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CLEAR AIR TURBULENCE FORECASTS : TURBULENCE ALGORITHM INTERCOMPARISON USING AMDAR INTENSIVE OBSERATION PERIOD OVER WESTERN EUROPE

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1. INTRODUCTION

Most of the CAT indexes were designed some years ago with large scale numerical prediction models. The main objective of this study is to determine the ability in forecasting of CAT indexes at the regional scale (especially over Europe and Eastern part of the North Atlantic ocean). Several CAT indexes are calculated with two different NWP models, ARPEGE with a resolution of 1° and ALADIN with a resolution of 0.1°. These indexes are then compared with turbulence observations from AMDAR messages over a intensive observation period (IOP) during 2005 winter.

2. AMDAR IOP : observation data set

Within the E-AMDAR program, commercial aircrafts, using integrated sensors, measure meteorological parameters.
This meteorological data is transferred to the ground in real-time, using the meteorological network, inside text messages called AMDAR (Aircraft meteorological data relay).
Currently, commercial aircrafts are equipped with sensors, which are able to measure temperature, pressure, wind intensity and direction, and geographical position.

The AMDAR message contains these parameters and, in addition, two parameters relevant to turbulence calculated on-board: a “turbulence intensity” IT along with a “gust index” GT.

Here we focus on the AMDAR data collected during an IOP (Intensive Observation Period) of 40 days that took place from the 21st November 2005 to the 31st December 2005.
During this IOP, three times more data were collected than over the same period the year before.

Three types of aircraft are collecting AMDAR data. These aircrafts are equipped with several AMDAR acquisition and communication systems. A previous study on the AMDAR IOP enabled to withdraw some of the data collected by a specific equipment.

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The comparison has been performed over Europe. The domain coordinates are from 9.96W to 10.30E and from 39.46N to 53.67N.

2.1 Turbulence Intensity Index (IT)

The turbulence intensity (IT) in the AMDAR message could have four values: Nil, Light, Moderate, or Severe.
These turbulence intensities are based on the vertical acceleration measured by the aircraft accelerometers. The vertical acceleration is converted according to the following scale (OMM scale):

Value	Intensity	AMDAR Code
$IT < 0.15g$	no turbulence	8
$0.15g \leq IT < 0.5g$	Light turbulence	9
$0.5g \leq IT < 1g$	Moderate turbulence	10
$IT > 1g$	Severe turbulence	11

Table 1 : IT thresholds

2.2 Derived equivalent vertical gust (DEVG)

The DEVG parameter helps to evaluate the speed of the vertical gust with respect to the vertical acceleration of the aircraft gravity centre. The interest of this value is that it does not depend on the aircraft type and characteristics. The DEVG value are directly transmitted. The correspondence between DEVG values and turbulence levels is described in the next table.

DEVG Value	Intensity
Less than 2m/s	no turbulence
from 2 to 4.5 m/s	Light turbulence
from 4.5 to 9 m/s	High turbulence
Higher than 9m/s	Intense turbulence

Table 2 : Vertical gust DEVG levels

2.3 AMDAR data

In AMDAR messages, six flight phases can be distinguished: ascension phase (ASC), descent phase (DES), unstable phase (UNS), cruising phase or flat level with regular observations (LVR), cruising phase or flat level associated with maximal wind (LVW) and unknown cruising phase (INC)

Observations are more numerous during the ascension and descent phases.
Transmitted AMDAR data is filtered in order to avoid the redundancy and to optimise the network traffic.
During the IOP, only ascension and descent phases observations were transmitted.
Data monitoring is performed at the UKMET Office to avoid possible errors in the measures. An aircraft could be “black listed” if problems are often encountered in its data.

In order to eliminate turbulence induced from convection, data are filtered by using lightning observation. If there is an lightning observation in a range of 50 kilometres and within a one hour time window AMDAR data are excluded.
The particularity of AMDAR data is that they are not well distributed on the domain. The turbulence information is concentrated around the airports.
The AMDAR number is dependent on the traffic and so, on the time in the day. The traffic is concentrated between 6 and 22TU, with a peak of activity in the morning.

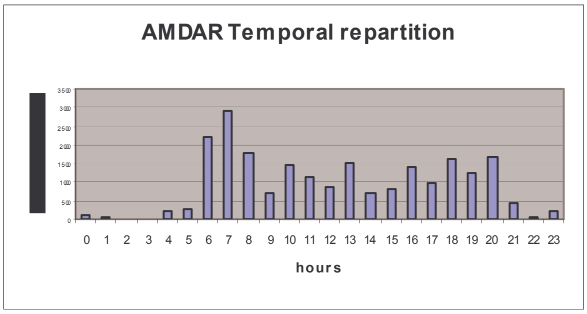

Figure 1 : Temporal distribution of AMDAR

2.4 Intensity repartition

The turbulence intensity is reported by DEVG or IT. In the IOP sample the intensities are reported differently for IT or for DEVG. The number of high intensities cases is very low but more numerous in IT observations than in DEVG observations. The no turbulence events are more numerous in IT observations.

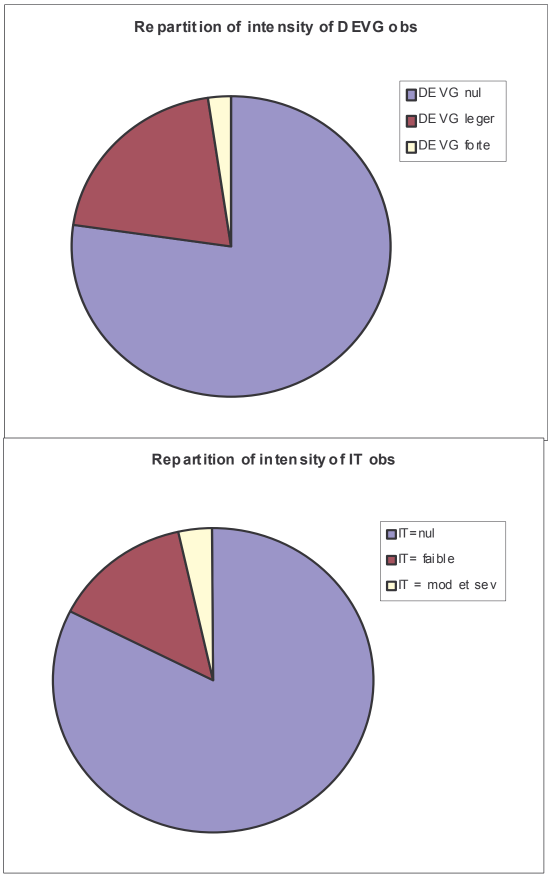

Figure 2 : Distribution of intensity of Vertical Gust observation (top) and of intensity of IT (bottom)

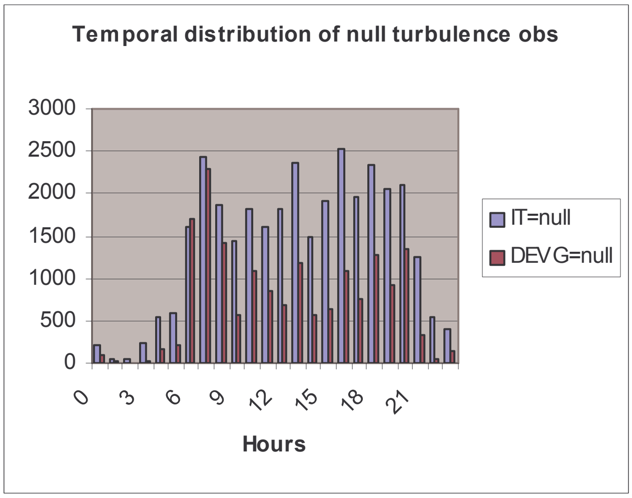

Figure 3 : Temporal distribution of null turbulence observations along the day

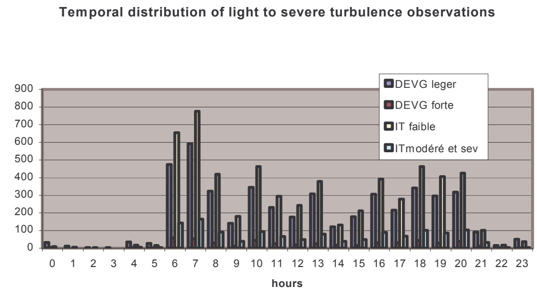

Figure 4 : Temporal distribution of light to severe turbulence along the day

3. SET OF TURBULENCE INDEXES

3.1. Description

In this study, two numerical models from Météo-France are used: ARPEGE and ALADIN. ARPEGE offers a global coverage with a mesh from 1° for global use, and to 0,25° over the European domain. ALADIN covers the European domain only with a finer resolution of 0,1°.

The development of the CAT indexes, more than 20 years ago, was based on models with larger mesh than models that are in use today.

Comparing CAT indexes calculated from ALADIN and ARPEGE models is a way to explore the behaviour of each index calculated depending on the mesh.

The characteristics of the models used are :

- ARPEGE
  - grid mesh 1°
  - Number of points 121x240
  - Levels in hPa 500, 400, 300, 250, 200, 150
  - model runs : 0,6, 12, 18 UTC
  - forecasts : 0, +3H, +6H
- ALADIN
  - grid mesh 0.1°
  - Number of points 221x281
  - Levels in hPa 500, 400, 300, 250, 200, 150
  - model runs : 0,6, 12, 18 UTC
  - forecasts : 0, +1H, +2H, +3H, +4H, +5H,+6H

The study is performed over the ALADIN domain. The indexes are calculated for the following levels: 500, 400, 300, 250, 200, and 150hPa.

3.2. Turbulence indexes

The following indexes are calculated: Brown, Dutton, Ellrod1 et Ellrod2.

The formulas of these indexes are presented in the following paragraphs. Details are available in annex.

<u>Dutton</u>

The Dutton index is based on linear regression analyses of a pilot survey of turbulence reports over the North Atlantic and North West Europe during 1976 and various synoptic scale turbulence indexes produced by the then-operational UK Met Office forecast model (Dutton 1980, [11]). The result of the analyses was the "best-fit" of the turbulence reports to meteorological outputs for a combination of horizontal and vertical wind shears.

The Dutton index is defined as follows:

*E = 1.25 * horizontal wind shear + 0.25 * vertical wind shear* ^{2} *+ 10.5*

<u>Brown</u>

Brown (1973) proposed a modified Richardson Number.

Brown=

$$\sqrt{0.3 absoluteVorticity^2 + StretchingDeformation^2 + ShearingDeformation^2}$$

<u>Ellrod1</u>

Ellrod's TI1 index (Ellrod and Knapp 1991, [12]) was defined to indicate the likelihood of encountering shear-induced CAT.
The TI1 index is defined as follows:

TI1= Vertical Wind Shear x Deformation

<u>Ellrod 2</u>

The TI2 index is defined as follows

TI2= Vertical Wind Shear x (Deformation + Convergence)

4. COMPARISON METHOD

This study focuses on the AMDAR data collected during the IOP (Intensive Observation Period) of 40 days that took place from the 21st November 2005 to the 31st December 2005.

AMDAR are sparse observations. To perform a verification of CAT forecast towards AMDAR data we need to assign to each AMDAR data one CAT forecast. We use a matching approach to connect the CAT index to the AMDAR observation. With this method, for each AMDAR observation, on the closest model level where turbulence observation is reported; the CAT index values on the four surrounding model grid points are compared.

For each index, thresholds have been defined (Brown et al. NCAR 1999).

Index	Threshold values
Dutton	0, 1, 2, 3,4, 5, 6, 7 ,8, 9, 10, 11,12,13, 14, 15, 16, 17, 20 , 25, 30, 50
Ellrod1	-1 E-05; 1 E-08; 5 E-05 ; 8 E-05; 1 E-07; 2 E-07; 4 E-07; 5 E-07; 6 E-07; 8 E-07; 1 E-06; 1,2 E-06; 1,4 E-06, 1,6 E-06; 1,8 E-06; 2,4 2 E-06; 1 E-05.
Ellrod 2	-1 E-05; 1 E-08; 5 E-05 ; 8 E-05; 1 E-07; 2 E-07; 4 E-07; 5 E-07; 6 E-07; 8 E-07; 1 E-06; 1,2 E-06; 1,4 E-06, 1,6 E-06; 1,8 E-06; 2,4 2 E-06; 1 E-05.
Brown	1, 77E-06, 1,15 E-05, 4,06 E-05, 5 E-05, 6 E-05, 7 E-05, 8 E-05, 9 E-05, 10 E-05, 11 E-05, 12 E-05, 13 E-05, 14 E-05, 15 E-05, 16 E-05, 17 E-05, 20 E-05, 23 E-05, 25 E-05, 30 E-05, 50 E-05 , 1,50E-03

Tableau 4 : Thresholds for CAT indexes (based on "Turbulence algorithm Intercomparison" B. Brown et al. NCAR 1999)

For each threshold, an (observation, forecast) couple is generated as follow :

-for a not turbulent observation (obs= No),

- if the CAT index of one of the four surrounding grid point is lower than the threshold, then the forecast gets a No value (for = No),
- if there is no CAT index in the four surrounding points with a value less than the threshold, then the forecast gets a Yes value (for = Yes)

-for a turbulent observation (obs=Yes)

- if the CAT index of one of the four surrounding grid points is higher than the threshold, then the forecast gets a Yes value (for = Yes)
- if there is no CAT index in the four surrounding grid points higher than the threshold, then the forecast gets a No value (for = No)

The verification domain is performed over a grid mesh of 1°. In the case of the ARPEGE model, the domain contains 4 points. For the ALADIN model, the domain contains 100 points.

Knowing the intermittent character of the turbulence phenomenon and the speed of the aircraft measuring the turbulence, this method for assigning a forecast value to an AMDAR observation is highly preferable to any kind of interpolation in space and time between grid points.

5. RESULTS

5.1. Distribution of each indexes for all thresholds

For each index, the percentage of match couples (obs=No, for= No) or (obs=Yes, for=Yes) according to the thresholds has been plotted separately depending on the intensity of the turbulence observed.

Each index was calculated twice :

- one calculated using ARPEGE model
- one calculated from ALADIN model.

The figure 5 presents here an example of the distribution obtained for the Ellrod 1 index, for observations of light turbulence (DEVG and IT).

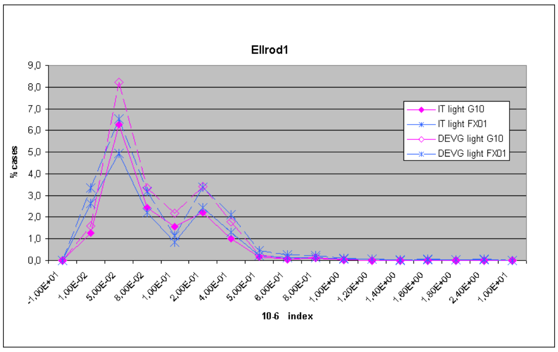

figure 5 : Percentage of cases for each Ellrod1 value for which light DEVG or light IT has been reported in the AMDAR messages.

For light turbulence observed, ELLROD1 shows a two peaks distributions (same values as for null turbulence). The distribution is flat above 6.10-5.

The maximum of the distribution is greater for DEVG than for IT.

The maximums of the distribution of ELLROD1 calculated from ARPEGE are higher than the maximums of the distribution of ELLROD1 calculated from ALADIN.

The distribution of ELLROD1 calculated from ALADIN shows a light increasing trend around 7. 10-5

The patterns appear to be quite similar for the different intensities of turbulence. No specific behaviour can be identified depending on the turbulence intensities.

For all indexes studied, the study of these distributions does not allow to conclude on the use of any particular threshold to discriminate turbulence intensities

5.2. ROC curves

Two kind of probability of detection are calculated:

- one, for the occurrence of turbulence or not (POD), this POD doesn't take into account the intensity of the turbulence (could be light, moderate or severe)
- one, for the occurrence of moderate or greater turbulence (PODMOG), light turbulence is considered as no turbulence.

The POD and PODMOG are calculated separately for DEVG observations and for IT observations.

ROC curve of indexes calculated with ARPEGE / DEVG observations

For DEVG observations, calculated from ARPEGE model (see figure 6), Ellrod 1 et Ellrod 2 indexes are similar. The best results are obtained by both Ellrod indexes followed by Dutton index and then Brown index with a lower score. The PODMOG for turbulence “moderate or greater” are better than the POD, this confirms the intuitive fact that the indexes forecast better strong turbulence than light one.

ROC curve of indexes calculated with ALADIN / DEVG observations

Calculated from ALADIN (see figure 7), the overall score is better than the one of the indexes calculated from ARPEGE.
The best score is first Ellrod 2 followed closely by Ellrod 1. Dutton and Brown have similar results. The scores are still better for the PODMOG, than for the POD.

ROC curve of indexes calculated with ARPEGE/ IT observations

The evaluation against IT observations (see figure 8) shows lower scores compared to the evaluation against DEVG observations.
Calculated with ARPEGE, the PODMOG for Ellrod 2 and 1 have the best scores, followed by Ellrod2 POD and then Ellrod 1 POD. The score of the Dutton PODMOG is close to the one of Ellrod1 POD, the three lower scores are Dutton POD, almost equal to the Brown PODMOG and then the Brown POD.

ROC curve of indexes calculated with ALADIN/ IT observations

For IT observations, calculated with ALADIN (see figure 9), all indexes show a great increase in their scores. The best score is obtained by Ellrod2 followed by Ellrod1. In the evaluation based on IT observations, the score of Brown index is better than the score of Dutton index.

6. CONCLUSIONS

The verification method shows some differences in the results of the four indexes depending on the model used and the AMDAR observations used (IT or DEVG).

In general, the use of the model ALADIN improves the results, even if the verification domain is reduced, whether if the observation data set is IT or DEVG.

A difference in the results between the two observation datasets is observed. Scores are better when the forecasts are compared to the DEVG dataset.

The use of “MOG” sample induces low differences for Ellrod 1 and Elrod2 indexes, compared to Dutton and Brown indexes.

The four indexes do not react similarly to the change of the numerical model. Ellrod 1 and Ellrod 2 indexes are best performing with the model ALADIN, independently of the use of DEVG dataset or IT dataset.

Dutton results are improved when it is calculated with ALADIN on a 100 points domain, but when the verification domain is smaller the scores are lower. The behaviour of Dutton index is not similar when compared to DEVG dataset or to IT dataset. The scores are higher when compared to the DEVG dataset.

The Ellrod1 and Ellrod2 indexes show the best skills. In addition they benefit of the increased resolution of the numerical model. With ALADIN model they improve their results even if the verification domain is changing. The comparisons to IT dataset or DEVG dataset show similar results.

The scores of Brown index are higher when calculated with the finer resolution model.

This study shows how difficult it is to evaluate the skills of the CAT indexes using AMDAR turbulence information. First , non-turbulence conditions are far more frequent than turbulence conditions, meaning that in the AMDAR data set the number of turbulence observations is low. A major difficulty is to be able to link the levels of turbulence observations with CAT index values.

As CAT is a micro-scale phenomenon, the CAT indexes, even calculated with a finer resolution model, only take into account macro scale parameters and thus show low skills in predicting a number of CAT situations.

7. BIBLIOGRAPHIE

[1] Brown, R. 1973: ‘New indices to locate clear-air turbulence’. Meteorological magazine, vol. 102, pp347-361.

[2] Buss S., Jäger E., Schmutz C., 2005: ‘Evaluation of turbulence forecasts with the aLMo’. Technical note, MeteoSchweiz.

[3] Brown B. G., Mahoney J. L., Bullock R., Henderson J., and Kane T. L., 1999: ‘Turbulence Algorithm Intercomparison 1998-99 Initial Results’. NCAR technical note.

[4] Dutton, M.J.O. 1980: ‘Probability forecasts of clear-air turbulence based on numerical model output’. Meteorological magazine, vol 109, pp293-310.

[5] Ellrod, G. P. and Knapp, D. I. 1992: ‘An Objective Clear Air Turbulence Forecasting Technique: Verification and Operational Use’. Weather Forecasting, vol. 7, pp 150-165.

[6] Turner, J. 1999: ‘Development of a mountain wave turbulence prediction scheme for civil aviation’. Met Office Forecasting Research Technical Report No. 265.

[7] Turp, D. J., Macadam, I., Bysouth, C. and Jerrett, D. 2006: ‘Development of GRIB Icing

and Turbulence Products for WAFC London: Progress Report'. Met Office Forecasting Research Technical Report (in preparation).

[8] Sousounis P.J., 2005: 'Short term turbulence forecasts over the Atlantic Ocean using WRF'. WSN 2005 proceedings.

[9] 'WMO AMDAR Reference Manual'. WMO technical publication n°958.

8. EQUATIONS

Input parameters for the CAT index

- Stretching deformation: DST= $\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$
- Shearing deformation: DSH= $\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$
- Absolute vorticity : VORABS= $f + \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$
- Horizontal Convergence : CVG= $-\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$
- Deformation DEF = $\sqrt{DST^2 + DSH^2}$
- horizontal wind shear:
  Sh=
  $$\frac{1}{u^2+v^2}\left(uv\frac{\partial u}{\partial x} - u^2\frac{\partial u}{\partial y} + v^2\frac{\partial v}{\partial x} - uv\frac{\partial v}{\partial y}\right)$$
- vertical wind shear:

Sv= = $\sqrt{\left(\frac{\partial u}{\partial p}\right)^2 + \left(\frac{\partial v}{\partial p}\right)^2}$

9. FIGURES

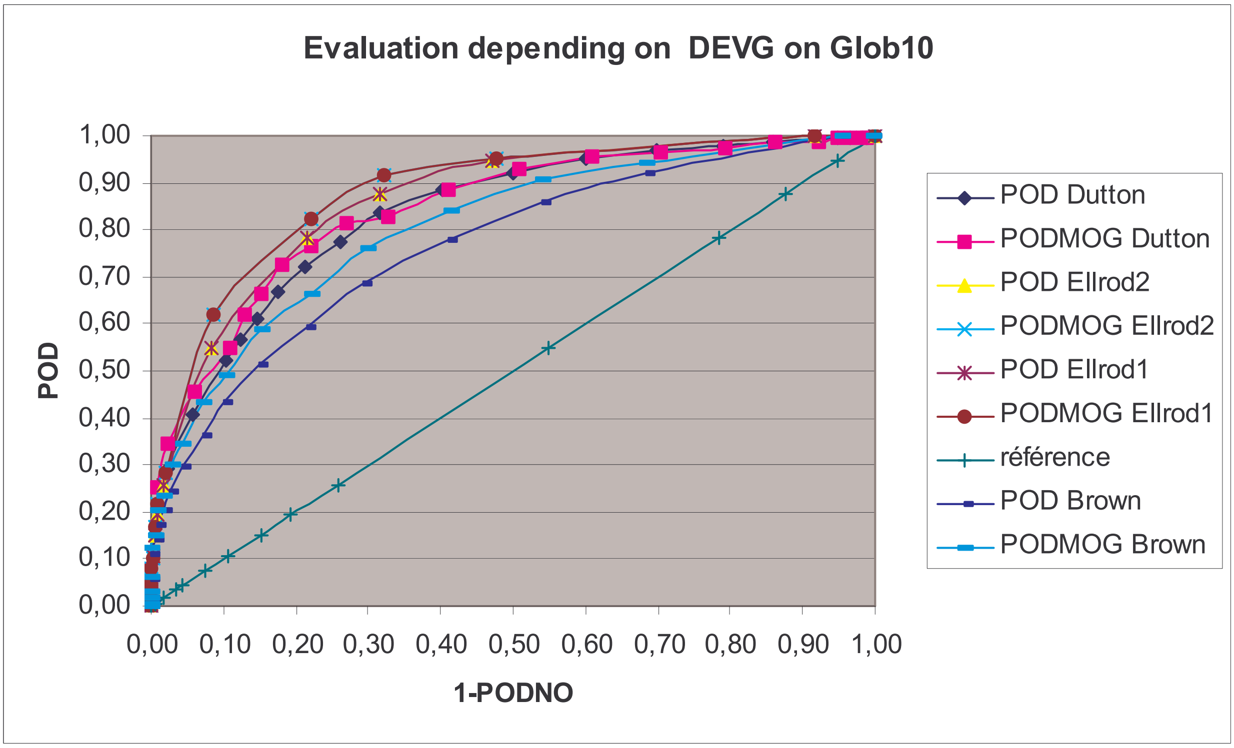

Figure 1: ROC curve for all CAT indexes calculated with ARPEGE model for DEVG observations only

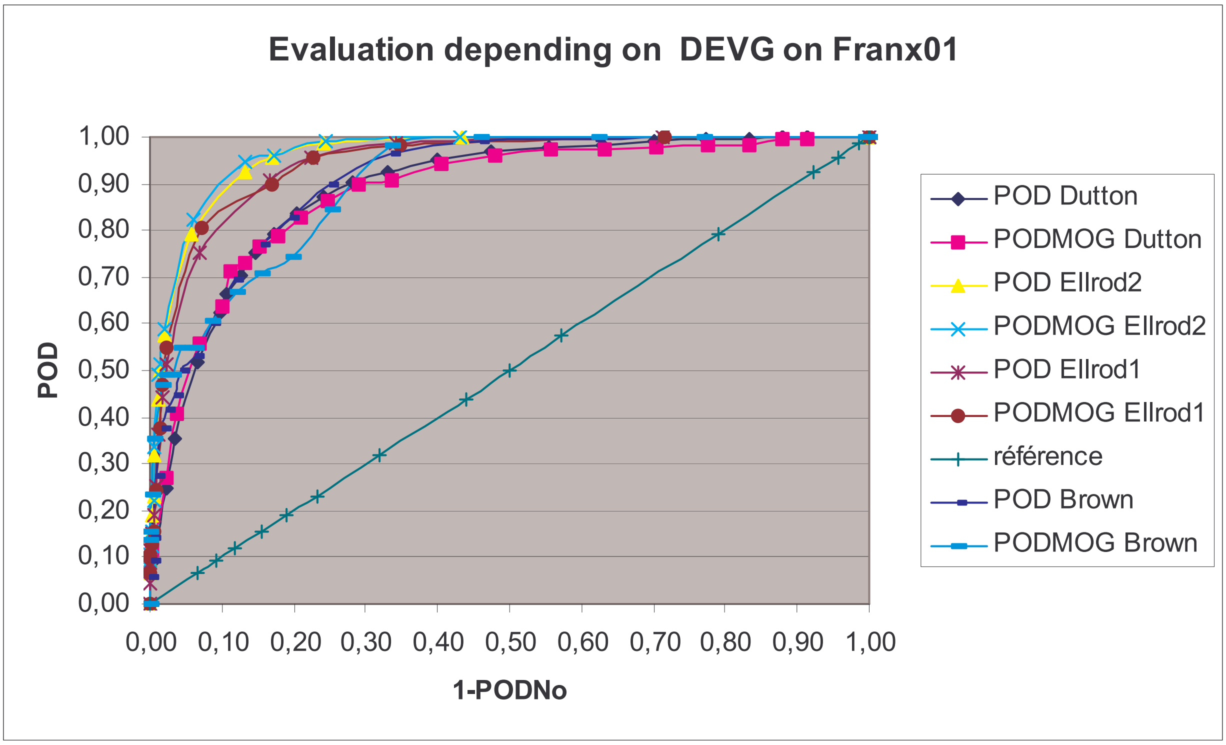

Figure 2: ROC curve for all CAT indexes calculated with ALADIN model for DEVG observations only

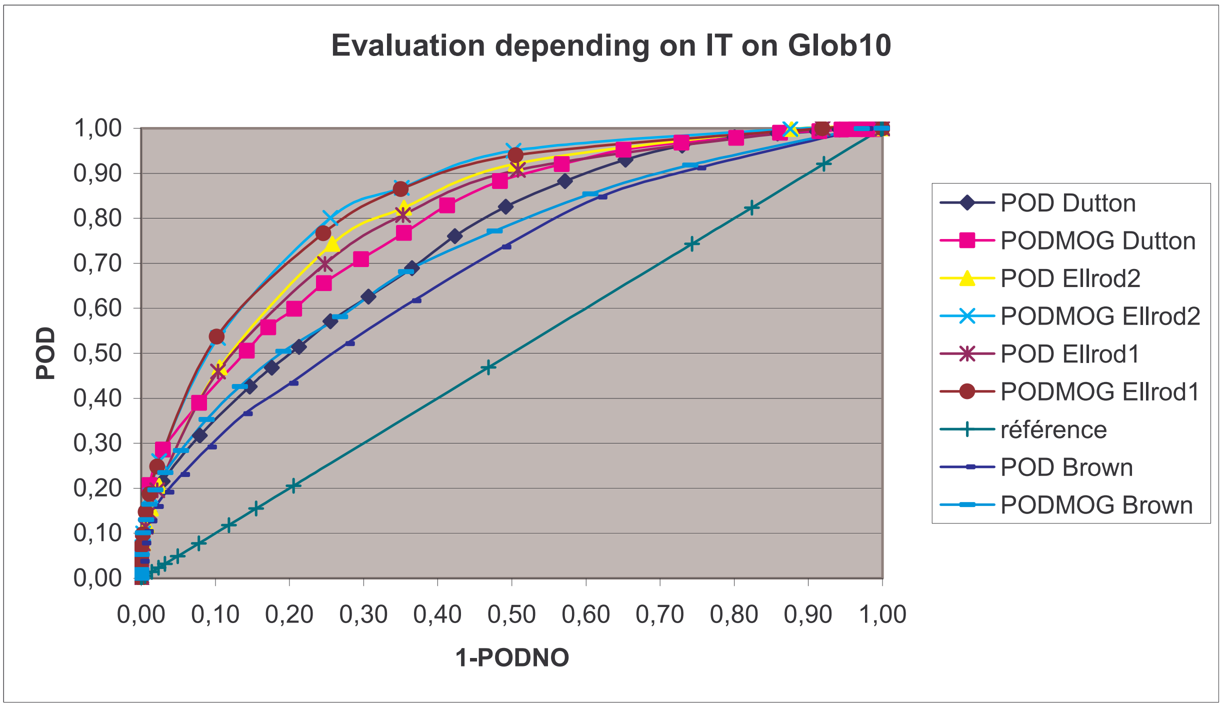

Figure 3: ROC curve for all CAT indexes calculated with ARPEGE model for IT observations only

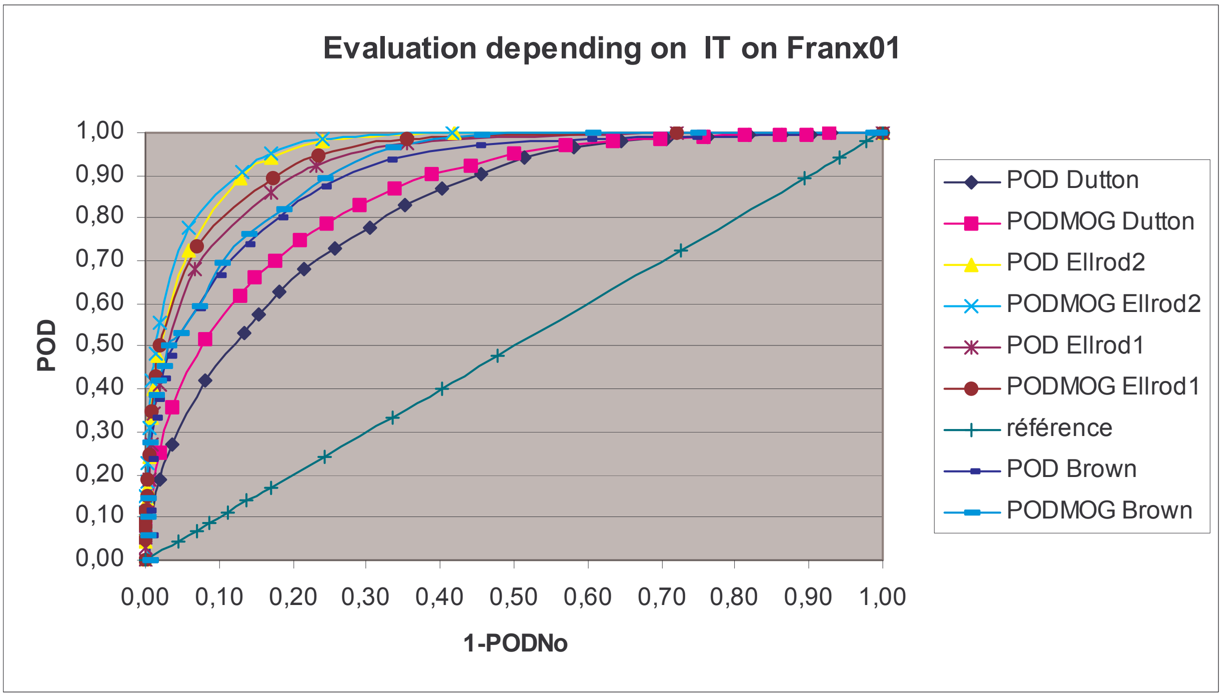

Figure 4: ROC curve for all CAT indexes calculated with ALADIN model for IT observations only