

Correlating the interplanetary factors to distinguish extreme and major geomagnetic storms

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Key Points:

- The average time rate of change of Dst during the main phase of storms is strongly correlated with the minimum Dst .
- The correlation between the solar wind electric field and $dDst/dt$ are positive and nonlinear, especially for the regime of extreme storms.
- The minimum Dst is positively correlated with the minimum B_z , but extreme storms tend to have more negative Dst than the overall trend.

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Abstract: We investigate the correlation between Disturbance Storm Time (Dst) characteristics and solar wind conditions for the main phase of geomagnetic storms, seeking possible factors that distinguish extreme storms (minimum $Dst < -250$ nT) and major storms (minimum $Dst < -100$ nT). In our analysis of 170 storms, there is a marked correlation between the average rate of change of Dst during a storm's main phase ($\Delta Dst/\Delta t$) and the storm's minimum Dst , indicating a faster $\Delta Dst/\Delta t$ as storm intensity increases. Extreme events add a new regime to $\Delta Dst/\Delta t$, the hourly time derivative of Dst ($dDst/dt$), and sustained periods of large amplitudes for southward interplanetary magnetic field B_z and solar wind convection electric field E_y . We find that E_y is a less efficient driver of $dDst/dt$ for extreme storms compared to major storms, even after incorporating the effects of solar wind pressure and ring current decay. When minimum Dst is correlated with minimum B_z , we observe a similar divergence, with extreme storms tending to have more negative Dst than the trend predicted on the basis of major storms. Our results enable further improvements in existing models for storm predictions, including extreme events, based on interplanetary measurements.

Keywords: extreme geomagnetic storm; Dst prediction; solar wind driving; major storms

1. Introduction

The modern definition of the geomagnetic storm is characterized by a prolonged depression in the horizontal component of the Earth's low-latitude magnetic field (Rostoker et al., 1997). This depression is caused by the ring current encircling the Earth in a westward direction (Kamide et al., 1998; Daglis et al., 1999). The Dst (Disturbance Storm Time) index is used to gauge the intensity of geomagnetic storms by measuring this overall ring current intensity (Iyemori, 1990) at low-latitude observatories.

The critical importance of the time derivative of Dst is manifested in part in its use for reconstructing global geomagnetic fields. The measurement of symmetric disturbances for the Horizontal geomagnetic field (SYM-H) is a de facto higher resolution Dst (Wanliss and Showalter, 2006) commonly utilized by the geospace model-

ing community to further the understanding of geomagnetic field dynamics. In Sitnov et al., (2008), the application of SYM-H and its time-related derivative were fundamental within their Nearest-Neighbor (NN) approach to spatially reconstruct the magnetosphere and identify storm phases. More recently, Stephens et al., (2019) built upon the NN approach, using SYM-H and its time derivative with the addition of the Auroral Electrojet Index Amplitude Lower (AL) and the AL time derivative to create 3-D models of magnetospheric stretching and dipolarization processes during substorm disturbances. Given the lengthy history of Dst usage, the focus of this paper is on the Dst metric over SYM-H, which was introduced in 1981, to ensure continuity and consistency across our storm analyses.

Two interplanetary factors that are widely thought to help drive the occurrence of geomagnetic storms are the solar wind convection electric field E_y and the southward component of the Interplanetary Magnetic Field (IMF) B_z (e.g., Yokoyama and Kamide, 1997), in the Geocentric Solar Magnetospheric (GSM) coordinate system. A southward B_z component indicates beneficial conditions for the process of magnetic reconnection to occur at the

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magnetopause, with subsequent storage of energy in the magnetotail. The release of this stored magnetic energy due to magnetotail reconnection results in particle injections that form the ring current around the Earth, which in turn causes the depression in the horizontal component of Earth's magnetic field (Lakhina and Tsurutani, 2017).

Many studies have investigated the empirical relationships between *Dst* and interplanetary factors, by using a basic form:

$$\frac{d}{dt}Dst^*(t) = Q(t) - \frac{Dst^*(t)}{\tau}, \quad (1)$$

where $Dst^* = Dst - a\sqrt{P} + b$ (a and b are constants) is correcting for solar wind dynamic pressure (P) since this pressure affects the magnetopause location and its associated current. Q represents the driving term, and Dst^*/τ represents the decay of the ring current primarily due to charge exchange between ions and neutral atoms. Burton et al., (1975) first laid the foundation for this empirical analysis, where $Q(t)$ depends on the solar wind electric field under southward IMF. O'Brien and McPherron (2000) modified the coefficients in the formula for Dst^* and redetermined τ . Wang CB et al., (2003) took into account the effect of the solar wind pressure in Q . In the Temerin and Li (2006) model, Dst depends on both the present and past solar wind conditions. Thanks to these studies, the *Dst* prediction has been much improved, for example, as demonstrated in Ji et al., (2012) where various *Dst* models are compared. We expand upon the previously studied regimes by analyzing 7 additional extreme storms to establish a positive and nonlinear correlation between the interplanetary electric field E_y and $dDst/dt$, showing that E_y is a less efficient driver of $dDst/dt$ for extreme storms.

The effect of IMF B_z on storms has long been recognized. The strength of a geomagnetic storm and its main phase duration were found to be directly proportional to the strength and duration of the IMF B_z component (Vichare et al., 2005; Alex et al., 2006; Rawat et al., 2007, 2010). Gonzalez and Echer (2005) completed an extensive study with the conclusion that the driving B_z component at the Lagrange L1 location tends to reach its peak value about 2 hours before the peak minimum *Dst*, corresponding to about 1 hour for the solar wind conditions to propagate to the Earth and an additional hour for the magnetosphere to respond. Li et al., (2011) conducted a statistical analysis of 89 storms with minimum *Dst* ranging from -100 nT to -422 nT, between 1996–2008. In this analysis, they noted a close correlative relationship between the amplitudes of the peak B_z and peak *Dst*, before and after removing the solar wind dynamic pressure effect. In this paper, we build upon these earlier findings extending the analysis to include more recent events.

Despite great improvements in *Dst* models and investigations of solar wind conditions, there is a lack of understanding whether extreme storms differ qualitatively from major storms in *Dst* characteristics and interplanetary driving conditions. In this study, we analyze the relationships among minimum *Dst*, the time derivative of *Dst*, the time duration of the main phase, the solar wind electric field, and IMF B_z , to elucidate features that distinguish extreme storms (minimum *Dst* < -250 nT) from major storms (-250 nT $<$ minimum *Dst* < -100 nT).

2. Methodology

The hourly averaged *Dst* data used in this study were acquired from the World Data Center for Geomagnetism, WDC-Kyoto. The hourly average solar wind parameters were acquired from the OMNI database for all except three extreme storms, where Advanced Composition Explorer (ACE) satellite data is substituted (shifted to the bow shock nose, according to the measured solar wind speed).

The primary period of interest for our analysis is from January 1967–August 2018, when solar wind data are available. We designated major storms as minimum -250 nT $< Dst < -100$ nT and extreme storms as minimum *Dst* < -250 nT, and selected 130 storms that fit into either of the two categories. An additional 40 geomagnetic storms during January 1957–May 1992 were used only for *Dst*-related calculations to further improve the statistical significance for extreme storms. In some events, *Dst* was found to exhibit two minima before returning to a quiet level. If there was marked separation and recovery between the relative minima, they were considered to be two storms. If the two *Dst* minima do not have a clear separation or recovery period, the storm is treated as a single event, which is classified as a Type 2 storm in Kamide et al., (1998).

All geomagnetic storm events were analyzed during their main phases, from the maximum *Dst* value before a significant decline to the absolute minimum of their *Dst* profiles. Storms that were separated into two events essentially were considered as two separate main phases. The interplanetary factors were analyzed during this same main-phase time frame, designated by using the *Dst* profiles.

3. Results

We first examine how the average rate of *Dst* change during the main phase ($\Delta Dst/\Delta t$) varies as a function of storm strength (Figure 1a). The calculation of $\Delta Dst/\Delta t$ was performed by taking the difference of the minimum *Dst* and relative maximum at the start of the main phase and dividing it by the time difference between the two points. All 170 storms are included in the analysis. Overall, $\Delta Dst/\Delta t$ and the minimum *Dst* show a strong linear correlation, with a correlation coefficient of 0.66. The points with minimum *Dst* > -180 nT fall close to the linear trend line. However, as storms of greater strength are observed there are points deviating from the trend line with a stronger $\Delta Dst/\Delta t$. For example, the two events marked with red circles denote an extreme storm on 13 March, 2001 ($\Delta Dst/\Delta t = -82.6$ nT/h, minimum *Dst* = -387 nT) and a major storm on 15 May, 2005 ($\Delta Dst/\Delta t = -59.8$ nT/h, minimum *Dst* = -247 nT). The common features for the outliers in Figure 1 are the strong initial pulse of *Dst* during the storms' sudden commencement. With the initial positive *Dst* at the start of the main phase, the minimum *Dst* tends toward less negative values. We have confirmed this explanation by examining $\Delta Dst/\Delta t$ as a function of the difference between the initial and minimum *Dst*, which indeed has a stronger correlation without significant deviations (data not shown).

In order to qualitatively understand further differences between extreme and major storms, the time duration of the storm main

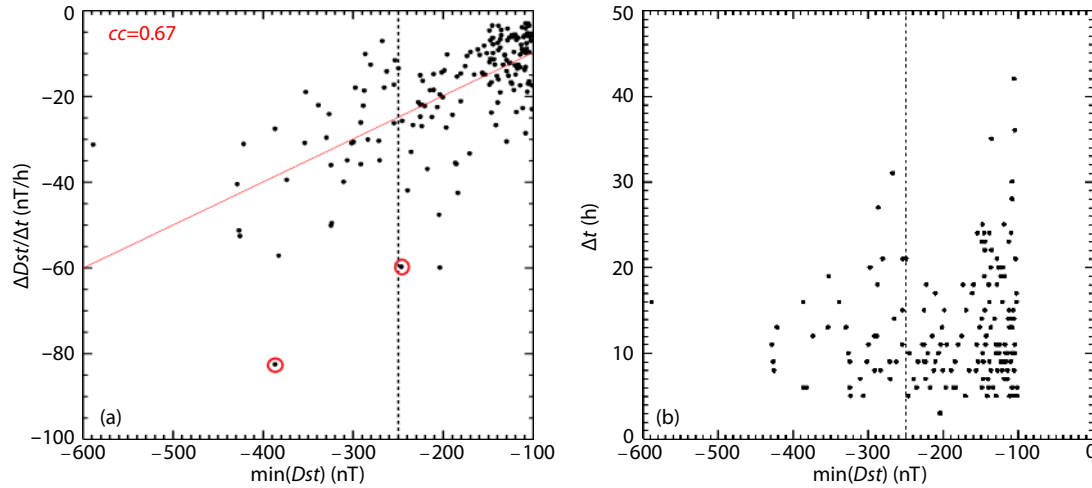


Figure 1. (a) Relationship between the average rate of Dst change during the main phase and minimum Dst. A linear fit is depicted with a correlation coefficient of $r = 0.67$. (b) Time duration of storm main phase as a function of minimum Dst.

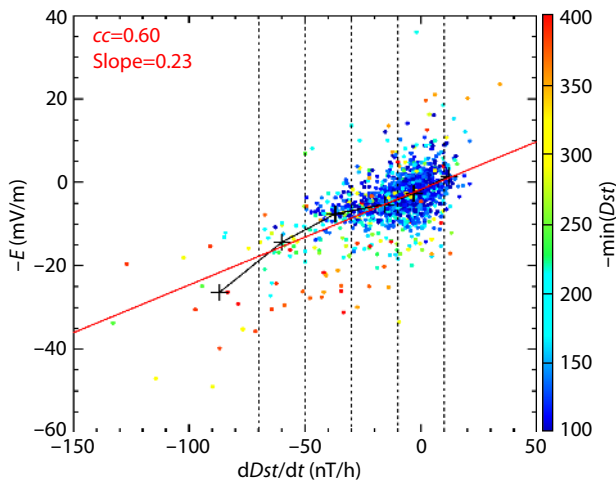


Figure 2. Solar wind electric field as a function of the rate of change of Dst during the main phase, using 1-hour resolution OMNI and ACE data. The coloring indicates the strength of the storm with blue being the weakest and red being the strongest. The black crosses represent the median value for each sub range, while the red line is the linear fit with a correlation coefficient of $r = 0.60$.

phase was compared with minimum Dst values. Notably, the time duration of storms is a critical factor in their impact on thermosphere heating and satellite drag (Oliveira et al., 2020). In Figure 1b, we provide the context needed to not only understand potential differences between extreme and major storms on thermosphere heating and satellite drag, but also elucidates the broader implications of Figure 1a. Despite the variation in the main phase duration for weak storms, overall the duration is around 10 hours. The uniformity of the main phase duration is the underlying reason for the correlation between $\Delta Dst/\Delta t$ and minimum Dst.

Next, we investigate the relationship between $dDst/dt$ and solar wind conditions. In Figure 2, we show the scatter plot for $dDst/dt$ and the solar wind electric field, where the hourly $dDst/dt(t=t_0) = (Dst(t_0+\Delta t) - Dst(t_0-\Delta t)) / (2\Delta t)$, and Δt is 1 hour. The analysis includes 124 events since 1967 with available solar wind paramet-

ers, primarily from the OMNI database except for three cases, in which we used ACE. The trend indicated by this figure points to higher amplitude E field as the amplitude of $dDst/dt$ increases. It also indicates a threshold for nonlinear behavior for higher E field values: the more extreme storms in red are skewed towards the lower half of the graph in a manner that departs from the linear trend. Data are divided into six subgroups according to $dDst/dt$. The edges of each bin are marked by dashed vertical lines, and the black crosses indicate the medians for each bin. At the black cross shown in the bottom left of Figure 2, there is a marked deviation that again supports the presence of some bias among the more extreme storms.

The existing studies about Dst have suggested that the solar wind dynamic pressure (P) and the ring current decay have effects on $dDst/dt$ (e.g., O'Brien and McPherron, 2000; Wang CB et al., 2003), as shown in Equation (1). In order to account for these effects, we follow the model by Wang CB et al., (2003):

$$Dst^* = Dst - 7.26\sqrt{P} + 11 \text{ nT}, \quad (2)$$

here, P is the solar wind dynamic pressure in nanopascals (nPa).

$$Q = -4.4(E - 0.49)(P/P_0)^\gamma \text{ for } E > 0.49 \text{ mV/m and} \\ Q = 0 \text{ for } E < 0.49 \text{ mV/m}, \quad (3)$$

in Equation (3), E represents the y-component of the solar wind electric field, with $P_0 = 3.0$ nPa and $\gamma = 0.2$. The characteristic time scale for the ring current decay is as follows:

$$\tau = 8.70e^{(6.6/(6.04+P))}, \quad B_z \geq 0, \quad (4)$$

$$\tau = 2.40e^{(9.74/(4.69+E))}, \quad B_z < 0, \quad (5)$$

Figure 3 helps illustrate a new correlation between the left and right-hand sides of Equation (1). The skewedness is less evident than that in Figure 2, illustrated by the proximity of the last two median values for left-most subranges to the linear trend line. It is still apparent that the black line representing the median values bends towards the lower extreme values. This in turn suggests that the pressure and decay terms remove some, but not all, of the bias towards more negative $Q - Dst^*/\tau$ values within this data-

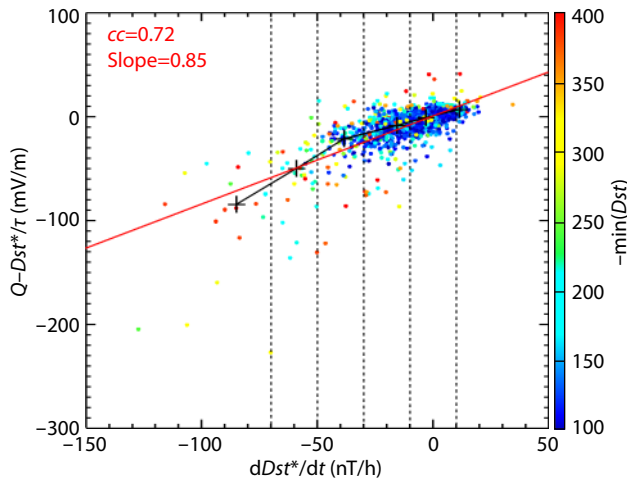


Figure 3. Relationship of Q (E with effects of pressure and decay rate term accounted) vs. rate of pressure-corrected Dst change during the main phase, with pressure accounted for. The blue to red coloring is again indicative of storm strength from weakest to strongest. The linear fit correlation coefficient is 0.72.

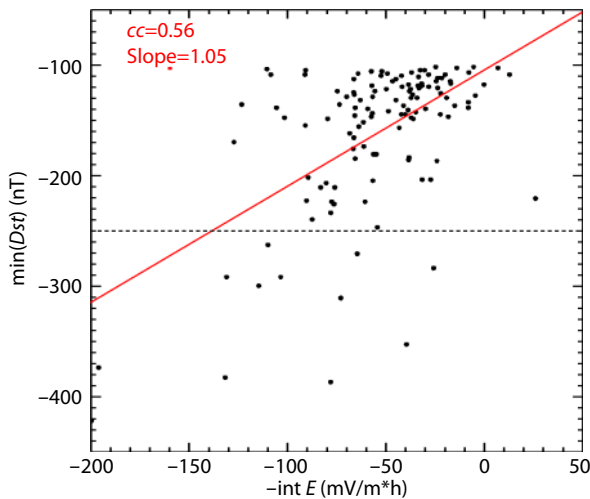


Figure 4. Minimum Dst versus the negative integral of the E -field component during the main phase. This figure includes 124 storms and the linear correlation coefficient is 0.56.

set. Still, across both figures, the driving E components are much stronger for extreme storms, departing from the linear trend line.

Due to the solar wind E -field's role as a main driver of $dDst/dt$, we further examine the relationship between the integral of E (int E) during the storm main phase and the minimum Dst . In Figure 4, we illustrate a moderate correlation between the two parameters, though many of the extreme storms depart from the trend line's predicted values.

The interplanetary magnetic field B_z component is a major parameter of interest for storms and has long been associated with the initiation of the storm main phase (Kokubun, 1972; Gonzalez and Tsurutani, 1987). In Figure 5, we present a correlative picture of minimum B_z vs. minimum Dst , including six additional geomagnetic storms with accessible B_z data to form a dataset of 130 storms. In the weaker range of storms ($> -250 Dst$) within Figure 5,

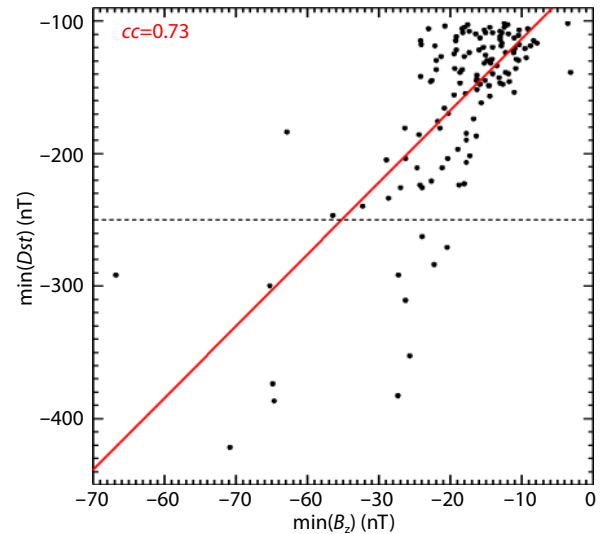


Figure 5. The relationship of the minimum z -component of the interplanetary magnetic field and the minimum value of Dst , for 130 storms (linear coefficient of $r = 0.73$).

the majority of data points are closely surrounding the linear trend line, however the extreme storms fall further from the trend line. Since the linear coefficient is fairly high, it is evident that there is a trend towards lower minimum B_z components as geomagnetic storms increase in strength. The results in Figures 4 and 5 are consistent with those presented in Gonzalez and Echer (2005). We include such analyses to emphasize the importance of sustained large values of solar wind E_y and southward IMF B_z in producing strong storms, and contrast the differences between these interplanetary measures for extreme and major storms that fall outside the scope of Gonzalez and Echer (2005). Based on the aforementioned graphical results, it is clear that extreme events tend to have more nonlinear correlations, pushing towards far-reaching values.

4. Discussion and Conclusions

In this paper, we examined the statistical relationships between driving interplanetary factors and Dst variations to differentiate the characteristics of extreme and major geomagnetic storms during the main phase. While strong correlations were observed in this study, extreme geomagnetic storms distinguish themselves in every factor of interest. In the case of $\Delta Dst/\Delta t$ in relation to minimum Dst , extreme storms tend to exhibit much higher rates during their main phase than their major storm counterparts. For the relation of solar wind E and $dDst/dt$, driving E is much stronger than the linearly predicted E for extreme storms even after adjusting for pressure and decay rates, indicating that the solar wind electric field is less efficient in driving $dDst/dt$ for extreme storms. The minimum Dst is correlated with the integral of E and the minimum B_z ; however, the extreme storms tend to have more negative Dst than the trend for major storms.

Our results indicate that during storms with major to extreme strengths, the magnetosphere response as an integrated system must be better understood to obtain more accurate storm predictions. In previous studies such as Wang CB et al., (2003), a uniform relationship between $dDst/dt$ and solar wind conditions was obtained for all storms, whereas our study points out the necessity

to consider qualitative differences between major and extreme storms. For example, our finding that the solar wind electric field is less efficient in driving $dDst/dt$ for extreme storms can have important bearing on how the magnetosphere handles the increased energy input during extreme storms. The solar wind energy input to the magnetosphere is mainly through dayside reconnection, while the polar cap potential associated with the dayside reconnection rate tends to exhibit saturations at large values of the solar wind electric field, possibly related to the effects of ionosphere outflow (e.g., Borovsky and Birn, 2014; Dorelli, 2019). In other words, the increasing rate of energy input through dayside reconnection could be regulated in part by the ionosphere and consequently affect ring current variations. One of the key implications is that the extreme-storm impact on the polar ionosphere is immediate and should be better quantified as part of the magnetosphere's response to extreme solar driving, in addition to *Dst*.

Supplementary Materials

Table S1. List of extreme and major storms analyzed in the paper.

Date of Storm	Minimum <i>DST</i>	Classification	MP Start Time	MP End Time
1957-03-02	-255	Extreme	1957-03-02/00:00:00	1957-03-02/08:00:00
1957-09-05	-324	Extreme	1957-09-04/14:00:00	1957-09-05/04:00:00
1957-09-13	-427	Extreme	1957-09-13/02:00:00	1957-09-13/11:00:00
1958-02-11	-426	Extreme	1958-02-11/04:00:00	1958-02-11/12:00:00
1958-07-08	-330	Extreme	1958-07-08/10:00:00	1958-07-08/23:00:00
1958-09-04	-302	Extreme	1958-09-04/14:00:00	1958-09-04/23:00:00
1959-07-15	-429	Extreme	1959-07-15/09:00:00	1959-07-15/20:00:00
1960-04-01	-327	Extreme	1960-04-01/09:00:00	1960-04-01/19:00:00
1960-04-30	-325	Extreme	1960-04-30/13:00:00	1960-04-30/19:00:00
1960-10-07	-287	Extreme	1960-10-06/10:00:00	1960-10-07/01:00:00
1960-11-13	-339	Extreme	1960-11-12/22:00:00	1960-11-13/10:00:00
1961-10-28	-272	Extreme	1961-10-28/10:00:00	1961-10-28/19:00:00
1967-05-26	-383	Extreme	1967-05-25/11:00:00	1967-05-26/05:00:00
1970-03-09	-284	Extreme	1970-03-08/14:00:00	1970-03-08/22:00:00
1981-04-13	-311	Extreme	1981-04-12/22:00:00	1981-04-13/07:00:00
1982-07-14	-325	Extreme	1982-07-13/15:00:00	1982-07-14/01:00:00
1982-09-06	-289	Extreme	1982-09-05/22:00:00	1982-09-06/11:00:00
1986-02-08	-307	Extreme	1986-02-08/18:00:00	1986-02-09/01:00:00
1989-03-14	-589	Extreme	1989-03-13/09:00:00	1989-03-14/01:00:00
1989-09-19	-255	Extreme	1989-09-18/17:00:00	1989-09-19/04:00:00
1989-10-21	-267	Extreme	1989-10-20/09:00:00	1989-10-21/16:00:00
1989-11-17	-266	Extreme	1989-11-17/08:00:00	1989-11-17/22:00:00
1990-04-10	-281	Extreme	1990-04-09/21:00:00	1990-04-10/18:00:00
1991-03-25	-298	Extreme	1991-03-24/03:00:00	1991-03-25/00:00:00
1991-10-29	-254	Extreme	1991-10-28/10:00:00	1991-10-29/07:00:00
1991-11-09	-354	Extreme	1991-11-08/12:00:00	1991-11-09/02:00:00
1992-05-10	-288	Extreme	1992-05-09/19:00:00	1992-05-10/14:00:00
2000-04-07	-296	Extreme	2000-04-06/15:00:00	2000-04-07/00:00:00
2000-07-15	-301	Extreme	2000-07-15/14:00:00	2000-07-16/01:00:00
2001-03-31	-387	Extreme	2001-03-31/02:00:00	2001-03-31/09:00:00
2001-04-11	-271	Extreme	2001-04-11/15:00:00	2001-04-11/23:00:00
2001-11-06	-292	Extreme	2001-11-05/18:00:00	2001-11-06/07:00:00
2003-10-29	-353	Extreme	2003-10-29/05:00:00	2003-10-30/00:00:00
2003-10-30	-383	Extreme	2003-10-30/16:00:00	2003-10-30/22:00:00
2003-11-20	-422	Extreme	2003-11-20/08:00:00	2003-11-20/21:00:00
2004-11-07	-374	Extreme	2004-11-07/18:00:00	2004-11-08/06:00:00
2004-11-10	-263	Extreme	2004-11-10/00:00:00	2004-11-10/10:00:00
1957-01-21	-250	Major	1957-01-21/14:00:00	1957-01-21/23:00:00
1957-09-29	-246	Major	1957-09-29/12:00:00	1957-09-29/17:00:00
1963-09-23	-236	Major	1963-09-22/18:00:00	1963-09-23/01:00:00
1967-01-14	-160	Major	1967-01-13/12:00:00	1967-01-14/06:00:00
1967-02-07	-120	Major	1967-02-07/14:00:00	1967-02-07/23:00:00

Continued

Date of Storm	Minimum <i>DST</i>	Classification	MP Start Time	MP End Time
1967-02-16	-130	Major	1967-02-16/08:00:00	1967-02-16/13:00:00
1967-12-31	-109	Major	1967-12-30/15:00:00	1967-12-31/21:00:00
1968-02-11	-124	Major	1968-02-10/16:00:00	1968-02-11/11:00:00
1968-04-05	-112	Major	1968-04-05/16:00:00	1968-04-05/21:00:00
1968-10-31	-224	Major	1968-10-31/09:00:00	1968-10-31/18:00:00
1969-02-02	-186	Major	1969-02-02/15:00:00	1969-02-02/22:00:00
1969-02-11	-136	Major	1969-02-10/21:00:00	1969-02-11/18:00:00
1969-03-24	-228	Major	1969-03-23/13:00:00	1969-03-24/01:00:00
1970-08-17	-181	Major	1970-08-16/21:00:00	1970-08-17/08:00:00
1971-04-15	-143	Major	1971-04-14/13:00:00	1971-04-15/01:00:00
1971-12-17	-171	Major	1971-12-17/15:00:00	1971-12-17/20:00:00
1972-06-18	-190	Major	1972-06-17/19:00:00	1972-06-18/03:00:00
1972-08-09	-154	Major	1972-08-09/02:00:00	1972-08-09/11:00:00
1972-09-14	-146	Major	1972-09-13/11:00:00	1972-09-14/06:00:00
1972-11-01	-199	Major	1972-10-31/17:00:00	1972-11-01/08:00:00
1973-02-21	-121	Major	1973-02-21/13:00:00	1973-02-21/22:00:00
1973-04-01	-211	Major	1973-04-01/12:00:00	1973-04-01/22:00:00
1973-04-14	-134	Major	1973-04-14/05:00:00	1973-04-14/11:00:00
1974-07-06	-204	Major	1974-07-06/03:00:00	1974-07-06/06:00:00
1976-01-10	-156	Major	1976-01-10/12:00:00	1976-01-10/23:00:00
1976-03-26	-226	Major	1976-03-25/21:00:00	1976-03-26/08:00:00
1976-04-01	-218	Major	1976-04-01/02:00:00	1976-04-01/08:00:00
1977-12-11	-112	Major	1977-12-10/22:00:00	1977-12-11/11:00:00
1978-08-28	-226	Major	1978-08-27/17:00:00	1978-08-28/10:00:00
1978-09-29	-210	Major	1978-09-29/02:00:00	1978-09-29/09:00:00
1978-11-25	-149	Major	1978-11-25/12:00:00	1978-11-25/18:00:00
1979-02-22	-107	Major	1979-02-21/16:00:00	1979-02-21/21:00:00
1979-03-10	-140	Major	1979-03-10/17:00:00	1979-03-10/23:00:00
1979-03-29	-122	Major	1979-03-29/03:00:00	1979-03-29/21:00:00
1979-04-04	-202	Major	1979-04-03/14:00:00	1979-04-04/04:00:00
1979-04-25	-149	Major	1979-04-25/00:00:00	1979-04-25/14:00:00
1979-08-29	-140	Major	1979-08-29/00:00:00	1979-08-29/18:00:00
1980-05-25	-126	Major	1980-05-25/03:00:00	1980-05-25/13:00:00
1980-12-19	-240	Major	1980-12-19/11:00:00	1980-12-19/18:00:00
1981-03-05	-215	Major	1981-03-05/05:00:00	1981-03-05/17:00:00
1981-05-09	-119	Major	1981-05-09/00:00:00	1981-05-09/07:00:00
1981-05-11	-137	Major	1981-05-10/15:00:00	1981-05-11/04:00:00
1981-05-16	-119	Major	1981-05-16/05:00:00	1981-05-16/14:00:00
1981-05-18	-118	Major	1981-05-17/23:00:00	1981-05-18/06:00:00
1981-07-25	-226	Major	1981-07-25/10:00:00	1981-07-25/20:00:00
1981-10-11	-113	Major	1981-10-10/16:00:00	1981-10-11/15:00:00
1981-10-22	-177	Major	1981-10-22/08:00:00	1981-10-22/17:00:00
1982-02-02	-112	Major	1982-02-02/03:00:00	1982-02-02/12:00:00
1982-02-05	-111	Major	1982-02-04/18:00:00	1982-02-05/03:00:00
1982-02-10	-105	Major	1982-02-10/09:00:00	1982-02-10/20:00:00
1982-03-02	-211	Major	1982-03-01/11:00:00	1982-03-02/05:00:00
1982-04-10	-137	Major	1982-04-10/00:00:00	1982-04-10/20:00:00
1982-11-22	-112	Major	1982-11-21/15:00:00	1982-11-22/05:00:00
1982-11-24	-197	Major	1982-11-24/11:00:00	1982-11-24/17:00:00
1982-12-17	-106	Major	1982-12-15/19:00:00	1982-12-17/13:00:00
1983-01-10	-213	Major	1983-01-09/23:00:00	1983-01-10/07:22:00
1988-01-14	-147	Major	1988-01-14/14:00:00	1988-01-14/23:00:00
1988-04-22	-109	Major	1988-04-21/21:00:00	1988-04-22/10:00:00
1989-04-26	-127	Major	1989-04-25/16:00:00	1989-04-26/06:00:00
1989-08-15	-147	Major	1989-08-14/06:00:00	1989-08-15/05:00:00
1989-08-28	-152	Major	1989-08-28/16:00:00	1989-08-29/05:00:00
1989-11-13	-131	Major	1989-11-12/22:00:00	1989-11-13/18:00:00
1989-12-30	-103	Major	1989-12-29/08:00:00	1989-12-30/00:00:00
1991-08-30	-107	Major	1991-08-30/06:00:00	1991-08-30/21:00:00
1991-11-01	-196	Major	1991-11-01/11:00:00	1991-11-01/23:00:00
1991-11-21	-139	Major	1991-11-21/01:00:00	1991-11-22/01:00:00
1993-03-09	-137	Major	1993-03-08/22:00:00	1993-03-09/06:00:00

Continued

Date of Storm	Minimum <i>DST</i>	Classification	MP Start Time	MP End Time
1994-04-17	-201	Major	1994-04-16/23:00:00	1994-04-17/08:00:00
1995-04-07	-149	Major	1995-04-07/01:00:00	1995-04-07/16:00:00
1995-10-18	-127	Major	1995-10-18/12:00:00	1995-10-18/23:00:00
1997-05-15	-115	Major	1997-05-15/02:00:00	1997-05-15/12:00:00
1997-10-11	-130	Major	1997-10-10/17:00:00	1997-10-11/03:00:00
1997-11-23	-108	Major	1997-11-22/20:00:00	1997-11-23/06:00:00
1998-05-04	-205	Major	1998-05-04/02:00:00	1998-05-04/05:00:00
1998-09-25	-207	Major	1998-09-24/23:00:00	1998-09-25/09:00:00
2000-08-12	-235	Major	2000-08-12/00:00:00	2000-08-12/09:00:00
2001-08-17	-105	Major	2001-08-17/11:00:00	2001-08-17/21:00:00
2001-09-26	-102	Major	2001-09-25/19:00:00	2001-09-26/01:00:00
2001-10-01	-148	Major	2001-09-30/21:00:00	2001-10-01/08:00:00
2001-10-03	-166	Major	2001-10-03/05:00:00	2001-10-03/14:00:00
2001-10-21	-187	Major	2001-10-21/15:00:00	2001-10-21/21:00:00
2001-10-28	-157	Major	2001-10-28/03:00:00	2001-10-28/11:00:00
2001-11-24	-221	Major	2001-11-24/05:00:00	2001-11-24/17:00:00
2002-04-18	-127	Major	2002-04-17/10:00:00	2002-04-18/08:00:00
2002-04-20	-149	Major	2002-04-19/08:00:00	2002-04-20/08:00:00
2002-05-11	-110	Major	2002-05-11/09:00:00	2002-05-11/19:00:00
2002-05-23	-109	Major	2002-05-23/10:00:00	2002-05-23/17:00:00
2002-08-02	-102	Major	2002-08-01/22:00:00	2002-08-02/05:00:00
2002-08-21	-106	Major	2002-08-20/16:00:00	2002-08-21/06:00:00
2002-09-03	-109	Major	2002-09-03/18:00:00	2002-09-04/05:00:00
2002-09-08	-181	Major	2002-09-07/13:00:00	2002-09-08/00:00:00
2002-10-01	-162	Major	2002-10-01/04:00:00	2002-10-01/16:00:00
2002-10-04	-146	Major	2002-10-03/08:00:00	2002-10-04/08:00:00
2002-10-07	-115	Major	2002-10-07/00:00:00	2002-10-07/07:00:00
2002-11-21	-128	Major	2002-11-21/01:00:00	2002-11-21/10:00:00
2003-05-30	-144	Major	2003-05-29/12:00:00	2003-05-29/23:00:00
2003-06-18	-141	Major	2003-06-18/01:00:00	2003-06-18/09:00:00
2003-07-12	-105	Major	2003-07-10/17:00:00	2003-07-12/05:00:00
2003-08-18	-148	Major	2003-08-17/13:00:00	2003-08-18/15:00:00
2004-01-22	-130	Major	2004-01-22/01:00:00	2004-01-22/13:00:00
2004-04-03	-117	Major	2004-04-03/13:00:00	2004-04-04/00:00:00
2004-07-25	-136	Major	2004-07-24/05:00:00	2004-07-25/16:00:00
2004-07-27	-150	Major	2004-07-26/21:00:00	2004-07-27/13:00:00
2004-08-30	-129	Major	2004-08-30/00:00:00	2004-08-30/22:00:00
2005-01-18	-103	Major	2005-01-17/14:00:00	2005-01-18/08:00:00
2005-05-08	-106	Major	2005-05-07/18:00:00	2005-05-08/18:00:00
2005-05-15	-247	Major	2005-05-15/02:00:00	2005-05-15/08:00:00
2005-05-30	-113	Major	2005-05-29/21:00:00	2005-05-30/13:00:00
2005-06-12	-106	Major	2005-06-12/16:00:00	2005-06-13/00:00:00
2005-08-24	-184	Major	2005-08-24/05:00:00	2005-08-24/11:00:00
2005-08-31	-122	Major	2005-08-31/11:00:00	2005-08-31/19:00:00
2005-09-11	-139	Major	2005-09-11/01:00:00	2005-09-11/10:00:00
2006-12-15	-162	Major	2006-12-14/13:00:00	2006-12-15/07:00:00
2011-08-05	-115	Major	2011-08-05/18:00:00	2011-08-06/03:00:00
2011-09-26	-118	Major	2011-09-26/12:00:00	2011-09-26/23:00:00
2011-10-24	-147	Major	2011-10-24/18:00:00	2011-10-25/02:00:00
2012-03-09	-145	Major	2012-03-08/10:00:00	2012-03-09/08:00:00
2012-04-24	-120	Major	2012-04-23/03:00:00	2012-04-24/04:00:00
2012-07-15	-139	Major	2012-07-14/23:00:00	2012-07-15/16:00:00
2012-10-01	-122	Major	2012-09-30/12:00:00	2012-10-01/04:00:00
2012-10-09	-109	Major	2012-10-08/04:00:00	2012-10-09/08:00:00
2012-11-14	-108	Major	2012-11-13/17:00:00	2012-11-14/07:00:00
2013-03-17	-132	Major	2013-03-17/05:00:00	2013-03-17/20:00:00
2013-06-01	-124	Major	2013-05-31/23:00:00	2013-06-01/08:00:00
2014-02-19	-119	Major	2014-02-18/13:00:00	2014-02-19/08:00:00
2015-03-17	-222	Major	2015-03-17/04:00:00	2015-03-17/22:00:00
2015-06-23	-204	Major	2015-06-22/17:00:00	2015-06-23/04:00:00
2015-10-07	-124	Major	2015-10-07/01:00:00	2015-10-07/22:00:00
2015-12-21	-155	Major	2015-12-19/22:00:00	2015-12-20/22:00:00
2016-10-13	-103	Major	2016-10-13/02:00:00	2016-10-13/23:00:00
2017-05-28	-125	Major	2017-05-27/20:00:00	2017-05-28/07:00:00
2017-09-08	-124	Major	2017-09-07/20:00:00	2017-09-08/01:00:00
2018-08-26	-174	Major	2018-08-25/12:00:00	2018-08-26/07:00:00

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