

# **Performance of the Ellrod-Knox and Lighthill-Ford-Knox clear air turbulence (CAT) algorithms at the Aviation Weather Center**

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# What Is/Why Care About CAT?

- CAT = in-flight bumpiness away from thunderstorms, generally above 500 hPa (Ellrod et al. 2003 *Encyclopedia of the Atmospheric Sciences*)
- CAT = unsolved aviation forecast problem (Sharman et al. 2006 *WAF* article on GTG)
- 65% of weather-related commercial aviation incidents attributable to turbulence; “tens of millions” in monetary losses and hundreds of injuries per year (Sharman et al. 2006)
- Rare but high-profile fatal CAT encounters:
  - December 1997, UAL Flight 826: 1 dead, 97 injured, 3 crew members seriously injured when plane descends abruptly (g forces 1.8G to -0.8G in 6 seconds) at 31,000 feet in severe turbulence over western Pacific
- Vast majority of turbulence incidents above 10,000 feet (Sharman et al. 2006)—many (but not all) CAT

# Overview of Cooperative and Educational Effort

- **UCAR/COMET-funded project** “Improving Clear Air Turbulence (CAT) Forecasts at the NOAA/NWS/NCEP/AWC with State-of-the-Art Research Diagnostics” (through 2012)
- **Work to date:**
  - Development of operational method of Ellrod-Knox index (**EKI**)
  - RUC 6-hour and 12-hour verification of EKI (Ellrod et al. poster)
  - [Independent verification with UKMO Global Model; Ellrod poster]
  - GFS 24-hour forecast verification of EKI (this talk)
  - Initial efforts to develop operational Lighthill-Ford index (2011-12)
  - Undergraduate/graduate seminar on research methods, focused on CAT forecast verification (Summer 2011)
  - M.S. thesis project on CAT forecast verification (Wilson, 2011-12)

# New CAT Forecasting Method: The EKI Diagnostic

(Ellrod and Knox, 2010 *Weather and Forecasting*)

- Original method: Ellrod and Knapp (1992 *Weather and Forecasting*) “Turbulence Index”, **TI**; used internationally (e.g., NOAA products)
- $TI = VWS \times DEF$
- New diagnostic: **EKI**, is  $TI +$  “divergence trend” DVT to account for CAT in unbalanced or highly divergent situations, especially in anticyclonic conditions (Knox 1997 *Mon. Wea. Rev.*)

# Operational Methodology of the EKI Diagnostic

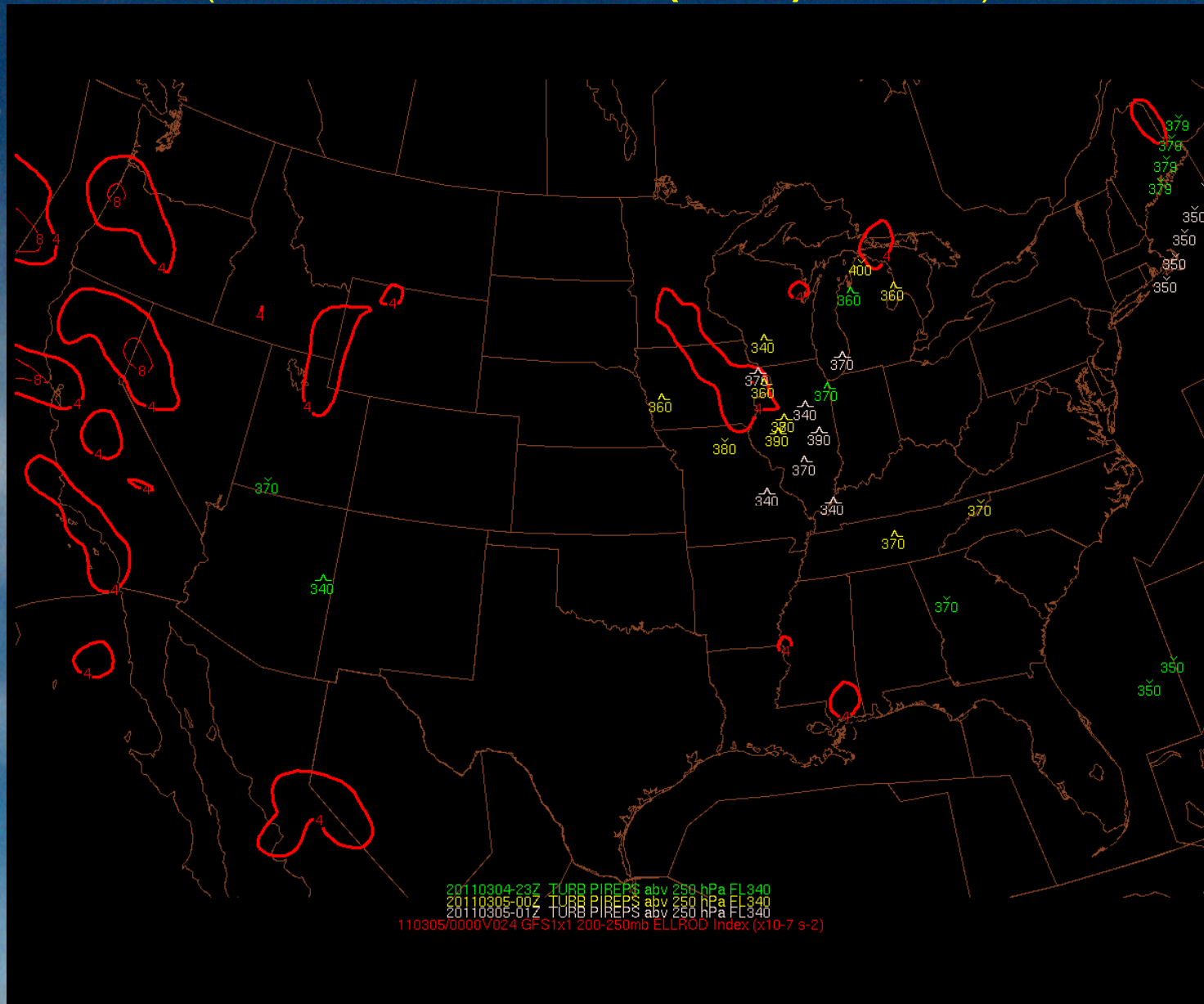
- Divergence *trend* used instead of *tendency* because tendencies calculated from model time steps are  $\sim 2$  orders of magnitude smaller than VWS and DEF
- $DVT = C [(du/dx + dv/dy)_{h_2} - (du/dx + dv/dy)_{h_1}]$   
where C is an empirical constant (scaled divergence tendency)
- Tests at AWC yielded good results for GFS for  $C = 100$  and a time step of 3 hours
- Forecasts made for 200-250 hPa layer (equiv., FL 340-390)
- Deformation and divergence calculated at top of layer

# Verification Methodology

- PIREPs for December 2010-March 2011
  - Over 4000 PIREPs included
  - Over 1000 moderate-or-greater “MOG” reports
  - Larger database than in Ellrod and Knox (2010)
- EKI and TI 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
- To attempt to eliminate mountain wave turbulence, PIREPs west of Denver, CO ignored
- To attempt to eliminate turbulence due to deep convection, PIREPs within 50 miles of radar reflectivities of 50 dBz or greater ignored
- Performance evaluated using various index thresholds for both EKI and TI: 0, 4, 6, 8, 10, 12 and 16 ( $\times 10^{-9} \text{ s}^{-2}$ )

# Ellrod-Knapp (TI) 5 Mar 2011 0Z

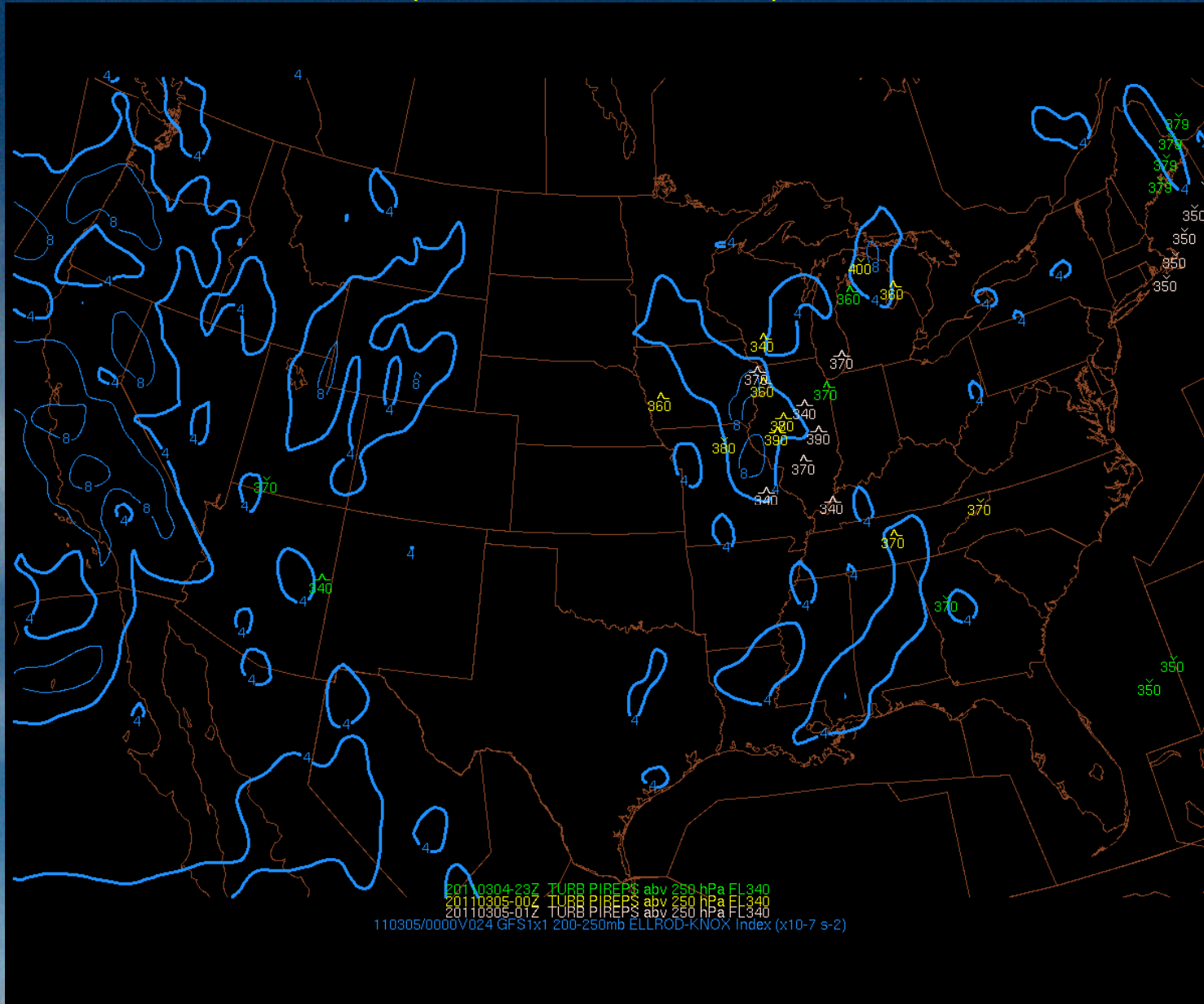
(threshold contours 4 (thick),8,16,32)



All PIREPs and index calculations from S. Silberberg, AWC

# Ellrod-Knox (EKI) 5 Mar 2011 0Z

(same thresholds)



- More hits for EKI, some more false alarms



# Forecast Verification Statistics

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

- Hit Rate (**POD<sub>y</sub>**):  $a/(a+c)$
- **POD<sub>n</sub>**:  $d/(b+d)$
- True Skill Statistic (**TSS**):  $POD_y + POD_n - 1$
- Critical Success Index (**CSI**):  $a/(a+b+c)$
- **ROC curves**: (POD<sub>y</sub> vs. 1-POD<sub>n</sub>)

# Results (all turbulence reports)

Boldface indicates better performance vs. other index

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	<b>0.516</b>	<b>0.856</b>	0.718	0.190	<b>0.235</b>	0.277	<b>0.368</b>
6	0.213	<b>0.345</b>	<b>0.936</b>	0.884	0.149	<b>0.229</b>	0.195	<b>0.296</b>
8	0.122	<b>0.199</b>	<b>0.954</b>	0.924	0.076	<b>0.124</b>	0.114	<b>0.180</b>
10	0.073	<b>0.130</b>	<b>0.986</b>	0.970	0.059	<b>0.010</b>	0.072	<b>0.125</b>
12	0.057	<b>0.098</b>	<b>0.990</b>	0.980	0.046	<b>0.078</b>	0.056	<b>0.095</b>
16	0.019	<b>0.032</b>	<b>0.992</b>	0.988	0.012	<b>0.020</b>	0.019	<b>0.031</b>

- **PODy: EKI improves upon TI by 53-78%**
- **PODn: TI better than EKI by only 0.4-19%**
- **TSS: EKI improves upon TI by 24-83%**  
(54% improvement at threshold = 6)
- **CSI: EKI improves upon TI by 33-74%**

# For Comparison: EKI vs. TI using RUC 6-h and 12-h forecasts (left and center) versus GFS results (right)

TI vs. EKI 6-h RUC  
(threshold of 4)

	July 2007 N=335		Dec 2007 N=833		Combined N=1168	
	TI	EKI	TI	EKI	TI	EKI
PODy	0.220	0.349	0.321	0.474	0.284	0.421
PODn	0.887	0.775	0.706	0.678	0.736	0.692
TSS	0.107	0.123	0.027	0.152	0.020	0.113

Ellrod and Knox, 2010 *Weather and Forecasting*

TI vs. EKI RUC  
(threshold of 6)

	RUC2 6h Fcst Dec '10- Jan '11 N=901		RUC2 12h Fcst Dec '10- Jan '11 N=602	
	TI	EKI	TI	EKI
PODy	0.480	0.662	0.450	0.577
PODn	0.796	0.713	0.836	0.754
TSS	0.276	0.375	0.286	0.331

Ellrod et al. poster at ARAM

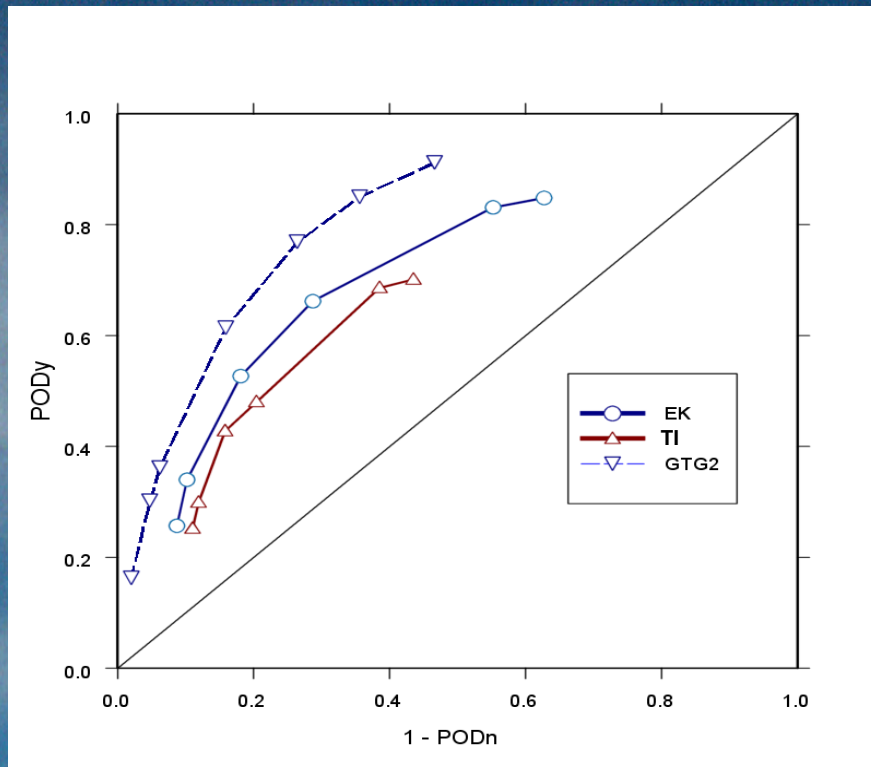
GFS EKI Results  
(thresholds 4 and 6)

GFS 24-h fcst	EKI 4 Dec 10- Mar 11 N=4028	EKI 6 Dec 10- Mar 11 N=4028
PODy	0.516	0.345
PODn	0.718	0.884
TSS	0.235	0.229

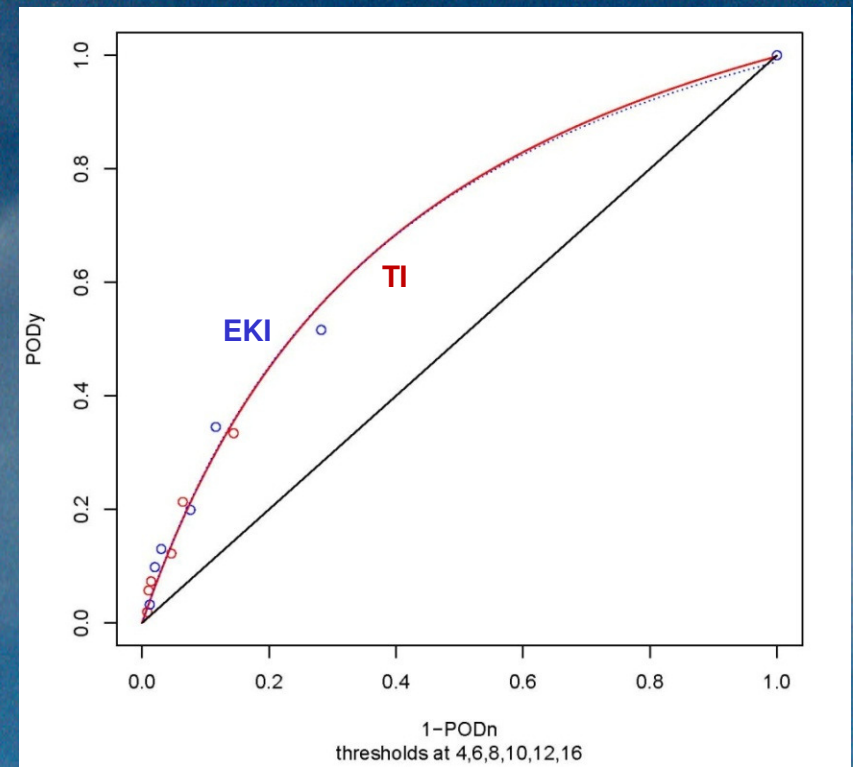
- GFS 24-h results better than Ellrod-Knox 6-h RUC results
- GFS 24-h results intermediate between Ellrod-Knox 6-h results and latest RUC 6-h and 12-h results

# Results: ROC Curves (all turbulence)

RUC 6-h  
Dec 2010-Jan 2011  
(Ellrod et al. poster)



GFS 24-h  
Dec 2010-Mar 2011



- Results improve upon Ellrod-Knox (2010) ROC curves (not shown)
- Improvement more obvious with RUC than GFS

# GFS Results (MOG turbulence only)

Boldface indicates better performance vs. other index

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	<b>0.658</b>	<b>0.856</b>	0.718	0.335	<b>0.376</b>	0.372	<b>0.421</b>
6	0.274	<b>0.442</b>	<b>0.936</b>	0.884	0.211	<b>0.326</b>	0.243	<b>0.359</b>
8	0.194	<b>0.305</b>	<b>0.954</b>	0.924	0.149	<b>0.228</b>	0.178	<b>0.264</b>
10	0.095	<b>0.163</b>	<b>0.986</b>	0.970	0.081	<b>0.133</b>	0.093	<b>0.154</b>
12	0.071	<b>0.127</b>	<b>0.990</b>	0.980	0.061	<b>0.106</b>	0.070	<b>0.122</b>
16	0.039	<b>0.069</b>	<b>0.992</b>	0.988	0.030	<b>0.057</b>	0.038	<b>0.068</b>

- **PODy: EKI improves upon TI by 37-79%**
- **TSS: EKI improves upon TI by 12-90%**  
(55% improvement at threshold = 6)
- **CSI: EKI improves upon TI by 13-79%**
- ROC curves: TI, EKI curves similar (not shown)

# Summary of Results and Future Work

- **Results of Ellrod and Knox (2010) confirmed, extended**
- **Ellrod-Knox Index EKI improves upon Ellrod-Knapp TI for most forecast metrics for 24-h GFS forecasts**
- **PODy, PODn and TSS values better for 24-h GFS forecasts than for RUC 6-h forecasts in Ellrod and Knox 2010 study**
- **EKI improves upon TI for both MOG and all levels of turbulence with GFS**
- **Thresholds of 4 or 6 appear to give the best results for GFS (similar to RUC results)**
- **2011-12: Case studies and expansion to additional models and CAT forecasting indices**
- **End result: New, improved operational CAT indices**

**Questions?**

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