Validation of MERIS Cloud-Top Pressure Using Airborne Lidar Measurements

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ABSTRACT

The results of a validation of the European Space Agency's (ESA) operational Medium-Resolution Imaging Spectrometer (MERIS) cloud-top pressure (CTP) product by airborne lidar measurements are presented. MERIS, mounted on the polar-orbiting ESA *Environmental Satellite* (*ENVISAT*), provides radiance measurements within the oxygen A absorption band around 761 nm. The exploitation of these data allows the retrieval of CTP. The validation flights were performed in the northeastern part of Germany between April and June 2004 and were temporally and spatially synchronized with the *ENVISAT* overpasses. The Cessna 207T of the Freie Universität Berlin was equipped with the portable lidar system (POLIS) of the Ludwig-Maximilians-Universität München and a GPS navigation system. The maximum flying altitude was around 3000 m; therefore, the validation measurements were limited to situations with low-level clouds only. The validation was done by comparing MERIS data and lidar data. The statistical analysis of the observations revealed a high accuracy of the MERIS CTP product for low-level clouds, apart from a slight systematic overestimation of cloud-top heights. The root-mean-square error was 249 m, with a bias of +232 m. In the average top height level of ~2000 m, these values are commensurate to pressure values of 24 hPa (rmse) and −22 hPa (bias). Furthermore, this validation campaign revealed deficiencies of the MERIS cloud mask to detect small-scale broken clouds.

1. Introduction

Clouds and their physical properties like top height, droplet size, and droplet distribution as well as optical thickness and geometrical thickness play a dominant role in the energy budget of the earth. However, the interactions between clouds and radiation are represented inadequately within current climate models—in part because of an insufficient understanding of the cloud–radiation interaction and the insufficient data basis available for the validation of the models (Houghton et al. 2001). It is therefore an important task for the remote sensing community to provide this information with a sufficient spatial and temporal resolution.

During the last decades, several methods for the remote sensing of cloud-top pressure (CTP) were developed. The most common technique is the so-called CO_2-slicing method (Wielicki and Coakley 1981; Menzel et al. 1983, 2002), which uses the cloud's emission within the carbon dioxide (CO_2) absorption band around 14 μm to derive the cloud-top temperature. On the basis of temperature and humidity profiles, the cloud-top height can be retrieved with an accuracy of ~1.5 km (Frey et al. 1999). Other techniques use the altitude-dependent shading of the earth's surface by clouds (Gurney 1982) or the parallax between two pictures of the same cloud taken from different viewing angles (Shenk and Curan 1973; Hasler 1981; Diner et al. 1998). A further method, which is applied to Medium-Resolution Imaging Spectrometer (MERIS) data, is based on measurements of the cloud-reflected solar radiation within the oxygen A band around 761 nm

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(Yamamoto and Wark 1961; Fischer and Grassl 1991). The latter technique is specified in section 2a.

Since the launch of the European Space Agency's (ESA) *Environmental Satellite* (*ENVISAT*) Earth-observation satellite in March of 2002, the oxygen-A-band method has been applied to MERIS data (Fischer et al. 1997). To validate this CTP product, 12 validation flights were conducted in the northeastern part of Germany between April and June of 2004. A Cessna 207T of the Freie Universität Berlin served as a measurement platform and was equipped with a GPS system and attitude sensors. On the Cessna, the portable lidar system (POLIS; Heese et al. 2002) was mounted to measure the cloud-top height. The comparison of POLIS and MERIS values revealed a high accuracy of the MERIS product for the examined days. The results are discussed in detail in section 3.

2. Instruments and techniques

a. MERIS cloud-top pressure retrieval

MERIS (Rast and Bezy 1999) is an imaging push-broom spectrometer that is mounted on the polar-orbiting *ENVISAT*. It is made up of five cameras that are identical in construction and have a viewing angle of ~14° each. The field of view of MERIS is 68°, corresponding to a swath of 1150 km over the ground. The spatial resolution is 1200 m × 1000 m for the "reduced resolution" mode and 300 m × 250 m for the "full resolution" mode, which is available for a subset of scenes only. MERIS provides 15 spectral channels, programmable in width and position in the range from 412 to 1050 nm. Measurements of channel 10 at a wavelength of 753 nm and channel 11 at 761 nm are used to derive the cloud-top height (Fischer et al. 1997).

Solar radiation at a wavelength around 761 nm is partly absorbed by atmospheric oxygen. The amount of absorption depends on the mass of penetrated air. In the case of a reflecting cloud within the optical path, the absorption mainly takes place in the air mass above the cloud, whose thickness is determined by the cloud-top height. The strength of the absorption is therefore a measure for the air mass above the cloud and thus for the pressure at the cloud top. In contrast to channel 11, the measurements of channel 10 are not subject to atmospheric gas absorption and can thus be taken as a reference. However, multiple scattering of photons within the clouds and between the clouds and the surface significantly increases the photon path lengths and must therefore be considered.

The retrieval algorithm is based on the idea to interrelate the input parameters to the cloud-top pressure by a multidimensional nonlinear regression. The regression coefficients were determined by an artificial neural network (ANN), described in detail in Fischer et al. (1997). Radiative transfer simulations with the Matrix-Operator Model (MOMO; Fischer and Grassl 1984; Fell and Fischer 2001) served as training datasets for the ANN. These simulations included a broad number of combinations of atmospheric parameters like temperature and humidity profiles, cloud heights and thicknesses, surface albedo values, and aerosol loads. The described technique is of high accuracy in cases of optically thick, low clouds but bares weaknesses in cases of thin, high cirrus clouds and high surface albedo values because of a strong impact of the mentioned multiple scattering between clouds and the earth's surface. To limit this uncertainty, the cloud optical thickness, derived from measurements of MERIS channel 10, and the surface albedo, taken from the Global Ozone Monitoring Experiment (GOME) ground albedo database, are additional input parameters to the retrieval algorithm. However, this database has a spatial resolution of 60 km × 60 km and is actually too sparse. A new surface albedo database from MERIS data with a spatial resolution of 10 km by 10 km is under construction. An additional inaccuracy is caused by the uncertain length of the photon paths within the cloud. This "penetration depth" could be determined if the geometrical extent and thus the extinction of the cloud were known. Because this parameter cannot be assessed by MERIS measurements, a global mean value of extinction is assumed by the algorithm. In cases in which the actual cloud extinction is higher than this climatologically assessed mean, the cloud-top height is expected to be overestimated because the penetration depth is smaller than that assumed. In case the extinction is lower, the cloud-top height is underestimated. The expected accuracy of the method is 30 hPa for low clouds and exceeds 70 hPa for thin, high clouds (Fischer et al. 1997; Preusker et al. 2006). The presented algorithm to extract the cloud-top pressure is implemented at ESA's ground segment.

b. POLIS cloud-top height retrieval

POLIS was developed and constructed by the Meteorological Institute of the Ludwig-Maximilians-Universität München for ground-based and airborne operation (Heese et al. 2002). The light source is a neodymium-doped yttrium–aluminium–garnet (Nd:YAG) laser emitting pulses at 355 or 532 nm with a repetition rate of up to 20 Hz. The main components of the detection system are a Dall–Kirkham telescope of a diameter of 20 cm and a Licel acquisition system. In its standard configuration POLIS is operated in a two-channel mode: two channels of mutually perpendicular polarization states at 355 nm, two channels at wavelengths of 355 and 532 nm, or two channels including elastic and Raman backscattering at 355 and 387 nm, respectively. Because of its optical design and the close mounting of the laser on the telescope, POLIS provides backscatter signals already from approximately 70 m onward. This ability makes POLIS especially useful for cloud-top detection also close to the aircraft. The vertical resolution is 7.5 m. The instantaneous field of view of the receiving optics is 2.5 mrad; that is, the diameter of a "lidar pixel" at the cloud deck is on the order of 2 m. Because backscattering from cloud droplets is significantly larger than backscattering from (background) aerosol particles, clouds can easily be identified by lidar signals on a single-shot basis.

POLIS was mounted "downward looking" into the Cessna 207T of the Freie Universität Berlin. In the frame of this experiment, only one wavelength (355 nm) and a reduced pulse repetition frequency of 5 Hz were selected, providing sufficient information to determine cloud-top heights accurately. The cloud-top height was defined by that range bin that detected the maximum number of photons. In case of cloud-free conditions, the surface return in the lidar data was used to check the flight height as determined from the GPS system.

3. Experiment

a. Flights

The maximum flying altitude of the aircraft was around 3000 m, limiting the observations to low-level clouds. Altogether, 12 flights were conducted in the northeastern part of Germany between April and June of 2004. The regions flown over were mainly composed of vegetated and agriculturally used areas. The validation flights are arranged into four categories, depending on the cloud conditions (see Table 1).

TABLE 1. Flight dates and cloud types.

Date	Cloud types
20 Apr 2004	Cumulus + cirrus
3 May 2004	Stratocumulus
6 May 2004	Cumulus + cirrus
12 May 2004	Stratocumulus
18 May 2004	Stratocumulus
24 May 2004	Stratocumulus
25 May 2004	Stratocumulus + cumulus
26 May 2004	Stratocumulus + cumulus
3 Jun 2004	Cumulus
7 Jun 2004	Stratocumulus
11 Jun 2004	Cumulus + cirrus
16 Jun 2004	Cumulus

b. Case studies

The validation of ESA's CTP product is carried out by a comparison between MERIS and POLIS measurements. However, the comparability of these datasets is limited by three dissimilarities that have to be considered for the assessment of the results:

1) MERIS measurements are an average of a two-dimensional 1-km^2 area, whereas POLIS measurements form a one-dimensional trace of "pinpoints" with a diameter of typically a few meters (depending on the distance between the aircraft and the cloud top) and a separation of 10 m. The POLIS values thus had to be averaged over a distance of 1 km, which corresponds to a time slot of 20 s at an aircraft speed of ~50 m s^{-1}.
2) Because of the different velocities of the satellite and the aircraft, POLIS measurements of the cloud field took more than 1 h, whereas MERIS radiances are obtained within a few seconds. The different measurements are thus to be considered as synchronous in terms of space but not in terms of time. To reduce the error that might occur when the clouds change with time, we only used measurements that are not separated more than ±5 min for our intercomparison.
3) MERIS cloud-top pressure values were converted to cloud-top heights. Therefore, temperature and pressure profiles from radiosondes released at Lindenberg, Germany, at 1200 UTC of each day were used. The spatial and temporal distance to the aircraft measurements, which were spread across northeastern Germany and took place between 0900 and 1100 UTC, introduces an additional inaccuracy of up to 2 hPa (~20 m in the considered lower atmosphere).

The vertical resolution is approximately 4 hPa (~40 m) for ESA's MERIS CTP and 7.5 m for POLIS cloud-top heights. However, the accuracy of POLIS is dominated by the uncertainty of the GPS, which is in the range of 20–30 m.

Figure 1 shows two representative vertical profiles of the atmosphere at Lindenberg. The stratocumulus case shows the typical temperature inversion at a height of ~2000 m, with a corresponding rapid decrease of humidity in this layer. The cumulus case reveals a higher inversion (~3000 m) that allowed the development of convective clouds. However, the humidity in the boundary layer is lower than in the stratocumulus case, causing the smaller amount of clouds (see Fig. 2 and 4).

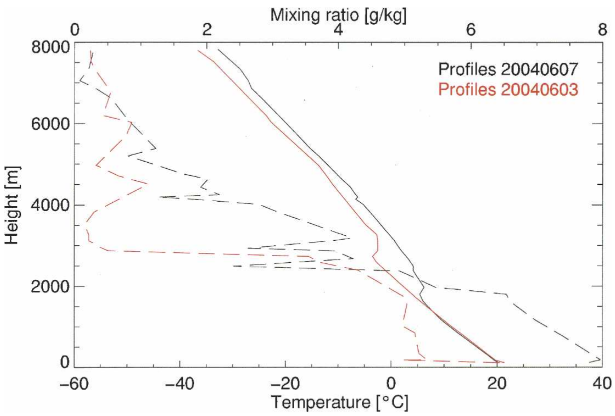

FIG. 1. Temperature (solid lines) and humidity (dashed lines) profiles for 7 Jun (stratocumulus; black) and 3 Jun (cumulus; red).

In the following sections, the results depending on the different cloud types are discussed on the basis of representative case studies. To document the cloud conditions, a MERIS "quasi true color" image of the scene and a photograph taken from the aircraft are displayed in each case. Within the true-color images there is the flight track plotted in red, with the overpass interval marked in blue and the location of the photo marked as a pink square. The whole time series of the aircraft measurements is displayed below with the overpass time frame shown in white and illustrated in detail underneath. In these figures the POLIS cloud-top height (black) values are juxtaposed with the value of the closest MERIS pixel (red).

1) STRATOCUMULUS CLOUDS

Observations related to this category took place in the presence of a closed stratocumulus cloud cover with a comparatively homogeneous top height. The day chosen for the case study is 7 June (Fig. 2). The displayed photograph and the true-color images give a rough idea of the cloud conditions. They show a smooth cloud layer without discontinuities.

The comparison of the measurements shows a very high agreement between cloud-top heights by MERIS and POLIS. Even the small-scale variability of the cloud-top height is reproduced accurately. However, MERIS does not correctly detect all clouds but rather misses some part of the cloud cover (e.g., 0946–0949 UTC). This deficiency probably results from an improperly working cloud mask [see section 3b(3)].

It is apparent that the POLIS cloud-top height values are increasing during the flight while the MERIS measurements stay on the same level of 1800–1900 m. This situation results from the mentioned different velocities of the satellite and the aircraft (see section 3b). The steady rise of the cloud-top height observed by POLIS is due to the development of the clouds during the day. A similar effect can be observed in Fig. 3. Hence, the most significant measurements are those at the overpass time of MERIS. A time frame of ±5 min of POLIS data around this moment was chosen as a data basis for the analysis. These time frames and the corresponding measurements are displayed at the bottom of each figure.

2) STRATOCUMULUS AND CUMULUS CLOUDS

This set of cases includes the observations with a mixture of stratocumulus and cumulus clouds. The cloud-top height is uneven because of penetrating cumulus tops. Because it perfectly matches the described criteria, 26 May was chosen as a representative day (Fig. 3). Again, the comparison shows a high correlation between MERIS and POLIS values. Especially during the *ENVISAT* overpass, the cloud-top heights and their small-scale structures are represented accurately by MERIS (e.g., 0930–0932 UTC). Here the overestimation of the cloud-top height by MERIS is in the range of 0–500 m (0–40 hPa at a mean cloud-top height of 2.5 km). Again, the development of the cloud-top height during the flight becomes apparent in view of the decreasing discrepancy between MERIS and POLIS measurements.

3) CUMULUS CLOUDS

Observations related to this category took place in the presence of cumulus clouds with more or less broad gaps between the clouds. The measurements show a high variance of cloud-top height relative to the other cases.

As a representative for this category, 3 June (Fig. 4) was only slightly clouded. The true-color images show a field of scattered cumulus cells in the measurement area. Within the *ENVISAT* overpass time frame (1011–1021 UTC), there is only one clouded MERIS pixel (at 1012 UTC) with a deviation of 300–400 m from the POLIS value.

The dimensions of the cloud cells can be estimated from the POLIS data. They are partially at the limit of the resolution of MERIS and are thus not detected. Nevertheless, the fraction of correctly identified clouds is way too small. The ESA cloud mask takes into account several parameters such as Rayleigh-corrected reflectances, derived surface pressure, and cloud-top pressure values and returns a value that is 1 (clouded) or 0 (cloudless). This classification seems to be conservative for cloudy cases; that is, the algorithm does not mistake clear pixels as cloudy. On the other hand, the

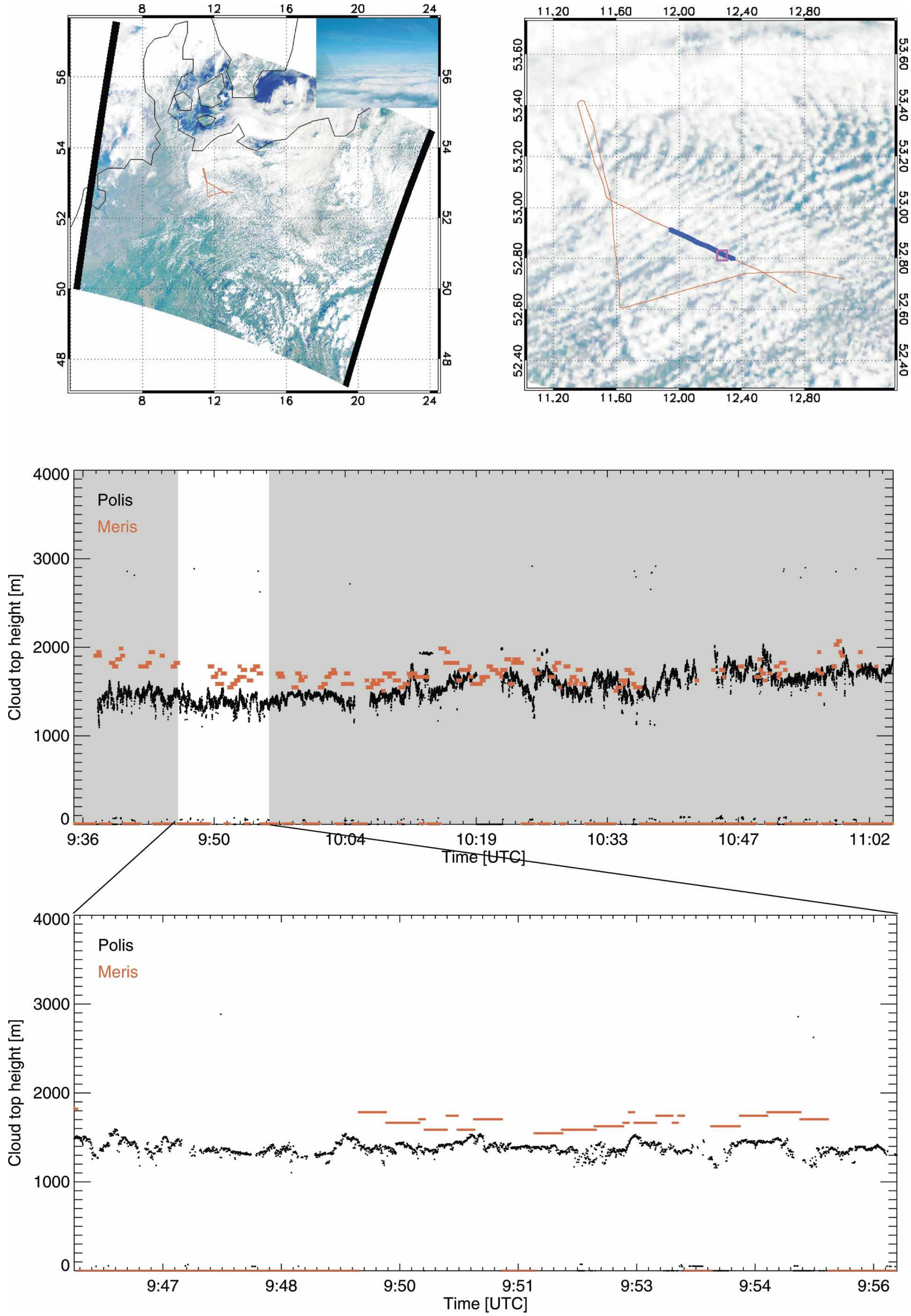

FIG. 2. Flight track and comparison of MERIS and POLIS for 7 Jun 2004.

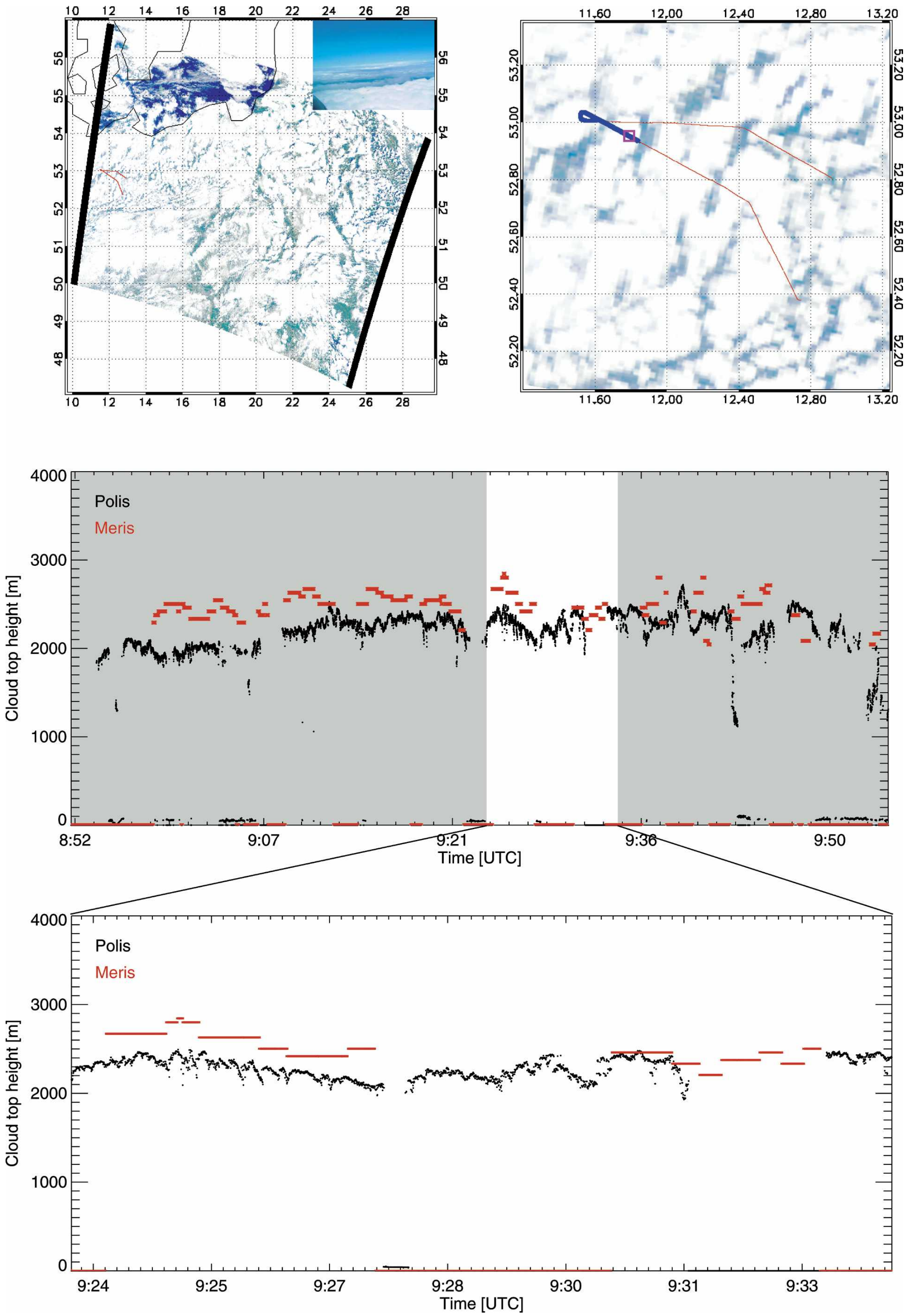

FIG. 3. As in Fig. 2, but for 26 May 2004.

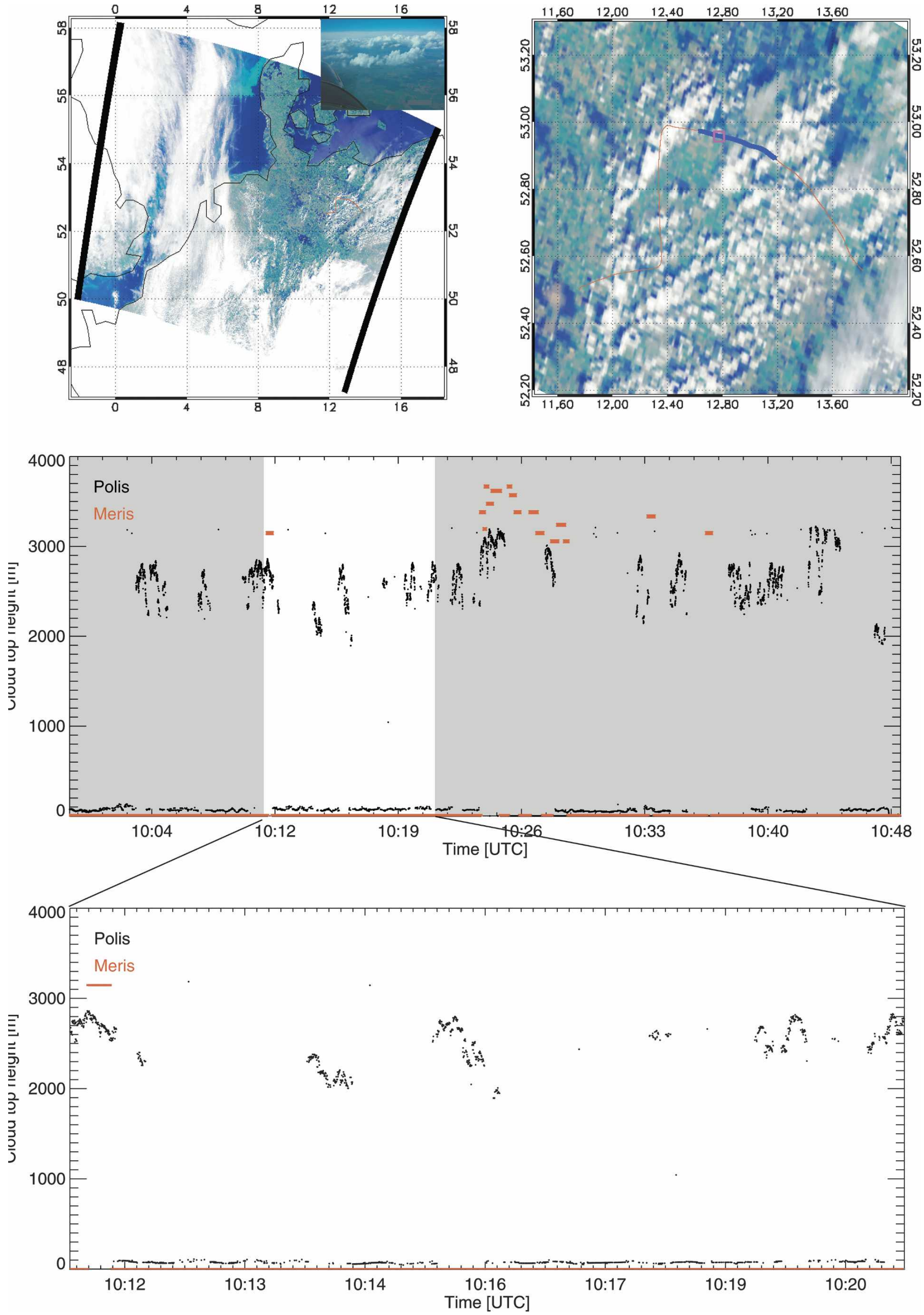

FIG. 4. As in Fig. 2, but for 3 Jun 2004.

cloud mask obviously bares weaknesses in the identification of clouds, so that many pixels are classified as cloudless that should be classified as cloudy. This behavior needs further investigation to find out whether there is a dependency on the height of the classified clouds that could lead to errors in further derived products.

4) Low-level and cirrus clouds

This set of days includes the cases with a presence of thin cirrus clouds above the examined cloud cover and the aircraft. They are thus not suitable for a validation of MERIS cloud-top heights.

The presence of a cirrus layer above the flight track can at least be guessed from the true-color images of 11 June (Fig. 5), which show the characteristic untextured veil around the measurement area. Quasi-simultaneous measurements from the Moderate-Resolution Imaging Spectroradiometer (MODIS) verified this assumption. The image displays the low cumulus field below the cirrus layer and the aircraft.

The comparison of MERIS and POLIS observations shows the expected deviation of MERIS cloud-top heights toward too-high values. However, the MERIS CTP retrieval algorithm also fails at the determination of the height of the cirrus cloud layer and returns a mixture of high and low cloud-top heights.

c. Summary of validation experiment

The statistical analysis reveals a high accuracy of the cloud-top pressure product of MERIS. Figure 6 shows a scatterplot of 91 corresponding MERIS and POLIS values. The gray crosses mark the measurements at the presence of cirrus clouds. These observations were not included in the statistical analysis but are displayed here to document the deviation of MERIS cloud-top heights toward too-high values. The error bars mainly result from the standard deviation of the 10 MERIS pixels located closest to the POLIS measurement position and the standard deviation of the POLIS cloud-top heights within the corresponding MERIS pixel, respectively. As mentioned, MERIS cloud-top pressure measurements were converted to cloud-top heights on the basis of radiosonde data from Lindenberg (52°13′N, 14°07′E) at 1200 UTC. To account for the spatial and temporal distance of these data, gradients of air pressure in space and time were determined with additional radiosonde measurements at 0600 UTC and data from Greifswald (54°06′N, 13°40′E) and Bergen (52°49′N, 9°56′E), Germany. The resulting deviations of up to 2 hPa ($\sim$20 m) were factored into MERIS cloud-top-height uncertainty for each case.

The statistical analysis reveals a root-mean-square error for MERIS of 249 m with a bias of +232 m, which corresponds to pressure values of 24 hPa and −22 hPa at a level of 2000 m. The tested retrieval algorithm thus systematically overestimates cloud-top heights. The "bias corrected" root-mean-square error is 90 m ($\simeq$9 hPa). The two datasets are highly correlated, with a correlation coefficient of 0.97.

4. Conclusions

A validation of MERIS cloud-top pressure was accomplished by airborne lidar measurements with POLIS. Twelve validation flights were conducted in the northeastern part of Germany between April and June of 2004. A Cessna 207T of the Freie Universität Berlin served as a measurement platform.

Apart from deficiencies of the MERIS cloud mask and a systematic underestimation of cloud-top pressure, the validation campaign revealed the high quality of MERIS CTP. The accuracy was found to be 24 hPa with a bias of −22 hPa in cases of low clouds. The small-scale variability of cloud-top pressure can be resolved by MERIS. The presence of thin cirrus leads to a decrease in the accuracy of MERIS CTP because of the ambiguity of the paths of the photons. Additional measurements provided by the Advanced Along-Track Scanning Radiometer (AATSR) on *ENVISAT* will be used in the future to identify cirrus clouds to account for the mentioned effects. The critical optical thickness of a cloud needed for it to be "noticed" by MERIS can be estimated as $\tau \sim 0.5$. Optically thicker cirrus clouds cause the mentioned errors. Further sensitivity studies are needed to assess the critical optical thickness needed by the algorithm to be able to retrieve the height of cirrus clouds correctly.

The authors suppose that the observed systematic overestimation of cloud-top heights is caused by a too-small extinction assumed by the algorithm (see section 2a). Further investigation is needed to define the effects of high surface albedo and differences among the individual cameras on the MERIS CTP product.

A similar validation study is planned for high clouds. Because the flying height of the aircraft used for this study is limited to 3000 m, this study could be performed using lidar measurements from the *Ice, Cloud, and Land Elevation Satellite* (*ICESAT*; Zwally et al. 2002). The outstanding applicability of lidar for the determination of cloud-top heights will furthermore be exploited by the *Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation* (*CALIPSO*, already launched; Winker et al. 2004) and Earth Clouds, Aerosols, and Radiation Explorer (EarthCARE; Kondo et

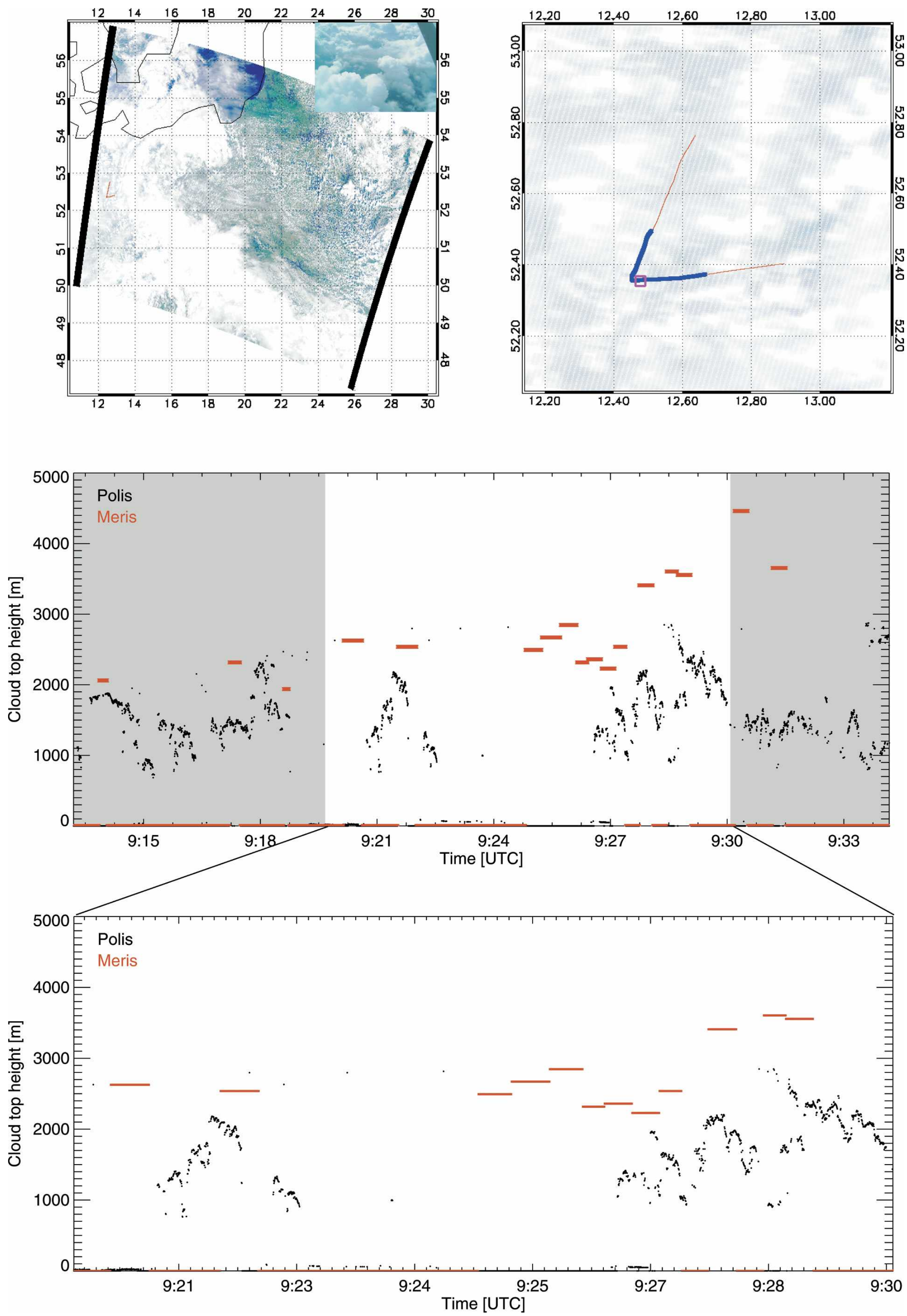

FIG. 5. As in Fig. 2, but for 11 Jun 2004.

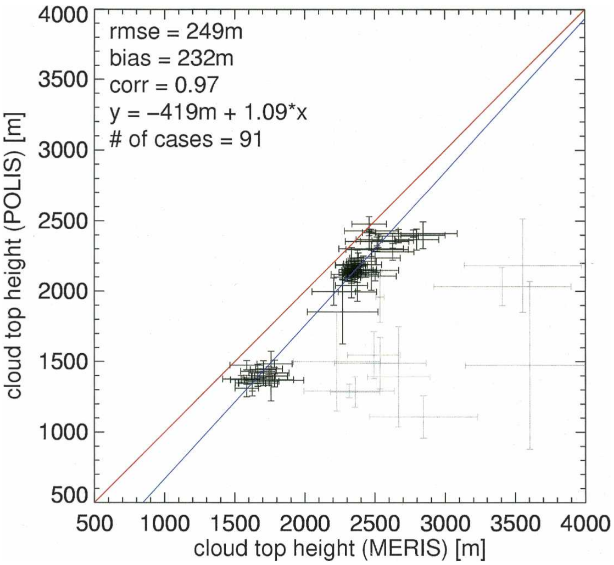

FIG. 6. Comparison of POLIS and MERIS cloud-top heights. Gray crosses mark cases with presence of cirrus clouds. The one-to-one line and the regression line are displayed in red and blue, respectively.

al. 2003) satellites. Both satellites will carry lidar instruments to measure vertical profiles of aerosols and cloud-top heights.

The oxygen-A-band method will be applied to data of the Orbiting Carbon Observatory (OCO; Crisp et al. 2004), which is planned to be launched in 2008. The cloud-top pressure will be a by-product used to determine the concentration of carbon dioxide in cloudy atmospheres with a high accuracy.

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