Opportunistic sensing with recreational hot-air balloon flights

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ABSTRACT

We report about a new 3rd party observation, namely wind measurements derived from Hot-Air Balloon (HAB) tracks. At first we compare the HAB winds with wind measurements from a meteorological tower and a radio acoustic wind profiler, both situated at the topographically flat Cabauw observatory in the Netherlands. To explore the potential of this new type of wind observation in other topographies, we present an intriguing HAB flight in Austria with a spectacular mountain-valley circulation. Subsequently, we compare the HAB data with a Numerical Weather Prediction (NWP) model during 2011-2013 and the standard deviation of the wind speed is 2.3 $ms^{-1}$. Finally we show results from a data-assimilation feasibility experiment that reveals that HAB wind information can have a positive impact on a hindcasted NWP trajectory.
Can you imagine that a balloon trip can improve your weather forecast or even improve the safety of your balloon trip? We envision that in the near future you might be able to transfer the location data from your smartphone to a meteorological center, where it is immediately assimilated to improve your short term forecast. In this paper we discuss some components of such a system.

We commence with data from HAB pilots and reveal the added value of just ordinary Global Navigation Satellite System (GNSS) location data. On board of a HAB wind information can be derived and they are opportunistic, because the location data were originally not intended to measure the wind components, (De Vos et al. 2020). Based on this concept we have developed an app for a smartphone that can collect data and transfer them in a timely manner to a meteorological datacentre. Subsequently the data have to be ingested in a data assimilation module of a NWP model and the updated forecast with a balloon trajectory should be disseminated via a dedicated app or the normal communication channels to the front end user.

NWP models with a horizontal resolution of 2 km or finer need detailed information for estimating the initial state of the atmosphere. Ground-based remote-sensing instruments like Sodars, Doppler lidars and Radar Wind Profilers provide already meteorological information of the Atmospheric Boundary Layer (ABL). The observational network has been extended over the years, but there are still gaps and it is not cost-efficient to extend the network infinitely.

Therefore we have commenced research to investigate data from third parties. We focus on wind-information of the ABL from recreational HAB flights. On yearly basis 6000 flights take place in The Netherlands and during an instance there might be more than 30 HAB’s airborne. HAB flights take usually place during the transition period (Lothon et al. 2014) when the atmosphere becomes stable. In the basic equipment of a HAB-pilot there is a professional navigator, which is compulsory for safety reasons. Similarly to routinely launched weather balloons, the Global Navigation Satellite System (GNSS) data from consecutive positions and the elapsed time are the
basis of the calculation of the horizontal wind vector. The HAB responds to changing wind with a response length of approximately 100 m. This response length which comprises the physical properties of the HAB, is derived theoretically in De Bruijn et al. (2016) and validated empirically in De Bruijn et al. (2020).

Collecting data can be achieved by using the off-line navigational data of a HAB-flight. Data are available in the archives of balloonists, but these data are not suitable for real-time application. Another method might be the application of smartphones which has been investigated in De Bruijn et al. (2020). This method relies on the collaboration of balloonists and passengers who should carry a smartphone and apply a dedicated app during a HAB flight. This requires some effort, but the collaboration is also for their own benefit, because they might receive better weather forecasts. Alternatively the collection of data could be organized via Air Traffic Control (ATC) using a transponder. However a transponder is not a compulsory device, and installing transponders on every HAB requires a lot of effort. HAB wind data have a limited availability, but HAB flights can give complementary and detailed wind information of the ABL. Of course the HAB winds are only present in a small time-slot, but if they are applied in a more flexible 4DVAR data assimilation module, its added value can be incorporated more effectively in a NWP model. Every third party wind instrument has its pro’s and con’s. The HAB wind is a simple straightforward measurement technique. Data from gliders and sailplanes are more complicated, because it requires also the measurement of the relative airspeed. Wind turbines deliver wind data continuously at one location at a fixed height and their number is growing rapidly.

We start with comparing HAB wind data from a flight of 18 June 2013 with observational wind data from the observatory at Cabauw (Bosveld et al. (2020)). We have used wind data from the instrumental tower and from a Radio Acoustic Sounding System (RASS) wind profiler for the comparison. The meteorological site is located in a flat rural area with scattered villages. The
HAB flight started in the outskirts of the city of Utrecht at 18:23 UTC and the touch down was 1 hour later at 4.8 km distance from the observatory. Details of this flight can be found in De Bruijn et al. (2016). In Figure 1 we show the last twenty minutes of the flight when the HAB was descending and approaching the observational site from the north. The HAB wind data are based on 30 s averages of the positions. Up to 200 m mast observations are shown, more aloft, data from the RASS wind-profiler are also presented. All the site data are available as 30 min averages. For the mast observations also the standard deviations are presented. The standard deviations are rather small, indicating that turbulence is dying out. The lower part of the HAB data is clearly affected by the local conditions like farmhouses and bushes. At the higher levels of the approach the match with observations improves, because the wind is less disturbed and representative for a larger footprint.

This example of a HAB-wind observation was taken from a topographically flat region in the Netherlands, but would this method also work in more complex terrain? We show an intriguing example of ballooning in mountainous terrain during winter conditions. The flight took place in Austria and is shown in Figure 2. The take-off was at Sankt Johann (Tyrol) and the flight lasted 96 min. The surface was covered with snow (see the photograph in Figure 2), which prevented the development of thermals and therefore this flight could start during the course of the morning, namely at 10:18 UTC. In the beginning the HAB went in northerly direction, and as soon as the balloon had gained height, it entered a different wind regime. The HAB turned around and returned to its starting position and went further South. Descending after 1 hour, at the valley bottom southerly winds prevailed and the HAB passed through a layer with considerable wind shear. Close to the surface the HAB was again advected in northerly direction. There was a weak synoptic influence allowing local wind effects to dominate (Zardi and C.D. Whiteman 2013). The synoptic situation showed a high pressure system centered over eastern Europe with a secondary
center over northern Italy. This pressure distribution favored an inversion in the valleys and the valley flow direction was obviously South to North. In the upper levels the region was under a ridge with a northerly flow. The collected balloon data was in some agreement with the local AWS station Hahnenkamm (see the right subplot in Figure 2), which was located 10 km south southwest of landing point. For NWP models it is a truly challenge to make a weather forecast of such a complex situation, see Goger et al. (2018).

In Figure 3 we compare HAB-winds with analyses of the High Resolution Limited Area Model (HIRLAM) (Undén et al. 2011) during 2011-2013. These data are based on 71 flights from Dutch balloonists who have shared their flight tracks with KNMI. We have run an experimental version of HIRLAM and its characteristics are summarized in table 1. We have applied a bi-linear interpolation method to obtain the model data at the HAB’s location. The balloon data is interpolated to 30 s averages. The data-set contains HAB flights mainly from The Netherlands, but also some flights from Belgium, France and Austria. The majority of the flights took place in the summer season, but occasionally flights took also place during the winter in snow conditions. Most HAB launches were made during the cooler hours of the day, at dawn or two to three hours before sunset. At these times of the day, the winds were typically light and less turbulent, making it easier for the launch and landing of the balloon. The large biases are attributed to extreme cases like for example a thermal updraft (De Bruijn et al. 2016), which were not captured by HIRLAM. The total vertical averaged values for bias and standard deviation are respectively 0.4 and 2.3 $ms^{-1}$.

Based upon the above results, we take the next innovative step namely the application of HAB data in the HIRLAM model. We conducted a data assimilation feasibility study with data from another HAB flight from The Netherlands (Figure 4), which started in De Bilt at 16 September 2013 16:05 UTC and ended in Amersfoort at 17:00 UTC with a traveled distance of 19.5 km. At 16:30 UTC the HAB reached the ceiling of the flight which was 1428 m. At that point we
see a remarkable change in direction. Apparently the balloon has entered a layer with a different wind regime. We now study a trajectory which is based on hindcasted NWP wind fields and which is depicted by the red line in Figure 4. The output field frequency is 15 min and we have used the Petterson (1956) scheme to compute the trajectory. For a fair comparison, the vertical displacement is completely prescribed by the HAB. Clearly, the NWP trajectory is different and the position error at the endpoint is 8.8 km. We have assimilated the observed HAB winds during 25 min of the flight and interpolated the observations to the analysis time at 16:00 UTC. In the pre-processing we have rejected the HAB data just after take-off, because the HAB cannot move freely at that stage. With the updated run, we calculate the trajectory which is depicted in blue in Figure 4. The deviation at the endpoint reduces to 2.9 km. When we study the transect in Figure 5, again we recognize a clear improvement. Note that the adjustment is alternating between negative and positive values. Note that also outside the assimilation time window which ends at 16:30, the improvement is still present, which is encouraging. Despite this positive result, we have to make some remarks. The predictive value in this experiment is rather short, the model improvement is very local and ideally the validation should be performed over a larger area with independent observations. Nonetheless, we may conclude that HAB winds are realistic and potentially useful for data assimilation.

Thus, HAB flights provide interesting wind information in the ABL and are in agreement with other upper air observations. Comparison with HIRLAM reveals that the error characteristics are acceptable. Mountain flights could provide data from local decoupled flows embedded in a larger scale circulation which are interesting phenomena especially when such phenomena are not captured by a NWP model or by the regular observational network. HAB derived winds make sense and can be applied in data assimilation and have a positive impact on the forecast. However, the NWP model should be implemented in a rapid update cycling method and the timely
availability of the new observation type is crucial for a successful application. Given the current state of the technique, it is a challenge to meet these requirements. Nonetheless, these 3rd party observations are a welcome supplement to the existing observation network and can be used for process studies, model validation and forecasting through data assimilation. And to answer the initial question, the answer is Yes, if you use your smartphone on board a HAB you may in future be able to improve the weather forecast.

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<td>Domain:</td>
<td>Europe and North Atlantic</td>
</tr>
<tr>
<td>Hor. res.:</td>
<td>$11 \times 11 \text{ km}^2$</td>
</tr>
<tr>
<td>Vert. res.:</td>
<td>60 layers; surface – 10 hPa</td>
</tr>
<tr>
<td>Data assimilation:</td>
<td>every 1 h, 3DVAR</td>
</tr>
<tr>
<td>Lateral boundaries:</td>
<td>every 3 h, from ECMWF model</td>
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<td>Physical parameterisation:</td>
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