Accuracy Matters in Radiosonde Measurements

/ WHITE PAPER

VAISALA

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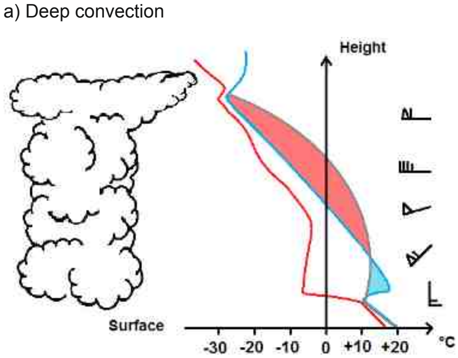
Introduction

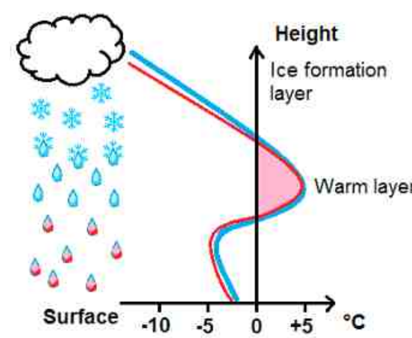
Radiosondes measure critical atmospheric variables with accuracy and precision that cannot be obtained with other meteorological observations. Radiosondes are unique instruments as they provide continuous, detailed profiles from the ground to altitudes of 30 km and above. The quality and reliability of the measurements are essential. Even small inaccuracies in the profiles can prevent the forecaster from observing critical details and making correct conclusions.

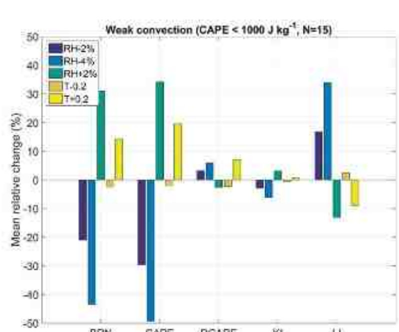
The chapters in this document provide information on the importance of radiosonde measurement accuracy, and how accuracy helps to successfully forecast high impact weather. Graphs, tables, and case study summaries illustrate how correct or incorrect observations of temperature inversion layers, ice forming layers, humidity, and other atmospheric properties can change a forecast in various weather situations.

a) Deep convection



d) Freezing rain





Sounding profile	Modified sounding: wet-bulb error
Ice formation	Shallow layer T < -10 °C ➔ Probable ice formation
Elevated warm layer	T_{max} = 1.9 °C ➔ Partial melting of ice ➔ Solid and liquid can occur
Surface	$T_{surface}$ < 0 °C ➔ Rain will freeze on the ground ➔ Ice accumulation / sleet
Forecast	Ice pellets (more probable) or freezing rain or mix

Quality of Radiosonde Measurements is Critical

The radiosonde is unique among other observation systems in that it provides a complete vertical profiling of the initial state of the atmospheric analysis that drives numerical weather prediction models. Furthermore, meteorologists are interested in several phenomena that are visible in the radiosonde data, including cloud layers, dry layers, temperature inversions, jet streams and wind shear. Radiosondes also have an important role in providing long-term high-quality time series of climatology trends of various parameters.

These applications place a high demand on the accuracy and precision of the measurement. It is important that radiosonde sensors work reliably in changing conditions throughout the harsh environment of the upper atmosphere. Erroneous measurements could entirely change the forecast conclusions. For example, the following challenging conditions could occur in cloudy weather situations:

- As the radiosonde emerges from a cloud, the temperature sensor is in danger of experiencing a 'wet bulb' error, generated as water or ice evaporates from the surface of the sensor. This may lead to incorrectly measuring the strength of the temperature inversion. Such erroneous observations can reduce the magnitude of the detected layer or even entirely mask the feature in the profile. In summertime this may lead the meteorologist to conclude that, for example, convection will start earlier in the day with less energy released into convection, or to predict that rain will start earlier and cool the land surface, with thunderstorms unlikely to form.

- If the humidity sensor freezes while passing through clouds, the radiosonde may incorrectly continue measuring high relative humidity. The sensitivity to detect cloud layers is reduced. For example, erroneously predicted upper cloud layers would block the solar radiation from reaching the ground and thus inhibit convection.

Convective Weather and Thunderstorms

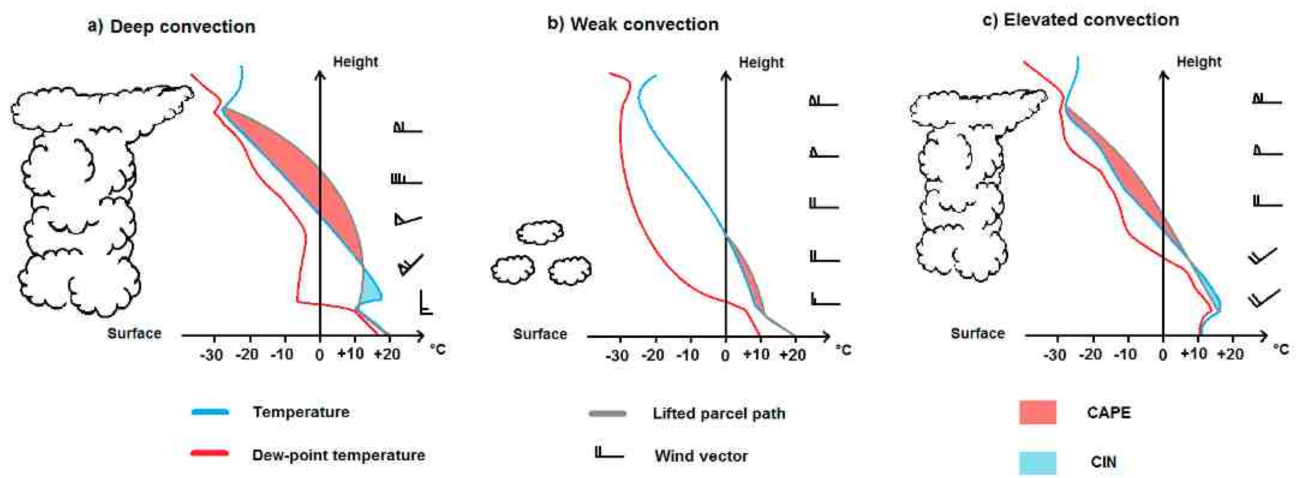


Figure 1. *Model radiosonde profiles of temperature, dew-point and wind, showing characteristic features that predict various types of convection. See further explanations in Table 1.*

During convection, warm air near the ground starts rising until it cools and becomes balanced with its surroundings. The following factors are needed for atmospheric convection to occur: enough moisture at the height from which convection initiates, instability, and a lifting mechanism. Strong convection in humid atmosphere can lead to thunderstorms.

Radiosondes in Forecasting Convection

In a convective situation, the analysis of the latest radiosonde profiles in the region is an essential step in forecasting. Convection is still poorly represented in the numerical weather prediction models due to inadequate spatial and temporal resolutions and the difficulty to quantify humidity.

Radiosonde measurements summarize the state of the atmosphere and give the basis for understanding how the weather will evolve in the next hours. **Figure 1** shows examples of three basic types of convective weather and how they can be forecasted from radiosonde profiles.

a) Deep convection

The air near the surface is warm, moist and well-mixed. There is a strong temperature inversion and enough convective inhibition (CIN) to prevent convection from beginning too early and thus enables convective available potential energy (CAPE) to build up. A relatively rapid decrease in temperature with height in the middle troposphere results in small stability. Cloud layers affect the amount of solar warming on the surface. If air near the surface

Factor	Explanation	Interpretation in radiosonde profile
Temperature inversion	Layer of warmer air above cool air.	A temperature inversion prevents ascending air from penetrating it and helps build up convective energy. A strong inversion may prevent convection entirely.
Dew-point temperature	The temperature where condensation begins. Moisture content of air is high when the dew-point is close to air temperature.	Humid and dry layers in the profile indicate the amount of energy available in the atmosphere. A deep dry layer can eat moisture from lower layers and thus prevent deep convection.
CAPE and CIN	Meteorological indices for convective available potential energy and convective inhibition.	Calculated from radiosonde profile. Indicate the stability of the atmosphere.
Vertical wind shear	Change in wind speed and direction over height.	Vertical wind shear is needed for thunderstorms to become severe and long-lasting.
Lifted parcel path	In free convection the air will become warmer than its surroundings and experience accelerating ascent along the lifted parcel path until it becomes of equal temperature with its surroundings.	A deep convective layer indicates a strong chance for thunderstorms. The top of convection shows the height that thundercloud tops will reach.

Table 1. *Factors affecting convective weather and examples of their interpretation in radiosonde profiles for weather forecasting.*

is being lifted, for example, by solar heating and penetrates the inversion layer, the air will become warmer than its surroundings and experience accelerating ascent until it becomes of equal temperature with its surroundings. This is where cloud tops form. Vertical wind shear is a main ingredient for severe and long-lasting thunderstorms.

b) Weak convection

Only weak convection and small cumulus clouds occur if the boundary layer is not moist enough, there is not enough convective inhibition to help build up convective energy, and the mid-troposphere is too stable for thunderstorms to appear.

c) Elevated convection

Even if the air near the surface is very stable, thunderstorms can develop by means of elevated convection. If the air above the stable layer has the required characteristics, convection can occur if the unstable air becomes lifted, for example, mechanically by a weather front.

Case Study 1: Convective Weather

A real world example can show how even small details in the radiosonde profile can be critical for understanding convective weather.

On Tuesday August 9, 2005, a weather front approached the Helsinki capital area from southeast Finland and caused one of the most dramatic moments during the course of the 2005 World Championships in Athletics. The historic open-air Helsinki Olympic Stadium was hit by an intense thunderstorm with pouring rain and severe wind gusts. Emergency services issued an evacuation of the stadium and electrical power was interrupted.

The storm also caused over 200 emergency incidents near the capital area, including fires, traffic accidents and injuries from fallen trees. Railway services and ship traffic from Helsinki harbor were affected, and thousands of households were left without electricity. Despite fans' disappointment, everyone was able to feel safe and in good hands. The authorities had been working hard since the early morning. The Finnish Meteorological Institute had issued several thunder alerts and kept the emergency organizations up to date of the changing weather.

What does the profile tell us?

At noon on August 9, 2005, the Jokioinen sounding station in southwest Finland provided the observation depicted on the thermodynamic diagram in **Figure 2**. This graph is from the Finnish Meteorological Institute meteorologist's workstation. The radiosonde profile shows clear evidence of the possibility of thunderstorms forming during the day. The most interesting details in the graph show how temperature and humidity (described by the dew point) behave through the atmosphere.

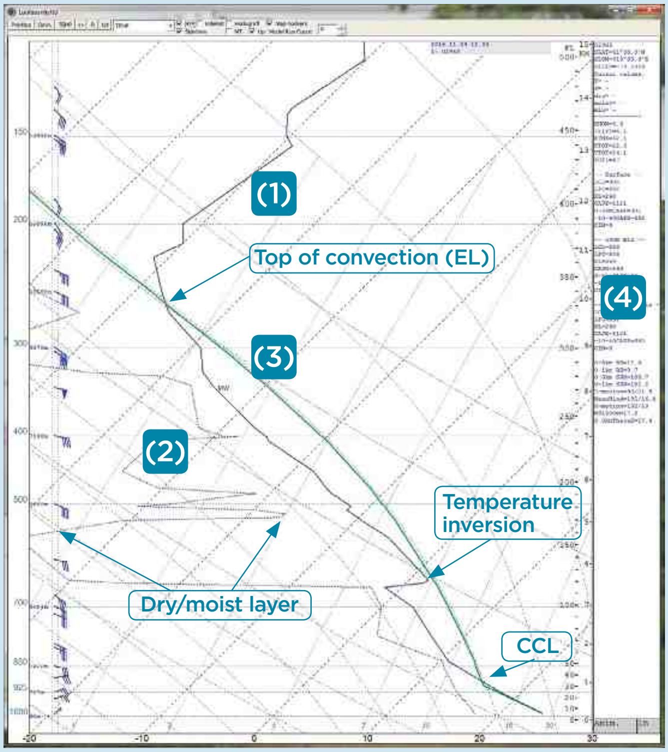
- The deep convective layer (925 to 250 hPa) indicates a strong chance for thunderstorms, with cloud tops reaching heights of around 10 km.
- There is a temperature inversion at above 700 hPa. The layer helps build up convective energy, however it is not going to stop the convection.
- The meteorological index CAPE of 1,121 J/kg in this case indicates an unstable atmosphere with a potential for moderate to strong convection in a cold climate.
- Humid and dry layers in the profile indicate the energy available in the atmosphere.
- Cloud layers affect the amount of solar warming on the surface.

What if the radiosonde profile cannot be trusted?

The correct interpretation of convective weather requires precise and accurate observations. The example radiosonde measurement has several details where a radiosonde providing erroneous profile details could have changed the forecast entirely.

Incorrectly measuring the depth of the temperature inversion (Figure 3)

An evaporative cooling error of 1.0 °C when the radiosonde emerges from a cloud reduces the depth of the observed inversion layer. The temperature sensor is measuring too low values (red curve) while water is evaporating from the surface of the sensor. The estimated weak inversion layer may lead the forecaster to predict the start of convection earlier in the day, with less energy and without forming thunderstorms.



(1) Radiosonde measured temperature profile.

(2) Radiosonde measured dew point profile. Dew point is the temperature where condensation begins, and describes the moisture content of air.

(3) Moist Adiabatic Lapse Rate. Shows the rate at which air packet which has reached 100% humidity is cooling when ascending.

(4) Stability indices such as CAPE and CIN describe the likelihood of thunderstorms forming.

Convective Condensation Level (CCL) represents the height where a lifting air packet becomes saturated. It can be used in estimating CAPE.

Figure 2. *Radiosonde observation shown on a thermodynamic diagram.*

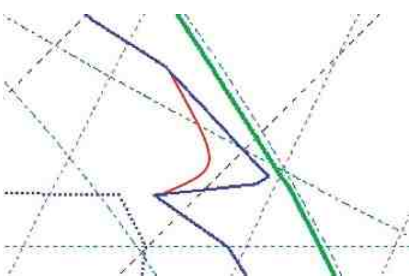


Figure 3. *A detail of the temperature inversion. The red curve depicts an incorrect measurement.*

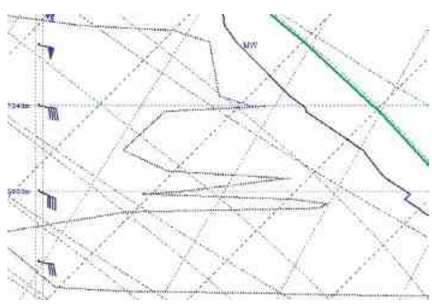


Figure 4. *A detail of the dew point profile.*

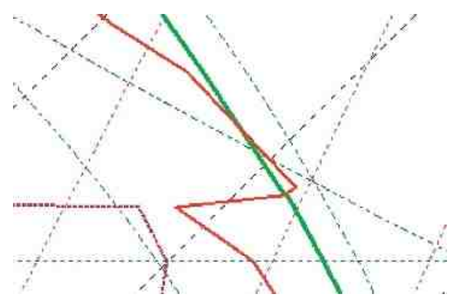


Figure 5. *A detail of the temperature inversion, depicting a capping inversion.*

Incorrectly detecting multiple cloud layers (Figure 4)

If the humidity sensor freezes while passing through clouds, or is not fast enough, the radiosonde may fail to detect fine structures in upper cloud layers. These cloud layers may be relevant in blocking solar radiation from reaching the ground, and preventing the start of the convective process.

Incorrectly detecting a capping inversion (Figure 5)

Only a one-degree error in the dew point measurement (about 3% RH) near the surface turns the inversion layer at 925 hPa into a capping inversion. A similar effect could occur if the temperature profile has offset due to incorrect calibration. The resulting thermodynamic diagram indicates that solar warming of the surface will not create enough lift and energy to break the air parcel through the warmer inversion. This prevents the release of convective energy in upward drafts and the formation of thunderstorms. In these weather conditions, it is important to measure accurately the temperature and especially the humidity in the lowest kilometer.

Case Study 2: Weak Convection

This example compares two radiosondes launched simultaneously from a site representing summer conditions of a humid continental climate zone. In this case the atmosphere was weakly unstable and only light showers were reported later in the day. The compared radiosondes were Vaisala Radiosonde RS41 and a radiosonde with less advanced technology, missing features such as hydrophobic protection for temperature sensor or active heating of the humidity sensor.

Temperature and humidity profiles from the two radiosondes are shown in **Figures 6 and 7**. The observations are rather similar close to the ground, however differences appear at above the lowest 1.5 kilometers. In this case, the temperature differences are of special interest. The RS41 radiosonde detected two temperature inversions, while the other radiosonde detected none. Temperature inversions block the ascending air motion and thus inhibit convection. According to the RS41 measurements, the ascending air would not likely penetrate the higher inversion layer and cloud tops would form already at the height of 4 km, indicating a weak possibility for thunderstorms.

According to the radiosonde with less advanced technology, there are no temperature inversions to inhibit convection. This radiosonde also observes a drier lower troposphere which indicates higher solar radiation reaching the surface, and thus a stronger lifting mechanism for convection. The measurement profile predicts that cloud tops could form at the height of 6.7 km, and could produce lightning as the cloud top temperatures are well below -20 °C. The thunder potential predicted by several meteorological indices (see chapter Meteorological Indices for more information) is different between the two radiosondes, as shown in **Table 2** below.

In this case a forecast based on the RS41 sounding shows a relatively

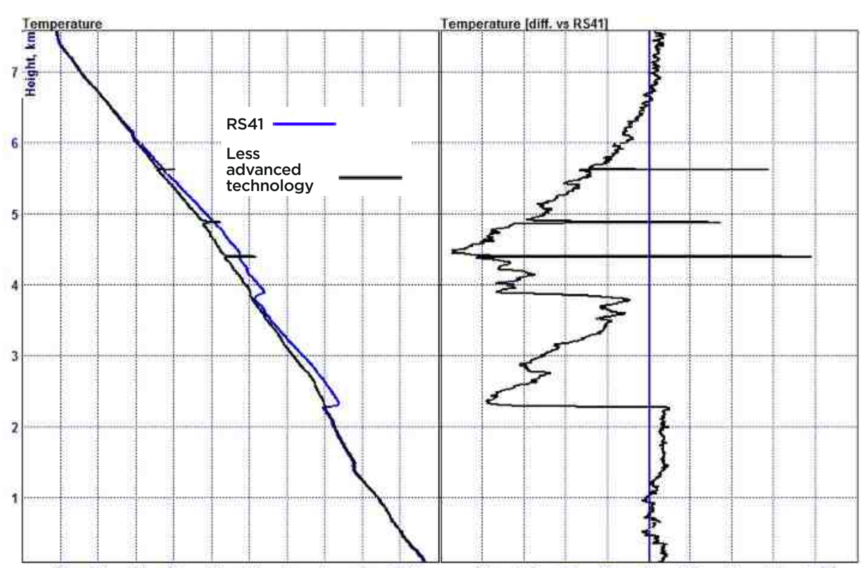


Figure 6. *Radiosonde observations of temperature profiles measured simultaneously with RS41 and a radiosonde with less advanced technology (left), and differences between the radiosondes (right).*

weak potential for thunderstorms. Only light showers developed during the next few hours. A forecast based on the less advanced radiosonde shows a high likelihood of thunderstorms.

This case demonstrates that the detection of temperature inversions and accurate humidity observations are important when forecasting development of convection. The lack of temperature inversions in the profile of the radiosonde with less advanced technology was possibly the result of a wet bulb cooling error in the measurement.

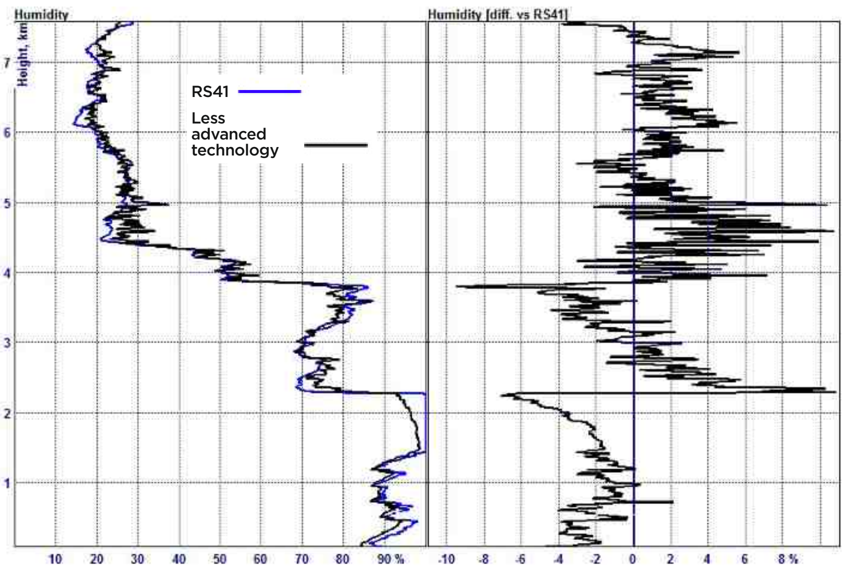


Figure 7. *Radiosonde observations of humidity profiles measured simultaneously with RS41 and a radiosonde with less advanced technology (left), and differences between the radiosondes (right).*

Radiosonde	RS41 technology	Less advanced technology
CAPE + CIN	Weak	Strong
LI	Weak-moderate	Moderate
TT	Moderate	Strong
KI	Moderate	Moderate
Cloud top	620 hPa (4 km)	430 hPa (6.7 km)
Forecast	Unlikely thunderstorm development	Probable thunderstorm development
Observed weather	Light rain showers, no thunder	

Table 2. *Forecasts based on RS41 and a radiosonde with less advanced technology, showing thunderstorm potentials (from meteorological indices) and cloud top heights calculated from the sounding profiles, example forecast decisions, and the weather observation at the sounding site later in the day.*

Winter Weather

Winter weather in cold climates often highly impacts the society. Accumulated ice due to freezing rain and heavy snow packs can damage energy transfer systems and cause cut-offs for many days. Transportation is heavily affected by winter precipitation and icing. Snowfall decreases road surface friction and visibility, and thus worsens driving conditions. For example, in the United States winter precipitation was shown to increase traffic collisions by 19 % and injuries by 13 %, compared with dry conditions (Journal of Transport Geography, Issue 48). Incorrect weather forecasts can become costly if roads are salted too early or when not necessary. The same applies to runway maintenance and de-icing decisions at airports, causing unnecessarily delayed or canceled flights. Furthermore, the risk of avalanches is highly related to the precipitation type.

Challenges in winter weather forecasting

Winter weather forecasting is mainly focused on predicting the track and intensity of synoptic scale low-pressure systems, surface temperatures, and precipitation rate and type at the ground. Low-pressure systems are currently relatively well forecasted, whereas numerical weather prediction (NWP) models have difficulty especially in forecasting small scale surface phenomena and shallow layers of air where temperature and humidity deviate from the surroundings. This stems mainly from a limited vertical resolution used in NWP models. As an example, nocturnal surface temperatures in the winter are highly dependent on cloudiness, and the type and amount of precipitation may vary notably due to an elevated warm layer.

Quantitative precipitation forecasting (QPF) is generally regarded as the least certain aspect in NWP models since very small changes in temperature or moisture can have a large effect on the type of precipitation. Temperature variations of ±0.5 °C can change the precipitation type to another.

Accurate precipitation type forecasting is especially difficult when temperatures near and at the surface are close to freezing. In such conditions, everything between snow and rain can occur within a small area. In particular, discerning between ice pellets and freezing rain can be difficult. Another example is the conversion of forecasted rainfall rate (mm h-1) to snow depth (cm), which depends on the density of snow, which in turn is drawn from the vertical profiles of temperature and moisture.

Radiosondes in Forecasting Winter Precipitation

Radiosonde soundings have an important role since they catch all the important 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 likely to be incorrect and misleading, and help interpret the upcoming precipitation type. In the following we discuss the six basic types of winter precipitation and their prediction from radiosonde profiles.

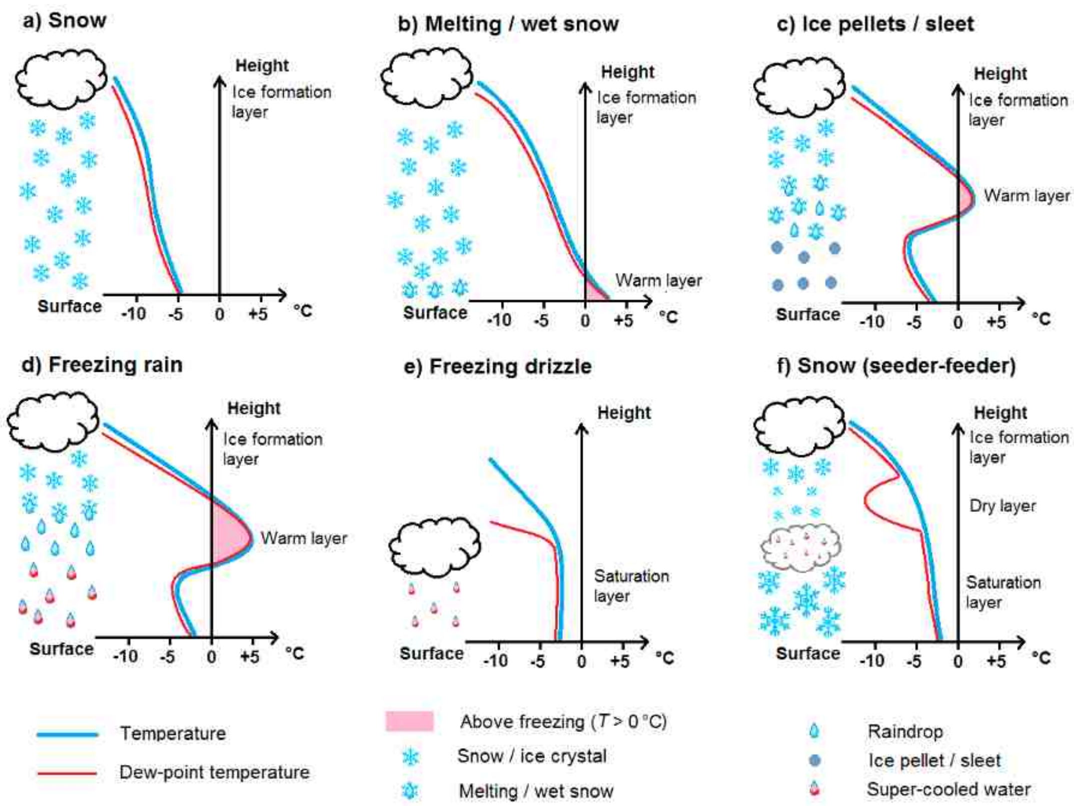


Figure 8. *Model radiosonde profiles of temperature and dew-point, showing characteristic features that correspond to various types of winter precipitation.*

Below is a description of the weather events in **Figure 8**. See also the terminology explanations in **Table 3**.

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

b) If the surface layer is above freezing, part of the flakes will melt to form melting (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 near-surface cold layer, either ice pellets (sleet) or freezing rain will occur. 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 freezing.

e) If the saturation layer is shallow and below freezing, 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. If any ice particles reach the lower cloud, they will start to glaciate the super-cooled cloud droplets and snowfall will be observed.

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

Table 3. *Factors affecting winter weather and examples of their interpretation in radiosonde profiles for forecasting various precipitation types.*

Case Study 3: Freezing Rain and Ice Storm

This case study demonstrates the importance of the accuracy of radiosonde observations in situations where NWP models are likely to be incorrect and misleading in predicting precipitation type.

In January-February of 2014 the Eastern Europe, especially parts of Slovenia and Croatia, were affected by a long-lasting freezing rain event that covered vast areas with ice. The extreme weather was caused by an encounter of cold arctic and moist subtropical air masses. Accumulation of ice damaged the power transmission network in both countries and large areas of forests were destroyed. The economic loss in both countries was estimated to be hundreds of millions of euros. NWP models had difficulties forecasting the right precipitation type during the event.

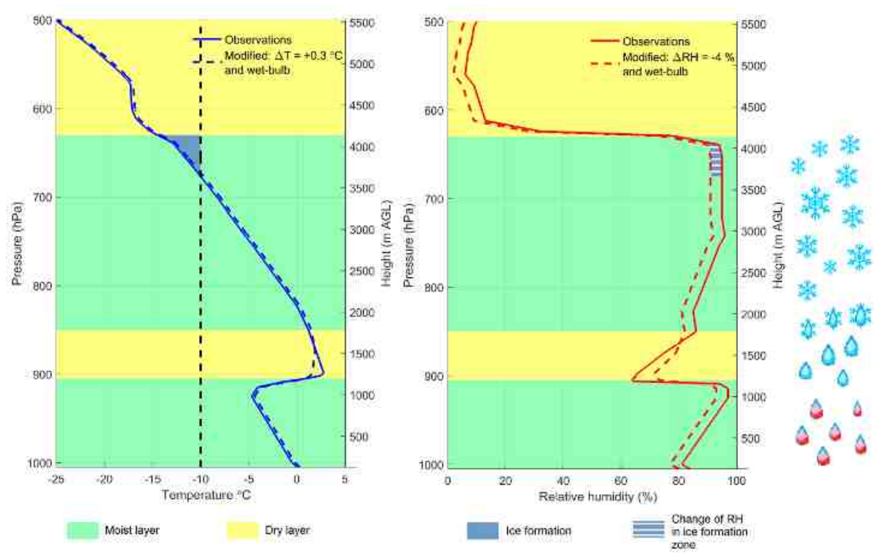


Figure 9. *Radiosonde observations of temperature (left) and relative humidity with respect to ice (right), showing original measurements (solid lines) and modified profiles (dashed lines). The precipitation types for moist (green) and dry (yellow) layers according to the original measurements are illustrated on the right.*

Temperature and humidity observations from a Vaisala Radiosonde RS92 launched at the Zagreb sounding station in Croatia on February 5, 2014, are presented in **Figure 9**. Light freezing rain was observed at the station during the soundings.

The radiosonde profiles show an elevated inversion layer with relatively dry and warm air at 900 hPa, and a saturated layer between 750 hPa and 640 hPa. The mid-tropospheric air is dry and the surface layer is not saturated. 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, and thus clouds will contain mostly super-cooled water and freezing rain will be observed at the ground.

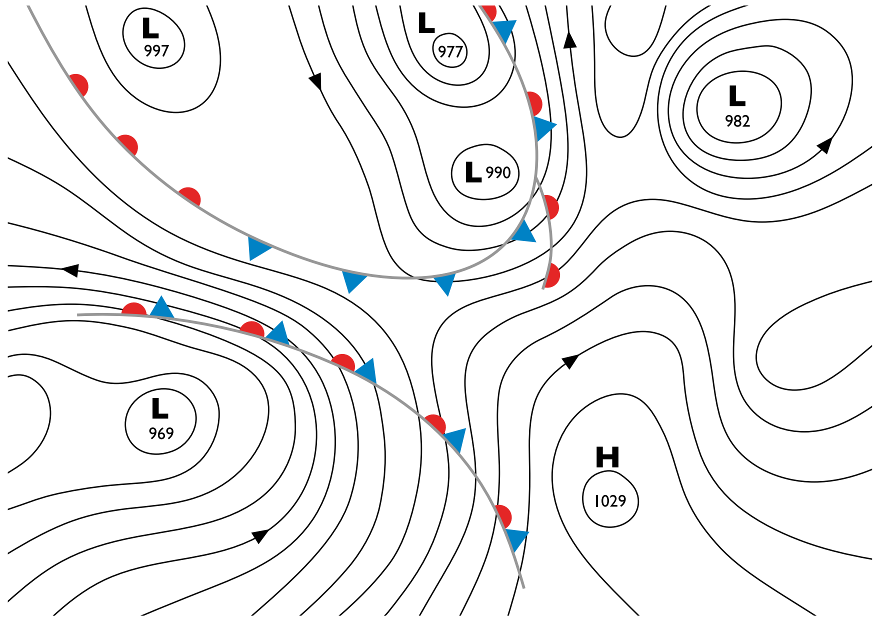
In this type of borderline situation, even small temperature and humidity offsets can change the forecast towards either solid or liquid precipitation. The impact of measurement quality was studied by introducing small offsets of +0.3 °C and -4 % RH, and a wet-bulb type error to the lowest dry layer, as shown in dashed lines in **Figure 9**.

Table 4 compares forecast results for the original sounding and for the modifications, using interpretation rules from **Table 3**. In this case a wet-bulb type error would decrease the level of melting in the elevated warm layer and thus increase the probability of forecasting ice pellets instead of freezing rain. On the other hand, a -4 % RH humidity offset would further decrease the efficiency of ice formation in the originally shallow ice formation layer. Combined with a temperature offset of +0.3 °C, which indicates a surface temperature above freezing, the forecasted precipitation type would be rain.

Sounding profile	Modified sounding: wet-bulb error	Original sounding	Modified sounding: ΔT = +0.3 °C, ΔRH = -4 %
Ice formation	Shallow layer T < -10 °C ➔ Probable ice formation	Shallow layer T < -10 °C ➔ Probable ice formation	Shallow layer T < -10 °C ➔ Less probable due to lower humidity
Elevated warm layer	T_{max} = 1.9 °C ➔ Partial melting of ice ➔ Solid and liquid can occur	T_{max} = 2.8 °C ➔ Partial melting of ice ➔ Rain more probable, also sleet can occur	T_{max} > 3 °C ➔ Complete melting of ice ➔ Rain
Surface	$T_{surface}$ < 0 °C ➔ Rain will freeze on the ground ➔ Ice accumulation / sleet	$T_{surface}$ < 0 °C ➔ Rain will freeze on the ground ➔ Ice accumulation / sleet	$T_{surface}$ > 0 °C ➔ No freezing on the ground
Forecast	Ice pellets (more probable) or freezing rain or mix	Light freezing rain (more probable) or ice pellets	Light rain
Observed weather	Light freezing rain		

Table 4. *Forecasts based on the original sounding profile (middle) and two modified profiles introducing a wet-bulb 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.*

Numerical Weather Prediction



Modern weather forecasting is strongly founded on numerical weather prediction (NWP) models. Numerical models rely on many sources of measurement data, and, for example, satellite based remote sensing has become crucial especially over the oceans. However, radiosonde observations remain among the most important model input. Their resolution, accuracy, and full vertical coverage of the atmosphere are essential for model initialization.

The significance of radiosonde observations as input data to NWP models has been studied in several denial studies. In the studies, the NWP model is run several times, each time neglecting some observation type from the input data. Singh, et al. (2014) showed that the radiosonde is one of the most effective terrestial-based instruments in reducing forecast error with the largest total and mean impact per observation, and with the largest impact on the rainfall prediction skill. Other studies have shown that radiosondes are among the main contributors to the quality of especially short-range forecasts, and in reducing forecast errors for wind, temperature, and humidity, especially on the Northern hemisphere. See the references below for more information.

Studies on radiosonde observations impact on NWP models:

Gelaro, R. & Zhu, Y., 2009. Examination of observation impacts derived from observing system experiments (OSEs) and adjoint models. Tellus A, Volume 61, pp. 179-193.

Ingleby, B., Rodwell, M. & Isaksen, L., 2016: Impact of halving the number of Russian radiosonde reports. The AMS 96th Annual Meeting, New Orleans, USA.

Kutty, G. & Wang, X., 2015. A Comparison of the Impacts of Radiosonde and AMSU Radiance Observations in GSI Based 3DEnsVar and 3DVar Data Assimilation Systems for NCEP GFS. Advances in Meteorology, Volume 2015, pp. 1-17.

Laroche, S. & Sarrazin, R., 2010. Impact study with observations assimilated over North America and the North Pacific Ocean on the MSC global forecast system. Part I: Contribution of radiosonde, aircraft and satellite data. Atmosphere-Ocean, 48(1), pp. 10-25.

Singh, R., Ojha, S. P., Kishtawal, C. M. & Pal, P. K., 2014. Impact of various observing systems on weather analysis and forecast over the Indian region. Journal of Geophysical Research: Atmospheres, Issue 119, pp. 232-246.

Zapotocny, T. H., Jung, J. A., Le Marshall, J. F. & Treadon, R. E., 2008. A Two-Season Impact Study of Four Satellite Data Types and Rawinsonde Data in the NCEP Global Data Assimilation System. Weather and Forecasting, Volume 23, pp. 80-100.

Radiosondes in Validating NWP Models

Radiosonde observations can be of great utility for determining which numerical weather prediction (NWP) model performs best, and for detecting phenomena that models fail to predict. Radiosonde profiles are helpful when forecasting phenomena that depend on the vertical profile of the atmosphere and exist at a resolution that is poorly represented in NWP models. They can also discern shallow features that models often fail to predict, such as melting and freezing layers, surface winds and low-level temperature inversions and clouds. These are important for predicting phenomena such as fog, low-level wind jets, and surface air quality. Inspection of radiosonde profiles may be currently underused due to the large variety of forecast products and model analysis tools that meteorologist's workstations offer.

The importance of measurement accuracy is emphasized when radiosonde observations are applied in forecasting. Accuracy of temperature measurements is important, for example, when determining the precipitation type based on the temperature of a cloud layer when temperatures are close to 0 °C. Accuracy of humidity measurements is important when determining whether a shallow cloud is deep enough to produce drizzle.

Case Study 4: Fog

Fog is an important winter weather phenomenon in the British Isles. For example, Heathrow Airport, one of the busiest airports in the world, is notorious for flight cancellations due to fog-related reduced visibility in the winter months.

> Forecasting fog is challenging for NWP models since the formation, evolution, and dissipation of fog depend on interactions between small-scale physical processes that are parametrized in the models. Fog is often more shallow than the height of the lowest grid point in the model. The forecasting of fog and its dissipation remain a great financial issue for airport operations.

A persistent layer of thick fog appeared over the whole British Isles during the first days of November 2015. The fog was formed as a radiation fog where night-time radiative cooling decreases the temperature of moist surface air below its dew-point. The density of the fog made it long-lasting since solar radiation could not reach the surface to dissipate it during the day.

Figure 10 compares an RS92 radiosonde observation and an NWP model run profiles at 11 UTC when a dense fog reduced the visibility at the Nottingham sounding station to below 100 m. Visibility did not improve over the day. The dense fog layer is well visible in

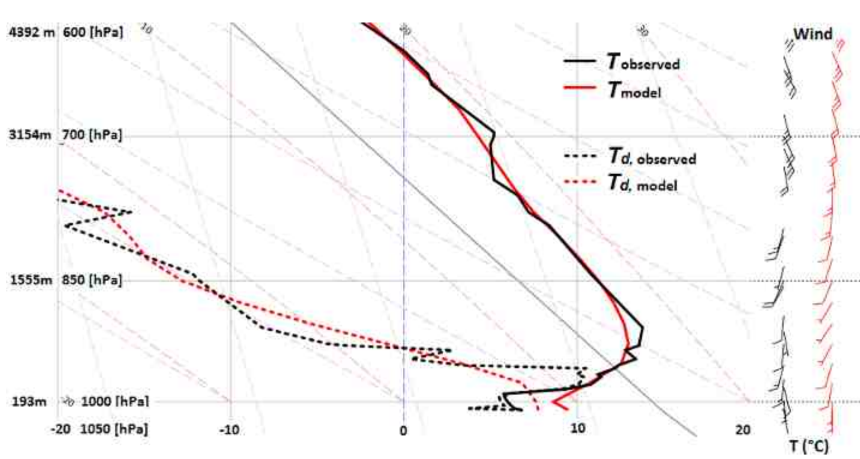


Figure 10. *Comparison of radiosonde sounding (black) and NWP model (red) profiles of temperature (solid lines) and dew-point profile (dashed lines). The sounding is from a sounding station in Nottingham, UK, at 11 UTC on November 2, 2015. The NWP model run (WRF-EMS) is for 11 UTC.*

the radiosonde observations, with a very moist surface layer with temperatures equal or close to their dew-point temperatures up to several hundreds of meters. There is a sharp inversion layer which prevents vertical mixing of the moist surface air with the relatively dry air above. The radiosonde profile correctly implies a persistent fog situation.

The NWP model forecast for 11 UTC was done 5 hours before the observation. The model prediction implies that the fog that existed during the previous night would have dissipated by 11 UTC. The model surface layer is relatively dry compared with the radiosonde profile, with differences between temperatures and dew-point temperatures of several degrees Celsius. The erroneous model prediction can be explained by the higher surface winds and a less sharp temperature inversion which weaken the fog layer. Once initiated, the dissipation of fog by solar radiation is self-feeding: a less dense fog layer permits more solar radiation to reach the ground and to heat the surface. Thus, relative humidity decreases and the fog layer continues dissipating.

A summary of the forecast results is presented in **Table 5**. This example shows the difficulty that models have in fog prediction for only a few hours ahead. Accurate sounding observations in the lower troposphere can be of great help. In this example, the sounding profile tells that the fog layer will not dissipate during the whole day, in contrast to the NWP prediction. This type of information is very important, for example, for airport operations. In addition to accurate temperature and humidity profiles, the accuracy of wind measurements can be crucial for correctly forecasting the dissipation of the fog layer.

Data source	Radiosonde	WRF-EMS numerical model
Surface layer	Saturated	Relatively dry
Low level winds	Very weak	Weak / moderate
Temperature profile	Sharp inversion	Moderate inversion
Forecast	Persistent fog	Dissipation of fog
Observed weather	Persistent fog	

Table 5. *Forecasts based on a radiosonde sounding and an NWP model, showing the reasoning from factors in the atmospheric profiles, the forecasts, and the weather observation at the sounding site later in the day.*

Meteorological Indices

Forecasting in severe weather situations requires making the right conclusions from a large amount of information sources in a short time. Meteorological indices can help the forecaster make faster conclusions from radiosonde observations when estimating the possibility of severe weather. Meteorological indices are calculated from sounding profiles. An index describes in a single value some aspect of the state of the atmosphere, such as the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. This index is known as the convective available potential energy (CAPE).

Most typical indices are so-called stability indices which have been specifically invented to improve forecasting of deep convection and thunderstorms.

Some of the most commonly used indices for predicting severe weather are described in **Table 6**. The indices show the potential for severe weather, typically expressed by the categories of "weak", "moderate", or "strong". Threshold values for the different categories are approximate and depend on the season and climate. Some indices 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.

INDEX	TYPE OF USE	UNIT	WEAK	MODERATE	STRONG
BRN Bulk Richardson Number	Storm cell type	-	< 10 (pulse type convection)	> 50 (multicells)	10-50 (supercells)
CAPE Convective Available Potential Energy	Deep moist convection (thunder)	J kg-1	USA: < 500 Europe: < 100	USA: 500-2000 Europe: 100-1000	USA: > 2000 Europe: > 1000
CIN Convective Inhibition	Likelihood of convection to form	J kg-1	< -50	> -50	
SWEAT Severe Weather Threat	Severe weather potential	-	< 200	200 – 300	> 300
DCAPE Downdraft CAPE	Downdraft strength	J kg-1	< 500	500 – 800	> 800
KI K-index	Instability	°C (or K)	< 20	20 – 30	> 30
LI Lifted index	Instability and thunder potential	°C (or K)	USA: > -2 Europe: > 0	USA: -2 ... -4 Europe: 0 ... -2	USA: < -4 Europe: < -2
SI Showalter Index	Instability	°C (or K)	> 0 (showers)	0 ... -3 (thunder)	< -3 (severe thunder)
TT Total Totals Index	Instability and storm strength	°C (or K)	< 44	44 – 50 (thunder likely)	> 50 (isolated severe storms)

Table 6. *Summary of common meteorological indices.*

Impact of Radiosonde Data Quality

Figure 11. *The geographic areas covered in the study.*

In the following we will look at the impact of radiosonde measurement accuracy on meteorological indices and the forecasts based on them.

To evaluate the impact of radiosonde data quality and its significance to meteorological indices, we studied a set of 56 soundings from three geographical areas in conditions that resulted in severe weather. The areas studied were North America, Central Europe, and Northern Europe. The soundings were done with either Vaisala Radiosonde RS92 or RS41.

The impact of measurement quality was simulated by introducing artificial errors to the original sounding profiles, which were used as the reference. Meteorological indices were calculated from original profiles, and from profiles with small offsets: -4 to +2 % RH for relative humidity and ±0.2 °C for temperature. These offset values are rather conservative, and demonstrate the sensitivity of the indices to small uncertainties in radiosonde observations. Wind speed and direction are also significant components in calculating indices. They were not modified in this study as the wind measurement accuracy is typically very good in radiosondes.

Results

Figure 12 shows the mean relative change (%) in five meteorological indices as a result of small humidity or temperature offset errors. BRN, CAPE, and LI were calculated using the surface as the start level. The results indicate how radiosonde measurement errors are propagated into errors in meteorological indices.

The indices were more sensitive to humidity offsets than temperature offsets. When all 56 soundings are considered (upper graph), a 4 % RH negative bias caused mean relative changes of -19 % in BRN, -29 % in CAPE, +21 % in LI, 5 % in DCAPE, and 6 % in KI indices. A ±0.2 °C temperature bias caused small changes of less than 7 % in all indices. Case examples from individual flights indicated that the impact of temperature may be more considerate in wet-bulb error situations. Complex indices which are calculated by integrating the values in the sounding profile (for example, CAPE) changed more, while simple indices using only a few heights (DCAPE, KI) were less sensitive.

The changes are more pronounced when we inspect borderline situations where the evolution of convection and the possible initiation of thunderstorms have more uncertainty. The lower graph shows the results for weakly convective cases with CAPE < 1000 J kg-1. A 4 % RH negative bias caused larger mean relative changes in CAPE, BRN and LI indices. The changes were -43 % in BRN, -49 % in CAPE, and +34 % in LI. A ±0.2 °C temperature bias caused 2 – 20 % changes in these indices.

Summary

The results show that radiosonde measurement accuracy is important for the correct estimation of the meteorological indices. In borderline situations even small errors can change the indices considerably and may lead the meteorologist to underestimate or overestimate the arrival of convective weather.

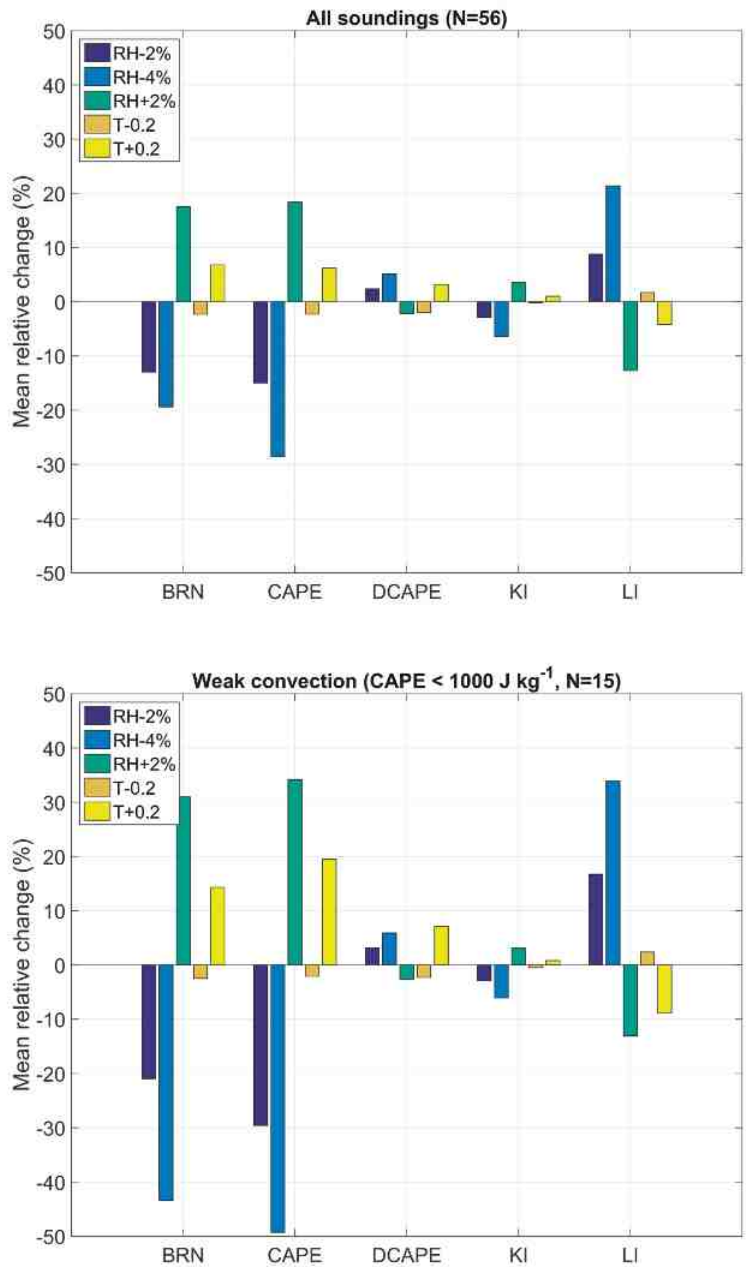


Figure 12. *Mean relative change (%) in meteorological indices calculated from radiosonde observations when humidity or temperature offset is added to the profiles.*

Radiosonde Pressure Measurement

Accurate observations of the atmospheric pressure are among the most important radiosonde observations for weather forecasting. In the following we will look at the two currently available pressure measurement technologies for the radiosonde and discuss how to conduct the pressure measurement to obtain the required measurement accuracy for different application purposes.

Pressure information is used in many ways. It is the vertical coordinate for temperature, humidity, and wind profiles from the radiosonde when they are assimilated into numerical models. It is needed for calculating other variables, such as height and mixing ratio, and for various corrections. Heights of standard pressure levels are important in forecasting the strength and evolution of weather systems.

It is essential to verify that pressure measurements are accurate. A low quality measurement associates the temperature and humidity values with wrong pressure levels. This can produce errors in numerical weather and climate models that are larger than the actual measurement uncertainty of the temperature or humidity sensor in the radiosonde.

WMO accuracy requirements for upper-air measurements for synoptic meteorology are 1 hPa near the surface, increasing to 2 hPa near 100 hPa, and 2 % from 100 to 10 hPa (WMO-No. 8, CIMO Guide, Annex 12.A, 2008 Edition).

Two pressure observation methods

Atmospheric pressure and height measurements are closely related. As the height increases, the pressure decreases, following a nearly logarithmic profile. Pressure and height profiles can be derived from each other with small corrections, taking into account the air density variations. Consequently, there are two main principles available for radiosondes for determining the atmospheric pressure.

Pressure can be measured indirectly using the radiosonde measurements of GPS height, temperature, and humidity, or directly with a pressure sensor. Similarly, height can be measured directly from the GPS satellite navigation system, or indirectly from pressure, temperature, and humidity sensors. The two procedures are depicted in **Figure 13**.

The two independent methods give useful options suitable for different radiosonde applications. In the following we will describe their respective strengths and weaknesses in terms of precision and accuracy of measurement. Choice of the optimal observation method depends on the application where the measurement is used.

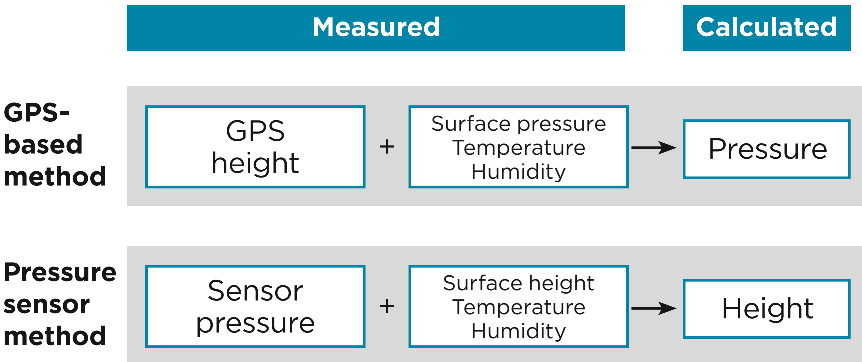
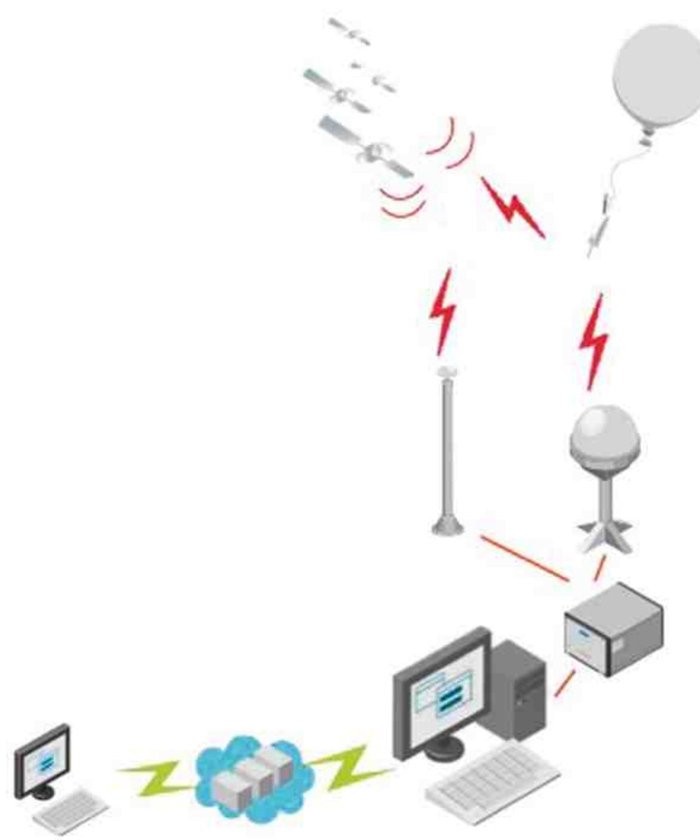


Figure 13. *Comparison of GPS-based and sensor-based pressure measurement methods.*

GPS-based Pressure

The use of GPS height, temperature, and humidity for estimating pressure is the most common method used at upper air sounding stations. Omitting the pressure sensor allows simpler radiosonde design and pre-flight preparations. The ground level value of the pressure profile is obtained from a barometer at the sounding station. The barometer observation also calibrates all values in the profile. The change in pressure between each measurement point is solved using the height, temperature, and humidity information. The method assumes a hydrostatic balance, which is a valid model for most situations.



A sounding system with GPS components.

Accuracy of GPS-based pressure measurements

The accuracy of GPS height measurement is fairly constant through the range of heights used in a radiosounding. As a result, the GPS-based method provides a very high precision of pressure in the stratosphere where the pressure change with increasing height is small. With this method, the measurement quality is critical in the lowest kilometers of the atmosphere where an error of a few meters in height will lead to several tenths of hPa error in pressure. The GPS antenna hardware and the GPS location algorithms must be designed to fulfill the requirements of the radiosonde application.

An important factor affecting the accuracy of the measurement is the surface pressure. The station barometer must be properly calibrated, and the height settings, such as the local antenna and barometer heights, correctly configured in the sounding software.

The quality of the radiosonde temperature measurement has a moderate impact on pressure accuracy, while the humidity measurement has a very minor impact. As an example, a persistent temperature bias of 0.1 – 0.2 °C causes an error of up to 0.15 – 0.3 hPa in the GPS-derived pressure profile.

When to select the GPS-based method?

The GPS-based pressure method is the WMO recommended choice (WMO-No. 8, CIMO Guide, Chapter 12.3) for synoptic soundings. This method provides sufficient accuracy for the lower atmosphere and the benefit of very high accuracy in the upper atmosphere, where the quality of long-term time series of quantities such as temperature and ozone require accurate pressure and height coordinates. The GPS-based method is also suitable for climate observations and atmospheric research campaigns.

Sensor-based Pressure

A pressure sensor observes the atmospheric pressure directly by measuring the force produced by the column of the atmosphere above the radiosonde. This is the "true" atmospheric pressure, in contrast to the GPS-based method which assumes a hydrostatic balance in the atmosphere.

The inclusion of the pressure sensor to the radiosonde design leads to some additional requirements, such as a calibration step during ground preparations. An adjustment against a well calibrated reference barometer takes into account sensor drifting during storage and transport.

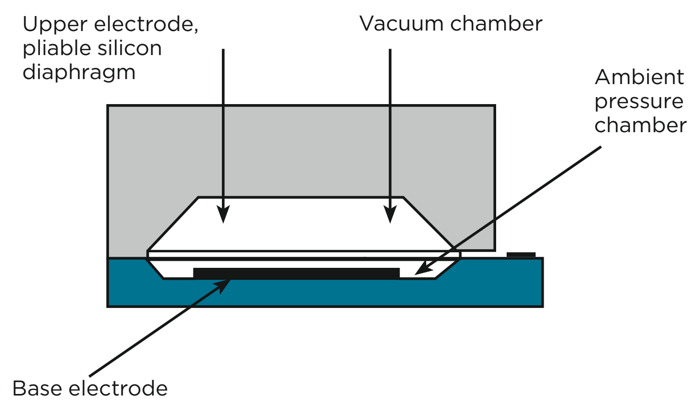


Figure 14. *Construction of a capacitive pressure sensor.*

Accuracy of pressure sensor measurements

A well calibrated pressure sensor provides very high accuracy and precision in the lowest kilometers of the atmosphere. The accuracy of the sensor measurement is limited by the sensor's dynamic range in the upper atmosphere. The absolute accuracy (hPa) remains fairly constant, but as pressure levels are very low, the relative errors become larger. When pressure is used as the vertical coordinate for other quantities, such as temperature and ozone, the pressure measurement uncertainty may produce inaccurate observations of those quantities in the stratosphere.

When to select the pressure sensor method?

The sensor-based pressure measurement is suitable for synoptic soundings. The data redundancy option by measuring both sensor pressure and GPS-based pressure from the same radiosonde sounding can be useful for researchers for understanding the atmospheric conditions. The sensor measurement may also be preferred for continuity of the measurement method for long time series of data for climate research, or when very high precision is needed for the lowest kilometers of the atmosphere. In highly non-hydrostatic conditions the pressure sensor may give more accurate results, as indicated by the following case study.

Case Study 5: Tropical Cyclone

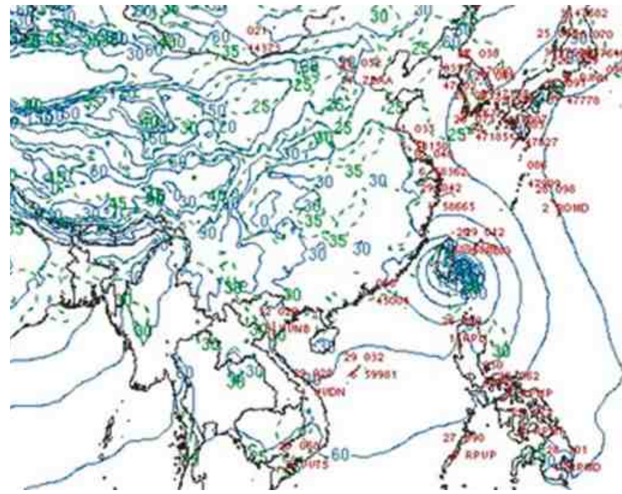


Figure 15. *. Map of 1000 hPa pressure level heights in South-East Asia at 12 UTC on July 22, 2014.*

Highly non-hydrostatic and horizontally non-homogeneous environments, such as those observed near the eye of a tropical cyclone, are interesting when comparing the two pressure measurement methods. Some differences between the results can be expected as the assumptions used in the GPS-based method may not describe the state of the atmosphere accurately.

Typhoon Matmo passed over Taiwan in July 2014, and tropical storm Fung-wong in September 2014. Radiosonde soundings using Vaisala Radiosondes RS41 and RS92 from a sounding station located in Taiwan were inspected from those time periods. A comparison of GPS and sensor pressure profiles from RS92 showed some unusual differences when typhoon Matmo was close to the sounding site, see **Figures 15 and 16**. Largest observed pressure difference was 5.5 hPa at near 400 hPa level. The heights of the maximum differences correlated with maximum wind velocities during the flights.

Smaller differences of 1 – 2 hPa were measured after the eye of the storm had passed the area, and also during the lower category tropical storm Fung-wong. Although a more comprehensive study is needed for verification, these results indicate that in highly non-hydrostatic situations a high quality pressure sensor measurement gives a more accurate result than the GPS-method.

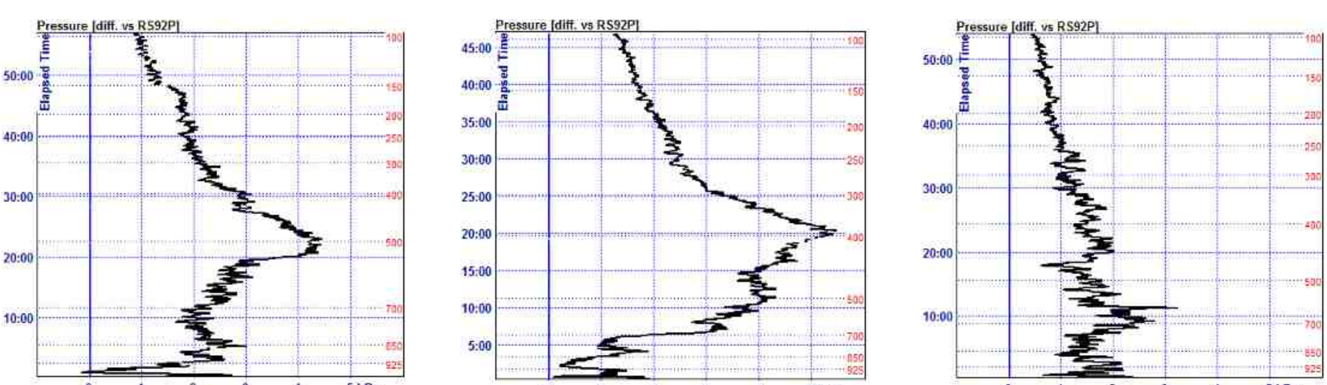


Figure 16. *Differences between GPS-based and sensor pressure during three soundings on July 22, 2014. Pressure levels are shown in red.*

Radiosonde Data in Climatology

Climate research and monitoring set very high requirements for the observation instruments. Changes in the trends of atmospheric variables should be detected early and understood quickly. This calls for an optimal mix of independent observations with strict accuracy and data continuity requirements.

Radiosonde measurements have several strengths compared with other observation systems. Data is available from the surface to the stratosphere and the height resolution is much better than with satellite data. The time series of radiosonde data span several decades; however, the homogenization of such long time series is challenging. Continuous monitoring of the Earth's climate is managed by the World Meteorological Organization (WMO) in collaboration with several regional and international organizations and programs, such as the GCOS Reference Upper-Air Network (GRUAN).

It is important to monitor the atmosphere with several independent observation systems. High measurement accuracy and data continuity are essential requirements. Radiosonde profiles are used in many ways in climatology:

- Monitoring temperature profiles and trends from all heights.
- Monitoring upper air humidity content. Mid-tropospheric to stratospheric water vapor impacts the thermal energy radiated into space and thus affects the global greenhouse effect.
- Understanding the vertical distribution of clouds, and the initialization and maintenance of cirrus clouds.
- Studying environmental characteristics, such as air quality, pollutant dispersion, and urban climate.
- Validation of reanalysis data used in climate studies.
- Verification and development of climate models.
- Radiosondes are used as a platform for measuring additional variables, such as atmospheric ozone.
- Radiosonde measurements form the baseline of performance for validating and calibrating satellite data, and help mitigate systematic errors that might otherwise go unnoticed.

Radiosonde profiles also help to understand and to prepare for the consequences of climate change, such as the increasing occurrence of extreme weather events.

Networks for upper-air climate observations:
GCOS Upper-Air Network (GUAN) www.wmo.int/pages/prog/gcos/
GCOS Reference Upper-Air Network (GRUAN) www.gruan.org

Radiosonde Accuracy Matters

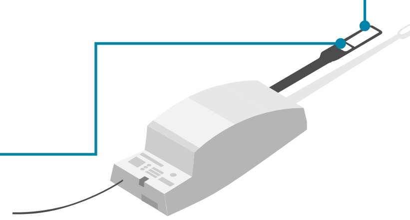
Radiosonde measurements are the most accurate information available for understanding weather. Their information is relevant for both long-range forecasts and for estimating how weather will change in the next few hours. An erroneous measurement could lead to wrong decisions. It does not make sense to measure with a non-optimal instrument.

Vaisala Radiosonde RS41

Usability and error preventive design of the radiosonde and MW41 sounding system bring efficiency and reliability to operations.

Platinum Resistive Temperature Sensor with excellent stability, very fast response time, small solar radiation error and effective protection from wet bulb cooling error.

Vaisala Humicap® Humidity Sensor with active de-icing method to prevent freezing and on-chip temperature measurement to eliminate solar radiation error.

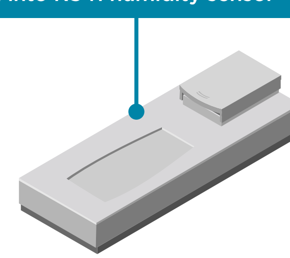


Ground Check Device RI41 is an important part of reliable operations. Each radiosonde is checked prior to launch to detect possible injuries e.g. during transportation and to remove contaminants from the humidity sensor.

- Humidity: integrated heating elements of RS41 provide physical zero reference level check without desiccants or other external references
- Temperature: stabile, yet verified with the secondary temperature sensor integrated into RS41 humidity sensor

Calibration against SI traceable references, comprehensively analyzed and verified regularly.

Proven measurement performance tested thoroughly in laboratory and in several test campaigns in different climates.



Further reading

Vaisala Radiosonde RS41 Measurement Performance White Paper

Vaisala Radiosonde RS41 Calibration Traceability and Uncertainty White Paper

Impact of Radiosonde Measurement Accuracy on Meteorological Indices, Vaisala 2015

GPS-Based Measurement of Height and Pressure with Vaisala Radiosonde RS41 White Paper

WMO Intercomparison of High Quality Radiosonde Systems, Yangjiang, China, 12 July – 3 August 2010

D. Edwards, G. Anderson, T. Oakley, P. Gault: UK MET Office Intercomparison of Vaisala RS92 and RS41 Radiosondes, 2014

www.vaisala.com > Sounding Systems and Radiosondes > Sounding Data Continuity

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