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Large-Scale Data Analysis for Characterization of the Effect of Wind Forecast Errors on ETAs

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This paper characterizes wind forecast errors and evaluates their impact on times of arrival estimation within a few hundred miles of the airport. The specific wind forecast product analyzed in this paper is the Rapid Update Cycle 1-hr forecast with 40km resolution. The forecast data is compared to the data reported by the aircraft using the Aircraft Communications Addressing and Reporting System. The data are compared for the complete year of 2011 by analyzing arrival operations within 200 nmi of the Phoenix Sky Harbor International Airport. The paper describes two metrics: (i) wind magnitude metric, and (ii) wind uncertainty metrics. These metrics are defined in terms of the effect the wind has on the aircraft's Estimated Time-of-Arrival (ETA) during its arrival phase of flight. Both metrics are computed for all the hourly forecasts between 6am to 10pm local time in the year 2011. The study illustrates the seasonal dependence of wind and wind uncertainty. It serves as the basis for selecting test days for NextGen concept evaluations in simulations.

I. Introduction

NASA and the FAA have been involved in extensive efforts to develop advanced concepts, technologies, and procedures for the Next Generation Air Transportation System (NextGen).[1] The objective of these research efforts has been to improve the capacity, efficiency, and safety in the next-generation National Airspace System (NAS). Improvements come in the form of more accurate and autonomous onboard navigational capabilities based upon the Global Positioning System, more accurate surveillance capabilities such as Automatic Dependent Surveillance-Broadcast, advanced communication capabilities such as Data Communications, improved vehicle designs, and improved air traffic operations realized through advanced automation systems. A significant portion of the NextGen research is aimed at (i) developing ground-based automation systems to assist controllers in strategic planning operations, (ii) developing controller decision support tools to tactically separate and space the traffic, and (iii) developing flight-deck automation to assist pilots in accomplishing airborne merging and spacing operations.[2]

A concept for future high-density terminal air traffic operations that has been proposed by the Airspace Super Density Operations (ASDO) researchers at NASA.[3] The concept includes five core components – two strategic planning elements in the form of Extended Terminal Area Routing and Precision Scheduling, as well as three tactical control elements in the form of Merging and Spacing, Tactical Separation, and Off-Nominal Recovery. Successful implementation of the Precision Scheduling component requires the following questions to be answered:

1. What is the range of feasible flight times for an aircraft to transit between two points along its flight path (e.g., from top-of-descent to the meter fix and from the meter fix to the runway threshold)?
2. What is the accuracy with which an aircraft can meet a scheduled time-of-arrival (i.e., the absolute timing error)?
3. What is the accuracy with which an aircraft can maintain self-separation with respect to a leading aircraft (i.e., the relative timing error)?

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From the foregoing list of key questions, the range of feasible flight times depends upon the following characteristics of the arrival operation:

- Aircraft performance characteristics
- Cruise and descent speeds selected by the aircraft's onboard flight management system
- Terminal area route geometry
- Observed atmospheric conditions such as temperature and winds aloft

Similarly, the time-of-arrival accuracy and self-separation performance depend upon the following:

- Uncertainty associated with the predicted atmospheric conditions
- Advisories from air traffic controllers, both manual as well as those assisted by automation tools
- Current-day and next-generation aircraft navigation capabilities

Not surprisingly, the prediction of atmospheric conditions and its associated uncertainty (most importantly the prediction of winds aloft) is a key driver in the successful implementation of Precision Scheduling. Therefore, the current work investigates the time-of-arrival uncertainty which results from the uncertainty associated with wind forecast errors. This paper specifically focuses on Phoenix Sky Harbor International Airport (PHX) arrival operations. The Rapid Update Cycle (RUC) forecast products generated by the National Oceanic and Atmospheric Administration (NOAA) is used to define the predicted winds. Aircraft Communication Addressing and Reporting System (ACARS) reports from participating aircraft are used to model the wind forecast errors. The data is further described in Section II. The PHX terminal airspace used for analysis is described in Section III. Definitions of wind magnitude and wind uncertainty metrics based upon time-of-arrival estimates are provided in Section IV. Finally, the data analysis results are presented in Section V, and some initial conclusions are discussed in Section VI.

II. Data Sources

The wind error is defined as the deviation between the actual (truth) wind vectors and the predicted (forecasted) wind vectors. Therefore, the statistical properties of a large number of observed deviations are used to model the probability distribution of the wind uncertainty. Sample truth wind sets are generated from these statistics and used to investigate the wind error's impact on time-of-arrival. This requires the following data: (i) truth wind data and (ii) forecast wind data. In this research, wind reports obtained from equipped aircraft are used as the truth data and wind predictions obtained from NOAA are used as the forecast data. These data are described in more detail in this section.

A. Truth Wind Reports

Many commercial aircraft operating today are equipped with sensors that can provide real-time weather observations (primarily winds and temperatures) via radio downlinks. The Meteorological Assimilation Data Ingest System's (MADIS)[4] automated aircraft dataset provides ACARS[5] data obtained from many U.S., European and Asian airlines. Each participating aircraft provides position and wind information at approximately one-minute intervals. Since this data is obtained from commercial aircraft flying through the airspace, the ACARS data are not available for arbitrary locations and times. It is only available for those spatial locations and times that the aircraft actually was present in. Moreover, not all aircraft report this data. However, a large amount of historical data is still available to characterize the statistics of the wind errors. Figure 1 shows a sample of ACARS wind report locations from aircraft operating in the Phoenix terminal area. PHX is located at the origin of this plot. Each small black arrow represents a single ACARS report received during between January 1, 2011 and January 15, 2011. The arrival and departure routes are clearly marked by a higher density of ACARS reports.

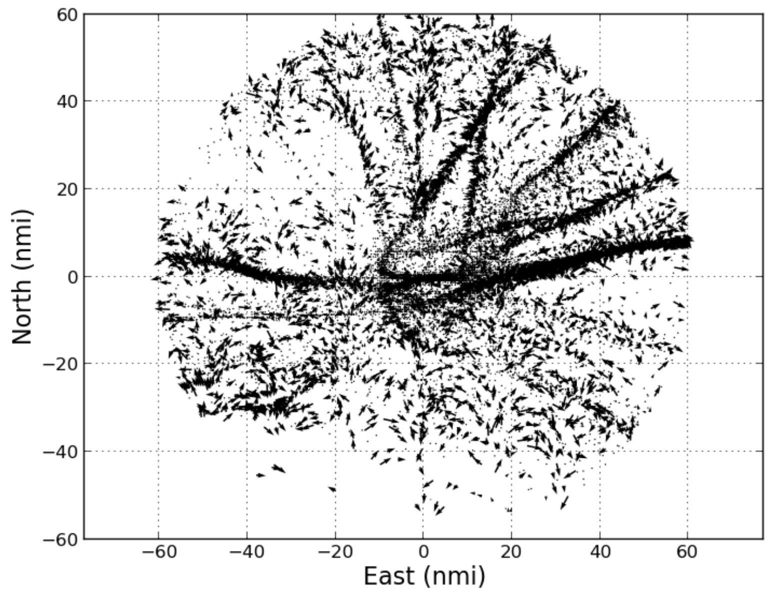


Figure 1. Sample of ACARS Wind Reports from Aircraft in the Phoenix Terminal Area

B. Forecast Wind Data

The NOAA provides predictions of wind and atmospheric conditions for the entire United States. These forecasts are obtained through a weather product referred to as RUC[6]. RUC is an operational weather prediction system covering North America that updates on an hourly basis. It consists of a numerical forecast model and an analysis/assimilation system to initialize that model. RUC provides 1-18 hour forecasts, updated hourly using either 40-, 20-, or 13-km horizontal resolutions and 50 vertical levels. This study uses the 40-km RUC 1-hour forecast (RUC-40) previously used by air traffic management applications. It provides the predicted North and East components of the wind velocity. Unlike the ACARS data, RUC data is available over a fixed grid of spatial locations. A bilinear interpolation scheme is used to compute the wind predictions for spatial locations in between the RUC grid points.

C. Potential Truth Wind Data

The ACARS wind reports represent individual wind conditions. They are not suitable for a comprehensive analysis of wind error on time-of-arrival accuracy, since they are spatial and temporally sparse. Reference 7 describes an approach to construct a spatio-temporally correlated model of wind error from a set of truth wind reports and forecast wind data. Application of this technique to a particular wind forecast (e.g., the RUC-40 1-hour forecast for March 4, 2005 at 06Z) is used to create a set of potential truth wind data that could have been present. This set of potential winds are used to investigate the range of times-of-arrival that would have been observed. Throughout the remainder of the paper, spatio-temporally correlated truth winds refer to these potential set of truth winds corresponding to a particular wind forecast based upon the historically observed wind errors.

D. Limitations and Applicability

This study compares the RUC-40 wind predictions and ACARS wind reports from 2011 in order to remain consistent with previous analyses performed for a series of ongoing NASA human-in-the-loop simulations of PHX arrival operations.[8,9] These simulations used traffic and wind scenarios constructed from 2011 data. The wind errors at PHX are assumed to exhibit similar year-to-year seasonal variations. Additional work is required to determine the extent to which the wind errors at PHX are similar to those present at other locations around the NAS.

In March 2012, NOAA replaced the RUC forecast model with the newer and more accurate Rapid Refresh (RAP)[10] forecast model. Although not part of the results presented here, later comparison of RAP wind predictions to the ACARS wind reports shows markedly reduced wind errors for altitudes above FL200. A discussion of this improvement is provided in subsequent sections.

Finally, although the current paper focuses on wind modeling, the same approach is applicable to other atmospheric data such as temperature and pressure. In that context, it is worth noting that both ACARS and RUC provide temperature and pressure data in addition to wind components.

III. Arrival Route Modeling

Figure 2 and Figure 3 show the East flow and West arrival routes respectively in the Phoenix terminal area used in this study. Each of the arrival routes is shown in a different color. Table 1 lists the combinations of the Area Navigation (RNAV) Standard Terminal Arrival Routes (STAR), en route transition fixes, and arrival runways. The en route transitions were chosen to represent the longest route from each direction. Runways 08 and 26 were used to represent the other parallel runways at PHX – Runways 07L/07R in East Flow airport configurations and 25L/25R in West Flow airport configurations, respectively.

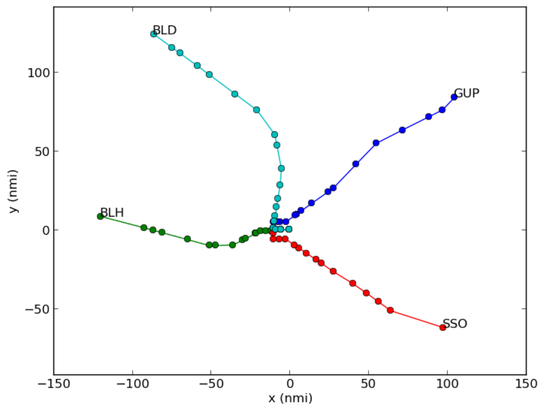


Figure 2. PHX East Flow Configuration

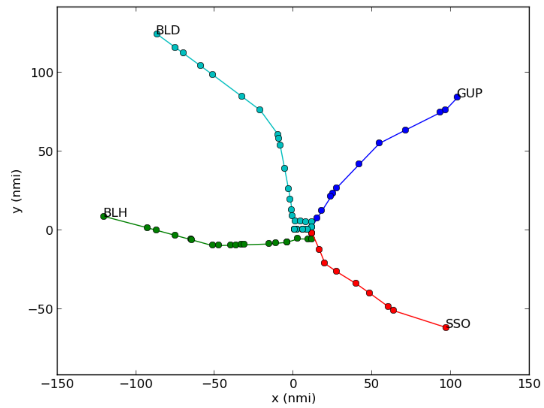


Figure 3. PHX West Flow Configuration

Table 1. STARs, Fixes, and Runway Combinations

RNAV STAR	TRANSITION FIX	ARRIVAL RUNWAY
GEELA6	BLH	08
GEELA6	BLH	26
MAIER5	BLD	08
MAIER5	BLD	26
KOOLY4	SSO	08
KOOLY4	SSO	26
EAGUL5	GUP	08
EAGUL5	GUP	26

IV. Definition of Wind Metrics

This section defines the wind magnitude and wind uncertainty metrics analyzed in this study. These metrics are based upon the ETA along each route from the en route transition fix to the runway threshold. Therefore, it is important to first identify the methodology used to compute the ETA.

A. ETA Computation

A piece-wise linear indicated airspeed (IAS) profile is developed from the following points along each of the routes shown in Figure 2 and Figure 3:

- 280 KIAS farther than 200 nmi
- 280 KIAS at 200 nmi
- 270 KIAS at 80 nmi
- 240 KIAS at 40 nmi
- 170 KIAS at 5 nmi (typical final intercept speed)
- 140 KIAS at 0 nmi (typical final approach speed)

The locations are expressed as distances to travel along the route (i.e., path distance). This speed profile was formulated as a reasonable approximation of the published speed constraints and standard operating procedures at PHX. They are similar to the observed speed profiles at other airports. In between the prescribed distances, the airspeeds are linearly interpolated. It should be noted that the full time-of-arrival error will be a combination of the error due to the differences between the modeled airspeed profile and the actual profile as well as the errors due to the predicted atmospheric conditions versus the actual conditions.

The following approach is then used to compute a set of ETAs along each route:

- Convert the IAS profile to a true airspeed (TAS) profile at the prescribed path distances
- Interpolate for the TAS as a function of path length between the prescribed path distances
- Discretize the horizontal path at 3 nmi intervals
- Calculate the winds at the 3 nmi intervals for three sets of wind data:
    - Zero wind
    - RUC-40 forecast wind
    - Set of sample random spatio-temporally correlated wind values
- For each scenario, compute the ground speed at the 3 nmi intervals by combining the prescribed true airspeed profile and the associated wind field
- Compute transit time over each 3 nmi segment using the computed ground speed

The ETA corresponding to the zero-wind scenario is represented as $ETA_{zerowind}$; the ETA corresponding to the RUC-40 forecast wind is represented as $ETA_{RUCforecast}$. The 5th and 95th percentile ETAs for the set of sample spatio-temporally correlated winds are represented as $ETA_{5Percentile\_i}$ and $ETA_{95Percentile\_i}$, respectively.

B. Wind Magnitude Metric

The Wind Magnitude Metric (WMM) characterizes the nominal strength of the wind in terms of its impact on the ETA, irrespective of the accuracy of the forecast. It is expected that winds affect the ETA; the stronger the wind magnitude the bigger the difference between the $ETA_{zerowind}$ and $ETA_{RUCforecast}$. However, the ETA difference will be different for each route. Winds aloft will make flights on some routes travel faster and flights on the opposite routes travel slower. For this study, a scalar metric that encompasses all routes is sought. The following definition satisfies the above requirements and can be applied to an arbitrary number of routes:

$$WMM = \frac{1}{n}\sum_{i=1}^{n} \frac{\left|ETA_{zerowind\_i} - ETA_{RUCforecast\_i}\right|}{ETA_{zerowind\_i}} \times 100 \quad (1)$$

where, i is a particular route, and n is the total number of routes. The absolute value of the numerator prevents cancellation of wind effects on opposite routes; the normalization by the denominator treats variations along shorter and longer routes appropriately; and the average over the number of routes prevents the expression from assuming very large values for large numbers of routes. The WMM can be interpreted as the average percentage variation of ETA with respect to the zero wind ETA for a given set of routes. Though the WMM is computed using a specific wind forecast product, namely the RUC-40 1-hour forecast, it is expected to be largely invariant to the particular wind forecast product, since all wind forecast products are intended to reflect similar large scale changes in atmospheric conditions.

C. Wind Uncertainty Metrics

The Wind Uncertainty Metric (WUM) characterizes the accuracy of the wind forecast products in terms of ETA variability. Again, a scalar metric that encompasses all routes is sought. Two different metrics are evaluated in the current research. The WUMs are based on the statistics of the ETA distributions obtained from a set of spatio-temporally correlated truth winds generated by 5000 Monte-Carlo simulation runs conducted for all routes and each RUC-40 1-hour wind forecast. The ETA variation in each Monte-Carlo simulation is used as a measure of the wind uncertainty. The variation is characterized using two different measures: (i) the 90-percentile interquartile range, and (ii) the standard deviation. The former is suited for all statistical distributions, whereas the latter is best suited for normal distributions. The WUM definitions are given below:

$$WUM_{90percentile} = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|ETA_{95Percentile\_i} - ETA_{5Percentile\_i}\right|}{ETA_{zerowind\_i}} \times 100 \tag{2}$$

$$WUM_{STD} = \frac{1}{n}\sum_{i=1}^{n}\frac{ETA_{STD\_i}}{ETA_{zerowind\_i}} \times 100 \tag{3}$$

This wind uncertainty metric specifically focuses on the impact of the wind errors on the corresponding ETA variation, i.e., ETA error. An alternative formulation of the wind uncertainty metric could investigate the impact of the wind errors on the corresponding inter-arrival error (i.e., the differential ETA error between two successive flights). This impact may be the subject of future analyses.

V. Results

Results obtained from analyzing the RUC-40 1-hour wind forecasts and ACARS wind reports in the PHX terminal area for the entire year of 2011 are presented in this section. As described in Reference 7, the wind error statistics are determined using a 15-day moving average in order to capture the seasonal variation of the atmospheric conditions and their associated errors.

A. Variation of Wind Uncertainty with Altitude

Figure 4 shows the variation of the North and East wind errors observed in the PHX terminal area as a function of altitude. These wind errors are the difference between the ACARS wind reports and the corresponding RUC-40 1-hour wind forecasts for the same time, location, and altitude. These results are consistent with other studies that have found similar wind error magnitudes.[11,12] Overall, there is no statistical difference between the North and East wind errors. For all altitudes, the mean wind error (not shown) is found to be effectively zero (i.e., the RUC-40 1-hour forecast is unbiased for sufficiently large data sets). For altitudes below FL200, the standard deviations of the North and East wind errors are approximately 5-10 knots. Meanwhile, for altitudes above FL200, the standard deviations of the North and East wind errors increase rapidly to 15-20 knots.

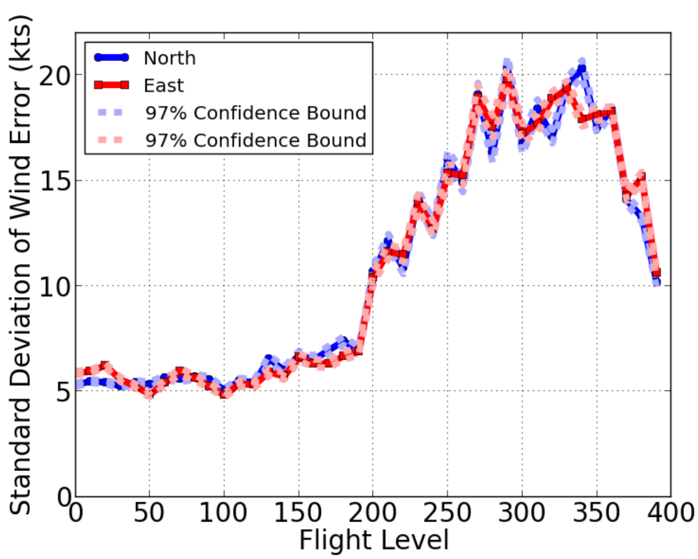


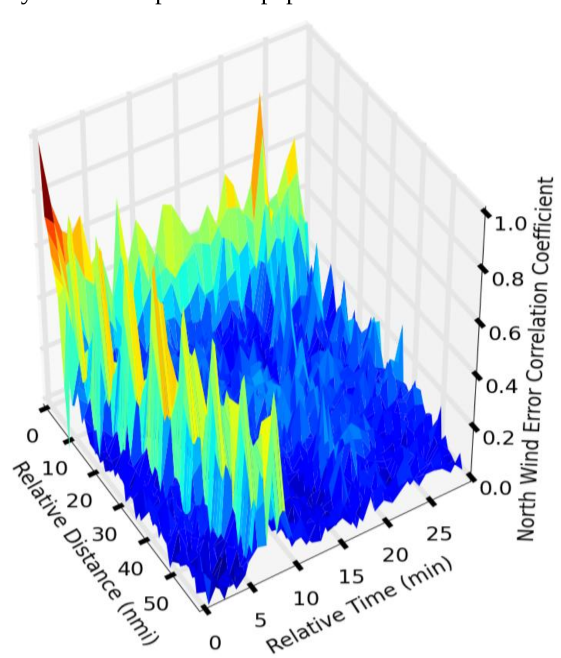
Figure 4. Variation of RUC-40 Forecast Wind Errors with Altitude

As previously mentioned, NOAA replaced the RUC forecast model with the newer and more accurate RAP forecast model in March 2012. Subsequent limited comparison of RAP wind predictions to the ACARS wind reports shows markedly reduced North and East wind errors for altitudes above FL200. This cursory examination was performed to understand how the RUC analyses would translate to the current wind forecast products available. While not presented in this paper, those results showed that the standard deviations of the wind errors of the RAP wind predictions above FL200 do not exhibit the same significant increase with altitude as shown in Figure 4. As a result of this improvement, the impact of the wind errors on ETA accuracy is expected to be lessened for the initial portion of the arrival route.

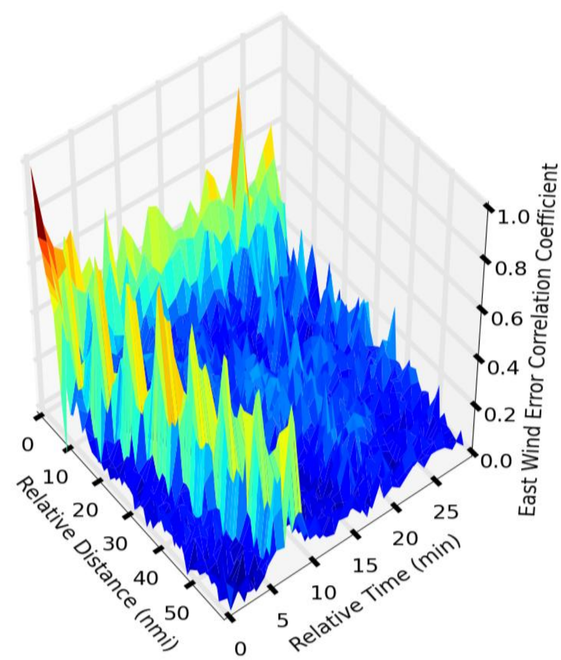
B. Spatio-Temporal Correlation in Wind Errors

At a given altitude, the standard deviations of North and East wind errors at two spatially and temporally separated locations and instances of time, are found to be correlated. From a physical perspective, this is expected since the wind error at a particular physical location will change gradually over time due to changes in the prevailing winds. Furthermore, the wind errors at nearby locations will be similar due to the large-scale nature of atmospheric winds and the overall sparseness of the RUC-40 grid. Consideration of this spatio-temporal correlation is necessary to properly simulate wind errors during high-fidelity air traffic simulations. Without both temporal and spatial correlation, an aircraft flying along a given path could potentially experience unrealistic changes of the predicted wind such as a strong headwind immediately followed by a strong tailwind. Modeling the proper amount of correlation is important since too little correlation underestimates the effect of the wind error on ETA accuracy but too much correlation overestimates the effect of the wind error on ETA accuracy.

An example of the correlation coefficient variation with respect to relative distance and time is shown in Figure 5. The correlation coefficient variation was calculated for each RUC-40 forecast using an N-day moving average, which in the present study was selected as 15 days. A strong correlation with respect to time is found at the same physical location (relative distance = 0 nmi). The correlation with respect to physical location at the same time (relative time = 0 minutes) is found to decrease exponentially. An interesting feature is the appearance of a ‘ridge’ of strong correlation along a line through the relative distance and relative time space. A possible cause is the availability of ACARS wind reports along specific arrival routes in the terminal area, instead of across a larger generic area. Wake vortices from a leading aircraft along an arrival route can affect the local wind pattern encountered by a following aircraft along the same route. This phenomenon requires further analysis which is beyond the scope of this paper.



(a) North Wind Error Correlation



(b) East Wind Error Correlation

Figure 5. Spatio-Temporal Correlation of North and East Wind Errors

Generally, the wind errors are found to exhibit low correlation when spatially separated by more than 10 nmi. Similarly, the wind errors are found to exhibit low correlation when temporally separated by more than 5 minutes. Both of these scales – distance and time – are significantly shorter than the typical air traffic management arrival planning horizons which are approximately 30-60 minutes and 150-250 nmi. As a result, the effect of wind error over sufficiently long routes will be attenuated. Both scales are also significantly shorter than the grid size and update period of the available RUC and RAP wind forecast products. The experimental High Resolution Rapid Refresh (HRRR) model with a grid size of 3km has the potential to provide a grid size and update period more similar to the typical arrival planning horizons.[13] Thus, use of the HRRR wind forecast product in future high-fidelity air traffic simulations might allow the effects of the wind errors spatial correlation to be simulated.

C. Seasonal Variation of Wind Errors

Figure 6 and Figure 7 show the seasonal variation of North and East wind errors as a function of the day of the year and altitude. The plots show different wind error behavior for altitudes above and below 10,000 feet. For altitudes above 10,000 feet, there is a significant seasonal variation. In this altitude range, the wind errors at PHX are smallest during the summer months of July through September and largest during the winter months of January through April. Conversely, there is little seasonal variation of the wind forecast errors for altitudes below 10,000 feet.

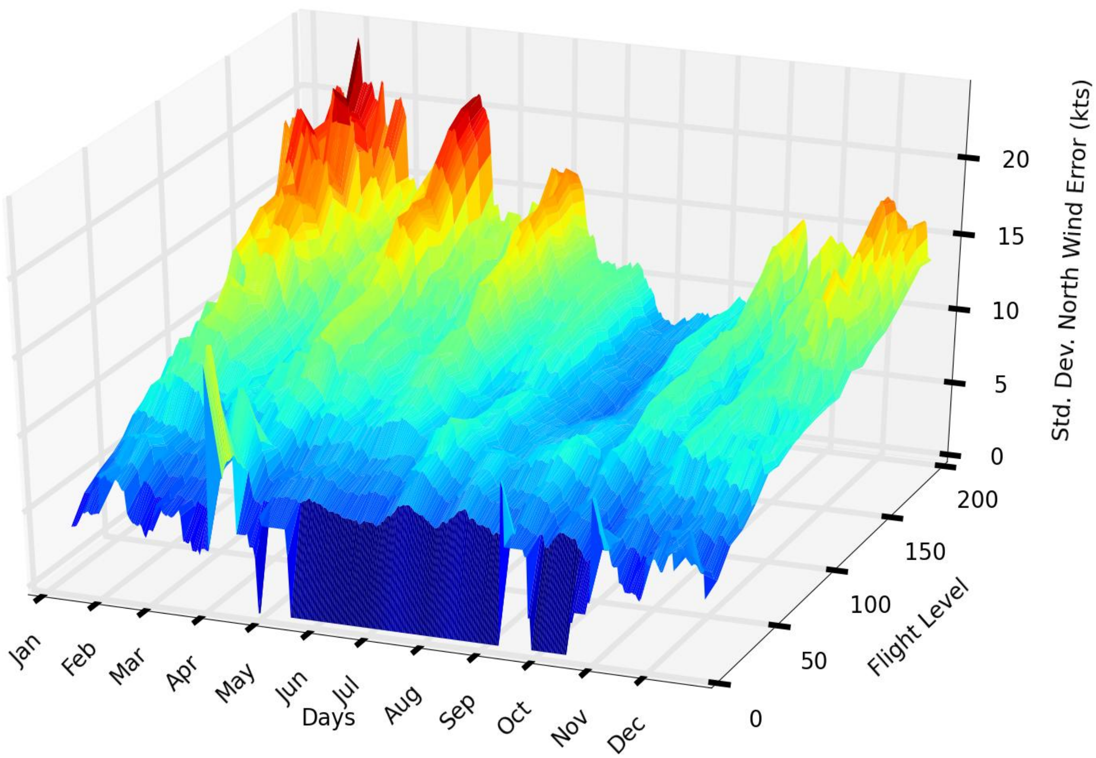


Figure 6. Seasonal Variation of North Wind Errors at PHX

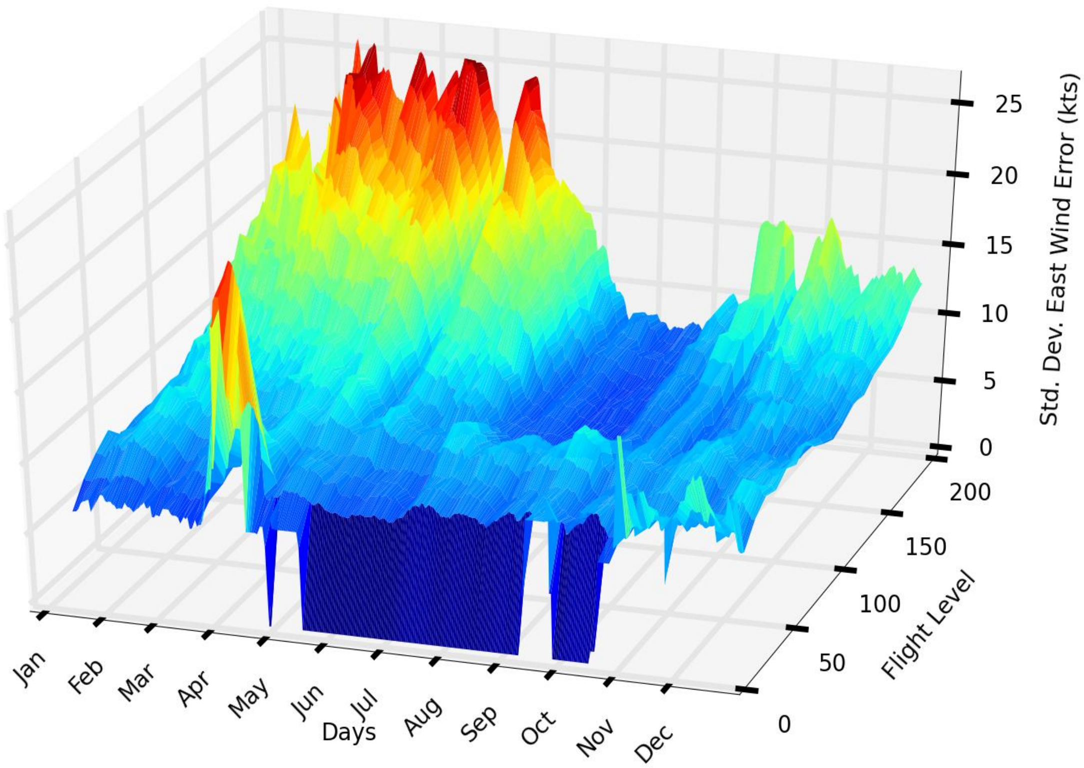


Figure 7. Seasonal Variation of East Wind Errors at PHX

D. ETA Variation Along PHX Routes

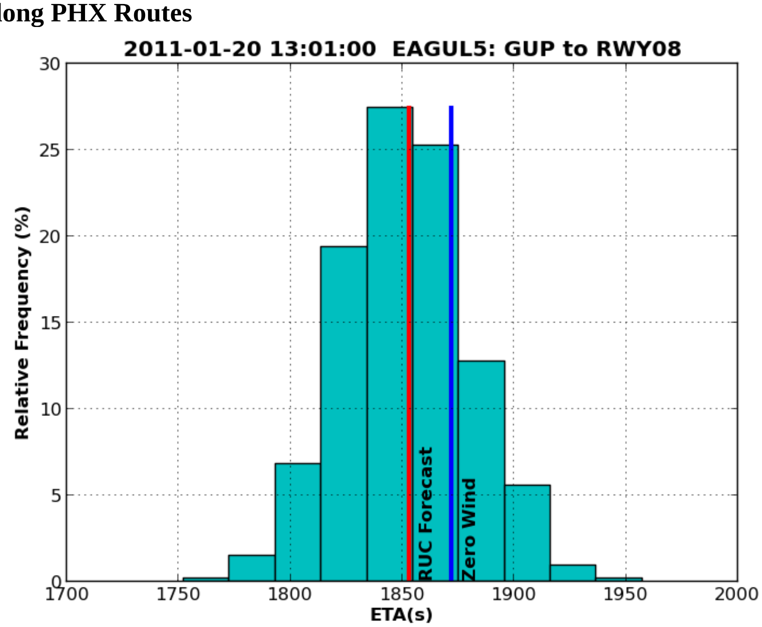


Figure 8. ETA Variation Along EAGUL5 Route from GUP to PHX Runway 08

In order to evaluate the effect of the wind and wind error on ETAs, a set of 5000 sample wind profiles were created by applying the observed spatio-temporally correlated wind errors corresponding to each RUC-40 1-hour forecast wind file as illustrated in Figure 4 (See Section IId). ETAs were then calculated based on that set of 5000 sample wind profiles, the RUC-40 1-hour forecast winds, and zero winds for each route. Figure 8 shows the results of the simulation runs conducted using the RUC-40 1-hour forecast for January 20, 2011 at 1300Z along the

EAGUL5 arrival route from the GUP en route transition fix to PHX Runway 08. The difference between the blue line and the red line is a measure of the wind magnitude's effect on ETA. The spread of the cyan colored histogram is a measure of the wind error's effect on ETA. Subsequent determination of the seasonal variations of the WMM and WUM are generated using results like those shown in Figure 8 for all RUC-40 1-hour forecasts and all arrival routes.

E. Seasonal Variation of the Wind Magnitude Metric

Figure 9 shows the seasonal variation of the WMM (as defined by Eq. (1)). This WMM can be interpreted as a statistical measure of the average ETA change due to wind aloft. The time series clearly shows both high frequency variations (i.e., changes over a period of a few days) and low frequency variations (i.e., changes over a period of months or the entire season). The results indicate that the months of July and August are the time period when the winds have the lowest impact on ETA. During these summer months, the ETA change due to the winds is less than 5% of the flight time from the en route transition to the runway threshold. During the other months of the year, the ETA change due to winds increases to 10-15% with some periods spiking to 20-25%. Furthermore, during these summer months, the wind effect is more consistent and the high frequency variations are attenuated.

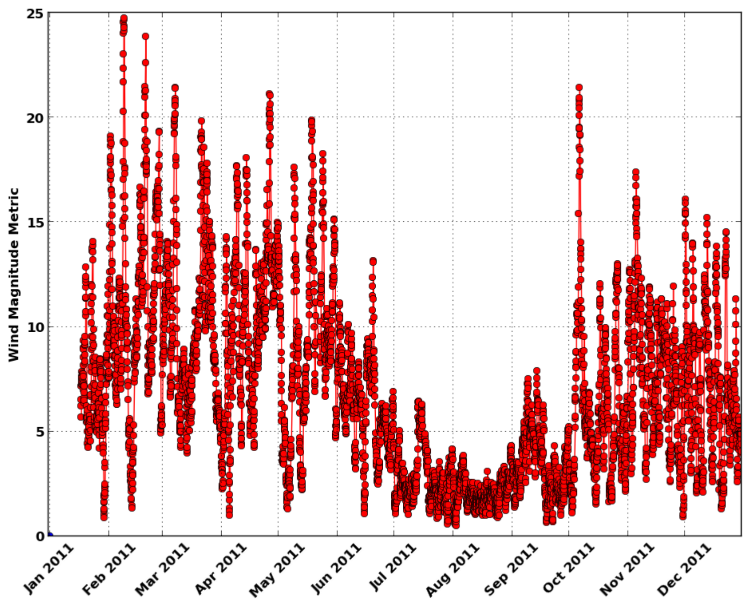


Figure 9. Seasonal Variation of the Wind Magnitude Metric

F. Seasonal Variation of Wind Uncertainty Metric

Figure 10 shows the seasonal variation of the WUM based on the standard deviation metric (as defined by Eq. (3)). The WUM results are very similar to the WMM results discussed earlier. The time series clearly shows both high frequency and low frequency variations. The results again indicate that the months of July and August are the time period when the wind errors have the lowest impact on ETA variability. During these summer months, the estimated standard deviation of the ETA due to the wind error is approximately 1% of the flight time. During the other months of the year, the estimated standard deviation of the ETA due to wind error increases to approximately 2% with some periods spiking as high as 2.5-3%. Furthermore, during these summer months, the wind error effect is more consistent and the high frequency variations are attenuated. These results suggests that the ETA uncertainty induced by wind error will be less than 1 minute for an arrival phase of flight generally lasting 20-30 minutes.

Figure 11 shows the seasonal variation of the WUM based on the 90-percentile interquartile range metric (as defined by Eq. (2)). The results behave nearly identical to the seasonal variation of the WUM based on the standard deviation. The magnitude is appropriately larger since the 90-percentile interquartile range is naturally larger than the standard deviation; for normal distributions, it is approximately 3.3 times larger.

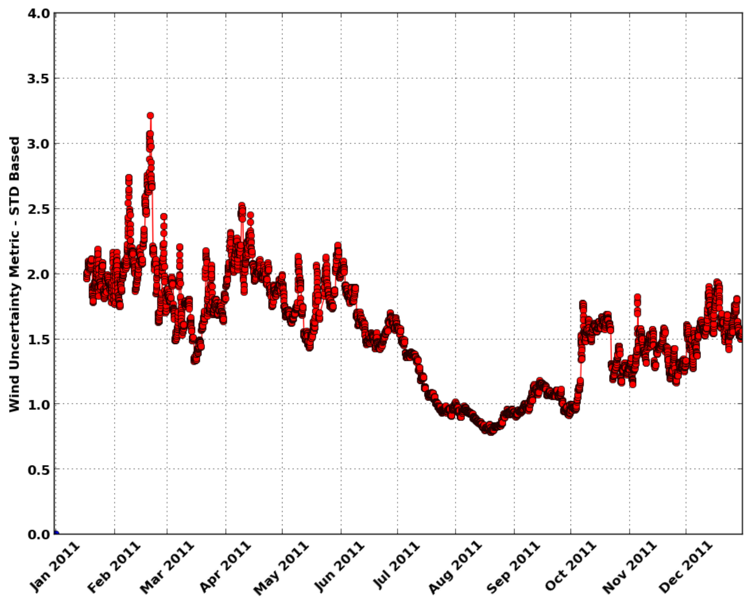


Figure 10. Seasonal Variation of Wind Uncertainty Based on Standard Deviation Metric

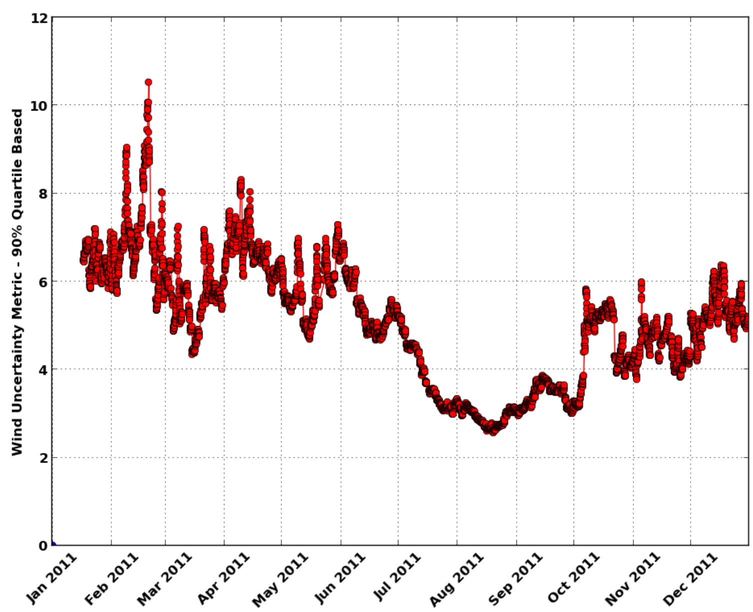


Figure 11. Seasonal Variation of Wind Uncertainty Based on 90-Percentile Interquartile Range Metric

VI. Conclusions

The current paper investigates the effect of wind uncertainty resulting from forecast errors on the expected times-of-arrival. The study specifically focuses on the PHX terminal area, NOAA's RUC-40 1-hour wind forecast product, and the year of 2011. It can be concluded from the results of this study that the wind forecast errors are: (i) dependent on the altitude, (ii) spatio-temporally correlated, and (iii) exhibit modest seasonal variation. The wind magnitudes generally cause ETA variations less than 10% when compared to ETAs with zero wind. However, the wind magnitudes can cause ETA variations as high as 25% in limited cases. The wind uncertainty resulting from forecast errors generally cause ETA variations less than 7% when compared to the ETA with zero wind errors. Under certain conditions, the wind uncertainty resulting from forecast errors can reach 10%. The study serves as a formal basis for understanding the effect of wind uncertainty on the trajectory prediction of NextGen air traffic management concepts.

Acknowledgments

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