1. INTRODUCTION

Radiosondes provide continuous, accurate profiles of temperature, humidity and wind from the ground up to the altitude of 35 km. This information is used for numerical weather prediction, climatology, and atmospheric research. In addition, the profiles measured by radiosondes serve as a reference for validating numerical weather prediction models, and they give weather forecasters a better understanding of the state of the atmosphere, thus improving the forecasting capability. However, the quality of the sensor measurements can affect the radiosonde’s capability to correctly detect important details, such as temperature inversions, cloud layers, and ice formation layers, which all are essential for weather prediction.

A set of studies evaluating the impact of radiosonde measurement accuracy on predicting various weather conditions have been made at Vaisala. In this paper, the key emphasis is on atmospheric conditions potentially leading to severe convective weather. The applied method was to take a sample of radiosoundings done in these conditions and to statistically analyze the sensitivity of meteorological indices on artificially added measurement offsets. In addition, forecasts of winter time precipitation type based on the radiosounding profile were examined. This study was further illustrated with a case example from freezing rain conditions by introducing offset and wet-bulb measurement errors into the profiles.

2. IMPACT OF RADIOSONDE DATA QUALITY ON METEOROLOGICAL INDICES

2.1 Meteorological Indices

Meteorological indices are calculated from radiosounding profiles and, in some cases, from surface observations. An index describes in a single value some aspect of the state of the atmosphere. For example, CAPE index gives an estimation of the amount of energy a parcel of air would have if lifted vertically through the atmosphere for a certain distance. The operational numerical weather prediction (NWP) models have limitations in spatial and temporal resolutions, and in quantification of humidity distribution in atmosphere, which cause challenges in representing, and thus, forecasting convection with the models. That is why most meteorological indices have been specifically developed to improve forecasting of deep convection and thunderstorms. Indices facilitate the interpretation of radiosounding profiles and can be used together with other information sources to make forecast decisions.

2.2 Methods

This study focuses on a set of seven commonly used meteorological indices for predicting severe weather, see Table 1.

<table>
<thead>
<tr>
<th>INDEX</th>
<th>PURPOSE</th>
<th>UNIT</th>
<th>WEAK</th>
<th>MODERATE</th>
<th>STRONG</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRN</td>
<td>Bulk Richardson Number</td>
<td>-</td>
<td>&lt; 20</td>
<td>10-50</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>CIN</td>
<td>Convective inhibition</td>
<td>J/kg</td>
<td>USA: &lt; 500</td>
<td>USA: 500-2000</td>
<td>USA: &gt; 2000</td>
</tr>
<tr>
<td>DCAPE</td>
<td>Downdraft strength</td>
<td>J/kg</td>
<td>USA: &lt; 20</td>
<td>USA: 20-30</td>
<td>USA: &gt; 30</td>
</tr>
<tr>
<td>KI</td>
<td>K-index</td>
<td>°C (K)</td>
<td>USA: &lt; 0</td>
<td>USA: 0-2</td>
<td>USA: &gt; 2</td>
</tr>
<tr>
<td>LI</td>
<td>Lifted index</td>
<td>°C (K)</td>
<td>0 …</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>SI</td>
<td>Showalter index</td>
<td>°C (K)</td>
<td>0 …</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1. Summary of meteorological indices used in the study (Weisman, 1986), (ERS, 2011), (George, 1960), (Galway, 1956), (Showalter, 1947) and their approximate threshold values.

The potential for severe weather estimated by the indices is typically categorized as “weak”, “moderate”, or “strong”. Threshold values for the different categories are approximate and depend on the season and climate. Some indices also

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have different calculation options; as an example, the calculation of CAPE can start from the surface or from a higher level, where the convection updraft is expected to initiate. Therefore, the optimal use of indices requires expertise of the local weather and of how to best apply the indices. To give some insight into the orders of magnitude for each index, very approximate thresholds are shown in Table 1. The given values are based on several sources (Bauman, et al., 2005; ERS, 2011; Gallus, 2008; Puhakka, 1996; Roine, 2001; Savijärvi, 2010; Skystef, 2015).

To study the effect of measurement accuracy on stability indices, a set of 56 radiosoundings performed with either Vaisala Radiosonde RS92 or RS41 were selected. The radio-soundings took place on two continents, in Europe and in continental United States of America, under conditions that resulted in severe convective weather. All radiosounding profiles used in this analysis are drawn using the data from the archive of the University of Wyoming (UWYO, 2015).

In the analysis, measurements done with Vaisala radiosondes were modified by adding an artificial offset to the whole vertical profile. Offset values of -2 %, -4 % and +2 % for the relative humidity and ±0.2 °C for the temperature were chosen based on WMO’s previous radiosonde intercomparison (Nash et al., 2011). The offset values represent typical statistical biases observed between the instruments in the intercomparison. However, the reported sounding by sounding variations showed substantially larger deviations. Therefore, the simulated error values in this study can be considered as conservative. The impact of wind measurement accuracy was not analyzed in this study.

Modifying the temperature and humidity values also changes the corresponding partial water vapor pressure e and the dew-point temperature Td values which were therefore recalculated using the formulas of Wexler, modified by Hardy (Hardy, 1998) and the Magnus formula (Buck, 1981), respectively. These formulas were tested to be similar to the formulas used for the sounding data drawn from the archive of the University of Wyoming.

The initial and modified sounding profiles were analyzed with RAOB version 6.3 (The Universal RAWinsonde OBServation Program, Environmental Research Services, LLC). RAOB automatically calculates index values based on the radiosounding and plots the data on a thermodynamic diagram. A thermodynamic diagram shows the relationship between the pressure, temperature and humidity content of air, and allows meteorologists to determine characteristics of the air mass, e.g. stability, cloud layers, fronts and vertical wind shear. In this study, the emagram type diagram type was used. It has temperature as the x-axis and the logarithm of pressure as the y-axis, and an area on the diagram is proportional to energy.

2.3 Results

All radiosounding profiles resulting severe convective weather

For all 56 radiosounding measurements, the mean index values and the mean relative and absolute changes due to humidity and temperature offsets applied to the original radiosounding measurements are presented in Table 2. The relative changes are also shown in Figure 1. For BRN, CAPE, LI, and NCAPE, the surface-based values (sfc) were used in the analysis.

<table>
<thead>
<tr>
<th></th>
<th>BRN&lt;sub&gt;0&lt;/sub&gt;</th>
<th>CAPE&lt;sub&gt;0&lt;/sub&gt;</th>
<th>CIN&lt;sub&gt;0&lt;/sub&gt;</th>
<th>DCAPE</th>
<th>KI</th>
<th>LL&lt;sub&gt;0&lt;/sub&gt;</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN VALUE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>2060</td>
<td>-34.3</td>
<td>800</td>
<td>31.7</td>
<td>-4.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>RH-2 %</td>
<td>-13 %</td>
<td>-15 %</td>
<td>-46 %</td>
<td>+2 %</td>
<td>-3 %</td>
<td>+9 %</td>
<td>+41 %</td>
</tr>
<tr>
<td></td>
<td>-15</td>
<td>-216</td>
<td>+4.7</td>
<td>+16</td>
<td>-0.8</td>
<td>+0.4</td>
<td>+0.3</td>
</tr>
<tr>
<td>RH-4 %</td>
<td>-27 %</td>
<td>-29 %</td>
<td>-86 %</td>
<td>+5 %</td>
<td>-6 %</td>
<td>+21 %</td>
<td>+91 %</td>
</tr>
<tr>
<td></td>
<td>-30</td>
<td>-444</td>
<td>-14.6</td>
<td>+33</td>
<td>-1.8</td>
<td>+0.9</td>
<td>+0.7</td>
</tr>
<tr>
<td>RH+2 %</td>
<td>+18 %</td>
<td>+18 %</td>
<td>+34 %</td>
<td>-2 %</td>
<td>+4 %</td>
<td>-13 %</td>
<td>-58 %</td>
</tr>
<tr>
<td></td>
<td>+18</td>
<td>+274</td>
<td>+6.2</td>
<td>-15</td>
<td>+1.0</td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>T-0.2 °C</td>
<td>-2 %</td>
<td>-2 %</td>
<td>+3 %</td>
<td>-2 %</td>
<td>0 %</td>
<td>+2 %</td>
<td>+4 %</td>
</tr>
<tr>
<td></td>
<td>-4</td>
<td>-41</td>
<td>+0.6</td>
<td>-14</td>
<td>-0.1</td>
<td>+0.1</td>
<td>+0.0</td>
</tr>
<tr>
<td>T+0.2 °C</td>
<td>+7 %</td>
<td>+6 %</td>
<td>+5 %</td>
<td>+3 %</td>
<td>+1 %</td>
<td>-4 %</td>
<td>-20 %</td>
</tr>
<tr>
<td></td>
<td>+6</td>
<td>+43</td>
<td>+1.1</td>
<td>+18</td>
<td>+0.3</td>
<td>-0.1</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

Table 2. For all 56 soundings: The mean index values and the mean relative (bolded) and absolute changes in index values due to a humidity offsets of -2 %, -4 % and +2 %, and a temperature offsets of ±0.2 °C applied to the whole sounding profile.

In general, the applied humidity offsets seemed to affect the index values more than the set temperature offsets. The only exception was DCAPE, for which the observed effects were comparable in magnitude. Furthermore, CAPE-based indices and CIN were the most affected indices by the offsets. This could be expected, since the calculation of these indices is based on integrating the measurements from near the surface to the upper levels of the troposphere, and thus, the measurement error accumulates to the index value at every measurement level. By contrast, KI, LI, and SI indices, being based on
measurement results from a few levels only, were less affected by the offsets.

Humidity offsets resulted in both notable relative and absolute changes of CAPEsfc, up to 29 % and 444 J/kg, respectively, for the 4 %RH offset. This was reflected as similar relative changes in BRNsfc, as can be expected since BRNsfc is directly proportional to CAPEsfc. Also, the CIN-index showed significant mean changes, up to -86%, due to the humidity biases. In the case of L1sfc, the relative changes were moderate, up to 21 %, whereas for DCAPE and KI the mean relative changes were weaker, within ±6 %. SI values showed the largest mean relative effects, up to 91%, but this was largely due to the fact that the initial index values were relatively low. Nevertheless, the interpretation of the SI value becomes clearly more uncertain due to the applied -4 %RH humidity offset.

As temperature profile modifications were studied, the added offsets of ±0.2 °C had relatively weak impacts on the studied indices, see Table 2 and Figure 1. The strongest effects were seen on BRNsfc and CAPEsfc, showing relative changes of 6 and 7 %, respectively. The seemingly large relative effect in SI can be considered weak when absolute scale is used in the interpretation of the results.

Figure 1 presents the distribution of absolute changes for CAPEsfc and CIN index values as -4 %RH offset was added to the humidity profiles. Generally speaking, from the forecasting point of view, probably the most interesting CAPE range is from 500 to 2000 J/kg (highlighted data points) as these values indicate an increasing potential for the emergence of severe convective weather, see Table 1. The data shows that significant shifts, ranging typically from -500 to -250 J/kg, took place at this range of the index. In addition, the CIN index shows decreased values with large dispersion, especially around the critical range of -50 J/kg and below. Thus, as a consequence of -4 %RH offset, the combination of significantly lowered CAPE value and the increased convective inhibition can lead to wrong conclusions of the evolving weather conditions.

![Figure 2](image1.png)

Figure 2. The absolute changes of CAPEsfc (top) and CIN (bottom) indices due to -4 %RH humidity offset as a function of the original index values. Data points corresponding pivotal CAPE range 500-2000 J/kg are highlighted.

**Radiosounding profiles of weakly unstable atmospheric conditions**

In order to study the impact of data accuracy in atmospheric conditions possessing less evident thunderstorm potential, the same analysis was conducted separately for 15 (out of 56) radiosoundings made in weakly unstable conditions, i.e. for profiles with CAPEsfc less than 1000 J/kg. These conditions represent typical borderline cases where the analysis of the state of the atmosphere and the forecasts based on the indices are more uncertain and, thus, either showers only or thunderstorms could be forecasted. The results for the chosen indices are shown in Table 3, and represented also in Figure 3.
In weakly unstable conditions, the mean CIN index value, -72.9 J/kg, was over double the mean value of the preceding analysis including all soundings. In addition, negative humidity offsets reinforced convective inhibition mean up to -23.4 J/kg. Thus, even though the relative change of CIN was lower in this case, the observed absolute change was even more significant.

DCAPE and KI showed very similar results in the two analysis cases. Both the mean absolute and relative effects of the applied offsets resulted close to identical outputs. The largest change was seen in the mean relative effect of +0.2°C temperature offset on DCAPE which shifted from +3% to +7%. However, the mean absolute shift, +28 J/kg, does not substantially change the interpretation of the index.

For LΙsfc and SI, the absolute changes are similar to the previous analysis, but this time in the case of LΙsfc, the largest seen absolute change, +0.8 °C, is of the same order of magnitude as the initial mean index value, -0.9 °C. This may change the conclusions driven from the radiosounding profiles.

As a summary of the analysis results, it can be stated that in weakly unstable atmospheric conditions, most of the studied indices showed increased sensitivity to the applied artificial measurement errors. It seems evident that, in these borderline conditions, the accuracy of the weather forecast can be significantly degraded by the bias and random type measurement errors observed in WMO’s previous radiosonde intercomparison.

3. FORECASTING WINTER PRECIPITATION USING RADIOSONDE PROFILES

3.1 Interpretation of Winter Time Radiosounding Profiles

Radiosonde soundings play an important role in forecasting winter time precipitation since they record many significant atmospheric features which, when assimilated into NWP models, help produce more accurate predictions. In addition, they help the forecaster understand situations where NWP models are known to be more uncertain, even misleading, and facilitate the interpretation of the upcoming precipitation type. The following discussion presents the six basic types of winter precipitation and how they can be predicted by radiosonde profiles. Lastly, a case example of a winter time radiosounding profile and its interpretation is given.
The six types of winter time weather conditions presented in Figure 4 can be described as follows. See also the terminology explanations in Table 4.

Figure 4. Illustrative radiosonde profiles of temperature and dew-point temperature, demonstrating characteristic features that correspond to various types of winter precipitation.

a) Snowfall is observed when snow crystals are formed aloft in an ice formation layer and temperatures remain below zero over the whole profile beneath.

b) If the surface layer temperature is above zero, part of the falling snow flakes will melt to form melting or wet snow.

c - d) If ice particles fall through an elevated warm layer, they will melt partly or entirely. Depending on the degree of melting and the thickness of the adjacent near-surface cold layer, either ice pellets, sleet, or freezing rain will be observed. Ice pellets are solid particles, while freezing rain consists of super-cooled liquid particles that partly freeze when in contact with a surface that is below zero temperature.

e) If the saturation layer is shallow and below zero, but warmer than -10 °C, freezing drizzle is likely to form.

f) In a snow seeder-feeder mechanism ice particles are formed in an upper-level cloud, whereas a lower-level cloud contains only super-cooled water. Falling ice particles will partly sublimate in a dry layer between the clouds, but if some proportion of the ice particles reach the lower cloud, they will start to aggregate the super-cooled cloud droplets and snowfall will be observed.

Table 4. Factors affecting precipitation type in winter time and examples of their interpretation based on radiosonde profiles.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Explanation</th>
<th>Interpretation of radiosonde profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice formation layer</td>
<td>Formation of ice crystals and snow by heterogeneous nucleation when air is saturated relative to ice.</td>
<td>Ice formation (&gt;50% chance): T &lt; -10 °C and air is saturated relative to ice.</td>
</tr>
<tr>
<td>Warm layer (T &gt; 0 °C)</td>
<td>Melting of ice or snow particles. Can be a surface layer or an elevated layer.</td>
<td>Warm layer maximum temperature Complete melting: Tmax &gt; 3 °C Partial melting: Tmax = 1-3 °C No melting: Tmax &lt; 1 °C</td>
</tr>
<tr>
<td>Near surface layer</td>
<td>Determines the precipitation type near and on the ground, and the possible formation of freezing rain, ice pellets, or sleet.</td>
<td>Snow: T_surface &lt; 1 °C Ice pellets / sleet: T &lt; -6 °C in a &gt; 750 m layer Freezing rain: T &lt; 0 °C in a &lt; 750 m layer and on the ground</td>
</tr>
<tr>
<td>Saturation layer</td>
<td>A layer in which water vapor condensates or is deposited on particles. Indicates the depth of cloud layer and the type of precipitation.</td>
<td>Minimum layer depth for precipitation to form: &gt;500 m</td>
</tr>
<tr>
<td>Dry layer</td>
<td>A dry layer can block precipitation from reaching the ground due to evaporation aloft, or change the precipitation type due to cooling.</td>
<td>Maximum layer depth for precipitation to occur: ~1000-1500 m</td>
</tr>
</tbody>
</table>

3.2 Case Study: Freezing Rain and Ice Storm

This case study demonstrates the importance of accurate radiosonde observations in situations where NWP models are likely to be incorrect.

In January - February 2014, the Eastern Europe, especially parts of Slovenia and Croatia, were exposed to long-lasting freezing rain conditions covering vast areas with ice. The extreme weather was caused by an encounter between cold arctic and moist subtropical air masses. The prolonged accumulation of ice damaged the power transmission network in both countries and large areas of forests were destroyed.

Temperature and humidity observations from a Vaisala Radiosonde RS92 launched from the area on February 5, 2014, are presented in Figure 5. Light freezing rain was observed at the station during the soundings.
Figure 5. Radiosonde observations of temperature (top) and relative humidity with respect to ice (bottom), showing original measurements (solid lines) and modified profiles (dashed lines). In contrast to the actual study, here the modified profile combines both the offset and wet-bulb errors. The precipitation types for moist (green) and dry (yellow) layers according to the original measurements are illustrated on the right.

The radiosonde profile shows an elevated inversion layer with relatively dry and warm air at 900 hPa, and a saturated layer between 750 and 640 hPa. The mid-tropospheric air is dry and the surface layer is not saturated either. There is a shallow ice formation layer at above 700 hPa, and the warm layer has a maximum temperature of 2.8 °C. In this case it is not obvious whether precipitation will fall in liquid or partly solid form. It is probable that ice formation will not be efficient enough, and thus clouds will contain mostly super-cooled water and freezing rain will be observed on the ground.

In this type of borderline situation, even small temperature and humidity offsets can change the forecast towards either solid or liquid precipitation. The impact of measurement quality was studied by introducing a wet-bulb type error to the lowest dry layer, or alternatively, small offsets of +0.3 °C and -4 % RH, as shown by the dashed lines in Figure 5. Table 5 compares the forecast results for the original and for the modified radiosoundings, using interpretation rules from Table 4.

<table>
<thead>
<tr>
<th>Sounding profile</th>
<th>Modified sounding: wet-bulb error</th>
<th>Original sounding</th>
<th>Modified sounding: ΔT = +0.3 °C, ΔRH = -4 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice formation</td>
<td>Shallow layer T &lt; -10 °C → Probable ice formation</td>
<td>Shallow layer T &lt; -10 °C → Probable ice formation</td>
<td>Shallow layer T &lt; -10 °C → Less probable ice formation due to lower humidity</td>
</tr>
<tr>
<td>Elevated warm layer</td>
<td>T_{max} = 1.9 °C → Partial melting of ice → Solid and liquid can occur</td>
<td>T_{max} = 2.8 °C → Partial melting of ice → Rain more probable, also sleet can occur</td>
<td>T_{max} &gt; 3 °C → Complete melting of ice → Rain</td>
</tr>
<tr>
<td>On the ground</td>
<td>T_{surf} &lt; 0 °C → Rain will freeze on the ground → Ice accumulation or sleet</td>
<td>T_{surf} &lt; 0 °C → Rain will freeze on the ground → Ice accumulation or sleet</td>
<td>T_{surf} &gt; 0 °C → No freezing on the ground</td>
</tr>
</tbody>
</table>

Relative effect: - - - Reference + + +

**FORECAST**
- Ice pellets (more probable) or freezing rain or mix
- Light freezing rain (more probable) or ice pellets
- Light rain or no rain

**OBSERVED WEATHER**
- Light freezing rain

Table 5. Forecasts based on the original sounding profile and two modified profiles introducing a wet-bulb type error (left) and temperature and humidity offsets (right). The table shows the reasoning based on factors in the sounding profiles, example forecasts, and the weather observation at the sounding site.

In these conditions a wet-bulb type error would decrease the level of melting in the elevated warm layer, and thus, increase the probability of ice pellet type of precipitation instead of freezing rain. In the other case, a -4 % RH humidity offset would further decrease the efficiency of ice formation in the originally shallow ice formation...
Combined with a temperature offset of +0.3 °C, which indicates a surface temperature above freezing, the forecasted precipitation type would more likely be rain.

4. SUMMARY

Among the upper air observation systems, radiosoundings provide a unique set of data by producing complete vertical profiles describing the state of the atmosphere. This information is essential in determining the initial state of numerical weather prediction models. Furthermore, meteorologists are interested in several phenomena visible in the radiosounding profiles, including cloud layers, dry layers, temperature inversions, cold and warm fronts, jet streams, and wind shear. Radiosondes also have an important role in providing long-term high-quality time series of climatology trends in various parameters. All these applications set a high demand on the accuracy and consistency of the radiosonde measurements.

By utilizing the analysis of artificially modified radiosounding profiles, this study demonstrates that even small measurement errors may lead to erroneous forecast conclusions. The impact of the errors was most significant in borderline situations when the evolution of convection involved increased uncertainty, or when predicting winter time precipitation type. Severe, high-impact weather conditions often imply a very challenging environment for the radiosonde sensors and the quality of the measurements determines the ability to detect important details properly. Yet, reliable measurements and correct forecast decisions are paramount in such circumstances as the severe weather predictions have a large impact on the society.

REFERENCES


Nash, J., Oakley, T., Vömel, H. & Wei, L., 2011. WMO Intercomparison of high quality radiosonde systems. Yangjiang, China, 12 July - 3 August 2010, s.l.: WMO.


