P3.22 VERIFICATION OF CLEAR AIR TURBULENCE (CAT) FORECAST INDICES DURING TWO WINTERS

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1. INTRODUCTION

- **Clear air turbulence:** in-flight bumpiness away from thunderstorms, generally above 500 mb (Ellrod et al. 2012)
- **CAT is an unsolved forecasting problem**, with techniques still falling short of Turbulence Joint Safety Implementation Team guidelines for probability of detection of its occurrence and absence (http://www.cast-safety.org/pdf/jsit_turbulence.pdf) developed by CAST, a collaboration of FAA, NASA, DoD, and aviation industry organizations
- **Turbulence is the leading cause of non-fatal flight injuries;** 65% of weather-related aviation incidents involve turbulence, costing carriers tens of millions of dollars and causing hundreds of injuries per year (Sharman et al. 2006)
- The vast majority of incidents occur above FL100 (flight level 10,000 feet), with **many of them being CAT-related**

Figure 1. Kelvin-Helmholtz billows indicative of CAT, as seen from an airplane. Photograph by John Knox.

- **Forecasting improvements are needed**, the inspiration for this collaborative research with the Aviation Weather Center to develop and implement new and improved methods (see also Poster 3.7)

2. FORECASTING METHODS

- Two methods were analyzed using forecasts from NCEP's Global Forecast System (GFS):
  - Ellrod-Knapp Turbulence Index (Ellrod and Knapp 1992), also known as "TI" for Turbulence Index TI1, based on vertical wind shear (VWS) and flow deformation DEF:

TI = VWS x DEF

  - The new Ellrod-Knox modification to Ellrod-Knapp (Ellrod and Knox 2010) which incorporates a divergence tendency term DVT to account for CAT that occurs in unbalanced flow situations (e.g., Knox 1997), abbreviated here as "EKI"

EKI = TI + DVT

3. OPERATIONAL METHODOLOGY

- Divergence tendency was calculated using 3-h time increments; scaling was used because tendencies calculated from model time steps are ~ 2 orders of magnitude smaller than VWS and DEF
- **DVT = C [(du/dx + dv/dy)$_{h2}$ - (du/dx +dv/dy)$_{h1}$] /10800,** where C is a model-dependent empirical constant (leading to scaled divergence tendency) and 10800 is the number of seconds in 3 hours
- Tests at AWC yielded good results for the GFS model for C = 100 and a time step of 3 hours
- Forecasts were made for 200-250 hPa layer (equiv., FL 340-390)
- Deformation and divergence were calculated at the top of the layer

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4. VERIFICATION METHODOLOGY

- **Two winters analyzed:** December-March 2009-10 and December-March 2010-11 using 1° x 1° GFS output
- Larger database than Ellrod and Knox (2010):
  - **2009-10 winter: Over 3500 PIREPs, over 1200 moderate-or-greater (MOG) reports**
  - **2010-11 winter: Over 4000 PIREPs, over 1000 MOG reports**
- **TI and EKI forecasts calculated from 24-h GFS forecasts** (23-km horizontal resolution) valid at 0Z and 18Z each day
  - PIREPS within +/- 1 h of forecast time included in analysis
- PIREPs west of Denver, CO ignored (to eliminate most mountain wave turbulence)
- PIREPs within 50 miles of radar reflectivities of 50 dBz or greater ignored (to eliminate turbulence due to deep convection)
- Performance evaluated using various index thresholds for both TI and EKI: 0, 4, 6, 8, 10, 12 and 16 (x 10^{-9} s^{-2})

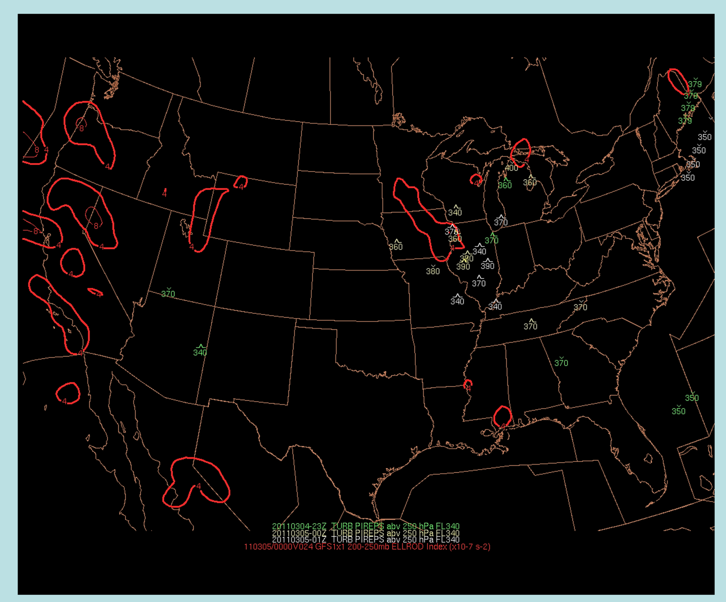

Figure 2. Ellrod-Knapp TI index for forecasting clear air turbulence, for a representative day during the study period. Contour levels start at 4, and PIREPs are overlaid.

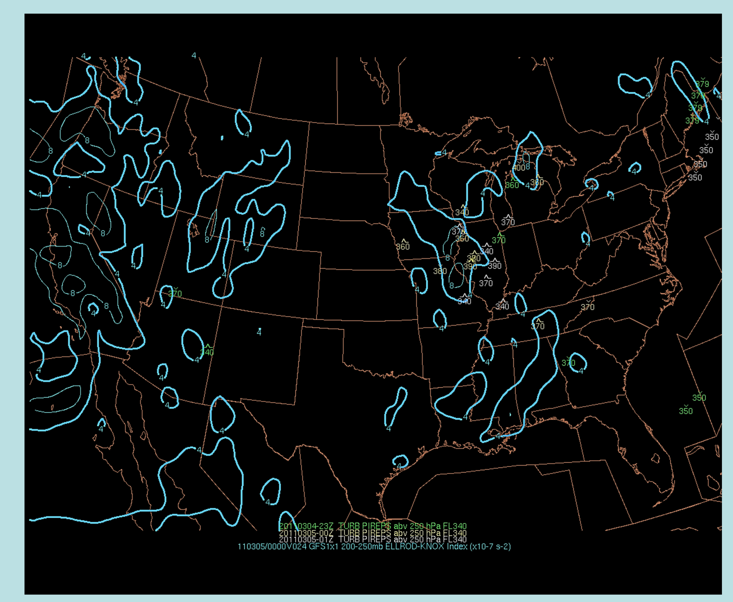

Figure 3. For the same time as in Figure 2, except for the Ellrod-Knox index EKI.

5. VERIFICATION METRICS

	Observed CAT	**Observed NULL**
Forecast CAT	**(a)** Hit	**(b)** False Alarm
Forecast No CAT	**(c)** Miss	**(d)** Correct Rejection

- Hit Rate (**PODy**): a/(a+c)
- **PODn**: d/(b+d)
- True Skill Statistic (**TSS**): PODy + PODn -1
- Critical Success Index (**CSI**): a/(a+b+c)

6. RESULTS

2009-10 WINTER:

Table 1: PODy, PODn, TSS, and CSI for **all turbulence reports** by threshold for TI and EKI December 2009-March 2010. Boldface indicates the superior statistic of the two indices for each threshold and metric.

GFS 24-h	Dec 2009-Mar 2010 0z and 18z n=3518 PIREPs							
	PODy		PODn		TSS		CSI	
Threshold	TI	EKI	TI	EKI	TI	EKI	TI	EKI
4	0.567	**0.777**	**0.768**	0.592	0.335	**0.369**	0.441	**0.518**
6	0.354	**0.542**	**0.880**	0.777	0.234	**0.319**	0.308	**0.426**
8	0.250	**0.385**	**0.934**	0.876	0.184	**0.262**	0.231	**0.334**
10	0.135	**0.208**	**0.969**	0.940	0.104	**0.148**	0.130	**0.194**
12	0.105	**0.160**	**0.979**	0.965	0.085	**0.125**	0.103	**0.154**
16	0.062	**0.094**	**0.988**	0.979	0.050	**0.074**	0.061	**0.092**

Table 2: As in Table 1, but for **MOG turbulence reports** by threshold for TI and EKI December 2009-March 2010.

GFS 24-h	Dec 2009-Mar 2010 0z and 18z MOG: n=3146 PIREPs							
	PODy		PODn		TSS		CSI	
Threshold	TI	EKI	TI	EKI	TI	EKI	TI	EKI
4	0.577	**0.795**	**0.768**	0.592	0.345	**0.387**	0.420	**0.480**
6	0.365	**0.554**	**0.880**	0.777	0.245	**0.331**	0.306	**0.408**
8	0.259	**0.397**	**0.934**	0.876	0.193	**0.273**	0.234	**0.331**
10	0.138	**0.220**	**0.969**	0.940	0.107	**0.159**	0.132	**0.200**
12	0.106	**0.166**	**0.979**	0.965	0.086	**0.131**	0.103	**0.157**
16	0.061	**0.096**	**0.988**	0.981	0.048	**0.077**	0.059	**0.093**

2010-11 WINTER:

GFS 24-h	Dec 2010-Mar 2011 0z and 18z n=4028 PIREPs							
	PODy		PODn		TSS		CSI	
Threshold	TI	EKI	TI	EKI	TI	EKI	TI	EKI
4	0.334	**0.516**	**0.856**	0.718	0.190	**0.235**	0.277	**0.368**
6	0.213	**0.345**	**0.936**	0.884	0.149	**0.229**	0.195	**0.296**
8	0.122	**0.199**	**0.954**	0.924	0.076	**0.124**	0.114	**0.180**
10	0.073	**0.130**	**0.986**	0.970	0.059	**0.100**	0.072	**0.125**
12	0.057	**0.098**	**0.990**	0.980	0.046	**0.078**	0.056	**0.095**
16	0.019	**0.032**	**0.992**	0.988	0.012	**0.020**	0.019	**0.031**

Table 3: All **turbulence statistics**, as in Table 1, but for December 2010-March 2011.

GFS 24-h	Dec 2010-Mar 2011 0z and 18z MOG: n=3552 PIREPs							
	PODy		PODn		TSS		CSI	
Threshold	TI	EKI	TI	EKI	TI	EKI	TI	EKI
4	0.479	**0.658**	**0.856**	0.718	0.335	**0.376**	0.372	**0.421**
6	0.274	**0.442**	**0.936**	0.884	0.211	**0.326**	0.243	**0.359**
8	0.194	**0.305**	**0.954**	0.924	0.149	**0.228**	0.178	**0.264**
10	0.095	**0.163**	**0.986**	0.970	0.081	**0.133**	0.093	**0.154**
12	0.071	**0.127**	**0.990**	0.980	0.061	**0.106**	0.070	**0.122**
16	0.039	**0.069**	**0.992**	0.988	0.030	**0.057**	0.038	**0.068**

Table 4: MOG **turbulence statistics**, as in Table 2, but for December 2010-March 2011.

7. CONCLUSIONS

- **EKI is generally superior to TI for 24-h GFS forecasts; for example:**
  - ✓ **PODy: EKI improves on TI by 37-78% (all turbulence), 37-79% (MOG)**
  - ✓ **TSS: EKI improves on TI by 10-48% (all turbulence), 12-90% (MOG)**
  - ✓ **CSI: EKI improves on TI by 17-74% (all turbulence), 13-79% (MOG)**

8. REFERENCES

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