Improvements to an Operational Clear-Air Turbulence Diagnostic Index by Addition of a Divergence Trend Term

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ABSTRACT

An operational clear-air turbulence (CAT) diagnostic index has been modified to improve its performance. The Ellrod–Knapp turbulence index (TI) was developed in the early 1990s and is in use at many aviation forecasting facilities worldwide. It has been recognized, however, that TI often does not sufficiently account for situations where anticyclonic shear or curvature is present. The proposed modification to TI is based on the addition of a proxy term for divergence tendency, appropriate for both anticyclonic flow and gravity wave generation in cyclonic regions. Examples show how the modified index [referred to as the divergence-modified turbulence index (DTI)] leads to better anticipation of significant CAT for two scenarios where rapid divergence changes were occurring. Preliminary objective evaluation of the 6-h forecast DTI derived from the Rapid Update Cycle-2 (RUC-2) was completed for 2 months in 2007 (using more than 1100 pilot reports). Results showed significant improvements over TI, based on verification metrics such as the probability of detection of turbulence (POD) and the true skill statistic (TSS). Further evaluation is planned using a larger database of pilot reports, as well as forecast data from additional state-of-the-art prediction models, altitude ranges, and forecast times.

1. Introduction

During the past four decades, various indices have been developed to help diagnose and forecast the likelihood of high-altitude clear-air turbulence (CAT) near the jet stream (e.g., Endlich 1964; Dutton and Panoisky 1970; Brown 1973; Lee et al. 1984; Ellrod and Knapp 1992; Marroquin 1998, Ellrod et al. 2002; Kaplan et al. 2005a,b, 2006). These forecast indices are typically based on variables derived from upper-air observations or numerical weather prediction (NWP) model data such as vertical and horizontal wind shears, static stability, scalar wind speed, horizontal deformation, frontogenesis, pressure gradient force, ageostrophic vertical vorticity, turbulent kinetic energy (TKE), and the nondimensional Richardson number (Ri). CAT indices based on NWP data were designed to attempt to capture grid-scale processes that produce the mesoscale (10–100 km) meteorological conditions conducive to subgrid-scale turbulence that affects aircraft.

A more recent statistical approach that uses a continually updated, weighted regression of ten of these diagnostics is known as Graphical Turbulence Guidance-2 (GTG2; Sharman et al. 2006). The diagnostics included in the upper-level version of GTG2 are: Ri (Endlich 1964), the North Carolina State University index (Kaplan et al. 2005b), the deformation–vertical shear index (TI; Ellrod and Knapp 1992), TKE formulations (Colson and Panofsky 1965; Marroquin 1998), and an unbalanced flow diagnostic (Knox 1997; McCann 2001; Koch and Caracena 2002). The GTG2 index (0 to 1) is a weighted sum of these diagnostic indices based on weights determined...
from verification with aircraft pilot reports (PIREPs). These weights are updated with each forecast cycle. At a typical aviation forecast center today, forecasters employ a “toolbox” consisting of many, if not all, of these turbulence diagnostic indices individually, as well as combined within GTG2, along with real-time PIREPs.

In addition to problems related to scale, a significant shortcoming of many of the indices is that they account for some, but not all, CAT-producing mechanisms in some, but not all, circumstances. For example, deformation can be frontolytic as well as frontogenetic, leading to a decrease in vertical wind shear. Most do not account for turbulence initiated by mountain waves. Then there is the long-noted connection between upper-level ridges and CAT (e.g., Lester 1994). Knox (1997) drew attention to problems with the application of various CAT indices in strongly anticyclonic flows. In such situations, deformation-based diagnostics may wrongly predict CAT, or correctly predict it for the wrong reasons, by relating deformation to frontogenesis. Also, Knox (1997) demonstrated that in anticyclonic horizontal shear and curvature, the ageostrophic vertical wind shear is additive with the geostrophic vertical wind shear, leading to large shears in ridges and therefore greater probabilities of Kelvin–Helmholtz instability (KHI). This is true especially as the wind speed approaches the limit of gradient balance, as is often observed in upper-level ridges. In the very strongest anticyclonic situations, CAT may also be related to inertial instability (Knox 2003) and/or gravity wave generation by this instability (O’Sullivan 1993).1

Taken together, the results of Knox’s (1997) analysis indicated that deformation-based diagnostics could be improved by incorporating a parameter appropriate for the dynamics of anticyclonic flow. One such parameter is divergence tendency, which is often large in two circumstances related to CAT: strong ridges, as well as cyclonic regions that are not in quasigeostrophic (QG) or gradient balance.

This paper describes efforts to improve an existing and widely used CAT diagnostic, the turbulence index (TI) of Ellrod and Knapp (1992). Versions of TI have been implemented by operational aviation forecast units globally, including the National Oceanic and Atmospheric Administration’s Aviation Weather Center (NOAA/AWC) (Behne 2008), the Air Force Weather Agency (Brooks and Oder 2004), the Met Office in the United Kingdom (Turp and Gill 2008), and the Canadian Meteorological Centre (Turcotte and Verret 1999). TI is popular because of its good performance (Brown et al. 2000), familiarity among forecasters, computational speed, and easy implementation.

The proposed change to TI is to add a proxy term for the divergence tendency to account for CAT in situations of rapidly changing divergence associated with anticyclonic flow (both shear and curvature), and in cyclonic regions not in gradient balance. To test the impacts of divergence tendency on TI, we used a divergence “trend” term, which is proportional to the divergence tendency. The performance of this new divergence-modified turbulence index, or DTI, was then compared to TI and GTG2.

In section 2 we briefly discuss the physical basis for DTI within the context of other recent work on CAT. In section 3, we describe DTI and the method used to identify improvements versus the earlier version of the index (TI). In section 4, two CAT episodes are presented using data from different numerical models that demonstrate how DTI could have improved the anticipation of significant turbulence in an operational setting. In section 5, we provide verification statistics for two separate 1-month periods (July and December 2007). Section 6 summarizes the results and discusses the operational utility of the new DTI diagnostic.

2. Physical basis of DTI

The physical basis for TI was initially attributed to frontogenesis through the process of deformation (Mancuso and Endlich 1966; Ellrod and Knapp 1992). The hypothesis was that stronger horizontal thermal gradients caused by frontogenesis would in turn lead to an increase in vertical wind shear, in accordance with the thermal wind equation, and thus a higher potential for CAT via the local production of KHI. In light of shortcomings described in section 1 however, a more universal and robust diagnostic index is desired.

Using the Lighthill–Ford theory of spontaneous imbalance, Knox et al. (2008) provided a relationship between one forcing term for spontaneous gravity wave generation and the sum of the deformation tendency (term A) and divergence tendency (term B) in the following equation:

$$\frac{\partial}{\partial t}[-2J(u, v)] \approx \frac{1}{2} \frac{\partial}{\partial t}(\text{DEF}^2 - D^2)$$

where

$$\text{DEF} = \frac{\partial D}{\partial t} \cdot \frac{\partial D}{\partial x}$$

and

$$J = \text{Jacobian operator, } \text{DEF is the resultant deformation, and } D \text{ is the divergence. Equation (1) provides}$$

\[1\]\n
Inertial instability has been found to be more common than many would expect, occurring as often as 10%–15% of the time in portions of the stratosphere as found in a climatological study (Knox and Harvey 2005).
a physical link between the deformation and divergence tendency in spontaneous gravity wave generation favorable for CAT. This may explain why deformation-based diagnostics such as TI can succeed even in nonfrontogenetical situations, by capturing regions of gravity wave generation. Although Eq. (1) describes one of the less dominant of the four terms in the Lighthill–Ford equation, it can become significant in situations where the Rossby number (Ro) is large, thus near the jet stream.

Spontaneous imbalance generally occurs in the laboratory in cyclonic flows (P. Williams 2008, personal communication). Therefore, the combination of deformation and changes in divergence would seem to capture two CAT mechanisms in cyclonic flows: frontogenesis as well as gravity wave generation by spontaneous imbalance. Observational studies using aircraft measurements in the vicinity of midlatitude fronts (e.g., Koch et al. 2005) have noted the presence of significant mesoscale waves (>100 km wavelength) that are locally modulated by smaller-scale gravity waves (1–20 km) that reduce Ri to values conducive to turbulence. Since divergence changes also characterize anticyclonic flows, combining the deformation and the divergence trend would also function as a CAT diagnostic in anticyclonic situations. This, then, is the physical basis for using a combination of deformation and the divergence trend as an improved CAT diagnostic in all types of flows.

3. Data and procedures

The index used as a basis for the experiments was TI, more specifically TI1 in Eq. (9) in Ellrod and Knapp (1992). TI is defined as

\[
TI = \left( \frac{(\Delta u/\Delta x - \Delta v/\Delta y)^2 + (\Delta w/\Delta x + \Delta u/\Delta y)^2)}{A} \right)^{1/2} \left( \frac{\Delta V/\Delta z}{B} \right).
\]

where term A is resultant deformation (DEF) and B is the vertical wind shear (VWS) of the total vector wind V at each grid point.

To improve TI by accounting for rapidly changing divergent flows, a simplified “divergence trend” term (DVT) was obtained:

\[
DVT = C[(\Delta u/\Delta x + \Delta v/\Delta y)_{h2} - (\Delta u/\Delta x + \Delta v/\Delta y)_{h1}]_2
\]

The subscripts h1 and h2 represent the two forecast intervals used in determining DVT. To evaluate the feasibility of this approach, 6-, 12-, or 18-h forecast times were used initially for the Eta Model, which is now known as the North American Mesoscale (NAM; Rogers et al. 2005), and the Global Forecast System (GFS; EMC/Global Climate and Weather Modeling Branch 2003) model, as these were the only model forecast periods available during the initial evaluation. For the latest version of the Rapid Update Cycle (RUC-2; Benjamin et al. 2004), the 3- and 6-h forecast times were used. The RUC-2 was used in the verification of DTI versus the original TI, discussed in section 5. (The time intervals used in this note are for demonstration purposes only, and a final determination of h1 and h2 will be made based on the findings of those evaluations.) Here, C is a constant; its value was subjectively assigned as 0.1 to allow the magnitude of DVT to be equivalent to the deformation-shear term in TI in situations where large changes in divergence are present. The same value of C was used for all models, which did not permit intercomparison of those results.

The divergence tendency is one of the terms contained in the residual of the nonlinear balance equation (NBE), which Zhang et al. (2000) identified as useful in diagnosing a case of gravity wave generation during East Coast cyclogenesis. McCann (2001) found that the total divergence tendency (derived by taking the horizontal divergence of the equation of horizontal motion) had the highest “postagreement” [one minus the false alarm rate (FAR)] of six CAT diagnostics (Richardson number, square of the wind shear, inertial advective wind, unbalanced ageostrophic wind, divergence tendency, and anticyclonic instability) evaluated for a large sample of cases (N = 1832) from 1 October 1996 to 31 January 1997.

DVT was used in Eq. (3) rather than the divergence tendency (divergence change divided by time interval in seconds) because the typical time steps of synoptic- and mesoscale numerical models are too large to yield divergence tendencies of meaningful magnitude. For example, divergence tendencies are on the order of 10^{-9} s^{-2} when using a time period of 3 h (\approx 10^7 s). In contrast, the product of the deformation and the vertical wind shear used in TI has a magnitude on the order of 10^{-7} s^{-2} (Mancuso and Endlich 1966). Thus, the divergence tendency is considerably smaller in magnitude than TI, and would not provide a significant contribution under most conditions.

The DVT is then added to TI to create the divergence-modified turbulence index:2

\[
DTI = TI + DVT.
\]

2 It should be noted that DTI is not the same as the TI2 of Ellrod and Knapp (1992), as the latter subtracts the instantaneous local divergence from TI, whereas DTI adds the local change in divergence for a specified time interval to TI.
The TI and DTI data were generated on a Man computer Interactive Data Access System (McIDAS) workstation. The model data were obtained from the National Centers for Environmental Prediction (NCEP) in Camp Springs, Maryland. TI and DTI were produced mainly for the 300–250-hPa layer, corresponding to flight altitudes of approximately 30 000–34 000 ft (9.2–10.4 km) above mean sea level (MSL).

TI and DTI output graphics consisted of both pseudocolor images and gridpoint plots, which were overlaid and posted on the National Environmental Satellite, Data, and Information Service (NESDIS) Satellite Applications and Research Web server. PIREPs were obtained from NOAA’s Family of Services (FOS) data stream. The images were scaled so that a full range of index values (0–16) corresponded to an 8-bit brightness count range (0–255). TI values larger than 16, when present, were assigned a brightness count value of 255. An enhancement table was designed to phase brightness count values gradually through green, yellow, and red, corresponding to low, moderate (TI > 4), and high risks (TI > 10) of turbulence, respectively. Images displayed in this note are grayscale versions of the pseudocolor images, similar to those available on the Web (http://www.star.nesdis.noaa.gov/smcd/opdb/aviation/turb/tifcsts.html).

4. Examples

Two examples of CAT episodes from 2005 are shown in this section to illustrate the effects of the divergence trend modification to TI. The cases represent 1) a broad, relatively flat, upper ridge and 2) a short-wavelength, sharply defined trough–ridge couplet. In both cases, the use of DTI would likely have resulted in better turbulence forecasts than those provided by TI.

a. Case 1: 5 February 2005

On the morning of 5 February 2005, a broad upper level ridge of high pressure extended over the southern United States in advance of a strong upper trough dropping southward across the Pacific Northwest. Figure 1 displays the 250-hPa radiosonde data at 1200 UTC 5 February (Fig. 1a) and 0000 UTC 6 February 2005 (Fig. 1b). A strong jet stream extended across a broad upper ridge from southwest Texas to Oklahoma, Missouri, Tennessee, and South Carolina. By 0000 UTC 6 February 2005 (Fig. 1b), the pattern was essentially unchanged, although significant backing of the winds had occurred in west Texas in advance of an approaching shortwave trough in eastern Arizona.

The 18-h forecast TI valid 1800 UTC from the Eta Model (Fig. 2a) showed an axis of maximum CAT risk oriented along the jet stream. The greatest threat was across Missouri, Kentucky, western North Carolina, and northern South Carolina. The DTI (Fig. 2b) shifted the axis of greatest turbulence risk southward to the anticyclonic side of the jet stream, but also widened the area of maximum risk near the ridge axis in Missouri. (The DVT term for this forecast was determined from the 12–18-h Eta forecast interval.) This broader DTI high-risk area was better correlated with the turbulence reports observed around that valid time than TI’s high-risk area, especially in west Texas, New Mexico, Oklahoma, Missouri, and South Carolina. In other regions, there was little noticeable difference between the two indices.

A Geostationary Operational Environmental Satellite-12 (GOES-12) IR image at 1815 UTC 5 February 2005 (Fig. 3) revealed variable thin cirrus across the upper ridge, interspersed with well-defined transverse bands, especially in west Texas and Oklahoma (shown by a 1-km-resolution GOES visible image in the lower right panel). Transverse bands are a well-known indicator of CAT activity (e.g., Ellrod 1985; Knox et al. 2010). Some of the cirrus bands were displaced a little to the east of the maximum DTI axis in west Texas, but otherwise correlated well. As expected, the radar composite at 1800 UTC (not shown) displayed no significant convection in the region of interest.

b. Case 2: 25 May 2005

The 250-hPa conditions for 1200 UTC 25 May 2005 (Fig. 4) revealed a sharply defined short-wave trough–ridge couplet over the Upper Midwest, extending into the northern Great Lakes region. Farther east, a closed upper low was entrenched over the northeastern United States, but moving slowly eastward away from the mid-Atlantic coast. A strong jet with maximum winds of 105 kt at the base of the short-wave trough was observed at Rapid City, South Dakota (RAP). In advance of the jet, diffusent/divergent flow could be seen in the exit region, creating a region of possible strong gravity wave generation toward the ridge axis, which extended from northern Michigan to southeast Iowa.

Figure 5 compares the 18-h forecast NAM TI (Fig. 5a) and DTI (Fig. 5b) output valid at 1200 UTC 25 May 2005. Both showed a maximum value in the northern Great Lakes due to the deformation and vertical wind shear near the ridge axis. DTI showed a second maximum over northwest Wisconsin to southern Minnesota, which was due to the increase in upper divergence that had occurred in the prior 6-h period in advance of the jet maximum in South Dakota. The PIREPs for the 0900–1500 UTC period (Fig. 5) indicated considerable moderate or greater turbulence in this region. Aside from the DTI maximum in southwest Minnesota, there were only minor differences between the two indices elsewhere.
A GOES water vapor image at 1215 UTC 25 May 2005 is shown in Fig. 6. Embedded convection is evident over Iowa and southwest Minnesota, with extensive transverse banding present in the cloud tops. The 1204 UTC radar display from Minneapolis (KMSP) (Fig. 7) indicated that two of the moderate or greater turbulence reports in southern Minnesota were likely associated with the convection. However, there were also numerous reports of light to moderate “chop” by aircraft approaching or departing Minneapolis–St. Paul (MSP) from/to the east at altitudes of flight level (FL) 290 (×100 ft) or lower, confirming a high threat for CAT associated with the southern DTI maximum. Radar showed no significant convection in this area.

5. Verification

a. Data and procedures

Evaluation of the DTI algorithm was completed by comparing PIREP turbulence intensity codes with RUC-2 model gridpoint values of the 6-h forecast of both DTI and the legacy TI. Data were collected for occurrences of light or greater turbulence intensity, and also for null (smooth) occurrences. The index value nearest the turbulence report was used for each data pair. Some manual interpolation was required in regions of strong gradients. Negative gridpoint values were rounded up to zero, and assumed to represent nonturbulent conditions.
Verification metrics such as the probability of detection of both turbulent (POD_y) and smooth conditions (POD_n), and the true skill statistic (TSS = POD_y + POD_n - 1) were then produced and compared for the two algorithms using various index thresholds (0, 1, 2, 4, 6, 8, 10, and 16) as turbulence discriminators. The TSS measures the ability of a diagnostic index to discriminate between “yes” and “no” turbulence forecasts. Common verification metrics such as FAR, critical success index (CSI), and bias are not considered to be appropriate for

![ETA 18hr Forecast VT 18Z, 5 Feb 05, 250-300 hPa](image1.png)

**FIG. 2.** Image showing 18-h Eta Model forecasts of (a) TI and (b) DTI for the 300–250-hPa layer, valid 1800 UTC 5 Feb 2005, with turbulence reports overlaid. Light-shaded regions indicate medium risk of CAT; medium gray regions contained inside the light-shaded areas indicate a high risk of CAT (TI or DTI >10). Numerical codes of turbulence intensity from PIREPs, aircraft type, and altitude (100s of feet) were from 1500 to 2100 UTC.

![GOES-12 IR satellite imagery at 1815 UTC 5 Feb 2005.](image2.png)

**FIG. 3.** GOES-12 IR satellite imagery at 1815 UTC 5 Feb 2005. The high-resolution GOES visible image (lower right) is a close-up of the area outlined by the dashed box in the IR image. (Source: NCDC.)
use with PIREPs since their values change as the numbers of yes or no PIREPs change (Brown and Young 2000). Plots of POD, versus $1 - POD_n$ for all thresholds were used to create a relative operating characteristic (ROC) diagram (Mason and Graham 1999). ROC curves allow a user to determine the optimum threshold value of an index that results in the best POD, with a corresponding acceptably low value of $1 - POD_n$.

Verification data were collected for two separate periods: 1) 26 June–31 July 2007 (hereafter July 2007) and 2) December 2007, for a total of 1168 forecast–observation pairs for each index. Decoded PIREPs and gridded RUC-2-derived values of TI and DTI were obtained at the World Weather Building, Camp Springs, Maryland, using a workstation provided by the NESDIS Center for Satellite Applications and Research. The data collection area covered the eastern two-thirds of the United States. Mountainous areas of the western United States were deliberately avoided to exclude possible mountain wave–related turbulence as much as possible. Model index

![Figure 4](image1.png)

**Fig. 4.** A 250-hPa analysis valid at 1200 UTC 25 May 2005. Contours and shading are the same as in Fig. 1. Approximate areas of TI and DTI forecasts are outlined by the black box. (Source: SPC.)

![Figure 5](image2.png)

**Fig. 5.** Grayscale image showing 12-h NAM forecasts of (a) TI and (b) DTI valid 1200 UTC 25 May 2005. Shading and PIREP codes are the same as in Fig. 2.
data were generated for the 250–300-hPa layer. PIREPs were obtained for a period within ±1 h of the valid time of the RUC-2 forecasts. The July 2007 data were screened to eliminate turbulence that could have been caused by summer convection using low-resolution Weather Surveillance Radar-1988 Doppler (WSR-88D) images [available online at the National Climatic Data Center (NCDC) Web site: www.ncdc.noaa.gov/oa/mpp/freedata.html].

b. Results

Table 1 shows values of POD$_y$, POD$_n$, and TSS for both the DTI and TI algorithms for July 2007, December 2007, and both months combined using a threshold value of 4 as a discriminator between turbulent and smooth conditions. This threshold value is the one typically used in operational forecasts of TI. For the combined dataset, the improvement in DTI over TI is approximately 50%.

![Fig. 6. GOES-12 water vapor image at 1215 UTC 25 May 2005. (Source: NCDC.)](image1)

![Fig. 7. Radar image from KMSP at 1204 UTC 25 May 2005 with turbulence reports ±1 h overlaid. Arrowed line segments show routes for numerous (NMRS) turbulence reports approaching–departing KMSP during this time. (Source: NCDC.)](image2)
for POD, and is better by a factor of 5 for TSS. POD was slightly worse for DTI for all three datasets, indicating that DTI has a slight tendency to overforecast CAT. Relative improvements for other threshold values (not shown) were similar, although the best verification metrics for DTI (based on the TSS value) were obtained using the threshold value of 4. The results for December 2007 were better for DTI than for July 2007, although the latter was a much smaller dataset.

A ROC diagram comparing DTI, TI, and the operational GTG2 for December 2007 is shown in Fig. 8. (GTG2 data were obtained from NOAA/Earth System Resource Laboratory's Real-time Verification System Web site: http://rtvs.noaa.gov/turb/op/stats/index.html) The area between the DTI curve and the diagonal line (representing the amount of skill) is larger than that of the TI, showing that the addition of the proxy for the divergence tendency has improved the performance of the original TI, which was the primary goal of this verification effort.

Figure 8 also shows that the performance of GTG2 for December 2007 was superior to that of DTI. GTG2 contained a much larger number of reports than for the DTI/TI dataset, due to a deeper atmospheric layer (FL200–400 versus FL300–340 for DTI/TI), and a wider domain [entire continental United States (CONUS) versus eastern half of CONUS]. For these reasons, we feel that the verification results for DTI cannot be fairly compared to GTG2 and are shown for informational purposes only.

Despite issues with the pilot report database, our results clearly show that DTI is a significant improvement upon TI and will be a valuable upgrade to existing operational forecast diagnostic tools, as well as a likely contribution to improved performance for the operational GTG2. A more extensive verification study of the DTI and other algorithms is planned at the Aviation Weather Center from early 2010 through 2011, using data from additional state-of-the-art prediction models, altitude ranges, and forecast times.

6. Summary and operational utility

Based on qualitative comparisons and two months of quantitative verification (using parameters such as POD, POD, and TSS), we conclude that maxima of the turbulence index (TI) in strong anticyclonic shear and/or curvature, and even in cyclonic flow situations in the exit region of strong jets, were enhanced considerably by the additions of a divergence trend (DVT) term, resulting in what we call the divergence-modified turbulence index (DTI) diagnostic. The DTI also related better spatially with turbulence reports than did TI in those regions. In other regions, there appeared to be no significant changes in TI, and thus it is believed that there will be minimal negative impact from the operational use of DTI. On many days, there were only minor differences between the DTI and TI anywhere within the domain of the CONUS and southern Canada. This would be expected in light of the relative rarity of the large divergence changes we are attempting to highlight. We encourage the evaluation of the DTI algorithm at aviation forecast centers to determine if implementation would bring improvements to their operational turbulence forecasts. Further evaluations of this DTI at AWC will begin during winter 2010 using state-of-the-art models at varying time intervals in an effort to obtain maximum benefits from this new diagnostic index.

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<td>N = 1168</td>
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Ankita Nagirimadugu, who obtained the summer 2007 verification statistics.

REFERENCES


