6.4 ASSESSMENT OF WIND SHEAR FORECAST PERFORMANCE AND IMPLICATIONS ON WIND COMPRESSION IMPACTS

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1. INTRODUCTION

Winds that change direction and/or speed with altitude, or wind shear, in critical airspace regions and in the presence of sufficient air traffic demand can result in wind compression constraints – where this wind shear, if not planned for, can result in the loss of required separation between aircraft (at worst) or excessive airborne vectoring, holding, or diversions (at best). Unanticipated wind compression can result in increased impacts and delays that cascade across the National Airspace System (NAS). Air Traffic Management (ATM) decision-makers currently seek to mitigate wind compression impacts by evaluating wind observations and weather model forecasts, but these efforts lack critical and explicit awareness of key objectively-identified and operationally-relevant wind shear thresholds and historical forecast performance which could otherwise enhance capabilities to proactively manage these constraints. Most wind compression events are therefore managed reactively by ATM, typically only after associated spacing impacts have begun, resulting often in a more difficult and challenging air traffic operation with increased disruptions and delay. This underscores the need for timely and reliable prediction of compression-conducive wind shear onset, duration, and severity.

This study initially addresses these operational wind shear forecast needs by leveraging objectively-identified airport-specific wind shear thresholds to assess the performance and utility of the High Resolution Rapid Refresh (HRRR) and Short Range Ensemble Forecast (SREF) weather forecast models in predicting the magnitude and timing of wind shear events at key airports. Isolation of these wind shear thresholds at each focus airport from distributions of historical wind shear during operationally impactful wind compression events and their potential operational applications beyond this weather forecast analysis will be described. The relationship between these wind shear thresholds and air traffic responses to these wind shear environments will also be evaluated (a) to initially characterize the overall wind compression severity and (b) to understand the potential operational implications and opportunities associated with thresholded wind shear timing and magnitude forecast performance. Opportunities to extend this analysis to identify existing gaps, shortfalls, and ATM needs in wind shear forecasts will also be discussed.

2. WIND COMPRESSION PREDICTION COMPLEXITY

The problem of wind compression is complex as it is inherently comprised of both a meteorological and operational component – the wind shear environment, which sets the stage for potential wind compression, and "operational sensitivity", or sufficiently high air traffic volume and active airspace configuration constraints. Even in the presence of significantly large wind shear, a given arrival flow may not experience severe compression constraints if arrival flow volume is low and/or the active airspace configuration allows some of the traffic to be offloaded onto other arrival paths. The severity of the overall wind compression event is therefore dictated by the interaction of the wind shear environment and air traffic volume / constraints.

Because of this complexity, assessing the performance and utility of forecast models in supporting operational planning and decision making must extend beyond a solely meteorological validation. This study provides an initial evaluation of wind shear performance "translated" into relevant potential wind compression impacts by capturing the fundamental elements of operational sensitivity. A myriad of nuanced considerations exist for both wind compression components, such as diurnal, seasonal, and regional variability, which motivates the need to scope the initial analysis to key contributors to both wind shear and operational sensitivity.

3. EXPERIMENT DESIGN

3.1 *Target Wind Shear Products*

As wind shear is quantified as the difference in wind vectors within an altitude layer, data sets providing predictions and observations of winds at multiple vertical levels in the atmosphere are needed for this study.

The first target 3-D wind forecast model for this study is the High Resolution Rapid Refresh (HRRR) model, generated by the Earth Systems Research Laboratory (ESRL). The HRRR is a high resolution (3 km) experimental forecast model capable of explicitly depicting convection which produces hourly fresh

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model realizations. The model receives its lateral boundary conditions from the Rapid Refresh (RAP) 13-km resolution model, inside which it is nested, and assimilates radar and satellite observations. This project focuses on the 3-D wind forecasts. An overview of the HRRR model can be found in Alexander et al. (2012) and Weygandt et al. (2012).

The second target 3-D wind forecast for this study is the Short Range Ensemble Forecast (SREF), a multi-model, multi-physics ensemble comprised of 21 members produced by the National Centers for Environmental Prediction (NCEP). Forecasts are issued every six (6) hours (at 0300, 0900, 1500, and 2100 UTC) for lead times every three (3) hours out to a maximum lead time of 87 hours using a 40 km grid resolution (Du et al. 2014).

The Velocity Azimuth Display (VAD) Wind Profile (VWP) product, derived from NEXRAD radar observations, will serve as the observation product in this study, against which the forecasts will be evaluated. The VWP product provides a vertical profile of winds for the volume above the radar location, leveraging the VAD algorithm to estimate winds at each profile altitude (Chrisman and Smith 2009). These observations are taken at the radar sites, typically located within a few miles of the Core airports, approximately every 10 minutes.

3.2 *Analysis Methodology*

To initially explore the complex relationship between wind shear environment and operational sensitivity, a preliminary evaluation of forecast performance at predicting critical wind shear thresholds, expressed as potential wind compression constraints, has been conducted. This evaluation focused on wind shear events at the ten airports which experienced the most wind compression events during the analysis study period of December 2013 – April 2014, as identified and documented by air traffic operators in the FAA National Traffic Management Log (NTML): ATL, EWR, JFK, LGA, DTW, LAX, PHX, IAD, DCA, and PHL airports.

Validation of the target forecast products was focused on two operationally critical components of wind shear prediction – onset timing and magnitude. The initial impact of a wind compression event is one of the most challenging aspects of handling these events for Air Traffic Control (ATC) and Air Traffic Management (ATM), particularly when unexpected, so there is significant potential benefit to understanding how the forecasts perform at predicting the onset of significant wind shear. To characterize and verify predictions relative to potential operational constraints, the maximum predicted and observed headwind wind shear was computed by evaluating the overall wind shear vector relative to the arrival flow direction within the typical altitude range for each arrival flow segment.

4. CHARACTERIZING WIND SHEAR

4.1 *Objective Identification of Wind Shear Categories*

Prior to forecast evaluation, categorical characterization of the meteorological wind shear environment is needed at the target airports to provide context for shear typically observed during impactful wind compression events and capture the regional variability in both wind climatology and aviation operations. In addition to being the foundation for the forecast validation in this study, these categories would potentially provide useful context and thresholding to wind shear observations and forecasts in support of ATM. Wind shear, as used in this study, refers to the wind shear vector magnitude within a given altitude layer.

These wind shear categories were objectively identified at all target airports through examination of maximum wind shear distributions generated in key arrival flow altitude bins during 69 NTML-identified wind compression events from 2009-2011. These key arrival flow altitude bins were first determined through assessment of arrival flows at each target airport as the expected change in altitude between each pair of fixes. Distributions of the maximum wind shear observed in each of these altitude bins were then generated, within which four key thresholds were identified as +/- 0.5 σ and +/- 1.0 σ from the median value (Figure 1). From these four thresholds, five wind shear categories ranging from “minimal” to “excessive”, can be defined as depicted in Figure 1. The “moderate” wind shear category captures the peak of the distribution and represents “typical” wind shear values observed during historical wind compression events. The “minimal” and “excessive” categories capture the extreme smallest and largest wind shear values associated with wind compression, respectively.

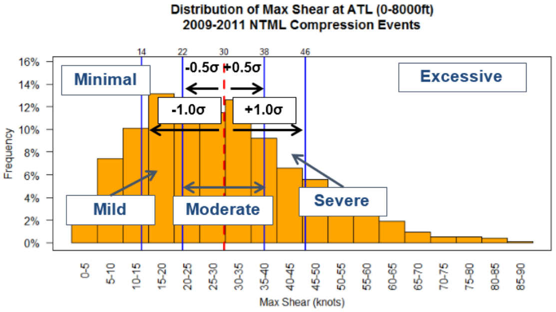

Figure 1. Example of wind shear threshold (blue lines) and associated category determination from 0-8 kft shear distribution at ATL.

Significant variability was found in the thresholds used to define the categories at the target airports in all key arrival altitude bins, indicating that a given wind shear value associated with wind compression could be considered “lower than typical” at one airport while being “much greater than typical” at another. For example, wind shear of 25 kts is anomalously large, or “excessive”, from 0-8 kft, at LAX while being more typical, or “moderate”, at DCA between the same two altitudes (Table 1).

Table 1. Wind shear thresholds for select altitude bins and airports.

		Wind Shear Categories		
		0-10 kft	0-5 kft	0-8 kft
DCA	Minimal	<15	<10	<15
	Mild	15-25	10-15	15-20
	Moderate	25-40	15-30	20-35
	Severe	40-50	30-35	35-45
	Excessive	>50	>35	>45
LAX	Minimal	<5	0	<5
	Mild	5-10	0-5	5
	Moderate	10-15	5-10	5-15
	Severe	15-20	10-15	15-20
	Excessive	>20	>15	>20

4.2 *Operational Response to Wind Shear Categories*

To characterize the operational response to the wind shear categories at each target airport, the average amount of excess vectoring in the TRACON above “typical” flight path distances was quantified during wind shear events. These track lengths were computed from historical Aircraft Situation Display (ASDI) flight trajectories as the distance flown between a 100 nmi radius and the airport, focusing only on arrival traffic into that airport.

Typical flight path lengths were computed at each target airport to provide a baseline against which path lengths flown during wind shear events could be compared. This baseline was computed as the average flight trajectory length from hundreds of paths across 10 days from 2014 with minimal terminal weather constraints, selected independently at each airport.

Flight path lengths were similarly computed during approximately 1600 wind shear events across the study period and stratified by both wind shear category and time of day. The ratio of each path length was computed relative to the baseline to more directly quantify any excess vectoring that may have occurred. Ratios greater than (less than) 1.0 indicate track lengths exceeding (below) the baseline, thus reflecting an excessive (lack of) TRACON vectoring response to the wind shear. Distributions of these track length ratios were generated across all historical wind shear events at each target airport.

Track lengths in excess of the baseline were observed during wind shear events at high demand periods at most of the target airports and tended to be longer (indicating more significant excess vectoring, or airborne holding) with increasing wind shear magnitude. At LGA, when severe and excessive wind shear were observed (indicating “greater than normal” shear during historical compression events) arrival traffic tended to vector beyond the baseline (track length ratio > 1.0) during its peak demand period of 12-00Z (Figure 2, top). Arrival traffic vectoring above baseline was observed during even mild to moderate wind shear (“more typical”) at ATL during its high demand period (Figure 2, bottom). This correlation between wind shear category and TRACON track lengths supports the method used to define and delineate the shear categories themselves.

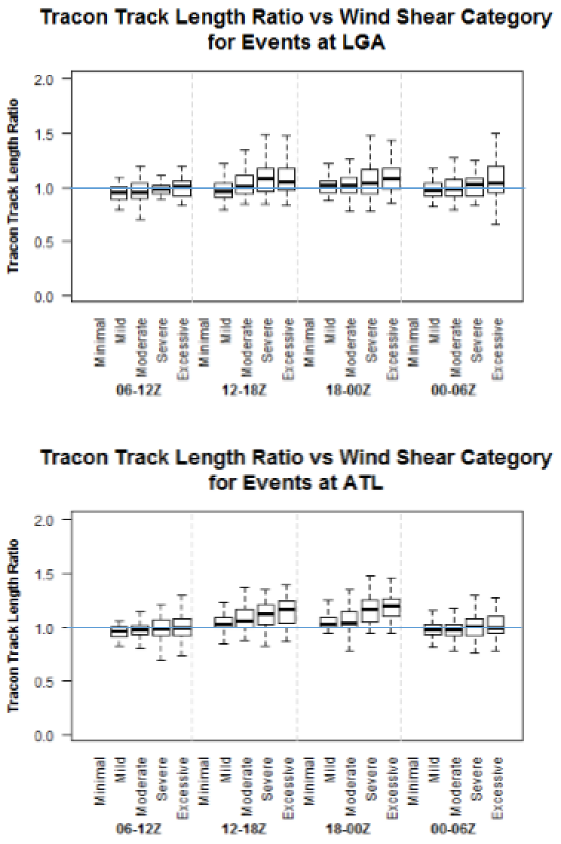

Figure 2. Distribution of TRACON track length ratios at LGA (top) and ATL (bottom), stratified by time of day (major category) and wind shear category (minor category).

4. FORECAST EVALUATION

The wind shear forecast evaluation described in this section was performed on both the HRRR and SREF products, but results are only described in detail here for the HRRR model.

4.1 *Onset Timing Prediction*

To evaluate forecast performance at predicting the operationally critical onset of significant wind shear, the difference in hours between the onset of the most severe 1-6 hour lead-time forecast and observed headwind shear was computed across all events in the study period. Onset of this most severe wind shear was defined as the earliest time that wind shear in either the “severe” or “excessive” category was predicted or observed. Across all wind shear events at each target airport, the predicted onset time was determined for all forecast lead times as well as the difference between this and the observed onset time. Timing difference values greater than (less than) zero reflect situations where the forecast predicted onset before (after) it was observed, or “early” (“late”). For example, if a 4-hour HRRR forecast predicted “severe” shear to first occur at 17Z (“forecast onset”) during a given event while the earliest observation of “severe” shear actually occurred at 20Z, the timing difference would be -3 hours (17Z – 20Z), reflecting that this forecast was 3 hours “late” in predicting the onset of significant shear. Distributions of these timing differences were then generated across all wind shear events at each airport.

The HRRR was “late” in predicting the onset of severe or excessive wind shear at most target airports with performance tending to improve with increasing forecast lead time. There was minimal variability in timing differences by lead time at IAD airport, with the largest differences associated with the 1- and 2- hour lead forecasts (Figure 3, left). At EWR, the timing differences decrease with lead time, indicating improved performance, with the 8-hour forecast most accurately predicting onset (Figure 3, right).

4.2 *Wind Shear Magnitude Prediction*

The forecast performance at predicting wind shear magnitude was quantified through evaluation of the headwind shear along all arrival flow segments into each target airport for the 1-6 hour lead times. For each hour during the wind shear events, the difference between forecast and observed headwind shear was computed across all arrival flow segments. Difference values greater than (less than) zero indicate under-forecasting (over-forecasting), meaning the forecast predicted wind shear with greater magnitude than was actually observed. Distributions of these differences were generated across all segments along each arrival flow, and stratified by forecast lead time.

The HRRR performance varied across the arrival flows, but tended to under-forecast the headwind shear magnitude at the target airports. In contrast to what was observed for the onset timing performance, there was little variability in headwind shear magnitude performance by lead time for all arrival flows at the target airports. Results at IAD are representative of these signals, where the HRRR tended to under-forecast headwind shear magnitude at all lead times for most arrival flows (Figure 4). Slight under-forecasting of headwind shear magnitude was observed along a few arrival flows, such as BARIN_IAD (flow 3 in Figure 4). All HRRR lead time forecasts performed well at predicting headwind shear at EWR, with minimal differences between those forecast and observed along most arrival flows (Figure 5). Larger spread in headwind shear differences were observed for the METRO_CEDDA arrival flow (flow 1 in Figure 5) relative to the other distributions, likely due to the multi-directionality of its segments.

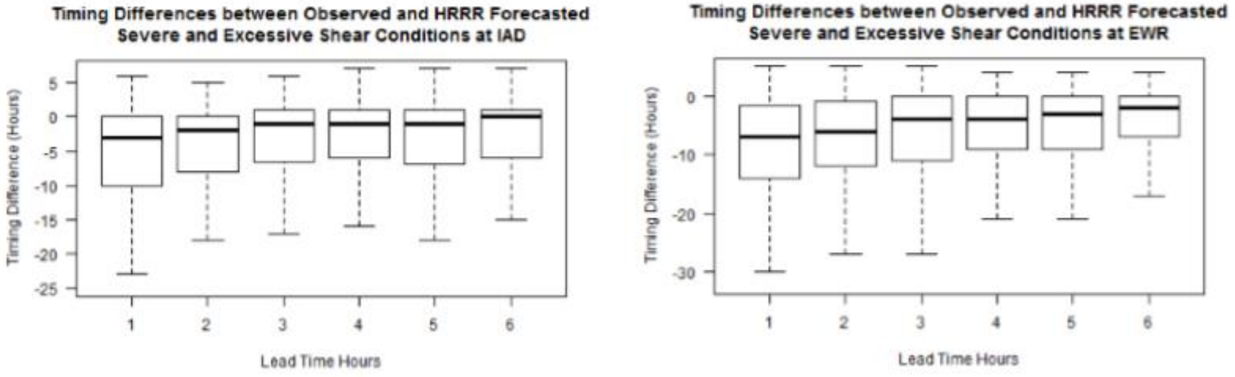

Figure 3. Severe/excessive onset timing difference distributions for HRRR 1-6 hour lead times at IAD (left) and EWR (right).

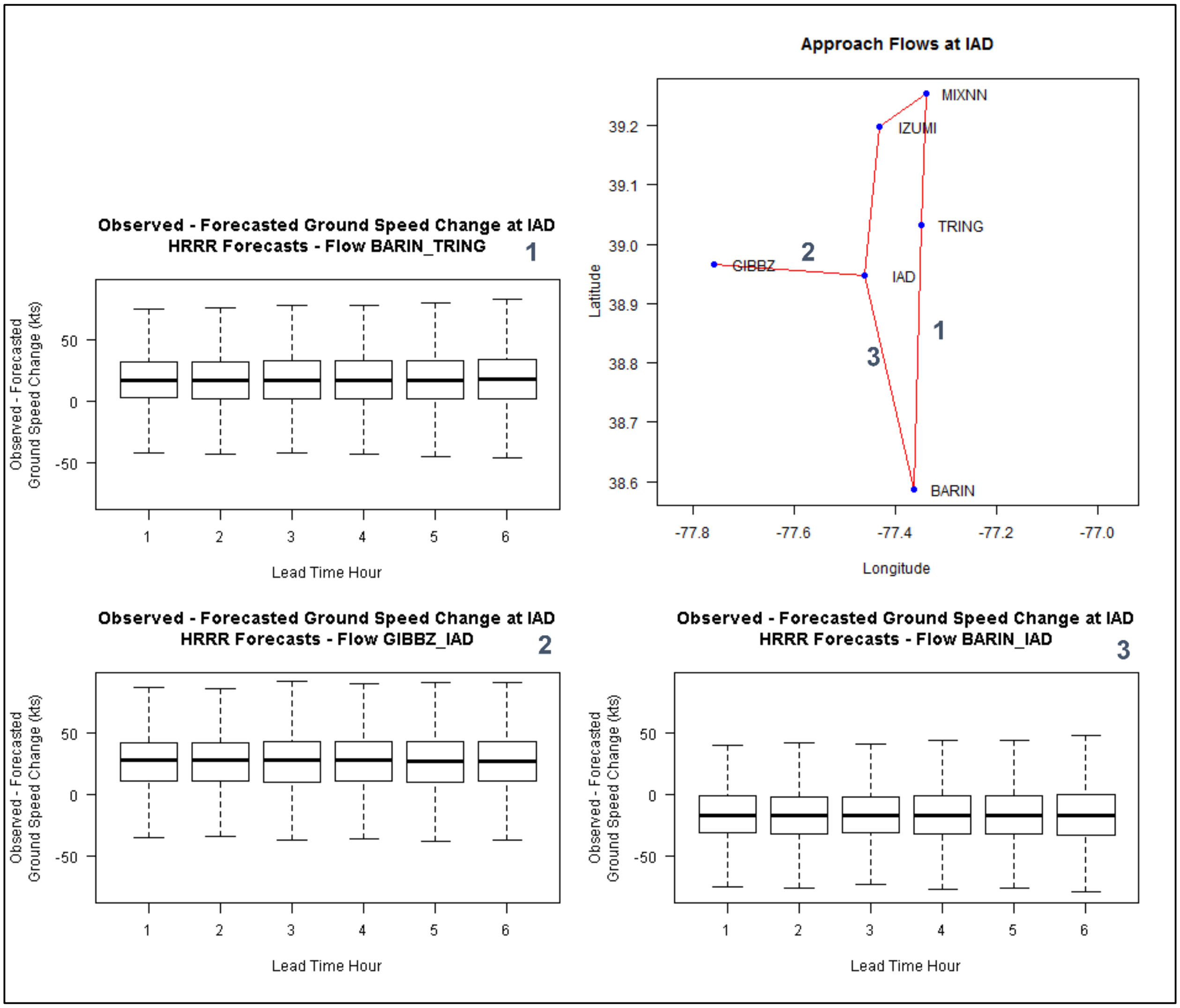

Figure 4. Distribution of wind shear magnitude differences for each arrival flow (keyed in top right panel) into IAD airport.

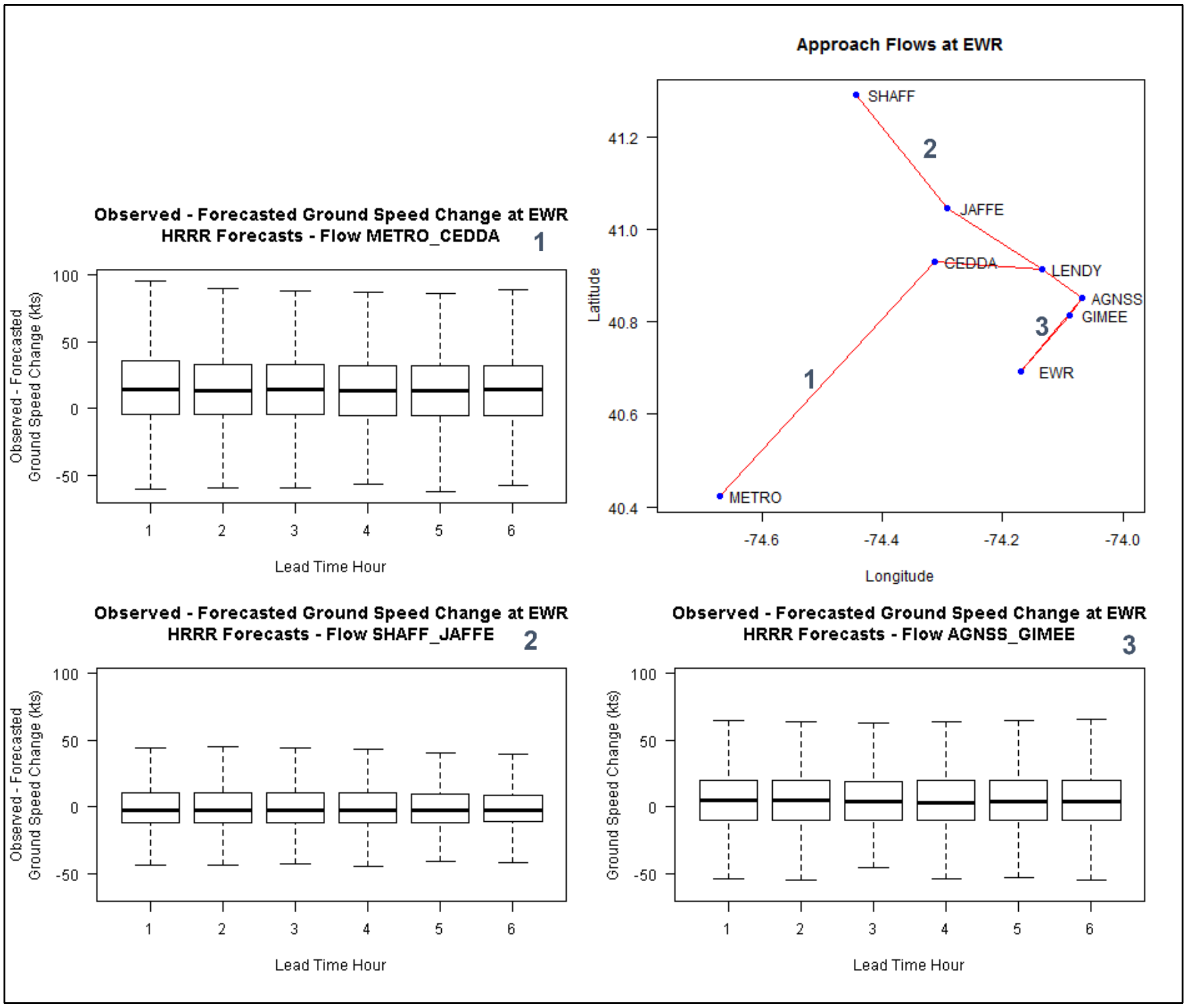

Figure 5. As in Figure 4 but for EWR airport.

5. SUMMARY

Critical wind shear categories were objectively identified at the 10 airports that experienced the most NTML-identified wind compression events during the study period of December 2013-April 2014. These data were used to support wind shear prediction validation of two forecast products (HRRR, SREF) in order to assess the applicability of numerical weather prediction to operational planning for aviation wind compression impacts. These airport-specific wind shear categories can also be used beyond this forecast evaluation to facilitate operational interpretation of forecast and observed wind shear in the context of “typical” values historically experienced during wind compression. As a preliminary characterization of the operational response to these wind shear categories, arrival flight paths within the TRACON during historical wind shear events at the target airports were computed relative to a “minimal weather” baseline to quantify any excess vectoring that may have occurred in response to the adverse wind shear environment. Additional vectoring of arrival flows was observed, especially during high demand periods, and was well correlated with wind shear category severity, supporting the method used in determining the wind shear thresholds.

Forecast verification was performed focusing on two operationally critical components of wind shear events – onset timing of most severe headwind shear and headwind shear magnitude. Onset timing was evaluated through determination of the earliest hour for which “severe” or “excessive” headwind shear was predicted and the difference computed between this time and when one of these two categories was first observed. Both the HRRR and SREF tended to be “late” in predicting the onset of “severe” or “excessive” shear at most target airports. Forecast performance at predicting headwind shear magnitude was evaluated by computing the difference between that which was predicted and observed along each arrival flow across all historical wind shear events during the study period. The HRRR and SREF both tended to under-forecast headwind shear magnitude along most arrival flows at the target airports, though slight over-forecasting was observed along some arrival flows. There was little variability in HRRR headwind shear magnitude performance by lead time.

This research can be extended to identify existing gaps and shortfalls in current wind compression prediction in support of ATM needs, by refining the forecast evaluation as guided by stakeholder defined operational needs. The preliminary forecast onset timing performance will be expanded upon to consider and focus on operationally relevant wind compression event duration and critical wind shear categories, extending upon the onset definition using “severe” and “excessive” categories as in the current study. Headwind shear magnitude differences will also be analyzed in the context of operational sensitivity to move toward translation of forecast performance to operational constraints.

6. ACKNOWLEDGEMENTS

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