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Interactive Comment

Interactive comment on "Effects of cosmic ray decreases on cloud microphysics" *by* J. Svensmark et al.

J. Svensmark et al.

enghoff@space.dtu.dk

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1 Introduction

In the comments on our work we notice common concerns about whether the response to Forbush decreases (FDs) in the studied cloud parameters is real or just a result of random fluctuations in the cloud data set. As always the main issue is the method of determining the significance of a potential signal. Central questions raised in the discussion are:

- Why superpose the 5 strongest FDs and not all 13 or some other number?

- Why focus on one extremum value in the period following the FD minimum, and how should one calculate the significance of this deviation?
- Why centre the data on the first 10 days of the 36 day period, and not the whole period?

These questions might leave doubts about the validity of our results even where a high significance level is apparent. Therefore, without retracting any of the findings so far, we now add a different approach where item 3 becomes irrelevant and item 1+2 are taken into account, by incorporating all the information from the 13 FDs. In what follows, highly significant signals are achieved, including a signal in cloud fraction (CF) following FDs that is significant at the 0.9993 level.

2 Model

We wish to study the temporal development of cloud parameter $P(t)$ at day t. As previously the adopted temporal range encompassing an FD event is 36 days, 15 days before the FD-induced minimum in the cosmic rays and 20 days after i.e. $t \in [-15, 20]$ days. Any linear trend in all time series is removed. The aim is now to extract as much information as possible from the cloud parameters in the days following the FD. From aerosol dynamics the growth time of small aerosols to cloud condensation nuclei (CCN) is expected to be within a range of a few days to a maximum of about two-weeks. Therefore the response A in this study is defined as the integrated signal of the linearly detrended time series within the period from day 3 to day 13 following the minimum in cosmic rays (FD minimum)

$$A = \sum_{t=3}^{13} P(t), \tag{1}$$

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where $P(t) = [P(-15),\ P(-14),\ \ldots\ , P(20)]$, is the 36-day cloud parameter time series.

The FDs are as before arranged according to strength with FD 1 being the strongest and FD 13 the weakest. So for a chosen cloud parameter one can construct 13 time series $P_k(t)$ (one for each FD event) where the added k index refers to FD number 1 to 13.

We will now construct 13 new time series from the above 13 time series $P_k(t)$ by the following procedure:

$$\begin{aligned}
\Gamma_1(t) &= P_1(t) \\
\Gamma_2(t) &= \frac{1}{2}(P_1(t) + P_2(t)) \\
\vdots \quad &\quad \vdots \\
\Gamma_{13}(t) &= \frac{1}{13}\sum_{k=1}^{13} P_k(t)
\end{aligned} \tag{2}$$

So the first $\Gamma_1(t)$ is the time series of $P_1(t)$ at the time of the strongest FD, $\Gamma_2(t)$ is the mean of $P_1(t)$ and $P_2(t)$ at the strongest FD and the second strongest, and so forth, until $\Gamma_{13}(t)$ which is the mean response of all 13 FDs. As before the response is expected and defined in the integrated time interval from day 3 to 13, and with the above $\Gamma_k(t)$ time series, 13 measures of the response can be found as

$$A_k = \sum_{t=3}^{13(\text{days})} \Gamma_k(t). \tag{3}$$

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Finally we define the integral of the responses A_k as

$$\Psi = \sum_{k=1}^{13(\mathrm{FDs})} A_k. \quad (4)$$

Note that $\Gamma_5(i)$ is the time series that was used in our the previous studies, and if we only integrated the response at day 10 then A_5 would be identical to the extremum value seen in Figure 1 (attached as supplement) of our uploaded discussion paper. Again by integrating within day 3 to day 13 a distributed response will be captured and not just an extremum.

3 Results

Such is the basis of our model and A_k and Ψ can readily be calculated for all of the six cloud parameters ϵ, τ, CF, CCN, LWP and Reff. The strength of the model is that it incorporates an interval within where the response can be found as well as 13 all FDs. The panels in the left-hand column of Figure 1 show, as the red curve, A_k as a function of index k, with one panel for each cloud parameter.

The significance of the responses can be estimated by a simple randomization or Monte Carlo procedure by inserting 13 FD dates at random within the cloud time series in the interval from 2000-2007, and subsequently following the same procedure as for the real FD dates. The black lines in the six figures of the left-hand column of Figure 1 are 500 realizations of random dates. The white dotted lines are the 1-σ levels and the blue dashed lines are 2-σ levels calculated from 10,000 realizations. Notice that, except for the parameter CCN, the red curves (the real FD signals) are at the 2-σ level over a large range of the index k.

Finally the right-hand column of panels in Figure 1 show the summed responses Ψ for 10,000 random realizations. Again the white dotted lines are 1-σ levels and the blue

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dashed lines are 2-σ levels calculated from all 10,000 realizations. The red lines show the size of the response for the real FD dates (observation). As seen in the plots the significance levels for five of the FD observations are respectively: ϵ 0.9968, τ 0.9782, CF 0.9993, LWP 0.9706 and Reff 0.9987. As expected, CCN is not significant but from previous work (the SBS-paper referred to in the discussions paper) it is known that a decrease in aerosols is seen in the AERONET observations following FDs.

4 Conclusions

These results demonstrate clearly a response found in cloud microphysics following FDs. The model adopted here either takes into account or makes irrelevant the problems mentioned in the critique of our previous approach and includes information from all FDs and an interval of days where a response can be detected. In addition to the highly significant responses the signs of the responses are as expected from a cosmic ray effect on cloud microphysics. So taking the significances together with the signs of the responses demonstrates within any reasonable criteria the reality of the impact of FDs on cloud microphysics.

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Figure text

Left: A_k (in standard deviations) as a function of k for the FD epochs (red curve) and random realizations of FD dates (black curves, 500 out of the 10,000 sets). White dotted and dark blue dashed lines represent 1 and 2 standard deviations of the 10,000 random realizations. The light blue curve represents the mean of the strength of the FDs scaled to -2. **Right:** Ψ values for all 10,000 sets of random realizations of FD dates (black diamonds) along with the Ψ value of the real FD dates (red line). White dotted and dark blue dashed lines represent 1 and 2 standard deviations of the 10,000 random realizations. The significance is calculated from the number of random realizations larger than the red line displayed on each plot.

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