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Investigating The Statistical Relationship Between Forbush Decreases and Coronal Mass Ejection

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ABSTRACT
Forbush decrease is a rapid decrease in the observed galactic cosmic ray intensity following a coronal mass ejection (CME). We have studied Forbush decreases (FDs) associated with coronal mass ejection. This was done using cosmic ray data observed at Climax neutron monitor, during the period of 2000 to 2005 with coronal mass ejections (CMEs) relative speed data. Manual method (epoch analysis) of Forbush decreases was used to analyze the cosmic ray data. We have found that about (96%) Forbush decreases associated with coronal mass ejections (CMEs), while about 4% of the observed FDs did not associate with CMEs. It was also observed that the higher the magnitude of FDs the longer the recovery time and vice versa. We have found positive but less significant correlation with correlation coefficient (cc = 0.078) between magnitudes of Forbush decreases associated with coronal mass ejections. This affirms that FDs are actually associated with CMEs.

Keywords:
Forbush decrease.
Coronal Mass ejection

INTRODUCTION

In 1937, S. Forbush discovered quick decreases on the intensity of galactic cosmic rays (GCR) occurring between one to two days depending on the cosmic ray cut off at their geomagnetic location which subsequently recovers its intensity in a much slower time range. The observed decreases on the intensity of GCR is popularly called Forbush de- creases (FDs) and are mainly observed on the earth by using neutron monitors since their transient GCR intensity decreases with a relatively fast depression, followed by a slower recovery process which last for several days (Belov, 2008; Forbush, 1958). Several scientific reports have established that FDs may have been caused by a shock and ejecta or shock wave only, or ejecta only and are observable after significant flares on the sun andcoronal mass ejection (CME) arising from interplanetary disturbances. From the early days of FDs, many studies in the literature attributed the cause of FDs to solar flares (Simpson *et. al.,* 1955); the shocks associated with the helium enhancement in the interplanetary conditions (Gold, 1960); the disordering of outer geomagnetic field by the outflowing gases from the sun (Parker, 1963); the sweeping effect of cosmic rays travelling disturbances whereby solar wind speed is increased and the diffusion co- efficient decreased (Nishida, 1983). Further explanation was offered by Burlaga, *et. al.,* (1981) and Zhang and Burlaga (1988) which posited that a magnetized plasma cloud might be a possible reason for FDs. However, the discovery of space coronagraphs in 1970s has helped in resolving the conflict on the actual cause of FDs. Today, the cause of FDs is mainly attributed to two solar wind disturbances arising from different solar sources namely; the interplanetary disturbances (ICMEs) emanating from coronal mass ejections (CMEs) and the high speed streams (HSS) arising from coronal holes (CHs) (Belov, 2009; Cane, 2000; Lingri *et al.*, 2016; Lockwood, 1971; Richardson, 2004).

Coronal mass ejections (CMEs) are large-scale solar eruptions during which mass and energy are being released from the Sun to the interplanetary (IP) medium (Belov *et al.*, 2014). They are magnetized structures, which can affect the heliospheric conditions, producing large fluctuations in the heliospheric magnetic field (Verma *et. al.*, 2014). CMEs travelling at different speeds tend to merge into what are known as complex ejecta, which are seen often in the interplanetary medium during times of high solar activity (Verma *et al.*, 2014). They are detected by several space-borne instruments such as the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) mission. The Apollo Telescope

Mount (ATM) coronagraph on board Skylab and the Solar wind coronagraph on board the P78-1 satellite (Yashiro *et. al.*, 2008). However, it has been established that only some of the observed ICMEs produce Forbush decreases in GCR intensity (Lingri *et al.*, 2016).

FDs are generally observed on the Earth with neutron monitors (NMs) because of their transient GCR intensity decreases with a relatively fast depression, followed by a slower recovery on a time scale of several days (Belov *et al.*, 2014). It is an important feature of FDs that the recovery time is much longer in the lower-energy region than in the higher energy region (Sankar *et. al.*, 2011). Cane (2000) studied cosmic ray intensity variations with coronal mass ejections and concluded that CMEs are large-scale phenomena that change the configuration of the interplanetary magnetic field (IMF) and clearly modulate the cosmic ray intensity on short-term (few day) scales.

However, the timing of FDs and its corresponding associated solar activities (e.g CMEs) are yet to be cleared. Lockwood *et. al.*, (1986) concluded thatthe recovery time of FDs does not depend on the energy of cosmic ray particles. Conversely, earlier studies of FDs observed by both NMs and ground-based muon detectors (see (Forbush, 1958)) suggest that the recovery time of a FD is shorter for more energetic particles. For a clearer understanding, Sankar *et. al.*, (2011) concluded that periodicities for the Forbush decrease indices by using the Scargle Periodogram method are significantly close to the results of periods for other solar activities. Thus, the need for the proper investigation of the association of FDs and solar activities (CME Precisely) becomes necessary.

In this present work, our goal is to find a sample of isolated Forbush decreases with well-identified corresponding CMEs. We have taken into consideration the daily and hourly timing of Forbush decreases and coronal mass ejection from the year 2000 to 2005to investigate the association of the two events.

METHODS

Materials

The major materials used for this work are the data of daily and hourly CR counts sourced from http://cr0.izmiran.ru and CME relative speed data from https://cdaw.gsfc.nasa.gov/CME. These data cover the period of the year 2000 to 2005. The data of cosmic ray counts were also restricted to Climax neutron station observations.

Methods

The traditional manual method of Forbush decrease analysis was applied in this present work. In this method, FD dates were manually chosen from the FD table of Dumbovi c, *et. al.*, (2011). The raw cosmic ray daily counts were sourced from the internet as mentioned above, these data were displayed and arranged in text editor. R. statistical program was employed using epoch analysis to show the wavefronts of this CR data. The generated plots showed the occurrence of various Forbush decreases. This Forbush decreases were characterized by an onset points and points of maximum depression. The former forms the main phase while the later forms the recovering phase of the Forbush decreases. These observed Forbush decreases from the plots were individually considered. The magnitude of the FDs was manually determined using the mathematical expression according to Okike (2019)

$$\mathrm{CR}(\%) = \left(\frac{\mathrm{CR}-\mathrm{CR_i}}{\mathrm{CR_I}}\right) * 100 \qquad (1)$$

Where CR (%) represents the magnitude of FD, CR stands for minimum cosmic rays count, CR_i represents onset count and CR_I stands for mean of the cosmic rays count. The hourly CR counts of this individual FD dates were then considered. The hourly plots of this individual FD dates were used to detect the onset time and the recovering time.A correlation test was carried out between FD magnitudes and CME.

RESULTS AND DISCUSSIONS

Results

Forbush decreases associated with coronal mass ejections and during the period of 2000 to 2005 are listed in table1 and 2 below. In the tables, the first column stands for serial number, followed by the date of events, the third column stands for the onset time (in hours) of the FDs followed by the recovery time (in hours), while the fifth and sixth column stands for CME speed and time of CME (in hours) respectively. Figure 1 shows the variations of raw cosmic ray counts for the year 2000 to 2005. The processes involved in epoch analysis are displayed in Figure 2 and 3. Figure 3 precisely is a sample of hourly plot for an FD event, the purple arrow describes the onset time/main phase while the red arrow describes the recovering time/phase of the FD event. Figure 4 shows scattered plot between Magnitude of Forbush decreases associated with CMEs.

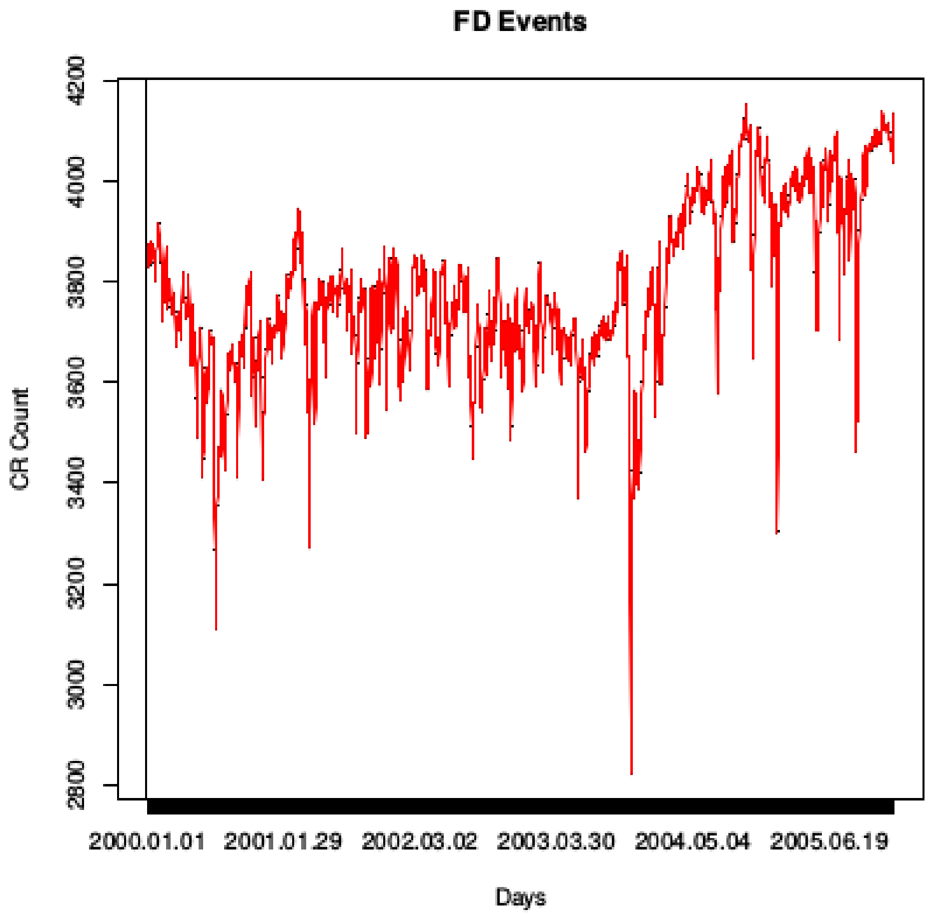

Figure 1: A Plot of raw CR counts for the year 2000 to 2005 from Climax neutron station

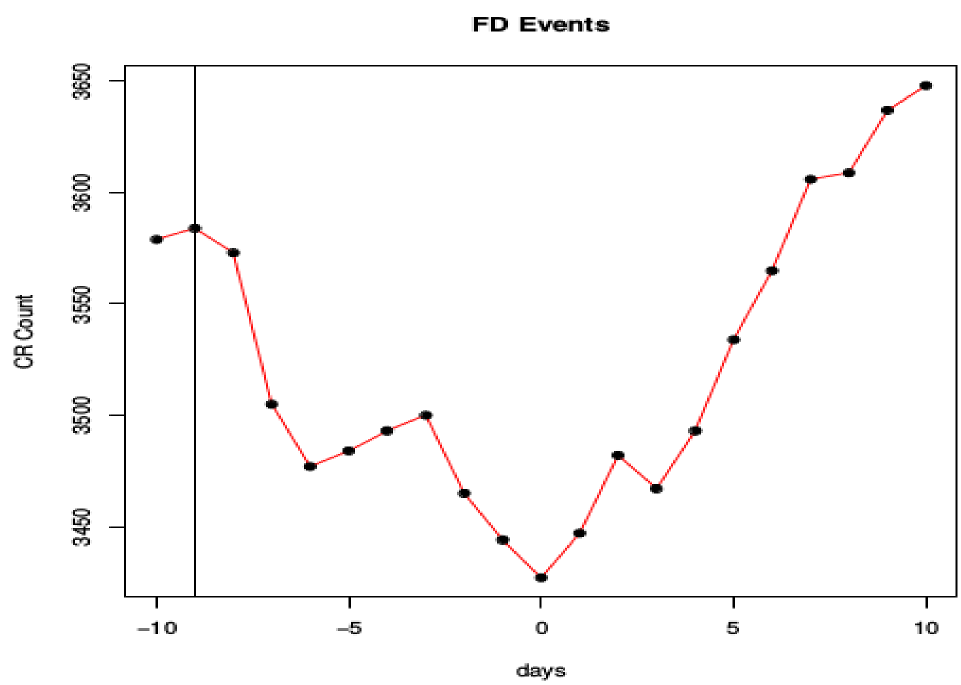

Figure 2: A daily Plot of the FD event of 12/08/2000 using epoch analysis

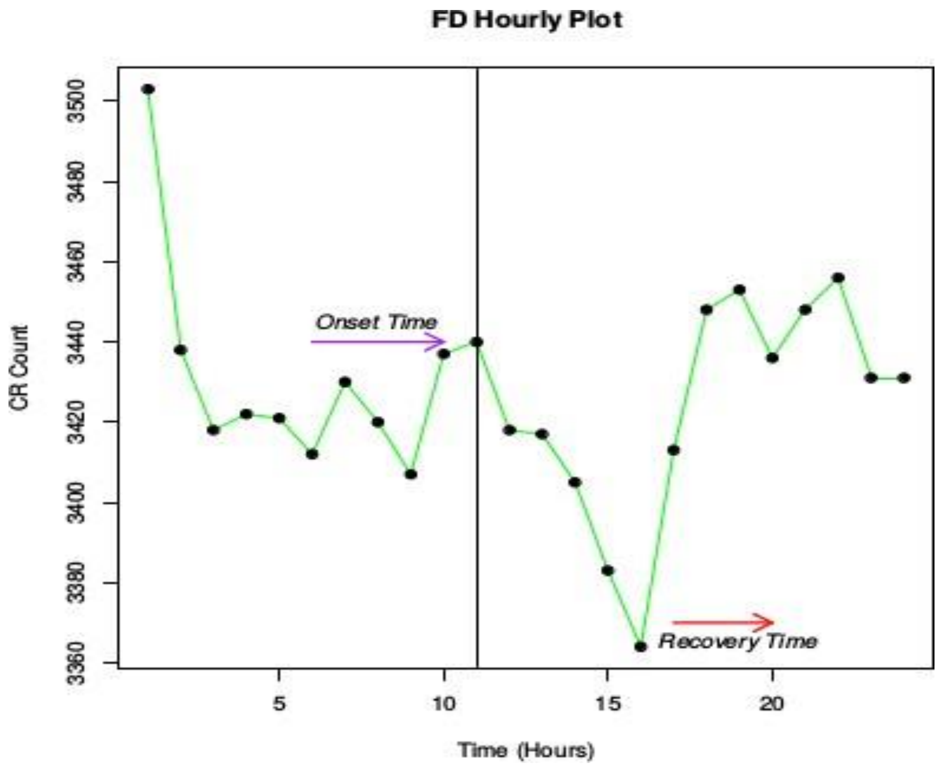

Figure 3: An hourly plot of the FD event of 12/08/2000 using epoch analysis.

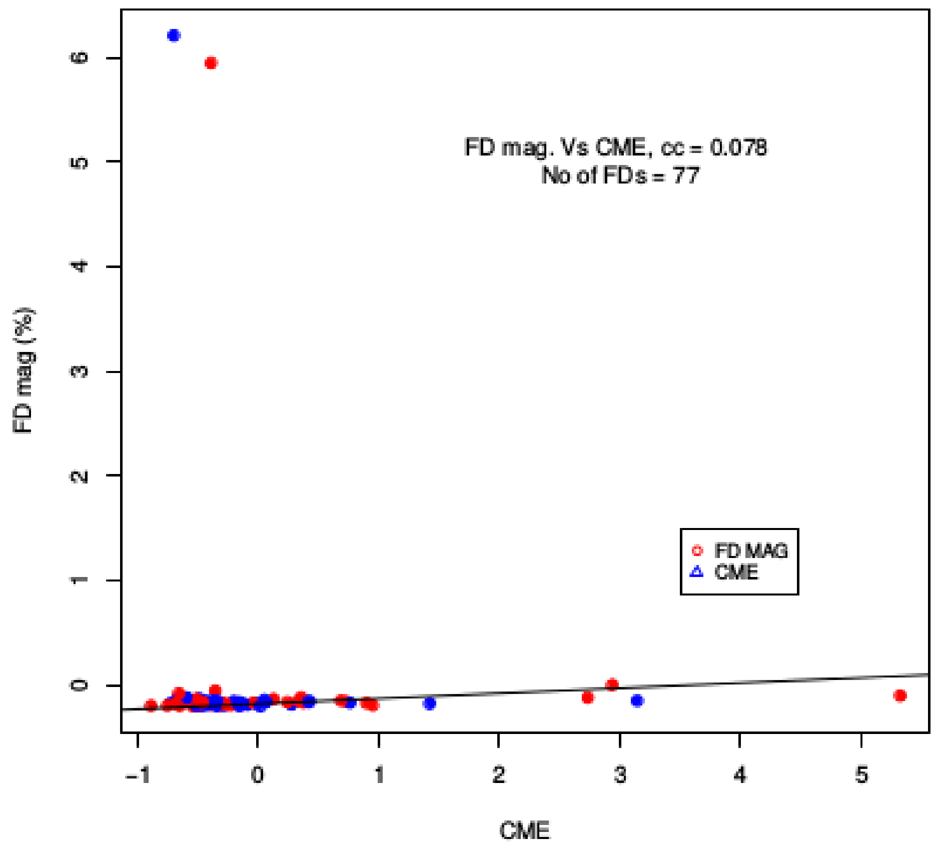

Figure 4: Correlation plot of the Magnitudes of Forbush decrease associated with CMEs.

Discussions

Manual method of FD analysis remains one of the most used approach for analysis of CR intensity variation despite its shortfalls. Figure 1 shows the peak and falls of the raw cosmic ray intensity variations which forms part of the bases of our investigation haven observed that there are existing depressions in the intensity of CRs. Figure 2 and 3 were used to explain epoch analysis on the FD dates. Figure 4 shows a correlation plot of FD magnitudes and CMEs where it was observed that both FDs and CMEs are strongly associated. From the result of the manual data analysis presented in Tables 1 and 2, it is observed that the total number of FDs associated with CME is 73. However, this accounts for 96% association rate between FDs and CMEs. These findings are in agreement with the observations of Verma *et al.*, (2014) who observed that 96.00% of his processed FDs are associated with halo and 04.00% associated with partial halo CMEs. Out of the 77 observed FDs, it was only 4 FDs that could not be associated with CMEs which accounts for about 4% of the total observed FDs. For instance, the FDs of 29-10-2000, 29-11-2000, 11-06-2003 and 17-06-2005 was not associated with CMEs. This in turn may suggest that CMEs together with FD may have come from the same origin which also agrees with the findings of Sankar *et. al.*, (2011) who interpreted that FDs have an association with other solar activities. A close look at the recovery time of FDs and the time of CMEs shows that the recovery of FDs occurred after several hours of the time of CMEs. The recovery time of majority of the Forbush decreases are found at 5 hours lag time of the CMEs. The recovery timescale of FDs whose magnitudes are less than 3% are found to fall within 3 hours. This size magnitude accounts for its short recovery time. It was also observed that FDs whose magnitude are greater than or equal to 5% have a recovery time of at least 4 hours and above. This disagrees with the submissions of Verma *et al.*, (2014) that large FDs have short recovery time. This is not a result of measurement errors caused by random variations in the neutron rate or diurnal variations.

Nevertheless, some pairs of FDs were observed to have similar magnitude different recovery times. For instance, the FDs of 02-08-2002 and 20-08-2002 have similar magni- tudes of (-5.6%). However, FD of 20-08-2002 has a shorter recovery of 1 hour whereas that of 02-08-2002 has a longer recovery of 3hours. Thus, slow FDs have recovery times that are as short whereas fast FDs have longer recovery time. The short recovery times of the slow FDs suggest that they rapidly decay. The long recovery times of the fast FDs suggest that their amplitudes might even increase with radius rather than decrease. For the fast events, the strength of the ICME could be increasing as it travels because multiple ICMEs merge or because the shock preceding the CME ejecta is enhanced as more ambient solar wind is encountered by the rapidly traveling ICME. When an ICME results in a Forbush event, the Forbush event commences within 10 hours of the ICMEs arrival at Earth (Cane *et al.*, 1996). The result of the correlation between FD magnitude and CME speed is observed to be positive with correlation coefficient value cc = 0.078. The poor significance level of the correlation coefficient is attributed to some errors involved in manual method of FD analysis. Therefore, the need for more sophisticated method of FD analysis is very necessary for CR researchers since the manual method are prone to some errors. This creates a loophole for further research on more sophisticated method of FD analysis. Such feat was recently achieved by Okike and Umahi (2019). Despite the poor significance level of the correlation coefficient (cc = 0.078), it still shows that CMEs associates with FDs and are likely major causes of FDs.

CONCLUSION

In the presented work, it is concluded that; (1) About 96% of FDs are observed to be associated with CMEs. (2) The higher the magnitude of FDs, the longer the recovery time and vice versa. (3) The positive correlation found between FD magnitudes and CMEs signifies that FDs are associated with CMEs.

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Table 1: Association of Forbush decreases with coronal mass for the perid of 2000 to 2001

	Date	FD.mag(%)	Onset Time(hr)	Recovery Time(hr)	CME	Time of CME(hr)
1	08-02-2000	-1.9	0	9	1079	9
2	13-02-2000	-4.17	12	13	194	1
3	21-02-2000	-1.16	3	4	232	1
4	01-03-2000	-2.46	0	4	529	3
5	25-03-2000	-2.84	1	3	296	21
6	04-04-2000	-0.99	2	7	398	2
7	08-04-2000	-1.09	0	5	307	4
8	03-05-2000	-4.13	0	7	568	1

9	09-05-2000	-1.81	0	9	418	5
10	15-05-2000	-2.82	11	13	721	5
11	24-05-2000	-5.78	3	6	244	9
12	09-06-2000	-8.36	1	6	222	2
13	21-06-2000	-2.04	1	3	368	1
14	24-06-2000	-1.55	0	4	428	1
15	16-07-2000	-16.79	1	3	389	2
16	06-08-2000	-3.06	1	7	378	2
17	12-08-2000	-4.45	10	15	556	1
18	25-08-2000	-0.91	2	6	330	8
19	18-09-2000	-6.3	0	5	297	3
20	29-09-2000	-6.59	4	7	380	6
21	07-10-2000	-1.79	0	2	314	3
22	29-10-2000	-6.59	0	6	NA	NA
23	07-11-2000	-4.79	0	6	422	0
24	29-11-2000	-8.76	0	5	NA	NA
25	09-01-2001	-4.97	5	6	476	3
26	24-01-2001	-2.51	0	2	487	1
27	05-03-2001	-1.9	0	4	457	3
28	12-04-2001	-9.34	0	5	264	6
29	29-04-2001	-6.55	3	8	752	8
30	28-08-2001	-6.3	0	8	350	2
31	26-09-2001	-7.91	1	11	644	4
32	30-09-2001	-2.03	22	23	390	2
33	02-10-2001	-1.87	4	9	291	7
34	12-10-2001	-5.39	0	4	610	1
35	06-11-2001	-6.09	3	19	315	18
36	25-11-2001	-8.56	0	5	320	1

Table 2: Association of Forbush decreases with coronal mass for the perid of 2002 to 2005

	Date	FD.mag(%)	Onset Time(hr)	Recovery Time(hr)	CME	Time of CME(hr)
37	03-01-2002	-6.55	6	9	371	4
38	22-03-2002	-6.83	0	6	208	2
39	25-03-2002	-6.55	2	9	260	11
40	23-05-2002	-4.48	10	16	318	9
41	30-07-2002	-4.64	0	7	774	1
42	02-08-2002	-5.61	5	8	469	4
43	20-08-2002	-5.62	1	2	961	2
44	23-08-2002	-0.91	2	5	496	6
45	26-08-2002	-0.91	0	13	291	1
46	28-08-2002	-1.39	0	20	306	4
47	06-11-2002	-1.44	4	6	178	1
48	12-11-2002	-4.58	1	11	979	4
49	19-11-2002	-6.63	0	4	938	3
50	23-12-2002	-2.21	0	7	351	7

51	27-01-2003	-4.29	0	7	1051	2
52	11-04-2003	-4.01	0	4	509	1
53	31-05-2003	-9.89	0	6	765	1
54	11-06-2003	-1.19	0	3	NA	NA
55	16-06-2003	-1.19	22	23	106	12
56	23-06-2003	-6.16	0	22	802	9
57	31-10-2003	-22.41	2	12	2126	5
58	07-11-2003	-6.53	1	7	2237	15
59	18-11-2003	-5.32	7	8	267	5
60	21-11-2003	-5.3	0	4	494	0
61	24-11-2003	-2.75	1	7	440	11
62	10-12-2003	-0.68	0	9	586	13
63	10-01-2004	-7.87	11	17	307	5
64	25-01-2004	-7.5	4	8	604	20
65	24-07-2004	-5.02	6	16	333	1
66	27-07-2004	-9.72	0	8	263	1
67	10-11-2004	-11.75	2	3	3387	2
68	04-01-2005	-4.88	3	9	487	0
69	19-01-2005	-9.84	0	7	2020	8
70	21-01-2005	-5.04	15	20	799	5
71	09-05-2005	-5.37	5	17	704	1
72	17-06-2005	-3.62	7	13	NA	NA
73	13-07-2005	-5.09	0	4	327	2
74	17-07-2005	-6.23	0	4	398	2
75	07-08-2005	-3.48	2	4	218	3
76	25-08-2005	-3.42	0	57	1327	5
77	13-09-2005	-14.25	15	2	229	13