Naval Research Laboratory
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Clear Air Turbulence Indices Derived from U. S. Navy Numerical Model Data: A Verification Study

G. N. Vogel
C. R. Sampson

Forecast Support Branch
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Two clear air turbulence indices (TI and CCAT) are computed using data from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model. The TI index is based on deformation and vertical wind shear; the CCAT index is based on the advection of vertical stability and absolute vorticity. Verification of both indices is accomplished by comparing model-derived analyses and forecasts with pilot reports of turbulence intensity. Correlations between turbulence intensity and index value indicate that only the TI index has any ability (viz., minimal) in the forecasting of any arbitrary (smooth through severe) turbulence event. Verification statistics for both indices show high false alarm rates (indicative of over-forecasting) and only modest capability in correctly forecasting observed moderate or or greater turbulence. Comparisons among analysis, 12- and 24-hour statistics do not indicate degradation of turbulence forecasting skill with lead time for either index. A reduction in model resolution from 2.5° to 1.0° provides slightly improved forecasting capability to the CCAT index, noticeably less improvement for the TI index. Overall results indicate a slight preference for the TI index in operational forecasting of clear air turbulence when using the NOGAPS model output.

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TABLE OF CONTENTS

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CLEAR AIR TURBULENCE INDICES DERIVED FROM U. S. NAVY NUMERICAL MODEL DATA: A VERIFICATION STUDY

1. INTRODUCTION

The U.S. Navy has had a long-standing interest in atmospheric phenomena which adversely affect aviation operations and flight safety. One of these phenomena is clear air turbulence (CAT), which results from breaking gravity waves in strongly sheared environments in the vicinity of upper-tropospheric jet streams and frontal zones. Due to CAT's small-scale and relatively rapid fluctuations, its analysis and short-range forecasting is a difficult operational problem. An early approach to CAT forecasting related upper-air synoptic flow patterns to the occurrence of CAT (Rammer, 1973). More recently, this approach has been broadened to include empirical relations between CAT and satellite cloud imagery (Ellrod, 1985), and is now available as an automated expert system (Peak, 1991). At various operational centers, CAT forecasts are routinely issued in terms of a turbulence index derived from numerical model data (FNOC, 1986; Ellrod and Knapp, 1992). Such indices attempt to correlate CAT occurrence with select factors deemed to contribute significantly to turbulence potential.

In this study, two turbulence indices will be evaluated using gridded numerical model data from the Navy Operational Global Atmospheric Prediction System (NOGAPS) collected during the spring of 1995. The first is a widely-used CAT forecasting/diagnostic algorithm described by Ellrod and Knapp (1992) based on horizontal wind deformation and vertical wind shear. The second, which has been available operationally at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for at least the last two decades, uses vertical stability as its forecast parameter (FNOC, 1986). Verification of the two indices is accomplished by comparing CAT analyses and forecasts with pilot reports (PIREPs) obtained from the National Center for Atmospheric Research (NCAR). The effect of model resolution and forecast length on CAT forecasting performance is examined in detail.

2. TURBULENCE INDICES

2.1 Ellrod (TI)

An index for clear air turbulence described by Ellrod (1989) is

$$TI = DEF * VWS$$

where *DEF* is the deformation of the wind composed of the stretching (*DST*) and shearing (*DSH*) components

$$DST = \partial u/\partial x - \partial v/\partial y$$

$$DSH = \partial v/\partial x + \partial u/\partial y$$

$$DEF = (DST^2 + DSH^2)^{1/2} \; ,$$

and *VWS* is the vertical wind shear

$$VWS = [\,(\partial u/\partial z)^2 + (\partial v/\partial z)^2\,]^{1/2} \; .$$

Here, u and v are the zonal and meridional wind components specified in Cartesian (x,y,z) coordinates. *TI* values are in units of $10^{-7}\ s^{-2}$, and range (in this study) from zero to about 18 units.

The choice of the product of deformation and vertical wind shear for *TI* was based on correlation studies of these parameters to turbulence occurrence. Synoptic-scale upper-level flow patterns that are associated with large deformation are conducive to CAT production. Large vertical wind shear within a stable layer exceeding a critical limit results in shearing instability, which breaks down the flow into turbulent eddies.

2.2 FNMOC (CCAT)

The turbulence index in current operational use at FNMOC is based on the advection of vertical stability and absolute vorticity. The index is an adaptation of Theodorsen's (1954) theoretical formulation of turbulence to available numerical meteorological data fields at the FNMOC. For a predetermined layer of depth Δz, the CCAT index (FNOC, 1986) is expressed as

$$CCAT = \frac{g}{T} \frac{\zeta + f}{f} \bar{V} \cdot grad \left[\frac{dT}{dz} \right],$$

where ζ and $\bar{V}$ are the mean relative vorticity and wind vector for the layer, f is the Coriolis parameter and g is the acceleration of gravity. The variable T is the mean temperature of the layer and is computed as $(\sqrt{T_u T_l})$, where T_u and T_l are the temperatures of the upper and lower levels of the layer. CCAT values are in units of 10^{-9} s^{-3}; absolute values range (in this study) from zero to about 37 units.

As defined, the CCAT index can be either positive or negative. When many individual CCAT index fields are averaged, the resultant mean field tends to be "noisy" and lacking definite structure. The choice of the magnitude (i.e., absolute value) of CCAT as the turbulence index results in a more coherent pattern structure in mean CCAT contour plots. Based on data in this study, negative correlations are found between turbulence intensity and CCAT index values. On the other hand, when the magnitude of CCAT is used as the turbulence index, positive correlations exist between index values and turbulence intensity. In this verification study, the magnitude of CCAT is used as the turbulence index value.

3. DATA

3.1 Model

The Navy Operational Global Atmospheric Prediction System (NOGAPS) provided the required data for computation of the turbulence indices evaluated in this study. The NOGAPS is run twice daily (at 00Z and 12Z) at the FNMOC. Data for the study is from the NOGAPS Version 3.4 forecast model which consists of a multivariate optimum interpolation analysis, a nonlinear normal mode initialization scheme, and a 159-wave triangular truncation (~ 3/4 deg. horizontal resolution), 18-level spectral forecast model (Hogan et. al., 1991; Goerss and Phoebus, 1993).

NOGAPS data were obtained from two distinct environmental databases, both of which provided interpolated meteorological fields on standard constant pressure surfaces. During the 3-month period March through May 1995, the Naval Environmental Operational Nowcasting System (NEONS) provided wind and geopotential height data required for the TI calculation on a 2.5° x 2.5° spherical grid. Although temperature data were available in early March, CCAT computations using NEONS did not commence until April 21 when absolute ($\zeta + f$) vorticity fields became available. During the second half of May 1995, meteorological data fields (u,v,z,T,ζ) on a 360 x 181 spherical grid (1 deg. horizontal resolution) were obtained using the ISIS (Integrated Software Information Standard) environmental database at FNMOC.

As available, meteorological data fields at both the 1.0° and 2.5° horizontal resolutions were archived at three forecast lengths (the analysis, and 12 and 24 hours) and at seven standard pressure levels (500, 400, 300, 250, 200, 150 and 100 mb). The data were collected for a regional grid encompassing the continental U.S. and adjacent areas (viz., 5°N - 60°N, 50°W - 130°W).

3.2 PIREPs

3.2.1 Description

For the period March through May 1995, a database comprising over 119,000 aircraft pilot reports was obtained from the National Center for Atmospheric Research. These PIREPs contain encoded numeric data which provide information on weather, cloud layers, icing and turbulence. For each PIREP, up to two turbulence layers or levels may be specified, each as a coded group containing turbulence base and top heights, frequency, intensity and type. Additional turbulence information may be available within a PIREP as alphanumeric remarks.

The base and top heights of a reported turbulence layer are generally specified to the nearest thousands of feet. Turbulence type is encoded as either clear air turbulence (CAT), chop, or low-level wind shear (not applicable to this study). Since no specific code is used to report mountain wave turbulence (MWT) or turbulence near thunderstorm tops (TNTT), such occurrences can only be ascertained through pilot remarks. Turbulence intensity is defined numerically as follows : 0) smooth, 1) smooth-light, 2) light, 3) light-moderate, 4) moderate, 5) moderate-severe, 6) severe, 7) severe-extreme and 8) extreme. For non-smooth intensities, turbulence frequency may be specified as either occasional, intermittent or continuous. Within a given PIREP, a numeric value of '-9' is assigned any turbulence code element (frequency, intensity, type) for which no information is given.

3.2.2 Selection Procedure

Various criteria were applied to the original PIREP database to select those pilot reports finally used as verification data for model-derived turbulence indices. PIREPs needed to be located within the study's model grid domain and were required to have occurred within one hour of 00Z or 12Z. Given model data at the appropriate date and time, a PIREP was matched to the grid point nearest to the PIREP, provided the report was no more than 80 km from that model grid point, and at an elevation above 500 mb (~ 5.5 km). Here, the 500 mb height was determined from the model's analysis (or, if unavailable, the 12 or 24 hr forecast) height at the gridpoint. For some PIREPs, pilot remarks concerning turbulence provided new or additional information which was numerically encoded. However, those PIREPs whose remarks clearly identify the cause of turbulence as due either to convection or mountain waves were not used, since neither turbulence index evaluated herein is designed to forecast such types of turbulence.

Having passed the above selection criteria, a PIREP's turbulence information was assigned (based on reported elevations) to one or more of the following constant pressure surface layers: 500-400 mb, 400-300 mb, 300-250 mb, 250-200 mb, 200-150 mb, and 150-100 mb. For each PIREP, the base and top height limits for these layers were given by model constant pressure surface heights at the chosen gridpoint. PIREPs within 5 minutes and 40 km of each other were retained as separate reports if their turbulence information was from different layers or, combined into one report, if they provided information for the same layer. In general, for any PIREP (individual or combined) reporting two different turbulence intensities within a single layer, the larger intensity value is selected for comparison with model-derived turbulence indices.

Since both the TI and CCAT indices forecast clear air turbulence, it seems appropriate to have included turbulence " type " in the PIREP database selection process. Unfortunately, very few PIREPs were identified as CAT type. Thus, in order to carry out this study, PIREPs whose "type" was not given as well as those described as type "chop" were utilized, on the assumption that most of these PIREPs described actual CAT events (and not MWT or TNTT).

3.2.3 Distribution

Two PIREP datasets were created for this study - one for comparison with NOGAPS 2.5° data, the other, for comparison with NOGAPS 1.0° data. The 2.5° dataset is based on 1119 PIREPS over the period March through May 1995; temporally, about two-thirds of these PIREPs correspond to 00Z and one-third correspond to 12Z. A total of 529 PIREPs from the second half of May 1995 were used to create the 1.0° dataset; temporally, about three-fifths of these were at 00Z, the remainder at 12Z. The two PIREP datasets are not independent, since 192 PIREPs are used mutually.

Characteristics of the 2.5° PIREP dataset are given in Table 1. Due to the availability of turbulence information in multiple layers with some PIREPs, the total number of (layer) reports (1281) is about one-seventh larger than the number of PIREPs included with this dataset. The number of reports is fairly steady for the lowest four layers, falling off dramatically for the highest (150-100 mb) layer. Only two reports identify the turbulence type as "CAT"; over three-fourths of all reports do not specify turbulence type. Reports of turbulence frequency are about equal between "occasional" and "continuous"; the frequency "intermittent" is seldom reported. In the dataset, about three-eights of all reports correspond to "smooth" turbulence, with the largest number of such reports within the 250-200 mb layer. About half of all turbulence intensities are either reported as light or moderate. The overall percentage of reports of intensity moderate or greater (MOG) is about 27%. Only about 3% of all reports identify turbulence intensity greater than moderate; of these, more than half occur in the lowest two layers. Extreme turbulence is reported only once; the rather ambiguous "smooth-light" category is never reported.

Spatially, the largest concentration of PIREPs included in the 2.5° dataset occurs over the southern Ohio Valley (Figure 1). A secondary maximum is centered over southeastern Colorado. Interestingly, perhaps due to generally low flight levels, only 10 PIREPs (less than 1%) come from the heavy traffic New York-Boston corridor. Although more actual cases of MOG turbulence are reported over the Ohio and Missouri Valleys, 50% or higher frequency of MOG turbulence (per 5° x 5° latitude-longitude bins of > 3 reports) only occurs over central California, Montana and the northwest Gulf of Mexico (including coastal Louisiana).

Table 1 - Characteristics of the 2.5° PIREP dataset, including the number of reports according to turbulence type, frequency and intensity, and the average base and top heights (in ft), for selected layers from 500 to 100 mb.

	LAYER (MB)						
	500-400	400-300	300-250	250-200	200-150	150-100	500-100
AVG. HGT.							
BASE	18495	23818	30537	34422	39040	44685	----
TOP	23858	30353	34482	39096	44994	53071	----
NO. RPTS.	252	303	253	308	160	5	1281
TYPE							
CAT	1	1	0	0	0	0	2
CHOP	55	73	66	68	28	0	290
NOT GIVEN	196	229	187	240	132	5	989
FREQUENCY							
NO (SMOOTH)	84	91	80	132	88	4	479
OCCASIONAL	28	28	27	29	16	0	128
INTERMITTENT	3	2	2	3	2	0	12
CONTINUOUS	19	28	38	33	15	0	133
NOT GIVEN	118	154	106	111	39	1	529
INTENSITY							
SMOOTH	84	91	80	132	88	4	479
SMOOTH-LGT.	0	0	0	0	0	0	0
LIGHT	56	86	86	73	34	0	335
LIGHT-MOD.	33	30	24	21	9	0	117
MODERATE	69	84	58	76	24	0	311
MOD.-SEVERE	4	3	2	4	2	1	16
SEVERE	5	9	3	2	2	0	21
SEVERE-EXT.	0	0	0	0	0	0	0
EXTREME	0	0	0	0	1	0	1
NOT GIVEN	1	0	0	0	0	0	1

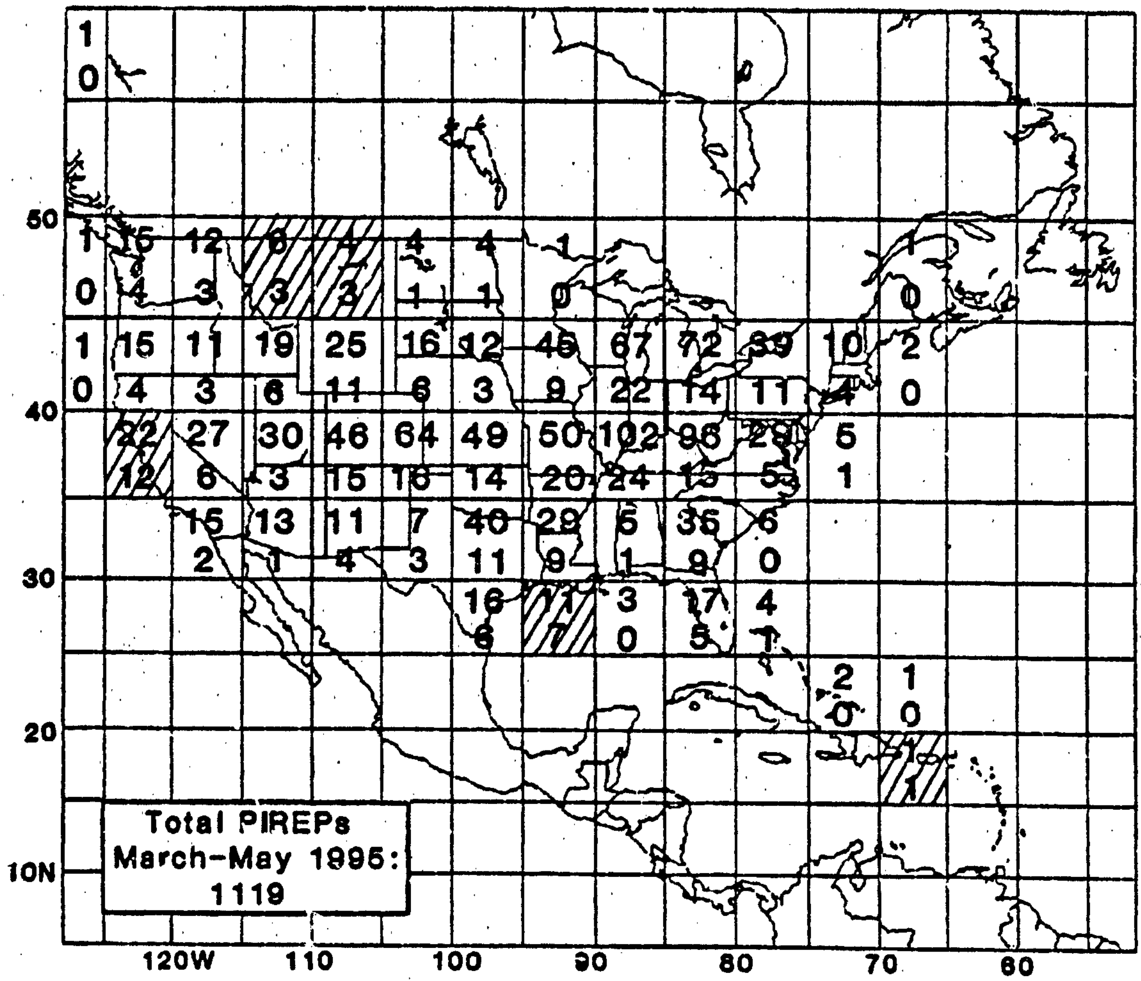

Figure 1 - Spatial distribution of the PIREP 2.5° dataset, corresponding to the period March - May 1995. For 5° x 5° latitude-longitude boxes, the total number of PIREPs and the number of MOG intensity are given. Striped boxes indicate ≥ 50% MOG intensity reports.

The distribution of pilot reports for the high resolution 1.0° dataset is presented in Table 2. Reflecting the late springtime period of this dataset, layer average base and top heights are considerably higher than those for the late winter/spring 2.5° dataset. In general, the distribution of turbulence elements (type, frequency and intensity) by categories is quite similar for the 1.0° and 2.5° datasets. For example percentages of smooth intensity reports and those of intensity MOG vary by less than 1% between the two datasets. One slight difference is the ratio of occasional to continuous turbulence frequency, with the reporting ratio about 1:1 for the 2.5° dataset and about 5:3 for the 1.0° dataset. Spatially, in agreement with the 2.5° dataset, the 1.0° PIREP dataset has the highest reporting density over the southern Ohio Valley with a secondary maximum over eastern Colorado (Figure 2). A distinct concentration of heavy turbulence (≥ 50% frequency of MOG) is observed from southern Texas north-northwestward to the western Great Plains for the 1.0° dataset. Of any 5° x 5° box, the one which includes Chicago, IL has the highest number of MOG turbulence reports.

4. RESULTS

4.1 TI 3-Month Dataset

For the period March through May 1995, only model-derived TI fields at a 2.5° horizontal resolution are available for verification. Table 3 presents average TI values at selected PIREP intensity categories. One notes that at all categories with more than 100 data (categories moderate or less), average TI values decrease slightly with forecast length, while overall averages decrease from $2.17 \times 10^{-7}\ s^{-2}$ at tau=0 hr to $1.87 \times 10^{-7}\ s^{-2}$ at tau=24 hr. To examine the relationship between intensity and average TI value, linear correlation coefficients (based on the product-moment formula) are computed for each forecast length. In these computations, the intensity categories 1 (smooth-light), 7 (severe-extreme) and 8 (extreme) are excluded due to lack of data. The very high correlations ($r = 0.99$ at tau=0 hr, $r = 0.81$ at tau=12 hr, $r = 0.96$ at tau=24 hr) strongly suggest that the assumption of a direct (linear) relationship between turbulence intensity and TI index value is reasonable.

Table 2 - Characteristics of the 1.0° PIREP dataset, including the number of reports according to turbulence type, frequency and intensity, and the average base and top heights (in ft), for selected layers from 500 to 100 mb.

	LAYER (MB)						
	500-400	400-300	300-250	250-200	200-150	150-100	500-100
AVG. HGT.							
BASE	18793	24278	30966	34859	39792	46210	-----
TOP	24253	30935	34968	39562	45696	54255	-----
NO. RPTS.	144	128	131	138	53	1	595
TYPE							
CAT	0	0	0	0	0	0	0
CHOP	24	25	32	32	6	0	119
NOT GIVEN	120	103	99	106	47	1	476
FREQUENCY							
NO (SMOOTH)	63	31	32	61	34	1	222
OCCASIONAL	15	15	20	16	7	0	73
INTERMITTENT	0	0	0	0	0	0	0
CONTINUOUS	9	8	13	12	1	0	43
NOT GIVEN	57	74	66	49	11	0	257
INTENSITY							
SMOOTH	63	31	32	61	34	1	222
SMOOTH-LGT.	0	0	0	0	0	0	0
LIGHT	26	36	48	40	9	0	159
LIGHT-MOD.	13	12	10	7	4	0	46
MODERATE	37	42	38	28	4	0	149
MOD.-SEVERE	3	5	0	1	0	0	9
SEVERE	2	2	3	1	2	0	10
SEVERE-EXT.	0	0	0	0	0	0	0
EXTREME	0	0	0	0	0	0	0
NOT GIVEN	0	0	0	0	0	0	0

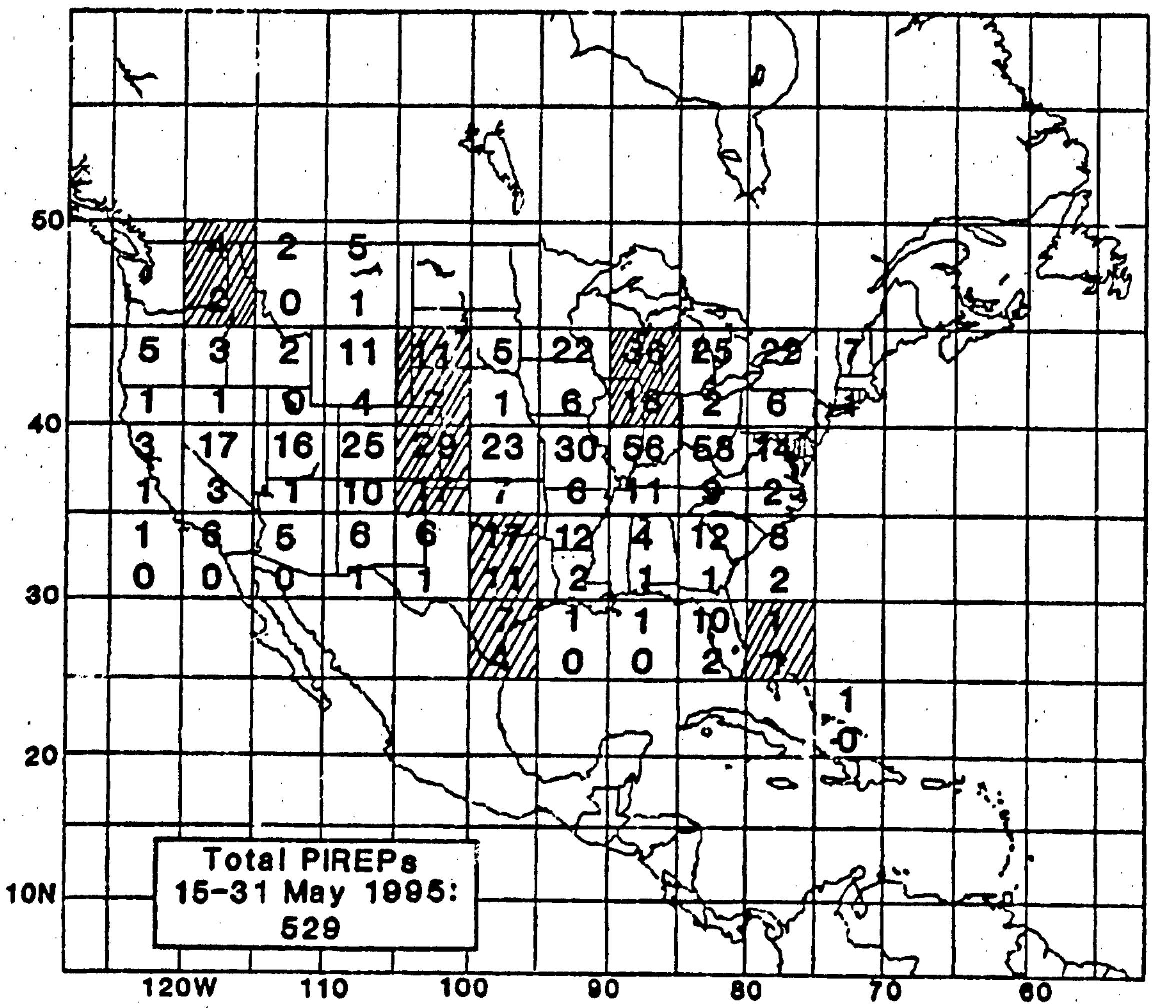

Figure 2 - Spatial distribution of the PIREP 1.0° dataset, corresponding to the period May 15-31, 1995. For 5° x 5° latitude-longitude boxes, the total number of PIREPs and the number of MOG intensity are given. Striped boxes indicate ≥ 50% MOG intensity reports.

Table 3 - NOGAPS 2.5° average TI values (units $10^{-7}\ s^{-2}$) and number of data for selected PIREP intensity categories, at tau = 0, 12, and 24 hr, for the period March-May 1995.

	TAU = 0 HR		TAU = 12 HR		TAU = 24 HR	
INTENSITY	NO. DATA	AVG. TI	NO. DATA	AVG. TI	NO. DATA	AVG. TI
SMOOTH	421	1.60	442	1.56	432	1.47
SMOOTH-LGT	0	----	0	----	0	----
LIGHT	312	2.21	322	1.89	300	1.88
LGT-MODERATE	116	2.55	110	2.36	109	2.28
MODERATE	287	2.70	304	2.30	298	2.20
MOD-SEVERE	13	2.90	15	3.20	16	2.69
SEVERE	20	3.16	20	2.45	18	2.63
SEV-EXTREME	0	----	0	----	0	----
EXTREME	1	0.80	1	1.10	1	1.20
ALL	1170	2.17	1214	1.94	1174	1.87

Table 4 - Distribution of reported intensities for a range of NOGAPS 2.5° TI index values (units $10^{-7}\ s^{-2}$), at tau = 0 hr.

	TI INDEX (TAU = 0 HR)							
INTENSITY	0 - <2	2 - <4	4 - <6	6 - <8	8 - <10	10 - <12	12 - <14	14- <16
SMOOTH	302	81	27	9	1	1	0	0
SMOOTH-LGT	0	0	0	0	0	0	0	0
LIGHT	183	84	24	14	4	3	0	0
LGT-MOD	63	29	17	1	3	2	1	0
MODERATE	152	71	37	9	3	10	4	1
MOD-SEVERE	7	3	0	3	0	0	0	0
SEVERE	9	5	2	2	1	1	0	0
SEV-EXTREME	0	0	0	0	0	0	0	0
EXTREME	1	0	0	0	0	0	0	0
MOG	169	79	39	14	4	11	4	1
ALL	717	273	107	38	12	17	5	1

The distribution of reported intensities with NOGAPS 2.5° TI analysis (tau = 0 hr) values is given in Table 4. One notes a wide range of intensities for a given TI index value $< 12 \times 10^{-7}\ s^{-2}$, suggesting low skill of the TI index in individual forecasting of turbulence intensity. Based on 1170 forecasts, the linear correlation coefficient relating intensity and TI is small ($r = 0.211$) yet sufficiently removed from zero (no correlation). Interestingly, this value is almost identical to the value $r = 0.219$ reported by McCann (1993) who correlated 567 turbulence intensities with TI values derived from gridded, objective analyses of upper-air rawinsonde data. Given correlation coefficients $r = 0.180$ and $r = 0.187$ at tau = 12 and 24 hr, respectively, no significant degradation of forecasting skill with lead time is noted for the NOGAPS 2.5° TI index.

To further examine the quality of TI (and later, CCAT) forecasts, three contingency table statistical indices - the probability of detection (POD), the false alarm rate (FAR) and the critical success index (CSI) - are computed. Given a particular event (viz., MOG turbulence), the probability of detection is the capability of correctly forecasting that event, and is defined as the number of correct (model) forecasts divided by the number of reported occurrences. The false alarm rate is a measure of the tendency to overforecast, and is defined as the number of incorrect forecasts divided by the number of forecast issued. As a measure of overall forecast skill, the critical success index (or threat score) is defined as the number of correct forecasts divided by the sum of the number of observed events and incorrect forecasts. Two TI threshold values (2 and 4 $\times 10^{-7}\ s^{-2}$) are selected for detecting moderate or greater turbulence; both these values were used by Ellrod and Knapp (1992) in verification of TI index derived from numerical models. Based on NOGAPS 2.5° analysis data (Table 4), slightly more than half (three-fourths) of all MOG turbulence reports occur at TI values < 2 (< 4); these percentages increase slightly with lead time (i.e., at tau = 12 and 24 hr).

Performance statistics of the TI index for 0, 12 and 24 hr NOGAPS 2.5° forecasts are given in Table 5. At the higher TI threshold value, a slight decrease in POD and CSI values occurs over the 0 to 24 hr forecast length. Performance statistics for the $2 \times 10^{-7}\ s^{-2}$ threshold value are more steady with lead time; the FAR actually improves very slightly from 0 to 24 hr (the lower the score, the better). More significant, POD and CSI statistics are considerably higher at the lower (2×10^{-7} s^{-2}) TI threshold value, while FAR values are only slightly higher. The improvement in forecast performance is most dramatic at tau = 24 hr, where the CSI score at the lower TI threshold value is two times higher than at the higher (4×10^{-7} s^{-2}) threshold value and the POD score is three times higher.

Table 5 - NOGAPS 2.5° March-May 1995 TI performance statistics at tau = 0, 12 and 24 hr, for two selected TI threshold values. Statistics based on MOG turbulence events.

TI THRESHOLD VALUE						
	2×10^{-7} s^{-2}			4×10^{-7} s^{-2}		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 HR	0.474	0.664	0.244	0.227	0.594	0.171
12 HR	0.447	0.651	0.244	0.171	0.594	0.136
24 HR	0.420	0.644	0.239	0.141	0.621	0.115

Although Table 5 performance statistics (for the TI 2×10^{-7} s^{-2} threshold) indicate some skill in forecasting MOG turbulence conditions, these statistical values are considerably worse than those reported by Ellrod (1989). In his validation study, based on analysis (tau = 0 hr) data from a numerical model of similar resolution as NOGAPS and a TI threshold value of 4×10^{-7} s^{-2}, Ellrod reported a 70% POD, a 20% FAR and a 60% CSI for the TI index. The large difference in forecasting skill between this study and Ellrod's results primarily from significant differences in verification techniques. Specifically, this study's verification criteria is much more restrictive - for a correct forecast, turbulence needs to occur within a rather shallow vertical layer and limited horizontal area (of radius 80 km from the nearest model grid point). On the other hand, Ellrod's verification criteria permits a successful forecast to occur over a considerably deeper layer and potentially a much larger (perhaps by a factor of ten) horizontal area.

4.2 Index Comparisons

4.2.1 2.5 Deg. Resolution

During the period late April through May 1995, a total of 75 NOGAPS 2.5° forecast runs (38 at 12Z, 37 at 00Z) are available for coincidental computation of TI and CCAT index fields. Average analysis (tau = 0 hr) fields of the TI and CCAT (magnitude) indices, for the 250-300 mb layer, are presented in Figures 3 and 4, respectively. On comparison, one notes that the structural pattern of both these average fields is quite similar. As expected, due to the presence of strong jet streams and frequent cyclogenesis, largest values for both indices are concentrated within the mid-latitudes; smallest values occur over the tropics and high latitudes. Both fields exhibit maxima over Colorado and the northeastern Unites States (New England and adjacent areas). Interestingly, the TI and CCAT maxima over Colorado, and the CCAT maximum over Ohio, occur in regions which contain high frequencies of turbulence reports during the late April-May period (see Figures 1 and 2). In a climatological sense, both the TI and CCAT indices appear capable of identifying regions of high risk for clear air turbulence.

Table 6 presents linear correlation coefficients and average index values for NOGAPS 2.5° TI and CCAT (magnitude) forecasts, for the period late April-May 1995. These statistics are based on about 500 coincidental TI and CCAT forecasts, of which only about 29% correspond to forecasts of MOG turbulence events. Both TI and CCAT average forecast values decrease slightly with increasing forecast length. Correlation coefficients for both indices indicate no degradation in forecasting skill with lead time, with correlation values highest at tau = 12 hr. Most significant, correlation coefficients are much higher (by about 0.2) for TI than those for CCAT. While the correlation coefficients for the TI index (from 0.223 to 0.265) indicate marginal skill in forecasting turbulence intensity, the very low CCAT correlation values (slightly above zero) indicate essentially no skill for this index in forecasting any individual turbulence event which could span a wide spectrum of intensities (i.e., smooth through severe).

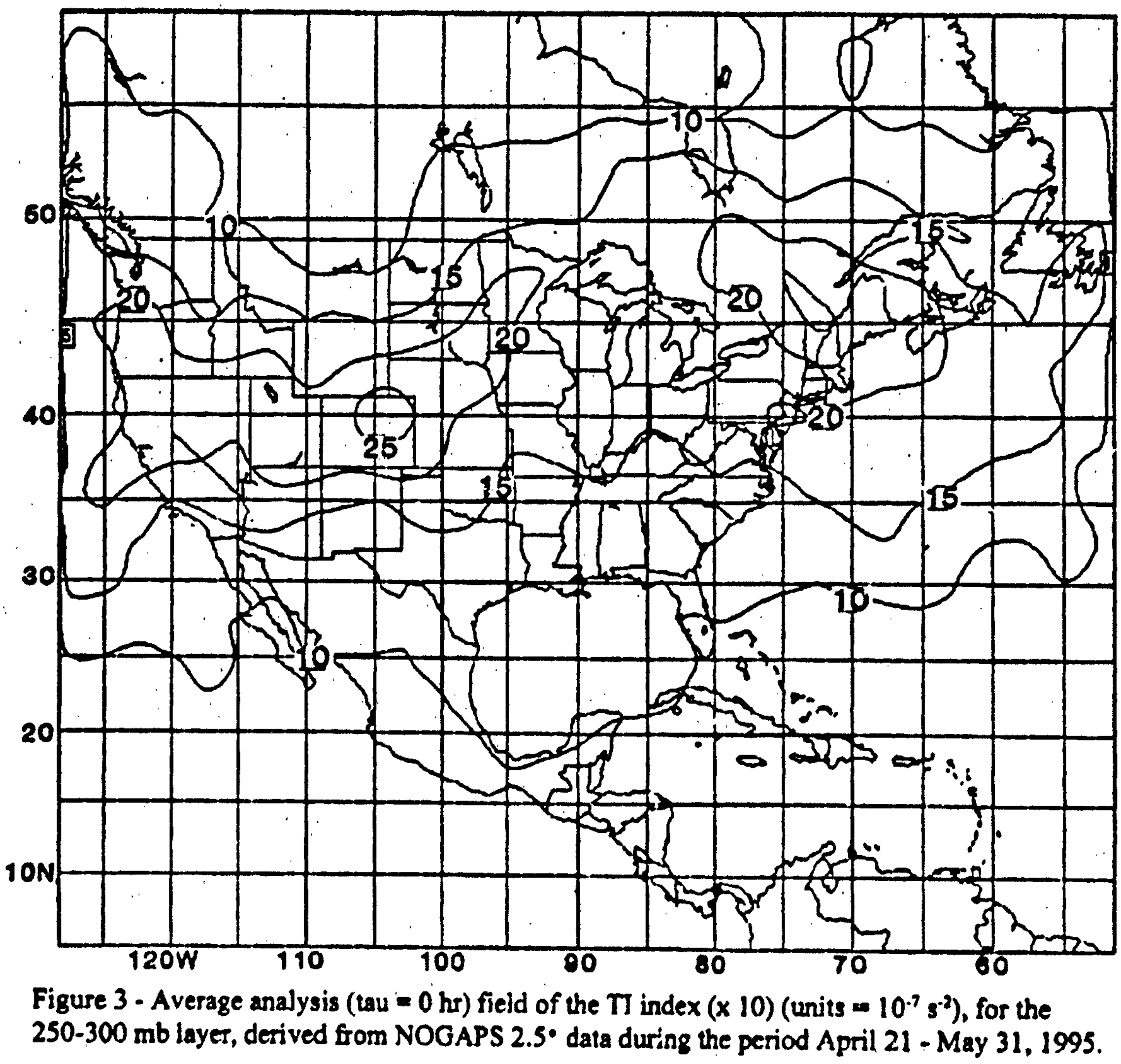

Figure 3 - Average analysis (tau = 0 hr) field of the TI index (x 10) (units = $10^{-7}\ s^{-2}$), for the 250-300 mb layer, derived from NOGAPS 2.5° data during the period April 21 - May 31, 1995.

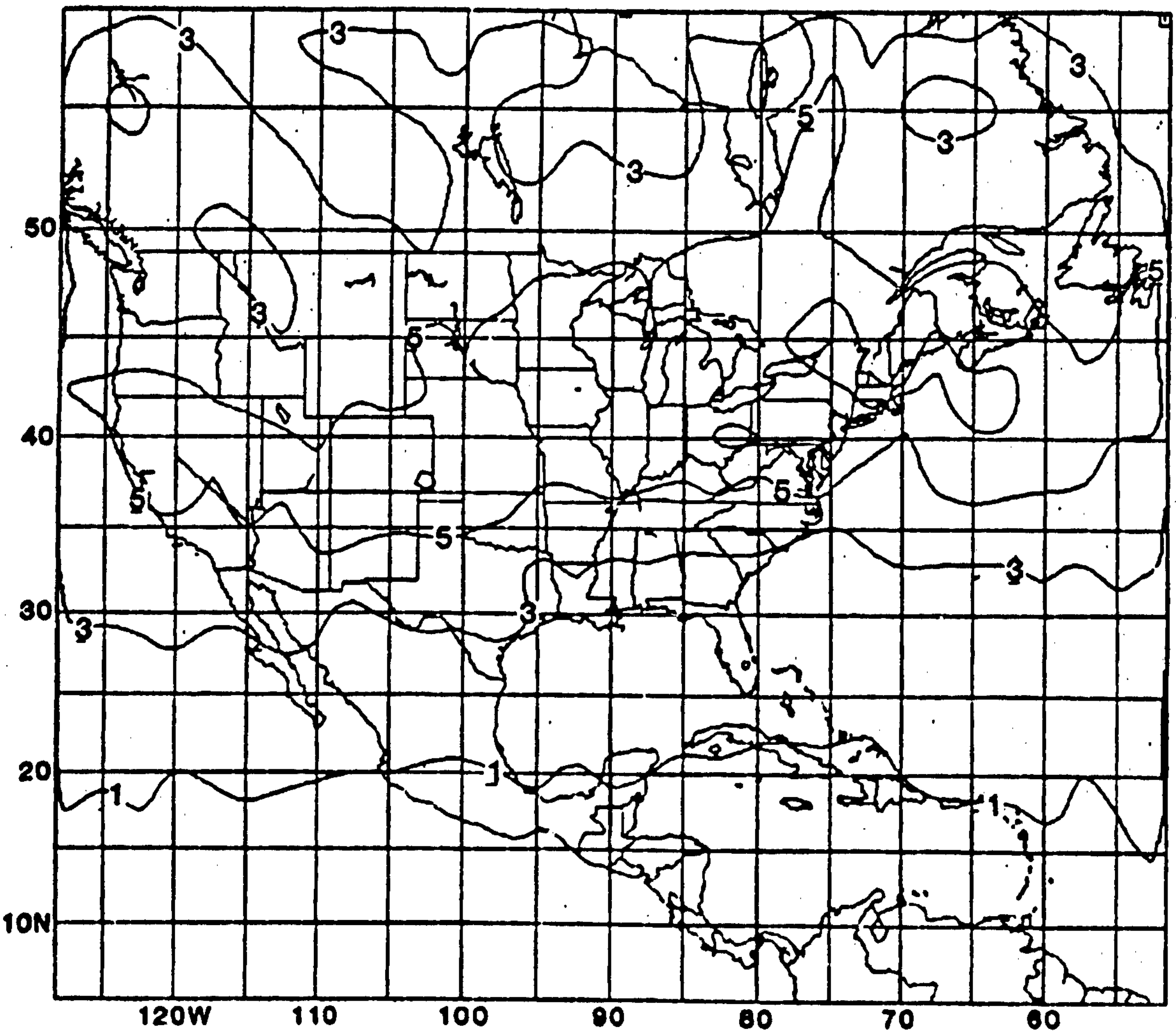

Figure 4 - Average analysis (tau = 0 hr) field of the CCAT (magnitude) index (units = 10^{-9} s^{-3}), for the 250-300 mb layer, derived from NOGAPS 2.5° data during the period April 21 - May 31, 1995.

Table 6 - Correlation coefficients and average index values for NOGAPS 2.5° coincidental TI and CCAT (magnitude) 0, 12 and 24 hr forecasts, for the period April 21 - May 31, 1995.

		TI INDEX		CCAT INDEX	
TAU	NO. DATA	AVG. (10^{-7} s^{-2})	r	AVG. (10^{-9} s^{-3})	r
0 hr	505	1.85	0.223	3.94	0.011
12 hr	495	1.78	0.265	3.78	0.048
24 hr	485	1.65	0.232	3.48	0.019

In order to compare NOGAPS 2.5° TI and CCAT performance statistics, CCAT threshold values of 3×10^{-9} s^{-3} and 6×10^{-9} s^{-3} are chosen for prediction of MOG turbulence events. These values provide similar distribution statistics of reported turbulence intensity versus index value as the threshold values previously chosen for TI. Specifically, for this dataset, the percentage of MOG turbulence reports which occur below a CCAT (magnitude) threshold value of 3×10^{-9} s^{-3} (6×10^{-9} s^{-3}) ranges from 55 to 62% (79 to 81%) for 0, 12 and 24 hr forecasts; for coincidental TI forecasts, percentages range from 57 to 63% (82 to 86%) at the 2×10^{-7} s^{-2} (4×10^{-7} s^{-2}) threshold value. Given the similarities in frequency distribution, direct comparisons will be made between statistics based on the lower (and the higher) TI and CCAT threshold values.

Performance statistics for NOGAPS 2.5° TI and CCAT (magnitude) forecasts, at selected threshold values, are given in Table 7. For both the TI and CCAT indices, POD and CSI 0, 12 and 24 hr statistics are considerably higher at their respective lower threshold value, while false alarm rates are lower (i.e., better) at the higher threshold values (except for CCAT at tau = 12 hr). For both CCAT thresholds, FAR scores are high (near 0.7). A comparison of TI and CCAT statistics at their respective lower threshold values shows very similar POD values (near 0.4) at all forecast lengths. In this same comparison, CSI values are slightly better, and FAR scores considerably better, for the TI index. For both TI threshold values and the lower CCAT threshold value, all three statistical indices were best at tau = 12 hr. For this dataset, there was no degradation of forecast skill over the 0 to 24 hr interval for any TI or CCAT performance statistic, at any threshold value.

Table 7 - (a) NOGAPS 2.5° TI performance statistics at tau = 0, 12 and 24 hr, for two selected TI threshold values. (b) Same as (a) except for CCAT (magnitude). Statistics based on MOG turbulence events and coincidental TI and CCAT forecasts over the period April 21-May 31, 1995.

(a) TI THRESHOLD VALUE						
	$2 \times 10^{-7}\ s^{-2}$			$4 \times 10^{-7}\ s^{-2}$		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.421	0.643	0.239	0.179	0.544	0.148
12 hr	0.431	0.595	0.264	0.181	0.469	0.156
24 hr	0.369	0.618	0.231	0.142	0.535	0.122

(b) CCAT THRESHOLD VALUE						
	$3 \times 10^{-9}\ s^{-3}$			$6 \times 10^{-9}\ s^{-3}$		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.407	0.726	0.196	0.214	0.713	0.162
12 hr	0.451	0.683	0.229	0.194	0.708	0.132
24 hr	0.376	0.710	0.196	0.206	0.659	0.147

4.2.2 1.0 Deg. Resolution

Average index values and linear correlation coefficients, for NOGAPS 1.0° TI and CCAT (magnitude) 0, 12 and 24 hr forecasts during the period May 15-31 1995, are presented in Table 8. These statistics are based on 543 (tau = 24 hr) to 580 (tau = 0 hr) coincidental TI and CCAT forecasts, of which about 28 % correspond to forecasts of MOG turbulence events. For both TI and CCAT, average forecast values are highest for the analysis (tau = 0 hr) and about the same for 12 and 24 hr forecasts. TI linear correlation coefficients decrease slightly with lead time (from r = 0.271 at tau = 0 hr to r = 0.211 at tau = 24 hr). These correlation values (comparable to those for the NOGAPS 2.5° late April-May dataset) suggest that the TI index has only a very limited ability in distinguishing between smooth and heavy (MOG) turbulence conditions. For CCAT, the largest correlation coefficient (r = 0.140) occurs at tau = 24 hr; this value cannot be considered representative of any useful skill in the forecasting of any arbitrary (smooth through severe) turbulence event.

Table 9 presents performance statistics for NOGAPS 1.0° TI and CCAT (magnitude) forecasts of MOG turbulence events. For this high resolution dataset, the CCAT threshold value $4 \times 10^{-9}\ s^{-3}$ ($8 \times 10^{-9}\ s^{-3}$) provides the best similarity to the TI threshold $2 \times 10^{-7}\ s^{-2}$ ($4 \times 10^{-7}\ s^{-2}$) in regards to index value versus intensity frequency distribution. Statistics based on the previously used CCAT threshold $3 \times 10^{-9}\ s^{-3}$ ($6 \times 10^{-9}\ s^{-3}$) are not best suited for direct comparisons, since the percentage of MOG turbulence reports which occur below this CCAT threshold value averages about 10% less than the percentage corresponding to the TI $2 \times 10^{-7}\ s^{-2}$ ($4 \times 10^{-7}\ s^{-2}$) threshold value. Table 9 POD and CSI statistics for TI and CCAT forecasts (at threshold values $4 \times 10^{-7}\ s^{-2}$ and $8 \times 10^{-9}\ s^{-3}$, respectively) are quite similar at tau = 0 and 12 hr, but CCAT values are slightly higher at tau = 24 hr. For this same comparison, FAR scores are considerably lower (by about 0.17 to 0.19) for the TI index. For both TI and CCAT, a decrease in threshold value results in a significant improvement in both POD and CSI statistics; unfortunately, such a decrease also results in considerably greater FAR scores for the TI index. Except for the POD statistic at tau = 24 hr, all performance statistics for TI at the $2 \times 10^{-7}\ s^{-2}$ threshold value are

Table 8 - Correlation coefficients and average index values for NOGAPS 1.0° coincidental TI and CCAT (magnitude) 0, 12 and 24 hr forecasts, for the period May 15 - 31, 1995.

		TI INDEX		CCAT INDEX	
TAU	NO. DATA	AVG. (10^{-7} s^{-2})	r	AVG. (10^{-9} s^{-3})	r
0 hr	580	1.77	0.271	4.07	0.091
12 hr	579	1.59	0.238	3.70	0.077
24 hr	543	1.57	0.211	3.73	0.140

Table 9 - (a) NOGAPS 1.0° TI performance statistics at tau = 0, 12 and 24 hr, for selected TI threshold values. (b) Same as (a) except for CCAT (magnitude). Statistics based on MOG turbulence events and coincidental TI and CCAT forecasts over the period May 15 - 31, 1995.

(a) TI THRESHOLD VALUE						
	2×10^{-7} s^{-2}			4×10^{-7} s^{-2}		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.439	0.600	0.265	0.171	0.462	0.149
12 hr	0.401	0.594	0.253	0.130	0.475	0.116
24 hr	0.373	0.593	0.242	0.159	0.400	0.126

(b) CCAT THRESHOLD VALUE									
	3×10^{-9} s^{-3}			4×10^{-9} s^{-3}			8×10^{-9} s^{-3}		
TAU	POD	FAR	CSI	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.494	0.680	0.241	0.421	0.644	0.239	0.189	0.648	0.140
12 hr	0.475	0.658	0.248	0.377	0.659	0.218	0.148	0.662	0.115
24 hr	0.523	0.665	0.256	0.431	0.658	0.216	0.216	0.566	0.168

slightly better than comparable statistics for CCAT at a threshold value of 4×10^{-9} s^{-3}. A comparison of CCAT statistics (Table 9(b)) indicates that a slight decrease in threshold value (from 4 to 3×10^{-9} s^{-3}) results in considerably better forecast capability (POD ~0.5) yet little if any increase in overforecasting. Taken collectively, POD, FAR and CSI statistics do not indicate any definitive degradation of forecasting skill with lead time for either predictor, at any threshold value.

4.2.3 1.0 Versus 2.5 Deg. Resolution

The availability of NOGAPS gridded fields at both a high (1.0°) and a low (2.5°) horizontal resolution during the second half of May 1995 permits an assessment of TI and CCAT forecasting skill in terms of data resolution. Differences in model-derived TI (or CCAT) index values at 1.0° and 2.5° resolutions essentially reflect the effect of interpolation from actual model data representation (spherical harmonics) and resolution (3/4 deg., 75-80 km) to each of these horizontal grid resolutions. Based on about 200 coincidental data, average forecast values for both the TI and CCAT (magnitude) indices are all somewhat larger, at each forecast length, at the higher (1.0°) resolution (Table 10). Based on analysis data, linear correlation coefficients for TI and CCAT are higher at the 1.0° resolution; however, at tau = 12 and 24 hr, the reverse occurs, with correlation values higher at the lower (2.5°) resolution. As in previous comparisons, correlation coefficients for TI are significantly higher than those for CCAT. With an average correlation value r = 0.25 (Table 10), TI shows some ability (albeit quite small) in forecasting any arbitrary (smooth through severe) turbulence event.

Performance statistics for TI 0, 12 and 24 hr forecasts, derived from coincidental 1.0° and 2.5° NOGAPS data, are presented in Table 11. At the 2×10^{-7} s^{-2} threshold value, both POD and CSI statistics at tau = 0 and 24 hr are somewhat higher for high resolution forecasts. For 12 hr forecasts, FAR and CSI statistics are marginally better when based on 2.5° data, while POD values are identical at the 1.0° and 2.5° resolutions. For the higher forecast threshold (4×10^{-7} s^{-2}), all statistics (POD,FAR,CSI) are marginally better at tau = 0 and 12 hr for forecasts based on

Table 10 - (a) Correlation coefficients and average index values for NOGAPS coincidental 1.0° and 2.5° TI 0, 12 and 24 hr forecasts for the period May 15 - 31, 1995. (b) Same as (a) except for CCAT (magnitude).

(a) TI INDEX		1.0 DEG. RESOLUTION		2.5 DEG. RESOLUTION	
TAU	NO. DATA	AVG. (10^{-7} s^{-2})	r	AVG. (10^{-7} s^{-2})	r
0 hr	201	1.89	0.294	1.73	0.260
12 hr	198	1.68	0.224	1.48	0.234
24 hr	199	1.65	0.236	1.41	0.263
(b) CCAT INDEX		**1.0 DEG. RESOLUTION**		**2.5 DEG. RESOLUTION**	
TAU	NO. DATA	AVG. (10^{-9} s^{-3})	r	AVG. (10^{-9} s^{-3})	r
0 hr	194	4.44	0.124	3.58	0.048
12 hr	180	4.24	0.124	3.24	0.135
24 hr	179	3.59	0.048	2.92	0.100

Table 11 - (a) NOGAPS coincidental 1.0° and 2.5° TI performance statistics at tau = 0, 12 and 24 hr, for a TI threshold of 2 x 10^{-7} s^{-2}. (b) Same as (a) except for TI threshold 4 x 10^{-7} s^{-2}. Statistics based on MOG turbulence events.

(a) TI THRESHOLD VALUE 2 x 10^{-7} s^{-2}						
	1.0 DEG. RESOLUTION			2.5 DEG. RESOLUTION		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.418	0.509	0.292	0.358	0.564	0.245
12 hr	0.348	0.549	0.245	0.348	0.500	0.258
24 hr	0.375	0.510	0.270	0.297	0.500	0.229
(b) TI THRESHOLD VALUE 4 x 10^{-7} s^{-2}						
	1.0 DEG. RESOLUTION			2.5 DEG. RESOLUTION		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.209	0.333	0.189	0.194	0.350	0.176
12 hr	0.136	0.357	0.127	0.106	0.417	0.099
24 hr	0.156	0.167	0.152	0.156	0.167	0.152

the higher resolution data. At tau = 24 hr, all statistics are identical at both resolutions; the very low FAR (0.167) results from only 2 (out of 12) incorrect forecasts of MOG turbulence.

Table 12 presents CCAT (magnitude) performance statistics at two selected thresholds (3 and 4 x 10^{-9} s^{-3}) for coincidental 1.0° and 2.5° forecasts. At all forecast lengths, comparisons of CCAT high and low resolution POD and CSI statistics indicate higher (and in a few cases, considerably higher) values for forecasts based on the 1.0° data. FAR analysis scores at both threshold values are somewhat better using 1.0° data; however, no significant differences in 1.0° and 2.5° FAR scores occur for 12 and 24 hr forecasts. For both CCAT high and low resolution forecasts, a noticeable improvement in POD and CSI (most especially, POD) statistics coupled with only minor fluctuations in FAR scores occurs when the forecast threshold is decreased from 4 to 3 x 10^{-9} s^{-3}. Comparing TI and CCAT statistics (Tables 11 and 12), an improvement (i.e., decrease) in NOGAPS data resolution (from 2.5° to 1.0°) appears more beneficial to the forecasting performance of the CCAT index. This probably occurs because the CCAT formulation contains a very small quantity (the vorticity, in units of 10^{-5} s^{-1}) which is likely quite sensitive to interpolation processes involved in converting from model to gridpoint representation.

5. SUMMARY AND CONCLUSIONS

Two turbulence algorithms for forecasting clear air turbulence are computed using meteorological data from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model. The TI index is based on deformation and vertical wind shear, and is used at several operational centers in support of aviation forecasting. The CCAT index, in current operational use at FNMOC, is based on the advection of vertical stability and absolute vorticity. Verification of both algorithms is accomplished by comparing model-derived analyses and short-range forecasts with pilot reports of turbulence intensity over the continental U.S. during

Table 12 - (a) NOGAPS 1.0° and 2.5° coincidental CCAT (magnitude) performance statistics at tau = 0, 12 and 24 hr, for a CCAT threshold of 3×10^{-9} s^{-3}. (b) Same as (a) except for CCAT threshold 4×10^{-9} s^{-3}. Statistics based on MOG turbulence events.

(a) CCAT THRESHOLD VALUE 3×10^{-9} s^{-3}						
	1.0 DEG. RESOLUTION			2.5 DEG. RESOLUTION		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.619	0.585	0.331	0.397	0.653	0.227
12 hr	0.642	0.580	0.340	0.574	0.574	0.315
24 hr	0.509	0.679	0.245	0.377	0.672	0.213
(b) CCAT THRESHOLD VALUE 4×10^{-9} s^{-3}						
	1.0 DEG. RESOLUTION			2.5 DEG. RESOLUTION		
TAU	POD	FAR	CSI	POD	FAR	CSI
0 hr	0.492	0.551	0.307	0.317	0.636	0.204
12 hr	0.528	0.576	0.308	0.377	0.600	0.241
24 hr	0.358	0.694	0.198	0.302	0.660	0.190

the spring of 1995. The forecasting capability of each turbulence index is evaluated statistically in terms of forecast (decision) threshold, model data resolution, and length of forecast.

The major findings of this verification study are as follows:

(1) Correlations between turbulence intensity and index value indicate that the magnitude of CCAT (and not CCAT) is the preferred turbulence predictor.

(2) Climatologically, both TI and CCAT appear capable of identifying high-turbulence threat regions.

(3) The TI index shows marginal skill ($r = 0.25$), and the CCAT index essentially none, in the forecasting of any arbitrary (smooth through severe) turbulence event.

(4) For a threshold value $2 \times 10^{-7}\ s^{-2}$, average TI 1.0° and 2.5° statistics (Tables 7 and 9) for forecasting MOG turbulence events are: POD = 0.41, FAR = 0.60 and CSI = 0.25. Coincidental statistics for CCAT (threshold value $3 \times 10^{-9}\ s^{-3}$) are quite similar, with POD = 0.45, FAR = 0.69 and CSI = 0.23. Overforecasting is a serious problem for both indices, most especially for CCAT.

(5) Collectively, comparisons among analysis, 12 and 24 hr statistics do not indicate any definitive trend in forecasting skill with lead time, although average forecast TI and CCAT index values generally show a slight decrease with forecast length.

(6) The use of high (1.0°) resolution data (as opposed to 2.5° data) provides slightly improved forecasting capability to the CCAT index, especially in POD. Such improvement in forecasting ability using higher resolution data is noticeably less for the TI index.

Although certainly not clear-cut, overall statistical results of this study indicate a slight preference of the TI index over CCAT for operational use. In addition to slightly better performance, the TI algorithm is computationally more simple, depending only upon wind and height data. Unfortunately, with high false alarm rates and only modest capability of correctly forecasting observed MOG turbulence events, both of the turbulence indices appear limited to providing operational users only "rough" estimates of encountering significant clear air turbulence over specified regional areas.

In this study, only data from a global numerical model was used to forecast CAT. With ever-increasing computer power, it is now feasible to run forecast models with resolutions similar to those in which CAT occurs. One such model - COAMPS, or Coupled Ocean/Atmosphere Mesoscale Prediction System (Hodur, 1993) - is presently being readied for operational implementation at FNMOC. COAMPS typically runs at horizontal resolutions < 20 km and can be configured to run at vertical resolutions of several hundreds of meters within the free atmosphere; its physics include explicit predictions of turbulent kinetic energy (TKE). When operational, COAMPS should be evaluated for turbulence forecasting potential, either by computing diagnostic indices (such as TI and CCAT) or, more challengingly, by relating model TKE predictions to in-flight turbulence.

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