THE JUNEAU TERRAIN-INDUCED TURBULENCE ALERT SYSTEM

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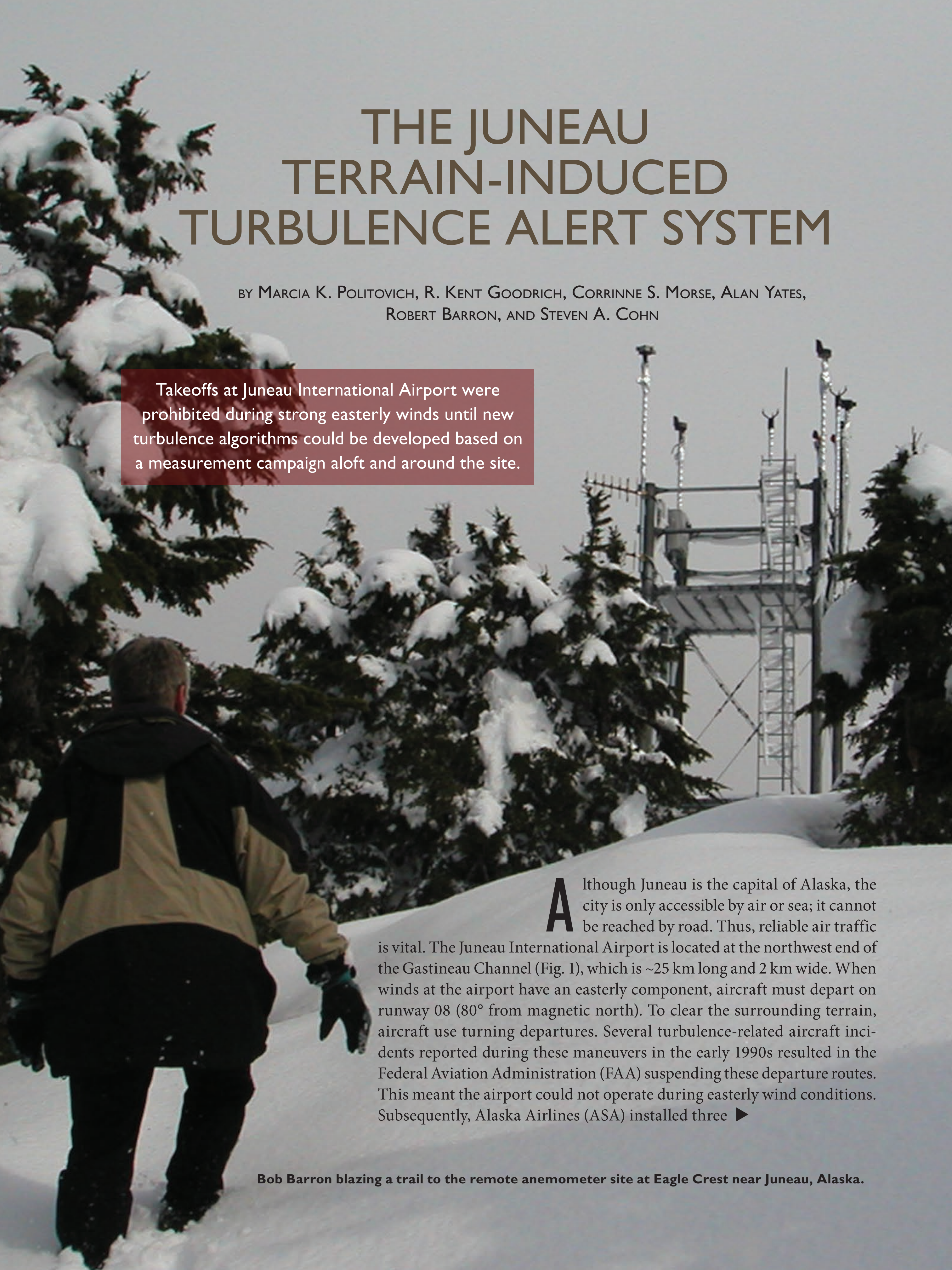
Takeoffs at Juneau International Airport were prohibited during strong easterly winds until new turbulence algorithms could be developed based on a measurement campaign aloft and around the site.

Although Juneau is the capital of Alaska, the city is only accessible by air or sea; it cannot be reached by road. Thus, reliable air traffic is vital. The Juneau International Airport is located at the northwest end of the Gastineau Channel (Fig. 1), which is ~25 km long and 2 km wide. When winds at the airport have an easterly component, aircraft must depart on runway 08 (80° from magnetic north). To clear the surrounding terrain, aircraft use turning departures. Several turbulence-related aircraft incidents reported during these maneuvers in the early 1990s resulted in the Federal Aviation Administration (FAA) suspending these departure routes. This meant the airport could not operate during easterly wind conditions. Subsequently, Alaska Airlines (ASA) installed three ▶



Bob Barron blazing a trail to the remote anemometer site at Eagle Crest near Juneau, Alaska.

mountaintop anemometers around Juneau to provide better wind information to their pilots. ASA and the FAA agreed on an operations specification (Ops Spec), based on the winds measured by these instruments, to reinstate these frequently needed departures. Congress and the FAA desired a more permanent solution, so the FAA sought the help of the National Center for Atmospheric Research (NCAR) to determine the feasibility of developing and implementing a wind hazard warning system. After determining that such a warning system was feasible, NCAR was contracted to develop the algorithms and a prototype implementation of those algorithms. This prototype system, the Juneau Airport Wind System (JAWS), underwent a series of operational evaluations and upgrades, with the result being that it will be implemented as a fully operational turbulence warning system in February 2012.

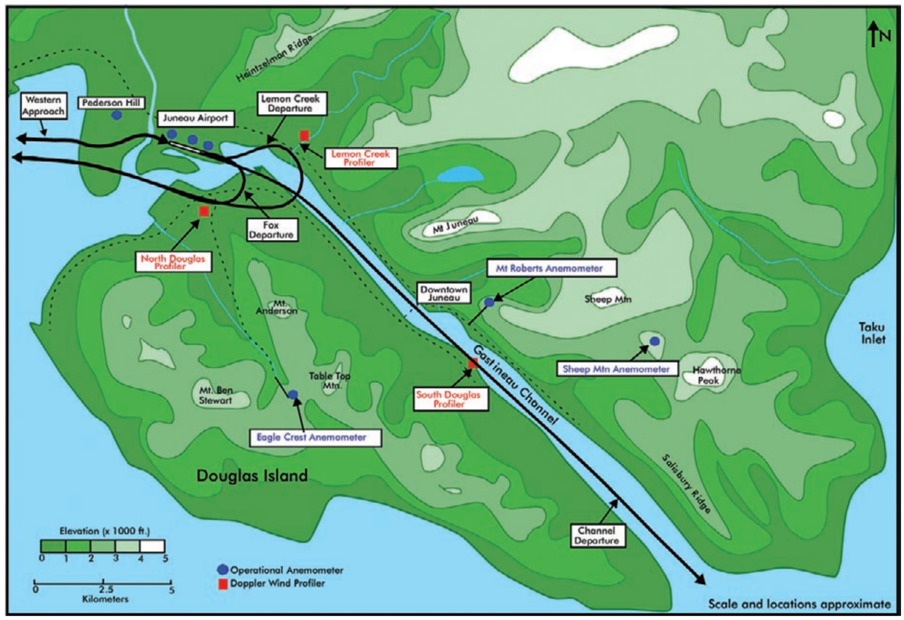


Fig. 1. Map of Juneau airport vicinity, with major geographic features, departure routes, and project instruments.

PRACTICAL CONSIDERATIONS. *Impacts of location.* Juneau is located on the coast of southeast Alaska. On Juneau's landward side, the coastal mountain range influences weather, with nearby peaks rising steeply from sea level to more than 1 km (Fig. 2). On the Gulf of Alaska side are the islands of the Alexander Archipelago. Local weather is strongly influenced by flows from both sides—moist maritime air masses of strong low pressure systems from the Gulf of Alaska and cold, dry continental air masses from interior Canada (Colman 1986). The synoptic patterns and mesoscale systems interact with local terrain to generate strong and complex local flows. These include drainage flows through the many local passes and valleys, "Taku" flow (the local name for amplified mountain wave events), and strong gap flow through the Gastineau and other local channels (Dierking 1998; Colman and Dierking 1992). When sufficiently strong, these flows create turbulence and wind shears that are hazardous to aircraft, especially during takeoff and landing maneuvers. More detail on these and other observations around Juneau are presented by Cohn (2004).

Hong Kong: A predecessor. At the beginning of the Juneau effort, NCAR was nearing completion of an operational turbulence and wind shear warning system for the new Chek Lap Kok Airport in Hong Kong, China. The high probability of significant turbulence and wind shear at this airport during certain meteorological conditions prompted the Hong Kong government to fund research and development toward a turbulence warning system. The final system, which became operational on the opening day of the new airport, includes sensors for real-time turbulence

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and wind shear detection and warning, as well as the communications and display systems. Sensors include automated weather stations and a 5-cm terminal Doppler weather radar for wind shear warnings. Turbulence and wind shear warnings are created by combining wind speed, direction, and variability information from anemometers placed near the airport and on nearby mountaintops. The similarity of the problem—terrain-induced turbulence—and the implementation of the sensor-based solution for Chek Lap Kok suggested that a similar system could be designed and deployed at Juneau.

RESEARCH AND ALGORITHM ENGINEERING CONSIDERATIONS. JAWS development was a multidisciplinary effort with hardware engineering to place instruments in remote locations, statistical analyses to develop and validate the warning algorithm, software engineering to develop a robust and redundant result, and scientific and meteorological guidance to insure validity of the data. In this section we describe the scientific considerations that guided the development process.

The need to understand where and when aircraft may encounter strong turbulence. Prior to the project's field efforts, the locations and weather conditions associated with turbulence were known only from a few documented encounters and a large body of anecdotes from local pilots. The first task for meteorologists was to understand the local flows and how they interact with terrain to generate strong turbulence. Two strong flow regimes dominate the Juneau weather (Colman and Dierking 1992; Cohn 2004). Taku flow, as it is locally known, is a mountain wave or mountain gap flow over the mountains and Taku Glacier northeast (inland) of Juneau (Fig. 1). Mountain waves can create turbulence throughout the Gastineau Channel. Mountain gap flow—cold air descending the creek drainages on the northeast side of the channel—generates turbulence where the drainage flow encounters wind from a different direction within the channel. Thus, the locations of turbulence during gap flows are well correlated with specific local creek drainages. For algorithm development, Taku and gap flows were combined into a single category, referred to here as "Taku."

Southeast flow is generated within the Gastineau Channel by pressure gradient forcing driven by a strong channel-aligned pressure gradient. Turbulence in this regime is found downwind of obstacles, such as the ridges on Douglas Island and in the Lemon Creek drainage from flow around and over the surrounding ridgelines (Fig. 1). Shear-generated turbulence can also be found near ridge height as southeasterly flow within the Gastineau Channel merges with the predominantly southwest flow above.

A calm regime is defined by a fuzzy logic algorithm that incorporates the wind speed and direction from the mountaintop anemometers and selected height regimes from the wind profilers, but it is generally correlated with wind speed <5 m s^{-1} at the mountaintop anemometers. For this regime, no warnings are issued.

Throughout the year, Taku flow occurs ~16% of the time, southeast flow ~36%, with the remainder classified as calm (Fig. 3). Calm events occur more frequently during the summer months. There is some year-to-year variation (Fig. 4) but the overall seasonal trends are fairly consistent. How these regimes are incorporated into algorithm development is described in the "Turbulence alert model development" section.

Fig. 2. View looking approximately east, with Juneau airport in the foreground and the Gastineau Channel in the background. Mountaintop anemometers include Eaglecrest peak and ski area to the right (south) of the channel, Mt. Roberts and Sheep Mountain to the left (north). Note the drainage wind "bands" visible on the channel surface matching gaps in the topography to the left. (Photo: John "Jack" Hermle.)

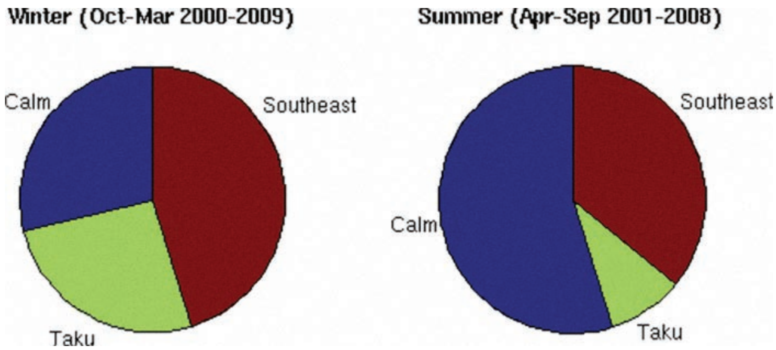


Fig. 3. Distribution of wind regimes for Juneau in (left) winter and (right) summer.

Use of eddy dissipation rate as a turbulence metric. Eddy (or energy) dissipation rate ε (m^2 s^{-3}) is a well-established objective measure used in the atmospheric science community to quantify turbulence intensity. This value is an atmospheric metric that is independent of an aircraft measurement platform, and its cube root $\varepsilon^{1/3}$ is the International Civil Aviation Organization standard (ICAO 2007). In the development of the warning system, methods were used to estimate ε from high-rate wind measurements collected during the winter experimental field seasons. However, different aircraft respond differently to atmospheric turbulence, with the main discriminator being the weight of the aircraft. The FAA wanted the system to warn for moderate or severe turbulence specific to aircraft type, that is, the turbulence intensity those aircraft would actually experience given certain conditions. Thus, the ε-based warnings needed to be translated to word descriptions of turbulence intensity (e.g., "moderate" or "severe"). This process is described in "Turbulence alert model development."

The importance of sensor type, sensor location, and hazard areas. The warning system produces turbulence estimates in "hazard boxes" identified along the primary flight paths to and from the airport. These real-time warnings are based on measurements from a network of anemometers and radar wind profilers around Juneau. Scientific guidance was needed to choose the locations, and especially boundaries, of these boxes, as well as the sensor types and placement. For example, the intersections of creek drainages with the Gastineau Channel are common locations of strong turbulence during southeast flow. If a hazard box boundary were chosen to be near such an intersection, small changes in wind direction could move the turbulent region between boxes. In that case, in situ data used to develop and test the algorithm would be split between these two boxes, making an accurate calculation difficult.

An understanding of the strengths and limitations of specific sensors was an important technical contribution. For example, in almost any location, terrain may block or distort flow from some directions. Sensor locations must minimize this from directions where accurate flow was most needed. In addition, instrument-specific requirements, such as the need to shield wind profiler antennas from ground clutter, were considered. Ultimately, locations were chosen as a compromise between scientifically desirable sites, for example, placing an anemometer at the top of the tallest peak for unobstructed fetch, and at logistically desirable sites where access, power, and communications were available.

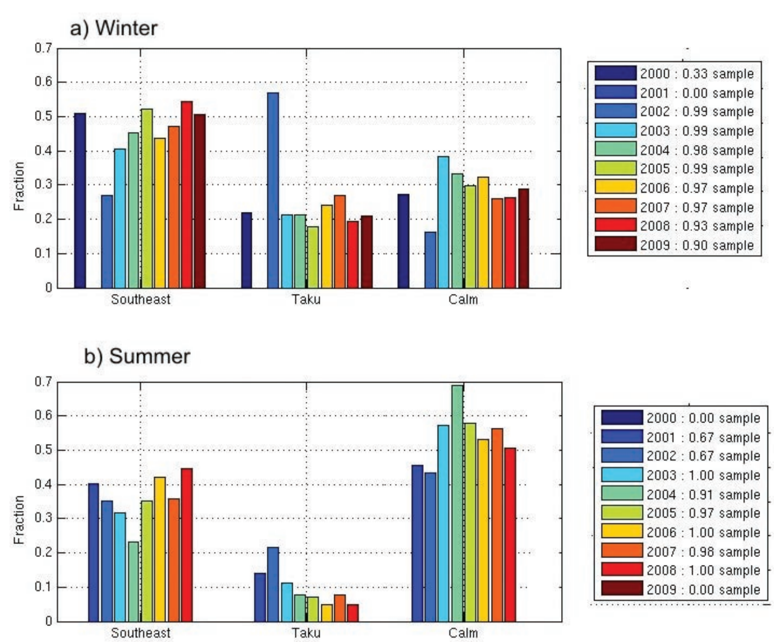


Fig. 4. Year-by-year wind regime statistics for Juneau for (a) winter (Oct–Mar) and (b) summer (Apr–Sep). Key is on the right and shows the fraction of data available each year.

SENSORS AND DATA QUALITY CONTROL. For the system to provide accurate warnings, the data upon which the algorithms are based must be of high quality. JAWS was constructed using measurements from three sources: wind profilers, anemometers, and instrumented aircraft. The aircraft measurements were collected over two field programs conducted in winter 1999/2000 and 2002/03. Estimates of turbulence intensity were computed from the aircraft high-rate wind measurements, and regression models were constructed to correlate the observed turbulence intensity from regressors derived from the profiler and anemometer measurements. In the real-time systems, these regressors are used to infer the location and intensity of turbulence an aircraft is likely to encounter.

Fig. 5. The South Douglas wind profiler.

Wind profiler data. Three 915-MHz radar wind profilers (Vaisala LAP-3000 with optional extended antenna aperture; see Fig. 5) are deployed in and around Juneau for JAWS (Fig. 1). The warning system application presented several challenges for standard wind profiler signal processing. Rather than the long time-averaging intervals typically used for profiler winds (30–60 min for consensus winds), a rapid-update estimate of winds and other profiler-derived regressors is required (for our case, every 30 s). Also, data quality problems are more severe than is typical because of the nearby mountains and water and the close collocation of the three instruments. In addition to the desired atmospheric signals, Doppler spectra routinely contain point targets, radio frequency interference (RFI), and ground clutter, which may interfere with atmospheric measurements as high as 1 km because of the mountainous terrain near the profilers. An accurate estimate for the atmospheric radial velocity is needed to estimate the wind. Peak-finding algorithms [such as the Profiler Online Program (POP) Carter et al. (1995)] may instead select a point target, RFI, or ground clutter as the first moment. This is especially harmful to rapid-update wind algorithms when a consensus algorithm cannot be used to identify these outliers. These limitations of wind profiler signal processing were noted in the Hong Kong project and motivated development of the NCAR Improved Moments Algorithm (NIMA; Morse et al. 2002).

NIMA, based on fuzzy logic image processing techniques, selects the atmospheric signal while rejecting nonatmospheric contributions. In addition to estimating first and second moments, NIMA also assigns a confidence value to these moments. While several factors go into the calculation of this confidence value, one of the factors given high weight is the signal-to-noise ratio. It was shown in Cohn et al. (2001) that the NIMA confidence algorithm may be used to remove most outliers in profiler data from Juneau. This was shown by using data from a large study in which human experts classified the data as outliers, such as point targets and RFI, and the results were compared to those produced by NIMA.

The moment and confidence values produced by NIMA are used to compute the horizontal winds and their confidence values using the NCAR Winds and Confidence Algorithm (NWCA; Goodrich et al. 2002). The confidence value for the horizontal winds is based on the confidence in the first moments from NIMA as well as several statistical tests of the data that check the assumptions made when computing a horizontal wind. Two such assumptions are that the flow was constant or changed slowly over the past few minutes and that the winds were approximately linear over the measurement volume. When constructing the JAWS regressions, an additional check was made by comparing the NWCA-processed winds to those measured by research aircraft in level flight near the North Douglas profiler. The square of the sample correlation coefficient between aircraft and NWCA winds was 0.86.

Fig. 6. The Sheep Mountain anemometer station.

These results demonstrated that the NIMA and NWCA have skill in removing outliers and suspect data and provide accurate wind measurements. Thus, it is possible to provide useful rapid-update (30 s) winds in the challenging environment found near Juneau. These wind products may then be confidently applied to further analyses and used in the regressions estimating turbulence intensity.

Anemometer data. As with the wind profilers, a network of anemometers was deployed around Juneau to support both the creation of the regressions and the operation of the real-time JAWS (Fig. 1). This network has some sites on top of mountain peaks and others near sea level. The harsh winter environment also presents challenges for these anemometers; structural icing of anemometers is a major problem (Fig. 6). For this reason the mountaintop anemometers, Taylor Scientific Engineering model WS3 and WD3 sensor heads, are supplied with enough power (1500 W) to remain uniced in most conditions. However, in the most severe icing conditions, several feet of rime ice may accrete on or upwind of the instrument. This can cause erroneous readings, for example, if the anemometer head continues to spin while the direction vane is frozen. For this reason, and in case of mechanical or electrical failures, each mountaintop location has two anemometers within several meters of each other. Measurements from the instruments are compared (continuously and automatically for the real-time system), and wind estimates are computed using a confidence-weighted algorithm combining the measurements from both anemometers when available. In this algorithm each measurement is multiplied by its confidence, and then these products are summed and divided by the sum of the confidence values. It was shown in Weekley et al. (2004, 2010) that despite many issues with the anemometers (spinning anemometer heads, frozen anemometers, and electronic problems) the algorithm showed skill in selecting the best data from the two collocated anemometers at the mountain tops.

Aircraft data. The University of Wyoming King Air 200T and an Alaska Airlines Boeing 737–200 (B737, Fig. 7) collected measurements to characterize airflow and the strength and location of turbulence in the Juneau area. The King Air is a specially equipped atmospheric research aircraft with high-quality wind sensors. The Alaska Airlines B737 carried a data recorder that obtained information from the inertial navigation system (INS) to measure winds from which turbulence estimates could be calculated. The advantage of this aircraft is that it was certified to operate in the Gastineau Channel during periods of low ceiling and visibility—conditions that are typical of southeast flow—and it is the same aircraft type flown commercially into the Juneau airport. The data sampling rate for the King Air INS measurements was 25 Hz; for the B737, the data rates varied from 1 to 8 Hz. The pilots also recorded their interpretations of turbulence levels (light, moderate, and so on) for comparison with the aircraft and warning system–derived values.

The King Air participated alone in the 1999/2000 field season and collected 74 h of data (Gilbert et al. 2004) between December and March. Preplanned flight tracks were followed, including standard approach and departure patterns, a series of constant altitude stacks up and down the Gastineau Channel incremented by 500 ft, and a constant altitude racetrack pattern around the airport basin, again incremented by 500 ft. The follow-on field season took place in winter 2002/03, during which the King Air

(119 h) was supplemented by the B737 (56 h). More details on the field efforts are described in Cohn et al. (2004).

Creating dependable estimates of wind and eddy dissipation rate from the aircraft measurements was critical to JAWS. The quality control of these data and derived products proved one of the greatest challenges to the project. Research aircraft can produce reliable wind estimates when in level and straight flight at constant altitude (Cornman et al. 1995). In Juneau, the aircraft were required to make sharp turns in the Lemon Creek and Fox departure routes (Fig. 1), which made estimating wind, and subsequently ε, difficult. To ensure only high-quality data were used to create the JAWS regressions, the aircraft data were first inspected using a standard outlier detection algorithm [least squares adaptive polynomial (LSAP); see Abraham and Ledolter (1983)] followed by close examination by a human analyst. Outliers in the aircraft data were removed. The ε estimates were calculated from a sliding window of 256 data points, overlapping by 25 points (1 s). For each window, a power spectrum was constructed from which an ε estimate (calculated and expressed as $\varepsilon^{1/3}$) was obtained. This was derived using a single parameter maximum likelihood model, assuming a 5/3 Kolmogorov power spectrum form (Smalikho 1997; Cornman et al. 1995).

The 1-s estimates of $\varepsilon^{1/3}$ calculated from the aircraft data were used to assign a single representative turbulence intensity value to each hazard box encountered along the flight path. A three-point (equivalent to 3 s) median filter was applied to the data, and the maximum $\varepsilon^{1/3}$ for the hazard box (defined in section 5) was selected to represent the turbulence intensity for that hazard box at the midtime of the aircraft transect. The median filter was applied to eliminate potentially unreasonable values remaining even after precautions were taken for data quality control. This combination of a median filter and selection of the maximum value was believed to provide a reasonable estimate of the highest turbulence expected in the hazard box during the aircraft transect.

Cornman et al. (1995) demonstrated that standard deviations in vertical acceleration (σ_W') are proportional to $\varepsilon^{1/3}$. The proportionality constant depends on the particular aircraft response function, the airspeed and weight of the aircraft, and flight conditions, such as altitude and Mach number. A comparison of median values of $\varepsilon^{1/3}$ with σ_W', over a 1-min window from a research aircraft, yielded a value of r^2 (the square of the correlation coefficient) of 0.94. This justified the numerous mathematical assumptions used in the calculation of $\varepsilon^{1/3}$. When the 19th percentile 1-min values were compared, r^2 was slightly reduced to 0.86; thus, there is some dependence on the manner in which the turbulence estimates are obtained. For the JAWS field dataset, the r^2 value using the maximum three-point medians of $\varepsilon^{1/3}$ and σ_W' in a given hazard box was 0.85 for the King Air aircraft and 0.71 for the B737. Thus, the King Air result is in good agreement with the Cornman et al. (1995) results, which is reassuring, given the complexity of the terrain (and subsequent effect on airflow) and the numerous flight maneuvers conducted by the King Air. However, the B737 result is lower than that reported in Cornman et al. (1995), where for a similar aircraft the r^2 value was 0.96. For some time, this poor result discouraged the use of B737 data in the regression database.

While the King Air dataset covered two field seasons and was larger than that of the B737, the B737 conducted flights in wind conditions that the King Air did not sample. Thus, it was considered desirable to combine the datasets to develop the JAWS warning algorithm. A calibration methodology that took advantage of the relation between $\varepsilon^{1/3}$ and σ_W' was devised to enable the combination of the datasets. Best-fit linear relations were found between σ_W' and $\varepsilon^{1/3}$ for each aircraft. Thus, given an aircraft type (King Air or B737) and a value of σ_W', one could apply the best linear fit for that aircraft and arrive at a new estimate of turbulence called $\varepsilon^{1/3}_{VAS}$, which is the $\varepsilon^{1/3}$ estimate based on σ_W' [or vertical acceleration sigma (VAS)]. These values should be highly correlated with the wind-based estimates of $\varepsilon^{1/3}$. To remove remaining outliers in the wind-based turbulence estimates, dif-

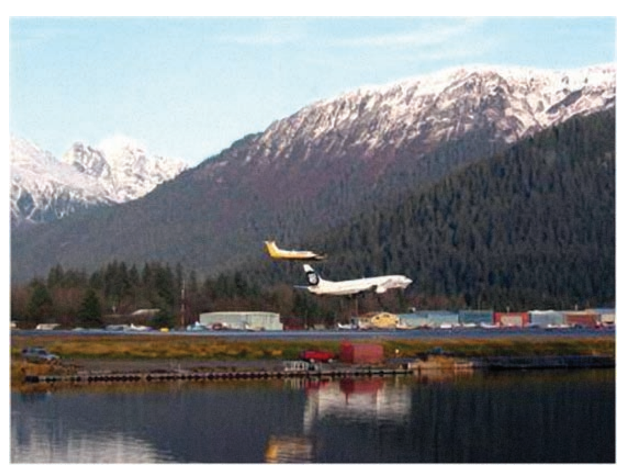


Fig. 7. The Wyoming King Air and Alaska Airlines B737.

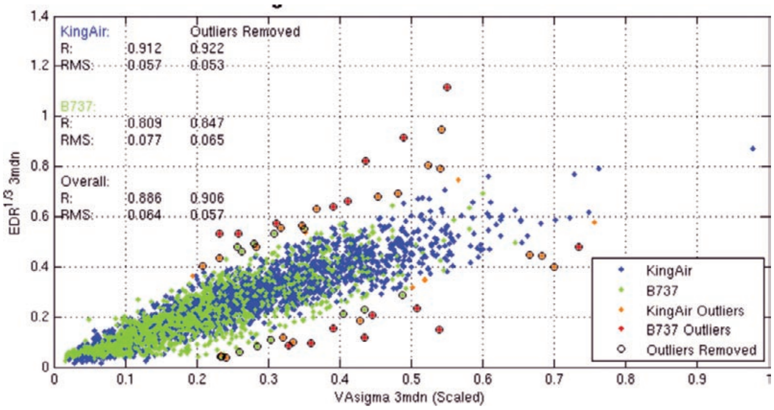


Fig. 8. Scatterplot of σ_w versus $\varepsilon^{1/3}$ for the King Air and B737.

ferences between $\varepsilon^{1/3}$ and $\varepsilon^{1/3}_{VAS}$ were used. The sample standard deviation of these differences was found, and if the absolute value of a difference was more than three standard deviations from the mean of that distribution, the corresponding value of the wind-based $\varepsilon^{1/3}$ was removed from the regression database. A scatterplot of $\varepsilon^{1/3}_{VAS}$ and $\varepsilon^{1/3}$ is shown in Fig. 8 with the outliers identified.

This new combined database of King Air and B737 data was larger than that provided by just the King Air by 61%, and the number of moderate turbulence cases was doubled. The final correlation coefficient of 0.80 is lower than from the Cornman et al. (1995) study. Considering the highly variable, terrain-influenced winds, the maneuvers of the aircraft, and the poorer quality of the B737 data, this correlation was still high enough to give us confidence that our turbulence estimates were valid.

TURBULENCE ALERT MODEL DEVELOPMENT. During the development of a turbulence analysis product for the Hong Kong Airport, multilinear regression models based on surface wind measurements were shown to have skill for diagnosing the intensity of turbulence that an airplane can be expected to encounter (Neilley and Keller 1995). Building on this result, the JAWS turbulence product development was also based on multilinear regression. Two extensions to the previous approach were considered: wind profilers to provide wind measurements at multiple altitudes and ensembles of regression models to generate the system alerts. Based on experience from the field programs and a scientific understanding of the causes of turbulence in the approaches to Juneau airport, it was decided to generate turbulence models for two wind regimes (Taku and southeast) and 11 hazard boxes near the Juneau airport (Fig. 9).

Selection of regressors and training. The JAWS multilinear regression models were trained against response $\varepsilon^{1/3}$ values derived from aircraft turbulence data collected during the field programs. The regressors were derived from wind data obtained from the anemometers and wind profilers. Twenty-five sensing locations are available in the system: three profiler sites, with six altitudes at each site (in 300-m height intervals averaged from the native 60-m wind profiler resolution from 300 to 2,100 m MSL); and seven anemometer sites. The regressors include overall and component wind speeds at 10° increments (wind direction was not explicitly used), wind speed and direction standard deviations, wind profiler estimates of turbulence, and vertical shear of the horizontal wind vector. Temporal averages of each regressor for the preceding 3, 6, 9, 12, and 15 min were also considered, but multiple time averages of the same regressor were not used. This provided a large set of potential regressors compared with the number of training cases, so the model selection problem was challenging.

The only way to be certain that the best model is achieved involves the generation of all possible models from the available regressors (Miller 1990), which presents an overwhelming combinatorial explosion of possibilities. Most practitioners impose constraints on the list of regressors to improve the efficiency of the model selection process, with the possibility of missing the best model. For JAWS, meteorologists examined the regressor list and eliminated those thought physically implausible for the generation of significant turbulence at any particular hazard location. Once the regressors were culled, model coefficients were determined using the singular value decomposition algorithm, the most numerically stable process for model training (Golub and Reinsch 1970; Golub and Van Loan 1996).

Additional constraints were imposed on the regressors to eliminate near redundancies and low-skill items from the regressor list while retaining a sufficient diversity of predictors to capture a substantial portion of the potential skill in the sensing system. The r^2 between the regression model calculations and observations represents the percentage of the variation in the observations explained by the model (Fisher 1925). When applied to a single regressor, r^2 provides a measure of the potential skill of that regressor. Only regressors with $r^2 > 0.1$ were considered. Forward selection (as in John et al. 1994) was used to create the candidate lists of regressors used in the selection process. This involves the successive addition of regressors based on their having a high single-regressor r^2 and low correlations with other regressors in the model (since two highly correlated regressors provide similar information). A preference for choosing regressors from different sites was also enforced, because these are more likely to contain independent information.

In a real-time operational setting, there is a possibility that some sensors may fail to report valid data at any given analysis time. The final selection of models from the ranked list explicitly included regression models that would ensure coverage under a variety of sensor outage scenarios.

Ensemble $\varepsilon^{1/3}$ estimates are computed for each hazard prediction area, based on the existing wind regime and its list of acceptable regression models. Each ensemble $\varepsilon^{1/3}$ estimate is the r^2-weighted average of $\varepsilon^{1/3}$ estimates from the 10 models with the highest merit scores and having their required data available. When sensor outages reduced the number of available models to fewer than 10, the ensemble estimate is computed from the available model estimates. A strength of using such an ensemble method is that the system is very robust to data outages at a limited number of sites.

For departing part 121 (commercial air carrier) flights, the turbulence warnings generated by JAWS are transmitted orally by the airline operations staff to the pilot while the aircraft is at the end of the runway waiting for clearance to take off. Other operators, including general aviation pilots, can obtain this information from the FAA Automated Flight Service Station (AFSS) or from the Internet during the planning phases of their flights. From that point, through takeoff and travel through the appropriate departure route, several minutes can transpire until the aircraft transects the appropriate hazard area. Thus, time continuity to provide a stable warning system is appropriate. A balance among "flickering" (warnings changing abruptly, minute by minute), transient conditions (isolated incidents lasting only 1 min), and timeliness of the warning (not waiting more than several minutes to issue a warning) is needed. JAWS does this by applying a $m \times n$ filter function, where m instances of turbulence descriptor (moderate or severe) are required over the past n minutes to issue a warning. Similarly, to cease a warning, another $m \times n$ function may be applied—there may be some hysteresis in the system with different m and n selected for the onset and cessation of warnings. It was found that a 2×3 function worked well for both the initiation and cessation of warnings.

Turbulence thresholds. Although the algorithm produces a numerical $\varepsilon^{1/3}$ value, the operational system requires a verbal, categorical description that can be easily communicated to pilots. The terms *light*, *moderate*, *severe*, and *extreme* are in common use and have operational definitions in aviation (see Table 1). There is also some history of relating these descriptions to numerical turbulence values (MacCready 1964), but these are not universally accepted. Note that the operational definitions are aircraft and pilot based—a given turbulent state of the atmosphere has a greater effect on a small, light aircraft than a larger one. Pilot experience will likely influence any opinion by that

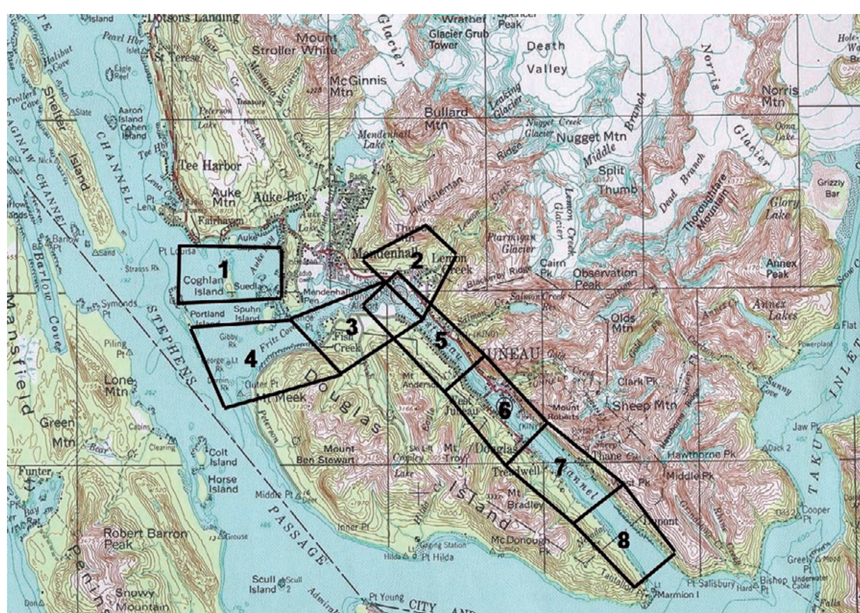


Fig. 9. Hazard boxes used for development of the JAWS algorithm. Note that the additional three hazard boxes are geographically coincident with boxes 5–7 shown above. Boxes 5–8 cover altitudes between the surface and 2,000 ft; boxes 9–11 cover altitudes 2,000–6,000 ft.

Table 1. Turbulence level descriptions and $\varepsilon^{1/3}$ values ($m^{-2/3}\ s^{-1}$).			
	Description	MacCready $\varepsilon^{1/3}$*	JAWS$\varepsilon^{1/3}$
Light	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Not used in JAWS.	0.028	N/A
Moderate	Turbulence that is similar to light turbulence but of greater intensity. Changes in altitude and/or attitude occur, but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed.	0.067	0.4 for B737
Severe	Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control.	0.161	0.55 for B737
Extreme	Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Not explicitly warned in JAWS.	0.379	N/A

*Originally reported as $cm^{2/3}\ s^{-1}$ (MacCready 1964).

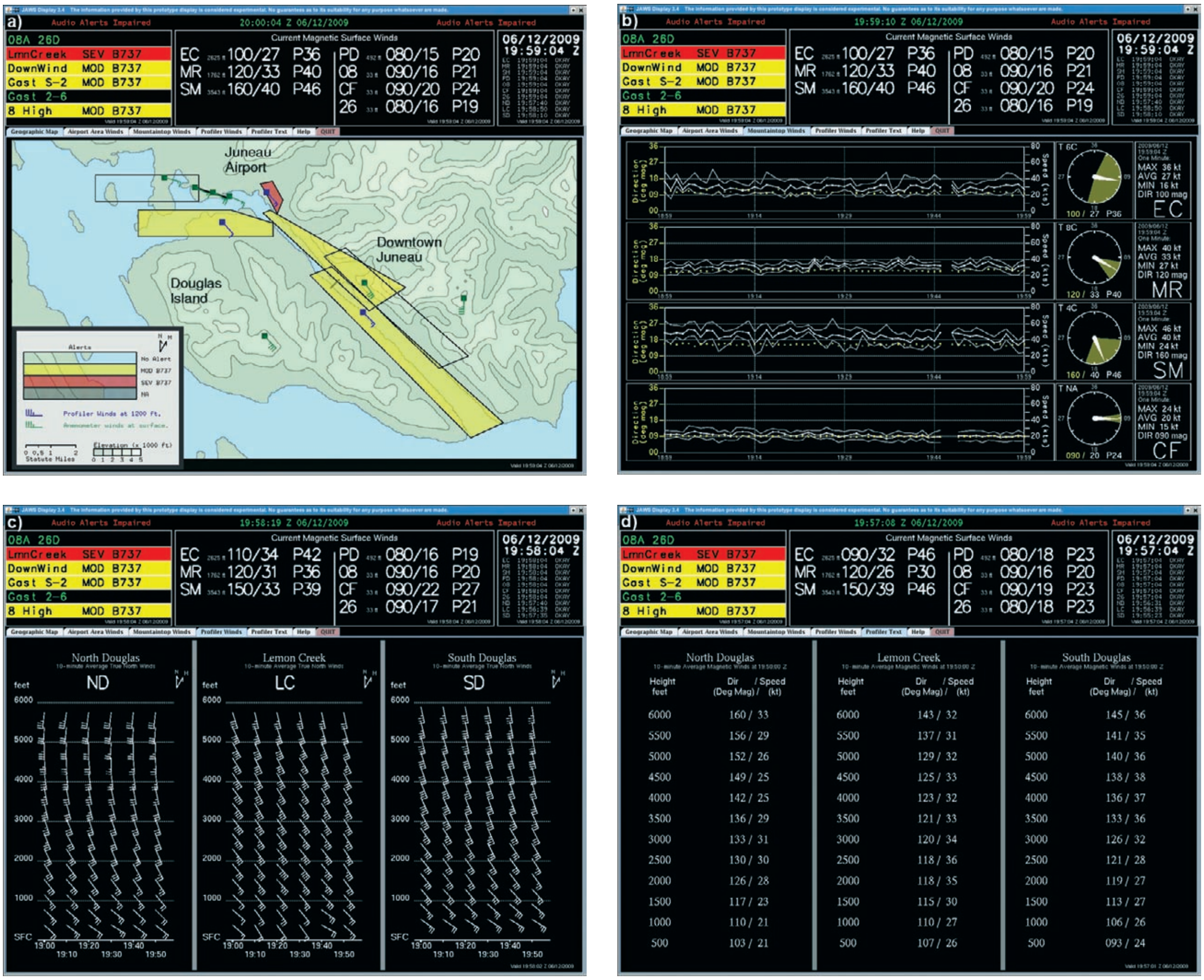
pilot of the magnitude of the turbulence. Thus, there is considerable "wiggle room" in any turbulence pilot report (PIREP). However, since pilots in airplanes are the final users of the system, their perception of the warned turbulence ought to weigh in on the final evaluation.

A consideration of the choice of thresholds for turbulence intensity definitions is the effect on safety and capacity. Selecting too high of a threshold results in missed detections and a tendency of the system to underreport hazardous turbulence conditions. Conversely, airport and flight operations may be needlessly restricted by a large number of false alarms, caused by setting the threshold too low. Alaska Airlines policy is to not take off or land if a severe B737 warning is issued; for other commercial operators and private pilots, such a decision is at their discretion; however, they are likely to cease operations during severe turbulence conditions. The algorithm and thresholds chosen should have a high level of safety (i.e., a high probability of detection) and a low number of false alarms. This can be done iteratively by selecting thresholds and then comparing resulting skill statistics so that the optimal algorithm performance is achieved. For JAWS, the thresholds were derived from inspection of the composite plots of the research aircraft $\varepsilon^{1/3}$ estimates and corresponding turbulence observations reported by pilots. The optimal thresholds were determined as 0.40 for moderate and 0.55 for severe B737 turbulence. These are lower than the ICAO standards to add a safety margin to the warning system.

THE OPERATIONAL SYSTEM. For the operational system, the FAA decided to combine the hazard boxes used for development and replace them with alert areas (shown as outlines in Fig. 10). These consisted of the Lemon Creek, Down Wind, Gastineau S-2 (surface to 2,000 ft MSL within the Gastineau Channel), Gastineau 2–6 (2,000–6,000 ft along the channel), and 8 high (a departure path from the airport through the channel to 8,000 ft). These alert areas correspond to segments of departure and/or arrival procedures considered particularly vulnerable to turbulence hazards. Two of the alert areas (08A and 26D) are geographically redundant because they are direction specific and refer to the outgoing complement of an incoming flight segment. In addition, two other alert areas (GC SFC-2 and GC 2–6) represent different altitude ranges over the same geographic area.

A key part of JAWS is the interface between the algorithms and the end users. JAWS generates a real-time display of turbulence warnings and also more detailed information to help users evaluate the current state of the atmosphere and note any anomalies in the warning system. The JAWS display is intended for use by pilots as one tool to assess flight conditions approaching and departing Juneau. The AFSS has dedicated displays used by briefing personnel. Alaska Airlines has a dedicated display for making operational go/no go decisions at Juneau. Display information provided via the Internet is used by Alaska Airlines' dispatch in Seattle for flight scheduling, as well as by other pilots for general flight planning in Juneau.

The display is a multipanel user interface updated every minute. The upper portion of the display (Figs. 10a–e) consists of a small time indicator above several time-stamped status panels that summarize alert status for JAWS alert areas, current surface winds, and system sensor status. The lower



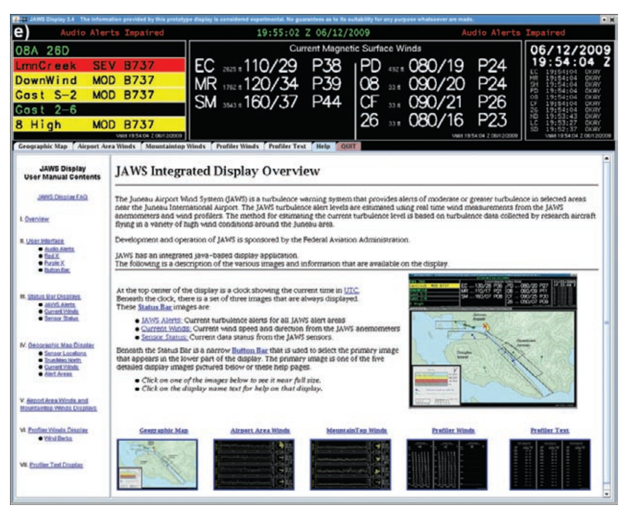


Fig. 10. (a) Geographic display, (b) anemometer wind history, (c) profiler winds history, (d) profiler text, and (e) help page.

(primary) panel is selected using a tab-type button panel. Selection of the appropriate tab displays the associated information. Six panels include a geographic display (Fig. 10a), airport anemometer wind history (Fig. 10b), profiler wind history as wind barbs (Fig. 10c), current profiler winds as numeric values (Fig. 10d), and user reference and help pages (Fig. 10e).

The geographic display depicts the current sensor data and JAWS alert area warnings on a topographic background. Fill colors and textures indicate the alert level (including unavailable information). Anemometer and 1,200-ft profiler winds are shown.

One-hour histories of anemometer winds are displayed in two panels: one panel shows winds at the airport and the other panel shows winds from the mountaintop sites. For each sensor location, the anemometer wind panels consist of three subpanels.

The largest subpanel is a record of the past hour of 1-min statistics summarizing wind speed and direction. Wind speeds are in knots, and wind direction is in degrees from magnetic north (the declination is ~30° at Juneau). Wind speed is displayed as an average bounded by the minimum and maximum values during the 1-min interval. Although wind plots are scaled to display the maximum value, for convenience of comparison, all anemometers on the same page are depicted using the same scale. The second subpanel represents a compass view summary of the most recent 1-min statistics on the wind data. The third subpanel displays a variety of information in numerical format, including date and UTC time; minimum, maximum, and average wind speed during the last 1-min period; and the average wind direction.

The profiler winds' history panel displays a 1-h time history, updated at 10-min intervals, of wind speed and direction for 15 levels of the three wind profilers. The wind profiler data here are the 10-min consensus values, for a quick glance by the user of wind trends at the displayed altitudes.

The profiler text panel displays the most recent 10-min-average winds as numeric values for convenient readout to pilots. Wind speed (kt) and direction (magnetic) are given for altitudes between 500 and 6,000 ft in 500-ft increments.

A help page includes a list of frequently asked questions and mouse-navigable set of explanatory pages.

JAWS SKILL. How well does JAWS work? There are several approaches to evaluating the performance of an operational system. One is to use the final algorithm in postanalysis to compare the JAWS-generated $\varepsilon^{1/3}$ values with aircraft estimates. Although there is some scatter of the values that will result in miscategorization of the warned turbulence intensity (Fig. 11), they are generally well correlated.

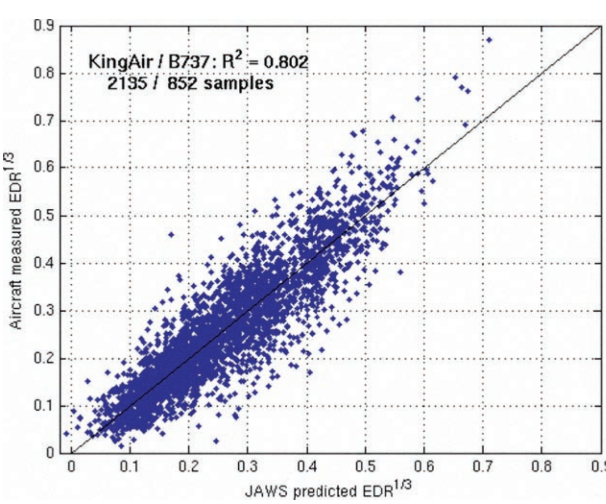


Fig. 11. Estimates of $\varepsilon^{1/3}$ from JAWS compared to measurements from the research aircraft.

In daily operations, the final user needs to be satisfied that the system provides accurate warnings. Reports from pilots in the Juneau airspace can be compared with JAWS warnings. The data in Fig. 12 represent the best possible data for such a comparison—the King Air data come from a research aircraft with a single highly trained pilot. The first two comparisons are essentially self-calibrations: pilot assessments of the turbulence level compared with the representative σ_W' or $\varepsilon^{1/3}$ value from the aircraft data. Both show good trends of increasing turbulence category with increasing turbulence metric. Comparison with the JAWS estimate of $\varepsilon^{1/3}$ shows the same favorable trend.

Even in this case, there is considerable overlap in turbulence categories for a given range of turbulence metrics, which introduces difficulty in assigning turbulence category thresholds for JAWS that would give high skill scores to research aircraft measurements compared to pilot reports. This argues for a set of scoring rules that give the benefit of the doubt to the system in ambiguous cases while taking into account pilot perception of system performance. To account for this uncertainty, "no harm, no foul" (NHNF) scoring rules were developed. Consider the NHNF rules for the moderate turbulence case. A moderate-or-greater system alert is labeled "yes" and is considered in agreement (YY) with each moderate-or-greater pilot report, which is scored as a second "yes" (YY). This same alert, when paired with a light or light-to-moderate pilot report is also labeled in agreement: "yes–yes" (YY). If this alert is generated and a null pilot report is received, then it is scored as a disagreement, "yes–no" (YN). Likewise, a null system alert is considered in agreement (NN) with null pilot reports, and light and moderate-to-light pilot reports, but in disagreement (NY) with moderate-or-greater pilot reports. In this set of scoring rules, the ambiguous cases are the light and light-to-moderate pilot reports. This scoring system gives the benefit of the doubt to the system in these cases. If the system gives a moderate alert, this counts as a disagreement (YN) *only* if the pilot report is given as null. In the case of a light or light-to-moderate pilot report, the pilot at least notes that there was some turbulence. In the case of a system alert of null turbulence, this counts as an agreement with all pilot reports of less-than-moderate turbulence since the pilot did not experience moderate turbulence. There is disagreement in this case only when the pilot reports moderate-or-higher turbulence since a pilot would consider such a situation as a missed detection.

Two datasets were used to evaluate the skill of JAWS using these NHNF scoring rules. The program

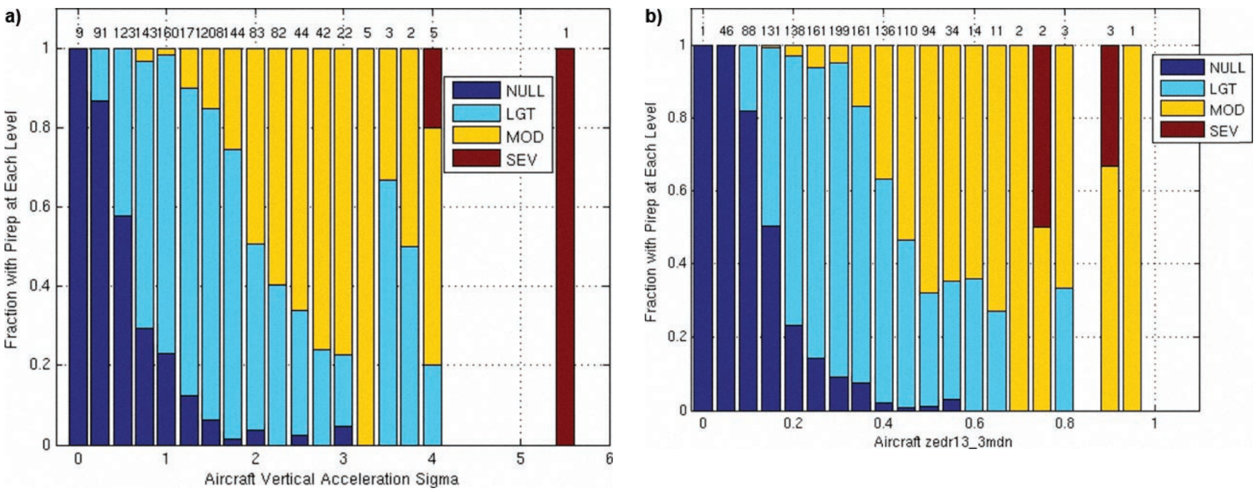
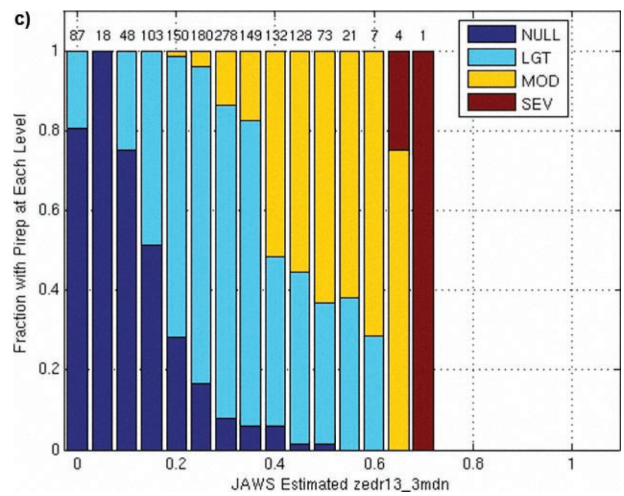


FIG. 12. Fraction of pilot-reported turbulence matched to (a) appropriate aircraft-measured σ_w', (b) appropriate aircraft-measured $\varepsilon^{1/3}$, and (c) JAWS estimate of $\varepsilon^{1/3}$.



data and accompanying pilot reports came from two aircraft types (King Air and B737) with highly trained pilots and under carefully controlled situations where locations and times of reports were very closely monitored. After the field program, when the initial JAWS was installed and provided warnings announced by the tower staff, an operational evaluation (OpEval) was conducted for the collection of turbulence warnings and local pilot reports. These OpEval pilot reports came from a wide variety of aircraft types and from pilots of varying experience, and they were subjected to significant quality control efforts to ensure the accuracy of time and location. It should be noted that the OpEval data contained far fewer reports of moderate-or-greater turbulence reports than found in the field program data. This makes intuitive sense in that during the field program, an effort was made to sample moderate turbulence, while in the OpEval, the pilots tried to avoid turbulent conditions. However, the OpEval data are valuable in that they represent an independent test of JAWS since none of those data was used to train the system. There is also the issue of representativeness of the datasets for year-round use of the system. The thresholds for selecting wind regimes (including calm, which occurs much more frequently in summer) were quite restrictive. Thus, we have confidence that the accuracy of the warnings should be seasonally independent.

The following statistics were computed for each of these two datasets: PODy = YY/(YY + NY); PODn = NN/(YN + NN); and FARatio = YN/(YY + YN). PODy is the probability of detection for a “yes” turbulence event—that is, the probability that a turbulence event was correctly warned. Similarly, the PODn is the probability of detection for a “no” turbulence event—that is, the probability that a report of null turbulence was not in a warned region. The FARatio is the false-alarm ratio and is the fraction of wrong warnings compared to the total warnings. For the field program, there were 1,189 samples (pilot reports) and the statistical scores were PODy = 0.97, PODn = 0.93, and FARatio = 0.06. The OpEval had 1,064 samples (pilot reports) and the statistical scores were PODy = 0.88, PODn = 0.96, and FARatio = 0.13. These are surprisingly similar scores. The requirements for the system were a POD_y of at least 0.6 and a FARatio not to exceed 0.2. These requirements have been exceeded.

SUMMARY AND RECOMMENDATIONS FOR THE FUTURE. An automated system has been developed to detect and warn for terrain-induced turbulence around the Juneau International Airport. JAWS is based on both meteorological understanding of the region and statistical regressions. Through comparisons both with painstakingly calculated turbulence metrics from research aircraft and reports of turbulence from pilots in the area, it has been found to perform remarkably well. The turbulence warnings JAWS generates are reliable and accurate.

The JAWS program started in late 1996 as a response to air carrier incidents involving severe turbulence. The system has evolved to the point where commercial air carriers today use it on a voluntary basis, in addition to their official operations specification, because it provides alerts that are well correlated with pilots' experience in the cockpit. Despite this, until recently the program suffered many delays, partly because of policy, rather than scientific, issues. The potential use of new, ICAO-based turbulence metrics in the air traffic control tower was seen as a policy issue that was very difficult to overcome, since JAWS is a one-of-a-kind system.

Recently the decision was made to use JAWS as an advisory system, available for use in the FAA Automated Flight Service Station (AFSS) and by air carriers, but it would not be installed in the Juneau air traffic control tower (meaning that commercial pilots would receive the warnings from their dispatch office and other aircraft would receive warnings from the AFSS). This decision cleared the policy hurdle. In December 2008, FAA senior management approved the completion of JAWS as an alerting system to be operated and maintained by the FAA. This will occur in two phases. First, a hybrid system will be created that integrates NCAR's algorithm and display system with an FAA-developed data ingest system. Once the hybrid system has been installed, integrated, and tested, the current prototype, which has been operating for more than 10 years, will be taken offline and all hardware components not used in the hybrid system will be removed. The second phase will incorporate software changes to bring JAWS online as a Linux-based system (the prototype is Microsoft Windows based; the hybrid will combine Windows and Linux features). Major milestones for the transition from prototype to end-state system call for hybrid operations beginning in October 2009, parallel operation of the prototype and hybrid systems for about 9 months, shutdown of the prototype system in early summer 2010 (as the hybrid system commences providing operational data), certification by the FAA that the system is fully functional and ready for operations, and an operationally ready date of 30 September 2011. At this point the FAA will take over nearly all operations and maintenance activities. The final transition of the system from a Windows–Linux hybrid to a fully Linux-based system will occur by 31 January 2012, with an operational system start in February 2012. This system is planned to operate until 2025, with a technical refresh planned for 2015.

For future development in new locations, different tools and systems could be used for the initial mapping of turbulence-prone areas around an airfield. Radars and lidars could be used if weather conditions favor these instruments. As numerical weather prediction models gain skill, especially in complex terrain, perhaps they could be used to provide climatologies of turbulence much in the same way as downscaling exercises are being done to provide wind resource information for the renewable energy community (Pryor et al. 2005).

Finally, an intriguing possibility for future turbulence warning systems is the incorporation of in situ aircraft turbulence sensors. Several airlines carry software that uses the onboard inertial navigation system to provide estimates of $\varepsilon^{1/3}$ and communicates these estimates to ground stations for use by the airline companies and the National Weather Service for input to numerical weather prediction models. As these onboard turbulence detection algorithms become more widespread, their turbulence data could be used not only to determine candidate airports for new warning systems but to extract information on the locations of turbulence encounters and to suggest strategies for sensor selection and placement.

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REFERENCES

Abraham, B., and J. Ledolter, 1983: *Statistical Methods for Forecasting.* John Wiley & Sons, 445 pp.

Carter, D. A., K. S. Gage, W. L. Ecklund, W. M. Angevine, P. E. Johnston, A. C. Riddle, J. Wilson, and C. R. Williams, 1995: Developments in UHF lower tropospheric wind profiling at NOAA's Aeronomy Laboratory. *Radio Sci.,* **30,** 977–1001.

Cohn, S. A., 2004: Flow in complex terrain: Observations by radar wind profilers and anemometer near Juneau, Alaska. *J. Appl. Meteor.,* **43,** 437–448.

——, R. K. Goodrich, C. S. Morse, E. Karplus, S. W. Mueller, L. B. Cornman, and R. A. Weekley, 2001: Radial velocity and wind measurements with NIMA–NWCA: Comparisons with human estimation and aircraft measurements. *J. Appl. Meteor.,* **40,** 704–719.

——, R. Barron, A. Yates, A. R. Rodi, P. Neilley, A. Praskovsky, and L. Cornman, cited 2004: Field programs to investigate hazards to aviation in Juneau, Alaska. [Available online at http://ams.confex.com/ams/11aram22sls/techprogram/paper_81795.htm.]

Colman, B. R., 1986: The winter climate of Juneau: A mean of contrasting regimes. *Natl. Wea. Dig.,* **11,** 29–34.

——, and C. F. Dierking, 1992: The Taku wind of southeast Alaska: Its identification and prediction. *Wea. Forecasting,* **7,** 49–64.

Cornman, L. B., C. S. Morse, and G. Cunning, 1995: Real-time estimation of atmospheric turbulence severity from in-situ aircraft measurements. *J. Aircr.,* **32,** 171–177.

Dierking, C. F., 1998: Effects of a mountain wave windstorm at the surface. *Wea. Forecasting,* **13,** 606–616.

Fisher, R. A., 1925: Theory of statistical estimation. *Proc. Cambridge Philos. Soc.,* **22,** 700–725.

Gilbert, D., L. B. Cornman, R. K. Goodrich, A. R. Rodi, and R. G. Frehlich, 2004: Calculating EDR from aircraft wind data during flight in and out of Juneau, AK: Techniques and challenges associated with non-straight and level flight patterns. Preprints*, 11th Conf. on Aviation, Range and Aerospace Meteorology,* Hyannis, MA, Amer. Meteor. Soc., 4.4. [Available online at http://ams.confex.com/ams/11aram22sls/techprogram/paper_81984.htm.]

Golub, G. H., and C. Reinsch, 1970: Singular value decomposition and least squares solutions. *Num. Math.,* **14,** 403–420.

——, and C. F. Van Loan, 1996: *Matrix Computations.* John Hopkins University Press, 694 pp.

Goodrich, R. K., C. S. Morse, L. B. Cornman, and S. A. Cohn, 2002: A horizontal wind and wind confidence algorithm for Doppler wind profilers. *J. Atmos. Oceanic Technol.,* **19,** 257–273.

ICAO, 2007: Annex 3: Meteorological services for international air navigation. 16th ed. International Civil Aviation Organization Rep., 187 pp.

John, G. H., R. Kohavi, and K. Pfleger, 1994: Irrelevant features and the subset selection problem. *Machine Learning: Proceedings of the Eleventh International Conference,* William W. Cohen and Haym Hirsh, Eds., Morgan Kaufmann Publishers, 121–129.

MacCready, P. B., Jr., 1964: Standardization of gustiness values from aircraft. *J. Appl. Meteor.,* **3,** 439–449.

Miller, A. J., 1990: *Subset Selection in Regression.* Chapman and Hall, 229 pp.

Morse, C. S., R. K. Goodrich, and L. B. Cornman, 2002: The NIMA method for improved moment estimation from Doppler spectra. *J. Atmos. Oceanic Technol.,* **19,** 274–295.

Neilley, P., and T. Keller, 1995: Meteorological conditions associated with significant terrain-induced windshear and turbulence at the new Hong Kong airport. Preprints, *Sixth Conf. on Aviation Weather Systems,* Dallas, TX, Amer. Meteor. Soc., 535–540.

Pryor, S. C., J. T. Schoof, and R. J. Barthelmie, 2005: Empirical downscaling of wind speed probability distributions. *J. Geophys. Res.,* **110,** D19109, doi:10.1029/2005JD005899.

Smalikho, I. N., 1997: Accuracy of turbulent energy dissipation rate estimation from the temporal spectrum of wind velocity fluctuations. *Atmos. Oceanic Opt.,* **10,** 559–563.

Weekley, A., R. Goodrich, A. Praskovsky, and L. Cornman, cited 2004: An anemometer data quality control method designed for a turbulence and wind shear prediction algorithm. [Available online at http://ams.confex.com/ams/11aram22sls/techprogram/paper_81919.htm.]

——, ——, and L. B. Cornman, 2010: An algorithm for classification and outlier detection of time series data. *J. Atmos. Oceanic Technol.,* **27,** 94–107.