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PREDICTIONS OF GALACTIC COSMIC RAY INTENSITY DEDUCED FROM THAT OF SUNSPOT NUMBER

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Abstract : A new method is proposed to predict cosmic ray intensity and solar modulation parameters. The method is coupled with McNish and Lincoln method, which predicts first smoothed sunspot numbers. The error done is estimated and compared with the same chain of predictions using two other methods developed for US and Russian space applications. The three methods give satisfactory results when applied, for example, to prediction of dose received on-board commercial aeroplane flights.

1- Introduction

The solar modulation of the intensity of galactic cosmic rays received at the Earth, as a consequence of the changes of topology of the interplanetary magnetic field in the course of the solar cycle, is related to the solar corona structure and activity. Number of applications are needing restitution, now-casting or forecasting the solar modulation of galactic cosmic rays. The purpose of the present work is to estimate errors done when the sunspot number itself is first predicted and when galactic cosmic ray intensity, modulation parameters and doses received on board aeroplane, are then derived from the sunspot numbers. The predictions are tested up to 4 years in advance.

For space applications, like study of SEU (single event upset) rate in computer memory chips on board satellites or study of biological dose received during Space Shuttle missions (Badhwar et al., 1995), the spectrum of the different primary particles and nuclei, varying with the solar cycle, has been parameterised with the so-called deceleration potential (Badhwar and O'Neill, 1996) and with the modulation potential (Nymmik et al., 1996). Both potentials are given in terms of sunspot numbers and, in the case of deceleration potential, in terms of the intensity of the galactic cosmic ray component observed, at the ground level, with the Climax neutron monitor (Badhwar and O'Neill, 1993). Another potential, called heliospheric potential (O'Brien, 1971), has been derived from neutron monitor (NM) measurements. Unlike the neutron monitor measurements, the potentials are global and not related to a specific geographic location.

Monitoring doses received on-board aeroplane is one of the application of modulation parameters. The widely distributed operational software CARI (Freidberg et al., 1999) is using the heliospheric potential, while the software called EPCARD (Schraube et al., 1999) is using the deceleration potential. It should be noted that there is a systematic difference of about 200 MV between heliospheric potential and the two others. Thus the different potentials are not equivalent. Because of that the corner stone of the present work will be prediction of the galactic cosmic ray intensity observed at a given station rather than prediction of the different potentials. A further interest of this choice is that the cosmic ray intensity is the only variable directly observed. Records of cosmic ray intensity are available, and homogeneous, over a long period which is not the case for the data obtained from space observations.

The first step is the prediction of the smoothed sunspot number. Then the galactic cosmic ray intensity could be predicted using three different methods, two being derived from Badhwar and O'Neill and Nymmik et al. works. For each prediction of cosmic ray intensity, the prediction of the heliocentric potential will be considered. Indeed, it has been shown (Lantos, Fuller and Bottollier-Depois, 2003) that one neutron monitor is sufficient to calculate properly the heliocentric potential using a second degree polynomial fit. Then the errors of the prediction of doses could be studied using CARI 6 software. The neutron monitor used here for the validation of the prediction is the French neutron monitor located at Port-aux-Français (Kerguelen Island, Indian Ocean).

2- Prediction of the sunspot cycle

Prediction of the smoothed sunspot number RI_{12}, a 12 month running average of the monthly sunspot number (SIDC, 2004) is one of the basic needs of Space Weather activities. A large number of methods have been proposed and tested : one group is based on the characteristics of the smoothed sunspot number time profiles (McNish and Lincoln, 1950, Waldmeier, 1968, Zhan Qin, 1996, Conway, 1998), another is based on precursors different in nature, like geomagnetic activity (see for example Lantos and Richard, 1998). We are using here the classical method of McNish and Lincoln, adapted by Stewart and Ostrow (1970) and Fessant, Pierret and Lantos (1996). The method has been evaluated by Hildner and Greer (1990). Figure 1 compares measurements of the present solar cycle (heavy line) with predictions done each six months, with a maximum horizon of four years (small circles). The first of the predictions, available in October 1998, gives predictions of RI_{12} index starting in April 1998 because of the delay of six months inherent to the smoothing calculation. This first prediction leads to a very overestimated maximum of the cycle, while the other predictions remain close to the observed values. Indeed the prediction is not precise during the first part of the ascending phase of the cycle (the prediction relative error could be as large as 50 %). It becomes much better 2 or 3 years after the beginning of the cycle, the agreement being then better than about 10 %.

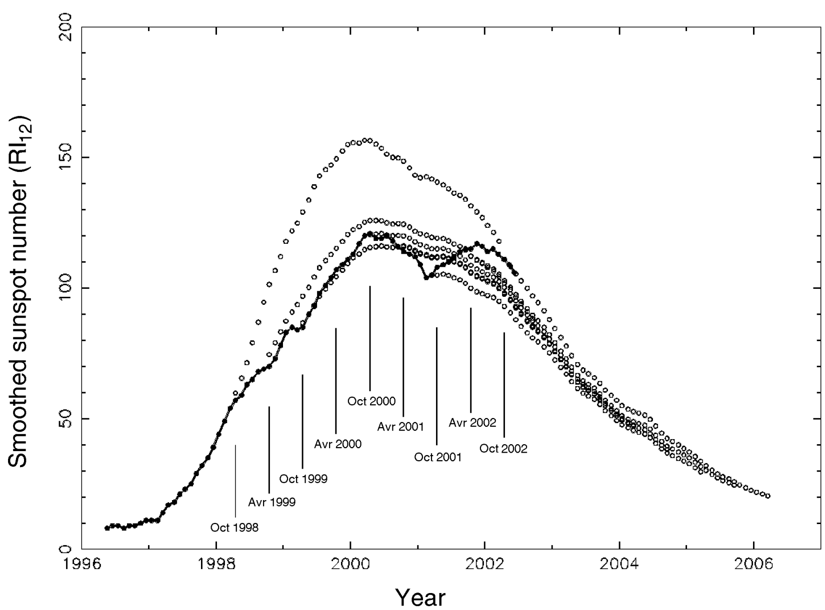

Figure 1: Solar cycle number 23 as observed with smoothed sunspot number RI_{12}.(heavy line) is compared to the predictions using McNish and Lincoln method. The dates of the beginning of predicted sequence (with a prediction each 6 months) is given under the curves.

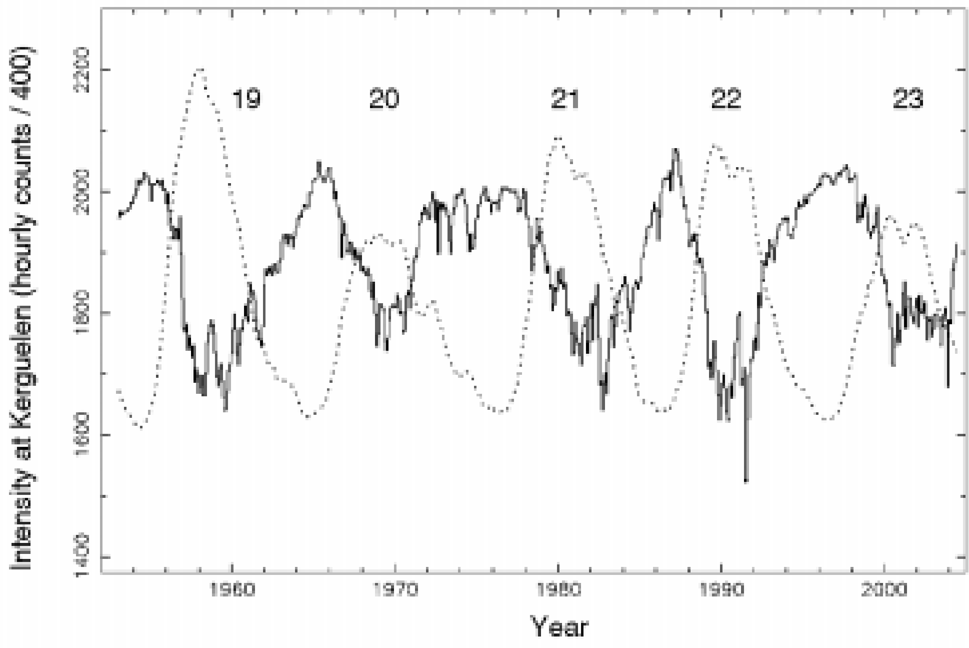

Figure 2: Monthly mean intensity of cosmic rays (full line) observed since 1957 with Kerguelen NM and before 1957 with Climax NM. Comparison to smoothed sunspot number RI_{12}, (dotted line)

3- Method A to predict intensity of galactic cosmic rays from smoothed sunspot numbers

Figure 2 shows the well known anticorrelation between intensity of cosmic rays and smoothed sunspot numbers. The cosmic ray intensity is from Kerguelen NM from 1957 to now. Before 1957, the intensity is obtained from Climax (USA) NM, normalised to the Kerguelen scale with linear regression. This provides a comparison over four entire cycles (cycles 19 to 22) and for the cycle in progress (cycle 23). The present cycle will serve as a test of methods of prediction based on the previous cycles.

When the running 12-month average is applied to cosmic ray intensity and when odd and even cycles are separated, one obtains figures 3a and 3b. Intensity of galactic cosmic rays is given in function of smoothed sunspot numbers. For a given parity both cycles are similar. For even cycles the loop is narrow. For odd cycles it is much larger. Indeed the inversion of the direction of the interplanetary magnetic field modifies the conditions of propagation of the cosmic rays within the heliosphere. On both Figure 3a and 3b the regression line between cosmic ray intensity and sunspot numbers RI_{12} is drawn. It is obtained over the whole period and corresponds to equation:

$$Intensity_{\,Kerguelen} = 2027 - 1.820 \times RI_{12} \qquad [1]$$

where the intensity units are hourly counts divided by 400.

We consider now the difference between each point and the regression line as new variable. With the phase of the cycle (varying from zero to one from one minimum to the next) as abscissa and the difference to the regression line in ordinate, Figures 3c and 3d, respectively for odd and even cycles show that the two trajectories are effectively similar for the same parity. The average of the curves is indicated on Figure 3c and 3d. In method A, this function is the basic correction to be added to the result of the regression line, in order to predict the intensity of cosmic rays from predicted smoothed sunspot numbers RI_{12}. The curve is then fitted to the last RI_{12} value available from observations.

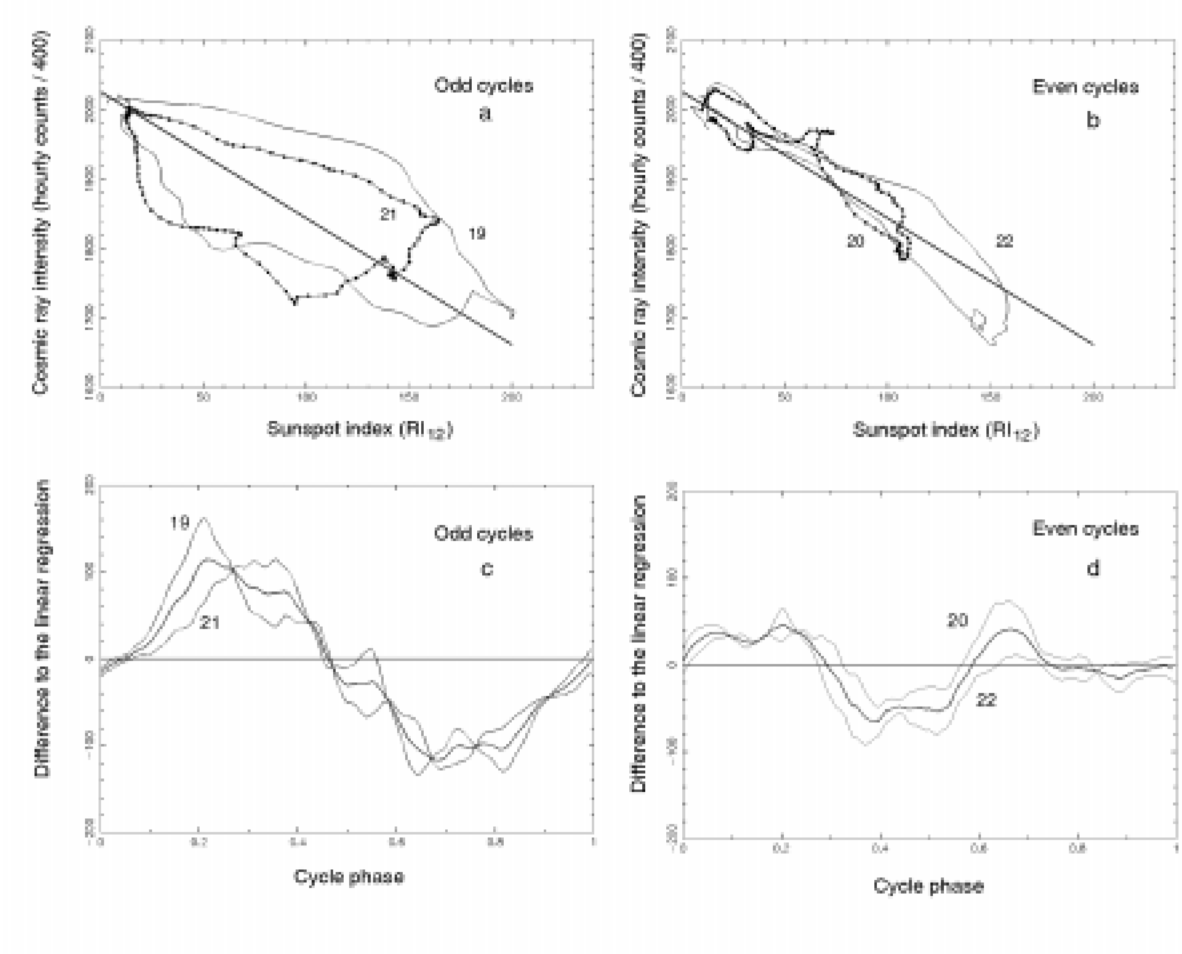

Figure 3:
a) Intensity of cosmic rays observed with Kerguelen NM (in ordinate) in function of smoothed sunspot index RI_{12} (in abscissa) for odd cycles 19 and 21 (dotted line).
b): Same figure for even cycles 20 (dotted line) and 22.
c): Difference between cosmic ray intensity and regression line for odd cycles 19 and 21.The heavy line is the average of both cycles.
d): Same figure for even cycles 20 and 22.

The intensity for another monitor could been obtained from a linear regression between intensities observed with the given monitor and intensities observed with Kerguelen neutron monitor. For example the relationship between Climax NM and Kerguelen NM is well fitted with:

$$Intensity_{Climax} = 2.447 \times Intensity_{Kerguelen} - 662 \qquad [2]$$

where the intensity units are hourly counts divided by 100 for Climax and hourly counts divided by 400 for Kerguelen. Although both monitors have different vertical cut-off rigidity (3 GV for Climax and 1.1 GV for Kerguelen), the transformation is reliable : the correlation coefficient is 0.9875 and the standard error of estimate is 42.7 (the intensity measured with Climax NM is of the order of 4000).

4- Method B deduced from Nymmik et al. and method C deduced from Badhwar and O'Neill

Nymmik et al. (1996) give a sequence of formulae which permits the calculation of the delay between sunspot indices and potentials. This delay is variable with the phase of the cycle (in contrary to the method of Badhwar and O'Neill which assumes constant delay) and with the amplitude of the cycle. When the delay is applied to the sunspot numbers, in the case of an odd cycle, the loops of Figure 3a become quite flat, so the relationship between cosmic ray intensities and delayed smoothed sunspot numbers could be adequately fitted with a second degree polynome:

$$Intensity_{Kerguelen} = 5.229x10^{-3} \times (RI_{12}*)^2 - 2.539 \times RI_{12}* + 2021 \qquad [3]$$

where RI_{12}* are the delayed smoothed sunspot numbers. The standard error of estimate is 22.0 (the intensity measured with Kerguelen neutron monitor is of the order of 2000). In the case of an even cycle, the original loop is much narrow (Figure 3b) but still improved by the delay taken into account and the resulting curves could be fitted with:

$$Intensity_{Kerguelen} = -9.079\ 10^{-3} \times (RI_{12}*)^2 - 0.814 \times RI_{12}* + 2016 \qquad [4]$$

The standard error of estimate is 23.6. Both above 2^{nd} degree polynomes provide a possibility (method B) to predict cosmic ray intensity when smoothed sunspot numbers are predicted. The above polynomes are for intensities measured with the Kerguelen neutron monitor. The same could be done for any neutron monitor of intermediate vertical cut-off rigidity. For Climax monitor for example the two fits become:

$$Intensity_{Climax} = 1.196 \times 10^{-2} \times (RI_{12}*)^2 - 6.245 \times RI_{12}* + 4303 \qquad [5]$$

for odd cycles and

$$Intensity_{Climax} = -2.835 \times 10^{-2} \times (RI_{12}*)^2 - 1.064 \times RI_{12}* + 4247 \qquad [6]$$

for even cycles. The standard error of estimate are respectively 53.9 and 63.0.

Badhwar and O'Neill (1993) have provided two sets of equations to calculate the deceleration potential. The first set is in function of cosmic ray intensity measured with Climax neutron monitor and the second in function of sunspot numbers. In the first case a delay of 95 days on cosmic ray intensity is introduced and in the second case a delay of 270 days (about 9 months) on sunspot numbers is introduced. For each set, three equations are given depending upon the configuration of the interplanetary magnetic field : positive (i.e. north hemisphere of the Sun with positive magnetic polarity), negative or magnetic field reversal. The dates of the different periods, starting with the maximum of cycle 19, are given Table 1 (Schraube, 2003 after Badhwar, 2001).

Table 1 : Changes of polarity of the interplanetary magnetic field

period	*beginning*	*ending*	*polarity*
1	1957.39	1959.39	field reversal
2	1959.39	1969.55	negative
3	1969.55	1971.55	field reversal
4	1971.55	1980.18	positive
5	1980.18	1982.57	field reversal
6	1982.57	1989.44	negative
7	1989.44	1991.64	field reversal
8	1991.64	1999.84	positive
9	1999.84	2001.99	field reversal
10	2001.99	2007.00 ?	negative

For each of the three interplanetary magnetic field configurations, it is possible to calculate the galactic cosmic ray intensity expected wit Climax NM in function of sunspot numbers. Indeed combination of the two equations available in each case from Badhwar and O'Neill (1993) permits to eliminate the deceleration potential. This leads to :

$$Intensity_{\,Climax} = -3.724 \times RI_{12}^* + 4330 \quad \text{for positive polarity} \quad [7]$$

$$Intensity_{\,Climax} = -3.866 \times RI_{12}^* + 4203 \quad \text{for negative polarity} \quad [8]$$

$$Intensity_{\,Climax} = -3.562 \times RI_{12}^* + 4071 \quad \text{for field reversal} \quad [9]$$

where RI_{12}^* is the smoothed sunspot number delayed by 175 days.
Applying inverted relation [2] given above, the cosmic ray intensity expected with measurements of Kerguelen neutron monitor could be calculated. Thus the above linear relations provide in fact a possibility (method C) to predict cosmic ray intensity expected to be observed with any neutron monitor when smoothed sunspot numbers are predicted.

5- Comparison of the three methods relating cosmic ray intensity to sunspot numbers

The skill of the three methods could be compared at two different levels. First, without prediction, the methods provide a restoration of the cosmic ray intensity from sunspot numbers. Restored intensities could be compared to observed intensities to validate the methods. The second step is to introduce predicted sunspot indices and to analyse the total error done in predicting cosmic ray intensity, heliocentric potential and biological doses received on board a given flight.

5.1 RESTORATION OF COSMIC RAY INTENSITY FROM SUNSPOT INDICES.

Using data from 1964 to 2002, Figure 4 shows the comparison of the restored intensity calculated from RI_{12} smoothed data (dots) with the cosmic ray intensities observed with the Kerguelen neutron monitor (step function). For readability of the figure, monthly observed intensities have been plotted, rather than smoothed. The restoration is satisfactory with methods A and B. With method C (which is also correct) there are important jumps at the times of the changes of the interplanetary magnetic field polarity. Statistics of the relative differences between 12-month smoothed observed intensities and values restored from RI_{12} gives histograms of Figure 5. To method A corresponds a rms error of 1.28 %, to method B (deduced from Nymmik et al., 1996) a rms error of 1.27 % and to method C (deduced from Badhwar et O'Neill, 1993) a rms error of 2.05 %. The maximum error is lower than 5 % with methods A and B and lower than 10 % with method C. It should be recalled nevertheless than the variation of cosmic ray intensity over a solar cycle is only of the order of 20 %.

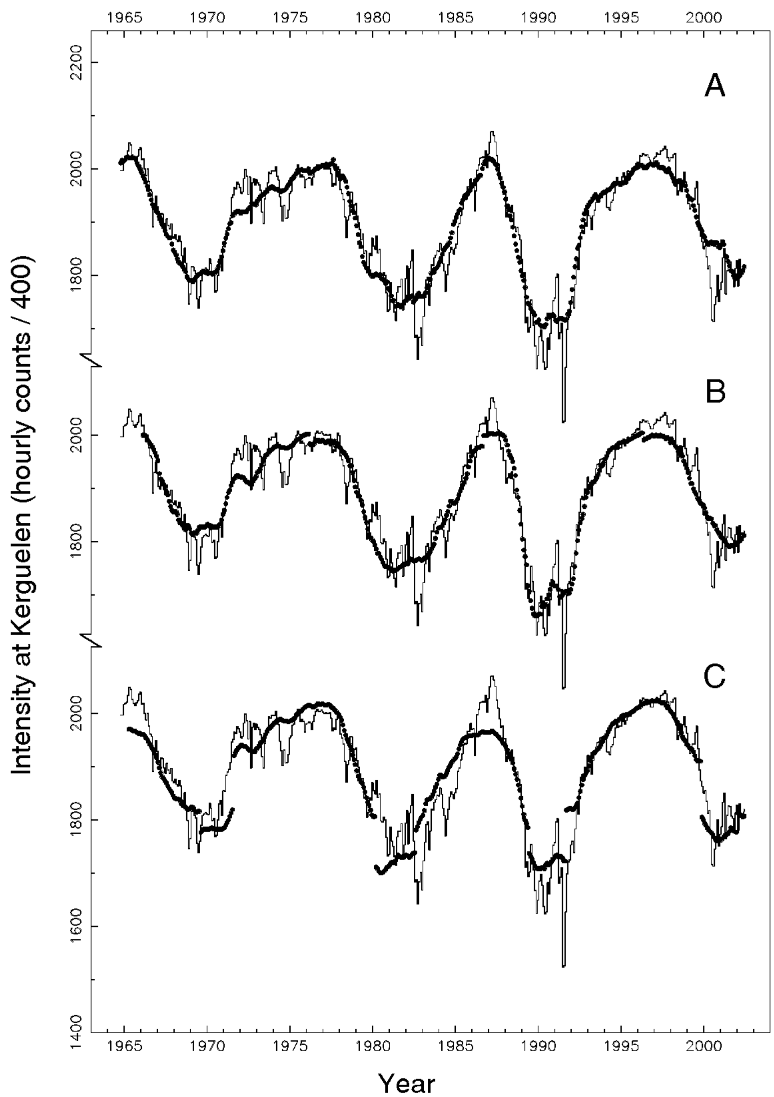

Figure 4: Restoration with the three methods of the intensity measured with Kerguelen NM. The curves are measured monthly intensities and the points are restored smoothed values. They are deduced from RI_{12} with the three methods A (top), B (middle) and C (bottom).

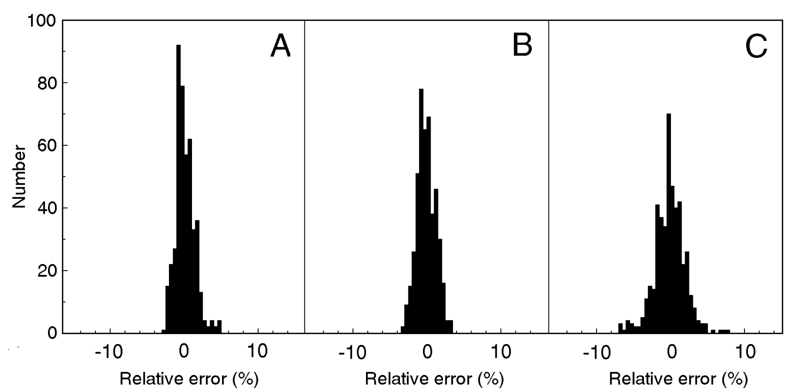

***Figure 5** : Histograms (with the three methods A, B and C) of relative errors (in %) of the restoration of the cosmic ray intensity measured with Kerguelen NM (smoothed values) from smoothed sunspot numbers RI_{12}.*

5.2- PRECISION OF THE THREE METHODS WITH PREDICTION OF COSMIC RAY INTENSITY

We consider relative errors cumulated with the four steps from RI_{12} prediction to cosmic ray intensity, heliocentric potential and dose received on board aeroplane. The doses are calculated with CARI 6 for a route from Paris to San Francisco, one of the most exposed (see flight plan in Lantos, Fuller and Bottollier-Depois, 2003 and Lantos and Fuller, 2004).

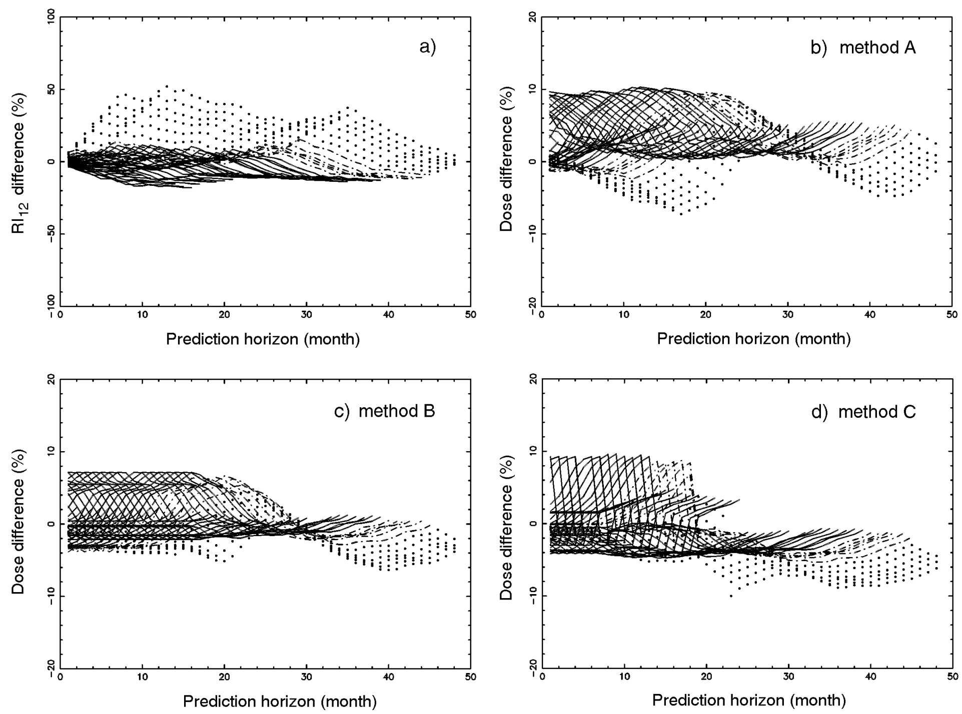

Figure 6: *Relative errors (in %) of the prediction of* RI_{12} *(6a) and of doses received on a Paris- San Francisco flight with methods A (6b), B (6c) and C (6d). The comparison is with variables calculated from* ***12 month-smoothed*** *cosmic ray observations with Kerguelen NM. See explanations in text.*

Figure 6a gives, in function of the horizon of prediction (in months), the relative error done for prediction of RI_{12}. On a different form, this is about the same information as on Figure 1. Figures 6b, 6c and 6d give the relative error done when biological doses are predicted using respectively methods A, B (derived from Nymmik et al., 1996) and C (derived from Badhwar et O'Neill, 1993). The comparison is done with the values calculated from observations of cosmic rays smoothed with a 12-month-average as done for RI_{12}. The points correspond to predictions done from October 1998 to March 1999. The dash-point lines correspond to predictions done from April 1999 to September 1999 and the rest of the predictions, until January 2003 are drawn with full lines. On the four diagrams the early predictions are the worse. They are obtained during the growing phase of cycle 23 (whose maximum is in April 2000) and the lower precision reflect the point already discussed section 2. Nevertheless one should note that even the important relative errors on RI_{12} (up to 50 %) are translated into much less important relative errors on dose predictions (less than 10 %). Similar calculations with a flight from Paris to New York on board Concorde gives the same quantitative result. Intermediate variables show relative errors less than 5 % for cosmic ray intensity and less than 20 % for heliospheric potential. Except the scale, the figures are similar as Figures 6a, 6b and 6c for cosmic ray intensity and the same but inverted for the potential. The origin of the difference between the large relative errors on RI_{12} and the much smaller relative errors on cosmic ray intensity is the small variation of cosmic ray intensity in the course of the solar cycle : for cycle 23 the variation of RI_{12} from 0 to 120 gives rise to variation of galactic cosmic ray intensity of only 10 % (see Figure 2). Figure 6, in fact compares intrinsic skills of the three methods, because the relative error is between smoothed galactic cosmic ray intensity and variables calculated from smoothed sunspot index RI_{12}. Nevertheless the user will be more interested by the relative error with the monthly cosmic ray intensity and corresponding doses, which are closer to the doses actually received, than the smoothed values.

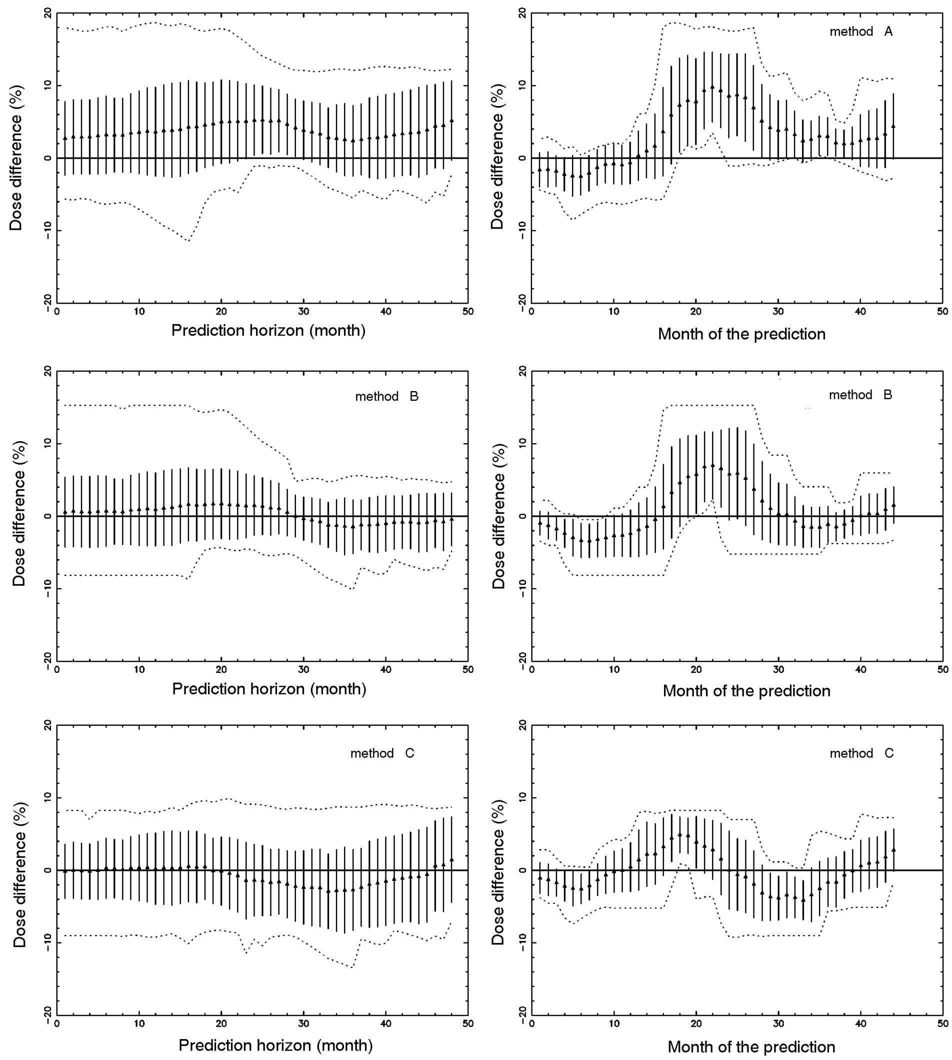

Figure 7: *Relative errors (in %) of the prediction of doses received on a Paris- San Francisco flight with methods A (top), B (middle) and C (bottom). The comparison is with variables calculated from* ***monthly*** *cosmic ray observations with Kerguelen NM. Left column in function of prediction horizon. Right column in function of the date at which the prevision is done (month 1 corresponds to a prevision done in October 1998). The largest errors are given with dotted lines. The bars are standard deviations.*

Figure 7 gives this information on two different forms. The left column the abscissa is prediction horizon (in months) and on right column the abscissa is month of the prediction (month 1 corresponds to a prediction done in October 1998). In both cases the bars give standard deviations centred on mean value of relative error. The dotted lines give error for the worse month. For the left column the statistics is on the months of prediction and for the right column the statistics is on the prediction horizon. The quality of the predictions, in average, are not varying to much with the prediction horizon (left column) while the period of the cycle at which the prediction is done induces larger differences (right column). The prediction is less good around the time of the solar cycle maximum (month 20 corresponds to a prediction done in May 2000), probably because the natural variations of the monthly cosmic ray intensity are much larger at that time (see Figure 2). Nevertheless for the predictions in terms of biological doses the standard deviation, whatever the method, remains lower than the precision of the best biological dose measurements which is about 15 % (Lantos et al., 2003). The maximal error (dotted line) remains lower than 20 %. For prediction of cosmic ray intensity, the standard deviations are 5 % with method A, 3 % with method B and 5 % with method C, the maximal error being about 8 % for the three methods. For potential, the standard deviations are 20 % with method A, 10 % with method B and 20 % with method C, the maximal error being about 30 % for the three methods. Finally it should be added that because the three methods are using, for their construction, data obtained before 1996, the results on cycle 23 are obtained on independent period.

6- Discussion and conclusion

Methods A and C are empirical while method B (derived from Nymmik et al., 1996) is semi-empirical and more satisfactory at the analysis point of view. The method A has the advantage of the simplicity and is lightly better when the restoration alone is considered (see Figure 5). Applied here to Kerguelen neutron monitor, this method could be easily applied to any neutron monitor, provided a sufficient quantity of observations is available (at least two consecutive cycles). Unlike the method A, the method B needs the knowledge of the maximum of the RI_{12} cycle, in order to calculate the delay to be applied to sunspot numbers. Before the maximum, it is necessary to use a prediction of the maximum value. This is what we have done and the results show that this does not handicap the method which is giving the best results when the comparison is with smoothed variables (Figure 6). The method C (derived from Badhwar et O'Neill, 1993) need the knowledge of the time of changes of polarity of interplanetary magnetic field (Table 1), and may need a prediction of the future dates of change. The method has the disadvantage to introduced rather important jumps at the time of polarity changes, but statistically speaking, it is given the best results when the comparison is done with variables deduced from monthly observed cosmic ray intensities (Figure 7).

The prediction method of McNish and Lincoln predicts presently (July 2004) next minimum (i.e. end of cycle 23), at the very beginning of 2007. At that time the prediction of amplitudes of cycle 24 will not be necessarily precise, because it is admitted that the cycle time profile is stabilised only when RI_{12} equals at least 50 (Waldmeier, 1968). Nevertheless, because the variations of predicted cosmic ray intensity and doses are attenuated compared to the variations of RI_{12}, it is likely that the three methods will work properly even at the beginning of the cycle 24. For the rest of the even cycle 24, the prediction will be more accurate than with odd cycle 23 as shown by Figure 3a and 3b and for some applications the use of the regression line could be even sufficient (Figure 3b).

The use of smoothed sunspot numbers is necessary because smaller time scales are not predictable with precision for sunspot numbers. In addition when cosmic rays are considered, some of their smaller scale variations like GLE or Forbush decrease occurrence, as well as variations due to geomagnetic storms are not directly related to sunspot numbers. Nevertheless, even with such limitations in precision, prediction of cosmic ray intensity and modulation parameters is useful for important applications.

The methods discussed here are all three giving satisfactory results in terms of prediction of the dose received on board aeroplane, which is an important application as pointed out by European air transport companies because they have to manage the doses received by aircrew in application of a European Directive (Commission of European Communities, 1996). According to the results presented here, the prediction of the doses received on board aeroplane seems correct at least with an horizon of four years. Nevertheless at the beginning of a new cycle, the precision might be less because of the intrinsic uncertainty on the amplitude of the coming cycle.

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