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Correlation between Solar Energetic Particle events and Earth's surface Temperature in North-East USA

G. Anagnostopoulos[1], S.A. Menesidou[1], V.G. Vassiliadis[2*] and A. Rigas[1]
[1]Department of Electrical and Computer Engineering,
Democritus University of Thrace,
[2]IBM Research Zurich

Abstract: The influence of space weather on the Earth's atmospheric weather and climate is an important scientific issue with great social interest. In this study we present, for the first time, statistical results during times of 28 strong ICMEs observed between 1997 - May, 2015, which confirm a strong correlation between the solar activity and the temperature T_M in east USA (Madison, Wisconsin). In particular we found that: (a) during a time period of 15 days (day=-7 to day=+7) centered at the day D_0 of ICMEs arrival at Earth, the temperature (T_M) in Madison shows maximum values around (+/- 1 day) or after the day D_0 in 89.2% of the cases examined, (b) the high (1880 - 4700 keV) energy solar proton (HESP) fluxes, show a much stronger correlation with T_M than the magnetospheric 68 - 115 keV ions and 38 - 53 keV electrons, before the ICME arrival, (c) the temperature increase reached on day D_0 is strongly ($r = 0.8, p < 0.001$) correlated with the time duration of the HESP events, (d) the temperature increase during the cases examined is very strongly and significantly correlated with the HESP flux increase, within $\sim$ 1 day ($r = 0.9, p < 0.001$) (e) warm air flows from the southward direction mediates the link between HESP fluxes and the temperature increase ΔT_M, and (f) the temperature increase ΔT_M during the HESP events shows an average rate of $\sim 2°C/day$ (28 events examined). We infer that the HESP events preceding the great ICMEs examined in this study strongly control the temperature T_M in east USA during the "winter" times, via a fast ($\sim$ 1 day) process due to northward air flows from the Gulf Stream.

1 Introduction

"A growing mass of evidence suggests that transient events on the Sun affect our weather and long-term variations of the Sun's energy output affect our climate. Solar terrestrial exploration can help establish the physical cause and effect relationships between solar stimuli and terrestrial responses. When these relationships are understood science will have an essential role for weather and climate prediction." This statement was a part of an early proposal of R.D. Chapman submitted to NASA [1]. Since those times, and in particular the two last decades, an amount of evidence has been gathered on links between Solar activity and variations in the Earth's ionosphere and atmosphere. Further advances in the prediction of Weather/Climate changes could help people's health and life, in particular during atmospheric extreme events, which have some dependence on space weather [2, 3].

There are many reports from the beginning of space era suggesting a correlation of solar flares with pressure gradients in atmosphere, within 2-3 days or less ($< 6h$) [4]. In the last two decades, great emphasis has been given in the solar cycle climate trends of cloudy, stratospheric changes, polar temperatures and winds, as well as the sea and surface temperature [4]. Most of these meteorological variations have been discussed in terms of solar irradiance as a stimuli, but recently energetic particle forcing driving dynamical changes in the atmosphere were suggested to be as intense as those arising from the solar irradiance variations [5]. In these studies, the solar particles were considered to affect the atmosphere via a slow process of catalytic ozone destruction. However, in a recent study for

[*]Work conducted while at Democritus University of Thrace

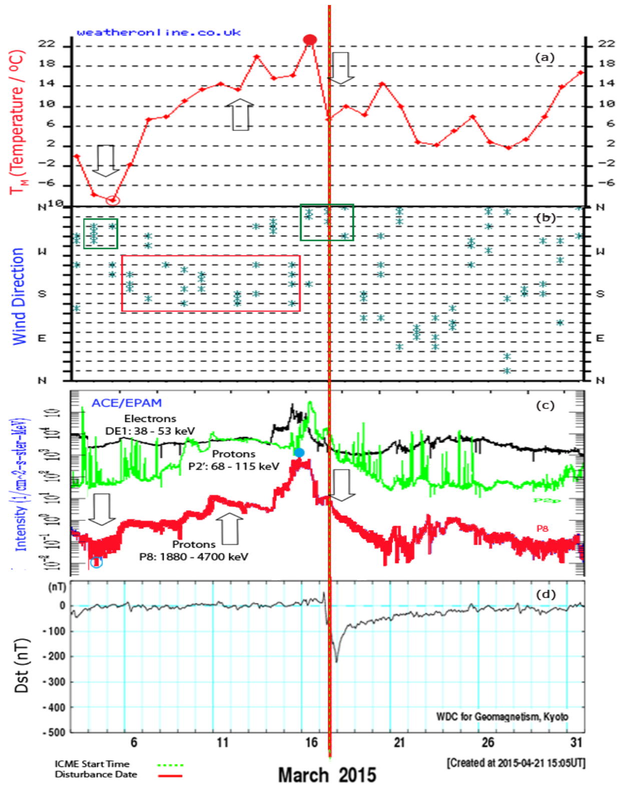

Figure 1: Time profiles of (a) temperature at Madison, Wisconsin (b) the direction of wind in the same town, (c) the fluxes of energetic proton and electrons observed by the ACE spacecraft and (d) the values of the geomagnetic index *Dst*, during March 3-31, 2015. It is evident that the temperature T_M profile (panel a) resembles that of the high energy solar proton flux *P8* (red curves).

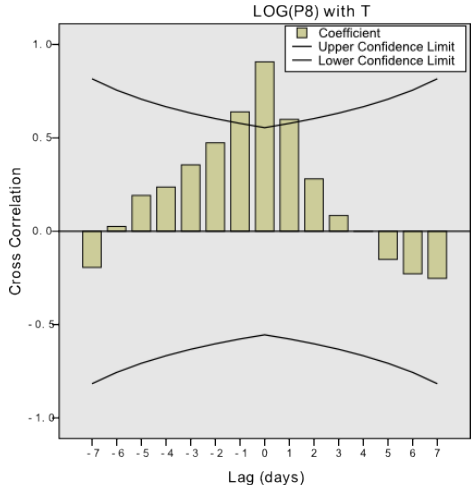

Figure 2: The estimates of the cross-correlation coefficients r for lags $k = 0, \pm1, \ldots, \pm7$, between the daily values of the logarithm of the *P8* proton flux values and the temperature T_M from day 6 until day 16, March 2015. The solid black lines present the asymptotic 95% confidence limits of the estimated coefficients. The very large r value at lag=0 confirms and explains the good resemblance of *P8* and T_M curves seen in Figure 1.

the March 2012 superstorm [2], the solar and magnetospheric particle events were found to control extreme weather events all over the globe, and in particular the historic March 2012 heat wave in East USA/Canada, via a fast (~ 1) day process [3]. During that Solar Energetic Particle (SEP) event solar protons of very high energy ($\gg 0.6$ GeV), were observed by PAMELA spacecraft, which seem to strongly influence the atmospheric conditions (Anagnostopoulos et al., 2015; paper to be published).

In this paper we present statistical results which strongly support the hypothesis that high energy (1880 - 4700 keV) solar protons arriving at Earth's environment during solar activity strongly affect the surface temperature in the north-east USA, via a fast processes, within ~ 1 day.

2 Data Analysis

In order to check the possible permanent link between the high solar activity and the temperature in north-east USA, we selected the ICME-related storms/superstorms with *Dst* index value as low as $Dst \leq -150nT$, from the beginning of ACE mission (1997) until May, 2015. By using a catalogue of ICMEs [http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm], we found 28 HESP events meeting the criteria of our study and we made full analysis for 26 events, due to data gap of 2 events. Then we compared the possible correlation of the HESP events observed by EPAM/ACE [http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_EPAM.html] before the arrival of the ICMEs with the temperature history at Madison, Wisconsin.

In Figure 1 we present a representative HESP event from the list of the 28 events examined. In

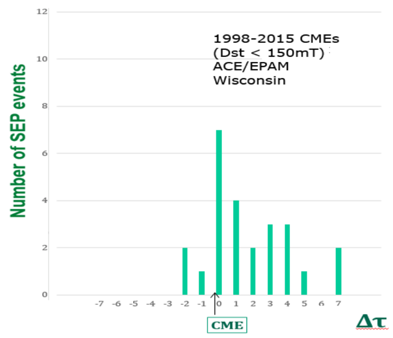

Figure 3: Distribution number of SEP events with time delay $\Delta\tau$ between the days of maximum temperatrue in Madison T_M and the maximum high energy solar proton flux *P8*, during a period of 15 days centered at the day of the ICME. The large number of non-negative values suggests that the maximum temperature T_M coincides with or follow the solar proton manixmum *P8*.

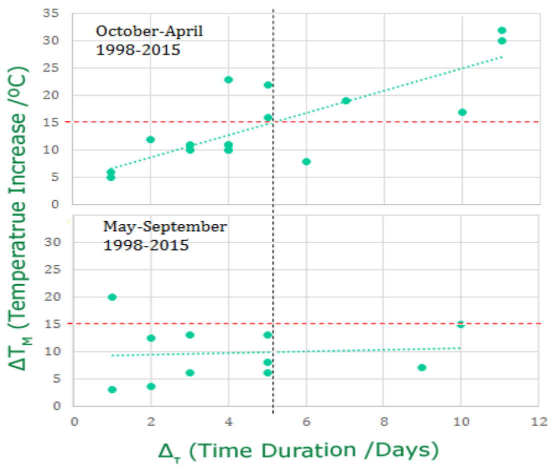

Figure 4: Surface temperature increase ΔT_M during SEP events as a function of their time duration $\Delta\tau$, during "winter" (a) and "summer" times (b). During "winter times", a strong and very significant ($r = 0.8, p < 0.001$) correlation was estimated.

particular, Figure 1 shows time profiles of the daily maximum value of temperature T_M at Madison (panel a), the direction of wind in the same town (panel b), the fluxes of energetic (38-53 keV; DE1 channel) electrons, and of both low (68-115 keV; P1 channel) and high (1880-4700 keV; *P8* channel) energy protons arrived from the sunward direction observed by the spacecraft ACE outside the Earth's magnetosphere (panel c) and the geomagnetic index *Dst* (panel a), for the time period March 3-31, 2015; the time series of Figure 1 have been centered around the time of the severe (G4) storm of March 17 which was triggered by the most intense CME of the solar cycle 24 (notice that the *Dst* index reached values on day 17, as low as -223nT).

By comparing the profiles of the ACE energetic particle flux profiles with the profile of temperature T_M, we see: (a) a good similarity, in particular, between $P8_M$ and T profiles and (b) a gradual increase of both *P8* flux and T_M values from day 6 until day 16 (the day before the ICME arrival). Further comparison between panels a-c and b demonstrates that during the time of the gradual increase of energetic protons at ACE and the temperature at Madison, the wind shows a flow from the southward direction (days 6-16; red great rectangular in panel b). On the contrary, we see that before day 6 (days 4-5) and after day 16 (days 17-19), both the *P8* proton flux and the temperature T_M at Madison show low values, which were accompanied by air flows from northern directions (green rectangulars). The above data suggests a good correlation between the flux of HESP and the temperature at Madison before the ICME of March 17, 2015, which was observed during a warm air transfer from the Gulf Stream.

In Figure 2 we present the estimates of the cross-correlation coefficients between the logarithm of the *P8* proton flux values and the temperature T_M from day 6 until 16 (Fig. 1) and for lags $0, \pm1, \ldots, \pm7$. The upper and lower confidence limits are denoted with solid black lines. We found a very significant positive correlation at lags -1, 0 and 1. Especially at lag = 0 the cross-correlation coefficient takes its maximum value r = 0.907 with $s.e. = 0.277 (p < 0.001)$. This indicates that one should notice an increase of the temperature T_M from the previous day till one day after of an analogous increase of the proton flux. The very large r value at lag = 0, confirms and explains the day to day simultaneous resemblance of the line plots of the temperature T_M and the *P8* proton flux at Figure 1 (a, c).

Figure 3 shows the distribution number of the 28 SEP events with a time delay $\Delta\tau$ between the day of the maximum temperature T_M at Madison and the day of the maximum solar proton flux *P8*, within a time interval of 15 days centered on the day of the ICME arrival. Positive (negative) values of delay time $\Delta\tau$ means later (earlier) recorder of maximum temperature T_M than that of the maximum solar flux *P8*. From Figure 3 we see that the majority of events show non negative values, which suggest that maximum surface temperature coincides ($\Delta\tau = 0$) with or follow ($\Delta\tau > 0$) the solar proton flux maximum *P8*.

In Figure 4 we present scatter plots of the total temperatures increase ΔT_M versus the time duration of the *P8* proton flux increases before the ICME arrivals, for winter times (October to April; panel a) and in summer times (May - September; panel b), respectively. Panel a shows a very strong correlation ($r \simeq 0.8$), between ΔT_M and $\Delta\tau$, which is very significant ($p < 0.001$). A linear interpolation shows a trend $b \simeq 2$, which suggests an average daily temperature increase in Madison before great ICME-related storms during winter times $\Delta T_M/\Delta\tau \ = 2°C/day$. From panel b we infer the absence of any significant correlation between $\Delta T_M - \Delta\tau$ during the "summer times"; furthermore, we see that lower temperature increases ΔT_M were in general recorded during the "summer" times (panel b) compared to the temperature variations during "winter" times.

3 Conclusions and Discussion

The main finding of this study is a strong and statistically significant correlation between the temperature increase ΔT_M at Madison/Wisconsin with the time duration of the HESP events before the arrival of ICMEs between 1998 - May 2015, during months October to April. A second result is that this correlation happens under atmospheric conditions of warm air flows from the southward direction, which are obviously related with the Gulf Stream.

Several physical mechanisms have been proposed in order to explain some links between high solar magnetosphereric activity and SEP event, with changes in atmospheric conditions. Such mechanisms include SEP relation with large stratospheric/tropospheric pressure gradient causing downward air flow, variation in the global electric circuits and stratospheric ozone-related chemical energy changes [1]. Since our results of the present study indicated a fast correlation (of the order of ~ 1 day; Figure 2), the catalytic ozone destruction, which is a slow process, should not be the major driver of the SEP related temperature variation in north-east USA (Wisconsin).

The results of the present statistical study suggest that the south air flow mediates the influence of SEP events with the surface temperature variations (increases in north-east USA). Here we note that during the last great ICME of March 2015, the temperature T_M increased from -9°C up to as high as 23°C (an increase of 32°C), within only 10 days (6-16 March, 2015) which suggests a very effective process in this case. The question tp be addressed is which is the physical link between the early SEP impact and the intensification of the warm Gulf stream. Although this question needs further examination, we note the following known physical phenomena: (1) a solar cycle periodicity of the Gulf Stream activity [6], (2) a correlation between SEP activity and the North Atlantic Oscillation (NAO), and (3) a correlation between NAO index and the sea surface temperature in the east USA [7]. These results may suggest a physical link between SEP flux increase / NAO index variation / Gulf stream intensification south warm air flows and temperature increases in east USA. Finally, we note the fast (within ~ 1 day) response of T_M to HESP variations, which rather suggests that a non-linear process controls the sequence of physical variations described above.

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