

# Opportunistic Sensing with Recreational Hot-Air Balloon Flights

Evert I. F. de Bruijn, Fred C. Bosveld, Siebren de Haan, and Albert A.M. Holtslag

**ABSTRACT:** We report about a new third-party observation, namely, wind measurements derived from hot-air balloon (HAB) tracks. We first compare the HAB winds with wind measurements from a meteorological tower and a radio acoustic wind profiler, both situated at the topographically flat observatory near Cabauw, 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 2011–13 and the standard deviation of the wind speed is  $2.3 \text{ m s}^{-1}$ . 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.

**KEYWORDS:** Europe; Trajectories; Turbulence; Aircraft observations; In situ atmospheric observations; Data assimilation

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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 hot-air balloon (HAB) pilots and reveal the added value of just ordinary Global Navigation Satellite System (GNSS) location data. On board a HAB, wind information can be derived and it is 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 data center. Subsequently, the data have to be ingested in a data assimilation module of a numerical weather prediction (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 already provide meteorological information about 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 about the ABL from recreational HAB flights. On a yearly basis 6,000 flights take place in the Netherlands, and during an instance there might be more than 30 HABs 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).

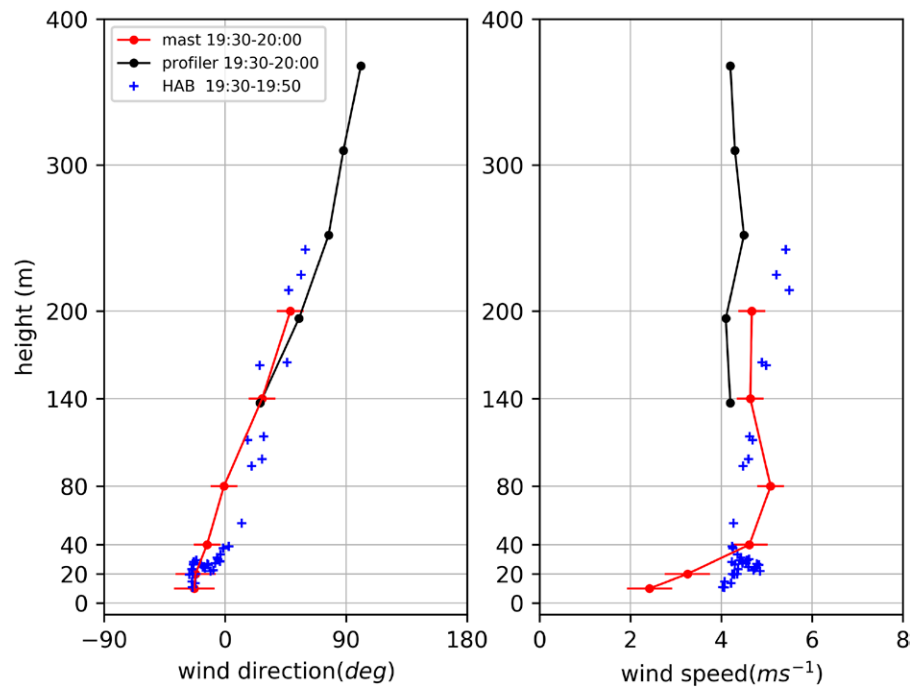
Collecting data can be achieved by using the offline navigational data of a HAB flight. Data are available in the archives of balloonists, but these data are not suitable for real-time application. Another method might be the application of smartphones, which has been investigated in de Bruijn et al. (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 about 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 an NWP model. Every third-party wind instrument has its pros and cons. The HAB wind is a simple, straightforward measurement technique. Data from gliders and sailplanes are more complicated, because they also require 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 on 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 on the outskirts of the city of Utrecht at 1823 UTC and the touchdown was 1.25 h later at 4.8 km distance from the observatory. Details of this flight can be found in de Bruijn et al. (2016). In Fig. 1 we show the last 20 min 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 the standard deviations are also presented. The standard deviations are rather small, indicating that turbulence is dying out. The lower part of the HAB data are 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 is 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 Fig. 2. The takeoff was at Sankt Johann (Tyrol), and the flight lasted 96 min. The surface was covered with snow (see the photograph in Fig. 2), which prevented the development of thermals, and therefore this flight could start during the course of the morning, namely, at 1018 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 farther south. Descending after 1 h, 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 a northerly direction. There was a weak synoptic influence allowing local wind effects to dominate (Zardi and 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 were in some agreement with the local automatic weather station (AWS) Hahnenkamm (see the right subplot in Fig. 2), which was located 10 km south-southwest of the 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 Fig. 3 we compare HAB winds with analyses of the High Resolution Limited Area Model (HIRLAM) (Undén et al. 2002) during 2011–13. These data are based on 71 flights from Dutch balloonists who have shared their flight tracks with KNMI. We have run an experimental



**Fig. 1.** Comparison of HAB wind with tower and RASS wind profiler observations at Cabauw, the Netherlands, during 1930–2000 UTC 18 Jun 2013. The solid lines correspond with wind data with a fixed horizontal position, while the moving HAB is depicted in plus signs. For the mast data the standard deviation of the wind is also presented.

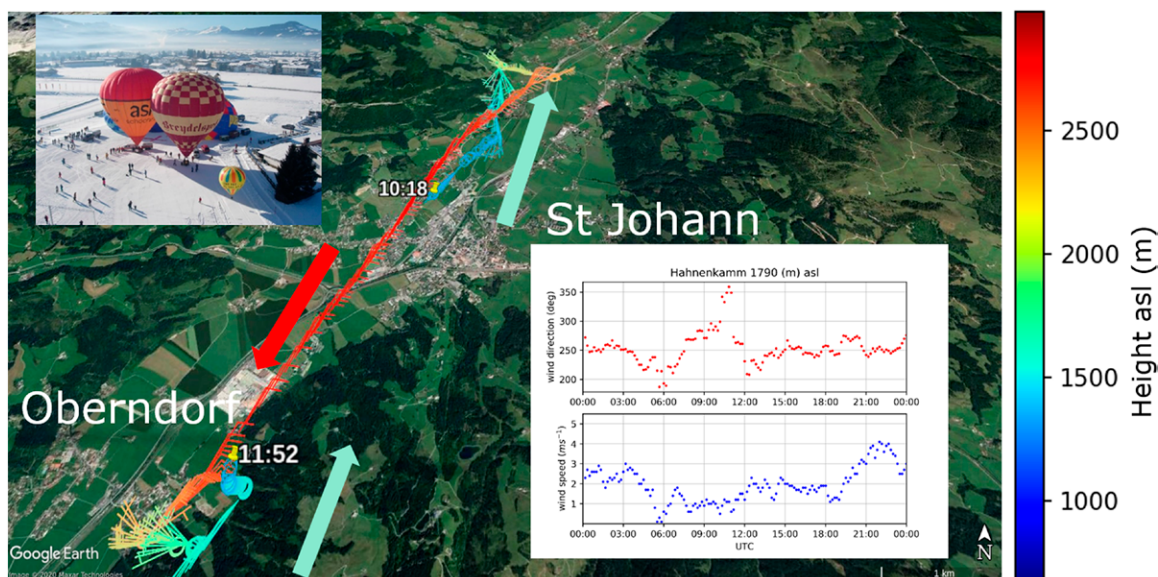


Fig. 2. Mountain HAB flight near Sankt Johann (Tyrol, Austria) during 1018–1152 UTC 16 Jan 2005; in the valley the winds are opposite to the winds above the inversion. The left and right inset plots show, respectively, the takeoff and the nearby Hahnenkamm AWS wind observations.

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 are interpolated to 30 s averages.

The dataset 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 2 or 3 h 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, such as 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 0.4 and 2.3  $\text{m s}^{-1}$ , respectively.

Based upon the above results, we take the next innovative step, namely, the application of HAB data in HIRLAM. We conducted a

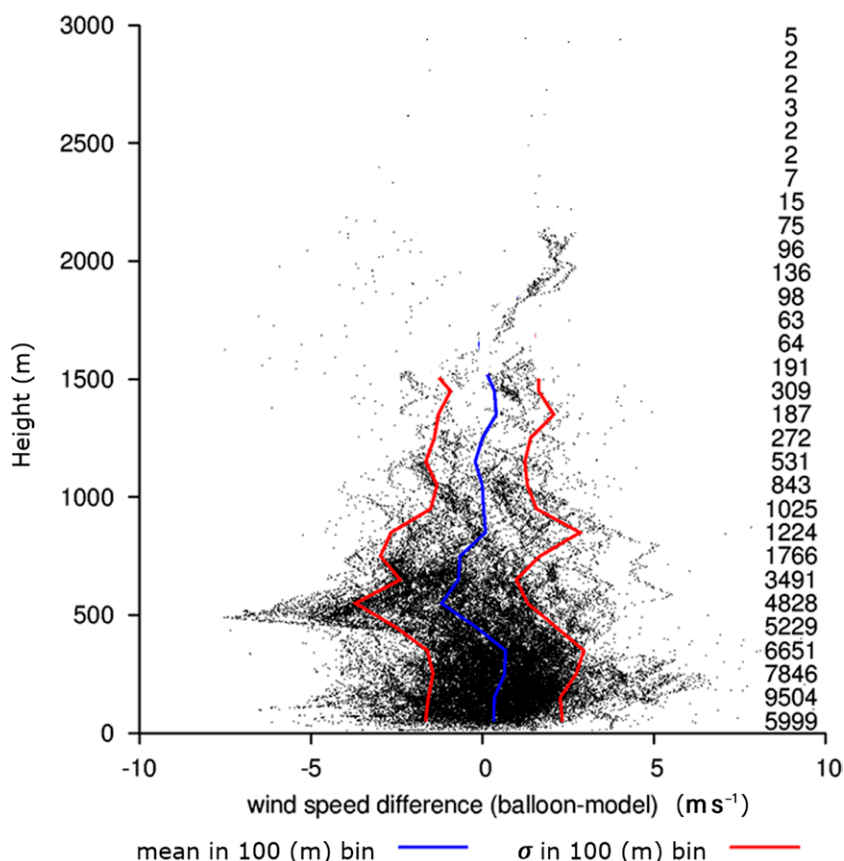


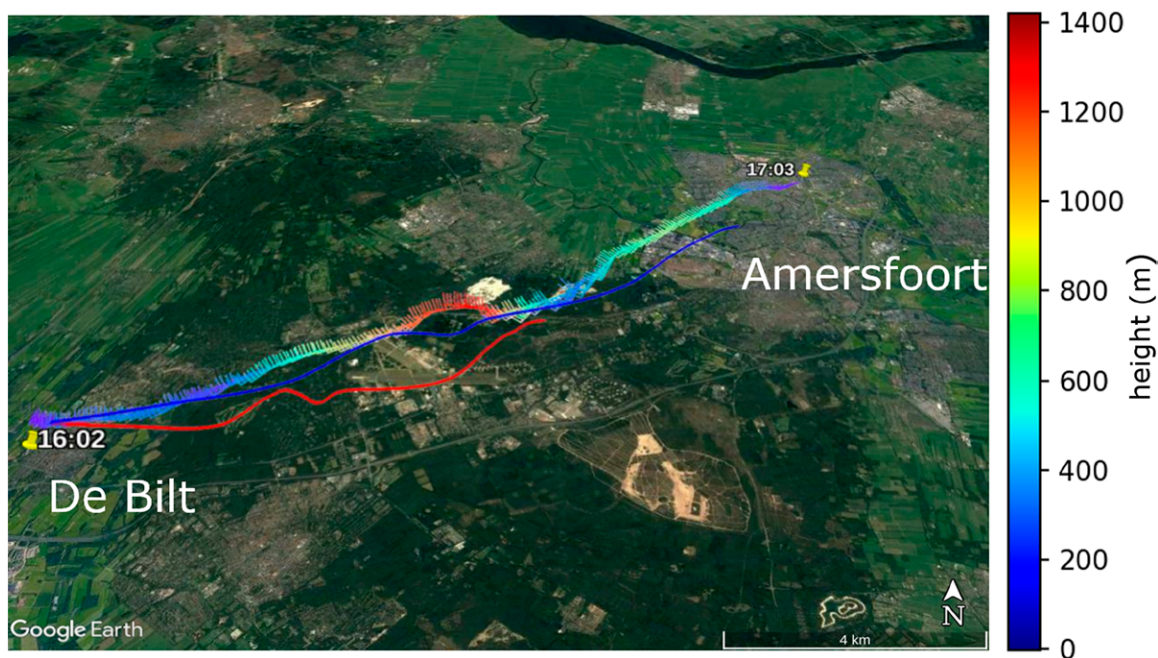
Fig. 3. Validation of HAB wind speed vs HIRLAM analyses (time window: 1 h) during 2011–13. The data are binned in vertical bins of 100 m, and per bin the bias and standard deviation are given. The sample size is depicted on the right. Only the significant statistics are plotted.

data assimilation feasibility study with data from another HAB flight from the Netherlands (Fig. 4), which started in De Bilt at 1602 UTC 15 September 2012 and ended in Amersfoort at 1703 UTC with a traveled distance of 19.5 km. At 1630 UTC the HAB reached the ceiling of the flight, which was 1,428 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 Fig. 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 28 min of the flight and interpolated the observations to the analysis time at 1600 UTC. In the preprocessing we have rejected the HAB data just after takeoff, because the HAB cannot move freely at that stage. With the updated run, we calculate the trajectory, which is depicted in blue in Fig. 4. The deviation at the endpoint reduces to 2.9 km. When we study the transect in Fig. 5, we again recognize a clear improvement. Note that the adjustment is alternating between negative and positive values. Also note that outside the assimilation time window, which ends at 1630 UTC, 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

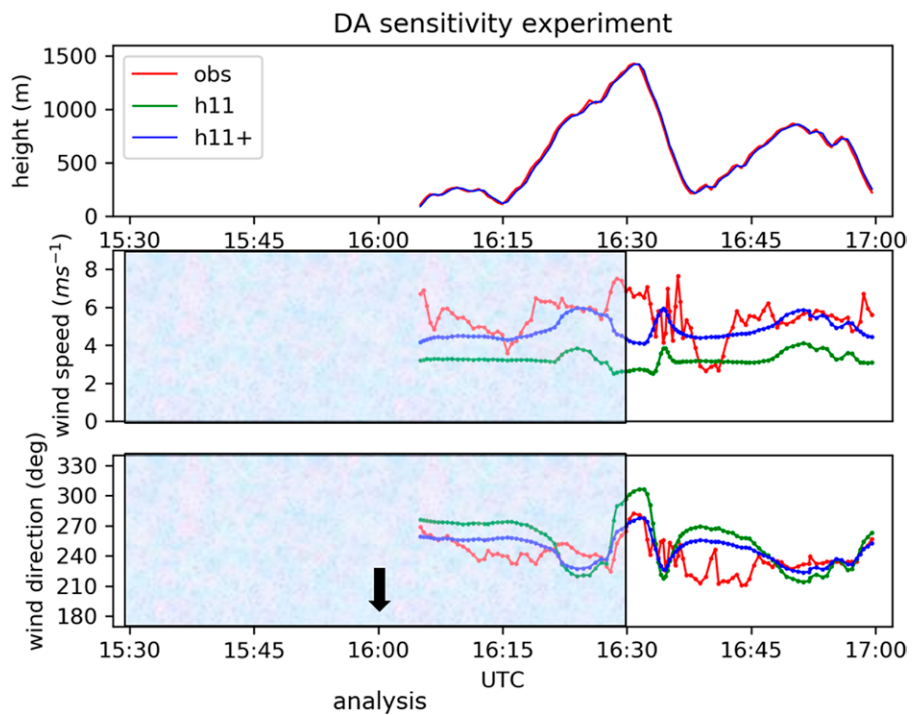
**Table 1. Model characteristics of HIRLAM.**

Domain	Europe and North Atlantic
Horizontal resolution	11 km × 11 km
Vertical resolution	60 layers; surface–10 hPa
Data assimilation	Every 1 h, 3DVAR
Lateral boundaries	Every 3 h, from ECMWF model
Physical parameterization	TKE-I, ISBA surface scheme



**Fig. 4.** Trajectories from a HAB flight during 1602–1703 UTC 15 Sep 2012 are depicted by wind flags, calculated trajectories from NWP are depicted by a red solid line, and calculated trajectories from NWP with assimilated HAB data are depicted as a blue solid line.

in a larger-scale circulation, which are interesting phenomena, especially when such phenomena are not captured by an 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 third-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 the future be able to improve the weather forecast.



**Fig. 5.** Transect of a HAB flight (red), NWP model (green), and NWP model with assimilated HAB data (blue) during 1602–1703 UTC 15 Sep 2012. The light blue box is the assimilation time window, and the analysis time is at 1600 UTC.

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## For further reading

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