P9.3

VERIFICATION RESULTS OF A TURBULENCE INDEX APPLIED TO LOW-LEVELS OF THE ATMOSPHERE

Gordon R. Brooks*, Ingrid Gotchel, and Christopher M. Stock
Air Force Weather Agency, Offutt AFB, NE

Jeffrey E. Passner
U.S. Army Research Laboratory, White Sands Missile Range, NM

David I. Knapp
NOAA/NCEP/NWS Aviation Weather Center, Kansas City, MO

1. INTRODUCTION

Forecasting clear air turbulence (CAT) is a complicated and frustrating problem because of the small timescale and resolution that turbulence is often observed. 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. The equation is expressed below:
where g is the gravitational acceleration, $\partial\theta/\partial Z$ is the

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

change of potential temperature with height, and ∂V is the vector wind shear occurring over the vertical distance ∂Z.

The U.S. Navy Fleet Numerical Meteorological and Oceanography Center (FNMOC) uses the Panofsky index (PI) to forecast low-level turbulence, where the low level is considered to be below 4,000 ft AGL. The formula for this index 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 for the FNMOC data. The higher the PI, the greater the intensity of turbulence at low levels (Boyle, 1990).

Corresponding author address: Mr. Gordon R. Brooks, HQ AFWA/DNXT, Suite 2N3, Offutt AFB, NE 68113 USA. E-mail: Gordon.Brooks@afwa.af.mil.

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

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:

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

Originally, they used the nested grid model and global aviation model 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.

Using the PI below 4000 ft AGL and the Richardson number above that level in the BFM to the model top of 7000m AGL, Passner (2000) found that the PI was most effective in the lowest 4000 ft while the Richardson number was generally ineffective between 4,000 to 10,000 ft AGL. The results in the Passner study indicated a need for an improved routine above 4000 ft AGL. Using the work by Knapp and Smith in their 1995 study, which proved that a combination of some of the features of the TI and the PI provided the highest correlation coefficients, it was determined to implement the TI above 4000 ft AGL, and use the PI below that level in this study.

2a. TURBULENCE EVALUATION AT ARL

During the winter season of 2002 (January-February) model runs were made using both the BFM and the MM5 produced at the U.S. Air Force Weather Agency (AFWA). These mesoscale models are very different. The BFM is a hydrostatic model run to 24-h that produces output at 10-km horizontal resolution with 16 terrain-following vertical levels to a top of 7000 m above the highest elevation on the grid. The BFM runs were initialized using 1200 UTC or 0000 UTC data. The AFWA MM5 output used in this study has a 15-km mesh on 41 vertical levels with output to 48 hr. The MM5 runs were 0600 or 1800 UTC model runs, with the first output periods at 1200 UTC or 0000 UTC respectively.

The method used in this study to verify turbulence is to compare pilot reports (PIREPs) to model forecasts. Using both the BFM and MM5 output, verification is limited to a one-h period surrounding the model forecast time. As an example, model forecasts of turbulence at 2100 UTC are compared to PIREPs from 2030 to 2130 UTC only. While all turbulence intensities were considered, any PIREPs that included two intensities, such as LGT to MDT, were classified as the more extreme intensity; moderate in this example. As a standard, only pilot reports close in height to the model forecast were accepted. For levels below 10000 ft AGL, the forecasted turbulence had to be within 1000 ft of the PIREP. From 10000 to 20000 ft AGL, the forecast had to be within 1500 ft of the PIREP, and above 20000 ft AGL, the forecast had to be within 2000 ft of the observed turbulence. Explicit "null" reports of turbulence were the only ones considered to be a report of "no turbulence."

Table 1 displays the results for the BFM and MM5 turbulence using the PI and TI combination with the PI used exclusively below 4000 ft AGL and TI above that level. These results include turbulence for all levels of the atmosphere and all forecast hours from each model. The statistical terms displayed are: probability of detection (POD), false-alarm rate (FAR), the correct prediction of the null event (Non-event), critical success index (CSI), true skill score (TSS), and the bias.

	BFM	MM5
Samples	177	362
POD	0.71	0.75
FAR	0.24	0.24
Non-event	0.59	0.61
CSI	0.58	0.61
TSS	0.29	0.36
BIAS	0.94	0.98

Table 1. "YES/NO" turbulence statistics using the combined PI and TI from the BFM and MM5 for winter 2001-2002

The results in the table indicate little variation in skill between the two models using the combination of PI and TI. Table 2 displays the results using the two methods; the PI below 4000 ft AGL and the TI above 4000 ft AGL.

	BFM	MM5
POD – Panofsky Index	0.82	0.84
FAR – Panofsky Index	0.22	0.15
TSS -- Panofsky Index	0.27	0.40
Bias – Panofsky Index	1.04	0.99
POD – Turbulence Index	0.63	0.70
FAR – Turbulence Index	0.27	0.28
TSS -- Turbulence Index	0.28	0.31
Bias – Turbulence Index	0.86	0.98

Table 2. "Yes/No" turbulence statistics for the two different methods used in the study, the Panofsky Index below 4000 ft AGL and the Turbulence Index above 4000 ft AGL.

Again, the results are almost identical, although the FAR is lower in the MM5 than the BFM in the lower 4000 ft of the atmosphere. Overall, the POD is higher in the lower levels, which may indicate that the Panofsky index, with an emphasis on wind speed, is a valid approach to forecasting turbulence in the lower levels.

An investigation of the turbulence intensity produced from the BFM and MM5. The BFM study consisted of 176 samples while the MM5 had 364 samples. Results of the BFM study can be seen in Figure 1, while the MM5 study is shown in Figure 2.

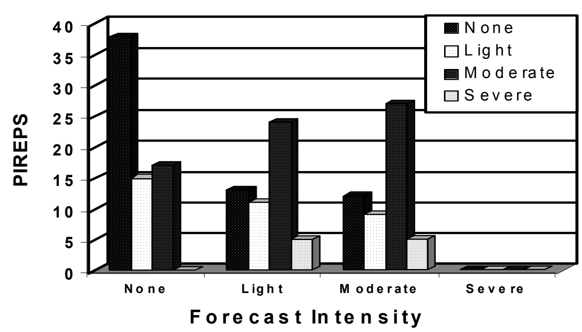

Figure 1. BFM turbulence intensity, all forecast hours and all levels. Study from winter 2002. Distribution of PIREP intensity (vertical bars) for all model forecast intensities.

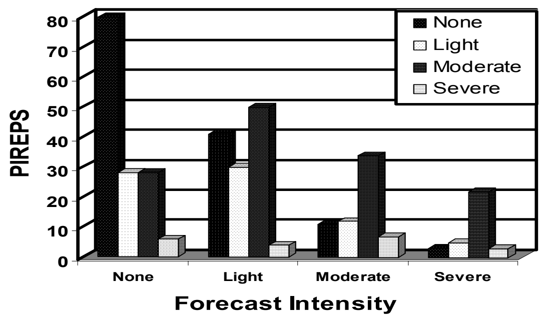

Figure 2. As in Figure 1, except for MM5.

The turbulence intensity follows the same pattern with both models using the PI–TI combination to forecast turbulence. Both the MM5 and BFM handle the "no event" case well, with most of the "no" forecasts having a "no" observation. There are some slight differences between the models in forecasting between light, moderate, and severe turbulence. The BFM does appear to forecast more moderate events, while the MM5 forecasts a higher percentage of light turbulence cases. Since the models were run over the same general areas on the same days, it is uncertain as to why this occurs, however, both models do show a trend to forecast too many moderate cases when light turbulence is observed. Conversely, the BFM has no forecasts of severe turbulence in the entire sample, but this may be a result of the BFM making no forecasts above 20,000 ft AGL, while the MM5 forecasts severe turbulence in 9 percent of the total sample. It is encouraging to see the MM5 have so many of the forecasts of severe turbulence reported as moderate turbulence since it proves that the severe forecasts are a good indicator of turbulence that would be difficult for military or commercial aviators.

2b. TURBULENCE EVALUATION AT AFWA

AFWA performed three low-level turbulence evaluations of PI and TI during the past three seasons. Different resolutions of MM5 data were compared during the summer test. Verification details are similar to the ARL study except the PIREP window was about 2 hours either side of the valid time. During summer 2001 collected PIREPs at or below 7000 ft AGL and found that PI (using 45km data) had the highest skill. PI PODy was 51%, which was 30% higher than the 45km TI, and 16% higher better than TI from 15km resolution data. PODn for the PI was 73% compared to 78% and 68% for TI from 45km and 15km resolution data, respectively. Fall 2001 data is in the analysis stage. The co-authors all desired a winter season test, hypothesizing better results than summer (in particular, PODy values), and this was performed during winter 2001-2002 (December-February, 3012 samples). AFWA's test was strictly low-level: PIREPs at or below 7000 ft AGL were used and TI was assessed at 2000ft and 5000ft AGL only. PI was computed for the surface to 5000 ft layer. We analyzed all PIREPs, then subsets of the data below and above the 4000ft AGL flight level (N=1329 below 4000 ft AGL and 1671 PIREPs at or above 4000 ft AGL). These results are summarized in Table 3.

	PI all	TI 2 all	TI 5 all	PI < 4	TI 2 < 4	TI 5 > 4
PODy	0.75	0.66	0.57	0.73	0.62	0.67
PODn	0.39	0.48	0.61	0.36	0.48	0.60
FAR	0.37	0.35	0.33	0.29	0.28	0.37
CSI	0.53	0.50	0.45	0.56	0.49	0.48

Table 3. Analysis of 3010 PIREPs, DEC 2001-JAN 2002. PODy includes all PIREP intensities (L, M, S). FAR uses explicit nulls.

The PI forecasts were then sorted by projection time to show the variance of PODy and PODn. The PODy values peaked at 80% for T+18 and T+24 hours, and remain at 75% at T+36 hours (Fig. 3).

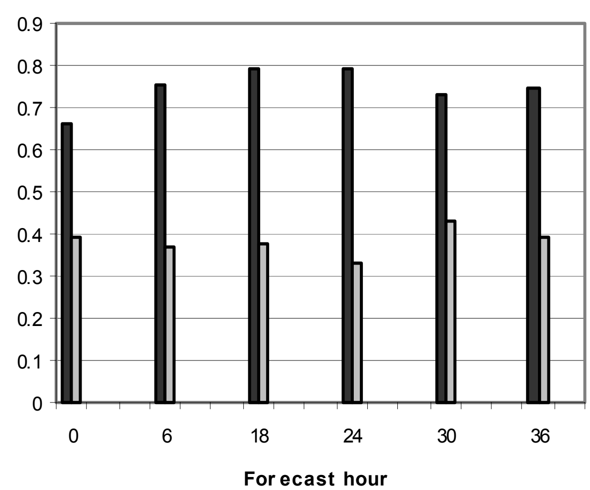

Figure 3. PI PODy (black) and PODn (shaded) values by forecast projection time.

In Figure 4, the distribution of PIREPs by PI forecast intensity is shown. Note that forecasts of severe turbulence were associated primarily with moderate turbulence PIREPs. Recall a similar observation was made with MM5 forecasts in the ARL study. Also, observed moderate turbulence was most often associated with at least light, if not moderate turbulence forecasts.

The subjective verification measures employed here tried to envision forecasters using algorithm output as a first guess tool—which allowed for an expansion of large forecast areas, and disregarding very small areas. This occurred mostly with TI, as it provides less of a broad-brush picture. This and the effect of using a less stringent time window than in the ARL study are primary reasons for the one reason for the low PODn values. During analysis it became evident that there were a number of cases where PIREPs of turbulence and null PIREPs coexisted in the same immediate area. A future study will test the one-hour PIREP window hypothesis.

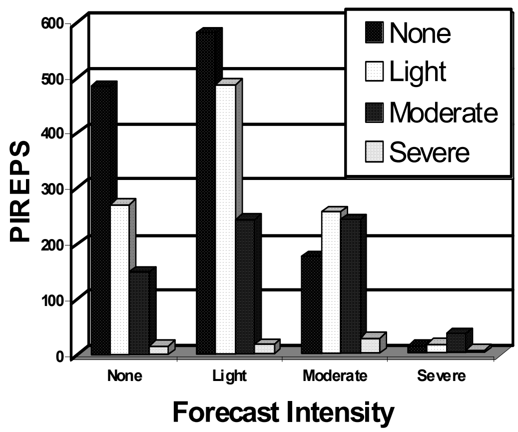

Figure 4. As in Fig 1, except for PI during AFWA study.

3. DISCUSSION

While not shown in a table or chart, another result derived in this study is that both the BFM and MM5 provide more accurate turbulence forecasts on days where widespread turbulence is observed, such as days with large storms and dynamical lifting. While no testing on this subject has been attempted, it is possible that the most difficult turbulence forecasts occur on days with rapidly moving mid-level short waves and weak convergence or deformation. Many of the errors in the study appear to be in the cases of occasional light turbulence, which are often forecasted to be "no turbulence," and may not be a significant error for most aircraft. The influence of terrain on the turbulence is not employed well in any of these methods, as none of existing methods, the PI, RI, or TI are capable of forecasting mountain waves or small-scale turbulence near slopes or smaller terrain differences.

It should be noted that since the BFM and MM5 have such different vertical resolutions the actual values of TI are highly model dependent. Initial tests led to the development of the TI value-turbulence relationship shown in Table 4.

Intensity forecast	BFM	MM5
No turbulence	<0.65	<3.00
Light turbulence	0.65- 1.59	3.00-8.99
Moderate turbulence	1.60-4.00	9.00-14.00
Severe turbulence	>4.00	>14.0

Table 4. Values used to forecast Turbulence Index (TI) used for each model

Overall, based on the results presented here, the combination of PI and TI provide excellent forecasts, however adjustments in the TI may handle some of the biases shown in Figures 1 and 2. Past experience with TI at upper levels at AFWA not shown in this paper strongly corroborates the ARL study and theory of combining PI at low levels and TI at mid and upper levels to provide our users with the best total picture of turbulence potential in the atmosphere.

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.

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,

Passner, J.E., An Evaluation of Three-Dimensional Weather Hazards Using Sounding Data and Model Output Data, ARL-TR-1046, U.S. Army Research Laboratory, White Sands Missile Range, NM, 2000.

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.