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Aircraft Wake Vortices Affecting Airport Wind Measurements

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Abstract

The influence of wake vortices on other aircraft has been extensively studied and is well understood. However, to date, it has not been investigated how wake vortices can affect wind velocity measurements at airports. This study investigates this previously overlooked issue, focusing on departures from runway 34 at Zurich Airport. These departures are suspected to affect a wind sensor situated at the runway's end. Through a combination of visual identification and application of a wake vortex model, instances where wakes affected the said anemometer were identified for a fifteen-month period. Analysis of the resulting data shows that approximately 5% of all departures generated such occurrences. In addition, specific wind conditions and aircraft types were identified as being necessary for such events to occur. The observed cases of wake hits have a significant effect on the wind measurements, altering even averaged values used by air traffic control for clearance by several knots and up to 50 degrees. That, in turn, can result in cases where aircraft performance does not allow take-off based on altered wind readings, even though the actual wind conditions would not prevent the departure. Such cases have the potential to cause significant disruption to flight operations. Even though this paper focuses on this phenomenon at Zurich Airport, similar issues are likely to occur at other airports as well.

Keywords: Wind Measurement, Wake Vortex, Aviation Weather, Airport Operation, ADS-B

1. Introduction

Aircraft wake vortices, also known as wake turbulence, are counter-rotating columns of air that form downstream of the wingtips as a direct result of lift generation [1]. These vortices dissipate relatively slowly and can pose a significant hazard to other aircraft that encounter them, even minutes after their initial formation [2]. In terminal airspace, the hazard of encounters is thereby considered to be particularly high due to the proximity to the ground during the take-off and landing phases, resulting in little time for reaction and recovery [3]. To mitigate the risk of such encounters, wake turbulence separation standards [4] have been established. They specify minimum separation distances between successive approaching and departing aircraft based on their respective wake turbulence categories. These separation standards govern current operations in the airspace around aerodromes and are one of the main factors limiting airport capacity [1]. To address this limitation, the International Civil Aviation Organisation (ICAO) initiated the wake turbulence re-categorisation (RECAT) to optimise the pairwise separation standards [5, 6]. In addition to RECAT, other current research includes work on plate lines, also with the ultimate goal of increasing capacity. Plate lines are an array of

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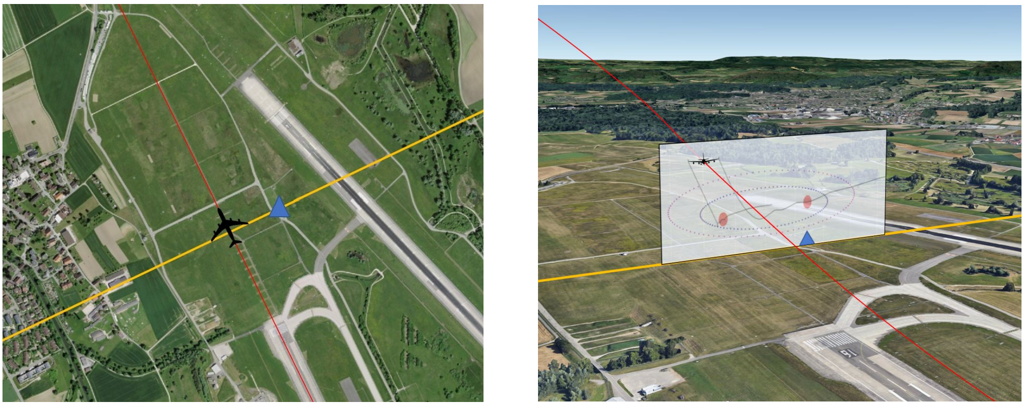
vertical plates placed in front of a runway to accelerate the decay of wake vortices and, thus, to reduce the required wake separation [7]. Overall, the physics of wake vortices is well researched and understood and the field is still active. However, while many aspects of how wakes impact airport operations are well-known and studied, the effect of wake vortices on airport wind velocity measurements has been overlooked.

When issuing a take-off or landing clearance, air traffic control provides the flight crew with information about the prevailing wind conditions at the relevant runway. Accurate wind information is considered safety-critical as aircraft are restricted to operations within specific wind limits, mainly dictated by the performance of the aircraft. Given the importance of accurate wind measurements, large airports usually host multiple anemometers that can be used as the source for up-to-date wind data representative for the relevant runway. ICAO provides guidance on meteorological measurement systems in Document 9837 [8]. This document recommends installing anemometers at a height of 10m above ground and outside of obstacle clearance areas. The document states that "whilst wind sensors should be located close to the runway(s) to achieve representative wind measurement, every effort should be made to site the sensors to minimise the effect from artificial gusts, e.g. due to jet efflux or wake vortices" [8, p. 3.6].

Nevertheless, one of the authors recently learned that at least one of the anemometers at Zurich International Airport, Switzerland, is suspected to be likely affected by wake vortices from departing aircraft on runway 34. The concerned anemometer is located in proximity to the thresholds of runways 14 and 16, approximately 215m and 170m away from their respective centrelines, as illustrated in Fig. 1. The sensor logs wind speed and direction measurements at 3-second intervals, which serve various applications. Amongst them is the computation of a 2-minute moving average that is displayed to air traffic controllers and is used in take-off and landing clearances.



(a) Top view **(b)** Side view

Figure 1. Overview of the wind sensor placement and the runway axes. The blue triangle indicates the position of the anemometer, the yellow line refers to a plane perpendicular to the centreline of runway 34 intersecting with the sensor, and the red line depicts an observed take-off trajectory. The opaque plane in 1b illustrates a simulation of a wake vortex that drifts close to the anemometer. (Figure background [9])

In addition to the aforementioned impact on safety, wind measurements influenced by wake vortices have the potential to detrimentally impact airport performance. As will be shown in a practical example later on, the change in the measured wind due to aircraft wakes can significantly reduce the permissible take-off weight, requiring a runway change or cargo offload. Subsequently, wakes hitting a wind sensor can create situations where aircraft are held back from taking off, despite the actual wind conditions allowing it. Such occurrences represent a significant disruption to airport operations.

This paper investigates the suspected effects resulting from take-offs on runway 34 at Zurich Airport. The aim is to identify cases where wake vortices have interfered with the wind sensor and to provide following-up analysis of the frequency of such incidents and the extent to which they affect the measurements. Furthermore, the research delves into the factors contributing to these occurrences and offers insights regarding their potential effects from an operational point of view. These insights are intended to inform the development of mitigation measures to alleviate this issue.

To the knowledge of the authors, no publication on the effects of wake vortices on operational wind measurements exists to date. This is somewhat surprising since it seems unlikely that such effects are exclusive to the specific situation in Zurich. Nevertheless, a comparable situation has been discovered at Frankfurt Airport in the wake vortex warning system (WVWS) project [10]. At the time, a sonic anemometer array was positioned in front of the threshold of the runways 25C and 25L, see [10, Fig. 3]. This anemometer array was situated in close proximity to where one of the airport's operational anemometers is currently situated [11, p. AD 2 EEDF 2-5, anemomenter B1/B2]. Since the setup for WVWS was explicitly designed to measure wake vortices of arriving aircraft (and successfully did so), one can reasonably argue that the operational anemometer of the airport was affected by wake vortices as well.

The remainder of this paper is organised as follows: Sec. 2, presents information on how occurrences of wakes affecting the wind measurements were identified. Subsequently, Sec. 3 contains an analysis of the resulting dataset, providing insights into the frequency and severity of these events as well as contributing factors leading to their occurrence. Sec. 4 explores the operational implications of hits from the perspective of airlines and the airport. The subsequent Sec. 5 discusses the results and their operational implications, ultimately leading to a conclusion in Sec. 6.

2. Occurrence identification

To analyse instances of wakes impacting the wind sensor, such events first needed to be pinpointed among departures from Zurich's runway 34. This section outlines the methodology used for this purpose, applied to all departures across a fifteen-month span. The proposed approach combines visual classification with a wake modelling approach, each of which will be detailed in the following subsections.

2.1 Data sources

The initial stage of the proposed identification approach requires two types of data: high-resolution wind measurements from the concerned sensor and trajectory data for departures on runways 34 and 32. The rationale to include departures from runway 32 is presented later on. The data from the anemometer was supplied by MeteoSwiss, the operator of the station of interest at Zurich Airport. The provided dataset contains measurements taken between 1 March 2022 and 31 May 2023, including wind direction in degrees and wind speed in knots with a resolution of three seconds. For the same period, all available ADS-B data corresponding to departures from runways 32 and 34 were retrieved from the OpenSky Network historical database [12] using functions available in the Traffic Python library [13]. A total of 2028 departures from runway 34 were retrieved. According to the figures published by Zurich Airport [14], this equates to around 70% of the total number of departures from this runway during the period under consideration. The second stage of classification requires supplementary data to be fed into the wake vortex model. This incorporates aircraft type-specific parameters such as aircraft dimensions and maximum take-off mass, which were obtained from the FAA's Aircraft Characteristics database [15]. Further atmospheric parameters, also required for the modelling process, were sourced via the MeteoSwiss data portal *IDAweb* [16].

2.2 Visual classification

For each available take-off trajectory from runway 34, the time of crossing the line perpendicular to the runway centreline and intersecting the measurement station (referred to as the yellow line in Fig. 1) was determined. The same approach was employed for departures from runway 32, using an analogous line aligned perpendicular to its centreline. This provided each take-off performed during the considered fifteen-month period from both runways with a timestamp, indicating the time when the aircraft passed the sensor. A plot was subsequently created for each departure from runway 34, displaying wind measurements (direction and speed) spanning from five minutes prior to ten minutes after this crossing time. The plots were enhanced with information about take-off crossing times. The analysed take-off is thereby depicted as a vertical black line, whereas other departures from both runways are illustrated in different colours. Other take-offs were integrated into the plots to help in determining whether the observed effects in the measurements are related to the specific take-off under assessment or to other concurrent take-offs. The reason for also including take-offs from runway 32 is that an initial data analysis indicated that their wakes might also hit the concerned wind sensor. In addition to the recorded wind direction and speed, a two-minute moving average is added for both parameters. This average reflects the wind data used by air traffic control for clearances. Furthermore, an arrow was added to the plot displaying the lateral propagation time of the wakes to the station, based on the prevailing crosswind. This results in a distinct plot for each departure from runway 34, illustrating the data as shown in the first two rows of Fig. 2.

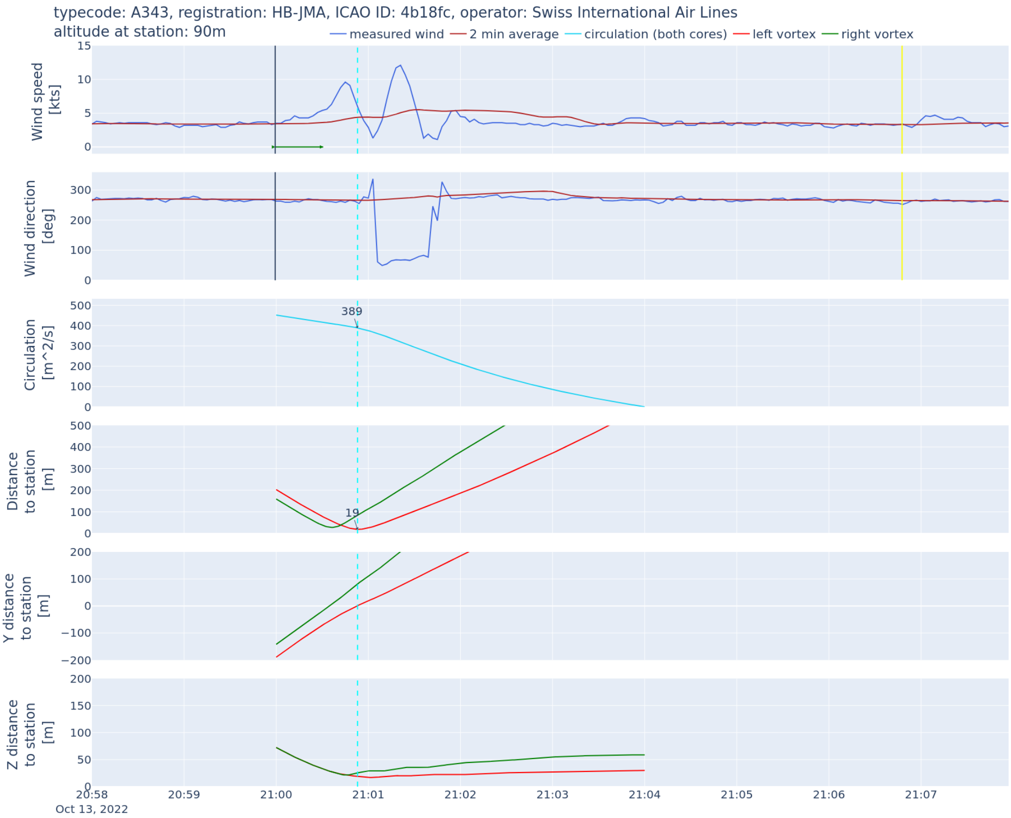


Figure 2. Illustration of a plot employed in the categorisation of takeoffs on runway 34. Initially, only the upper two rows were used for the first visual classification. The lower four rows, representing the wake model's output, were subsequently incorporated for a secondary verification step applied to all take-offs previously classified as hits.

Three assessors then examined all departures using these plots and categorised them based on whether or not the aircraft wake appeared to impact the wind sensor. This assessment was carried out using conservative approach, where only the cases demonstrating clear anomalies were classified as hits. Subsequent application of a majority rule meant that a take-off was considered to have caused a hit if at least two assessors agreed on this assessment. The primary justification for using visual classification as a first step is based on the assumption that any event that is not clearly visible in the wind measurements may be considered operationally irrelevant. In addition, the diverse manifestations of hit events within the measurements made the development of an automated identification method very challenging. Although visual classification is to some extent subjective and relies on the judgement of the assessor, this potential bias was minimised by conservative classification and a second step using a wake model which is described further.

2.3 Wake-model verification

In order to minimise the probability of false positives in the classification and thereby its precision, all cases initially identified as hits by visual assessment were subjected to a secondary verification step. This step consists of simulating the wake vortex evolution on a vertical plane perpendicular to the runway axis and intersecting the wind sensor (see Fig. 1b) using the DLR P2P wake vortex model [17]. This model predicts the wake transport and decay, taking into account specific aircraft and atmospheric conditions. For each take-off previously labelled as a hit, the required input parameters at the moment of crossing the virtual plane were determined before using them to run the wake simulation. These parameters include aircraft-specific attributes like speed, altitude, geometry, and weight, as well as the prevailing atmospheric conditions during wake formation. Aircraft-specific parameters were extracted from the ADS-B trajectory of each departure, supplemented with data from the FAA's Aircraft Characteristics Database. Meteorological and atmospheric information was derived from the provided high-resolution wind measurements, with additional parameters obtained via IDAweb. The resulting model output corresponds to a prediction of the temporal evolution of the wake along the plane, including its position and vorticity. The position information was then transformed to distances relative to the wind sensor before being added as four new rows to the previously generated plots, as shown in Fig. 2. With the additional insight provided by the wake model, each take-off initially marked as a hit was re-evaluated to confirm that the model output also suggests a high probability of a hit. Cases where this secondary verification contradicted the initial judgement, were reclassified as non-hits. This refined classification served as the basis for all subsequent analyses.

3. Occurrence analysis

Based on the classification of the 2028 departures from runway 34, a preliminary exploratory analysis was conducted to gain insight into the occurrences and possible contributing factors. A model was then fitted to the classification data to further understand the relationship between external factors and hits, as well as to identify the conditions most favourable to an occurrence. The aim of the exploratory analysis and the modelling was to develop an intuition for the issue at hand, not to produce a predictive model. Finally, the impact of wake hits on the wind measurements was also investigated. Details on each of these steps are given in the following subsections.

3.1 Exploratory analysis

Out of the 2028 analysed departures, 102 (5.03%) were found to have generated wakes that hit the wind sensor. Given the suspected role of wind conditions in the occurrence of hits, the first step was to investigate the prevailing wind conditions at departure. Fig. 3 illustrates the wind conditions at take-off for all departures, distinguishing between cases that caused hits and those that did not.

Wind speed and direction were calculated by averaging the high resolution wind measurements for a window of two minutes before the aircraft passed the anemometer. The graph implies that certain wind conditions are required for hits to occur. Almost all hits were recorded for wind directions between 160 and 340 degrees (from the left of departing runway 34) in combination with wind speeds of less than 10 knots. It is also worth noting that there is a cluster of hits of particularly high density for wind conditions between 180 and 270 degrees and wind speeds of less than 7.5 knots.

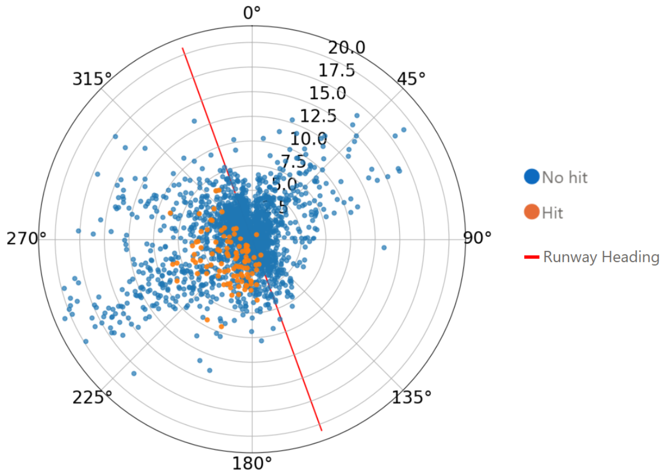


Figure 3. Polar plot illustrating wind conditions during take-offs on runway 34, with angular positions indicating wind direction in degrees and radial distances signifying wind speed in knots. Blue data points correspond to takeoffs that did not cause hits, while orange points denote takeoffs resulting in hits.

Another factor suspected to influence the occurrence of wake hits is the aircraft type of the departing flight. Fig. 4 therefore shows the distribution of typecodes for the analysed departures from runway 34, including the proportion identified as having caused sensor hits.

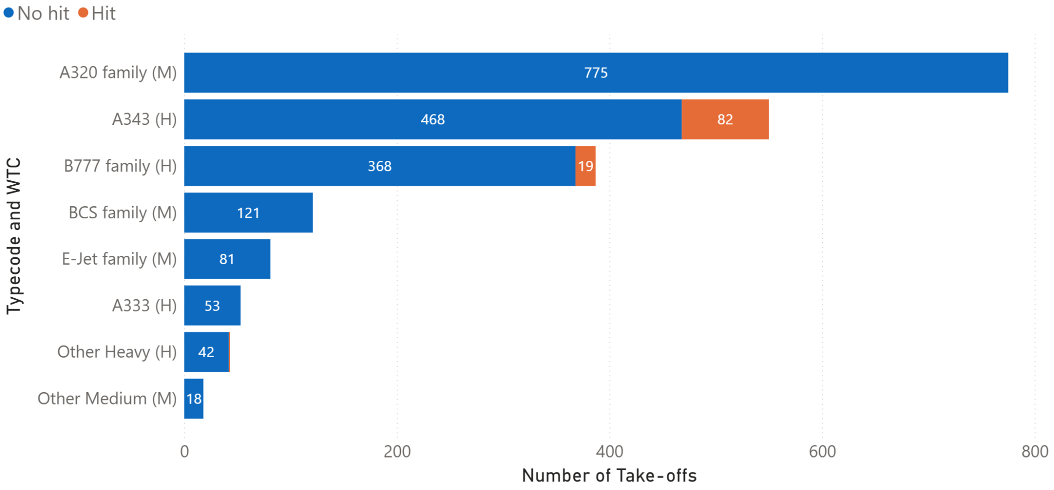


Figure 4. Bar chart depicting the number of take-offs per typecode, distinguishing between take-offs that caused a hit of the wind sensor and those that did not.

Similar types belonging to the same aircraft family (e.g. A320 family) have been grouped together to make the visualisation more readable. Furthermore, typecodes with few departures have been grouped into an 'other' category based on their wake turbulence category. It should be highlighted that the Airbus A340 and Boeing 777 types are responsible for almost all of the recorded hits (101), despite being accountable for only 937 departures (about 46% of the total departures). Only one other hit is attributed to an Ilyushin IL76, which is included in the 'Other Heavy' group in Fig. 4. Moreover, the Airbus A340 is responsible for around 80% of all incidents and has the highest within-category occurrence rate. It should be also noted that all positively classified cases involved heavy aircraft in terms of wake turbulence category. A potential explanation for these differences might be the varying strength of wake turbulence generated by different aircraft types. Another aspect to consider is the altitude at which aircraft pass the sensor. Such variations are due to different aircraft performance, take-off mass, head and tail wind variations and other meteorological conditions. Fig. 5 shows the distribution of altitudes above the runway threshold at the moment of passing the sensor, distinguishing between typecode categories and also between departures that caused hits and those that did not.

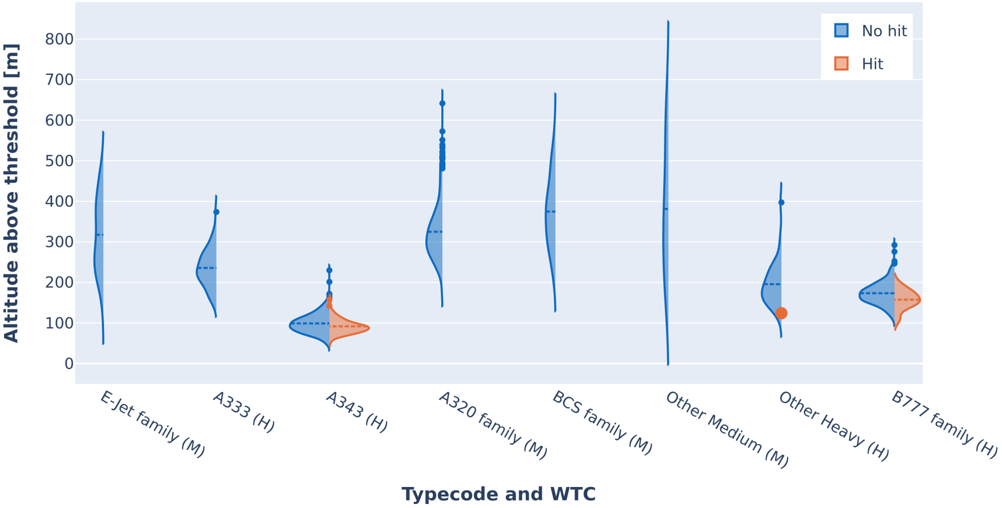


Figure 5. Violin plot showing the distribution of altitude above the runway threshold at the time of passing the sensor, categorised by aircraft type code. The data is separated into take-offs that resulted in hits and those that did not. Since only one hit was observed for the 'Other Heavy' category, no distribution can be plotted and a dot is used to symbolize the occurrence instead.

The data appears to support this hypothesis, showing that aircraft types involved in occurrences tend to pass the sensor at lower altitudes. In particular, all recorded hits correspond to departures passing at altitudes less than 200 metres above the runway threshold. This preliminary analysis strongly indicates a link between the probability of a wake hit and factors such as the prevailing wind conditions and the aircraft type. Notably, the aircraft type's influence seems to be, among other factors, associated with the altitude at which the aircraft passes the sensor. Further explanations about the possible causes are provided at the end of the next section.

3.2 Occurrence model

To better understand the correlation between different factors and the probability of a hit, as well as to determine the conditions under which a hit is most likely to occur, a Generalised Additive Model (GAM)[18, 19] was used. This model was fitted to a subset of the classification data, containing only take-offs of typecodes that caused hits. The Ilyushin IL76 was excluded from the GAM since it is a rare guest at Zurich airport and is with its single departure operationally not as relevant as, say the Airbus A340 with 550 departures. One could include the whole group 'Other Heavy', but this makes little sense due to its heterogeneous composition. The basic form of the GAM uses a Bernoulli distribution to estimate the probability, p, that the station will be hit by a wake. However, instead of predicting p directly, the model estimates the *logit* transform, or log-odds, of p. The used model is

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 \cdot \{\mathit{typecode} = \mathit{A434}\} + f_1(\mathit{wind\ speed}) + f_2(\mathit{wind\ direction}) \qquad (1)$$

with β_0 being the intercept and β_1 a model coefficient to be applied if the aircraft typecode is *A434*. f_1 and f_2 are smooth functions fitted to the data, with f_2 being a *cyclic cubic regression splines* to ensure no discontinuities at the jump at 360 degrees [19, Sec. 5.3.2].

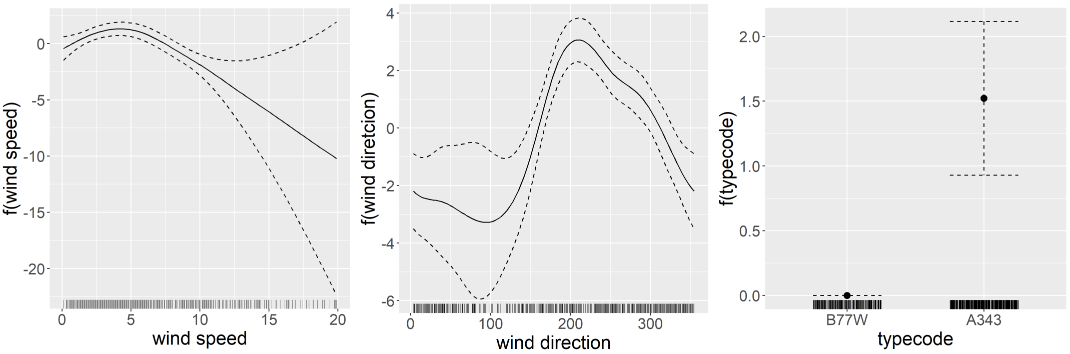


Figure 6. Visualisation of the terms (wind speed, wind direction, typecode) in the generalised additive model. The higher the value, the higher the probability that a wake vortex will hit the anemometer.

The resulting model is shown in Fig. 6. The only model parameter not reflected in the figure is the constant intercept term ($\beta_0 = -4.8$). The interpretation of the model coefficients and smooth functions is not straightforward, but suffice to say that a higher value results in a higher probability of the anemometer being hit by a wake.

The results of the initial data analysis are confirmed by the model highlighting wind direction and speed, as well as aircraft type code, as variables that significantly influence the probability of a hit. Specifically, the probability peaks are associated with scenarios where an aircraft, in particular an Airbus A340, takes off in conditions characterised by a wind direction of around 210 degrees and a wind speed of around 4 knots.

The results from the model are consistent with the intuition that if the wind blows from the wrong direction, the wake will not reach the station. The peak of the probability around 210 degrees corresponds to the wind coming roughly at right angles from the left with a slight tailwind component. Similarly, if the wind is too strong, the wake will drift over the station without having enough time to descend to the ground and thus affect the anemometer. The reason why departures of Airbus A340s and Boeing 777s almost exclusively affect the anemometer is probably not only related to the stronger wake vortices generated by these heavy aircraft. Due to their comparatively lower climb performance, they are at a lower altitude above the ground when passing the station and therefore the wake has a greater chance of hitting the sensor before it dissipates.

3.3 Impact on wind measurement

To ensure the operational relevance of wake hits, it is also important to assess the magnitude of their effect on the wind measurements. For this purpose, Fig. 7 provides an example of the observed severity. The graph shows the recorded wind data and the corresponding two-minute trailing moving average over a 35-minute window of favourable conditions for wake hits to occur. The bottom two rows additionally show the resulting tail and crosswind components for an aircraft departing from runway 34, calculated from both the recorded wind data and the moving average.

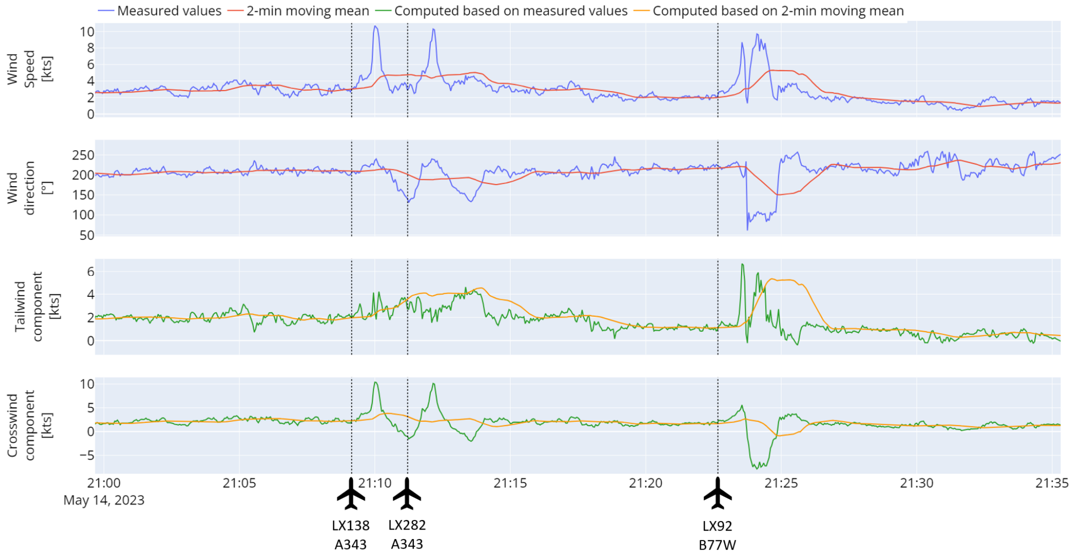


Figure 7. 35 minutes of wind measurements under conditions prone to wake turbulence reaching the anemometer, coinciding with three takeoffs from runway 34. The top two rows depict wind speed and direction measurements from the station (in blue), along with a two-minute moving average (in red). Simultaneously, the bottom two rows showcase derived tail and crosswind components based on raw wind data (in green), along with components based on two-minute moving averages (in orange).

During the considered window, three aircraft departed from runway 34, each generating a wake that significantly affected the station's measurements. The two-minute moving average of wind speed and direction represent the values displayed to air traffic controllers as the current wind condition. Furthermore, they are also presented with information about current gusts which corresponds to the peak measured wind speed within the last two minutes. All three values (wind direction, wind speed and gusts) are contained in the wind report provided to flight crews along with take-off clearances.

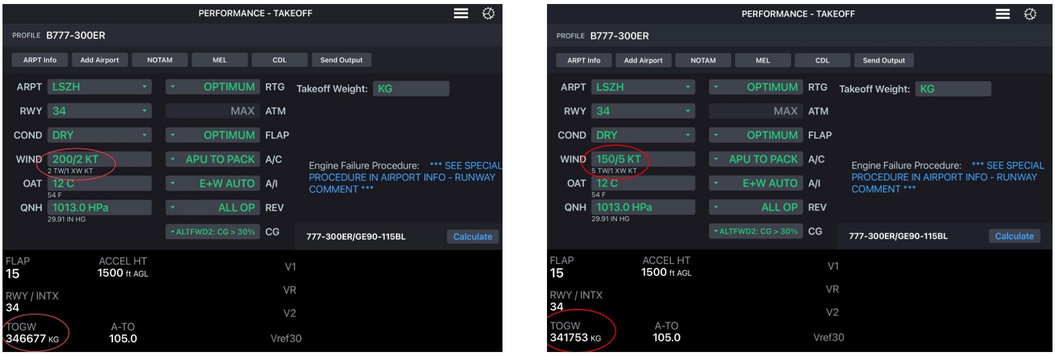
The first two departures by Airbus A340 aircraft had a cumulative and significant effect on both the moving average of the measured wind speed and wind direction for about three minutes. The averaged wind speed increased by approximately two knots and the averaged wind direction shifted slightly from about 200 degrees to 180 degrees. At the same time, wake hits of both aircraft also resulted in peaks of the measured wind speed of just over ten knots. Evaluation of the tailwind component derived from the averaged wind data shows an increase from about two to four knots, lasting about two minutes. The third wake, coming from a Boeing 777 departing some fifteen minutes later, affected the measurements for only about one and a half minutes. This wake caused an increase in wind speed similar to the previous two, but the effect on wind direction was more pronounced. As a result, the mean of the tailwind component increased by four knots, reaching a peak of five knots, which lasted for about one minute. The maximum of the observed tailwind component based on the raw measurements even reached more than six knots.

It is worth noting that, although these three events present similar characteristics, other events manifest themselves differently. While in some cases, the wake effect was evident in both wind speed and wind direction, in other cases, only one parameter was affected. Overall, this example highlights the magnitude of wake events on the measurements. It shows that wakes have the potential to alter the 2-minute moving average by several knots in speed and up to fifty degrees in direction. The effect on the raw measured values is even more pronounced. This results in an influence of the tailwind component of several knots, which can persist for periods in excess of one minute. Such variations are sufficient to have a significant operational impact, as demonstrated in the following section.

4. Operational Implication

The effects demonstrated in the previous section can have a significant impact on aircraft performance, even to the point where take-offs are not allowed due to changes in wind data. This is best illustrated using a specific example. Consider a hypothetical situation in which a Boeing 777 obtains take-off clearance for runway 34 on May 14, 2023, at 21:25 UTC. The wind measurements during the take-off clearance are heavily influenced by the wakes of a previous Boeing 777 departure, that has happened few minutes prior (see Fig. 7).

Along with the take-off clearance, the tower controller reports the current wind direction at 150 degrees with a speed of five knots, and gusts reaching ten knots. Shortly before departing the gate, the flight crew completes the final take-off performance calculation based on the latest ATIS report. This report shows a baseline wind condition of 200 degrees at 2 knots. From these calculations, the maximum allowed takeoff weight is determined at 346,677 kg, as illustrated in Fig. 8a.



PROFILE B777-300ER
ARPT LSZH
RWY 34
COND DRY
WIND 200/2 KT
2 TW/1 XW KT
OAT 12 C
54 F
QNH 1013.0 HPa
29.91 IN HG
OPTIMUM RTG
MAX ATM
OPTIMUM FLAP
APU TO PACK A/C
E+W AUTO A/I
ALL OP REV
ALTFWD2: CG > 30% CG
Takeoff Weight: KG
Engine Failure Procedure: *** SEE SPECIAL PROCEDURE IN AIRPORT INFO - RUNWAY COMMENT ***
777-300ER/GE90-115BL
FLAP 15
ACCEL HT 1500 ft AGL
RWY / INTX 34
TOGW 346677 KG
A-TO 105.0
V1
VR
V2
Vref30

PROFILE B777-300ER
ARPT LSZH
RWY 34
COND DRY
WIND 150/5 KT
5 TW/1 XW KT
OAT 12 C
54 F
QNH 1013.0 HPa
29.91 IN HG
OPTIMUM RTG
MAX ATM
OPTIMUM FLAP
APU TO PACK A/C
E+W AUTO A/I
ALL OP REV
ALTFWD2: CG > 30% CG
Takeoff Weight: KG
Engine Failure Procedure: *** SEE SPECIAL PROCEDURE IN AIRPORT INFO - RUNWAY COMMENT ***
777-300ER/GE90-115BL
FLAP 15
ACCEL HT 1500 ft AGL
RWY / INTX 34
TOGW 341753 KG
A-TO 105.0
V1
VR
V2
Vref30

(a) Output for a wind of 2 knots and 200 degrees (Screenshot Boeing Onboard Performance Tool (OPT)).

(b) Output for a wind of 5 knots and 150 degrees (Screenshot Boeing Onboard Performance Tool (OPT)).

Figure 8. Output of take-off performance calculations using the Boeing Onboard Performance Tool for wind conditions associated with the baseline (without wake effect) and the wind conditions observed during the wake influence at 21:25 UTC as shown in Fig. 7.

The aircraft's payload for the given environmental conditions has been determined with this weight limit in mind, also accounting for potential wind variations. However, the wind conditions reported by the tower represent an increase in wind speed of three knots and a shift in wind direction of 50 degrees compared to the anticipated conditions used in the performance calculations. To safely take off in these reported conditions, the aircraft's weight should not exceed 341,753 kg, as shown in Fig. 8b. The decrease of almost five tonnes in take-off weight surpasses the standard buffer in performance calculations, resulting in an inability to take off with the reported wind. The situation is even worse if the pilot-in-command considers the reported gusts of up to ten knots. In this case, the maximum take-off mass is 334,480 kg, a difference of more than twelve tonnes compared to the calculation at the gate. Facing this, the flight crew has the following two options: selecting an alternate runway or returning to the gate to offload cargo. Even if the conditions would still allow a take-off, the crew must complete a runway condition change checklist if confronted with unexpected wind conditions. This process takes about five minutes with the aircraft potentially blocking the runway for that time.

In the specific case of runway 34 at Zurich Airport, delays can have a significant impact on flight operations. Runway 34 is predominantly used when the east approach concept is in operation (see Fig. 9). This concept is typically used from 9 p.m. until the night curfew at 11:30 p.m. local time.

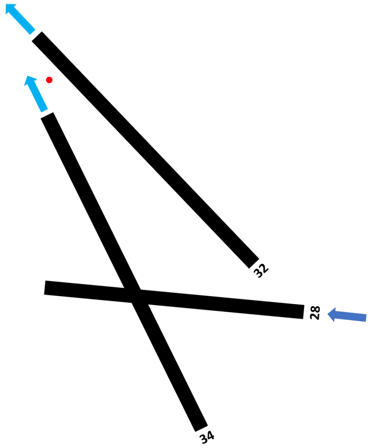


Figure 9. Schematic depiction of the east approach concept: landings occur on runway 28, with the majority of takeoffs departing from runway 32 and a limited number from runway 34. The red dot indicates the position of the concerned anemometer.

Under this concept, landings take place on runway 28 while most departures occur on runway 32. Runway 34 is, however, used by aircraft limited by their performance, as it offers an additional 400 meters of length as well as a different obstacle in the departure sector. Consequently, aircraft using this runway already operate within tight performance margins and even a slight increase in tailwind can result in an inability to take off.

The runway configuration at Zurich Airport requires coordinated take-off procedures on runway 34 due to departures intersecting with both the landing runway 28 and the departure path of runway 32. This amplifies the impact of take-off delays on runway 34 on overall airport operations. Furthermore, a series of daily long-haul flights, primarily featuring A340 and B777 aircraft, are scheduled to depart just before the night curfew, frequently using runway 34. Alterations in wind readings due to aircraft wake turbulence, causing delays or even runway changes, can result in departure times extending beyond the night curfew, leading to flight cancellations. This highlights that wake turbulence can affect wind readings in a way that prevents aircraft from taking off when relying on affected wind data. Moreover, the operational concept employed at Zurich Airport implies that such occurrences can significantly affect the entire operation of the airport and even result in flight cancellations.

5. Discussion

This study demonstrates that departures from runway 34 at Zurich Airport can generate wake vortices that affect the anemometer situated at the end of the runway. Instances in which wind measurements are affected by wake vortices depend on a specific combination of wind conditions and aircraft type. Within the scope of this analysis, such wake disturbances were generated by approximately 5% of all the observed take-offs over a 15-month period. The effect of wake vortices on the anemometer can be seen not only in the raw measurements, but also in the derived 2-minute moving average used by air traffic controllers for take-off clearances. An operational example has furthermore shown that affected wind measurements used for take-off clearances can prevent aircraft from taking off, even though a take-off would be possible under the prevailing wind conditions.

The limited body of research on this specific topic highlights a general lack of awareness regarding the potential influence of wake turbulence on airport wind velocity measurements and the resulting impact on flight operations. As the work on the wake vortex warning system in Frankfurt showed, it can be assumed that similar situations exist at other airports as well. Further supporting the notion that this phenomenon extends beyond the scope of our specific study, wind disturbances that resembled wake impacts were observed during the visual identification, even when there were no take-offs on runway 34. However, these events coincided with take-offs from runway 32. Moreover, the prevailing wind conditions also indicated the potential for wake hits from take-offs on this runway. These specific cases were not further investigated in this study.

6. Conclusion

The findings of this study show that the wind measurement of one particular anemometer can be affected by wake vortices of departing aircraft and that it can have consequences for the operation of the airport. Unfortunately, discussions with the involved parties at Zurich Airport did not yet result in a simple solution to deal with this issue in daily operations. Potential mitigations include using a different anemometer for the take-off clearance, relocating the existing wind sensor to a less vulnerable position, installing a second anemometer on the other side of the runway and using the signal from the windward side, or raising awareness of this phenomenon among pilots and air traffic controllers. However, all of these solutions have their limitations and potential side effects. Which solution will work best for Zurich Airport is to be determined by the operational experts. Nevertheless, this study provides a basis for a well-informed decision. Additionally, the authors hope that this study will help to raise the awareness that wake vortices can affect operational wind measurements and can subsequently have a negative impact on airport operations.

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Author contributions

- Jan Krummen: Conceptualization, Data Curation, Formal Analysis, Software, Writing–Original draft
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Open data statement

Sample data has been shared at: https://zenodo.org/doi/10.5281/zenodo.10066817.

Reproducibility statement

The P2P wake model is the intellectual property of DLR and is protected by a licence agreement.

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