An analysis of the frequency and distribution of ducting events in simulated radio occultation measurements based on ECMWF fields

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Abstract. A study of the occurrence of ducts valid at GPS frequencies in the European Center for Medium Range Weather Forecasts (ECMWF) atmospheric fields is presented. A radio occultation simulator has been applied to determine the mean location of the occultations for a 10 day period in May 2001. In total, 5348 occultations were found. Refractivity profiles have been calculated at the mean occultation location, by extracting temperature and water vapor profiles from ECMWF data. The gradient of refractivity with respect to altitude was analyzed for ducting conditions, which occurs below about -160 N-units/km. About 10% of the simulated measurement profiles show ducts. Polar ducting events are mainly occurring over land, very close to the surface. Mid-latitude ducting events are almost evenly distributed over land and sea, where land events are close to the surface too. Tropical ducting events are mainly located over the sea. Events over the sea show ducts within a vertical altitude interval of 0 km to 2.5 km. Tropical events tend to occur at higher altitudes than mid-latitudes ones. The thickness of the layer over which ducting conditions occur increases with altitude, and reaches about 120 m for higher altitudes. Near surface ducting events show the lowest refractivity gradients. Higher up in the atmosphere the gradient increases, where tropical events are generally lower. The found gradient does not support ducting conditions above about 2.5 km. Based on our study, about 4% of all occultations can be affected by ducts in the altitude range of 0.2 km to 2.5 km. The number of affected occultations depends on the latitude band, none are found at polar latitudes, 2% are at mid-latitude, and about 10% are at tropical locations.

1. Introduction

Global Navigation Satellite Systems (GNSS), such as the American Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), or the planned European Galileo system, provide a continuous source of signals at radio frequency of about 1.5 GHz. These signals can be used in various ways for atmospheric remote sensing. In particular low Earth orbit (LEO) satellite based receivers are capable of global coverage profile information on temperature and water vapor [Kursinski et al., 1997].

A first proof-of-concept mission for radio occultation was the GPS Meteorology (GPS/MET) experiment, led by the University Corporation for Atmospheric Research (UCAR) in Boulder, U.S.A. [Ware et al., 1996]. The instrument was launched in April, 1995 onboard the small research satellite MicroLab-1. The mission continued until March, 1997, measuring up to 150 GPS settings per day during dedicated periods. Further currently active missions applying the radio occultation principle include the CHAMP [Reigber et al., 2000] or SAC-C satellites [Hajj et al., 2002b].

Radio occultation measurements can provide temperature profile information from about 40 km altitude down to the lower troposphere and water vapor profiles in the lower tro-
posphere. Validation of temperatures derived from radio occultation data with numerical weather prediction (NWP) models, radiosondes, and satellite radiometers shows statistically good agreement of 1-2 K in the range of 5 to 25 km altitude [Kursinski et al., 1996; Rocken et al., 1997; Wickert et al., 2001; Hajj et al., 2002a]. Data in the lower, moist troposphere is usually presented in terms of refractivity, and validations with NWP models have shown a negative bias in this region [Rocken et al., 1997]. In addition, radio occultation data is often corrupted in the lower troposphere. The corruption and the bias depend on latitude, they are stronger in the tropics than in polar regions [Sokolovskiy, 2001].

Several factors are discussed that can cause this bias and corruption, including the momentary disappearance of the occulted signal caused by atmospheric ducts [Hajj et al., 2002b]. Ducting conditions affecting radio occultation data are usually associated with a strong vertical gradient of specific humidity in the lower troposphere and can be produced at or near the top of the planetary boundary layer [Kursinski et al., 1997], especially when clouds are present [Sokolovskiy, 2001].

But ducting conditions can occur at lower altitudes as well. An introduction into the occurrence of ducts is for example given in Hsu [1988]: Ducts over the sea are usually separated into evaporation ducts and elevated ducts. Evaporation ducts are caused by the rapidly decreasing water vapor with height. They occur within about 30 m above the surface and are found over relatively warm water. Elevated ducts can be caused by temperature inversions aloft, generated by sinking or subsidence of air masses, as for example off the western coasts of the continents, particularly in areas with cool upwelling water from the bottom to the surface. Another cause is the diurnal warming and cooling of the planetary boundary layer (PBL). Diurnal variations of the PBL are much smaller over the sea than over the land, due to the large heat capacity of water. Consequently, large temporal and spatial variability exists in the PBL height across the coastal zone.

A study of ducts based on 6 years of radiosonde profiles is presented in Patterson [1982], but no global information is currently available on the number of occultations affected by elevated ducts. Based on European Center for Medium Range Weather Forecasts (ECMWF) atmospheric analysis fields of temperature, water vapor, and surface pressure we find the number of occultations affected and the characteristics of these ducting events. This paper discusses in Section 2 the study setup. Section 3 discusses the underlying ECMWF data potential and limitations for the detection of ducting events, while Section 4 analyzes the locations where ducts occurs with respect to altitude and location. Section 5 investigates the impact of water vapor on ducts. A further analysis with respect to altitude is presented in Section 6, where events are separated into sea and land locations. Section 7 deals with the thickness of the layer over which ducting occurs, Section 8 deals with the minimum in the refractivity gradient, and Section 9 analyzes the variability in these two parameters. Section 10 summarizes the findings and Section 11 lists areas of future research.

2. Study Setup

We use simulated radio occultation measurements made by a single LEO satellite for a 10 day period in 2001. An assimilation study, determining the impact of radio occultation data on a Numerical Weather Prediction model is under way at the Naval Research Laboratory, and we thus focus on the same period: May 18 to May 27, 2001. One LEO satellite, using only signals of the GPS constellation, would be able to detect about 250 setting events and 250 rising events per day [Kursinski et al., 1997], a fully installed GLONASS or Galileo system would double the number of soundings.

The End-to-end GNSS Occultation Performance Simulator (EGOPS [Kirchengast, 1998; Kirchengast et al., 2002]) tool was used to derive the location of the mean tangent points. EGOPS reads in orbit parameters for the GNSS and the LEO satellites and predicts in a first step approximated occultation locations. Orbit parameters for the LEO satellite are based on the planned MetOp-1 satellite (orbit altitude 835 km, orbit inclination 98.7°). The existing GPS constellation is used as the source of radio frequency signals.

Within EGOPS, the occultation locations are determined based on the positions of the satellites and the influence of the atmosphere on the ray. The atmospheric influence is approximated by a simple bi-exponential atmospheric model consisting of a dry component (bulk atmosphere) and a wet component (water vapor distribution) in this study. Both dry air density and water vapor density are assumed to decrease exponentially with height based on a constant scale height [Kirchengast, 1998]. Occultation locations derived from this simplified atmospheric model are very close to locations calculated by a ray tracer [von Engeln et al., 2003].

The 10 day period of simulated measurements used here ensures almost complete coverage over the globe. However measurement coverage with respect to local time is not randomly distributed, hence regions tend to be sampled at similar local times over this 10 day period. By using the occultations calculated in EGOPS we are able to accurately simulate the spatial and temporal coverage provided by a single LEO receiver.

For the 10 day period chosen we find a total of 5348 setting and rising occultations that are almost uniformly distributed over the Earth’s surface. These were analyzed for
the occurrence of ducting events. In our analysis, we separate these occultations according to latitude θ into three different bands: polar (|θ| ≥ 60°; 1374 occultations), mid-latitude (30° ≤ |θ| < 60°; 2090 occultations), tropical (|θ| < 30°; 1884 occultations).

The atmospheric variables at the EGOPS derived mean tangent point are then extracted from global high resolution ECMWF atmospheric field. We use atmospheric fields with 60 vertical model levels and a horizontal resolution of about 0.351° (T51L60) in 6 h time-intervals [Miller, 1999; Teixeira, 1999b; Jakob et al., 2000]. The resulting vertical resolution of the ECMWF model levels is: 20 m, 150 m, 200 m, and 300 m around 0.0 km, 0.5 km, 1.0 km, and 1.5 km altitude respectively. Refractivity $N_r$ is calculated at each level $i$ following the formula given by Smith and Weintraub [1953]:

$$N_r = 77.6 \frac{p_i}{T_i} + 3.73 \times 10^5 \frac{e_i}{T_i^2}$$

(1)

where $p_i$ is the atmospheric pressure at level $i$ in [hPa], $T_i$ the atmospheric temperature at level $i$ in [K], and $e_i$ the water vapor partial pressure at level $i$ in [hPa]. ECMWF temperature and water vapor profiles are cubic-spline interpolated in the vertical to a 20 m resolution, thus retaining the high resolution of ECMWF fields at low altitudes. In the horizontal a polynomial interpolation is applied to determine the exact value at the mean tangent point. This approach is an approximation to the limb geometry of radio occultation and assumes a horizontally homogeneous atmosphere around the tangent point. Thus the horizontal extent of the ducting layer in the 3-dimensional ECMWF field has been neglected in this setup. Surface topography has been removed from the profiles, thus the altitudes shown indicate the distance from the Earth’s surface.

The gradient $dN/dr$ of the refractivity $N$ with respect to altitude $r$ is used to classify the profiles [Almond and Clarke, 1973]. Layers where $dN/dr$ is positive are called subrefractive. These conditions lead to radio waves being refracted away from the Earth’s surface. Layers with $dN/dr$ between -76 km$^{-1}$ and 0 km$^{-1}$ show normal refraction. Layers with $dN/dr$ between -76 km$^{-1}$ and about 160 km$^{-1}$ are called super refractive. Critical refraction occurs when the radius of curvature of the ray is equal to the radius of curvature of the atmosphere and the ray will propagate at a fixed height above the surface. Ducts appear when $dN/dr$ leads to rays that curve down into the surface at low altitudes, thus:

$$\frac{dN}{dr} \leq -10^6 \frac{1}{R_c}$$

(2)

where $R_c$ is the radius of curvature of the atmosphere. This condition is fulfilled when $dN/dr$ is less than -160 km$^{-1}$ for a mean value of $R_c$ [Kursinski et al., 1997].

3. ECMWF data

The high vertical and horizontal resolution of ECMWF data and the representation of the PBL are key elements for an investigation of ducts in the model data. Both elements are discussed more thoroughly within this section, where the potential and limitations of the model data are outlined.

Ducting events over the sea will generally follow the PBL, since sharp gradients of specific humidity and temperature occur at the PBL top [Hsu, 1988]. Model based investigations into the PBL at subtropical latitudes off the coast of California show that the PBL will grow down the trade winds due to higher sea surface temperatures and lower subsidence [Teixeira and Hogan, 2002]. Thus ducting events will occur at higher altitudes further from the coast. Furthermore, the gradient decreases with distance from the coast, hence less events with larger layer thickness will occur.

An investigation of ducting conditions near the coast of California showed events at altitudes varying from 0.32 km to 0.46 km with layer thicknesses (i.e. the vertical extent over which ducting persists) of about 100 m [Haack and Burk, 2001]. Similar results are found in a comparison of model simulations and aircraft observations (ATEX) of stratocumulus [Duynkerke et al., 1999], where the top of the PBL is located at 0.6 km with a thickness of 100 m. Observation campaigns downwind of the trades show that when there are cumulus under stratocumulus the PBL grows to about 1.5 km and there is an inversion thickness of about 200 m (ATEX [Stevens et al., 2001]). In a typical cumulus situation the PBL grows to about 1.75 km with an inversion thickness of 400 m (BOMEX [Siebesma et al., 2003]).

ECMWF is using model levels in the vertical, which are surface pressure dependent. The vertical resolution of the data, as given above, is sufficient to investigate ducting events within the PBL at altitudes up to at least 1.5 km. Very thin layers will not be captured by the ECMWF data, but thin layers are less likely to influence radio occultation data, owing to diffraction [Kursinski et al., 1997]. Only strong events at altitudes above 1.5 km will be captured, due to the decrease in vertical resolution. The horizontal resolution has to be sufficient as well, since a too coarse resolution will smooth out the gradients in the vertical because data is averaged over larger regions.

The impact of a coarser vertical resolution on $dN/dr$ for a ducting event at the top of the PBL is shown in Figure 1, where the original 20 m resolution has been boxcar averaged with widths varying from 10 to 40 vertical grid points. Ducting conditions are reached at about 0.9 km altitude, and continue up to about 1.1 km. A boxcar average of 10 grid points retains this ducting layer as expected since the vertical resolution of the underlying ECMWF data is about 200 m, only
the amplitude is reduced. Older versions of the ECMWF model using 31 vertical levels had a vertical resolution of 70 m at the surface, and about 350 m at 1.0 km [Teixeira, 1999b]. These coarser resolutions will smooth out the layer, thus causing ducting conditions to disappear. This is already evident in the 20 grid point boxcar average. Hence coarser model resolutions will severely underestimate the number of ducting events, since only very strong layers will still be visible. In addition events will be broader with a coarser resolution, as is evident from Figure 1. This is also a limiting factor for ducting events found higher up in the atmosphere for this dataset. Kursinski et al. [1997] use a radiosonde profile obtained over Hilo, Hawaii for an investigation into ducting conditions at about 4 km altitude, with a layer thickness of the duct of only 80 m. The ECMWF dataset used here is not sufficient for an investigation at these altitudes.

A correct representation of the PBL within the ECMWF model is especially important as noted above. The following physical parameterizations in the ECMWF model can have a profound impact on the temperature and humidity structure of the PBL: the prognostic cloud scheme [Tiedtke, 1993], the moist convection scheme [Tiedtke, 1989], the vertical diffusion parameterization [Beljaars and Betts, 1993; Louis et al., 1981] and the soil/surface scheme [Viterbo and Beljaars, 1995; Viterbo et al., 1999].

A detailed comparison between radiosondes and ECMWF model profiles has been carried out in order to investigate how realistic the ECMWF predictions of PBL height are. Twenty-four hour forecasts are compared against radiosondes from 10 locations over the ocean (see Table 1 for locations). These correspond to island stations located in the Atlantic and Indian oceans. The height of each station is usually not much above sea level in order to represent as realistically as possible the ocean conditions.

Twelve days are analyzed with a total of 120 radiosondes, from which 86 were selected. The ones that were not selected correspond to situations where the inversion was not clearly defined. These days correspond to forecasts verifying on June 2nd to June 13th, 1996. The observed mean inversion height for these 10 locations is about 855 hPa, whereas in the ECMWF model it is about 857 hPa. This gives a bias of about 2 hPa (around 20 m) for the ECMWF forecasts of the PBL height, which can be considered a very positive result. The RMS error is about 30 hPa (around 300 m).

In Figure 2 a scatter plot of the observed versus the model (24 h forecasts) inversion height is shown. It can be seen that the ECMWF model slightly overestimates the boundary layer depth from the surface up to about 900 hPa and slightly underestimates it above 850 hPa. It should be noted that the PBL height in the analysis and in the 24 h forecast is usually very similar.

The representation of boundary layer inversions in the ECMWF model has been also extensively validated by several studies for many different physical situations: Beljaars and Betts [1993] show how a new k-profile [Treon and Mahrt, 1986] closure for dry convection situations substantially improves the PBL inversion in the model; Duynkerke et al. [1999] show that the single-column version of the ECMWF model is able to capture some of the fundamental characteristics of the stratocumulus PBL during the Atlantic Stratocumulus Transition Experiment - ASTEX [Albrecht et al., 1995; Bretherton and Pincus, 1995]; Duynkerke and Teixeira [2001] compare the ECMWF Re-Analysis data against observations during the FIRE [Albrecht et al., 1988] stratocumulus observational campaign off the coast of California and show that the inversion structure is realistically described by the ECMWF model; Bretherton et al. [1999] compare the ECMWF single-column model simulation of the transition from stratocumulus to cumulus during ASTEX against observations and show that the ECMWF model is able to capture the most important properties of this transition, including in particular the growth of the PBL height and the widening (in the vertical) of the PBL inversion.

4. Occurrence of Ducts

In total, 536 occultation events showed ducting conditions. Figure 3 shows the locations of these events, using a color code to indicate the altitude where the minimum in \(\frac{dN}{dr}\) is found.

Several events at polar latitudes show ducting conditions, mostly over land, especially on the Antarctic continent. All polar ducting events are found in the lowest 200 m of the atmosphere. Mid-latitude events showing ducting conditions are roughly equally distributed over land and over the ocean. Events over land are again found in the lower atmosphere, while events over sea can be found up to almost 2.5 km. Tropical events showing ducting conditions are mainly found over the sea.

While a discussion of all regional events would go beyond this study, the following specific areas of duct occurrence can easily be identified:

1. The presence of ducting events in the lower parts of the PBL, over the East and West coasts in the Northern hemisphere can be attributed to fog [Hsu, 1988; Teixeira, 1999a]. Fog and low stratus clouds are also quite frequent over bays and lake regions during the spring and summer months of the Northern Hemisphere, e.g. [Pettersen, 1969; Warren et al., 1986]. The strong long-wave radiative cooling (of up to the order of a degree per hour) and evaporative cooling from the top of the fog (or stratus cloud) will strongly contribute...
Figure 1. Impact of different vertical resolutions on a ducting layer at 1.0 km. Occultation location is at 25.6° N, 134° W near the coast of California. Number of grid points entering the boxcar average is given in legend.

Table 1. Radiosonde station locations used for a comparison with ECMWF PBL heights.

<table>
<thead>
<tr>
<th>Station</th>
<th>Lat</th>
<th>Lon</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAL (Cape Verde)</td>
<td>16.73</td>
<td>-22.95</td>
</tr>
<tr>
<td>MARTIN DE VIVIES (Ile Amsterdam)</td>
<td>-37.8</td>
<td>77.53</td>
</tr>
<tr>
<td>FORT-DAUPHIN (Madagascar)</td>
<td>-25.03</td>
<td>46.95</td>
</tr>
<tr>
<td>VACOAS (Mauritius)</td>
<td>-20.3</td>
<td>57.5</td>
</tr>
<tr>
<td>FUNCHAL (Madeira)</td>
<td>32.63</td>
<td>-16.9</td>
</tr>
<tr>
<td>SEYCHELLES INTER. A/P</td>
<td>-4.68</td>
<td>55.53</td>
</tr>
<tr>
<td>TENERIFE (Canary Is.)</td>
<td>28.45</td>
<td>-16.25</td>
</tr>
<tr>
<td>ST. HELENA IS.</td>
<td>-15.93</td>
<td>-5.67</td>
</tr>
<tr>
<td>WIDE AWAKE FIELD (Ascension Is.)</td>
<td>-7.97</td>
<td>-14.4</td>
</tr>
<tr>
<td>DIEGO GARCIA</td>
<td>-7.35</td>
<td>72.48</td>
</tr>
</tbody>
</table>

Figure 2. PBL height from radiosondes versus the PBL height from the ECMWF model.
to the strengthening of the inversion and consequently to the occurrence of ducting regions in the profiles. It has been shown that the ECMWF model is capable of reproducing the main characteristics of the global fog climatology [Teixeira, 1999a].

2. Mid-latitude events around 35° N, 130° W are caused by the sharp gradient of specific humidity and temperature that occurs at the PBL top associated with stratuscumulus clouds. The altitude where ducting conditions are present increases with distance from the coast line, as discussed in Section 3.

3. Mid-latitude events over the Mediterranean Sea, Black Sea can cause ducts in the lower atmosphere, near the coast line. These evaporation ducts are likely to be caused by sea breeze effects [Hsu, 1988].

4. Tropical events close to the West coast of the Americas and Africa occur at low altitudes and are caused by the sharp gradient of relative humidity and temperature associated with stratuscumulus clouds in the PBL. The events further to the West and toward the Equator are at higher altitudes, and are associated with trade wind cumulus. The higher altitudes of the events further from the coasts is consistent with data presented in Patterson [1982], who found that the mean top of the elevated ducts is at about 1.7 km.

5. Tropical events in the Red Sea, Persian Gulf, and on the South-East coast of Yemen, Oman are found mainly at low altitudes. Slightly elevated ducts are found further away from the coasts of Yemen, Oman. Surface based ducts have already been documented over the Persian Gulf in Brooks et al. [1999], they can be attributed to the surrounding desert landmasses. The flow of warm dry air from the desert over cooler and humid waters of the Gulf causes a strong gradient in refractivity. High specific humidity is seen as well at the 2 m level in NCEP-NCAR reanalysis data [Kistler et al., 2001] over the sea. Elevated ducts off the coast of Oman are observed in Hsu [1983], where the altitude of the duct increases with distance from the coast.

6. Tropical events in the Gulf of Mexico are mainly found near the coast, at low altitudes, and thus can be attributed to sea breeze effects as well. NCEP-NCAR reanalysis data [Kistler et al., 2001] at the 1000 hPa and 850 hPa level shows that dry polar air masses meet more humid, tropical air masses in this region, which explains events found at higher altitudes.

7. Tropical events around 20° S, 160° W are found at a range of altitudes, and include the highest altitude ducting events. This area is known as the South Pacific Convergence Zone. NCEP-NCAR reanalysis data [Kistler et al., 2001] shows wave like structures in the specific humidity at the 1000 hPa level here, where tropical humid air meets dry polar air. Higher up in the atmosphere, a flow of humid, tropical air to polar, less humid air-masses is observed. Surface based and elevated ducts with mean altitudes up to about 1.7 km have also been found in Patterson [1982].

Preliminary results found in von Engeln et al. [2003] indicated that about 5% of the investigated occultations show ducting conditions, where none of the events was found at polar latitudes or near the surface. The difference to results presented here can be attributed to the slightly higher vertical resolution applied for the refractivity profiles, and the larger dataset.
5. Impact of Water Vapor on Ducts

Data has been further analyzed to determine the impact of water vapor on the ducting events. The dry refractivity gradient has been calculated at the altitude where the minimum was found in the wet refractivity gradient by neglecting the second term on the right hand side of Eq. 1. Figure 4 shows the strength of the dry refractivity gradient in terms of the critical refraction limit of \(-160 \text{ km}^{-1}\).

In particular, events at polar latitudes are caused by strong surface inversions which can produce ducting conditions based entirely on the dry term in Eq. 1. NCEP-NCAR reanalysis data [Kistler et al., 2001] shows low, but variable specific humidity over the Southern tip of Africa. While this alone is not always sufficient to cause a duct, Figure 4 shows that the majority of the events are close to ducting conditions based on the dry term in Eq. 1. Further analysis of these events reveals that the area is mainly sampled in the early night when surface based temperature inversions occur over the Kalahari desert (25°S, 20°E).

Similar patterns are observed over the deserts of Australia. The Sahara does not show many ducting events, even though it is sampled at a similar time as the Kalahari. The Sahara would not be expected to show as many ducting events in our simulated dataset both because in May the temperatures are higher than in the Kalahari, and because the sunset at this time of year will occur later in the day than in the Kalahari.

Almost all events over the sea/lakes, and at higher altitude are entirely based on the wet term in Eq. 1. Contributions from the dry term are below 30%.

6. Altitude of Duct

Figure 5 (left hand side) shows the number of ducts found in a certain altitude interval. Data has been averaged over 200 m vertical intervals, and data points have been plotted at the center of that interval.

About 18% of all ducting events fall into the polar domain, all within the lowest 200 m of the atmosphere. Further analysis shows that the majority is actually right above the surface, as was apparent from Figure 3. Thus dry ducting here is caused by strong surface inversions of temperature. About 25% of the events are found at mid-latitudes, they show a similar pattern as polar ones at low altitudes, i.e. most of them are right above the surface. Additionally, several mid-latitude events appear at higher altitudes up to almost 2 km, with a peak around 0.8 km. Tropical events account for almost 60% of all events with ducting. Near surface events show the same pattern as polar and mid-latitudes ones. Events higher up in the atmosphere peak around 0.9 km, but are found at altitudes up to about 2.3 km.

Applying a 1 degree resolution land-sea-mask, events have been further separated into sea locations (Figure 5, right hand side). As was already evident from Figure 3, polar events are mainly found over land, only about 8% of all polar locations are found over sea. Further analysis shows that polar ducts over the sea are within the lower 100 m of the atmosphere. About 60% of mid-latitude events and 76% of the tropical ones are over sea. As already found for the total distribution of tropical and mid-latitude events, most events in the lower 200 m of the atmosphere are very close to the sea surface. Almost all events at altitudes above 200 m are over sea.

7. Thickness of Ducting Layer

The thickness of the layer over which ducting conditions occur is shown in Figure 6. Data has been averaged over 200 m vertical intervals, and mean thicknesses have been plotted at the center of that interval.

The mean thickness of all near surface events is very small, about 30 m to 50 m. The application of the land-sea-mask shows that events close to the surface tend to be thicker over the sea. Based on the few polar events found over sea, results indicate that the mean thickness is about three times that found for events over land. As mentioned in Section 6, polar sea events near the surface are within the lowest 100 m of the atmosphere. Thus they can probably be attributed to a very low PBL at high latitudes associated with surface inversions.

The layer thickness increases with altitude up to about 0.5 km height for mid-latitude events, and to about 0.7 km for tropical events, caused by the increase of the height of the PBL, and a decrease in the relative humidity gradient [Teixeira and Hogan, 2002]. A scatter plot of all thicknesses reveals that the thickness of mid-latitude layers increases with altitude over the lower 0.5 km up to about 120 m, as visible in Figure 6, and is very variable above. A scatter plot of tropical events shows very similar features, but the data above 0.7 km is more variable. Generally, events at higher altitudes show a mean layer thickness of about 120 m, where tropical layers tend to thicker. These results are also found in Patterson [1982], where a mean duct thickness for elevated ducts over the sea of about 130 m is found. Another factor influencing the presented thickness results lies in the vertical resolution of the ECMWF atmospheric fields, as discussed in Section 3.
Figure 4. Strength of the dry refractivity gradient for ducting events in terms of the critical refraction limit of $-160 \text{km}^{-1}$ at the altitude where the minimum in $dN/dr$ is found.

Figure 5. Number of ducting events in certain altitude interval for all affected events (left) and sea events (right). The number in brackets give the total events in that band.
8. Minimum Gradient of Ducts

The minimum value found for $\frac{dN}{dr}$ is shown in Figure 7. Data has been averaged over 200 m vertical intervals, and mean minimum gradients have been plotted at the center of that interval.

Near surface events show the lowest gradients (Figure 7, left hand side). The restriction of these events to sea locations shows that mid-latitude and polar minimum gradients are slightly higher, while tropical events are slightly lower (Figure 7, right hand side). Hence near surface events at mid-latitude and polar regions tend to have lower gradients over land, while tropical events are lower over the sea.

The averaged minimum refractivity gradient above the surface increases with altitude, since the variability in the atmosphere decreases. Tropical events generally show lower refractivity gradients than mid-latitude ones, and they are still affected by the sea mask at 300 m where they show lower refractivity gradients when compared to all events.

The vertical extent of a ducting event in radio occultation data $\Delta r$ depends on the atmospheric vertical extent of the event $\Delta z$, and the ratio $\eta$ of $dN/dr$ to $-160 \text{ km}^{-1}$ [Kursinski et al., 1997]:

$$\Delta r \approx \eta \Delta z$$  \hspace{1cm} (3)

Figure 7 shows only the minimum found in the refractivity gradient, a more accurate approach would take into account the variability of $dN/dr$ over the ducting layer. Hence, combining Figure 6 and 7, a conservative estimate of $\Delta r$ in radio occultation data is around 150 m for altitudes between 0.5 km and 2.0 km, since $\eta$ varies between about 1.4 and 1.2 at 0.5 km, and 2.0 km respectively and the layer thickness is around 120 m.

The vertical resolution of radio occultation data is diffraction limited. It is about 0.5 km in the lower troposphere and increases to about 1.5 km at 40 km altitude [Kursinski et al., 1997]. The vertical resolution near a ducting event can be much higher, around 100 m to 200 m near strong gradients in $dN/dr$ [Kursinski et al., 1997]. Hence ducting events found here can limit the vertical coverage of radio occultation measurements.

9. Variability of the Ducting Layer

Variability of the ducting layer is investigated by analyzing the standard deviation of the mean layer thickness and the mean minimum refractivity gradient, as plotted in Figure 6 and Figure 7. Results are shown in Figure 8.

The layer thickness variability for near surface events is very high for all regions, ranging from about 40 m (polar) to about 60 m (mid-latitude, tropical), while mean values for the variability in all regions is around 35 m. The layer thickness of tropical and mid-latitude events at altitudes above 200 m are very similar, but variability is about double for tropical events.

The variability in the minimum refractivity gradient is highest for events near the surface. Mid-latitude and polar events show similar variabilities here, while tropical events have the highest variability. A decrease is found for altitudes above the surface, where tropical events again show the highest variability.
Figure 7. Mean minimum refractivity gradient found for all affected events (left) and sea events (right).

Figure 8. Standard deviation of layer thickness (left) and minimum refractivity gradient (right) for all affected occultations.
10. Conclusion

Radio occultation data has shown a great potential for deriving accurate temperature profile information for an altitude range of 5 to 25 km. RefRACTivities derived from radio occultation measurement below 5 km show a bias with respect to NWP models, and the raw data is frequently corrupted. Bias and corruption are latitude dependent, with the largest problems occurring in the tropics.

Several sources for this bias and corruption are currently discussed, ranging from instrumental effects to atmospheric effects. The variability especially of water vapor at low altitudes can contribute to these observed effects. Other possible sources include ducts, where the signal of the GNSS satellite is momentary lost. Ducts occur when the gradient of the refractivity with respect to altitude is less then -160 km/s.

We study the occurrence of ducts in ECMWF analysis fields by first determining the mean location of the occultation with the radio occultation simulator EGOPS. Atmospheric temperature and water vapor fields are then extracted out of the high resolution ECMWF (T511L60) fields, and the refractivity and its gradient with respect to altitude are calculated.

ECMWF data with its T511L60 resolution proves to be useful for an investigation of ducting events, both in terms of resolution and the representation of the PBL. Coarser model resolutions will only show very strong ducts at higher altitudes, thus underestimating the total number of events. The PBL representation agrees well with radiosonde data.

The present study encompassed 10 days in May 2001. A total of 5348 occultations were found for this period, out of which 536 showed ducting conditions. The majority of the ducting events are in the tropics, over the sea. Polar events are mainly over the land, while mid-latitude ones are about evenly distributed over land and sea.

The altitude where ducting conditions occur over land is almost always within the lowest 200 m of the atmosphere. These ducts are caused by inversions near the surface. Ducting events over land at polar latitudes and over deserts are generally almost entirely caused by the dry refractivity variability. Mid-latitude and tropical events appear at higher altitudes as well, up to 1.9 km and 2.3 km, respectively. All events at higher altitudes are over the sea. The altitude of mid-latitude and tropical events near the West coasts of Africa and the Americas follows the PBL, with higher altitudes further from the coast.

The mean thickness of the layer over which ducting conditions occur is usually very small for near surface events, about 30 m to 50 m. Events at higher altitudes show a mean thickness of about 120 m. Events near the surface tend to be highly variable, while events at higher altitude show lower variability. In the tropics they are more variable than at mid-latitudes.

The mean minimum in the refractivity gradient is highest for tropical events, and increases with altitude. Variability in the minimum refractivity gradient is highest near the surface, and decreases with altitude.

The number of occultations penetrating the lower atmosphere decreases significantly, especially in the tropics. While about 80% of all occultations penetrate altitudes down to 2 km, only about 35% of all tropical events reach below 0.5 km [Haji et al., 2002b]. Thus ducts occurring at altitudes above about 0.2 km are most likely to affect the propagation of radio occultation signals, while near surface ducts, within the lowest 200 m of the atmosphere, are less likely to be sampled by the satellite. In total, 225 events are found above 0.2 km. Out of these events, more than 80% fall into the tropical region, and the rest are at mid-latitudes. Globally about 4% of the occultations are affected at altitudes above 0.2 km, but there is a significant latitudinal dependence. In the tropics about 10% of the occultations are affected, while at mid-latitudes only about 2% show ducting. The number of occultations affected decreases with increasing altitude. Globally, 159 ducting events are found for altitudes above 0.5 km, 86 ducting events occur above 1.0 km, and only 33 events occur above 1.5 km respectively.

Ducting events found on the West coast of continents follow the trades. The transition from fog and stratus at the West coast of continents, to stratocumulus and finally to cumulus in the trades is a fundamental aspect of the dynamics of the tropics and sub-tropics (e.g. [Siebesma, 1998]). The trade inversion was found in the end of the 19th century and has been studied in detail at least since von Ficker [1936]. The impact of the sub-tropical boundary layer on human daily activities in these regions is enormous and it has been recently discovered that it has a fundamental role in the seasonal and climate dynamics of the tropics [Philander et al., 1996; Ma et al., 1996; Larson et al., 1999]. Detailed global observations of the dynamics of the sub-tropical boundary layer height are still lacking. The results shown in this paper suggest the usefulness of the occurrence of ducts as a tool to diagnose and analyze the boundary layer height in a global context, as opposed to local measurement campaigns.

It should be pointed out that results presented over here do apply to some currently discussed active microwave LEO occultations as well. These would utilize frequencies around 22 GHz or 183 GHz for active water vapor profile soundings. No distinct frequency dependence of a duct has been observed for frequencies of up to about 30 GHz [Pidgeon, 1970], thus our results are valid for active observations around 22 GHz too.
11. Future Research

While this study was limited to 10 days in May 2001, it has shown that ECMWF analysis fields can be used to derive valuable information about the occurrence, and the characteristics of ducts. Future research will focus on model data and observations:

1. Model data can be used to derive a global climatology of ducting events by extending the time period to at least one year. This will help to understand how the seasons affect ducting occurrences and further identify areas of high ducting occurrence.

2. Estimate the horizontal extent of ducting layers using model data. Results presented here apply only to the profile at the tangent point, but the larger the horizontal extent of the layer, the larger the impact on radio occultation data.

3. Model data with a high temporal resolution can be used to investigate the dependence of regional ducting events on local time, e.g. PBL and fog evolution. Our data set does not allow these kind of investigations, since data of this satellite orbit is only geographically about equally distributed over the globe, not with respect to time. Hence specific areas tend to be sampled at similar universal times.

4. Further relate regional ducting events to meteorological patterns, e.g. sea breeze effects, convergence zones, larger scale weather patterns (as discussed in e.g. Rosenthal [1976]; Gossard and Strauch [1983]) by focusing on model data and observations.

5. Use higher vertical resolution models and radiosondes to derive ducting characteristics at higher altitudes. A six year climatology of ducting events based on radiosonde data has been performed by Patterson [1982], but radiosondes are mostly launched over land.

6. Relate the minimum of the refractivity gradient to the PBL top. This work focused on ducting events, but the minimum of the refractivity gradient usually appears at the height of the PBL.

7. Identification of ducting events in radio occultation and radiosonde observations. These events can be used to first validate model results and second to derive valuable information about the ducting occurrence and characteristics.

8. Derive corrections to the impact of ducting events in radio occultation data in order to allow accurate recovery of the refractivity structure below the ducting event.

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