Evaporation Duct Profile Comparisons

Using Kites and Bulk Methods

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Introduction

An important tool in understanding the behavior of UHF, VHF and microwave frequencies in the troposphere is the modified index of refraction (or modified refractivity), M. M is strongly dependent on three atmospheric parameters: pressure (p), temperature (T), and the partial pressure of water vapor (e). For frequencies greater than 3 GHz, strong gradients of T and e near the surface can lead to evaporation ducting, leading to significant increases in propagation distances compared to the standard atmosphere. Since these gradients cannot normally be measured precisely near the surface, bulk methods are used to approximate the profile of M. The purpose of this study is to measure p, T and e directly (using a kite) in order to compare the results with those obtained from bulk measurements.

Background

The index of refraction, n, of the atmosphere determines what will happen as waves pass through it. The value of n is very close to 1, so \( N=(n-1) \times 10^6 \) is used. The actual value of N is not important, but the gradient of N with respect to z is. The following table illustrates the relationship between N and the distance to the horizon.

<table>
<thead>
<tr>
<th>Class</th>
<th>dN/dz</th>
<th>Distance to Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>subrefraction</td>
<td>( dN/dz &gt; 0 \text{ km}^{-1} )</td>
<td>reduced</td>
</tr>
<tr>
<td>normal</td>
<td>( 0 \text{ km}^{-1} &gt; dN/dz &gt; -79 \text{ km}^{-1} )</td>
<td>normal</td>
</tr>
<tr>
<td>superrefraction</td>
<td>( -79 \text{ km}^{-1} &gt; dN/dz &gt; -157 \text{ km}^{-1} )</td>
<td>increased</td>
</tr>
<tr>
<td>trapping (ducting)</td>
<td>( dN/dz &lt; -157 \text{ km}^{-1} )</td>
<td>greatly increased</td>
</tr>
</tbody>
</table>
It is obvious from the table above that it is difficult to identify regions of ducting from visual inspection of a profile of \( \frac{dN}{dz} \). This problem is alleviated by the use of \( M \), where \( M = N + (157 \text{ km}^{-1})z \). Since \( \frac{dM}{dz} = \frac{dN}{dz} + 157 \text{ km}^{-1} \), ducting will occur when \( \frac{dM}{dz} < 0 \). If this occurs only close to the surface, the duct is likely due to evaporation and is thus deemed an evaporation duct. The level at which \( \frac{dM}{dz} = 0 \) is the evaporation duct height. Evaporation is favorable for duct formation due to the existence of a strong negative vapor pressure gradient near the surface. \( M \) can be calculated directly (see attachments “esat2.m” and “mod_refract.m”) using measurements of pressure, air temperature and vapor pressure (derived from relative humidity) using the following equation:

\[
M = 77.6 \frac{P}{T} - 5.6 \frac{e}{T} + 375000 \frac{e}{T^2} + 0.157z
\]

In addition to direct calculation, a profile of \( M \) versus \( z \) can also be obtained using bulk methods. Using the equation below, the partial derivatives of \( N \) as well as the variation of pressure with height are assumed to be constant.

\[
\frac{dM}{dz} = \frac{\partial N}{\partial q} \frac{\partial q}{\partial z} + \frac{\partial N}{\partial T} \frac{\partial T}{\partial z} + \frac{\partial N}{\partial p} \frac{\partial p}{\partial z} + 157 \text{ km}^{-1}
\]

This leaves only the vertical gradients of \( T \) and \( q \) to be determined. These gradients are assumed to have a certain shape based on the Monin-Obukhov scaling length, which requires knowledge of the vertical profile of wind speed. Omitting the rather lengthy details, a profile of \( M \) versus \( z \) can be obtained with single measurements of air temperature, surface temperature, wind speed, relative humidity and pressure and the heights at which these measurements were taken (see attachments “evap_duct_model.m,”)
“evap_duct_profile.m,” “scaling_params.m,” “spec_hum.m,” “stability_m.m” and “stability_t.m” for details of this iterative method).

Measurements

In this experiment, four independent systems were used to measure the atmospheric variables needed to calculate M directly and also those needed to obtain profiles of M using bulk methods. R/V Point Sur’s Serial ASCII Interface Loop (SAIL) system (see attachment “SailFeb10.txt”) was used to obtain air temperature, wind speed (port true wind speed), relative humidity, pressure and sea surface temperature (boom probe temperature). The data was received after being averaged over 52 to 58 second intervals. All of the instruments (excluding the boom probe) were mounted 17 meters from the sea surface. An independent system operated by the Naval Postgraduate School (NPS) meteorology department (see attachments “Channels for Feb 2001 Student Cruise: R/V Point Sur” and “cruiseFeb10.txt”) collected air temperature, wind speed, relative humidity, pressure, and infrared detected sea surface temperature. The data was sampled every five seconds and was received after being processed using two-minute integrations. The wind speed, air temperature, relative humidity and pressure were measured from 13.6 meters, 10.6 meters, 10.6 meters and 10.1 meters above the sea surface, respectively. A rawinsonde attached to a kite (see attachment “KiteFeb1020z.txt”) was used to collect air temperature, relative humidity, pressure, dew point temperature and height. This was done three times, 08Feb2001 at 1600 UTC and 10Feb2001 at 1700 UTC and 2100 UTC. The data was sampled every two seconds for a total of two hours for each flight as the kite was raised and lowered. Additionally, a hand-held infrared detector was used to
measure sea surface temperature (see attachment “Quick Observation Data Sheet”). This was done hourly as part of routine meteorological observations.

Problems and Assumptions

Prior to describing the results obtained from the data collected, it is important to understand the limitations of this data. An assumption was made that the skill of raising and lowering the kite improved with time. In accordance with this, only the results from 2100 UTC on 10Feb2001 are shown. Unfortunately, the NPS infrared sea surface temperature instrument was not functioning at all on 10Feb2001 (see figure 1). While the kite was flying, surface pressure was not constant (see figure 2). Since height is calculated from pressure, this caused the data to contain negative heights. This problem was corrected by assuming that the minimum height of the kite was 1 meter each time it was lowered. As the kite was flying, visual observations of the height of the kite from the sea surface and the distance of the kite from the ship were recorded. At the time, it was not known that the rawinsonde data would only be recorded for two hours, so this additional information could not be used since this practice was not instituted until after the two-hour point.

Figure 1       Figure 2
It has been suggested that this is a naïve approach, as the kite may not have gotten as low as 1 meter each time. If this is indeed the case, it would only strengthen the discrepancy between the kite derived profiles and the bulk derived profiles (see Table 1 and discussion below) by increasing the kite derived evaporation duct height. It has also been proposed that a time lag between the sensors and the environment causes the kite derived duct heights to be higher. This is not supported by the results of experiment 18, since a lag would require that the kite derived evaporation duct heights be lower than those derived from bulk methods, which is not the case.

**Analysis**

Each time the kite was raised and lowered, a profile of M versus z was created (see attachments “MATLAB Command Window” and “project.m”). Since the kite was generally further from the ship when the kite was being raised, it was assumed that the “up” profiles were less contaminated by the ship’s effects than the “down” profiles. Two calculations of vapor pressure were made for each two-second observation, one using air temperature, pressure and relative humidity and another using dew point temperature and pressure. These were averaged and used with air temperature, pressure and height to calculate M. Since height was only recorded to the whole meter, multiple values of M were observed at each level. These were averaged and a cubic function was fitted to the averaged values. Additionally, kite pressure, air temperature and relative humidity at approximately one-fourth, one-half and three-fourths of the maximum height of the kite were used with the NPS wind speed and the hand-held infrared sea surface temperature to calculate profiles of M using bulk methods.
The SAIL data were averaged over the time of the kite profile. If this was less than five minutes, additional data was used from just before and just after the time of the kite profile to obtain at least a five-minute average. The averaged data were used to calculate a profile of M using bulk methods. The NPS data were time averaged in a similar manner. Since no sea surface temperature was available, hand-held infrared sea surface temperature was used to obtain an M profile. This created an undesirable dependence between this profile and those obtained from the kite data.

Results

Three profiles were examined. The first started just before 2130 and is termed “Experiment 17.” This was an “up” profile, meaning that the data was sampled while the kite traveled from the surface to approximately 60 meters. Experiment 18 immediately follows 17 and is a down profile; experiment 19 is the next up profile. Experiments 17, 18 and 19 contained 141, 261 and 141 data points, respectively.

<table>
<thead>
<tr>
<th></th>
<th>Experiment 17 (up) 141 data</th>
<th>Experiment 18 (down) 261 data</th>
<th>Experiment 19 (up) 141 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kite</td>
<td>14.4</td>
<td>16.9</td>
<td>13.1</td>
</tr>
<tr>
<td>SAIL</td>
<td>6.7</td>
<td>6.2</td>
<td>5.9</td>
</tr>
<tr>
<td>NPS</td>
<td>6.4</td>
<td>6.8</td>
<td>6.4</td>
</tr>
<tr>
<td>¼</td>
<td>7.6</td>
<td>7.6</td>
<td>7.3</td>
</tr>
<tr>
<td>½</td>
<td>7.1</td>
<td>7.6</td>
<td>7.0</td>
</tr>
<tr>
<td>¾</td>
<td>7.3</td>
<td>7.5</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 1. Evaporation duct heights (in meters) for experiments 17, 18 and 19. Kite is the cubic interpolation of the averaged M values obtained from kite data. SAIL and NPS are the bulk profiles from the SAIL data and NPS data. ¼, ½ and ¾ are the bulk profiles obtained using the averaged kite data at approximately ¼, ½ and ¾ the maximum height of the kite. The color scheme is intentional and is used in all figures.
Figures 3-6. Figure 3 shows pressure versus height for the kite data (blue x’s), SAIL data (red line), NPS data (green line) and the bulk profiles from the kite data at ¼, ½ and ¾ of the maximum height of the kite (cyan, magenta and black, respectively). Figures 4 and 5 show similar plots for temperature and relative humidity, with the addition of height averaged kite values (blue o’s) and a best-fit cubic of the kite data (blue line). Figure 6 shows a similar plot for M, with *’s indicating evaporation duct height.

The M profile calculated directly from the kite data from experiment 17 was compared to a bulk profile calculated using an average of five minutes and 24 seconds of SAIL data and to another bulk profile calculated using an average of eight minutes of NPS data. These data (SAIL and NPS) were centered about the halfway point of the kite data collection times. Experiment 18 was compared to an average of eight minutes and eight seconds of SAIL data and six minutes of NPS data. Experiment 19 was compared to an
average of five minutes and 24 seconds of SAIL data and six minutes of NPS data. The evaporation duct heights obtained from the analyses described above are listed in Table 1.

The three parameters affecting evaporation duct height were also examined for each experiment. Since all three gave similar results, only experiment 17 will be presented. The SAIL system appears to have a two millibar pressure bias when compared to the NPS data and the kite data (see figure 3). Kite temperature lies between NPS and SAIL temperature and all are within 1 degree Kelvin of each other (see figure 4). The most significant difference is in the relative humidity, where NPS and SAIL data overestimate the kite values by approximately 5% (see figure 5). Although the bulk profiles of pressure and temperature calculated from the kite data are very well grouped, the bulk profiles of relative humidity calculated from the kite data show an 8% difference between the highest and lowest values. It is clear from the M profiles (see figure 6) that these differences in relative humidity have the greatest impact of the three parameters.

Operational Relevance

Due to the significant differences in duct height (see table 1 and figure 6) based on the method used to calculate the vertical profile of modified refractivity, radar propagation for frequencies greater than 3 GHz should be affected. In order to investigate this, the M profiles obtained above were used to describe the environment in the Advanced Refractive Effects Prediction System (AREPS) version 2.1. The platform chosen was a generic U.S. Navy cruiser (CG). A fictional radar operating at a frequency of 3.5 GHz, peak power of 5 MW and mounted 55 feet above the sea surface (see attachment “Radar Parameters-DLM” for other parameters used) was used to detect three targets, described in AREPS as “small jet,” “medium jet” and “stealthy jet.” The maximum detection range
(in nautical miles) for a 90 percent probability of detection at 50 feet is increased by 93% (from 26.1 nm to 50.5 nm) for the small jet, by 93% (from 27.3 nm to 52.7 nm) for the medium jet and by 86% (from 23.2 nm to 46.2 nm) for the stealthy jet when the averaged kite profile is used instead of the bulk profile derived from NPS data (see figures 7-9).

When the probability detection percentage versus range and height is plotted (see figures 10-12), there is clearly a difference due to evaporation ducting. This is especially evident at a height of 50 feet.

Figures 7-9. Figure 7 shows a graph of target height (plotted for 4, 50, 150, 300, 450, 600 750, 900, 1050, 1200, 1350 and 1500 feet) versus maximum detection range (in nautical miles) for a 90 percent probability of detection of a small jet. Figures 8 and 9 show the same information for a medium jet and a stealthy jet, respectively.
Figures 10-12. Figure 10 shows the percent detection as a function of range and height for a small jet using the averaged M values from the kite data as the environment. Figures 11 and 12 show the same information but use the cubic interpolation of the averaged M values from the kite data and the bulk profile derived from the NPS data, respectively.

Summary

The vertical gradient of modified refractivity, which is a function of water vapor pressure, temperature and pressure, indicates if and at what level evaporation ducting will occur. M can be calculated directly from a profile of these parameters or inferred from bulk methods, which require fewer measurements. Using a rawinsonde attached to a kite to sample the surface layer gives much higher evaporation duct heights than bulk methods applied to two different sets of data which were collocated with the kite in time.
and space. The higher duct heights indicated by the kite data are much closer to the height of the radar (for experiment 17: 14.4 meters is approximately 47 feet which is very close to the radar height of 55 feet), which leads to a doubling in the distance at which a small jet could be detected from a cruiser using a radar with a frequency of 3.5 GHz. This means the ship would have approximately twice as much warning time until the jet was overhead.

Acknowledgements

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