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APPLICATION AND VERIFICATION OF CLEAR-AIR TURBULENCE (CAT) FORECAST INDICES IN KOREA

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1. INTRODUCTION

The needs of aviation meteorology have been increasing gradually with the development of observational instruments and numerical prediction models. Information on items such as fog, clear air turbulence (CAT), thunderstorm, and icing plays an important part in the aviation society, since an accurate prediction of severe phenomena contributes to the prevention of disastrous aircraft accidents. Turbulence can give discomfort to cabin crews and passengers, or cause physical injuries when its intensity is larger than moderate during flights. In particular, the prediction of CAT as well as microburst and mountain wave occurring locally seems to be indispensable in Korea, where the terrain is very complex and mountainous.

Many people involved in the aerial community have reported damage to aircraft, humans, and the economy caused by unexpected turbulence, but unfortunately prediction of turbulence has many difficulties. A main problem is that turbulence is a phenomenon with a short spatial and temporal range. It is impossible to forecast the fluctuation of atmosphere from the output of numerical prediction models and turbulence observations because of their coarseness and inadequacy.

Fortunately, the turbulent kinetic energy cascade down from large scales of eddies to those of small scales. Thus the turbulence-forecasting problem can be resolved if the numerical prediction is sufficiently accurate and if there is a linkage between the large-scale output, such as routine meteorological observations or numerical weather prediction models, and turbulence observations (Sharman *et al*, 2000). This paper describes and applies several indices, which have been previously presented for forecasting CAT, in Korea. The verification of the results based on 24-hourly forecast data was accomplished during a passage of a well-developed upper -level trough in October 2001.

2. THEORETICAL DESCRIPTION OF THE INDICES

Colson and Panofsky (1965) defined CAT as any turbulence above 18,000 ft m.s.l. not associated with cumulus-type clouds, and do not exclude the possibility of turbulence in or near cirrus cloud. From measurements and statistical analysis made by airplanes flown into turbulence, the probability that CAT will occur is largest in regions of strong vertical wind shear and strong horizontal temperature gradient. Since the vertical wind shear is related to the horizontal temperature gradient through the thermal wind equation, sloping baroclinic zones or internal fronts and the toropopause region are favored areas for CAT

2.1 *Richardson Number (* Ri *)*

Assuming CAT is not associated with mountains, it can be illustrated in a statically stable atmosphere in combination with strong vertical wind shear. The role of these effects in producing turbulence is expressed by the Richardson number (Dutton and Panofsky, 1970),

$$\mathrm{Ri} = \left(\frac{g}{\theta_m}\frac{\partial\theta}{\partial z}\right) \Bigg/ \left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right], \qquad (1)$$

where g is the acceleration of gravity, θ_m is the vertical mean potential temperature, z is the height, and u and v are the wind components in two orthogonal horizontal directions. Hence they assumed in equation (1) that the generation of mechanical turbulence depends essentially on the square of the vertical wind shear while the destruction of turbulence by the stable stratification depends on the first power of the gradient of potential temperature. Since the area near the internal front showed usually small Richardson numbers which is less than unity in many other case studies, Ri has been used as one of the most popular and important parameter in forecasting CAT (Colson, 1963; Rustenbeck, 1963).

2.2 *Brown indices*

Though Ri was judged to be slightly better than vertical wind shear regarded as most important parameter in identifying CAT, the verification showed that areas where Ri was less than one were found to contain approximately 40 % of all the CAT (Kronebach, 1964). Endlich (1964) suggested from his observational study that several mesoscale conditions including large vertical variations of both wind speed and direction (which is equate to small Ri) were considered to contribute the development of the turbulence. This implies that minimum Ri

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values are necessary but sufficient condition for the onset of CAT. Furthermore, the coarser the numerical or synoptic data is used to calculate Ri, the worse the accuracy of the prediction is assessed.

Roach (1970) attempted to avoid the problem of evaluating Ri from synoptic data by identifying areas where Ri was reduced by the large-scale flow. To deduce the Ri tendency equation, he considered that CAT could be represented by discontinuities of wind and temperature in the vertical plane by shearing and stretching deformation. However, the value of the index was found to be sensitive to the orientation of the vertical wind shear vector, it was impossible to derive angles calculated from vertical wind shear, pressure gradient, and north measured in a clockwise direction.

Brown (1973) modified this approach by removing the effects of fluctuations in the orientation of the vertical wind shear vector, and the changed equation took the form,

$$\Phi_m = \frac{D}{Dt}\ln \mathrm{Ri} = \left(0.3\,\zeta_a^2 + D_S^2 + D_T^2\right)^{1/2}, \qquad (2)$$

where ζ_a is absolute vorticity, D_S is horizontal stretching deformation, and D_T is shearing deformation. We will dub the index Φ_m the BROWN-1 index in order to distinguish it from the following index derived from the relationship between Ri and the deformation process. Assuming that the turbulence works against the deformation process the energy dissipation, ε that is named as the BROWN-2 index can be represented as,

$$\varepsilon = \Phi_m \frac{\left(\Delta \vec{V}\right)^2}{24}, \qquad (3)$$

where $\Delta \vec{V}$ denotes the vertical shear of the horizontal components of the wind across the turbulent layer.

2.3 *Ellrod Indices*

Based on the fact that strong CAT is quite common along certain cloud boundaries that are referred to as "deformation zone", Ellrod and Knapp (1992) assert the importance of horizontal deformation. Thus, an index was made by considering the product of the horizontal deformation and the vertical wind shear. In this paper, the index is called the TI1 index and is written as,

$$\mathrm{TI1} = \mathrm{VWS} \times \mathrm{DEF} \qquad (6)$$

where VWS is vertical wind shear and DEF is deformation. DEF is described by combining stretching deformation and shearing deformation. Another index described by Ellrod and used at the Air Force Global Weather Center (AFGWC) includes the horizontal convergence (CVG) term in the ELLROD-1 index. The index is defined as the TI2 index and given by

$$\mathrm{TI2} = \mathrm{VWS} \times \left[\mathrm{DEF} + \mathrm{CGV}\right]. \qquad (7)$$

Since CGV is known as having a small value comparing with DEF, TI1 is nearly same with TI2, but in some cases such as the occurrence of severe thunderstorm, it could contribute significantly to CAT potential (Ellroad, 1985).

3. VERIFICATION

In order to show the accuracy and the ability of the five indices to forecast CAT, two case studies over South Korea was been examined during a passage of a large-amplitude upper-level trough in October 2001: The one is related to a mesosclae convective system in which the PIREPs reported MOD turbulence at 260 FL for 03 UTC 9 and the other CAT at 290 FL for 06 UTC 11.

The Korea Meteorological Administration (KMA) provided the required data for computation of the turbulence indices evaluated in this study. Data for the study were from the Regional Data Assimilation and Prediction System (RDAPS), which was run twice daily (at 00 and 12 UTC) at KMA. As available, the meteorological data field consisted with 5 km horizontal resolution was archived at every hours and at 33 non-uniformly composed layers from SFC to 30 mb. The data were collected for a regional grid encompassing the South Korea and adjacent areas (viz., 32°N - 39°N, 122°E-132°E). All of the data used in the case studies were forecast output produced at 00 UTC before the occurrence time of the turbulence.

In case 1, all of the indices presented broad distributions of the turbulence potential extended from West Sea to East Sea. Ri contours less than 2 didn't comprehend the PIREP reported at the vicinity of Gwangju (Fig. 1), and this fact certifies that Ri by itself is insufficient to hold the turbulence prediction as mentioned above. It is very interested that the distribution of the BROWN-1 index (Fig. 2) is similar to the situations of TI1 (Fig 4) and TI2 (not shown) because the formulas that theoretically construct them have some differences. A remarkable contrast between BROWN-1 index and BROWN-2 index was that the turbulence potential at the Southeast provinces and South-west Sea showed contrast features. It might be inferred from an enhance GMS satellite imagery (not shown) that because a deep convection system located around the South-east part of Korea contributed to the increase of the vertical wind shear which give a potent influence to Ri, BROWN-1, TI1, and TI2, they showed contrary fields of more intense turbulence potential. Comparing the forecast with PIREP, all of the indices except for Ri revealed to be useful in identifying turbulence from the 5 km RDAPS data. The second example showed same results for the above indices.

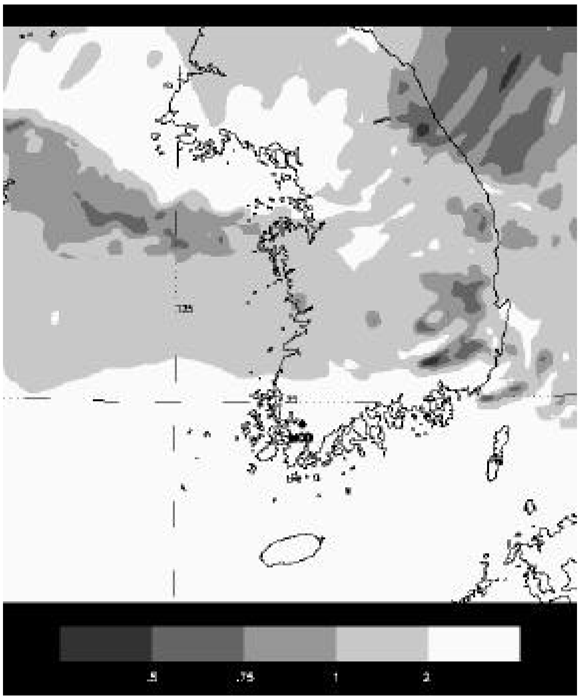

Fig.1. Ri forecast at 260 FL for 03 UTC 9 October 2001. The diamond (♦) indicates the location of the PIREPs, and its intensity is given under the symbol. The darker shaded areas correspond to more intense turbulence potential.

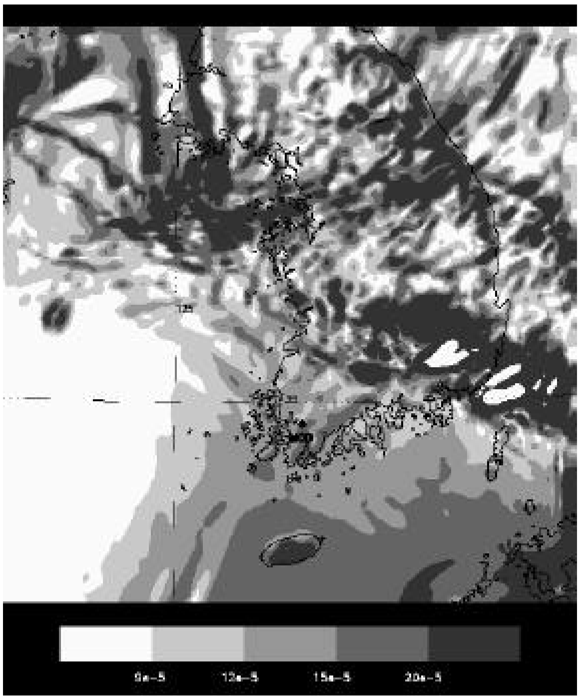

Fig. 2. Same as Fig. 1 except for Brown1 index in units of 10^{-5} s^{-1}.

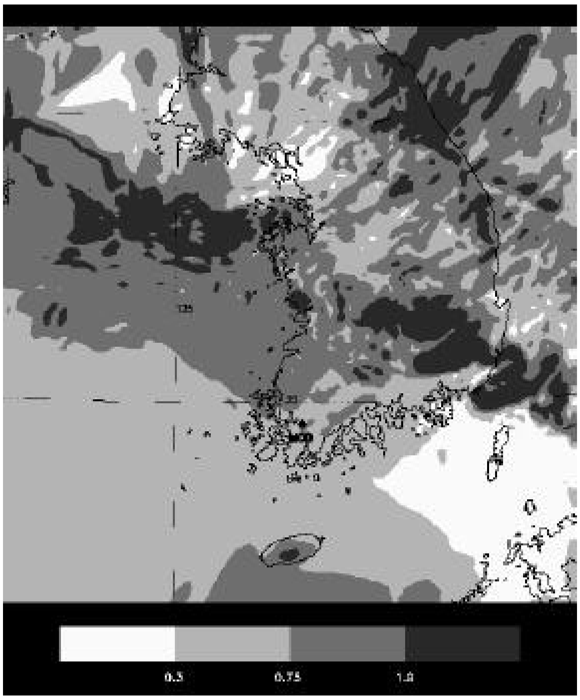

Fig. 3. Same as Fig. 1 except for Brown2 index in units of cm^2 s^{-3}.

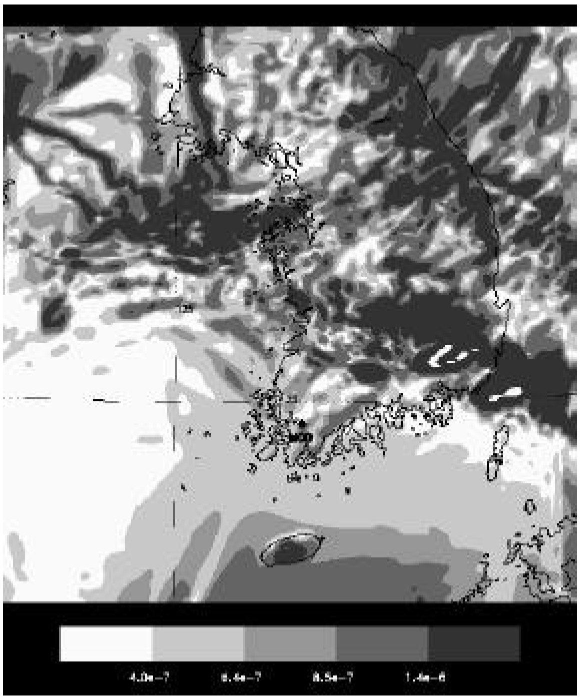

Fig. 3. Same as Fig. 1 except for TI1 index in units of 10^{-7} s^{-2}.

Since the 24-h forecast of the turbulence is run twice daily, two prediction fields of the indices is obtained for a target time. It is need to compare and analyze the difference of the computational results generated from the NWP model output.

Figure 5 shows that for the data prior to 12 hours the areal distribution of TI1 forecast is clearly wider and its intensity is more intense than the result obtained from the 12-hour later data (as shown figure 4). For other four indices, the results were very similar to the above case with the same manner. It would be suggested that different criteria determine the turbulence intensity to optimize the forecast must be applied along with prediction time.

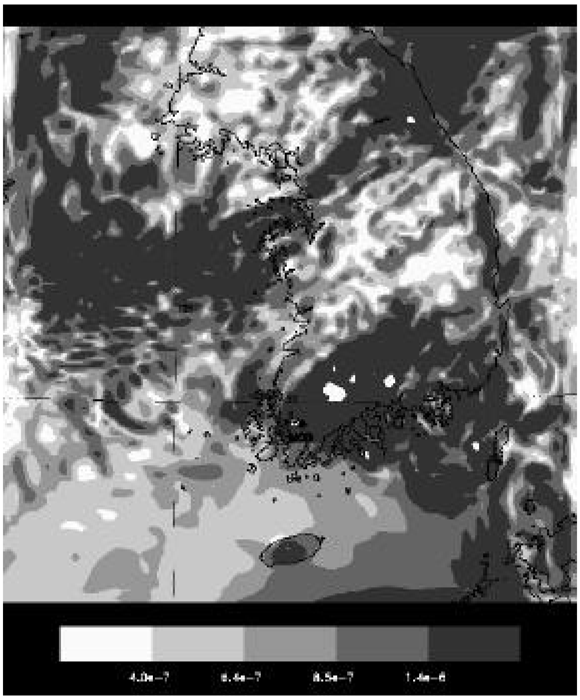

Fig.5. Same as Fig. 4 except for using data produced prior to 12-hour.

4. REMARKS AND CONCLUSIONS

Five indices which hash been used to forecast atmospheric turbulence in other studies were applied in aerial space of Korea, and their efficiency were verified with PIREPs despite the limitation due to use only one observational data. The case studies presented here show that Richardson number Ri fields less than unity presented an inaccurate distribution comparing with PIREPs and other contour maps of other four indices. This discrepancy between Ri and other indices certifies again that horizontal shearing and stretching terms must be appropriately considered in forecast of the atmospheric fluctuation.

The distributions of the turbulence diagnostics computed using 12-h previous output showed larger values and broader areas than those for later time. Thus, we need to apply different threshold values to prevent faults from analyzing the turbulence potential obtained from two output data having a 12-hour time difference for target forecast. It should be emphasizes that since all of the indices were deduced empirically, the criteria that imply the turbulence intensity must be modified properly with meteorological characters in Korea and Northeast Asia.

In further works, the verification of the indices will be continuously carried out with more PIREPs, and other indices based on various concepts to the onset of turbulence will be accomplished by comparing turbulence reports.

Finally, it must be remarked that though many problems such as an accuracy of the PIREP and the NWP model are remained, this study will be helpful to develop an optimized turbulence forecast system in Korea.

5. ACKNOWLEDGEMENTS

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