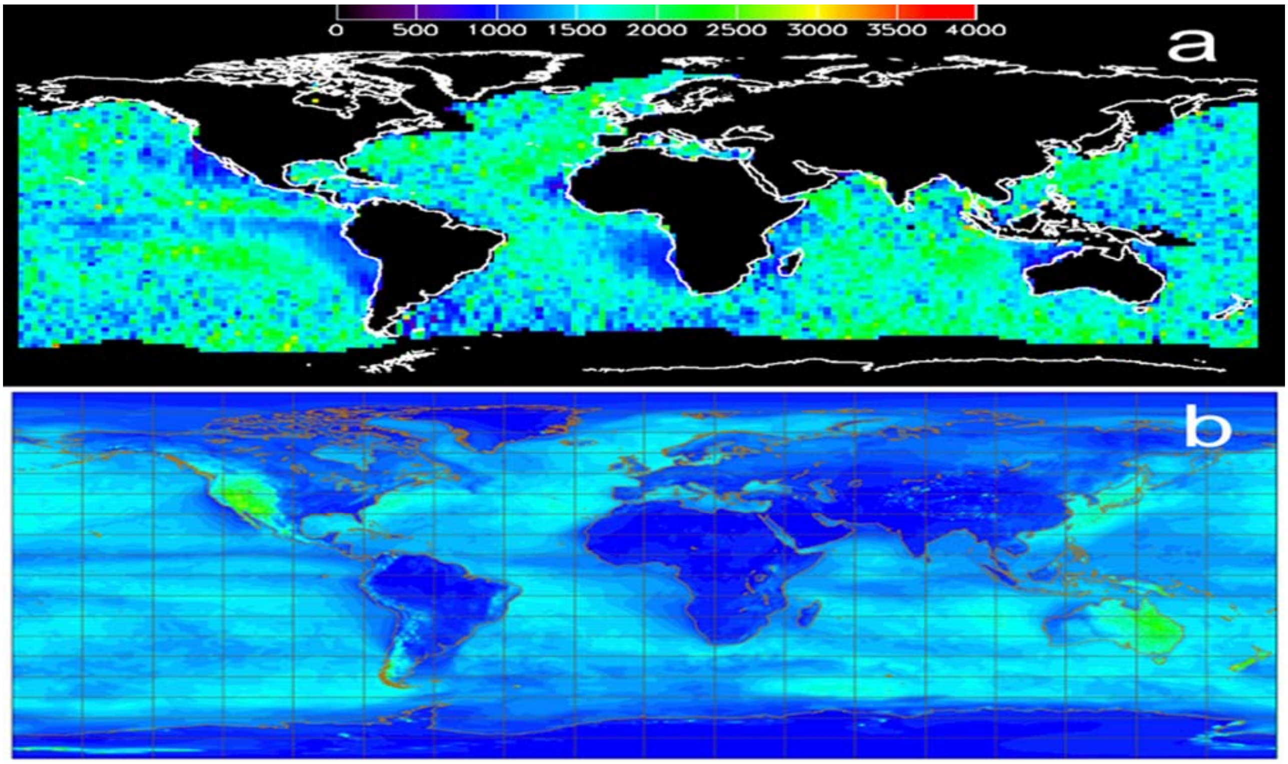

Fig. 3. GLAS average PBL height over ocean for the month of October 2003 (a) and the average of ECMWF 12 hour forecasts of PBL height valid 00 GMT for each day of the month of October, 2003.

to the different definitions of PBL top used by the model and the GLAS PBL height retrieval algorithm. The critical Richardson number of 0.25 (which defines the ECMWF PBL top) may very well be reached at a lower height than the maximum aerosol backscattering gradient as seen by GLAS. Regardless, it was observed that relatively small scale (100 km) changes of model 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 since the ECMWF is ingesting these surface wind speeds, it could explain this correlation. In addition, one month of GLAS PBL measurements were mapped to a global grid and compared with the average ECMWF PBL height for the same period (October, 2003). 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.

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