1 What effect do substorms have on the content of the radiation

2 belts?

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5 Abstract

6 Substorms are fundamental and dynamic processes in the magnetosphere, converting

7 captured solar wind magnetic energy into plasma energy. These substorms have been

8 suggested to be a key driver of energetic electron enhancements in the outer radiation

9 belts. Substorms inject a keV "seed" population into the inner magnetosphere which is

10 subsequently energized through wave particle interactions up to relativistic energies;

11 however, the extent to which substorms enhance the radiation belts, either directly or

12 indirectly, has never before been quantified. In this study, we examine increases and

13 decreases in the total radiation belt electron content (TRBEC) following substorms and

14 geomagnetically quiet intervals. Our results show that the radiation belts are inherently

15 lossy, shown by a negative median change in TRBEC at all intervals following substorms and

16 quiet intervals. However, there are up to three times as many increases in TRBEC following

17 substorm intervals. There is a lag of 1-3 days between the substorm or quiet intervals and

18 their greatest effect on radiation belt content, shown in the difference between the

19 occurrence of increases and losses in TRBEC following substorms and quiet intervals, the

20 mean change in TRBEC following substorms or quiet intervals and the cross correlation

21 between SuperMAG AL (SML) and TRBEC. However, there is a statistically significant effect

22 on the occurrence of increases and decreases in TRBEC up to a lag of 6 days. Increases in

23   radiation belt content show a significant correlation with SML and SYMH, but decreases in

24   the radiation belt show no apparent link with magnetospheric activity levels.

25

26   Introduction

27   Earth's radiation belts consist of trapped electrons and protons at MeV energies drift-

28   bouncing around the Earth at radial distances between 1000 km and 6 R_E. The flux of

29   particles in the radiation belts is the result of competing enhancement and loss mechanisms

30   and can vary by orders of magnitude. Enhancements in the radiation belt population occur

31   through direct injection of energised particles, radial diffusion and energization through

32   conservation of adiabatic invariants, or wave-particle interactions, whereas losses from the

33   radiation belts generally occur via pitch-angle scattering, adiabatic diffusion or particle drift

34   paths intersecting the magnetopause [see reviews by Millan and Thorne, 2007; Ebihara and

35   Miyoshi, 2011; Ukhorskiy and Sitnov, 2012]. While the loss and acceleration mechanisms

36   have been long-studied, the phenomenological processes which lead to radiation belt

37   increases and losses remain unclear [e.g. Reeves et al., 2003] and thus are a key target for

38   the Van Allen Probes mission [Mauk et al., 2012].

39

40   One mechanism that is thought to be a major contributor to increases in the radiation belt is

41   substorm particle injections. Rather than directly injecting MeV energy particles into the

42   radiation belts, substorms are thought to provide a low energy population of keV electrons

43   which are subsequently accelerated to higher energies [e.g. Baker et al., 1998; Horne and

44   Thorne, 1998; Fok et al., 2001; Meredith et al., 2002, 2003a, b, c].

45

46   It has long been established that particle injections into the inner magnetosphere and outer

47   radiation belts occur during substorms [e.g. Pfitzer & Winckler, 1969; Akasofu et al., 1968;

48   Reeves et al. 1990; Borovsky et al., 1993; Baker et al., 1998; Fok et al., 2001]. Early studies

49   suggested that these injections occurred across a wide injection boundary [e.g. Mauk and

50   McIlwain, 1974; Konradi et al., 1975; Mauk and Meng, 1983; Moore et al., 1981], however

51   later studies have shown that the injection region is limited in MLT extent [Reeves et al.,

52   1990], with a greater proportion of injections occurring in the premidnight sector [Birn et

53   al., 1997a, b; Thomsen et al, 2001; Gabrielse et al., 2014]. The injected particles do not, on

54   average, have sufficient energy to significantly enhance the relativistic particle population.

55   Although the injection of MeV particles directly into the outer radiation belts by substorm

56   dipolarizations has been reported [e.g. Dai et al., 2014], Baker et al [1979] found that more

57   than 80% of substorms did not result in an injection of >0.3 MeV protons at geosynchronous

58   orbit. Instead, the substorm injection is considered to provide a "seed" population of keV

59   particles [Baker et al., 1998] to the outer radiation belt. This seed population is anisotropic

60   and unstable to the generation of whistler-mode chorus waves [Li et al., 2010 and

61   references therein]. The seed population is subsequently locally accelerated through wave-

62   particle interactions with these whistler mode chorus waves [Horne & Thorne 1998;

63   Summers et al., 1998; Horne et al., 2005a,b; Li et al., 2007; Janyes et al., 2015] up to

64   relativistic energies. Hence substorms are thought to be the source of the electron seed

65   population and the source of the wave growth that provides the acceleration of these

66   particles to relativistic energies.

67

68   Reeves et al. [2003] have shown that the radiation belts do not show a consistent response

69   to storm activity, with the outer belt relativistic electron fluxes increasing, decreasing or

70 remaining invariant for storms with a similar Dst profile. In this paper we ask whether a

71 similar result can be found for substorms. To that end, we assess the extent to which

72 substorms enhance the content of the electron radiation belts by comparing times of

73 increases and decreases in the radiation belts with substorm activity. We also examine how

74 the increase and decrease of the radiation belt content compare with a measure of the size

75 of the substorm. Our observations show that 50% of substorm intervals are followed by an

76 increase in radiation belt content and 50% by a decrease. To fully understand variations in

77 the radiation belt fluxes, any phenomenological framework or physical model must explain

78 both the enhancements and reductions of the radiation belts following substorms.

79

80 ## Instrumentation and Methodology

81 The Van Allen Probes (Mauk et al., 2012) are a pair of identical spacecraft in 500 x 30,600 km near-

82 equatorial orbits of the Earth. The orbits of the two spacecraft are slightly different, such that the

83 separation between the spacecraft changes with time. Each spacecraft has an identical suite of five

84 instruments designed to measure the radiation belt plasma and electromagnetic fields.

85

86 We use data from the Van Allen Probes Magnetic Electron Ion Spectrometer (MagEIS; Blake et al.,

87 2013) instrument in the Energetic Particle, Composition, and Thermal Plasma suite (ECT) (Spence et

88 al., 2013) from 1st Jan to 31st December 2013. From this data, and building on the ideas of Baker et

89 al. [2004], the total radiation belt electron content (TRBEC) has been calculated. The calculation is

90 detailed in Boyd [2016] and Huang et al [in preparation] (Huang, C.-L., H. Spence, A. Boyd, A. Jordan,

91 L. Chen, Y. Zheng, G. Reeves, J.B. Blake, D. Baker, Y. Shprits (2016), Spatial, Temporal and Energy

92 Dependence of Total Radiation Belt Electron Content, GRL, in preparation). In summary, TRBEC is

93 calculated using the Jacobian determinant calculated using the three action integrals of the

94   electrons' three quasi-periodic motions, J1, J2, and J3, with respect to gyration, bounce motion, and

95   drift motion [Schulz, 1991]. From this, the number of electrons can be calculated as

96

$$N = \iiint (2\pi)^3 f(\mu, K, L^*) \frac{8\sqrt{2}\pi^2 m_0^{3/2} \mu_0}{R_E} \frac{\sqrt{\mu}}{L^{*2}} d\mu dK dL^*$$

97   By integrating across an appropriate range of the first adiabatic invariant (μ), pitch angle (K) and L*

98   along each half orbit of the spacecraft, the TRBEC for different energies of electrons can be

99   calculated. In this case, the distributions are integrated between μ=1000-2000 MeV/G to give an

100   estimate of the number of particles in the "core" radiation belt population. This corresponds to

101   particles in the energy range 0.3-6 MeV at L=3-6. This provides an estimate of the radiation belt

102   content approximately every 3 h. This data is then interpolated onto a regular 3 hr time line.

103

104   In order to determine changes in TRBEC as a function of substorm occurrence, we require a reliable

105   estimate of substorm expansion and recovery phase times that is continuous over the period

106   covered by the Van Allen Probes TRBEC data. We define substorm intervals using the SOPHIE

107   technique [Forsyth et al., 2015]. This technique provides the onset times of expansion and recovery

108   phases, as well as substorm intensifications (expansion phases directly following recovery phases),

109   based on the SuperMAG AL (SML) index [Newell & Gjerloev, 2011]. In summary, the technique

110   identifies:

111

112   •   Expansion phase as a negative rate of change in smoothed SML below a determined

113   threshold;

114   •   Recovery phase as a positive rate of change in smoothed SML above a different determined

115   threshold;

116   •   Possible growth phase at any other time.

117

118   The SOPHIE technique also determines those intervals in which SML shows substorm-like

119   characteristics, but in which the SML variations are mirrored by the SuperMAG AU (SMU) index.

120   These are interpreted as being intervals of enhanced magnetospheric convection and not substorm

121   events. The thresholds for the expansion and recovery phase identifications are calculated from a

122   specified percentile of the rates of change in SML. Forsyth et al. [2015] found that the expansion

123   phase onsets determined using the 75th percentile gave good agreement with existing auroral-based

124   [Frey & Mende, 2006; Liou et al., 2001] and magnetometer-based (Newell & Gjerloev, 2011)

125   substorm onset lists. Thus we use this percentile for all phase identifications in this study.

126

127   In order to compare substorm activity with TRBEC and changes in TRBEC, we identify whether one or

128   more expansion or recovery phase onsets occurred within the three-hour window of the TRBEC

129   data. In the following, these intervals are described as "substorm intervals". If there was no

130   expansion or recovery phase onset and no evidence of an enhanced convection event within the

131   time window, the interval is considered to be a "quiet interval".

132

133   We also compare TRBEC and changes in TRBEC with SML and SYMH. SML provides a measure of

134   substorm activity and the strength. Similarly, SYMH provides a measure of storm activity and

135   strength. In order to compare these data with the TRBEC data, we down-sample SML and SYMH by

136   calculating the mean of the data over the three hours corresponding to each TRBEC data point.

137
138   Comparison between radiation belt content and substorms

139   Figure 1 provides an overview of the data used in this study and shows (a) the total radiation belt

140   electron content, (b) the 3 h mean of the SML index, (c) the 3 h mean of SYMH between 01 January

141   2013 and 31 December 2013 inclusive. It is these data that we will use throughout this paper. Figure

142   1d shows the cross correlation of these data using the square of the Pearson's correlation coefficient

143   (r^2) plotted against lag times. The correlation between TRBEC and SML is shown in black, the

144   correlation between TRBEC and SYMH is in red and the correlation between SYMH and SML in blue.

145   Positive lags indicate that changes in TRBEC follow changes in SML or SYMH and that changes in

146   SYMH follow changes in SML. The time of the maximum cross correlation is given in the figure.

147

148   Figure 1a shows that during 2013 TRBEC varied by over two orders of magnitude and on a variety of

149   timescales, although the most noticeable on this scale are the large scale variations that occur

150   approximately twice per month. Figure 1b shows that SML tends to vary on shorter timescales, as

151   we would expect for substorms that occur, on average, four times per day, and Fig. 1c shows that

152   SYMH varies on a slightly longer period, as expected for storm activity. Figure 1d shows that there is

153   a weak (<15%) anti-correlation between TRBEC and both SML and SYMH, with the cross correlations

154   maximising for TRBEC lagging SML by 45 hr and lagging SYMH by 33 hr. This is consistent with the

155   framework in which particles injected during a substorm take some time to be energised to

156   relativistic energies, but the time scales are longer than the 24 hr timescale predicted by Horne et

157   al., [2005a]. Figure 1d also shows that the 3-hr mean SYMH and SML are 45% correlated with SYMH

158   lagging SML by 3 hr. It is therefore difficult to deconvolve substorm effects from storm effects on a

159   three-hour timescale. In the analysis presented later in this paper, we account for this by comparing

160   changes in TRBEC with SML and SYMH in parallel.

161

162   In order to determine the extent to which substorms influence the electron content of the radiation

163   belts, we determine the change in TRBEC following a substorm or quiet interval. The change in

164   TRBEC is calculated as ΔTRBEC=TRBEC(t_0+T)-TRBEC(t_0), where T is the differencing time lag and t_0 is

165   the reference time (the time of the substorm or quiet window from which we wish to know the

166   change in TRBEC). This change is thus the net or time-integrated change in the radiation belt content

167   from the reference event. The data at each time step forms a 2x2 contingency table. An example

168   contingency table is shown in Table 1, showing the number of increases (column 1) and decreases

169   column 2) in TRBEC 24 h following substorms (row 1) or quiet intervals (row2). By dividing each row

170   element by that row's total, we are able to determine the proportion of increases or decreases

171   following substorm or quiet intervals. In this case, approximately 50% of substorms are followed by

172   an increase in TRBEC whereas only 30% of quiet intervals are followed by an increase in TRBEC.

173   Alternatively, we can rearrange the data to examine the proportion of increases or decreases

174   preceded by a substorm or quiet interval, as shown in Table 2. This shows, from the same data, that

175   ~75% of increases in TRBEC are preceded by a substorm interval 24 h beforehand, whereas only 50%

176   of decreases are preceded by a substorm. In order to determine whether the the ratios of increases

177   to decrease of TRBEC following substorms or quiet intervals are statistically significantly different,

178   we need to compare them to a null hypothesis that substorms have no effect on increases or

179   decreases in the radiation belts. The expected values from this hypothesis for each cell in the table

180   are the product of the row total and column total divided by the total number of observations. We

181   can also thus use the χ^2 statistic to assess whether the observed occurrences are statistically

182   significantly different from expected values assuming the null hypothesis.

183

184   Figure 2a show the proportion of (black) substorm intervals and (red) quiet intervals that were

185   followed by an increase (solid line) or decrease (dashed line) in TRBEC, for different time lags (T),

186   following the presentation of data in Table 1. It shows that for each three-hour interval up to 33 hrs

187   following substorm intervals there was a ~50% chance that TRBEC was increased above the level

188   during the substorm interval, after which time the likelihood of a decrease in TRBEC increased,

189   tending towards 55% after 144 hrs. In contrast, the likelihood of a decrease in TRBEC following a

190   quiet interval was 55% in the 3 hrs following the quiet interval, but steadily increased to ~75% at 45

191   hrs following the quiet interval. Using the Z-statistic ($Z=(a-b)/(a+b)^{0.5}$, not shown), we find that there

192   were statistically significantly more decreases than increases (at the 99.9% level) following quiet

193   intervals up to a lag of 219 hrs. Following substorms, the difference between increases and

194   decreases in TRBEC was statistically insignificant up to a lag of 69 hrs, in keeping with the 50/50 split

195   shown, after which time there were significantly more decreases. In summary, our results show that

196   there are statistically significantly no more increases than decreases following substorms up to 69

197   hrs after the reference interval, but statistically significantly more decreases following quiet intervals

198   up to 219 hrs (9 days) after the reference interval.

199

200   Using the contingency table analysis, we calculate the χ^2 statistic at each time lag (Figure 2b). The χ^2

201   statistic was much greater than the 99.9% significance level for lags between 6 hrs and 144 hrs and

202   had a broad peak ($\chi^2 > 100$) between 0.5 and 2.5 days. Over a lag of ~0-1 day, the increase in χ^2 is

203   driven by an increasing proportion of decreases following quiet intervals whilst the proportion of

204   increases following substorms was constant. Over a lag of 1-2 days, the proportion of decreases

205   following quiet intervals is approximately constant, while the proportion of increases following

206   substorms decreases, resulting in an decrease in χ^2. Finally, between over a lag of 2-6 days, the

207   change in χ^2 is driven by a decreases in the proportion of decreases following quiet intervals.

208

209   We are also able test whether substorms are a good predictor of increases (and conversely that

210   quiet intervals are good predictors of decreases) by calculating the Heidke Skill Score (HSS; Heidke,

211   1926) and the accuracy of the prediction. For the interested reader, these are described in the

212   Supplementary Information. Under the premise that substorms lead to increases in TRBEC and that

213   quiet intervals lead to decreases in TRBEC, we can take the occurrence of substorm and quiet

214   intervals to be a forecast of increases or decreases in TRBEC and assess the skill of this forecast in

215   terms of the HSS and accuracy as a function of time lag. In this analysis, we are only assessing the

216   occurrence of increases or decreases, not the size of the change in TRBEC. The HSS (black) and

217   accuracy (red) of using substorms or quiet times to predict increase or decreases in TRBEC is shown

218   in Fig. 2c. For HSS > 0, substorm intervals have some skill in predicting increases in TRBEC (the

219   maximum possible HSS is 1). Figure 2c shows that the calculated HSS is greater than 0 for all time

220   lags up to 216 hrs intervals and peaks at 0.21 after 27 h, in keeping with the maximum in the χ^2

221   statistic. Thus using substorm and quiet intervals to predict radiation belt increases and decreases

222   has some skill over that interval. The accuracy of the prediction peaks at 58% for a time lag of 30 hrs,

223   but remains above 50% up to a lag of 183 hrs.

224

225   Overall, the analysis shown in Fig. 2 indicates that there is a statistically significantly higher likelihood

226   of an increase in the radiation belts up to six days following a substorm than in the same period

227   following a quiet interval. The difference in the occurrence of increases or decreases in TRBEC

228   following substorms or quiet intervals is most significant 0.5-2.5 days following the substorm or

229   quiet interval, in keeping with the 48 h cross correlation lag between SML and TRBEC. Up to half of

230   the substorm intervals were followed by an increase in TRBEC and up three-quarters of quiet

231   intervals were followed by a decrease in TRBEC. Similarly, up to three-quarters of increases in TRBEC

232   were preceded by a substorm, as were half the decreases in TRBEC.

233

234   The results of Figure 2 show that there is a statistically significant difference in the response of the

235   radiation belts to substorms and quiet intervals, but does not show which has the greater influence.

236   If we take assume that the magnetosphere is normally quiet times and that substorms are a

237   perturbation to this quiet system, then the results of Figure 2 can be interpreted as showing that

238   substorm activity doubles the likelihood of the radiation belts increasing. However, the "memory" in

239   the radiation belts of substorms and quiet times is far longer than the initial 3-hour interval. For up

240   to 6 days after substorms and quiet times, the proportion of increases and decreases in TRBEC are

241   statistically significantly different from those expected if substorms and quiet intervals have no

242   effect on the radiation belts.

243

244   Figure 3a shows a superposed epoch analysis of the change of TRBEC following substorm (black) and

245   quiet (red) intervals. The solid lines show the results of the analysis taking the means of the changes

246   in TRBEC at each time lag and the dashed lines show the medians. The error bars on the solid lines

247 show the standard error in the means. Figure 3b shows the probability that the mean (black) or

248 median (blue) change in TRBEC following substorms or quiet intervals is statistically significantly

249 similar. These are the P-values resulting from Student's T-Test of the difference in the means and the

250 Wilcoxon-Mann-Whitney Rank Sum Test of the difference in the medians. Figure 4 shows the

251 probability density of a change in TRBEC following substorm intervals (black) and quiet intervals

252 (red) at lags of (a) 3 hrs, (b) 24 hrs, (c) 48 hrs and (d) 144 hrs

253

254 Figures 3 and 4 show that the radiation belts are inherently lossy: the median changes in TRBEC are

255 negative at all times following both substorm and quiet intervals (Fig 3.), which is replicated in the

256 highest probability densities occurring for negative changes in TRBEC (Fig. 4). However, Figure 3a

257 shows that the mean change in TRBEC following substorm periods is positive up to a lag of 144 hrs.

258 As such, the distribution of increases in TRBEC following substorms has a much longer tail than the

259 distribution of decreases. The effect of this can be seen as the sawtooth-like profile of TRBEC in

260 Figure 1a; the increases occurred over short periods whereas the decreases extend over several

261 days.

262

263 Following substorm intervals, the mean change in TRBEC is positive, peaking 48 hrs after the

264 substorm interval. Similarly, the mean change in TRBEC following quiet intervals is negative,

265 minimising 48 hrs after the quiet interval, although we note that these peak and trough of the mean

266 changes are broad, as per the results of Figure 2. This is consistent (to within 1 data point) with the

267 cross correlation between SML and TRBEC shown in Figure 1. In contrast, while the median change

268 in TRBEC following quiet intervals also shows a decrease, the median change in TRBEC following

269 substorms shows little or no increase. The significance tests shown in Fig. 3b show that the

270 difference in the mean changes in TRBEC following substorms or quiet interval is statistically

271 significant beyond the 99.9% level up to a lag of 90 hrs whereas the median changes are statistically

272 significantly different up to a lag of 129 hrs.

273

274   Comparing the distributions of changes in TRBEC we see that the distributions of positive changes in

275   TRBEC are elevated following substorms, with respect to that following quiet intervals, at lags of 3,

276   24 and 48. After 144 hrs, the distributions of changes in TRBEC following substorms and quiet

277   intervals are more similar, in keeping with the lack of statistically significant differences in the

278   averages and occurrences shown above. The probability distributions shown indicate that the losses

279   from the radiation belt are slightly elevated following quiet intervals as compared to following

280   substorm intervals, but not to the extent that the increases differ following substorms compared to

281   quiet times.

282

283   The vertical dotted lines in Figure 4 show the median increases and decreases of TRBEC following

284   substorms (black) and quiet intervals (red). Dividing each change in TRBEC by the time lag gives a

285   mean rate of change, from which we convert the dotted lines to the median mean rates of change

286   (shown in Table 2). There is no statistically significant difference in median mean rate of decrease in

287   TRBEC following substorms and quiet intervals at lags of 3, 24 and 48 hrs. In contrast, the median

288   mean rate of increase in TRBEC is statistically significantly greater following substorms than

289   following quiet times. It should be noted that the analysis we have presented effectively low-pass

290   filters the variations in TRBEC with increasing window length. As such, directly comparing the

291   average rates of the changes is somewhat problematic. For a window length of 3 hours, the rates of

292   change can be dominated by the uncertainty in the data, whereas larger windows may smooth out

293   significant but short term variations.

294

295   Given that substorm occurrence enhances the mean change of TRBEC, we examine whether a

296   measure of substorm activity is linked with the change of TRBEC following substorms. Figure 5 shows

297   (a) a 2D histogram of the mean increase in TRBEC against 3-hour mean SML and 3-hour mean SYMH,

298   (b) the mean mean increase in TRBEC averaged over all SML plotted against 3-hour mean SYMH, (c)

299 the mean mean increase in TRBEC averaged over all SYMH plotted against 3-hour mean SML. The

300 increases are calculated for a lag of 24 hrs from the measurements of SYM-H and SML. The red

301 traces in Figs. 5b and c show the number of data points in each mean value. Figure 6 presents the

302 decreases in TRBEC against SML and SYM following a substorm in a similar fashion.

303

304 Figure 5 shows that the increase in TRBEC is greater for higher SML and SYMH. Figures 5b and c

305 show that, on average, the increase in the mean TRBEC averaged over all SYMH shows a 88% linear

306 correlation with SML whereas averaging over all SML gives a 76% correlation with SYMH, although

307 both are significant beyond the 99.9% level from the Student's T-Test. Correlating the raw data gives

308 correlations of ~30% using the Spearman's Rank Order Correlation for both SML and SYMH, as one

309 would expect from Figure 1. This implies that, on average, the size of substorms is a better indicator

310 of the subsequent change in the radiation belt content than the storm size, although fully

311 deconvolving storm and substorm effects from these data may not be possible.

312

313 Figure 6 shows the same analysis for decreases in TRBEC following substorms and increases and

314 decreases in TRBEC following quiet intervals. For these data, there is only a 42% correlation between

315 the mean decreases in TRBEC following substorms and SML, which is much lower than the

316 correlation shown above for increases in TRBEC following substorms. Similarly there is only a

317 correlation of 7% between decreases in TRBEC and SYMH following substorms. The statistical

318 significance of the SML correlation was slightly below the 99.9% level, but there was no significant

319 correlation between decreases in TRBEC and SYMH.

320

321 Changes in TRBEC showed no significant correlations with SML or SYMH following quiet intervals. For

322 brevity, these data are presented in the Supplementary Information for the interested reader.

323

324   In summary, our results show the radiation belts are inherently lossy such that the median change in

325   the radiation belt content of 1000-2000 MeV/G electrons is negative following both quiet and

326   substorm intervals. Following a quiet interval, there is up to a 75% chance that the radiation belt

327   content will decrease, however following substorms there is up to a 50% chance that they will

328   increase. The difference in the proportion of increases and decreases following substorm or quiet

329   intervals is significantly different up to 6 days after the fact, with this difference peaking after 0.5-2.5

330   days. The mean change in TRBEC following substorms shows a broad peak centred on 48 h after the

331   event window, in keeping with the cross-correlation between SML and TRBEC. This indicates that

332   there can be a lag between the occurrence of magnetospheric activity and its effect on the radiation

333   belts or that radiation belts have a "memory" of substorm and quiet activity. Furthermore, the

334   distribution of increases in the radiation belt content is found to be enhanced following substorm

335   intervals with respect to quiet intervals and the increases in the radiation belt content showed a

336   stronger correlation with substorm activity levels than storm activity levels. Substorms are thought

337   to be a key component of radiation belt energisation, providing the injection of a seed population of

338   keV electrons and enhancing wave power in the inner magnetosphere that then accelerates this

339   seed population to MeV energies [Baker et al., 1998; Horne and Thorne, 1998, Meredith et al., 2001,

340   2002, 2003a, Horne et al., 2005a,b; Jaynes et al., 2015]. Our results show that the occurrence of

341   increases in the radiation belts is enhanced following substorm times compared to quiet times and

342   that the increase in the radiation belt content is related to the level of substorm activity, although

343   the extent to which losses are dependent on substorm activity levels is much weaker. As such there

344   are nuances in substorm processes that must be taken into account if we wish to understand how

345   substorms affect the radiation belts.

346

347   Discussion

348   By examining the radiation belt content following both quiet and substorm intervals, we have shown

349   that the radiation belts are inherently lossy. Following quiet intervals there is up to a 75% chance of

350   there being a loss of particles from the radiation belts with average loss rates from 20-200x10^{25}

351   electrons per day. The effect of substorms is to reduce the likelihood of the radiation belt content

352   decreasing, or alternatively increase the likelihood of it increasing. The result of this can be seen in

353   Figure 1, particularly on long time scales, with relatively short duration increases followed by an

354   extended period of decreasing TRBEC. The average rate of decrease was higher following substorms

355   than following quiet intervals for the first 24 hrs after the event, implying that substorm activity

356   enhances losses as well as increases in the radiation belt content. This is consistent with increases in

357   plasmaspheric hiss, whistler-mode and EMIC wave activity which can enhance pitch angle scattering

358   rates [e.g. Tsurutani and Smith, 1974; Meredith et al., 2004; Usanova et al. 2012], however the

359   average losses showed no correlation with substorm activity levels. Due to the nature of the

360   observations, we do not measure the enhancement and loss rates directly, instead examining the

361   net change in the radiation belt content. Hence we cannot separate out the increase and loss rates

362   and our results should thus be taken as such.

363

364   Our results presented above clearly show that some substorm intervals result in increases in the

365   radiation belt while others do not. One reason why a substorm may not lead to an increase in the

366   radiation belts is that particles injected towards the inner magnetosphere during substorms do not

367   get sufficiently close to the Earth to provide a seed population for the wave generation and

368   acceleration processes. Boakes et al. [2009] showed that, for a subset of 135 events in the Frey et al.

369   [2004] list, only ~50% of substorms showed the signature of a clear injection of electrons into

370   geosynchronous orbit and ~25% showed no injection signature at all. Sergeev et al. [2012] discussed

371   that the injection of particles into the inner magnetosphere depends on the injected particle

372   population having a similar entropy to the plasma in the inner magnetosphere in order to penetrate

373   into the radiation belt region via the interchange instability. Thus this does not necessarily mean that

374   50% of events do not have injections, but may indicate that these injections do not penetrate into

375   the inner magnetosphere and hence the injected particles are not accelerated up to high levels.

376 Jaynes et al. [2015] discussed that if any of the necessary populations (particle or wave) were not

377 present in the radiation belts, the radiation belts would not be enhanced. Thus, following 50% of the

378 substorm intervals that we studied, either the substorms did not produce the necessary wave

379 population to accelerate the seed population, or the seed population was not injected into the

380 radiation belts. Taking the Boakes et al. [2011] results to be a statistically representative subset of

381 events, it is more likely that only 50% of substorms inject particles into the radiation belts.

382

383 Our results show a number of interesting features with regards to the timescales of acceleration and

384 loss following substorms or quiet intervals. Firstly, the radiation belts appear to be inherently lossy.

385 After 33 hrs following a substorm interval, and for up to >200 hrs following a quiet interval, there are

386 statistically significantly more decreases in the radiation belt that increases. This can, in fact, be seen

387 in Figure 1a, with large-scale increases in the radiation belts being sharp and short lived, while the

388 decreases have a much longer period, giving a saw-tooth like profile to the the radiation belt

389 content. Secondly, our analysis shows that, on average, changes in the radiation belt content are

390 lagged by ~1-3 days following magnetospheric activity or a lack thereof. Examining the occurrence of

391 increases or decreases in TRBEC shows that the effect of substorms or quiet times is most significant

392 at ~1 day following the event, whereas the mean changes in TRBEC are greatest after 48 h, as is the

393 cross correlation between SML and TRBEC. Thirdly, our analysis shows that the radiation belts have a

394 "memory" of the substorm or quiet interval. The effect of substorms is to increase the likelihood of

395 the radiation belts increasing 6 days after their occurrence. This implies that the acceleration

396 mechanism is enhanced by the substorm activity but not limited to it. Conversely, the effect of quiet

397 intervals is to increase the likelihood of the radiation belts decreasing for more than 6 days after the

398 fact. This implies that a relatively short period with no substorm activity can suppress acceleration

399 within the radiation belts for a far longer period afterwards. In the context of wave-particle

400 interactions causing enhancements and losses in the radiation belts, it is interesting to ask what the

401 lifetime of the seed population and whistler-mode chorus and other waves are following substorm

402 interval and quiet intervals. To date, we are not aware of any study that addresses this question.

403

404 Previous studies have reported that changes in electron flux at geosynchronous orbit at storm

405 commencement are correlated with the size of the storm. Moon et al. [2004] examined the ratio of

406 the electron fluxes before a storm and following the storm commencement for 50-400 keV electrons

407 during 22 storm events and found that these correlated with the minimum storm-time Dst index,

408 with correlation coefficients (r) of 0.64-0.84 corresponding to 40-70% correlation (r^2). It is therefore

409 unsurprising that the change in the higher energy population is also somewhat correlated with

410 SYMH (a comparable measure to Dst), as shown in this study. However, the complex interplay

411 between particle injection, wave generation and wave-particle interactions that results in different

412 losses and gains in the high energy electron population mean that the correlation between the

413 changes in higher energy particle fluxes and SYMH does not necessarily reflect the correlations seen

414 with lower energy particles. Furthermore, we consider the correlation between the increases in the

415 radiation belt content and SML or SYMH for a far greater number of events.

416

417 The loss and acceleration mechanisms in the radiation belts are a complex interplay of different

418 wave-particle interactions as well as plasma transport. Our results show that losses and acceleration

419 occur after both quiet and substorm intervals, although with a greater proportion of loss periods

420 following quiet intervals and a greater proportion of acceleration intervals following substorms.

421 From modelling, the timescale for the radiation belt electron flux to increase by an order of

422 magnitude has been put at ~24 hrs [e.g. Horne et al., 2005a], whereas our results show that the

423 mean change in TRBEC following substorms is positive and statistically significantly different to that

424 following quiet intervals up to 96 hrs after the fact. Within that time there are likely to be both

425 substorm and quiet intervals. As such, increases or decreases in the radiation belt content may also

426 depend on activity prior to or following the reference interval. Take, for example, a quiet interval

427   following a period of substorm activity: if the loss rate increases, it may not overcome the pre-

428   existing acceleration rate thus the overall result is an increase, albeit at a lower acceleration rate.

429   However, if we similarly consider a substorm interval following a quiet interval, we would expect

430   that the acceleration of particles would reduce any rate of decrease. This is not seen in the data.

431   Rather than the distribution of changes in TRBEC being shifted towards increases in TRBEC following

432   substorm intervals, the distribution of radiation belt losses is approximately the same following

433   substorm and quiet intervals at the lags examined, with substorms providing an additional

434   population of increases. As such, in order to predict changes in the radiation belts following

435   substorms, one must be able to determine what controls whether or not the substorm provides

436   enhancements in radiation belt.

437

438   Meredith et al. [2003 a] suggested that a prolonged period of substorm activity may be needed to

439   energise the radiation belts. Using data from the extended solar activity minimum at the end of solar

440   cycle 23, Rodger et al. [2015] showed that recurrent substorms from the Newell and Gjerloev [2011]

441   list (separated by less than 82 min) are more efficient that isolated substorms (separated by more

442   than 3 hrs) in enhancing the radiation belts, although both recurrent and isolated substorms showed

443   increase in the radiation belt electron flux. Within this study, we have considered substorm

444   expansion and recovery phase occurrences within 3 hr windows thus we do not separate isolated

445   and recurrent substorms, however we do show that the largest changes in radiation belt content

446   occurred during periods of large SYMH, suggestive of storm times in which we would expect to see

447   periods of recurrent substorms.

448

449   It is generally thought that whistler-mode chorus waves are the dominant process that accelerates

450   the seed population up to MeV energies [e.g. Horne et al., 2005a, 2005b, Li et al., 2007; Thorne et

451   al., 2013; Reeves et al., 2013; Jaynes et al., 2015]. The amplitude of these waves relates to their

452   ability to accelerate particles and this has been shown to increase with AE and thus substorm activity

453 (Meredith et al., 2001; 2003b). However, whistler-mode chorus waves are also implicated in pitch-

454 angle scattering that can move particles into the loss cone [Horne and Thorne 2003]. Similarly, EMIC

455 waves can efficiently scatter particles into the loss cone [Meredith et al., 2003c; Bortnik et al., 2006;

456 Hendry et al., 2014; Usanova et al., 2014; Rodger et al., 2015]. A modelling study by Li et al. [2007]

457 suggested that during storms the whistler-mode chorus waves should give a net acceleration of

458 particles, whilst EMIC waves were the dominant loss mechanism. However, both Horne et al.

459 [2005a] and Li et al. [2007] used average wave-power distributions observed during substorms

460 determined by a single spacecraft (based on Meredith et al., 2001, 2003b). These spatio-temporal

461 averages can hide important information and are not necessarily representative of any individual

462 event. Given that our results show that increases and decreases in the radiation belt content occur

463 following substorms, the important question is how do the wave populations vary for increases and

464 decreases in radiation belt content and how does this relate to substorm activity? Our results show

465 radiation belt increases and decreases for all levels of substorm activity. However, while radiation

466 belt increases are reasonably well correlated with SML, radiation belt decreases are less dependent

467 on substorm size. This is somewhat counter-intuitive if one expects the loss mechanisms to depend

468 on wave amplitudes which, on average, increase with substorm size.

469

470 A number of studies have examined how the acceleration of radiation belt particles may be related

471 to upstream solar wind conditions, thus giving a way in which to predict future variations in the

472 radiation belt [e.g. Baker et al., 1979; Reeves et al., 2011; McPheron et al., 2009; Li et al. 2015; Kim

473 et al., 2015]. The solar wind can directly influence the radiation belts through the generation of ULF

474 waves and modifying the particle population to generate VLF waves [e.g. Elkington, 2006; Shprits et

475 al., 2008; Ebihara and Miyoshi, 2011, Miyoshi et al., 2013] or can indirectly influence the radiation

476 belts by enhancing the energy of the plasma sheet population prior to substorms that are then

477 subsequently injected [Forsyth et al., 2014; Sergeev et al., 2015]. In this study, we have not

478 considered the impact of the solar wind on the radiation belts, but rather statistically examined

479   whether substorm activity alone shows any correspondence to changes in the radiation belt. It is

480   worth noting that many of the studies that have examined the solar wind impact on the radiation

481   belts show that the solar wind conditions that lead to radiation belt acceleration include a prolonged

482   southward IMF, elevated solar wind speed but low solar wind density (thus giving a low dynamic

483   pressure). These solar wind conditions are similar to those that are conducive to causing storms and

484   substorms [e.g. Gonzalez and Tsurutani, 1987; Morley and Freeman, 2007], and as such the link

485   between solar wind conditions and increases in the radiation belts may be both direct and indirect.

486

487   It should not be a surprise that the response of the radiation belts show a multi-faceted response to

488   substorms, given that the radiation belts can be energised, depleted or unchanged during storms

489   [Reeves et al., 2003]. In fact, our results show some similarity with those of Reeves et al. [2003], in

490   that only 50% of substorms resulted in an increase in the radiation belt content, in keeping with

491   their result that only 50% of storms show an increase in the radiation belt electron fluxes. However,

492   our results cover a large range of SYMH values showing that both storm-time and non-storm-time

493   substorms show increases and decreases in the radiation belts.

494

495   Conclusions
496   We have statistically compared changes in the total radiation belt electron content from the Van

497   Allen Probes over time with substorm activity determined by the SOPHIE algorithm. Substorm

498   activity was broken down into three-hour windows in which substorm expansion or recovery phases

499   began (substorm intervals) or there were no expansion and recovery phase onsets (quiet intervals).

500   Changes in the radiation belt content were calculated as a net change over increasing time intervals.

501   Our results show that:

502   • There is a 50% chance of an increase or decrease in the radiation belt content up to 33 hrs

503   following a substorm interval;

504   • There is up to a 75% chance of a decrease in radiation belt content following quiet intervals;

505   • The radiation belts have an apparent "memory" of substorms and quiet intervals, extending

506   out to 6 days after the event;

507   • Substorms and quiet intervals are good predictors of increases and decreases in radiation belt

508   with this skill and accuracy of this prediction maximising at a lag of between 0.5 and 2.5 days;

509   • The increases in radiation belt content 24 hrs following substorm intervals are correlated with

510   both SML and SYMH, along the correlation with SML is stronger.

511   Furthermore, we have provided the median increases in TRBEC 24 hrs following a substorm for

512   given ranges of SML and SYMH.

513

514   These results raise important questions for the existing framework for substorms increasing the

515   radiation belt contents, namely what prevents half of substorm intervals from increasing the

516   radiation belt content and what controls the radiation belt loss rate? These are fundamental

517   questions that must be answered in order to develop accurate modelling of the radiation belts with

518   respect to substorm activity.

519

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821   *Table 1*: Contingency table of TRBEC increases and decreases 24 hrs following substorm or
822   quiet intervals.

	Observed values		Proportion of substorm/quiet observations		Expected values for null hypothesis (no relation between increases or decreases with substorms or quiet intervals)	
	TRBEC Increase	TRBEC decrease	TRBEC Increase	TRBEC decrease	TRBEC Increase	TRBEC decrease
Substorm Interval	851	838	0.504	0.496	714	975
Quiet Interval	303	738	0.291	0.709	440	601

823
824   *Table 2*: Contingency table of TRBEC increases and decreases 24 hrs following substorm or
825   quiet intervals.

	Observed values		Proportion of increases or decreases following:		Expected values for null hypothesis (no relation between increases or decreases with substorms or quiet intervals)	
	Substorm Interval	Quiet Interval	Substorm Interval	Quiet Interval	Substorm Interval	Quiet Interval
TRBEC Increase	851	303	0.737	0.263	714	440
TRBEC Decrease	838	738	0.532	0.468	975	601

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829   *Table 3:* Median mean rates of change of TRBEC for different lags. Results given in units of
830   1e25/day.

	3 hrs	24 hrs	48 hrs	144 hrs
Rate of Increase following Substorms	216	115	84	31
Rate of Increase following Quiet Intervals	110	24	24	34
Rate of Decrease following Substorms	-206	-50	-34	-26
Rate of Decrease following Quiet Intervals	-127	-41	-34	-24

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833   Figures
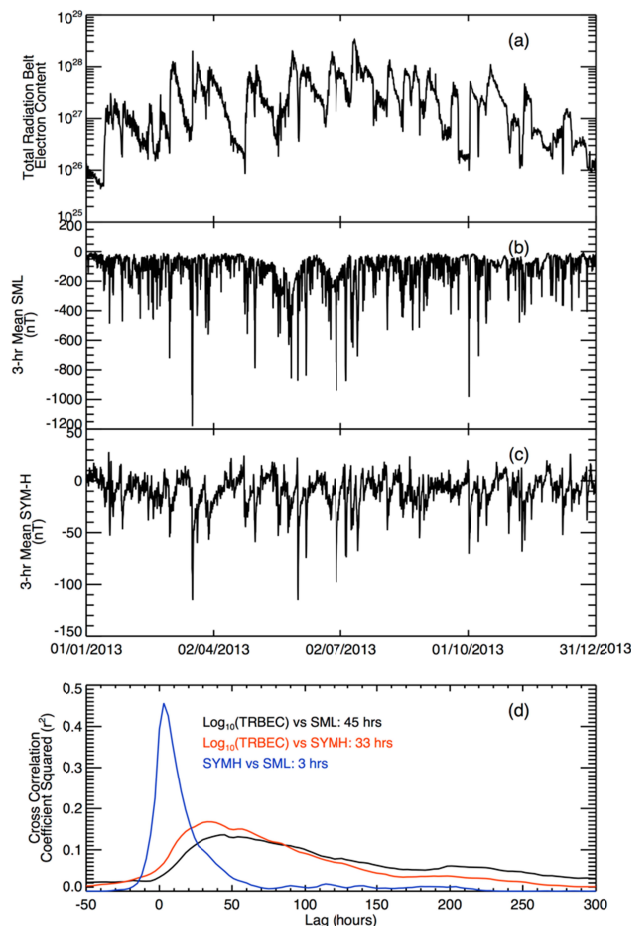
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836   Figure 1: Plot showing (a) the total radiation belt electron content of 1000-2000 MeV/G

837   electrons as measured by the Van Allen Probes, (b) and three-hour averaged (mean)

838   SuperMAG AL (SML) index and (c) SYM-H against universal time for 2013. Panel (d) shows

839   the Pearson's correlation coefficient determined for different lags between (black) TRBEC

840   and SML, (red) TRBEC and SYM-H, (blue) SYM-H and SML. The lag corresponding to the peak

841   correlation coefficient is shown in the panel. The data show that TRBEC is weakly correlated

842   with SML and SYM-H at 45 and 33 h respectively (TRBEC varying after SML or SYM-H), and

843   that SYM-H and SML are moderately correlated at a lag of 3 h.

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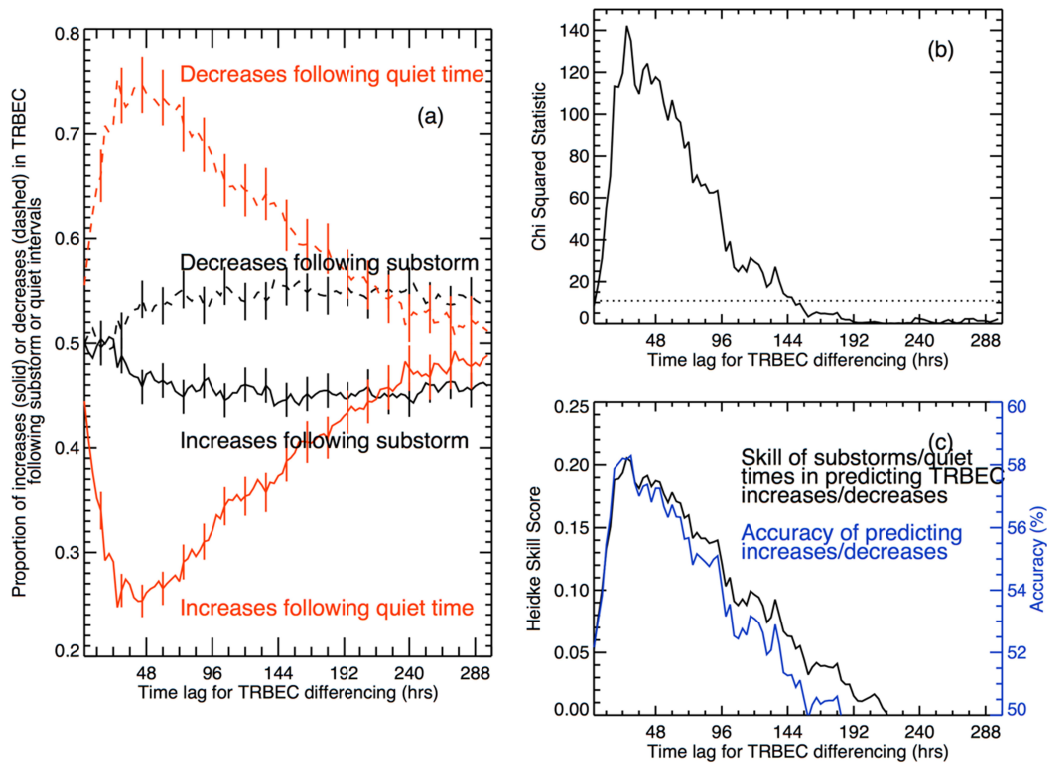
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846 Figure 2: (a) The proportion of (red) quiet intervals and (black) substorm intervals that are

847 followed by an increase (solid lines) or decrease (dashed lines) in TRBEC for different lags.

848 The change in TRBEC is calculated as $TRBEC(t_0+dt)-TRBEC(t_0)$ where dt is the lag. (b) Plot of

849 the χ^2 statistic showing the statistical significance of the differences in the proportions in

850 Panel (a). The dotted horizontal line shows the lower limit for the results to be significant

851 beyond the 99.9% level. (c) The Heidke Skill Score (black) and accuracy (blue) obtained for

852 using substorms or quiet times to predict increases or decreases in TRBEC. The data show

853 that up to 33 h after a substorm interval, 50% of events show an increase in TRBEC and 50%

854 show a decrease, whereas following a quiet interval there is up to a 75% chance of TRBEC

855 decreasing.

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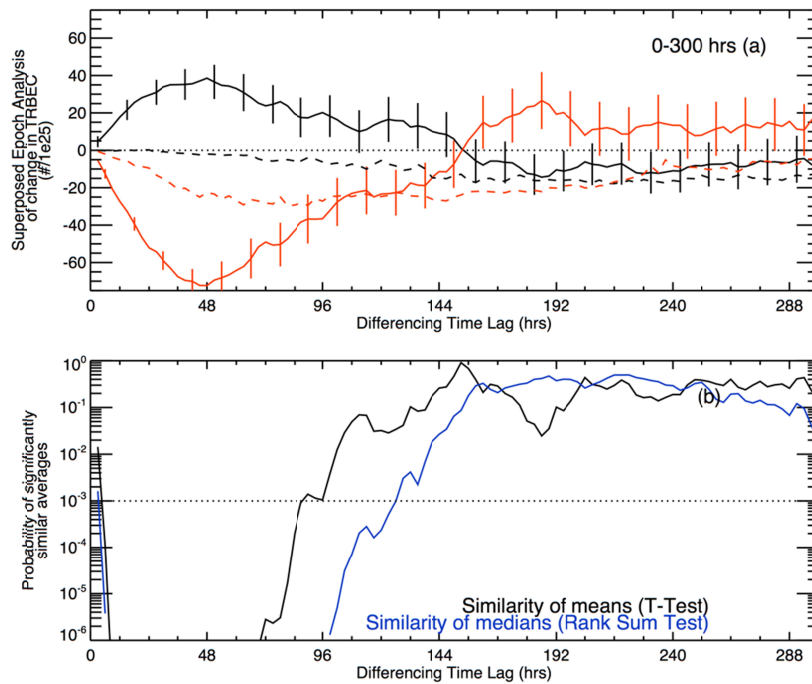
Figure 3: (a) Superposed epoch analysis of the change in TRBEC following (black) substorm

and (red) quiet intervals. (b) The probability that the (black) means and (blue) medians of

the change in TRBEC following substorms and quiet intervals are statistically similar. Points

below the horizontal line have a probability of less than 0.1% or being similar, or are

statistically significantly different at the 99.9% level. This value is calculated from the

Student's T-Test for the means and Wilcoxon-Mann-Whitney Rank Sum Test for the

medians.
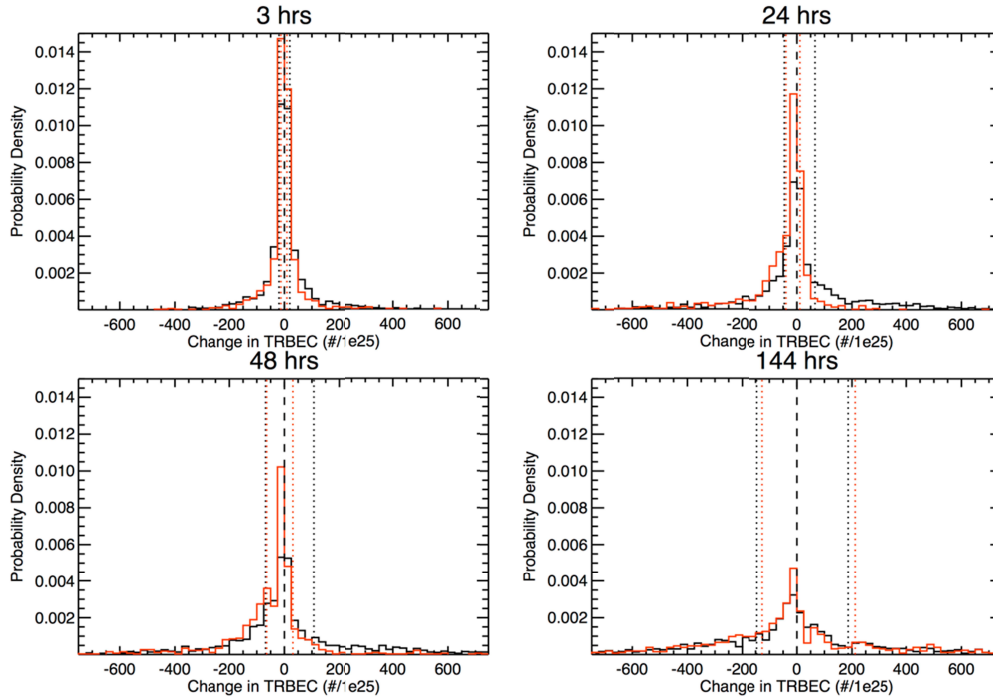
867
868 Figure 4: Histograms of the probability density of changes in following substorms (black) and
869 quiet intervals (red) at lags of (a) 3 h, (b) 24 h, (c) 48 h and (d) 144 h. The vertical dotted
870 lines show the median increase and decrease in TRBEC. The plots show that the distribution
871 of decreases in TRBEC is largely similar following substorms and quiet intervals at all lags,
872 whereas substorms enhance the distribution of increases in TRBEC. However, this
873 enhancement is sensitive to the time from the substorm interval and has all but vanished by
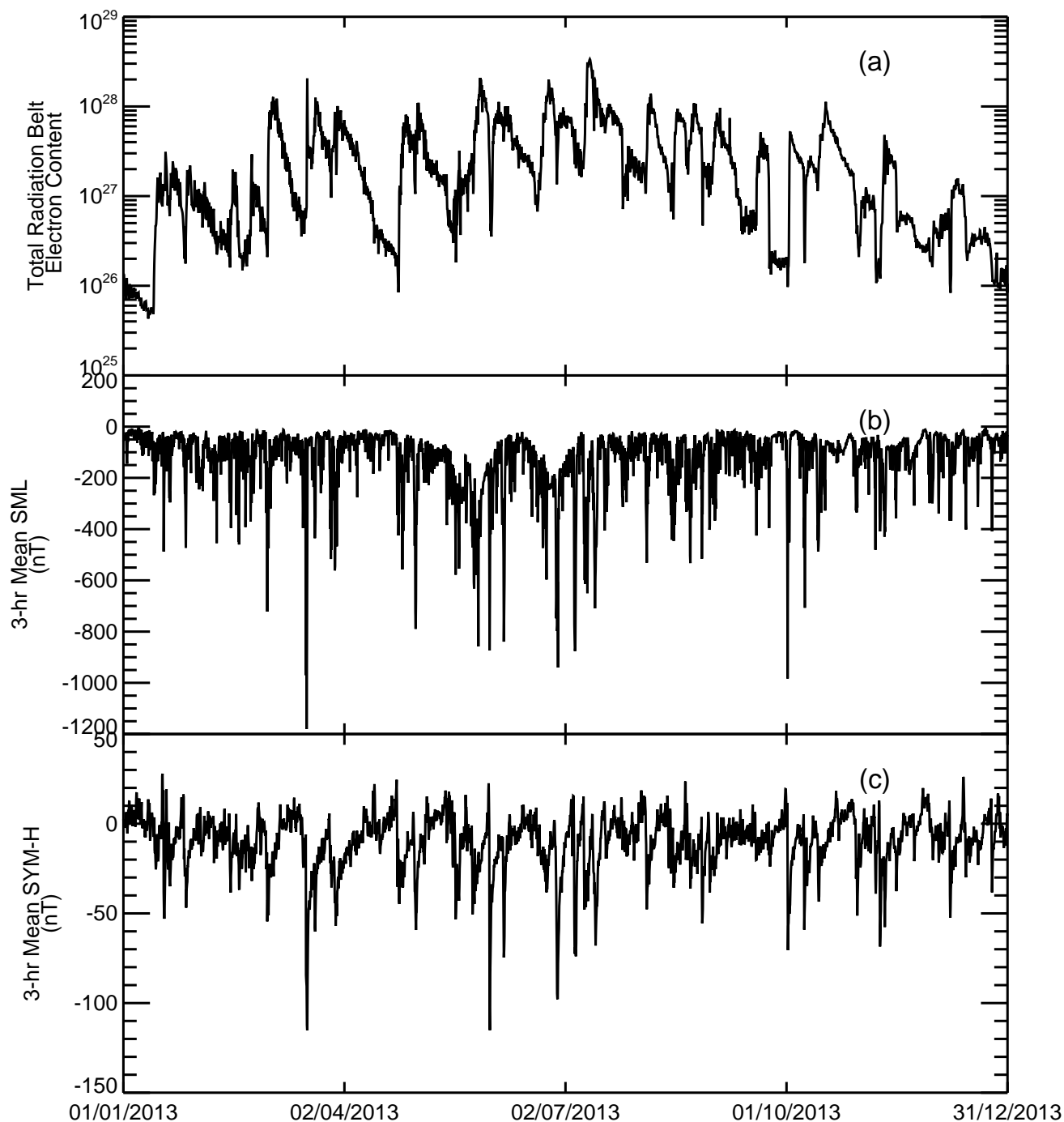874 a lag of 144 h.
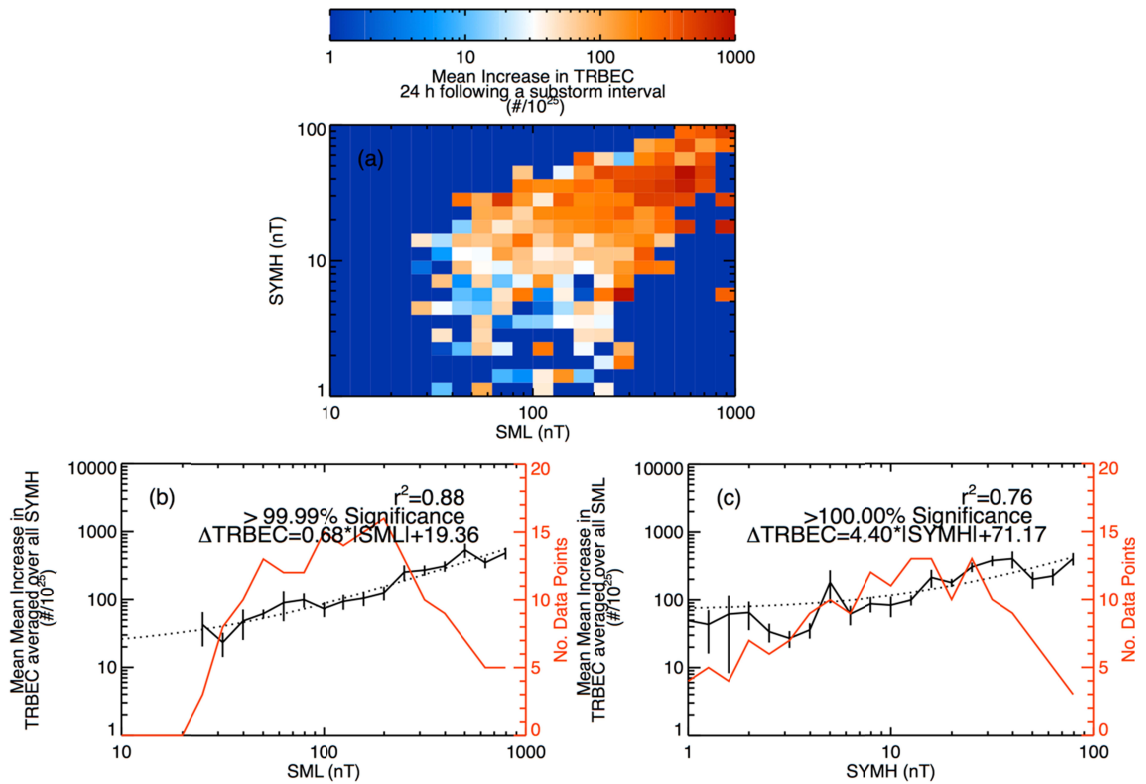
875
876 Figure 5: (a) 2D histogram of the mean increase of TRBEC (divided by 10^{25}) 24 hrs following

877 substorm intervals against |SML| and |SYMH|. (b) The mean mean increase in TRBEC

878 averaged over all |SYMH| against |SML|. (c) The mean mean increase in TRBEC averaged

879 over all |SML|. The red traces in Panels (b) and (c) show the number of data points making

880 up the mean values. The square of the Rank Order Correlation coefficient is given in (b) and

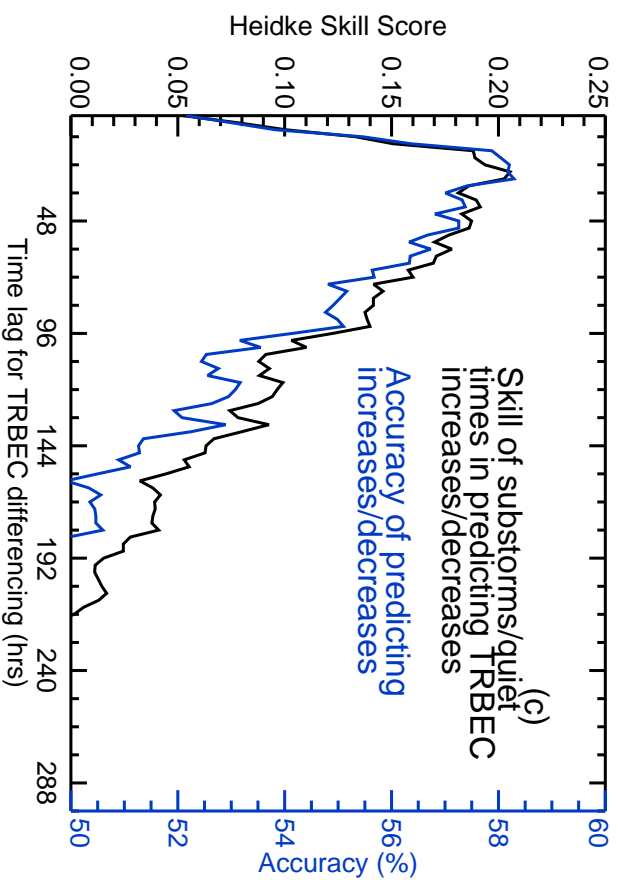881 (c), along with the significance of this correlation determined by the Student's T-Test.
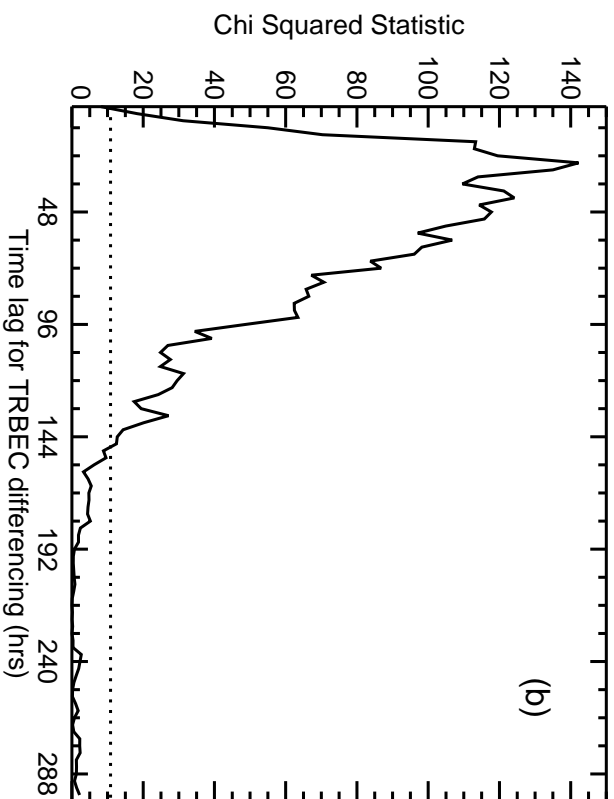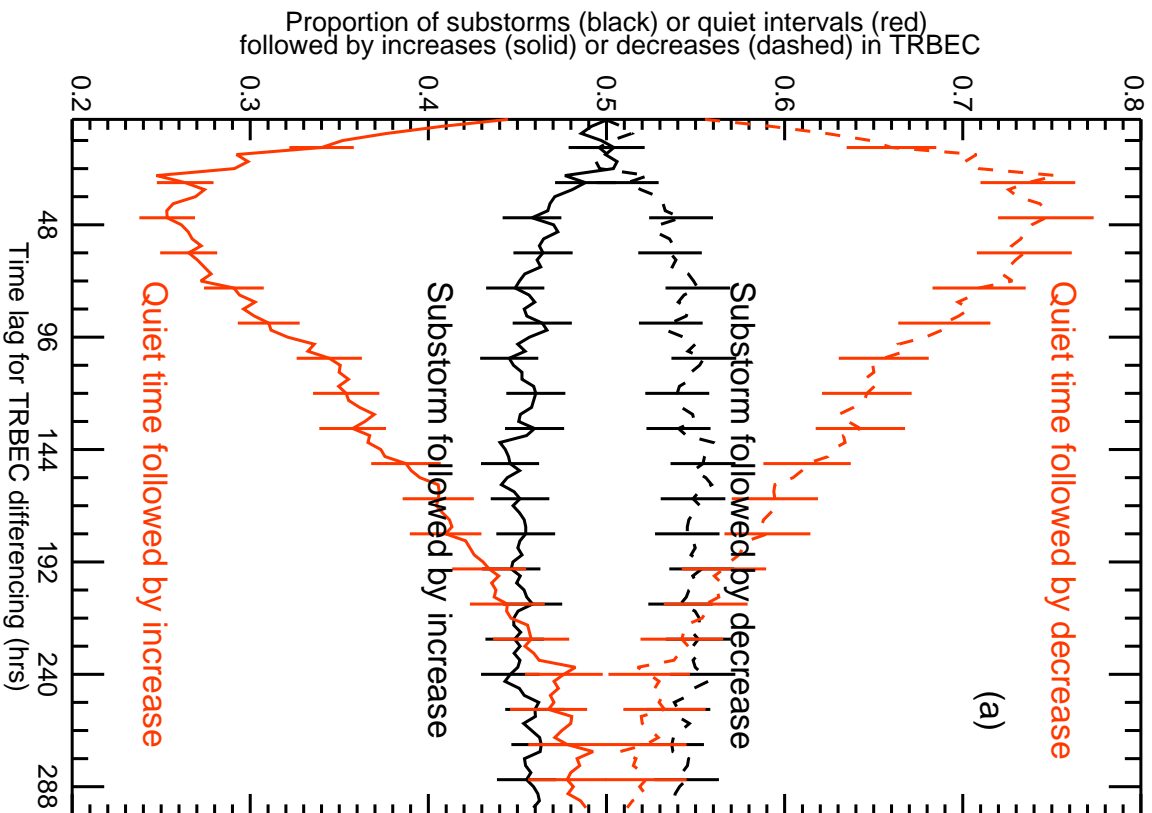
882
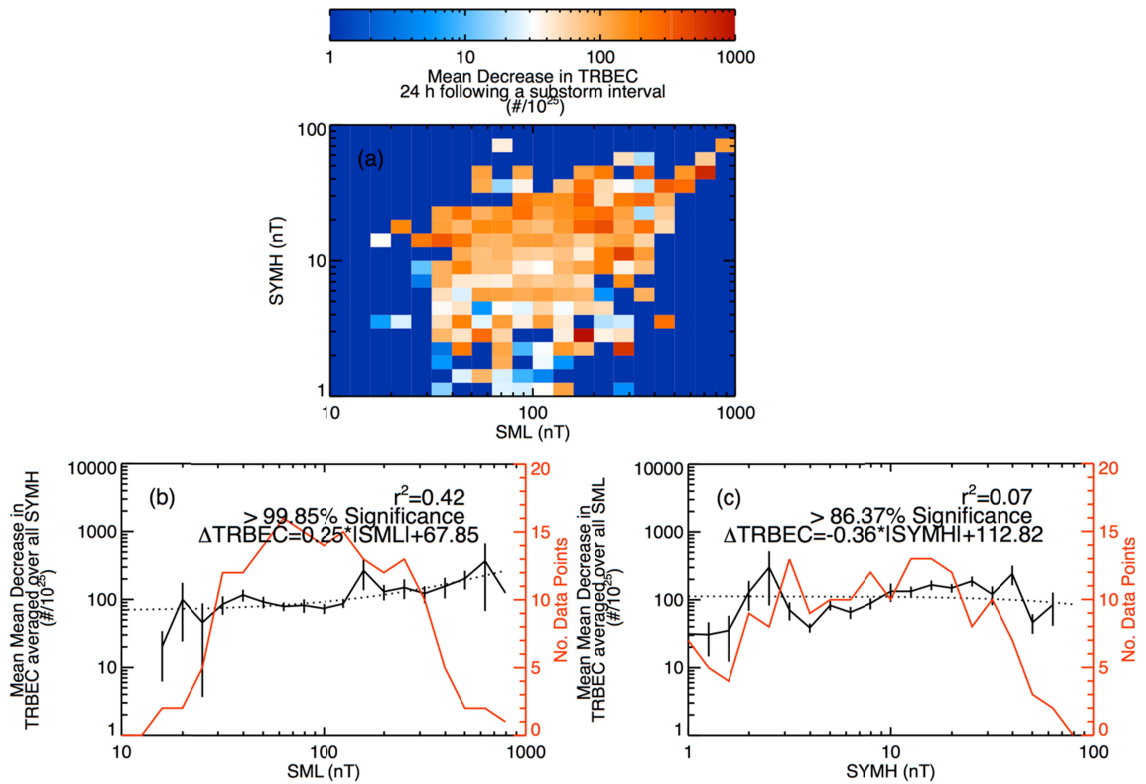
883
884 Figure 6: (a) 2D histogram of the mean decrease of TRBEC (divided by 10^{25}) 24 hrs following

885 substorm intervals against |SML| and |SYMH|. (b) The mean mean increase in TRBEC

886 averaged over all |SYMH| against |SML|. (c) The mean mean increase in TRBEC averaged

887 over all |SML|. The red traces in Panels (b) and (c) show the number of data points making

888 up the mean values. The square of the Rank Order Correlation coefficient is given in (b) and

889 (c), along with the significance of this correlation determined by the Student's T-Test.
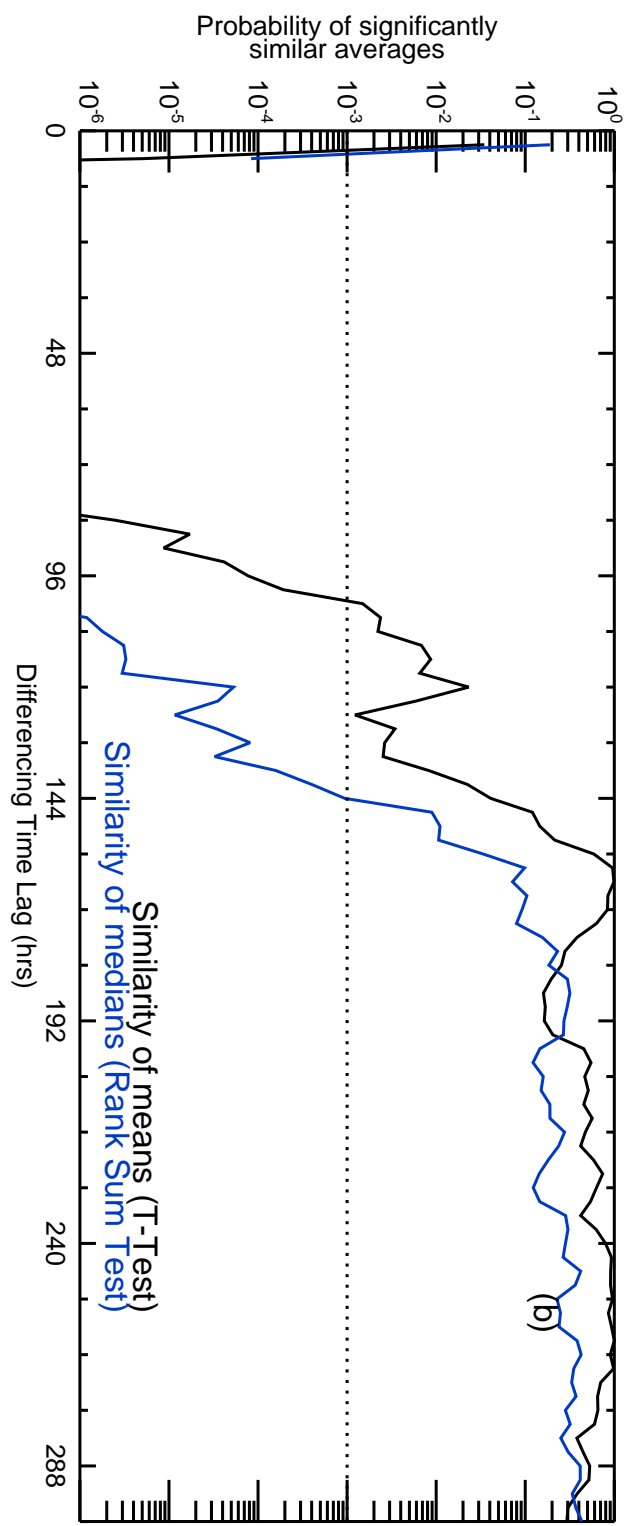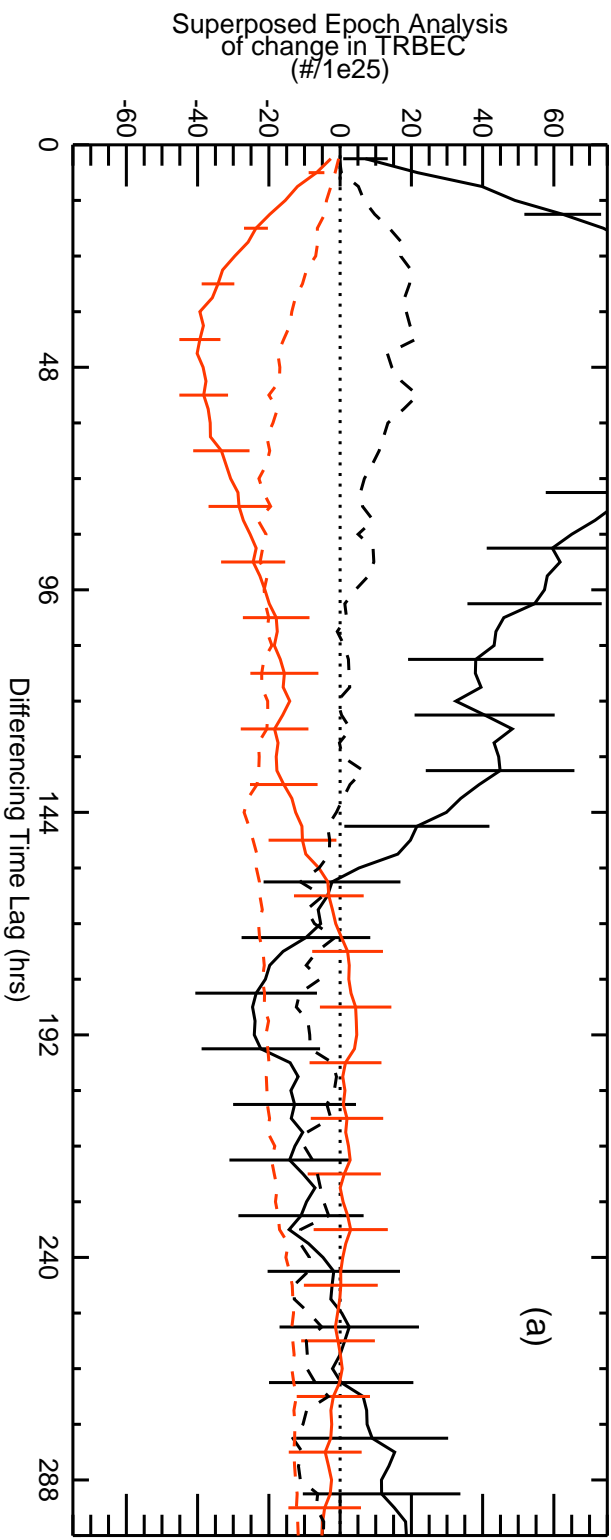
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Figure 1. Figure

Figure 2. Figure

(a)

Proportion of substorms (black) or quiet intervals (red)
followed by increases (solid) or decreases (dashed) in TRBEC

Quiet time followed by decrease

Substorm followed by decrease

Substorm followed by increase

Quiet time followed by increase

Time lag for TRBEC differencing (hrs)

(b)

Chi Squared Statistic

Time lag for TRBEC differencing (hrs)

(c)

Heidke Skill Score

Skill of substorms/quiet
times in predicting TRBEC
increases/decreases

Accuracy of predicting
increases/decreases

Accuracy (%)

Time lag for TRBEC differencing (hrs)

Figure 3. Figure

(a)

Superposed Epoch Analysis
of change in TRBEC
(#/1e25)

Differencing Time Lag (hrs)

(b)

Probability of significantly
similar averages

Similarity of means (T-Test)
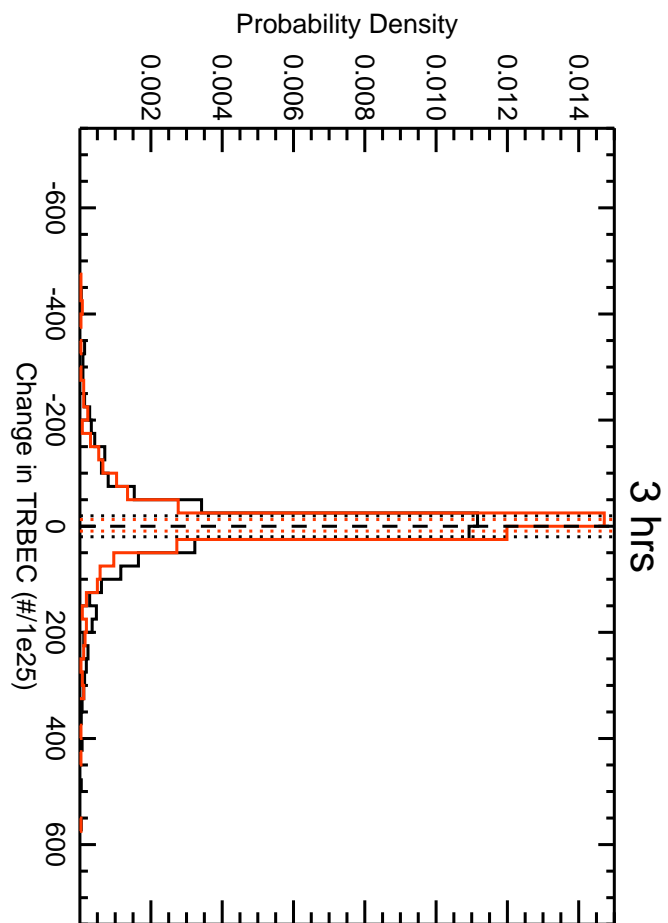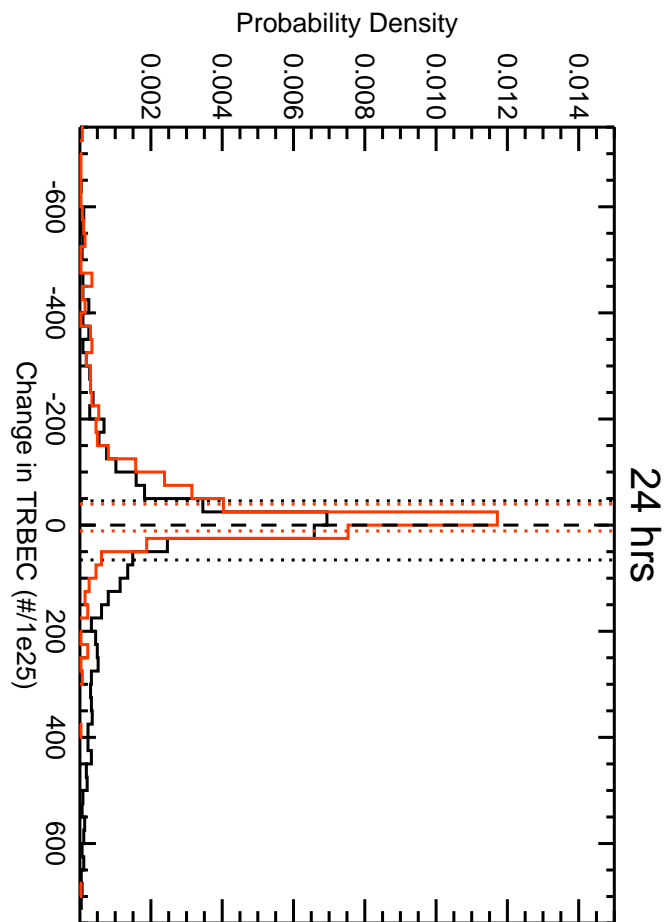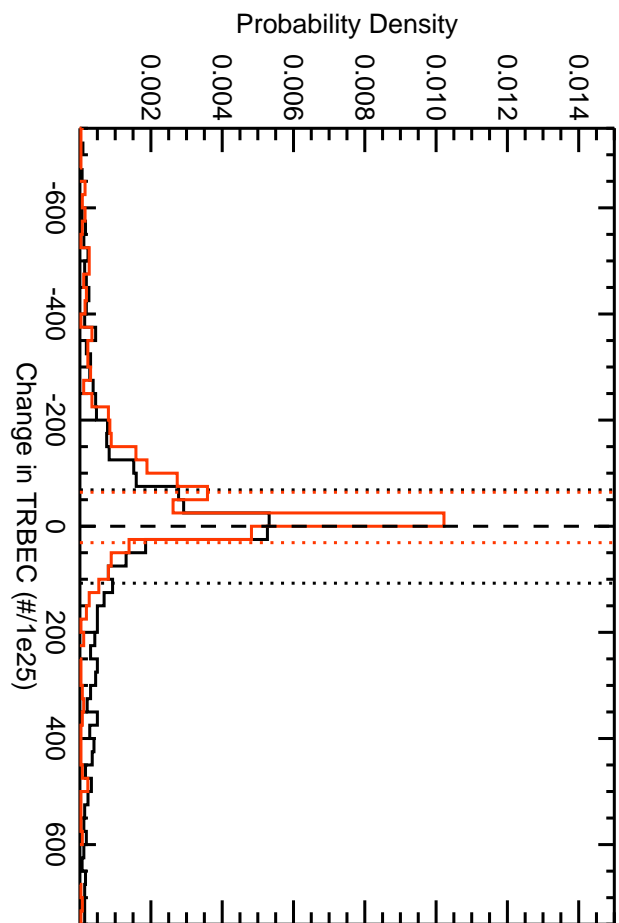Similarity of medians (Rank Sum Test)

Differencing Time Lag (hrs)

Figure 4. Figure

Figure 5. Figure

(a)

SYMH (nT)

SML (nT)

Mean Increase in TRBEC
24 h following a substorm interval
(#/10²⁵)

(b)

Mean Mean Increase in
TRBEC averaged over all SYMH
(#/10²⁵)

SML (nT)

No. Data Points

> 99.99% Significance
ΔTRBEC=0.68*|SML|+19.36
r²=0.88

(c)

Mean Mean Increase in
TRBEC averaged over all SML
(#/10²⁵)

SYMH (nT)

No. Data Points

>100.00% Significance
ΔTRBEC=4.40*|SYMH|+71.17
r²=0.76

Figure 6. Figure

(a) Mean Decrease in TRBEC 24 h following a substorm interval (#/10²⁵)

SYMH (nT)

SML (nT)

(b) Mean Mean Decrease in TRBEC averaged over all SYMH (#/10²⁵)

ΔTRBEC=-0.25*|SML|+67.85

r^2=0.42

> 99.85% Significance

SML (nT)

No. Data Points

(c) Mean Mean Decrease in TRBEC averaged over all SML (#/10²⁵)

ΔTRBEC=-0.36*|SYMH|+112.82

r^2=0.07

> 86.37% Significance

SYMH (nT)

No. Data Points