Ground Fog Detection from Space Based on MODIS Daytime Data—A Feasibility Study

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ABSTRACT

The distinction made by satellite data between ground fog and low stratus is still an open problem. A proper detection scheme would need to make a determination between low stratus thickness and top height. Based on this information, stratus base height can be computed and compared with terrain height at a specific picture element. In the current paper, a procedure for making the distinction between ground fog and low-level stratus is proposed based on Moderate Resolution Imaging Spectroradiometer (MODIS, flying on board the NASA Terra and Aqua satellites) daytime data for Germany. Stratus thickness is alternatively derived from either empirical relationships or a newly developed retrieval scheme (lookup table approach), which relies on multiband albedo and radiative transfer calculations. A trispectral visible–near-infrared (VIS–NIR) approach has been proven to give the best results for the calculation of geometrical thickness. The comparison of horizontal visibility data from synoptic observing (SYNOP) stations of the German Weather Service and the results of the ground fog detection schemes reveals that the lookup table approach shows the best performance for both a valley fog situation and an extended layer of low stratus with complex local visibility structures. Even if the results are very encouraging [probability of detection (POD) = 0.76], relatively high percentage errors and false alarm ratios still occur. Uncertainties in the retrieval scheme are mostly due to possible collocation errors and known problems caused by comparing point and pixel data (time lag between satellite overpass and ground observation, etc.). A careful inspection of the pixels that mainly contribute to the false alarm ratio reveals problems with thin cirrus layers and the fog-edge position of the SYNOP stations. Validation results can be improved by removing these suspicious pixels (e.g., percentage error decreases from 28% to 22%).

1. Introduction

Fog, which often occurs during winter in central Europe, is a severe obstacle for land, air, and sea traffic. Unfortunately, an accurate and reliable spatiotemporal nowcasting of fog still reveals technical problems, both by using interpolated synoptic observing station (SYNOP) data and NWP model results (Jacobs et al. 2005; Bendix 2004). Data from second-generation weather satellite systems [such as the Meteosat Second-Generation—Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI) and the National Aeronautics and Space Administration (NASA) Terra and Aqua satellite’s Moderate Resolution Imaging Spectroradiometer (MODIS)] seem to offer new opportunities to improve the spatiotemporal nowcasting and monitoring of fog dynamics.

Several techniques for spaceborne fog detection have been developed over the last few decades. A common method makes use of the blackbody temperature difference between the IR 11- and 3.9-μm bands of the Advanced Very High Resolution Radiometer (AVHRR) on board the polar-orbiting National Oceanic and Atmospheric Administration (NOAA) satellites, especially during nighttime (Eyre et al. 1984; Turner et al. 1986; Bendix and Bachmann 1991; Dybroe 1993; Bendix 1994, 1995a; Reudenbach and Bendix 1998; Bendix 2002). This algorithm was successfully implemented on the basis of the Geostationary Operational Environmental Satellite-8 imager (GOES-8; Ellrod 1995; Wetzel et al. 1996; Lee et al. 1997; Greenwald and Christopher 2000; Underwood et al. 2004) and the new Meteosat-8 SEVIRI instrument (Bendix et al. 2004a,b) to the geostationary orbit. Fog detection dur-
ing daytime is more complicated due to a similar spectral behavior of snow, fog, and other water clouds in the visible bands and the contamination of the 3.9-μm band by solar radiation (e.g., Bendix and Bachmann 1991; Güls and Bendix 1996). However, the combination of the visible reflectance and blackbody temperature at 11 μm could be successfully used to exclude mid- and high-level clouds (e.g., Anthis and Cracknell 1999).

Furthermore, false color composites using AVHRR bands 3A (1.6 μm), 2, and 1 can help in detecting fog from satellite data by visual inspection techniques (Dyras 2000). In a recent work, the high potential of the boosted spectral resolution provided by MODIS (for more information on MODIS, refer to King et al. (1992) on board the semioperational Terra and Aqua platforms for the detection of very low stratus was presented (Bendix et al. 2005, manuscript submitted to Meteor. Appl., hereafter B05).

Unfortunately, all of the methods addressed are only able to detect low stratus clouds with a high probability of poor visibility at ground level. It is currently not possible to calculate ground visibility or to distinguish between very low stratus and ground fog from satellite data [for a more detailed description of the problem refer to Bendix (1995b) and Fig. 1]. Hence, a scheme for discriminating between very low stratus and ground fog with ground contact is required for a proper spatiotemporal monitoring of fog extension and fog dynamics from space.

A method for the detection of ground fog should consist of four steps (Fig. 2).

1) Discrimination between very low stratus clouds and other surfaces is needed. Operational algorithms are already available for this step as mentioned above.
2) The calculation of cloud optical (spectral albedo, optical depth) and microphysical properties is performed [liquid water path (LWP), effective radius]. This step is required for the determination of the geometrical thickness (step 3) of a cloud layer by specific approaches. Various algorithms for the retrieval of optical and microphysical properties based on NOAA AVHRR data have been successfully used in the past (e.g., Bendix 1995a; Nakajima and Nakajima 1995; Bendix 2002) and have recently been adapted to the MODIS instrument (Platnick et al. 2003; Nauß et al. 2004, 2005). The implementation as described in Nauß et al. (2004, 2005) is used in the current study for the retrieval of low stratus properties, which are required to derive geometrical thickness by means of empirical relationships and the adiabatic approximation (section 2).
3) A proper determination of low stratus geometrical properties is made. This means, especially, that the calculation of top height and geometrical thickness of a low stratus layer is necessary. The top heights of clouds can generally be calculated by using the corrected brightness temperature in the split-window

![Fig. 1. Schematic depiction of the common problem in remote sensing of fog.](image1)

![Fig. 2. Proposed scheme for spaceborne fog detection.](image2)
channels as compared to atmospheric profiles like radiosonde data (e.g., Saunders 1988; Nakajima and Nakajima 1995), or from backscattered radiances, for example, in the oxygen A band (e.g., Fischer and Grassl 1991). Unfortunately, weather situations with fog or very low stratus are normally characterized by a complex thermal stratification with temperature inversions in the lowest 100 m of the boundary layer. Standard atmospheric profiles frequently do not resolve this structure in time and space and, hence, greater errors must occur for top height retrievals as mentioned above. To overcome this problem, an algorithm was developed that extracts the top height of very low stratus clouds by superimposing the initial binary stratus mask onto a digital elevation model (DEM). The edge pixels (i.e., pixels that form the boundary between the fog layer and the surrounding, fog-free terrain) of the initial stratus mask are extracted using a spatial filter and their height is derived from the colocated DEM pixels. The irregularly distributed height points are used to interpolate a top height surface of the low stratus layers by means of polynomial fitting in a standard trend surface analysis (for general information on trend surface analysis cf. Chorley and Haggett 1965). The resulting image consists of the top height of every grid element proven by the initial low stratus detection scheme to be contaminated by stratus. This procedure reveals deviations of $<\pm50$ m if higher terrain is around a undisturbed fog/low stratus layer not in the dissipation stage (Bendix and Bachmann 1993; Bendix 1994; Reudenbach and Bendix 1998) and is applied in the current study. The retrieval of cloud geometrical thickness using data from optical sensors exclusively is still an open question but it is a precondition for step 4, the discrimination between very low stratus and fog with ground contact by using satellite data (section 4).

The main goal of the current study is to present a new parameterization scheme for the estimation of low stratus geometrical thickness for Germany based on MODIS daytime data and radiative transfer calculations (section 3). The results will be compared with other approaches (sections 2 and 4). Finally, two case studies of different stratus–fog situations shall highlight the potential of the methodology for the discrimination between low stratus and ground fog by using satellite data (section 4).

2. Current methods for the retrieval of stratus cloud geometrical thickness

Low stratus geometrical thickness can generally be calculated if the optical and microphysical cloud properties are well known for both the columnar values (LWP, $\tau$) and the vertical profiles [liquid water content (LWC); Bendix 1995b; Hutchison 2002]:

$$\Delta Z = \frac{\text{LWP}}{\text{LWC}} \cdot \frac{\tau}{\beta_{\text{ext}}},$$

where $\Delta Z$ is the low stratus geometrical thickness (m), LWP is the liquid water path (g m$^{-2}$), LWC is the liquid water content (g m$^{-3}$), $\tau$ is the optical depth, and $\beta_{\text{ext}}$ is the extinction (m$^{-1}$).

Unfortunately, information on vertical profiles or mean values of $\beta_{\text{ext}}$ and LWC is normally not available from spaceborne optical sensors. As a result, some authors have derived empirical relationships between columnar values and the geometrical thickness of stratus clouds. Minnis et al. (1992) found the following relationship for marine stratocumulus in California:

$$\Delta Z = -45.6 + 84.3 \cdot \rho^{0.5},$$

where $\Delta Z$ is the geometrical thickness (m) and $\tau$ the optical depth.
Heidinger and Stephens (2000) present a slightly modified version of this equation:

$$
\Delta Z = 45 \tau^{2/3},
$$

where $\Delta Z$ is the geometrical thickness (m) and $\tau$ the optical depth.

Brenguier et al. (2000) assume that liquid water content within a boundary layer cloud reveals an adiabatic increase from cloud base to cloud top and that the observed LWP (e.g., as calculated by means of satellite data) is a product of adiabatic processes ($\text{LWP} = \text{LWP}_{\text{ad}}$). By using this assumption (adiabatic approximation), they derive cloud thickness from

$$
\Delta Z = \sqrt{\frac{\text{LWP}_{\text{ad}}}{0.5C_w}},
$$

where $\Delta Z$ is the cloud geometrical thickness (m), $\text{LWP}_{\text{ad}}$ the adiabatic liquid water path (g m$^{-2}$), and $C_w$ the moist-adiabatic condensate coefficient (g m$^{-4}$), which is temperature dependent and varies between $1 \times 10^{-3}$ and $2.5 \times 10^{-3}$ in a range from 0°C to 40°C (Brenguier 1991; Brenguier et al. 2000).

Figure 3 shows that the relations between optical depth and geometrical thickness are generally comparable for all three approaches. A strong increase in thickness with optical depth is obtained in the range of low $\tau$ (<20), which is typical for central European fog (Chourlaton et al. 1981; Steward and Essenwanger 1982; Bendix 1995a, 2002). For the mode optical depth of fog layers in Germany and adjacent areas [$\tau_{\text{mode}} = 8$; Bendix (2002)], the difference between the Minnis and Heidinger approaches yields $192 - 180 = 12$ m whereas the adiabatic approximation reveals a span from 163 m ($-29$ m as compared to Minnis) to 238 m ($+46$ m compared to Minnis) within a typical thermal range (0°C–15°C) of central European fog. Maximum thickness is obtained by Brenguier et al.’s (2000) function for a temperature of 0°C, and a strong decrease of thickness can be observed between 0°C and 5°C. At fog temperatures >5°C, the influence on geometrical thickness especially in the lower range of the optical depth is nearly negligible.

### 3. A new approach for the retrieval of stratus geometrical thickness

#### a. Principal considerations

A more direct calculation of geometrical thickness from satellite data according to Eq. (2) would require a proper estimate of the mean values of LWC or extinction of the stratus layer. Platnick (2000) stresses that multispectral sensing of clouds could be useful to estimate vertical profiles of cloud properties (such as LWC) based on a wavelength-dependent difference in the penetration depth of photons in cloud layers. This can be illustrated by means of two in situ profiles of extinction and LWC taken through ground (radiation) fog and a low stratus cloud (uplifted fog; Fig. 4) by Pinnick et al. (1978) in Grafenwöhr (southern Germany). Optical depth–LWP are calculated by integration of the observed extinction–LWC over height. The effective radius is obtained from (Hu and Stamnes 1993; Bendix 2002)

$$
r_e = \int_0^\infty \frac{r^2 n(r) dr}{r^2 n(r) dr} \approx \frac{3\text{LWC}}{2\beta_{\text{ext}}},
$$

where $r_e$ is the effective radius ($\mu$m) and $\beta_{\text{ext}}$ extinction (m$^{-1}$).

The horizontal visibility is derived using Koschmieder’s law (e.g., Bendix 1995a):

$$
\text{VIS} = \frac{3.91}{\beta_{\text{ext}}},
$$

where VIS is the horizontal visibility (km) and $\beta_{\text{ext}}$ the extinction at 0.55 $\mu$m (km$^{-1}$).
The ground fog layer reveals a thickness of 155 m and is characterized by a nearly constant visibility <100 m with a slight increase at ground level. Consequently, columnar values are relatively high with $\tau = 10.55$ and $LWP = 48.05 \text{ g m}^{-2}$. The calculated effective radius lies in the range of 6.66–7.47 $\mu$m. The uplifted fog is thinner ($\Delta Z = 90 \text{ m}$) if the cloud base is defined by a visibility >1 km. Transition from mist to fog is reached at a height of 60 m above ground. From that point, extinction increases with height, which leads to an optically dense low stratus layer (VIS <100 m) in the upper part of the profile. However, columnar values are reduced ($\tau = 2.98$, $LWP = 8.85$) in comparison to the ground fog case.

Radiative transfer calculations reveal different penetration depths for MODIS bands 1 (0.65 $\mu$m), 6 (1.64 $\mu$m), and 7 (2.1 $\mu$m) within the fog layer (Fig. 5). In the spectral range <0.7 $\mu$m, water absorption is negligible (e.g., Stephens et al. 1984). The penetration depth is relatively large. Droplets in the upper 30 m of the fog layer (125–155 m) contribute only ~50% to fog-top albedo; saturation (>90% contribution to top albedo) begins at 65 m above ground. This means that the lower half of the fog layer contributes only ~10% to the albedo signal measured at the fog top. In the NIR bands, absorption increases with wavelength [Fig. 5; Pilewskie and Twomey (1987)], which reduces the albedo of the ground fog layer from 0.82 in MODIS band 6 (1.64 $\mu$m) to 0.64 in MODIS band 7 (2.1 $\mu$m). The penetration depth decreases with increasing wavelength. Saturation begins at 135 m for MODIS band 6 and at 140 m for MODIS band 7, which means that almost the entire signal at satellite level originates from the upper 15–20 m of the fog layer.

Similar results are obtained for the low stratus case. Chang and Li (2002, 2003) and Chang et al. (2002) were able to show that a multi-NIR wavelength approach can be useful in retrieving vertical profiles of the droplet effective radius from satellite data. Because the effective radius is related to LWC [Eq. (6)] and LWP–LWC is related to geometrical thickness [Eq. (2)], it can be deduced that multiband albedo must also include infor-
mation on the geometrical thickness of a cloud. Hence, the alternative approach for the determination of stratus thickness in the current paper is to relate the MODIS multiband albedo to the geometrical thickness by developing a parameterization scheme based on radiative transfer calculations.

b. MODIS data processing

The method developed for the retrieval of low stratus geometrical thickness is organized in the form of a conventional lookup table approach. The approach consists of two steps:

(i) preprocessing of the MODIS data, and
(ii) calculation of a lookup table relating multiband albedo to low stratus geometrical thickness.

The Terra and Aqua MODIS data (for further details of the MODIS instrument refer to King et al. 1992) are received operationally at the Marburg Satellite Station for Germany and adjacent areas (Bendix et al. 2003). For the current study, five spectral bands in the VIS and NIR have been considered (Table 1).

Gray values are converted to normalized spectral albedos using the method described in Bendix (1995a). Calibration and rectification of the MODIS images are performed by means of the MODIS Operational Processing Scheme (MOPS; Nauß and Bendix 2005). MOPS also includes the retrieval of stratus optical (optical depth $\tau$) and microphysical properties (LWP, $r_e$) based on the ATSK3 algorithm (Nakajima and Nakajima 1995; Kawamoto et al. 2001; Bendix 2002; Harshvardhan et al. 2004), which has recently been ported to the MODIS sensor (Nauß et al. 2004, 2005).

The lookup table approach is based on the normalized spectral albedos in selected MODIS bands. Only pixels that have been proven to be low-stratus-contaminated in a preceding detection scheme (Bendix et al. 2004a,b) are considered. The required lookup table is calculated by means of radiative transfer calculations (RTCs).

The assignment of the geometrical thickness ($\Delta Z$) from the lookup table is based on the iteration step with the minimum deviation between observed (MODIS) and calculated ($a_l$) albedos:

$$\Delta Z = \Delta Z_1 \quad \text{if} \quad \min(\chi^2),$$

where $\Delta Z$ is the assigned geometrical thickness (m), $\Delta Z_1$ the geometrical thickness from the lookup table (m), and $\chi^2$ least squares variance between observed and theoretical albedos.

The minimum least squares variance ($\chi^2$) between the observed and theoretical (radiative transfer) albedos is calculated according to Chang and Li (2002):

$$\chi^2 = \frac{\sum_{b=1}^{n} (a_{obs}^b - a_l^b)^2 w_b}{\sum_{b=1}^{n} w_b},$$

Table 1. MODIS bands used.

<table>
<thead>
<tr>
<th>Spectral band</th>
<th>Bandwidth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.620–0.670</td>
</tr>
<tr>
<td>2</td>
<td>0.841–0.876</td>
</tr>
<tr>
<td>5</td>
<td>1.230–1.250</td>
</tr>
<tr>
<td>6</td>
<td>1.628–1.652</td>
</tr>
<tr>
<td>7</td>
<td>2.105–2.155</td>
</tr>
</tbody>
</table>

Fig. 5. Height-dependent contribution to (left) albedo and (right) absorption of the ground fog case in Fig. 4 for MODIS bands 1 (0.62–0.67 µm, solid line), 6 (1.628–1.652 µm, dashed-dotted line), and 7 (2.105–2.155 µm, dashed line).
where \( a_{\text{obs}} \) is the observed spectral albedo in MODIS spectral band \( b \), \( a_b \) the spectral albedo from the lookup table for MODIS spectral band \( b \), and \( w_b \) the weighting factor for MODIS spectral band \( b \).

The weighting factors are derived from the two in situ profiles of Fig. 4. The well-known optical, microphysical, and geometrical properties of these two fog–very low stratus cases are converted to spectral normalized albedos in MODIS bands 1, 2, 5, 6, and 7 by means of the RTC scheme. This dataset is then iteratively applied to the lookup table approach with different combinations of weighting factors until a minimum deviation of the theoretical thickness \( (\Delta Z_t) \) and the observed thickness, as indicated by the data in Fig. 4, is obtained. The resulting weighting factors (Table 2) corroborate and reflect the theoretical considerations of Fig. 5 the greater importance of the shortwave bands with their increased penetration depth compared to the NIR bands where absorption prevents a deeper penetration of photons.

According to this result, a trispectral approach with MODIS bands 1, 2, and 6 will yield the best results. The accuracy of the \( \min(\chi^2) \) situation is presented in Table 3 in comparison with the empirical approaches described in section 2.

All approaches overestimate the real fog–very low stratus thickness. The average deviation between the observed and calculated thicknesses obtained by applying the new scheme [Eq. (8)] to the two in situ profiles (Table 2) is 4.6 m. In comparison to that value, the three other approaches seriously overestimate the result, especially the thickness of the ground fog. The low stratus case is well represented by all approaches with the equation of Heidinger and Stephens (2000), which yields the best fit to the real situation.

### 4. Case studies for discrimination between low stratus and ground fog

To estimate the potential of the presented thickness retrievals in distinguishing between very low stratus and ground fog, two different weather situations from the winter period of 2001/02 in Germany have been selected: 1) a local valley fog situation with observed ground fog and 2) an extended very low stratus case where visibility fell below 1 km in different regions of Germany.

#### a. Intercomparison of thickness retrievals for a valley fog case

Patches of valley fog formed on 7 December 2001 in Germany as a postfrontal weather phenomenon. The northern part of the mid–Rhine River valley and tributaries like the Mosel, Sieg, Lahn, and Ahr Rivers were, in particular, affected by significantly reduced ground visibilities, indicating dense fog (Fig. 6; Table 4). The fog detection scheme is applied as described in Fig. 1. The fog–low stratus top-height values are between 200 and 300 m ASL in the Rhine River valley and increase toward the higher terrain in the western part of the fog layer (Fig. 6c). The fog–low stratus geometrical thickness is calculated according to the four methods presented in sections 2 and 3 and illustrated in Fig. 7. Visual inspection reveals similar thickness patterns for all methods. The lookup table approach is characterized by the most pronounced spatial heterogeneity while the adiabatic approximation shows the lowest thickness values.

The results also seem to point to a drawback of the empirical approaches of Minnis at al. (1992) and Heidinger and Stephens (2000), which rely on optical depth only. Significantly higher values of geometrical thickness occur directly along the axis of the Rhine River. However, this does not seem to be a realistic situation as modeling studies have shown that the optical depth of radiation fog of equal geometrical thickness is often much higher over a river than over the bordering rural/built-up areas (Forkel 1986), mainly due to the higher water contents of the river fog. The poor performance of the Minnis approach can have several causes. The published relation, which is based on in situ observations in marine stratus, reveals a clear scatter. The prediction of low stratus thickness using Eq. (3) yielded an rms error of 61.6 m for a Californian

### Table 2. Spectral weighting factors for \( \min(\chi^2) \) related to the in situ profiles of Fig. 4.

<table>
<thead>
<tr>
<th>MODIS spectral band</th>
<th>( w_b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
</tr>
<tr>
<td>2</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 3. Deviations between observed – retrieved geometrical thickness (m) based on the two in situ profiles of Fig. 4: Mi, Minnis et al. (1992); HS, Heidinger and Stephens (2000); Br, Brenguier et al. (2000); and RTC, the lookup table approach.

<table>
<thead>
<tr>
<th>Observed thickness (m)</th>
<th>Mi</th>
<th>HS</th>
<th>Br</th>
<th>RTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground fog</td>
<td>155</td>
<td>-78.0</td>
<td>-66</td>
<td>-97.1</td>
</tr>
<tr>
<td>Very low stratus</td>
<td>90</td>
<td>-9.9</td>
<td>-3.2</td>
<td>-14.8</td>
</tr>
<tr>
<td>Mean deviation</td>
<td>-43.95</td>
<td>-34.6</td>
<td>-55.6</td>
<td>-4.6</td>
</tr>
</tbody>
</table>
dataset (Minnis et al. 1992). This is mainly due to different microphysical profile characteristics in marine stratus layers (also in comparison to continental fog), which cannot be represented by a simple relation between geometrical and optical depths (also cf. Boers et al. 1996). The study of Allam (1987) has shown in this context that the retrieved thickness for a specific incoming radiance at satellite level significantly varies with different droplet spectra in fog layers. Miles et al. (2000) stressed that the effective droplet diameter in low-level stratiform clouds can vary between 5.1 and 28 μm. Bendix (2002) found a significantly enhanced effective radius for the coastal areas of Germany in comparison to the continental pre-Alpine basin. Tampieri and Tomasi (1976) showed that the droplet spectrum also changes over the diurnal life cycle of fog layers.

A pixelwise intercomparison of the different thickness retrievals reveals significant differences between the lookup table approach and the empirical relationships (Fig. 8). As expected, the Minnis and Heidinger–Stephens approaches do not show great deviations. In comparison to the adiabatic approximation, both approaches tend to calculate greater values with increas-

![Topography](image1.png)

![Initial fog/low stratus mask](image2.png)

![Fog/low stratus top height](image3.png)

**Table 4.** Reported ground visibility at SYNOP stations (1000 UTC) in the image subset and hits (H = ground fog indicated by MODIS retrieval and VIS ≤ 1 km observed at SYNOP station) vs misses (M = low stratus indicated by satellite retrieval but VIS ≤ 1 km observed at SYNOP station) for fog detection in the MODIS image (1024 UTC).

<table>
<thead>
<tr>
<th>Station</th>
<th>Altitude (m ASL)</th>
<th>Visibility (m)</th>
<th>Mi</th>
<th>HS</th>
<th>Br</th>
<th>RTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cologne–Bonn airport</td>
<td>92</td>
<td>100</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Bonn–Roleber</td>
<td>159</td>
<td>50</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Nürburg</td>
<td>485</td>
<td>200</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Mendig</td>
<td>181</td>
<td>100</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>Bendorf</td>
<td>127</td>
<td>100</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
</tr>
</tbody>
</table>
The correlation between the lookup table data and the other approaches is generally poor ($r^2 = 0.15-0.21$), although a similar trend is illustrated by the scatterplots. The best correspondence is reached with the adiabatic approximation even if the lookup table approach yields higher thickness values. All three algorithms often show low stratus thicknesses, where the lookup table approach reports values $>150$ m.

To estimate the feasibility of the four approaches for spaceborne fog detection, the results of the entire scheme are compared with SYNOP observations at stations of the German Weather Service (Deutscher Wetterdienst, DWD) (Table 4). It should be stressed that there is a time difference of 24 min between SYNOP observations (1000 UTC) and satellite overpass (1024 UTC). Hits (H) and misses (M) are derived analogous to Eq. (1). False alarm ratio is not presented because all stations indicate ground fog (VIS $< 1$ km).

The best performances, with four hits each, are obtained by the newly developed lookup table approach (RTC) and the empirical relation of Minnis et al. (1992). The adiabatic approximation shows the worst result with three misses. All approaches reveal a miss for the Cologne–Bonn airport, with the result closest to a hit obtained by the lookup table approach (calculated cloud base $= 7$ m above ground as compared to 31 m for the Minnis approach), and the greatest underestimation by the approach of Brenguier et al. (2000) with a calculated cloud base height of 76 m above ground. However, the SYNOP station is located at the northern edge of the valley fog patch, which means that there is a certain possibility of increased ground visibility 24 min after the SYNOP observation. Detection also fails for the Bendorf station with the Heidinger–Stephens approach and the adiabatic approximation, as well as for the Mendig station with the adiabatic approximation.

b. The low stratus case—Potential of distinction between low stratus and ground fog

A complex low stratus–ground fog situation occurred on 14 January 2002 during an extended high pressure weather situation with stagnant cold arctic air in the boundary layer over Germany, overlain by relatively
warm Mediterranean air from the south-southeast. Such weather situations are well known to produce extended low stratus fields over Germany and can cause severe smog episodes if they persist over several days (Kraus and Ebel 1989). The initial stratus mask reveals that most basins were covered by low stratus clouds whereas at the higher terrain of the lower mountain ranges, like the Black Forest (B, Schwarzwald),

Fig. 8. Comparison of the four thickness retrievals ($n = 32,000$ pixel). Refer to axis titles for retrieval type: RIC means the lookup table approach; BR, Brenguier et al. (2000); Mi, Minnis et al. (1992); HS, Heidinger and Stephens (2000).
Wasserkuppe (W), and Harz Mountain (H), typically the peaks protruded through the cloud layer (Fig. 9).

The problem for fog detection from space during such weather situations is that the low stratus layer top height changes from south to north (e.g., Roth 1987) and, depending upon thickness/top height, may locally cause low visibility at ground level (ground fog). Radiosonde data from several regions of Germany underline this complex geometry (Fig. 10).

The boundary layer in the southern part (especially Munich and Meiningen) close to the Alps is characterized by an inversion base between 900 and 1000 m ASL. The humidity profile shows relatively high values up to 900 m, which points to the top height of the stratus layer being between 500 and 900 m ASL. The situation changes toward the central and northern parts of Germany where the inversion base and saturation humidity level (e.g., Idar-Oberstein) fall below 400 m ASL. Close to the coast of the Baltic Sea, the inversion base is located at ~200 m ASL (e.g., Schleswig) and humidity values indicate a very shallow stratus layer probably below 100 m ASL. This situation is also confirmed by the calculated stratus top-height image.

Ground visibility observations at 1000 UTC (time difference of 14 min from the satellite overpass) point to the occurrence of ground fog in several areas of Germany (Fig. 11). In particular in southern Germany, almost all stations with altitudes >900 m are situated within the high stratus layer and, therefore, report fog.
But some stations in the lowlands also report low visibilities. An inspection of specific stations shows that several stations along the coast of the Baltic Sea report fog but so do stations in the central part of Germany with greater altitudes, which are immersed in the low stratus layer. Other stations with lower to moderate altitudes, such as Freiburg (300 m ASL) in the upper Rhine River valley, report low stratus.

Figure 12 illustrates the spatial result of the fog detection scheme according to the method of Fig. 2 for the four different approaches to thickness retrieval. All images show that ground fog occurs in specific areas: in the coastal lowlands of the Baltic Sea close to the Danish border, at the slopes of the lower mountain ranges in the central part of Germany, and along the northern Alpine slopes. However, the shapes of these areas are different for the four thickness retrievals. The Minnis and Heidinger–Stephens approaches reveal similar patterns, but only a very small patch in northern Germany (coast of the Baltic Sea) is detected as ground fog. This area is extended considerably by using the lookup table approach and the adiabatic approximation. On the other hand, the eastern part of the Alpine slopes in southern Germany indicates ground fog but is significantly smaller especially for the lookup table approach.

To test the reliability of the retrievals, the results are compared with the visibility observations at 113 SYNOP stations of the German Weather Service. Although the spatial distribution of areas with ground fog is in general accordance with the SYNOP observations 14 min after satellite overpass, several misclassifications seem to occur, as is shown in the contingency analysis (coefficients are defined in the appendix). In general, the contingency coefficients (Table 5) and the pseudo–receiver operating characteristic (ROC) diagram (Fig. 13) reveal that the lookup table approach gives the best representation of the SYNOP observations even if 28% of the pixels are incorrectly classified [error (ERR) = 0.28]. However, the portion of misclassified SYNOP stations increases to 34% for the Minnis approach, which shows the poorest performance (for possible reasons refer to section 4a). The probability of detection (POD) illustrates that especially in the case of the lookup table approach (POD = 0.76) a fairly high number of SYNOP stations with fog observations (VIS ≤ 1 km) are well detected by the retrieval scheme. It should be stressed that the detection quality significantly decreases, especially for the two empirical approaches, which rely on optical depth only (Mi, HS). Unfortunately, the false alarm ratio (FAR) is rather high for all thickness retrievals, again with the best performance of the lookup table approach. The relatively high FAR coefficients mean that pixels identified as fog display VIS > 1 km at SYNOP stations.

3. Evaluation of misclassified pixels

Apparently misclassified grid cells have been especially examined. The relevant stations contributing to the high false alarm ratio show that the mean overestimation of cloud base (39 m) is within the error margins of the top-height retrieval (±50 m). Seventy-one percent of these stations report visibilities < 5 km (mist) and most of them are characterized by a very low ceiling. The stations with great deviations (overestimation of cloud base > 100 m) are examined in detail. There is a group of pixels in the northeastern region (five stations: Greifswald, Angermünde, Bath, Leinefeld, Kaltennordheim) where the albedo signal of the stratus cloud is contaminated by thin cirrus, which increases the albedo (and, hence, the retrieved thickness) but does not lead to an exclusion during the initial stratus classification. In a recent study, Nasiri and Baum (2004) were able to show that MODIS daytime data can be used to detect optically thin cirrus clouds (optical depth > 0.1) over lower-level water clouds by using near-infrared reflectances and the 11-μm brightness temperature. A comparable algorithm is presented for MODIS nighttime data, which uses the CO2-slicing method (15-μm-band data) and the bispectral cloud phase discrimination technique based on 8.5- and 11-μm IR bands (Baum et al. 2003). For the current scheme, a proper separation of the multispectral albedo of the low stratus and the contaminating thin cirrus would be a precondition for retrieving the thickness of the stratus cloud and, hence, for a proper discrimination of fog and low stratus under thin cirrus cover. However, the separation of both signals is not yet realized in the published algorithms mentioned above.
Three other stations (Nürburg, Lichtenhain, Kempen) are edge pixels of the initial stratus mask and, hence, uncertainties can occur due to possible collocation errors or fog clearance in the time between SYNOP observation and satellite overpass. Removing suspicious pixels from the validation statistics produces significantly better results. For the lookup table approach, the FAR is reduced from 0.48 to 0.39 and the percentage error decreases from 28% to 22%. The CSI increases from 0.43 to 0.51. Furthermore, 63% of the SYNOP stations reporting fog but assigned to low stratus by the presented scheme are characterized by light fog with visibilities >500 m.

5. Discussion and conclusions

The proposed scheme for discriminating between low stratus and ground fog shows encouraging perfor-
mance, especially by using the newly developed lookup table approach for the retrieval of stratus geometrical thickness. However, the percentage error of 28% and especially the relatively high false alarm ratio must be examined in future studies. Although the presented method does not yet allow an indisputable distinction between ground fog and low-level stratus, as indicated by the percentage error, the results of the current study represent a clear step forward in fog detection from space. The current implementation should be useful for nowcasting purposes in areas without ground observations of visibility (e.g., along motorways) because a value of $Z_B$ [Eq. (1)] equal to or below the terrain altitude indicates at least a high probability of ground fog. By adapting the procedure to geostationary orbit (to MSG-SEVIRI), the diurnal dynamics of fog (e.g., uplift in the course of solar heating) can be examined on a spatial basis. Additionally, the retrievals can also be used for spatial comparison with NWP models that are devoted to the forecast of fog formation and clearance.

It should be stressed that there are several uncertainties when comparing SYNOP data and satellite retrievals that will never allow for a perfect fit of both datasets. First, SYNOP data are point observations that are compared with pixel values. The spectral albedos used represent spatially integrated counts over the $1 \times 1$ km$^2$ pixel environment. Consequently, the subpixel ground truth at a SYNOP station could significantly diverge from these values. Second, there is no quality information on visibility data that are partly taken by human observers. Because visibility is a meteorological element with a very high variability in time and space, the time lag between a SYNOP observation in hourly resolution and a satellite overpass is also a problem for a proper comparison of both datasets. Additionally, slight collocation errors of the satellite and SYNOP data can lead to blurred validation statistics.

One important source of uncertainty is in the retrievals. In particular, the method used for extracting the stratus-top height has significant limitations in complex situations like those of the extended stratus layer on 14 January 2002. It should be kept in mind that under optimal conditions low stratus-top height can be determined with an error of $<\pm 50$ m. One planned improvement is to use an entity-based calculation of the stratus-top height, which should reduce the uncertainty in the top-height retrieval especially during fog situations with a patchy top-height structure. This procedure will be based on the segmentation of the binary low stratus mask. Each single low stratus patch (= entity) has to be assigned a specific ID by means of connected-components labeling (e.g., Lumia et al. 1983). Then, height extraction by spatial interpolation as described in section 1 will be applied to each individual low stratus entity. In particular, small-scale variations in low stratus-top height as caused by locally elevated basins are expected to be retrieved with higher accuracy.

The distinction between ground fog and low stratus according to Eq. (1) should be reconsidered in the future. By applying the current decision rule, even very small numbers of $(Z_B - Z_{DEM})$ lead to an unambiguous result that may not be realistic in light of the occurring errors and uncertainties in the retrieval schemes. A fuzzier definition could be used to describe the probability that a low stratus layer has ground contact and could be implemented in a fashion similar to the MODIS cloud product (Ackermann et al. 1998), where the probability of cloud contamination of a pixel is derived from the results of a set of spectral tests. The validation data of the two case studies indicate that a range of $(Z_B - Z_{DEM})$ between 50 and $-50$ m could be useful for defining a linear increase of probability for ground contact from 0 to 1. However, the proper derivation of such
a function requires future investigations on the basis of a more comprehensive dataset.

The presented scheme is developed for MODIS daytime data. However, nighttime application should be possible if geometrical thickness or optical depth–liquid water path (for the empirical relations) could be related to infrared emissivity. Allam (1987) concluded on the basis of radiative transfer calculations that the brightness temperature difference between 3.9- and 11-µm bands can be used for thickness retrieval if the droplet spectrum of the low stratus layer is known. Algorithms for the determination of optical and microphysical properties (especially effective radius) by means of emissivities at 3.7, 8, 11, and 12 µm during nighttime are available but in comparison to daytime schemes are generally less accurate (e.g., Lin and Coakley 1993).

It should be stressed that one great advantage of using MODIS data for remote sensing of fog is the better spatial sampling in comparison to the geostationary orbit. Based on the empirical relations or the adiabatic approximation, the scheme could also be applied to the MODIS 250-m bands if optical depth was retrieved from MODIS band 1 at 0.65 µm exclusively (Bendix 1995a). An example for the advantages of using MODIS high-resolution data is presented elsewhere (B05). It shows that a synergetic use of high-resolution MODIS data with geostationary data could help to determine the relative subpixel fog coverage in a lower-resolution (geostationary) image, which has been proven to be important for valley fog detection in narrow river valleys in Germany.

Ongoing studies will focus on the adaptation of the presented procedures especially to the new European geostationary platform [Meteosat Second Generation SEVIRI imager, MSG-1 (Meteosat-8)]. One key issue will be the quality of performance during low solar elevation angles (especially in the twilight zone). The sensitivity of the presented scheme with regard to the solar zenith angle has not been examined in the current study because this is normally not a problem at the relatively fixed MODIS overpass times. However, several investigations show that the accuracy of optical and microphysical property retrievals from satellite data, which are the basis for the thickness calculation, decreases for low solar elevation angles <5° (e.g., Nakajima and Nakajima 1995; Bendix 1995a). When adjusting the scheme to the geostationary orbit, this problem has to be examined in more detail.

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APPENDIX

Contingency Analysis Coefficients

Definitions of the coefficients are as follows:

False alarm ratio:

\[ \text{FAR} = \frac{\text{yn}}{\text{yy} + \text{yn}} \]

Probability of detection:

\[ \text{POD} = \frac{\text{yy}}{\text{yy} + \text{ny}} \]

Critical success index:

\[ \text{CSI} = \frac{\text{yy}}{\text{yy} + \text{yn} + \text{ny}} \]

Percentage error:

\[ \text{ERR} = \frac{\text{ny} + \text{yn}}{\text{yy}} \]

Hit rate:

\[ \text{HR} = 1 - \text{ERR} \]

Above, yn = percentage of pixels classified as fog but low stratus in SYNOP data, ny = percentage of pixels classified as low stratus but fog reported by SYNOP data, yy = percentage of pixels with fog in both datasets, and nn = percentage of pixel with low stratus in both datasets.

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