Developing a Weather Impact Index for O. R. Tambo International Airport, South Africa

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ABSTRACT

Weather-related delays in the aviation sector will always occur; however, through effective delay management, the impact and duration of delays can be reduced. Part of delay management is thoroughly assessing adverse weather risks. A weather impact index was specifically designed for O. R. Tambo International Airport, in Kempton Park, South Africa, the busiest airport in Africa, in order to identify the level of risk forecasted adverse weather will have on departure delays. The index is based on a study of all departure delays due to adverse weather over the aerodrome for the period 2010–13. The index is marked for use on 30-h terminal aerodrome forecasts (TAFs) as a planning tool.

1. Introduction

The aviation industry and associated operations are significantly influenced by weather. Aviation safety, efficiency, and capacity are sensitive to weather, and adverse weather can have negative impacts to the sector (Sasse and Hauf 2003). The increase in aviation demand can push an airport's capacity to its limits, and even a small weather change can lead to a reduction of the airport capacity (Markovic et al. 2008). Weather conditions affect all aspects of aerodrome operations such as aircraft fueling, cleaning, baggage handling, catering, aircraft maintenance, and the actual scheduled flights. The operational capacity of airports, and even a region's entire airspace, can be significantly reduced because of bad weather, resulting in delays, diversions, and cancelations of flights (Sasse and Hauf 2003). For instance, Mitchell and Suckling (1987) demonstrate that 23% of all flights were affected on severely foggy days at Sacramento International Airport, in Sacramento, California. Van Schalkwyk and Dyson (2013) have developed a fog-type classification method that classifies fog events at Cape Town International Airport (CTIA), in Cape Town, South Africa, according to their primary formation mechanism. This fog-type classification method aims to assist aviation forecasters with a detailed description of the types of fog, their characteristics, and associated synoptic circulation patterns to limit the impacts of fog at CTIA.

The operational response to a delay often varies, even under similar weather and traffic conditions, as a result of the multitude of factors that influence the response. Such factors include the accuracy of terminal and en route weather forecast products, airspace design and traffic flow management, scheduling times and overscheduling by airlines, airport procedures and constraints, and so on (Klein et al. 2009). Delays can be divided into two categories: avoidable and unavoidable. Unavoidable delays are directly related to the severity of the weather and the airspace procedures and regulations (Klein et al. 2009). The avoidable portion of delays is related to many factors, but typically is affected by the accuracy of a weather forecast, together with the response to the forecast (Klein et al. 2009). An overforecast may lead to unnecessary ground delay programs, and an underforecast can lead to last-minute air traffic flow management (ATFM) actions such as unplanned delays and reroutes, which can cause a significant ripple effect throughout the national airspace (Klein et al. 2009). According to the National Center for Atmospheric Research (NCAR), as much as 60% of delays and cancelations due to weather, particularly convective weather, are potentially avoidable (Klein et al. 2009).

Airports and air traffic service providers adjust their scheduled throughput according to the forecasted weather

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conditions. For example, if a thunderstorm is expected, an airport's throughput can be systematically reduced by up to 75% to prevent additional delays and flight cancelations (Pejovic et al. 2009). Such techniques help to minimize the impact of weather on aviation operations. However, when unexpected events occur, there is far less ability to adjust operations, and thus the impact is more severe. Therefore, weather and weather forecasts are critical components of aviation operations, and gaining a better understanding of both elements at an aerodrome is crucial in order for aviation operations to run with fewer disruptions.

According to Cunningham et al. (2012), forecast products and techniques have greatly improved in recent years. However, improvements are needed for tactical and strategic airport planning. The authors developed one said product relating to predicting the airport arrival rate, specifically during adverse weather. A weather translation model for ground delay programs was developed to translate weather forecasts into probabilistic airport arrival rate predictions. The model finds correlations between historical weather forecast and airport capacity data and uses these correlations to project future airport capacities bases on recently issued forecasts (Cunningham et al. 2012). This paper utilizes this initiative and examines the correlation between historical weather delays and weather. Identifying a level of risk for delay could be incorporated into a ground delay program.

DeLaura et al. (2008) developed a tool to assist with estimating the impacts of convective weather on future departures, called The Route Availability Planning Tool. It is an automated decision support tool for air traffic controllers and airline dispatchers to determine the specific departure routes and departure times that will be affected by convective weather (DeLaura et al. 2008). Such studies show that numerous support tools exist. Typically, these tools are designed specifically for individual airports; however, no such tools have been developed for O. R. Tambo International Airport (ORTIA) in South Africa.

According to EUROCONTROL (2014), it is possible to reduce delays caused by bad weather if the following criteria are put in place:

1) a robust, accurate weather forecast;
2) a proper assessment of weather-related risks; and
3) well-timed, collaborative decision-making based on delay impact assessment simulations.

Jacobs (2015) assesses the accuracy of weather forecasts for the aviation sector in South Africa and asserts that forecaster-adapted forecasts are, in general, superior to the raw model output. The aim of this research is to target the second criterion, namely *assessing weather-related risks*. The authors identified a gap where there is insufficient assessment of the terminal aerodrome forecast (TAF) provided for the aviation industry. The TAF should be taken one step further and the question of "how will this weather forecast affect the running of the airport today?" should be asked. Thus, the development of a decision support tool is deemed necessary. One tool that could be used to do that is a weather impact score or index, which could be used in estimating and planning for airport delays. Even when delays are unavoidable, such an index can help reduce a delay's length and impact. A weather impact index system has been designed for ORTIA and is presented in this paper. ORTIA is the busiest airport in Africa (Peck and Hedding 2014) and is a major regional hub in the aviation industry. It is also located where a range of significant weather types, such as thunderstorms and fog, occur frequently and thus weather is a critical aspect of ORTIA's aviation operations. It is, therefore, an ideal airport to base the study on.

As most air traffic managers are required to predict the capacity at a given airport up to 10 h or more into the future (Cunningham et al. 2012), and capacity is greatly influenced by weather, the use of a TAF-based product could prove beneficial. However, the accuracy of the TAF would significantly impact the prediction product. Thus, it is imperative that such a product is deemed as a forecast in itself, and therefore a degree of uncertainty should be attached to the said product.

2. Study site and data

O. R. Tambo International Airport is located at 26°8′1.30″S, 28°14′32.34″E, at an altitude of 1694 m (5558 ft) above mean sea level (Fig. 1). It is situated 20 km east-northeast of the city of Johannesburg and 40 km south of Pretoria. The airport opened on 1 September 1953 and has become the busiest airport in Africa (Peck and Hedding 2014). ORTIA has a mean annual temperature of 17.7°C and receives an average of 713 mm of precipitation per annum. Typically, ORTIA experiences 73 and 35 annual thunderstorm and fog days, respectively. The average hourly wind speed at ORTIA is 4.2 m s^{-1} (8.2 kt).

Similar to other international airports, ORTIA has two distinct morning and evening peaks. The low demand hours are between 0500 UTC in the morning and 1700 UTC in the evening (Tilana 2011). It has the capacity to handle up to 28 million passengers annually, with a current demand of 51 aircraft movements per peak hour, and 40 aircraft movements per nonpeak hour (Tilana 2011). This level of demand is expected to grow to approximately

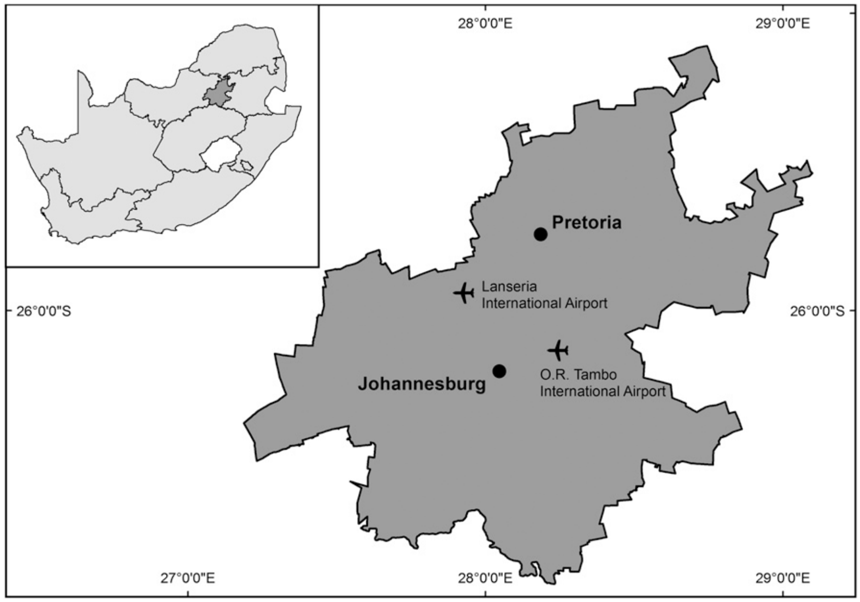

FIG. 1. Locations of the two commercial airports in Gauteng Province of South Africa that offer service to international destinations. Inset map situates the Gauteng Province within the borders of South Africa.

80 peak hour movements and 65 nonpeak hour movements by the year 2022 (Tilana 2011). ORTIA is classified as a category II airport, which permits flight operations in reduced horizontal visibilities as low as 300 m.

ORTIA has two parallel north–south runways. The western runway, 03L/21R, is over 4400 m long, and the eastern runway, 03R/21L, is 3400 m long. As a result of the high altitude of the airport, and hence thinner air, the western runway is one of the world's longest international airport runways. The runways are equipped with instrument landing systems (ILSs) and approach lighting systems. Weather readings of temperature, wind speed and direction, humidity, rainfall, cloud height, and runway visual range (RVR) are recorded next to the runway threshold of runway 03L. Temperature, RVR, and wind speed and direction are also recorded at the thresholds of runways 03R, 21L, and 21R. Furthermore, RVR is also captured at the center point of both runways (SAWS 2012).

Before 2009, there was no mechanism in place at ORTIA for measuring and monitoring weather-related delays (Tilana 2011). In addition, other airports in South Africa do not measure or monitor weather-related delays. These factors represent major limitations for our research in that it prevents validating the weather impact index temporally (outside of the study period) or spatially across South Africa. Four years' worth of delay data at ORTIA, from 2010 through 2013, were analyzed. The research examined all aircraft departure delays at the airfield due to adverse weather affecting the aerodrome. The following numbers of weather delay incidents and delay hours were analyzed:

- 2010, 555 incidents (261 delay hours);
- 2011, 499 incidents (256 delay hours);
- 2012, 552 incidents (274 delay hours); and
- 2013, 754 incidents (549 delay hours).

Each delay was then assigned a dominant weather type deemed responsible for the delay through the use of historical weather observations (i.e., METARs). Often, more than one type of weather is reported in a single observation report. To simplify the delay analysis, a hierarchy method was implemented. The weather categories as listed in Table 1 are in order of importance. Therefore, if more than one type of weather was reported in a METAR, the weather type categorized as most significant would have been analyzed. For example, if cumulonimbus clouds (CB) and towering cumulus cloud (TCU) conditions were reported in a single METAR, the delay would have been categorized as a CB event. The most inclement weather within 2 h prior to a delay time was extracted from the METAR to link the weather phenomena to the delay. Six main weather categories were identified as significant weather phenomenon influencing aviation operations at ORTIA, as per Table 1. The negative impacts that such types of weather have on aviation are widely documented. As the weather impact index is intended to be applied to

TABLE 1. Weather phenomenon categories (adapted from Mahapatra and Zrnić 1991).

Main category	Comments
Cumulonimbus cloud (CB) or thunderstorm	Thunderstorms are born from CB and thus are termed convective weather. The aviation hazards that are associated with thunderstorms include severe turbulence, lightning, hail, heavy precipitation, severe icing, and strong winds and gusts. It is most often the turbulence that poses the most significant threat to aircraft, especially upon takeoff and landing, when there is no altitude buffer to recover from turbulent motions. Thunderstorms are responsible for the majority of global weather-related aircraft accidents and incidents, and make up a significant fraction of global delays (Mahapatra and Zrnic 1991).
Towering cumulus cloud (TCU)	TCU is the first stage of thunderstorm formation. This type of cloud is, therefore, also convective in nature and, hence, contains unstable air. As a result, turbulence may be present, together with showers of rain. Because of the presence of supercooled water in TCU, icing also poses a danger. Therefore, even though TCU may not appear to be as dangerous as cumulonimbus clouds, they still pose significant threats to aviation, and should be avoided. Flights operating under visual flight rules (VFR) are not allowed to fly within the vicinity of any TCU.
Fog	The meteorological definition of fog is a suspension of water droplets reducing the visibility to less than 1 km. Thus, fog is an extreme reduction in visibility and can have a profound effect upon air transportation (Mitchell and Suckling 1987). Similarly to mist, all ground operations would also be affected by the poor visibility, and operations would be slowed. No flights operating under VFR rules would be allowed to operate during fog conditions. Even instrument flight rules flights would need to have a specific rating (which would depend on the situation) in order to takeoff or land within fog conditions. Fog requires greater separation between aircrafts, which leads to delays.
Mist	The meteorological definition of mist is water droplets suspended in the atmosphere that cause a reduction in visibility to a value between 1 and 5 km. Flights operating under VFR rules are thus not allowed to operate when mist is reported. Because of the reduction in visibility, aircraft separation is increased, which could lead to delays in peak traffic hours. Also, ground operations will also be affected by the poor visibility and thus operations will be slowed.
Rain	This category refers to rainfall not associated with any convective cloud (i.e., CB or TCU), including drizzle. Rainfall is often a meteorological condition that is overlooked as an aviation hazard. However, rain can result in unfavorable flying conditions, often yielding delays. First, rainfall can cause a significant reduction in visibility, often affecting VFR flying. Rainfall also results in wet runways, which will influence an aircraft's takeoff and landing performance. Thus, a greater separation between aircraft must be maintained, leading to delays. Rainfall can also effect ground operations such as baggage handling, catering, etc. Heavy rain will slow all vehicular movement and foot traffic on and around the airfield, which could lead to significant delays.
Low ceiling	Clouds with low bases (defined here as ceilings of below 1000 ft) can pose problems for low-flying aircrafts (during takeoff or landing) that are VFR rated. The incidence of low clouds at ORTIA is high, generally because of the high altitude of the airport. Again, separation between aircraft would be increased during very low clouds. This category refers to scenarios where only low cloud was reported, without a reduction in visibility.

TAFs, weather outside the scope of a TAF (i.e., icing, extreme temperatures) was not categorized.

3. The weather impact index

a. Users of a weather impact index

A weather impact index would typically be used as a component or variable in an airport model. It would ultimately be used for planning purposes by the air traffic management center of the airport, which, at ORTIA, is referred to as the Central Airspace Management Unit (CAMU). Such a division typically manages a slot allocation program and the general use of airspace for a particular time period (ATNS 2017). CAMU is also responsible for rerouting traffic affected by adverse weather and balances demand against capacity using an ATFM system (ATNS 2017). A weather impact index could be utilized as part of an ATFM system. To maximize the potential benefits of such an index, it should be used in the preplanning stages of traffic management. It is, therefore, recommended to apply the index to TAFs, as a long-term TAF typically covers a 30-h forecast period.

b. The weather impact index at ORTIA

An index was developed specifically for ORTIA, based on historical weather and delay data, with the following scoring system:

$$\text{Probability Score} + \text{Frequency Score} + \text{Duration Score} = \text{Weather Impact Score}. \quad (1)$$

Thus, the total impact score comprises three components, namely a probability score, a frequency score,

TABLE 2. Probability calculations for weather category CB for the year 2013.

Month	No. of days with CB	No. of delay days with CB	Probability of delay (%)
Jan	10	5	50
Feb	10	2	20
Mar	10	5	50
Apr	6	5	83
May	2	1	50
Jun	0	0	—
Jul	0	0	—
Aug	1	0	0
Sep	3	2	67
Oct	10	7	70
Nov	12	10	83
Dec	11	6	55
Avg			53

and a duration score. The probability score is based on what the probability or risk is that adverse weather will cause a delay. This score was calculated by establishing the number of days with adverse weather (as defined in Table 1) and comparing it to the number of days of delay with the same adverse weather conditions during the study period. The average over the 4 yr for each weather category was defined as the probability score. As an example, Table 2 displays the raw calculations for the probability score of thunderstorms for the year 2013. The frequency score marks how often a weather type causes delays. Table 3 records the number of delay incidents over the 4-yr period per weather phenomenon. The frequency score uses the percentage contribution of each weather phenomenon to the total number of weather delays over the 4 yr. As is highlighted in Table 3, thunderstorms contribute to the vast majority of delay incidents. The duration score can be defined as the average duration of a delay event as a percentage of an hour. This score is based on the averaged total number of minutes of each weather phenomenon as per Table 4. Once again, thunderstorms are responsible for the longest delay duration compared to other variables. On the other hand, fog had the lowest duration length of 19 min, whereas fog ranked second in Table 3. The sum average of the three scores (probability, frequency, and duration) yields the total impact score as a percentage. The score is given as a percentage, as the score reflects the risk or probability of a delay. For instance, the total impact score for a thunderstorm is 57% and thus there is 57% chance of a delay because of thunderstorms (just as TAFs use percentages for adverse weather). Table 5 displays the total impact scores for ORTIA and illustrates that cumulonimbus clouds or thunderstorms have the highest total impact score on aviation operations at the airport.

c. *The final weather impact index*

The total impact score can be further adjusted to reflect the expected or current air traffic, by multiplying the score with a traffic coefficient:

$$\text{Total Impact Score} \times \text{Traffic Coefficient} = \text{Final Weather Impact Index}. \quad (2)$$

The coefficient variable can be adjusted per day or per hour, depending on the situation at hand and would be predetermined by the air traffic management center (i.e., CAMU at ORTIA). Simply from a general peak traffic point of view, the traffic coefficient variables as per Table 6 can be used as a general guideline. The traffic coefficient range should be between 1.0 and 1.6, where 1.0 would typically be used in normal or below capacity traffic, and 1.6 used in high-traffic situations. The final weather impact index will give a percentage score. The higher the index is, the higher the probability of disruption to air traffic as a result of the adverse weather.

4. Applying the weather impact index to TAFs

By converting a TAF into a set of hourly forecasts, each hour can be assigned the weather impact index.

TABLE 3. The number of delay incidents per weather phenomenon (and percentage contribution to the overall number of incidents per year) for the years 2010–13, ranked from highest to lowest frequency.

Weather phenomenon	2010	2011	2012	2013	Total/rank
CB or thunderstorm	383 (69%)	349 (70%)	412 (75%)	493 (65%)	1637 (69%)
Fog	94 (17%)	72 (14%)	72 (13%)	52 (7%)	290 (12%)
Rain	16 (3%)	25 (5%)	8 (1%)	124 (17%)	173 (7%)
TCU	31 (6%)	20 (4%)	27 (5%)	47 (6%)	125 (5%)
Mist	24 (4%)	24 (5%)	27 (5%)	33 (4%)	108 (6%)
Low ceilings	7 (1%)	9 (2%)	6 (1%)	5 (1%)	27 (1%)
Total	555	499	552	754	2360

TABLE 4. The average number of delay minutes per single weather delay event in order from highest to lowest.

Weather phenomenon	2010	2011	2012	2013	Ave. total minutes	Length of an hour (%)
CB or thunderstorm	33	32	32	52	37.25	62
TCU	31	38	34	30	33.25	55
Mist	14	37	19	13	20.75	35
Rain	10	17	20	36	20.75	35
Low ceilings	14	23	23	22	20.50	34
Fog	16	24	20	16	19.00	31

The limitation of a weather impact index, which is based on a TAF, is that the index relies on the accuracy of the TAF for air traffic planning. The tool would be ineffective in the case of missed events. Therefore, the reliability of the weather impact index would be directly related to the accuracy of the TAFs used. Table 7 indicates the accuracy of the TAFs used in the development of the weather impact index. However, as the TAF is amended or corrected during the forecast period, the index can be applied again, and can still give some lead time for planning. The following sections show the TAF evaluation technique used and a few examples of how the index can be applied on a daily basis.

a. TAF evaluation technique

Each METAR was compared to the selected TAF through a manual comparison, and the forecast was determined to be either a hit or a miss. The TAF was selected with a lead time of at least 6 h. For example, if the 1300 UTC METAR was used, the TAF issued at 0400 UTC would have been selected. The following criteria were designed and used to classify the TAF as a hit or a miss:

- the time at which the inclement weather was correctly forecasted;
- the type of weather, as per the main categories of Table 1, was correctly forecasted; and
- the forecasted horizontal visibility was in line with Table 8.

This evaluation technique is displayed in Fig. 2. As can be seen, if any of the evaluation criteria are not met, the TAF is regarded as a missed forecast.

The production of TAFs is standardized by International Civil Aviation Organization (ICAO) regulations. As per the standardization, the forecast of horizontal visibility should be forecasted within specific ranges, as set out in Table 8. Therefore, if the reported visibility lies within a group that is less than the forecasted visibility, the forecast will be regarded as a missed forecast.

An overforecast was classified as a hit. An overforecast can be classified as a forecast that projects the weather situation to be worse than that which occurred. An underforecast was classified as a miss. An underforecast can be classified as a forecast that projects the weather situation to be better than that which occurred.

b. Weather impact index case study 1

A thunderstorm event on 25 January 2013 at ORTIA led to 14 reported delays, with a total of 381 delay minutes (6 h and 35 min of delay time). The first delay occurred at 1550 UTC, and the last delay occurred at 1815 UTC, with the remaining 12 delays falling within this period. The 30-h TAF that was issued at 1000 UTC indicated a risk of thunderstorms between 1300 and 1900 UTC, with low cloud ceilings and mist expected in the morning of 26 January and thunderstorms expected again in the afternoon.

By applying the weather impact index system for the afternoon of 25 January 2013, as displayed in Table 9, the applicability of such an index on a day with adverse weather can be assessed. The index scoring system revealed that potential disruption to air traffic could be around 57%, increasing to 80% by the evening. Several delays did occur in the afternoon and evening, and thus,

TABLE 5. Total weather impact scores.

Weather phenomenon	Total impact score (%)
CB or thunderstorm	57
Fog	29
Rain	21
TCU	27
Mist	19
Low ceilings	13

TABLE 6. Proposed traffic coefficients based on peak and off-peak traffic periods.

Time period	Traffic coef
Morning off peak (0500–1000 UTC)	1
Morning peak (2200–0500 UTC)	1.2
Afternoon off peak (1000–1700 UTC)	1
Night peak (1700–2200 UTC)	1.4

TABLE 7. TAF accuracy during the period 2010–13.

Year	TAF accuracy (%)
2010	62
2011	48
2012	59
2013	66
Overall	59

by using the index, and assessing the results through collaborative decision-making, appropriate traffic planning and management could potentially have reduced the impact and *duration* of the delays.

c. *Weather impact index case study 2*

Extensive delays occurred on 6 September 2012 as a result of afternoon and evening thunderstorms. A total of 23 delays were recorded, resulting in 29 h and 20 min of delay time, with an average delay time of 70 min. Table 10 shows the weather impact index applied to the TAF that was issued. The entire day was at risk of delays because of the poor weather expected. The risk started at 30% during the morning, dropping to 21% for the early afternoon, picking up again to 57% for the afternoon, increasing even further to 80% for the early evening, and then dropping down to around 20% for the remainder of the night. The vast majority of the delays occurred between 1300 and 1700 UTC. The index during this period was at its highest for the day, ranging from 57% to an 80% risk. Only three delays occurred after 1700 UTC, and hence the index handled the decrease in delay risk well. This case study reflects a situation where a degree of delay risk is present throughout the day, but the worst delays occurred when the delay risk was at its highest.

d. *Weather impact index case study 3*

On 1 March 2013, 6.5 h of delay time occurred with an average delay time of around 16 min. Consecutive delays occurred over 2 h (from 1700 to 1845 UTC) as a result of thunderstorms over the aerodrome. As is highlighted in Table 11, this is when the delay risk was at its highest (80%). Applying the index during the morning of 1 March would have given air traffic management (ATM) a clear indication when to expect the highest risk of disruption.

e. *Weather impact index case study 4*

On 29 October 2010, fog resulted in five delays with 56 delay minutes. From applying the index, a risk of 23%–35% was apparent for the morning. Table 12 shows that the delays occurred during this period of risk.

TABLE 8. Horizontal visibility groups (adapted from ICAO 2013).

Horizontal visibility groups	Horizontal visibility height range [m (ft)]
A	150–350 (492–1148)
B	350–600 (1148–1969)
C	600–800 (1969–2625)
D	800–1500 (2625–4921)
E	1500–3000 (4921–9843)
F	3000–5000 (9843–16 404)

5. Further research

It can be reasonably assumed that arrival delays (due to weather at ORTIA) would be caused by the same set of weather conditions, with the same or similar characteristics (i.e., time of day, frequency, etc.) to those of the departure delays. It is the duration or length of an arrival delay, and the financial cost of an arrival delay, that would be significantly different to that of a departure delay. Thus, the weather impact index system would have to be adjusted to take into account the difference in duration characteristics in order to be applied to arrival delays. Thus, research into arrival delays would be the next progressive step. Also, once this has been established, research is needed to evaluate the skill of such a program at ORTIA in South Africa. The next step in the development of a new tool, such as the weather impact index, is to test the tool for skill or reliability. One method of testing the skill of a probabilistic forecast is through the use of the Brier skill score, with the development of a reliability or attributes diagram. An attributes diagram plots the observed frequency (in this case the observed frequency of delays) against the forecasted value (in this case the

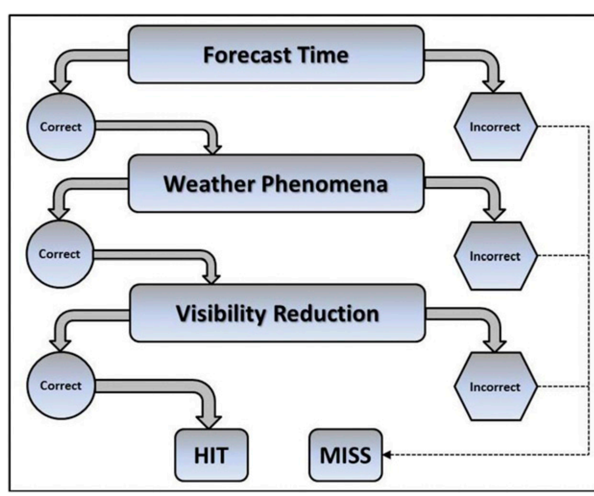

FIG. 2. TAF evaluation technique flowchart.

TABLE 9. The weather impact index case study at ORTIA for 25 Jan 2013.

Hour (UTC)	Forecast	Index	Coef	Final weather impact index (%)	Delay
1200	No hazards present	0	1	0	No
1300	Thunderstorms	57	1	57	No
1400	Thunderstorms	57	1	57	No
1500	Thunderstorms	57	1	57	Yes
1600	Thunderstorms	57	1	57	Yes
1700	Thunderstorms	57	1.4	80	Yes
1800	Thunderstorms	57	1.4	80	Yes
1900	Thunderstorms	57	1.4	80	No
2000	No hazards present	0	1.4	0	No
2100	No hazards present	0	1.4	0	No
2200	No hazards present	0	1.4	0	No
2300	No hazards present	0	1.2	0	No
2400	No hazards present	0	1.2	0	No

weather impact index). A line of perfect reliability is included together with a ''no skill'' line. Thus, by evaluating where the observed frequency lies (i.e., close to the reliability or no-skill line), the skill of the probabilistic forecast can be determined.

The weather impact index could also possibly be adjusted to include a new variable in the equation that acknowledges the month of the year. Taking into account the specific weather characteristics of the month (instead of averaging them out for the year) could potentially produce a more skilled index. It has also been established that a longer study period, together with such an index developed for other airports, would be necessary. In addition, research should be conducted on the use of numerical weather prediction data for verification purposes of the weather impact index proposed here.

6. Conclusions

Delays in aviation are not completely avoidable. Because of the very (dynamic) nature of weather, there will

TABLE 10. The weather impact index case study at ORTIA for 6 Sep 2012.

Hour	Forecast	Index	Coef	Final weather impact index (%)	Delay
0000	Mist	19	1.2	23	No
0100	Mist	19	1.2	23	No
0200	Mist	19	1.2	23	No
0300	Mist	19	1.2	23	No
0400	Mist	19	1.2	23	No
0500	Mist	19	1.2	23	No
0600	Mist	19	1	19	Yes
0700	Mist	19	1	19	Yes
0800	Rain	21	1	21	No
0900	Rain	21	1	21	No
1000	Rain	21	1	21	No
1100	Thunderstorms	57	1	57	No
1200	Thunderstorms	57	1	57	No
1300	Thunderstorms	57	1	57	No
1400	Thunderstorms	57	1	57	No
1500	Thunderstorms	57	1	57	Yes
1600	Thunderstorms	57	1	57	Yes
1700	Thunderstorms	57	1.4	80	Yes
1800	Thunderstorms	57	1.4	80	Yes
1900	Thunderstorms	57	1.4	80	Yes
2000	Low ceilings	13	1.4	18	Yes
2100	Low ceilings	13	1.4	18	Yes
2200	Mist	19	1.4	27	No
2300	Mist	19	1.2	23	No
2400	Mist	19	1.2	23	No

TABLE 11. The weather impact index case study at ORTIA for 1 Mar 2013.

Hour	Forecast	Index	Coef	Final weather impact index (%)	Delay
0000	No hazards present	0	1.2	0	No
0100	No hazards present	0	1.2	0	No
0200	No hazards present	0	1.2	0	No
0300	No hazards present	0	1.2	0	No
0400	No hazards present	0	1.2	0	No
0500	No hazards present	0	1.2	0	No
0600	Thunderstorms	57	1	57	Yes
0700	Thunderstorms	57	1	57	No
0800	No hazards present	0	1	0	No
0900	No hazards present	0	1	0	No
1000	No hazards present	0	1	0	No
1100	No hazards present	0	1	0	No
1200	Thunderstorms	57	1	57	No
1300	Thunderstorms	57	1	57	No
1400	Thunderstorms	57	1	57	No
1500	Thunderstorms	57	1	57	Yes
1600	Thunderstorms	57	1	57	Yes
1700	Thunderstorms	57	1.4	80	Yes
1800	Thunderstorms	57	1.4	80	Yes
1900	Thunderstorms	57	1.4	80	Yes
2000	Thunderstorms	57	1.4	80	Yes
2100	Thunderstorms	57	1.4	80	Yes
2200	Thunderstorms	57	1.4	80	No
2300	Low ceilings	13	1.2	16	No
2400	Mist	19	1.2	23	No

always be weather-related delays as long as weather negatively influences the performance of aircraft and/or operations at airports. The fact that there are delays indicates that safety is a priority within the industry. Indeed, if delays did not exist, major concerns should be raised. Therefore, research with reference to aviation delays should not be expected to eliminate delays altogether, but rather to reduce the number and duration of delays, as a result of effective delay management and improved weather forecasting. Departure delays due to adverse weather are largely unavoidable. However, it is still important to be prepared for delays in order for airport operations to run efficiently, and therefore planning is crucial. Through preparedness, planning, and the use of TAFs, the length and impact of departure delays could be reduced, but not completely avoided.

Improved weather forecasts, enhanced assessments of the weather forecasts, and collaborative and timely decision-making are the three identified pillars necessary to reduce the impact of weather on aviation delays (both departure and arrival), as set out by EUROCONTROL (2014). The development and use of a weather impact index system is given here, and this approach should be applied to a TAF at least once a day. Ideally, once such a system is developed and operational, a simple comparison of the delays before and the delays after would show the benefits of the process. However, in reality, this would be difficult. No two delays are the same and delays are very sensitive to changes in air traffic (Evans and Robinson 2005). Delays arise from a complicated combination of actual weather characteristics, the nature of weather forecasts, the decision-making process, and the ability to execute mitigation plans in a timely manner (Evans and Robinson 2005). Instead, interviews from those utilizing the index system and/or direct observations of air traffic management (ATM) and airline decisions can be used to investigate the efficacy of the weather impact index system. The effectiveness of the impact index would relate to the extent that it changes user decisions and enhances collaborative decision-making.

A product based on a TAF would inherit the uncertainty of the TAF. However, TAFs are used worldwide with the understanding of their probabilistic nature, and thus such a product should be used with the same approach and understanding. A weather impact index tool should be used as one decision support option and should be used within a framework of support elements. A weather impact index tool based on the inputs set out in this paper is the first of its kind and is still in the developmental phase, and thus further research, particularly on probabilistic verification where the forecast probabilities are compared with the observed

TABLE 12. The weather impact index case study at ORTIA for 29 Oct 2010.

Hour	Forecast	Index	Coef	Final weather impact index (%)	Delay
0000	Mist	19	1.2	23	No
0100	Mist	19	1.2	23	No
0200	Mist	19	1.2	23	No
0300	Fog	29	1.2	35	No
0400	Fog	29	1.2	35	Yes
0500	Fog	29	1.2	35	Yes
0600	Fog	29	1	29	Yes
0700	No hazards present	0	1	0	No
0800	No hazards present	0	1	0	No
0900	No hazards present	0	1	0	No
1000	No hazards present	0	1	0	No
1100	No hazards present	0	1	0	No
1200	No hazards present	0	1	0	No
1300	No hazards present	0	1	0	No
1400	No hazards present	0	1	0	No
1500	No hazards present	0	1	0	No
1600	No hazards present	0	1	0	No
1700	No hazards present	0	1.4	0	No
1800	No hazards present	0	1.4	0	No
1900	No hazards present	0	1.4	0	No
2000	No hazards present	0	1.4	0	No
2100	No hazards present	0	1.4	0	No
2200	No hazards present	0	1.4	0	No
2300	No hazards present	0	1.2	0	No
2400	No hazards present	0	1.2	0	No

frequencies, would be needed before full implementation. It is also recommended that data be collected over a longer period, incorporating additional airports in southern Africa, to test the weather impact index further.

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