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LOW-LEVEL TURBULENCE ALGORITHM TESTING AT-OR-BELOW 10,000 FT

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1. INTRODUCTION

The Air Force Weather Agency tested and ultimately implemented a version of the Panofsky Index (PI) valid for the surface to 4,500 ft AGL (above ground level) layer in July 2002. This provided up to an 18% higher POD, and a lower false alarm area (based on explicit null PIREPs) over the previously provided low level products, affording a significantly better low level turbulence product for our customers worldwide (Brooks et al., 2002).

This paper will discuss recent work to evaluate the potential usefulness of (1) PI calculated at two slightly higher layers, 5,000-8,000 ft AGL and 7,000-10,000 ft AGL (primary goal) and (2) PI calculated for a smaller (surface to 3,000 ft AGL) layer (secondary goal). (Please note: our customers desire these products in “ft AGL”.) Some useful background information on turbulence and the PI follows.

Forecasting clear air turbulence (CAT) is a complicated task because of the very small time and space scales that turbulence is often observed (both in the horizontal and vertical). Theoretical studies and empirical evidence have associated CAT with Kelvin-Helmholtz instabilities. Miles and Howard (1964) indicate that the development of such instabilities require the existence of a critical Richardson number (RI) <=0.25. However, Stull (1989) notes that the Richardson number is a simplified term or approximation of the turbulent kinetic energy equation, where the RI is expressed as a ratio of the buoyancy resistance to energy available from the vertical shear.

This relationship is shown in equation (1), where g is the gravitational acceleration, $\partial\theta/\partial Z$ is the change of potential temperature with height, and ∂V is the vector wind shear occurring over the vertical distance ∂Z.

$$RI = \frac{\frac{g}{\theta} * (\frac{\partial\theta}{\partial Z})}{(\frac{\partial V}{\partial Z})^2} \qquad (1)$$

The formula for the PI is shown in equation (2), where RI is the Richardson number and RI_{crit} is a critical Richardson number empirically found to be 10.0. The wind term is the average wind speed in the layer (m/s). The higher the PI value, the greater the intensity of turbulence at low levels (Boyle, 1990).

$$PI = (windspeed\ )^2 * (1.0 - \frac{RI}{RI_{crit}}) \qquad (2)$$

Approaching the turbulence-forecasting problem from an operational viewpoint, Ellrod and Knapp (1992) listed environments where significant CAT was found to be prevalent. Their study combined vertical wind shear, deformation, and convergence into a single equation known as the turbulence index (TI). This work by Ellrod and Knapp was based on the Petterssen’s (1956) frontogenesis equation and was ideal to utilize the gridded output of a mesoscale model. Assuming that frontogenesis results in an increase in vertical wind shear (VWS), horizontal deformation (DEF) and horizontal convergence (CVG), the turbulence index is derived as:

$$TI = VWS * (DEF + CVG)$$

They used the Nested Grid Model (NGM) and Global Aviation Model (AVN) to develop and evaluate their turbulence index. Later, Knapp researched and validated the TI using the 16-level Battlescale Forecast Model (BFM) at the Army Research Laboratory (ARL) (Knapp and Smith, 1995) and later with the MM5 run at AFWA.

In the summer of 2002, AFWA replaced TI products created for 2,000 ft AGL and 5,000 ft AGL when implementing the PI for the surface to 4,500 ft AGL layer. An example of this product is shown in Figure 1 at the end of this paper. It is important to note that the TI was developed using mid- and upper-level data and designed primarily for CAT above ~15,000 ft MSL. We continue to use it exclusively from 10,000 ft MSL to 50,000 ft MSL for our mid- and upper-level turbulence products available to customers on our Joint Air Force & Army Weather Information Network (JAAWIN) and Interactive Grid Analysis and Display System (IGrADS).

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2. DATA COLLECTION AND ANALYSIS

The study period encompassed 03 September 2003 through 11 May 2004. The AFWA 45km MM5 CONUS theater was used to create 12hr forecasts of PI for four layers, valid at 1800 UTC. The four layers were: surface to 3,000 ft AGL, surface to 4,500 ft AGL (our existing algorithm in production), 5,000 ft to 8,000 ft AGL, and 7,000 ft to 10,000 ft AGL. An example showing the domain of the 45km MM5 CONUS theater is shown in Figure 2. The final output value and also the values for each of the wind speed and buoyancy terms of the equation were collected. The 12-hr forecast TI products were also obtained at 10,000 ft MSL. Although not in production nor sent to customers, it was serendipitously discovered that the low-level TI products were still being post-processed, so these were saved for an additional check on PI performance.

PIREPs were collected from the Internet at the Aviation Weather Center's Aviation Digital Data Service (ADDS) site. PIREPs were carefully analyzed to obtain their approximate height AGL from their reported MSL value. PIREPs used in the study were limited to those +/- one hour from valid time. That is, only PIREPs with turbulence information—null, light, moderate, or severe—reported between 1700 and 1900 UTC were used. In the vertical, only PIREPs plus or minus 500 ft above the top or below the bottom of the layer, respectively, were used (e.g., PIREPs of 4,500 – 8,500 ft for used with the 5,000-8,000 ft PI tests).

The CONUS verification data was separated into four regions to look at algorithm and individual algorithm term performance by region. The regions were broadly based on surface elevation to look at terrain effects and allow appropriate groupings for MSL-AGL conversions. It was felt that it would also be interesting to analyze PIREP distribution by area, reported intensity, etc.

3. RESULTS

These results are preliminary. Due to time constraints, three months of data during the collection period -- September and November 2003, and April 2004—were analyzed. The total observation-forecast pairing count for these three months ranged from 127 for the sfc-3,000 ft AGL verification over our Mountainous West region to 830 for the 5,000-8,000 ft AGL verification over our Low Elevation region. Not surprisingly, it was found that the number of pairings was not high enough to produce meaningful statistics in our other two regions, the High Plains and the Appalachian Mountains.

Through 2X2 contingency tables, PODy was analyzed for each intensity, but given the nearly universally known arguments against taking PIREP intensity verbatim (e.g, aircraft and aircraft loading dependence on turbulence intensity, human subjectivity, etc) it was felt wise to combine (1) moderate and severe reports together and (2) *any* positive report of turbulence together. All explicit-NO turbulence reports were also analyzed, enabling some PODno and FAR statistics to be computed. These statistics are not meant to be taken verbatim and are truly meant to only be used in a relative sense when looking at two algorithms side-by-side. The three-month results are summarized in Tables 1 and 2 for the Low Elevation and Mountainous West regions of our dataset, respectively.

	Sfc-3000	Sfc-4500	5,000-8,000	7,000-10,000
PODy	0.83	0.80	0.57	0.56
FAR	0.14	0.19	0.36	0.45
CSI	0.73	0.67	0.43	0.37

Table 1. Analysis of the 2385 PIREPs available over our Low Elevation subset of CONUS during the three specified months. PODy includes all PIREP intensities (L, M, S). FAR uses explicit null reports only.

	Sfc-3000	Sfc-4500	5,000-8,000	7,000-10,000
PODy	0.76	0.79	0.61	0.66
FAR	0.25	0.26	0.33	0.34
CSI	0.61	0.62	0.47	0.49

Table 2. Analysis of the 992 PIREPs available over our Mountainous West subset of the CONUS during the three specified months. PODy includes all PIREP intensities (L, M, S). FAR uses explicit null reports only.

For one of the months analyzed, April 2004, the TI at 5,000 ft AGL and 10,000 ft was collected to compare with the Panofsky performance. This data, along with the previously mentioned calculation of PODn using only explicit-NO turbulence PIREPs, is also shown in Table 3.

	Sfc-3000	Sfc-4500	TI-5	5,000-8,000	7,000-10,000	TI-10
PODy	0.71	0.79	0.18	0.58	0.61	0.25
FAR	0.27	0.21	0.29	0.31	0.28	0.12
PODn	0.62	0.68	0.89	0.62	0.64	0.89
FARn	0.41	0.32	0.80	0.53	0.48	0.46

Table 3. Analysis of the 992 PIREPs available over our Mountainous West subset of the CONUS during April 2004. PODy includes all PIREP intensities (L, M, S).

FAR, FARn, and PODn make use of explicit null reports.

The TI values presented here are likely subject to an incomplete POD and an unfairly high FAR to some extent. This is because the PIREP heights used would have been constrained further if the goal was to verify TI only. Since TI is calculated over a smaller layer than the PI, fewer PIREPs should have been paired with TI forecasts. Nevertheless, it is clear from the PI performance that the change made in 2002 has been justified again in this 2003-2004 study.

Again, the actual values in Table 3 should be used with caution. The important issue is a comparison between the two and it is clear that the PI did a better job forecasting turbulence. The TI is not tuned to nor created for these lower levels, which resulted in small areas forecast and a subsequent very low PODy.

Table 4 shows some preliminary statistics regarding the aforementioned analysis of the individual terms. Shown are the average values of the buoyancy (Richardson number) and wind speed terms. The terms are denoted R and W and the values shown are for the month of April 2004, for all regions. This data was collected and computed for two layers only, surface-4,500 ft AGL and 7,000-10,000 ft AGL. OBS=NO were explicit-null reports, and OBS=YES indicates turbulence of any intensity was reported.

	R low	W low	R high	W high
OBS=NO	0.78	5.19	0.20	11.23
OBS=YES	0.81	7.29	0.30	14.74

Table 4. April 2004 average values of each term for all regions, stratified by OBS = YES or NO.

3. CONCLUSIONS AND FUTURE STUDY

Research and analysis presented here has shown that work is proceeding very favorably toward achieving our goal of providing customers with improved turbulence forecasts below ~10,000 ft AGL.

The results in the Table 4 suggest that additional statistical and regression analysis of the individual terms of the PI is prudent. This will lead to correlation coefficients and likely, an adjusted formula with unique weighting functions applied to each of the terms.

More months will be analyzed since it is strongly desired to study each season to quantify seasonal performance differences. For example, it has already been observed that the buoyancy term introduces a diurnal cycle, peaking during the hours of maximum daytime heating.

Work remains to produce more meaningful intensity forecasts but this will be difficult to accomplish as long as there is human subjectivity and aircraft type dependence inherently contained in a PIREP. That being said, the authors still wish to emphatically thank pilots for providing PIREPs. Until such time as reliable automated sensors are developed, tested, and fielded en masse, PIREPs remain absolutely essential to researchers continually striving to make better forecasts of aviation impact variables like turbulence and icing.

REFERENCES

Boyle, J.S., 1990: NOARL Technical Note 47, Turbulence Indices Derived From FNOC Fields and TOVS Retrievals. Naval Oceanographic and Atmospheric Research Laboratory, 22 pp.

Brooks, G.B., I. Gotchel, C.M. Stock, J.E. Passner, and D.I. Knapp, 2002: Verification Results of a Turbulence Index Applied to Low Levels of the Atmosphere. Tenth Conference on Aviation, Range, and Aerospace Meteorology, Portland, Oregon, Amer. Meteor. Soc., 307-310.

Ellrod, G.P., and D.I. Knapp, 1992: An Objective Clear-Air Turbulence Forecasting Technique: Verification and Operational Use. Wea. Forecasting, **7**, 150-165.

Knapp, D.I., T.J. Smith, and Robert Dumais, 1995: Development and Verification of a New Low-Level Turbulence Analysis and Forecasting Index Derived From Mesoscale Model Data. Sixth Conference on Aviation Weather Systems, Dallas, Texas, Amer. Meteor.Soc., 436-440.

Miles, J.W. and L.N. Howard, “Notes on Heterogenous Shear Flow,” J. Fluid Mech, **20**, pp. 331-336.

Petterssen, S., 1956: Weather Analysis and Forecasting, Vol 1. McGraw-Hill Book Co, 428 pp.

Stull, R.B., 1989: An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, 666 pp.

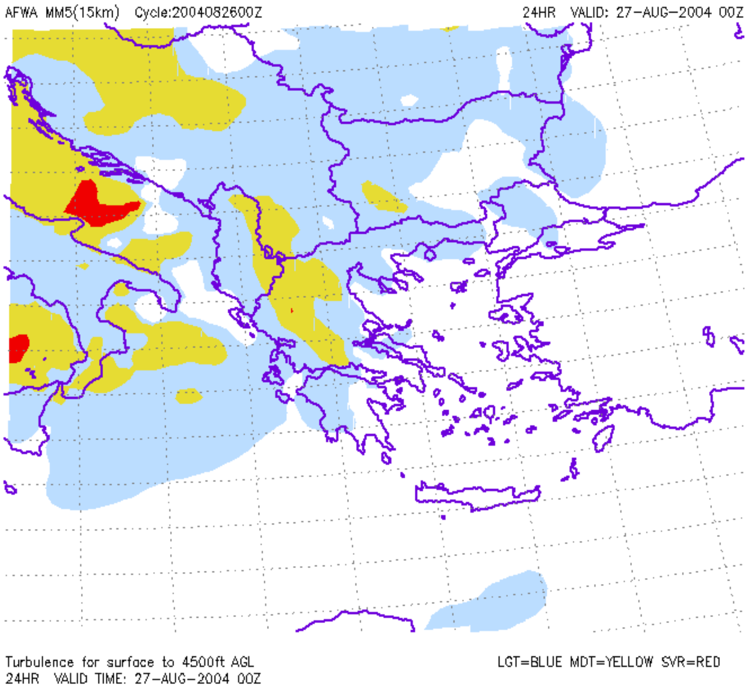

Figure 1. Panofsky low-level turbulence Index (PI) for the surface to 4500 ft AGL layer. This example is a 24hr forecast valid 27 AUG 2004 0000 UTC for the 15km MM5 domain AFWA implemented for customers in support of the XXVIII Summer Olympics in Athens, Greece.

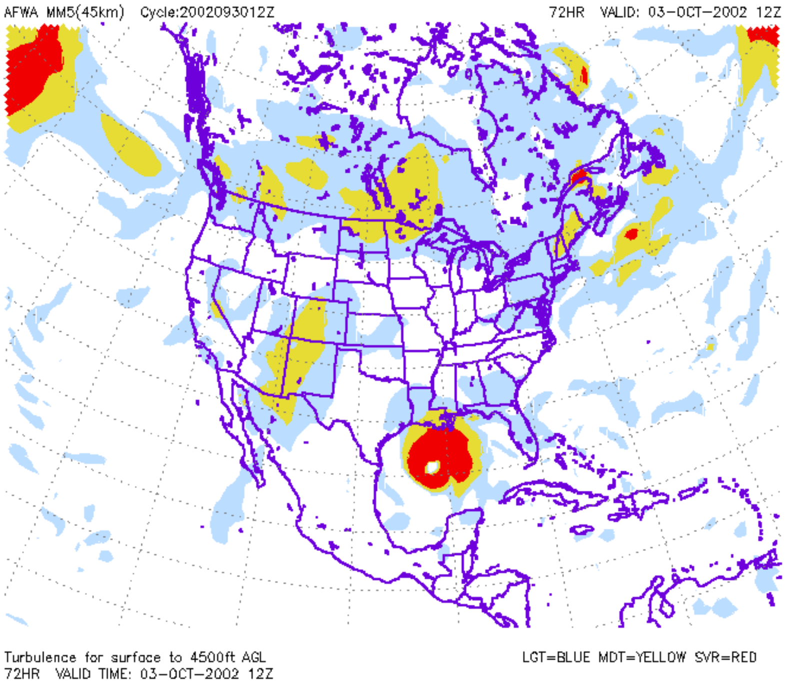

Figure 2. PI over the 45km MM5 CONUS domain used in this study that is run every six hours at AFWA. This example is a 72hr fcst valid 03 OCT 2002 1200 UTC. The red severe turbulence serves to highlight Hurricane Lili nicely in the Gulf of Mexico.