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AIRCRAFT MEASUREMENTS OF TERRAIN-INDUCED WINDSHEAR ON THE APPROACHES TO JUNEAU AIRPORT

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1. Introduction

In Aviation Meteorology, wind shear refers to a change in the winds, which is sufficiently abrupt to affect the performance of an aircraft so significantly that it challenges the compensation capabilities of the pilot and the aircraft. Clearly this definition is conditioned on the capabilities of the aircraft. Less obvious is its dependence on the flight situation. For example, an aircraft cruising at altitude has options to trade altitude for airspeed that are not available to an aircraft in its final approach or making a low-altitude turn to avoid terrain. There is also the question of what shear magnitudes constitute a hazard. Studies of microburst and frontal windshear and their affects on commercial aviation, during takeoffs and landings, dominate the wind shear literature. For these situations, the standard is that a 10 m/s loss or gain over a distance of 1-4 Km is considered moderate wind shear and that a headwind change in excess of 15 m/s over that distance is considered severe (Fujita et al, 1997) and (McCarthy, 1997). From these definitions, the most severe shear occurs when the net change is achieved over the shortest distance.[1] There does not seem to be a consensus regarding hazard levels for cross-wind shear.

Our belief is that it is prudent to provide wind shear alerts for the intermediate altitude operations in regions with complex terrain. We present evidence to support this position, based on studies of terrain-induced wind shear near the Juneau airport. The focus is on intermediate altitude operations, which we define to include altitudes between 300m and 1200m. Although aircraft at intermediate altitudes usually have options for altitude tradeoffs to compensate for moderate headwind and crosswind shears, our experience is that pilots perform these compensations more efficiently when they are alert to the possibility of wind shear. In some flight situations, their options are constrained by associated turbulence and terrain avoidance.

The methodology for the estimation of wind shear from data taken by instrumented aircraft is discussed in Section 2. The source data for this study are University of Wyoming King Air measurements, taken during two winter seasons (1999-2000 and 2002-2003) in the air space near Juneau Airport (Barron, 2004) and (Gilbert, 2004). Illustrative examples are discussed in Section 3. The selection of hazard regions[2] is described in Section 4, where we also provide a statistical summary of the wind shear occurrences. A statistical comparison of terrain-induced wind shear and turbulence is presented in Section 5, and evidence that skillful wind shear alerts can be produced is presented in Section 6.

2. The Analysis of Aircraft Data

The impact of wind shear on an aircraft is understood through the change in the aircraft's total energy, the sum of its kinetic and potential energy. Changes in kinetic energy are related to changes in the airspeed, and changes in the potential energy are related to changes in altitude. The pilot and flight control systems can influence this allocation. The total energy of the aircraft may also be modified by changes in the engine torque, another pilot decision. In short, energy analysis is fundamental to our problem, and to make a complete analysis would involve an understanding of the intentions of the pilot. This information is unavailable, so approximations are necessary.

It is possible to obtain a fairly good approximation of the net effect of a wind shear on the aircraft by measuring the net changes in the winds that are derived from the basic aircraft measurements. The derivation of these winds is based on the flight equations of the aircraft and a variety of recorded flight parameters. The derived aircraft winds are most accurate when the flight track is straight and level. It is known that wind measurement errors increase during maneuvers (Gilbert et al, 2004), especially tight turns, but we know of no way to quantify the increase of errors due to these effects. No compensating adjustments are attempted in the analyses that follow.

Turbulence and the derived aircraft winds are base on aircraft measurements which are recorded at 25 Hz. Turbulence is expressed in terms of the Eddy Dissipation Rate (Edr), which is estimated by a spectral analysis on sliding 1-Km data windows (Gilbert et al, 2004). The wind shear estimations use the derived aircraft winds (U,V), where U denotes the East-bound component and V denotes the North-bound component. Wind shear is estimated at two

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[1] The greatest rate of change occurs when the distance is the shortest, so the associated rates are .010 1/s for moderate wind shear and .015 1/s for severe wind shear.

[2] The operationally significant regions were determined through consultations with FAA Air Traffic Controllers and commercial pilots.

analysis scales: over sliding 1-Km data windows and over sliding .5-Km data windows. While the time series of these wind data have a fairly significant high-frequency chatter, the 12-second[3] example in Figure 1 indicates that there is also a perceptible trend. We use the estimated trend to estimate the mean impact of wind change on an aircraft by using a least squares fit to estimate the slope of the change (U',V'). We then estimate the net impact over a time interval of length t. If denotes the average airspeed over that time interval, and we wish to estimate the wind shear over a scale distance D, then the net change in the wind field (U, V) is estimated by

$$(\Delta U, \Delta V) = \Delta t * (U', V')$$
$$where \quad \Delta t = \frac{D}{v} \quad . \qquad (1)$$

Two distance scales are implied by these formulas. The distance D, over which the net shear is experienced, appears explicitly. In these studies, we choose D= 1 Km, which conforms to the lower length scale used in previous microburst studies. There is also the implicit scale, which is used in the estimation of the slopes (U', V'). Although the matched wind shear scale is 1 Km, we have found that it is also useful to estimate these slopes at the .5 Km scale. All estimates are normalized to provide the loss or gain over a 1 Km distance, at the estimated rate.

An abrupt change in the headwind has a direct impact on the aircraft energy. The net change in the headwind is determined by the wind shear component in the direction of the aircraft track (X,Y). We estimate the direction of the aircraft track to be the unit direction vector (secant) of the actual ground track. We estimate the components (X',Y') of this direction vector by least squares slope estimation. If (X, Y) denotes the unit aircraft track heading vector, then the headwind (HS) and crosswind (XS) wind shears are estimated by

HS = -(U, V) • (X, Y)

(2)

XS = | (U, V) • (- Y, X)|

Total shear (TS), the magnitude of (U, V), is a meteorological property, since it is not related to the aircraft track by the formulas (2). Even though TS is independent of the direction of the track, there is an influence by the aircraft track, since the underlying wind measurement locations are on that track. For example, if the aircraft flies at a fixed altitude, then (U, V) reflects a shear in the horizontal wind field, but if the aircraft changes altitude, then (U, V) reflects a combination of the horizontal wind shear and the vertical shear of the horizontal winds. The vertical shear is sometimes viewed as less hazardous, since the pilot may mollify its impact by adjusting his rate of ascent. In our investigations of the aircraft performance in these shears, we have observed that pilots can make these adjustments more efficiently if they are aware that vertical shear is a possibility. Warnings of all significant wind shear events provide operational benefits.

3. Two Case Studies

The evaluation of wind shear and its consequences involves many considerations. To promote a better understanding of our approach to understanding these issues, we first present a rather standard example, shown in Figures 2A and 3. This flight segment, from Oct. 19, 2002, approaches the airport from the West, executes a low fly-by, and then executes a Lemon Creek departure. In this maneuver, pilots make a left turn immediately after lift-off to enter the Lemon Creek basin, which is enclosed on three sides by 3000' hills. They execute a 180^{o} turn in the basin, exiting beside the departure runway in the reverse direction. The plan view of the aircraft track is provided in Figure 2A. Since the flight path in the Lemon Creek is below the surrounding hilltops, the preferred track is safely within the confines of the basin, illustrated by the white arc in the Figure 2. In this rather benign situation there is no difficulty with staying within these confines.

We investigate the impacts on the wind shear on the aircraft by comparing the estimated wind shear with several aircraft flight parameters. Panel A shows the aircraft altitude above ground level (agl). The black bar indicates the extended runway location and the orange bar indicates the flight time within the Lemon Creek basin. We see that there is a low pass over the runway and a climb to 300m for the pass through the Lemon Creek basin. From Panel B we note that except for a brief dip in airspeed when they first pull up, they hold a nominal airspeed of 80 m/s, typical for the King Air. In Panel C, we note a sharp negative roll as they turn off of runway heading, and a continuous positive roll of about 25^{o} as they follow the right turn within the basin. They climb with a 10^{o} pitch and hold a slight positive pitch as they turn through the basin. This flight profile is fairly typical of a Lemon Creek departure.

The accompanying wind and wind shear measurements are indicated in Panels D-F, D: wind components U, V and Edr, E: 1 Km wind shear, and F: .5 Km wind shear. From Panel D, we note that there is a moderate Southeast flow, with a southerly component (V) of about 5 m/s and a easterly component (-U) of about 10 m/s over the airport. From panel E, we note that the 1 Km wind shear agnitude is mostly less than 5 $10^{-3}s^{-1}$, with one crosswind spike to 10 $10^{-3}s^{-1}$. From Panel F, we see that there is considerable choppiness at the .5 Km scale, with headwind shears of $\pm$ 10 $10^{-3}s^{-1}$ and a crosswind shear of nearly 20 $10^{-3}s^{-1}$. There is very little turbulence, with the Edr values consistently

[3] *At a typical airspeed of 80 m/s, 12 seconds corresponds to a flight distance of approximately 1 Km.*

below .1. We note a slightly erratic pitching of the plane during the choppy wind shear conditions within the Lemon Creek basin, and a dip in the intended roll at the time the plane re-enters the Southeast flow.

Figure 4 provides the same time-series graphs for a flight along a similar track the next day, Oct. 20, 2002. The plan view of this flight path is presented in Figure 2B. Note that the path straightened in the back of the basin, widening the turn substantially. Figure 4 indicates that there is a somewhat stronger Southeast flow, with the southerly component increased from 5 m/s to 10 m/s. However, the wind shear and turbulence conditions have increased from light to severe in Lemon Creek basin. The irregularity of the roll graph in would lead us to believe that the pilot was fighting for control of the aircraft. This is really rough air, with bursts of severe wind shear (HS exceeding $\pm$ 20 $10^{-3}s^{-1}$) and severe turbulence (Edr=.9) from the entrance, well into the Lemon Creek basin. The 20 m/s loss of airspeed indicates that there was a significant adverse impact on aircraft total energy. The pilot compensated by pushing the nose down (negative pitch) and briefly returning to 0^o roll, thereby widening the turn to the limits of the confines of the basin. From these two examples, we see that a moderate change in the strength of the winds in the Lemon Creek basin can be accompanied by significant changes in the aircraft hazard.

4. Shear Hazards at designated locations

Wind shear hazards are studied for specific regions near the Juneau Airport, which are relevant to aviation operations (Barron, 2004). These regions have the shapes of various quadrilaterals and are called the hazard boxes. The geographic extents of the hazard boxes are shown in Figure 5. Each hazard box in the Gastineau Channel is partitioned vertically. The lower boxes extend from the surface to 2000 feet, and are labeled 5, 6, 7, and 8. Directly above these and extending from 2000 to 6000 feet are boxes labeled A, B, C, and D.

Since each hazard box has an extent of several kilometers, a typical aircraft track that crosses a hazard box will make a succession of wind shear estimates during its passage. The measured wind shear hazard level in a box for a particular crossing is defined to be the 90^{th} percentile of all wind shears measured in the hazard box during the crossing. Separate estimates are made for HS, XS, and TS.

Turbulence levels are similarly estimated from the aircraft data. One question is whether the instances of moderate and severe wind shear coincide with the instances of moderate and severe turbulence. Several studies have shown that turbulence levels are higher near regions of strong wind shear (Endlich, 1965) and (Mancuso and Endlich, 1966). There is less information regarding a quantitative relationship.

Since specific alerts are to be issued for each hazard box, it is important to understand the nature of the wind shear hazard occurrences as experienced in each hazard box. An important observation is that there are a two dominant wind patterns in the Juneau region, which are associated with most of the terrain-induced wind shear and turbulence (Cohn, 2004). These wind regimes are the southeast flow (SE), which is the result of a synoptic situation that forces strong winds up the Gastineau Channel, and the Taku flow (TK), which results from the drainage of a cold air mass from the Taku Glacier across the Gastineau Channel. The aircraft were flown repeatedly, under three prevailing wind situations (SE, TK, and Neither). Counts of the total penetrations are shown in Table 1. Counts of the wind shear and turbulence events experienced, divided by the total number of penetrations, provide estimates for the probabilities of hazardous encounters during probes by the project aircraft.

We shall present evidence that the quantitative relationship is weak for the terrain-induced wind shear near Juneau. For each hazard box and wind regime, we estimate of the probabilities of the occurrence, for moderate and severe events, and we estimate the correlations of the intensities of turbulence and wind shear. In counting the occurrences, we have used the traditional wind shear thresholds: 0-10 m/s is light wind shear, 10-15 m/s is moderate wind shear, and >15 m/s is severe wind shear, and Edr thresholds: 0-.2 is light, .2-.4 is moderate, and >.4 is severe. Based on these thresholds, we find that there is substantially more moderate-severe wind shear than turbulence. Composite results for all hazard boxes combines are: the probabilities of moderate and severe turbulence over all aircraft flights are .07 and .01, respectively; the probabilities of moderate and severe .5 Km total shear are .13 and .11, respectively. The correlation of turbulence and .5 Km total shear is typically .6 -.7 in the various hazard boxes. Correlations in this range indicate wind shear and turbulence frequently collocated, but that there is only a moderate possibility of a causal quantitative relationship.

These estimates of the probabilities that turbulence and wind shear will be experienced in the various hazard boxes under the different wind regimes are used to estimate the magnitude of the impact on aviation. The data collected indicate that there is little wind shear or turbulence when neither the Southeast or Taku conditions are present. Tables 2 and 3 present these probabilities for the Southeast and Taku wind regimes, respectively. Each table contains the probabilities for several hazard boxes, with the SE events in the first columns and the TK events in the last columns. Bold figures indicate the more significant cases. The pair of numbers (100/55) following the hazard box name provides the number of cases, which were used in the SE and TK probability estimates, respectively. We caution that when one of these counts is less than 50, then the estimates are prone to small sample error. All wind shear results refer to the shears computed at the .5

Km scale.

The results presented in Tables 2 and 3 indicate that Lemon Creek experiences significant wind shear and turbulence in both wind regimes (note that there are only 25 SE cases for Lemon Creek). We note that the Gastineau Channel experiences its most significant wind shear and turbulence in the Taku situation, but that there are many SE wind shear and turbulence events in the channel. Finally, Coghlan Island, North Douglas Island, and Outer Point hazard boxes experience their most significant wind shear and turbulence in the Southeast wind regime.

5. The Correlation of Wind shear and Turbulence

If the intensities of wind shear and Turbulence were highly correlated, then we might conjecture that these events had a causal relationship or were subject to a common forcing mechanism. If this were the case, then it might be prudent to consider issuing unified alerts. In our experience, this kind of strong linkage would result in a correlation coefficient greater than .90, even from measured data.

The correlations between the wind shear and turbulence intensities are presented in Table 4 for all cases where there is significant wind shear and turbulence. We note that the correlation coefficients are high enough to indicate frequent collocation of the events, but low enough to indicate frequent variation in their relative intensities. Indeed, we note from Tables 2 and 3 that moderate and severe wind shears occur much more frequently than moderate and severe turbulence. While it is not reflected in the statistics presented here, we have observed some cases when there is strong turbulence that is not associated with strong wind shear.

In addition, there are different pilot responses to anticipated wind shear and turbulence. Pilots anticipating a headwind loss will typically attempt to compensate by adding airspeed. Pilots anticipating turbulence are inclined to reduce airspeed to reduce stress on the airframe. So distinguishing between these events is important to flight decisions.

Based on these findings, we conclude that separate alerts for wind shear and for turbulence have operational value. There is a clear need for wind shear alerts for the Gastineau Channel during Taku Flows, for Coghlan Island, North Douglas Island, and Outer Point during Southeast Flows, and for Lemon Creek during both of these conditions. Finally, there is a sufficient likelihood of moderate shear in the Gastineau Channel during Southeast Flows, that there would be operational value in providing these alerts as well.

6. Anticipated Skill of Wind Shear Alert Models

We now consider the evidence that skillful wind shear alerts can be provided. Table 5 provides a listing of some skill statistics, taken from Appendix 3 of a skill analysis report (Fowler, et al, 2004). The probability of detection (POD), false alert ratio (FAR), and the Peirce skill statistic (PSS) are listed for HS, XS, TS, and Edr, in cases where there is enough data to reliably estimate these skill statistics. These statistics provide different indications of the skill of a model. The POD is the measure of the model skill for issuing an alert when it is needed. The FAR is the measure of the failure rate for issued alerts. The PSS is a composite measure of the rates of correct detections and false positives.

The entries in Table 5 indicate the preliminary wind shear models comparable skill to the more carefully studied turbulence alerts. We see that there are skillful wind shear alert models for most of the important situations.

7. Conclusions

Terrain-induced wind shear occurs near Juneau and it can have a significant adverse impact on aircraft. Pilots can adapt to wind shear events more efficiently if they and warnings that a wind shear encounter is likely. There is evidence that regression-based models have acceptable skill in diagnosing wind shear events.

8. References

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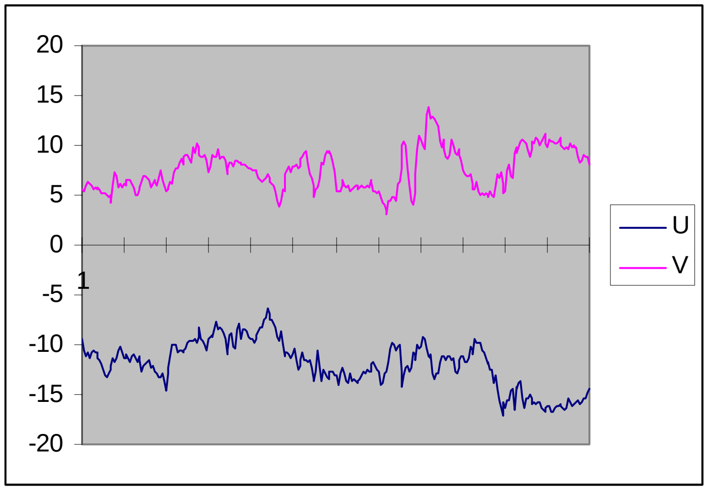

Figure 1. Typical aircraft winds for a 12 second period.

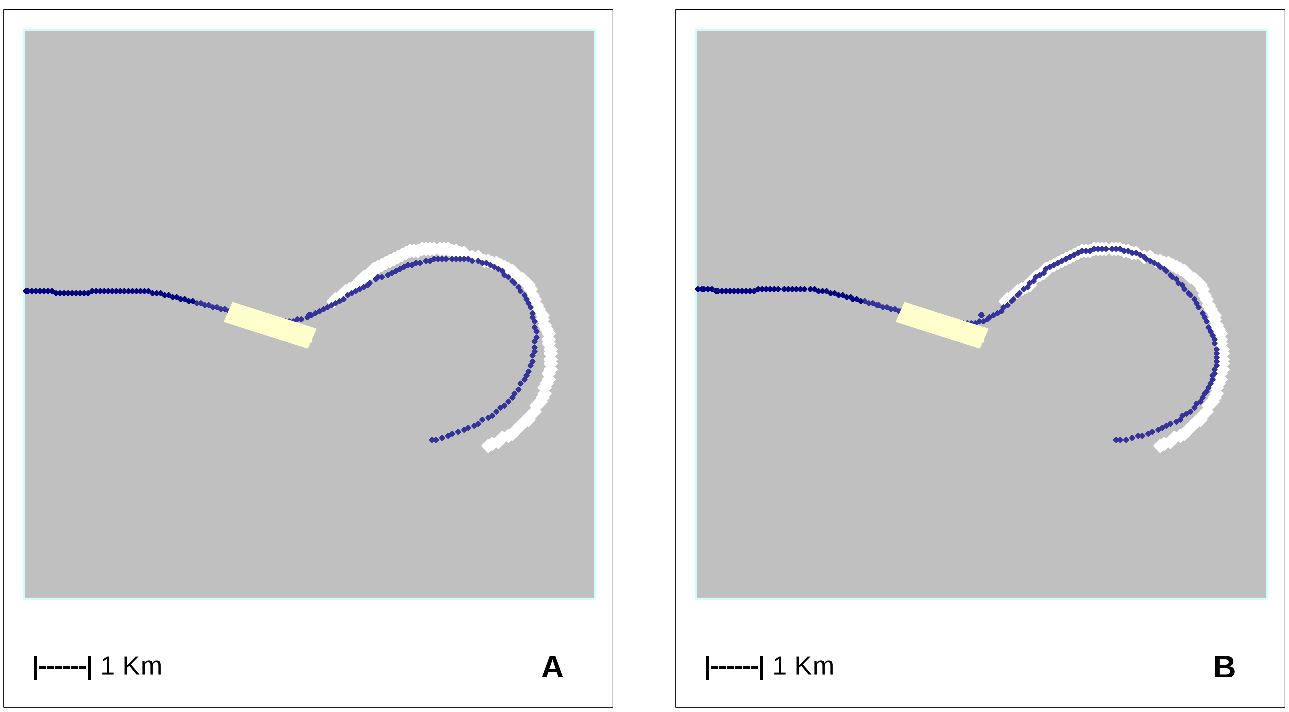

Figure 2. University of Wyoming King Air flight paths, approaching Juneau Airport from the West and continuing to Lemon Creek departures. The yellow rectangle represents the runway; the white arc represents the usually accepted flight path constraint in the Lemon Creek basin. The box dimensions are 10 Km by 10 Km. Picture A represents a smooth case and Picture B represents a turbulent case.

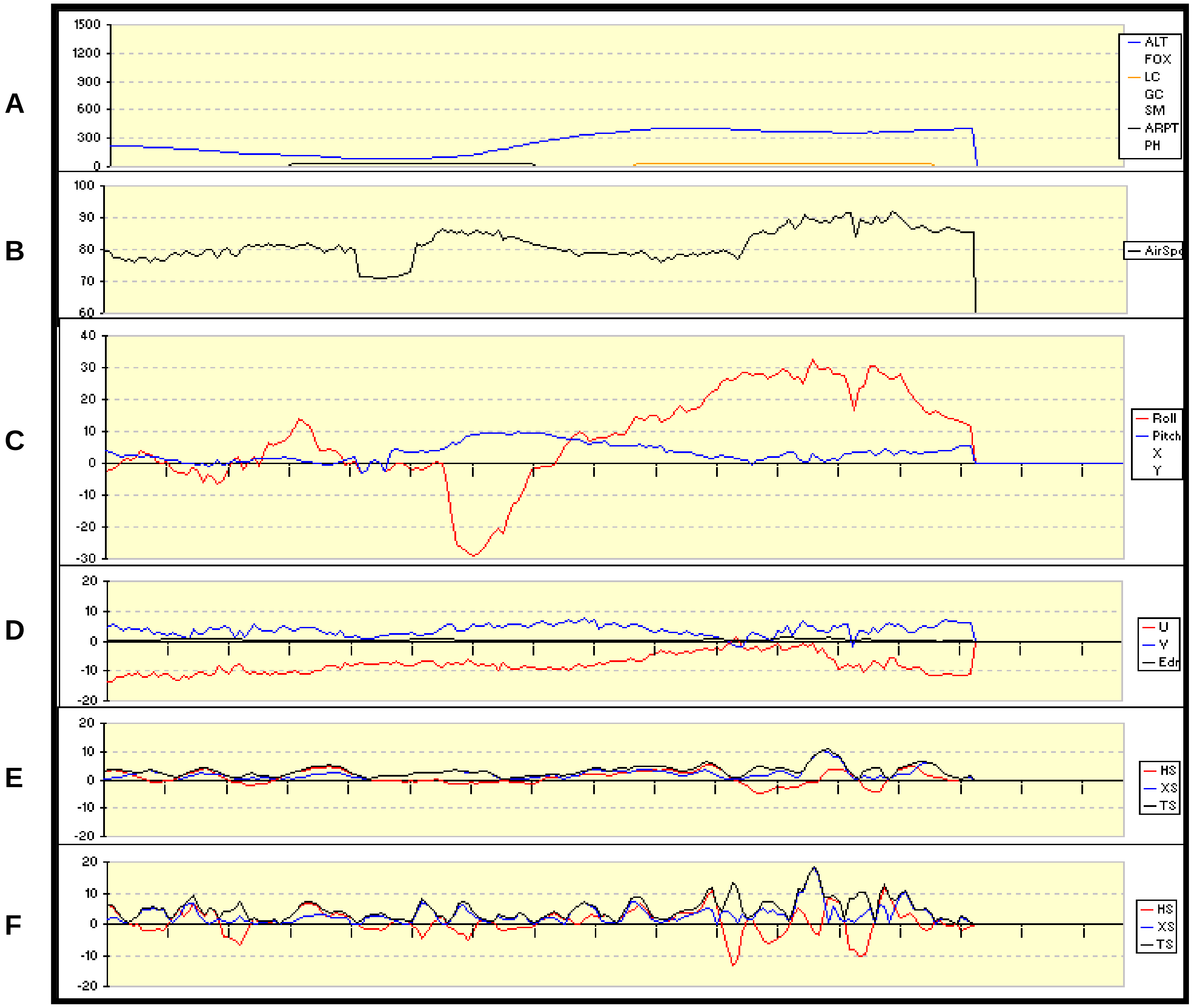

Figure 3. University of Wyoming King Air Flight segment from Oct. 19, 2002. Time series graphs of winds, wind shear, and flight parameters. Tic marks indicate 12 seconds of flight time (approximately 1 Km). Contents of the six panels:

- *A. AC altitude and location, Gridlines 300m (Arpt-black, Lemon Crk.- orange)*
- *B. Airspeed, Gridlines 60, 80, 100 m/s*
- *C. AC roll and pitch, Gridlines 10 deg. (Roll-red, Pitch-blue)*
- *D. Winds and Turbulence, Gridlines 10 m/s (U-red, V-blue, 10*Edr-black)*
- *E. 1.0 Km Wind Shear, Gridlines 10 m/s (HS-red, XS-blue, TS-black)*
- F. *0.5 Km Wind Shear, Gridlines 10 m/s (HS-red, XS-blue, TS-black)*

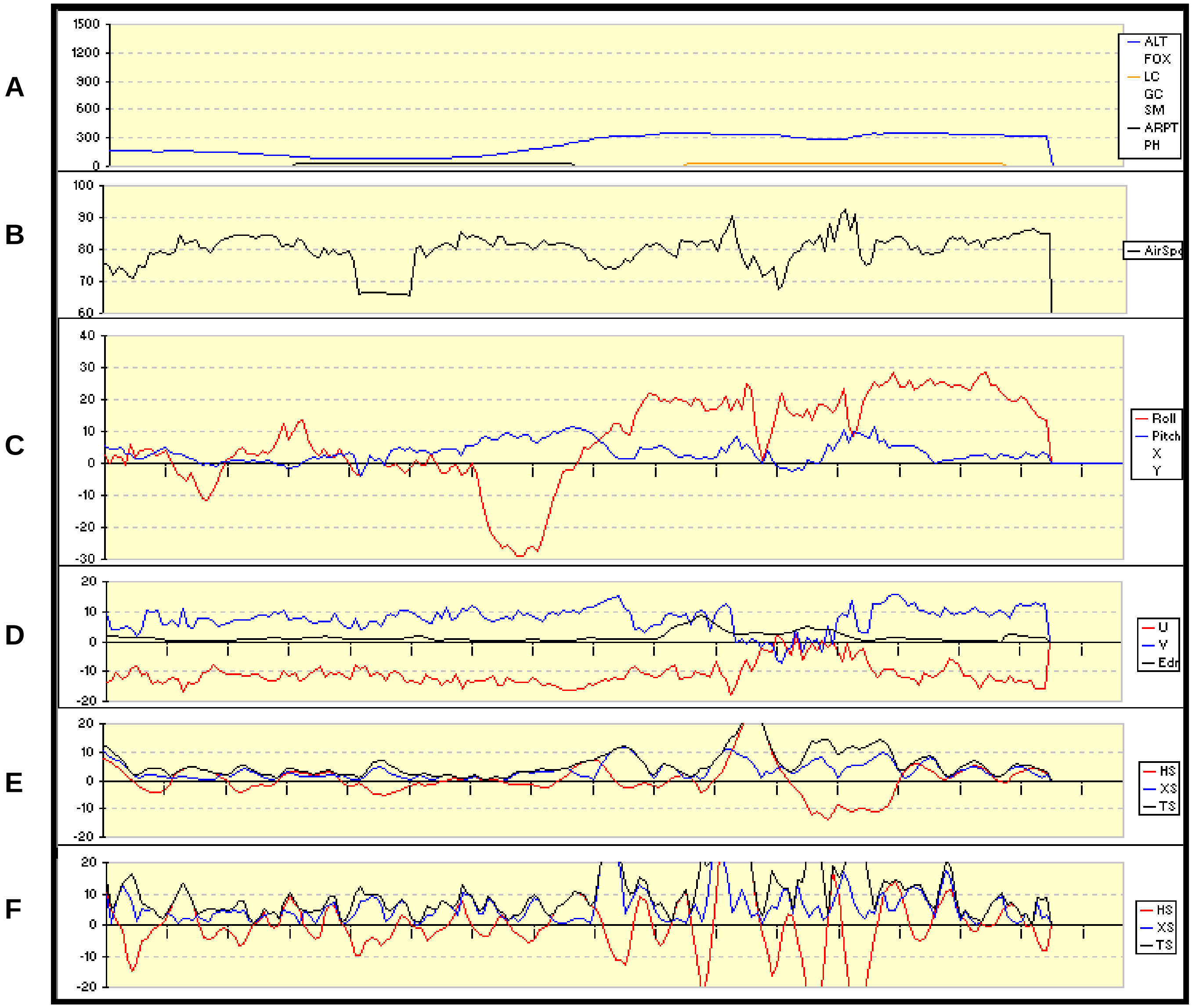

Figure 4. University of Wyoming King Air Flight segment from Oct. 20, 2002. Time series graphs of winds, wind shear, and flight parameters. Tic marks indicate 12 seconds of flight time (approximately 1 Km). Contents of the six panels:

- *A. AC altitude and location, Gridlines 300m (Arpt-black, Lemon Crk.- orange)*
- *B. Airspeed, Gridlines 60, 80, 100 m/s*
- *C. AC roll and pitch, Gridlines 10 deg. (Roll-red, Pitch-blue)*
- *D. Winds and Turbulence, Gridlines 10 m/s (U-red, V-blue, 10*Edr-black)*
- *E. 1.0 Km Wind Shear, Gridlines 10 m/s (HS-red, XS-blue, TS-black)*
- *F. 0.5 Km Wind Shear, Gridlines 10 m/s (HS-red, XS-blue, TS-black)*

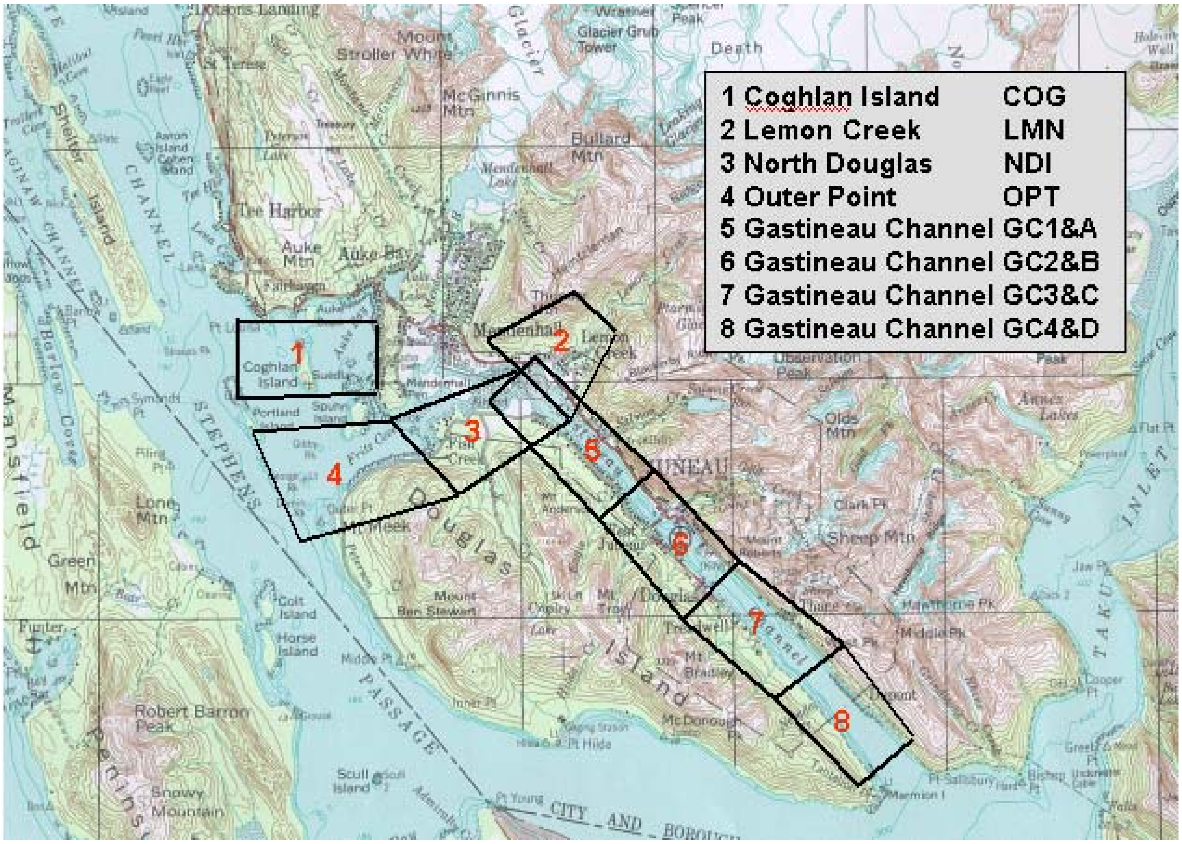

Figure 5. Plan view of the Juneau Airport region with indications of the hazard boxes.

	SE	TK	Neither
COG	379	112	34
GC1	152	95	30
GC2	56	58	0
GC3	57	56	0
GC4	57	59	0
GCA	80	157	0
GCB	187	198	28
GCC	106	66	0
GCD	104	66	0
LMN	104	29	0
NDI	230	67	30
OPT	151	54	27

Table 1. Counts of the penetrations of hazard boxes, by wind regime.

		Southeast			Taku		
GC1	**96/95**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		1.00	0.00	0.00	**0.99**	**0.01**	**0.00**
HW loss	**0.5 Km**	1.00	0.00	0.00	**0.96**	**0.04**	**0.00**
HW gain	**0.5 Km**	1.00	0.00	0.00	**1.00**	**0.00**	**0.00**
XS	**0.5 Km**	0.97	0.03	0.00	**0.85**	**0.12**	**0.03**
TS	**0.5 Km**	0.95	0.05	0.00	**0.77**	**0.15**	**0.08**
GC2	**48/58**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		1.00	0.00	0.00	**0.60**	**0.38**	**0.02**
HW loss	**0.5 Km**	1.00	0.00	0.00	**0.83**	**0.17**	**0.00**
HW gain	**0.5 Km**	1.00	0.00	0.00	**0.76**	**0.24**	**0.00**
XS	**0.5 Km**	1.00	0.00	0.00	**0.36**	**0.28**	**0.36**
TS	**0.5 Km**	0.98	0.02	0.00	**0.31**	**0.19**	**0.50**
GC3	**49/56**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		1.00	0.00	0.00	**0.59**	**0.34**	**0.07**
HW loss	**0.5 Km**	1.00	0.00	0.00	**0.88**	**0.13**	**0.00**
HW gain	**0.5 Km**	1.00	0.00	0.00	**0.84**	**0.16**	**0.00**
XS	**0.5 Km**	1.00	0.00	0.00	**0.14**	**0.43**	**0.43**
TS	**0.5 Km**	1.00	0.00	0.00	**0.11**	**0.23**	**0.66**
GC4	**49/59**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		**1.00**	**0.00**	**0.00**	**0.69**	**0.31**	**0.00**
HW loss	**0.5 Km**	**1.00**	**0.00**	**0.00**	**0.88**	**0.12**	**0.00**
HW gain	**0.5 Km**	**1.00**	**0.00**	**0.00**	**0.97**	**0.03**	**0.00**
XS	**0.5 Km**	**0.92**	**0.08**	**0.00**	**0.47**	**0.22**	**0.31**
TS	**0.5 Km**	**0.80**	**0.20**	**0.00**	**0.32**	**0.29**	**0.39**
GCA	**33/132**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		**1.00**	**0.00**	**0.00**	**1.00**	**0.00**	**0.00**
HW loss	**0.5 Km**	**1.00**	**0.00**	**0.00**	**1.00**	**0.00**	**0.00**
HW gain	**0.5 Km**	**1.00**	**0.00**	**0.00**	**1.00**	**0.00**	**0.00**
XS	**0.5 Km**	**0.88**	**0.12**	**0.00**	**0.92**	**0.08**	**0.00**
TS	**0.5 Km**	**0.85**	**0.09**	**0.06**	**0.86**	**0.14**	**0.01**
GCB	**79/198**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		**1.00**	**0.00**	**0.00**	**0.86**	**0.13**	**0.01**
HW loss	**0.5 Km**	**1.00**	**0.00**	**0.00**	**0.96**	**0.04**	**0.01**
HW gain	**0.5 Km**	**1.00**	**0.00**	**0.00**	**0.92**	**0.08**	**0.00**
XS	**0.5 Km**	**0.86**	**0.14**	**0.00**	**0.62**	**0.22**	**0.17**
TS	**0.5 Km**	**0.77**	**0.23**	**0.00**	**0.46**	**0.27**	**0.27**
GCC	**52/66**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		**0.96**	**0.02**	**0.02**	**0.73**	**0.27**	**0.00**
HW loss	**0.5 Km**	**1.00**	**0.00**	**0.00**	**0.94**	**0.06**	**0.00**
HW gain	**0.5 Km**	**1.00**	**0.00**	**0.00**	**0.94**	**0.06**	**0.00**
XS	**0.5 Km**	**0.90**	**0.10**	**0.00**	**0.17**	**0.47**	**0.36**
TS	**0.5 Km**	**0.73**	**0.27**	**0.00**	**0.11**	**0.30**	**0.59**
GCD	**50/66**	**Light**	**Mod.**	**Severe**	**Light**	**Mod.**	**Severe**
EDR		**0.96**	**0.04**	**0.00**	**0.86**	**0.12**	**0.02**
HW loss	**0.5 Km**	**0.98**	**0.02**	**0.00**	**0.91**	**0.09**	**0.00**
HW gain	**0.5 Km**	**0.98**	**0.02**	**0.00**	**0.94**	**0.06**	**0.00**
XS	**0.5 Km**	**0.82**	**0.16**	**0.02**	**0.52**	**0.38**	**0.11**
TS	**0.5 Km**	**0.74**	**0.22**	**0.04**	**0.26**	**0.44**	**0.30**

Table 2. Hazard Encounter Probabilities for the Gastineau Channel.

		Southeast			Taku		
LMN	104/25	Light	Mod.	Severe	Light	Mod.	Severe
EDR		0.71	0.24	0.05	0.96	0.04	0.00
HW loss	0.5 Km	0.79	0.15	0.06	0.96	0.04	0.00
HW gain	0.5 Km	0.73	0.21	0.06	1.00	0.00	0.00
XS	0.5 Km	0.42	0.37	0.21	0.76	0.20	0.04
TS	0.5 Km	0.23	0.37	0.40	0.64	0.28	0.08
NDI	230/59	Light	Mod.	Severe	Light	Mod.	Severe
EDR		0.92	0.07	0.00	1.00	0.00	0.00
HW loss	0.5 Km	0.97	0.03	0.00	1.00	0.00	0.00
HW gain	0.5 Km	0.96	0.04	0.00	1.00	0.00	0.00
XS	0.5 Km	0.70	0.24	0.06	1.00	0.00	0.00
TS	0.5 Km	0.54	0.33	0.13	0.95	0.05	0.00
OPT	151/45	Light	Mod.	Severe	Light	Mod.	Severe
EDR		0.80	0.19	0.01	1.00	0.00	0.00
HW loss	0.5 Km	0.99	0.01	0.00	1.00	0.00	0.00
HW gain	0.5 Km	0.95	0.05	0.01	1.00	0.00	0.00
XS	0.5 Km	0.76	0.21	0.03	1.00	0.00	0.00
TS	0.5 Km	0.45	0.45	0.10	1.00	0.00	0.00
COG	237/80	Light	Mod.	Severe	Light	Mod.	Severe
EDR		0.91	0.08	0.00	1.00	0.00	0.00
HW loss	0.5 Km	0.97	0.03	0.00	1.00	0.00	0.00
HW gain	0.5 Km	0.97	0.03	0.00	1.00	0.00	0.00
XS	0.5 Km	0.86	0.13	0.02	1.00	0.00	0.00
TS	0.5 Km	0.72	0.22	0.06	1.00	0.00	0.00

Table 3. Hazard Encounter Probabilities near Juneau Airport.

		Southeast	Taku
GC1	HW loss	NA	0.64
	HW gain	NA	0.73
	XS	NA	0.73
	TS	NA	0.76
GC2	HW loss	NA	0.65
	HW gain	NA	0.61
	XS	NA	0.69
	TS	NA	0.70
GC3	HW loss	NA	0.41
	HW gain	NA	0.56
	XS	NA	0.57
	TS	NA	0.61
GC4	HW loss	NA	0.57
	HW gain	NA	0.56
	XS	0.78	0.76
	TS	0.80	0.73
GCA	HW loss	NA	NA
	HW gain	NA	NA
	XS	0.84	NA
	TS	0.82	NA
GCB	HW loss	NA	0.61
	HW gain	NA	0.66
	XS	0.66	0.66
	TS	0.70	0.70
GCC	HW loss	NA	0.50
	HW gain	NA	0.35
	XS	0.75	0.59
	TS	0.76	0.65
GCD	HW loss	0.64	0.50
	HW gain	NA	0.37
	XS	0.83	0.70
	TS	0.84	0.66
LMN	HW loss	0.73	0.81
	HW gain	0.66	0.64
	XS	0.57	0.71
	TS	0.69	0.82
NDI	HW loss	0.66	NA
	HW gain	0.53	NA
	XS	0.69	NA
	TS	0.73	NA
OPT	HW loss	0.61	NA
	HW gain	0.70	NA
	XS	0.71	NA
	TS	0.77	NA
COG	HW loss	0.79	NA
	HW gain	0.84	NA
	XS	0.81	NA
	TS	0.85	NA

Table 4. Correlations of Wind Shear and Turbulence intensities.

		POD	FAR	PSS
GC2 TK	Edr	0.78	0.15	0.70
	HS	0.80	0.10	0.88
	XS	0.95	0.15	0.66
	TS	0.98	0.15	0.59
GC3 TK	Edr	0.82	0.21	0.68
	HS	0.29	0.00	0.29
	XS	1.00	0.04	0.75
	TS	0.98	0.02	0.81
GC4 TK	Edr	0.72	0.13	0.67
	HS	0.28	0.50	0.25
	XS	0.84	0.13	0.70
	TS	0.85	0.11	0.64
GCB TK	Edr	0.32	0.57	0.29
	HS	0.50	0.20	0.50
	XS	0.66	0.29	0.50
	TS	0.77	0.26	0.45
GCC TK	Edr	0.67	0.08	0.65
	HS	NA	NA	NA
	XS	0.84	0.36	0.40
	TS	0.98	0.11	0.28
LMN SE	Edr	0.87	0.32	0.71
	HS	0.63	0.22	0.59
	XS	0.85	0.18	0.60
	TS	0.98	0.09	0.65
NDI SE	Edr	0.50	0.10	0.50
	HS	NA	NA	NA
	XS	0.50	0.23	0.44
	TS	0.83	0.19	0.66
OPT SE	Edr	0.50	0.35	0.43
	HS	NA	NA	NA
	XS	0.56	0.31	0.48
	TS	0.75	0.17	0.56
COG SE	Edr	0.48	0.33	0.45
	HS	0.50	0.40	0.49
	XS	0.56	0.24	0.53
	TS	0.71	0.25	0.62

Table 5. Skill Statistics for the statistical predictions of wind shear and turbulence.