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Journal of Atmospheric and Solar-Terrestrial Physics 66 (2004) 1085 – 1091

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Mid-latitude ionospheric effects of a great geomagnetic storm

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Received 16 June 2003; received in revised form 11 November 2003; accepted 14 April 2004

Abstract

On March 13, 1989 magnetic storm effects on the mid- and low-latitude ionosphere were investigated. For this, peak electron density of F2-layer (NmF2) data from four chains of ionospheric stations located in the geographic longitude ranges 10°W–15°E, 55°E–85°E, 135°E–155°E and 200°E–255°E were used. Relative deviations of perturbed NmF2 from their respective quiet-time values were considered. Long-lasting negative storm effects were the dominant characteristic observed at middle latitudes, which occurred since the main phase of the storm. In general, the most significant negative disturbances were observed at middle-high latitudes. In the longitudinal sectors in which the storm started at day-time and pre-dusk hours, positive storm effects at middle and low latitudes were observed during the main phase. The role of some physical mechanisms to explain the ionospheric effects is also considered.

Keywords: Geomagnetic storm; Ionosphere; Positive and negative effects

1. Introduction

Perturbations of the ionosphere in association with geomagnetic storms have been an object of a close attention of the specialists on the ionosphere for several decades. However, many features of this phenomenon still are not clear due to many different processes interacting in the magnetosphere–ionosphere–thermosphere system. These studies are of great practical importance because severe storms may degrade radio communications, cause power blackouts, and affect satellite orbits.

Basically, the electron density can either increase or decrease during geomagnetic storms. These variations are denoted as positive or negative ionospheric storms, respectively. Electric fields, thermospheric meridional winds, a "composition bulge" and high latitude particle precipitation have been suggested as probable physical mechanisms to explain the ionospheric reaction to geomagnetic storms observed at different latitudes (see for example Fuller-Rowell et al., 1994; Prölss, 1995; Danilov, 2001, and references therein).

The most significant problems and recent advances in the study of the ionospheric storms have been reviewed by Bounsanto (1999).

The great geomagnetic storm that occurred on March 13, 1989 was large enough to produce numerous disturbances in Earth's magnetosphere and ionosphere.

The ionospheric response to this very strong geomagnetic storm has been studied in some confined sectors. Cander and Mihajlovic (1998), using data from the European ionospheric region, found long-lasting negative storm effects. Batista et al. (1991) observed large negative effects produced in the equatorial and low latitude ionosphere in the Brazilian longitude sector.

The objective of this study is to ascertain the features of the ionospheric effects produced in response to this geomagnetic storm at middle and middle-low latitudes in different longitudinal sectors. In addition, some possible physical mechanisms of the observed features are considered.

Ground-based hourly foF2 data (proportional to the square root of NmF2) provided by the Space Physics

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1364-6826/$ - see front matter
doi:10.1016/j.jastp.2004.04.003

Table 1
The station names and their locations

	Geographic latitude	Geographic longitude (E)	Geomagnetic latitude
Slough	51.5	359.4	54.2
Poitiers	46.6	0.3	49.4
Lisbonne	38.7	350.6	43.7
Gibilmanna	37.9	14.0	38.4
Ouagadougou	12.4	358.5	16.5
Novosibirsk	55.0	82.5	44.6
Karaganda	49.8	73.1	40.3
Tashkent	41.3	69.6	32.3
Ashkhabad	37.9	58.3	30.4
Canberra	−35.3	149.0	−43.9
Townsville	−19.3	146.7	−28.4
Vanimo	−2.7	141.3	−12.5
Boulder	40.0	254.7	48.9
Point Arguello	35.6	239.4	42.2
Maui	20.8	203.5	20.9
Tahiti	−17.7	210.7	−15.3

Interactive Data Resource (SPIDR) of the NGDC–NOAA have been collected. The station names and their locations are listed in Table 1.

Four longitudinal sectors have been considered: 10°W–15°E, 55°E–85°E, 135°E–155°E and 200°E–255°E. The idea of considering strongly different longitudinal intervals is to have stations for which the sudden commencement of the storm is produced on different moments of LT. A limited number of ionosonde data there were available due to the most of ionosonde records were strongly disturbed during the storm period.

Similar analysis of the variations of the foF2 critical frequency from ionospheric stations located on different meridians have been already done (e.g., Szuszczewicz et al., 1998; Blagoveshchensky et al., 2003). The contribution of this paper is to give a global description of the ionospheric effects observed during a major geomagnetic storm.

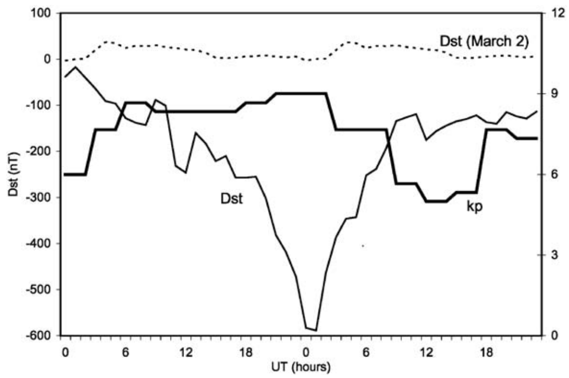

Fig. 1. Hourly Dst geomagnetic index and k_p index on March 13–14, 1989 (full line) and on a quiet geomagnetic day of the month of the storm, March 2 (dashed line).

2. Observations

The Dst geomagnetic index and the k_p index variations during March 13–14, 1989 are shown in Fig. 1. The geomagnetic storm started on March 13 ($\Sigma k_P = 60$; $A_P = 246$) with a sudden commencement (sc) at 0127 UT (Solar-Geophysical Data prompt reports, May 1989, 537, p. 136). An irregular main phase remained until about 01 UT on March 14 ($\Sigma k_P = 55^+$; $A_P = 158$) followed by a relatively rapid recovery. Dst values corresponding to a quiet geomagnetic day of the month of the storm, March 2 ($\Sigma k_P = 30$; $A_P = 25$) are also represented.

As a measure of the ionospheric disturbance the hourly relative deviation of NmF2 from their respective quiet geomagnetic day values at each station on the storm day and the following day was calculated. This deviation is given by

$$\text{DNmF2} = \{[\text{NmF2} - \text{NmF2}(q)]/\text{NmF2}(q)\} \times 100,$$

where NmF2 is the hourly perturbed peak electron density value of F2 layer (related with foF2 by the relation: $\text{NmF2} = 1.24 \times 10^{10}\ \text{foF2}^2\ (\text{m}^{-3})$, with foF2 in MHz) and NmF2(q) is the corresponding value of a quiet geomagnetic day (March 2).

Thus, positive and negative values of DNmF2 correspond to positive and negative ionospheric storms respectively.

Fig. 2 shows the temporal behaviour of DNmF2 on March 13–14, 1989 at ionospheric stations located between 10°W and 15°E geographic longitude. For this sector, the storm started after local midnight. Irregular long-lasting negative effects began at Slough, Poitiers and Lisbonne from around 02 UT on March 13 and from 05 UT at Gibilmanna (with

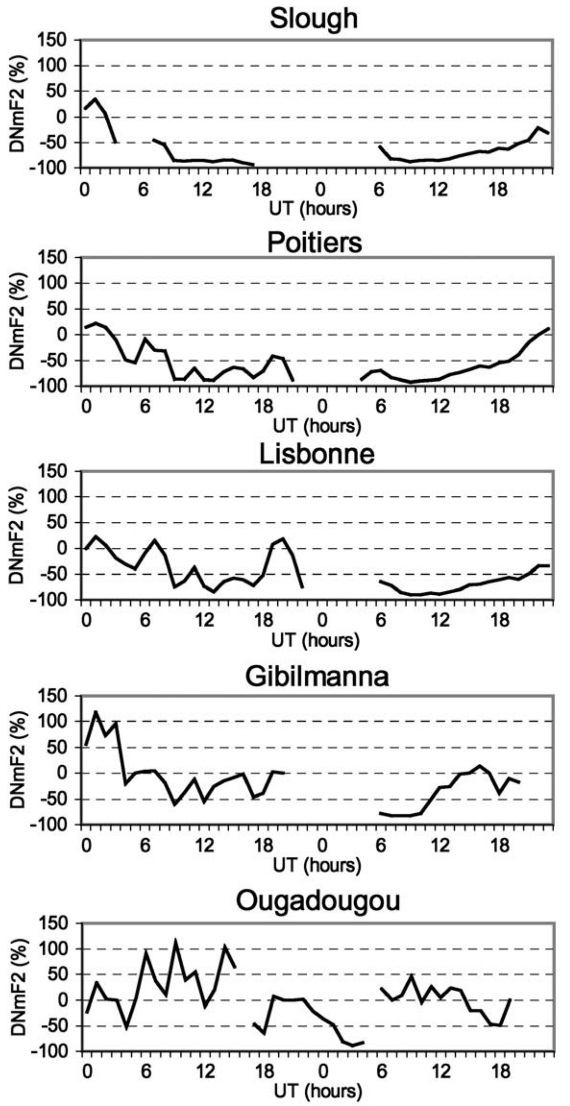

Fig. 2. Temporal behaviour of DNmF2 at ionospheric stations located in the 10°W–15°E longitudinal sector on March 13–14, 1989.

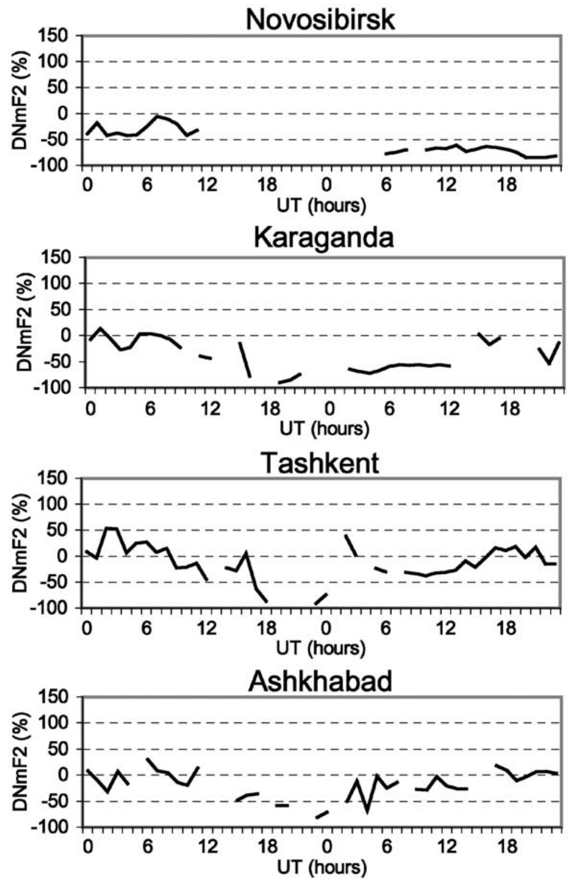

Fig. 3. The same as Fig. 2, but for 55°E–85°E longitudinal sector.

positive values prior to the sc). In general, the negative variations lasted more than 36 h at all these stations. The maximum depression, of about 90% at higher latitude stations, occurred since the development of the main phase of the storm. Similar disturbances were observed at other mid-high latitude stations not shown here. During the last stage of the recovery phase NmF2 trended to recover undisturbed values at Slough, Poitiers and Lisbonne (DNmF2 tending zero) while at Gibilmanna an oscillating behaviour was observed. At low latitudes (Ouadadougou), a fluctuating increase of ionization was observed during the first stage of the main phase of the storm. This positive storm effect remained until local afternoon on March 13 (14–16 UT), followed by a negative one in the local evening (0–6 UT on March 14) and by a subsequent smaller positive effect in the local day-time on March 14 during the recovery phase.

For the 55°E–85°E sector the storm began in pre-dawn hours. Fig. 3 shows DNmF2 variations in this longitudinal sector during the considered storm period. An irregular latitudinal behaviour in response to the sc was presented. Although there was data gap, it can be seen that long-lasting decreases of ionization at Novosibirsk and Karaganda arose at 08–10 UT on March 13 after local noon. The trend of available data suggests that these negative effects lasted throughout the storm period. Relative deviations of about 60–80% can be observed during the recovery phase. A short-duration positive storm effect was initially observed at Tashkent and at Ashkhabad no appreciable storm effect was observed. At these stations negative disturbances arose around 12 UT on March 13 in the afternoon hours, which lasted till later afternoon hours on March 14 when a slow and irregular recovery toward undisturbed values was observed.

Fig. 4 presents the DNmF2 variations in the 135°E–155°E longitude sector (Southern Hemisphere). For this

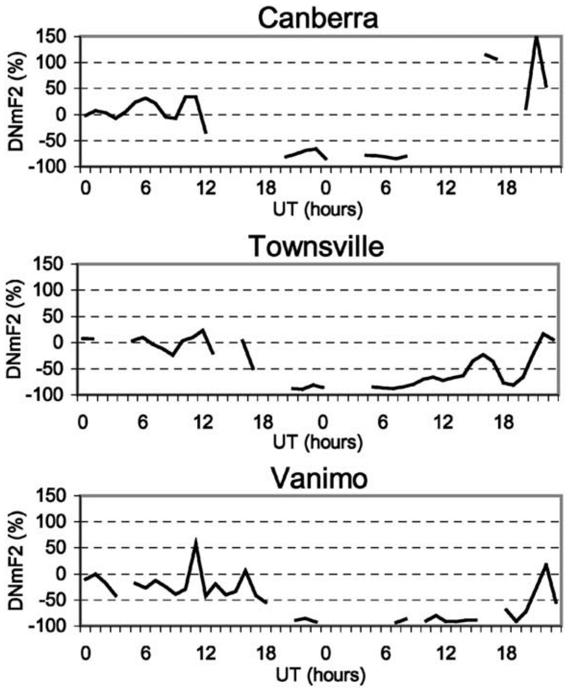

Fig. 4. The same as Fig. 2, but for 135°E–155°E longitudinal sector.

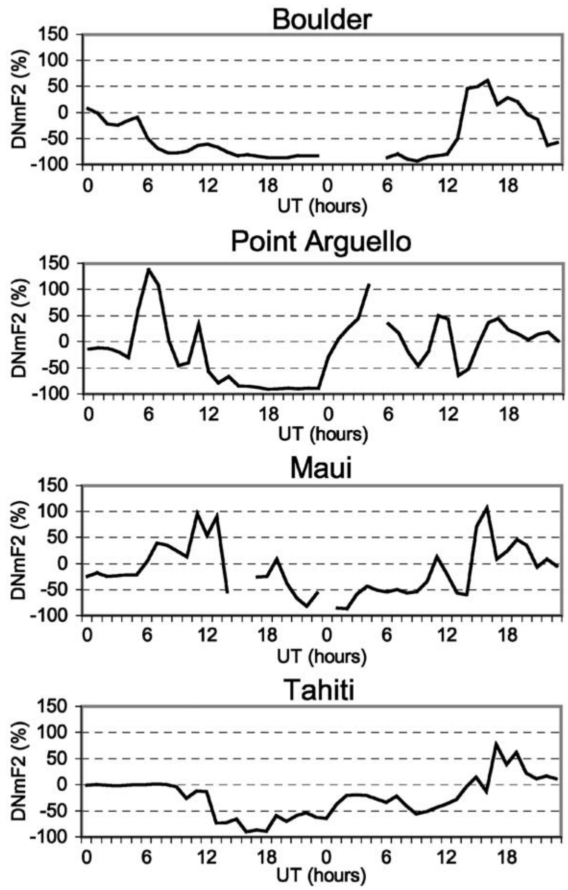

Fig. 5. The same as Fig. 2, but for 200°E–255°E longitudinal sector.

sector, the storm started during day-time. At Canberra, a short-duration positive effect was produced in response to the onset of the storm while at lower latitudes (Townsville and Vanimo) no significant disturbances were initially observed. Irregular negative storm effects began at all three stations at local midnight (11–12 UT on March 13) which lasted throughout the following day at Townsville and Vanimo. At Canberra, a strong delayed increase of ionization can be seen in the night-time hours on March 14 during the last stage of the recovery.

Fig. 5 shows the variations of DNmF2 at the longitudes 200°E–255°E. The sc occurred in the local afternoon in this longitude sector. At Boulder a long-lasting negative disturbance (about 36 h) arose in response to sc, which changed to positive around 14 UT on March 14 during the storm recovery phase, in the pre-dawn hours. At Point Arguello and Maui positive effects with amplitudes up to 100% or higher were initially observed from afternoon hours to past local midnight (about 04–12 UT on March 13), which were followed by negative effects. At Point Arguello the negative disturbance changed to an irregular positive disturbance around 02 UT on March 14; at Maui the negative effect lasted till 14 UT on March 14 when changed to a positive one during the recovery phase in the night-time hours. Solely the low latitude ionosonde at Tahiti had available data in the Southern Hemisphere in the longitude sector under consideration. No response to the storm occurred during the first stage of the main phase till around 09 UT when began an irregular negative effect of about 20–30 h and after that a positive disturbance.

3. Discussion

As indicated by collected data, the ionosphere showed a very complex behaviour during the March 13, 1989 geomagnetic storm. However, the common feature observed at mid-high geomagnetic latitudes in the longitudinal sectors 10°W–15°E, 55°E–85°E, 135°E–155°E and 200°E–255°E were strong long-lasting negative storm effects. The negative disturbance amplitude decreased with decreasing latitude. In this case study, the NmF2 decreases started during the main phase development. Moreover, initial short-time positive storm effects at middle-low latitudes in sectors in which sc began during day-time and more prolonged positive effects at lower latitudes in the longitudinal sector in which the storm onset occurred during night-time hours were also observed.

The typical qualitative pattern of ionospheric behaviour during moderate geomagnetic storms at mid-latitudes consists of a positive storm effect, followed by a negative effect during the main phase for storms started at night-time. A positive effect during the main phase of the storm may occur principally at low latitudes or winter mid-latitudes for storms with commencement in the day-time (e.g., Rishbeth, 1989). For the sectors in which the storm onset took place in the day-time hours the typical pattern of latitudinal distribution of F2-layer storm effects was observed at middle and middle-low latitudes stations during the main phase. At the middle latitude station Canberra there was a short-duration positive storm effect while at Point Arguello and Maui more important positive effects were observed, which corresponded to afternoon and night hours of the local time.

However, the ionosphere showed a variety of storm behaviours still in the same sector.

These results suggest that the ionospheric responses do not follow a determinate pattern during strong storms, that is, their features are not easily reproducible. This is because the eventually observed ionospheric behaviour depends on the interplay and balance of many processes at work in the magnetosphere–ionosphere–thermosphere system and this balance changes significantly for intense geomagnetic storms (Yeh et al., 1994).

With respect to negative storm effects it is widely believed that they are caused by a neutral composition disturbance zone generated during geomagnetic storms at auroral latitudes, which is then transported to lower latitudes by the disturbed thermospheric wind circulation produced by Joule heating and particle precipitation in the auroral region.

Since in a first approximation the peak electron density is directly proportional to the O/N_2 ratio, being N_2 the molecular nitrogen composition and O the atomic oxygen composition (Rishbeth and Barron, 1960) we can expect a decrease of NmF2 in regions where O/N_2 has decreased.

Thus, neutral composition changes alter the balance between electron production and loss rates resulting in NmF2 decreases (that is, negative storm effects).

Increases of the molecular nitrogen composition and decreases of the atomic oxygen composition determined from satellite measurements during geomagnetic disturbances correlated with negative ionospheric storm effects have been observed on numerous occasions (e.g., Prölss, 1980, 1987).

The long-lasting negative storm effects observed at mid-high latitudes can be explained in terms of these composition changes. The storm-induced circulation (bringing the heated gas with low O/N_2 ratio from the Joule heating zone equatorward) is so strong that even at day-time the background circulation (poleward) is not able to stop it. The heated gas stays at these latitudes even in the day-time maintaining the negative effect.

Unlike weak geomagnetic storms in the day-time the background circulation stops the storm-induced circulation and so lifts the F2 layer at heights where the recombination is slower producing positive effects.

Long-lasting negative storm effects seem to be the dominant feature during severe geomagnetic storms. Mikhailov and Foster (1997) and Mikkailov (2000) reported that peak electron density of F2 layer (composed primarily of O^+ ions) can fall below that of the F1 layer NmF1 (G-conditions). Their results showed that the observed “G-conditions” were due to large decreases in the O/N_2 ratio (consequence of O decreases and N_2 increases) below that the predicted by the MSIS-83 model and an increase of the O^+ loss rate.

A distinctive feature in the 10°W–15°E sector is the positive effect at Gibilmanna before the sc. Positive effects sometimes have been observed before the beginning of the magnetic disturbances. Some papers (Danilov and Belik, 1991, 1992; Danilov, 2001) suggest for this effect a mechanism associated to soft particle precipitation in the region of the day-side cusp. The cusp is the only formation that starts to react to the coming geomagnetic disturbances before any geomagnetic index does: the cusp begins to move equatorward a few hours before the beginning of the Dst decrease producing the positive effects.

Another possibility is that the positive storm effect observed at Gibilmanna is due to the north crest movement to higher latitudes because of storm time electric fields. This mechanism seems to be more likely because the magnetic latitude of this ionosonde station is quite low for any cusp effect.

The initial increase produced at Ouagadougou (located near the north crest of the equatorial anomaly) requires a fairly rapid mechanism since it begins to occur within an hour or so of the sc. An increase of the eastward component of the electric field at equatorial latitudes increases the upward drift and the subsequent drainage from the equatorial region towards low latitudes. This explanation is supported by observations of significant F-region height changes and upward drifts at equatorial region during disturbed conditions (see Prölss, 1995 and references therein). Unfortunately no data from stations located at similar or equatorial latitudes there were available which prevent to corroborate the mechanism in this case study.

It is unlikely that the initial increase of ionization at the crest of the equatorial anomaly was produced by equatorward-directed meridional winds carried along by travelling atmospheric disturbances (Prölss, 1993) because several hours are required for the generation and propagation from high to low latitudes of these storm winds. Any effect produced by them is expected to be produced with a time delay of 4–5 h after sc.

A possible cause for the negative storm effects at low latitudes would be the arrival of the neutral winds carrying the composition changes. This is supported by satellite measurements obtained during the first part of the recovery phase of intense geomagnetic storms at the crest region. Significant increases in the composition of molecular nitrogen N_2 and atomic oxygen O were observed which produced decreases in the O/N_2 ratio in association with the negative storm effects as in mid-latitudes (Mansilla, 2003).

A probable mechanism for the positive effects observed at Point Arguello and also at Maui may be the downwelling of the neutral gas (for details see Danilov, 2001 and the references therein). As the electron density is proportional to $[O]^n$ with $n = 0.7–0.85$ (Mikhailov et al., 1995), simultaneous variations of O and N_2 with the O/N_2 ratio remaining constant still leads to an increase of NmF2. The storm-induced circulation leads to a downwelling of the thermospheric gas at low latitudes ($< 30–40°$) and so to an increase of O and N_2 sometimes without any significant changes in the O/N_2 ratio.

The delayed positive ionospheric storms are attributed to increases of the O density relative to N_2 to O_2 (Chandra and Stubbe, 1971; Mayr et al., 1978; Rishbeth, 1991). According to this mechanism, the storm-induced circulation transports air rich in atomic oxygen from higher latitudes towards lower latitudes. The enhanced O density will produce the increases in NmF2. However, the observational evidence found for these composition changes is not yet conclusive (e.g., Prölss and Von Zahn, 1977; Burns et al., 1995).

4. Conclusions

In this study, longitudinal features and the role of possible physical mechanisms for the explanation of the ionospheric response to the great geomagnetic storm occurred on March 13, 1989 have been considered.

Different mechanisms seem to leave their signatures for controlling the phenomenology of the ionosphere at different longitudinal sectors and at different latitudes during the strong geomagnetic storm.

The main features observed may be summarized as follows:

- Severe long-lasting decreases of ionization were dominant at mid- and mid-high latitudes, which started in the beginning of the main phase for sectors in which the storm onset occurred both at night-time and day-time hours. These variations did not follow the pattern expected during moderate geomagnetic storms (positive disturbances are mostly observed at day-time).
- The negative effects extend to low latitudes during the main phase of geomagnetic storm for longitudinal sector in which the storm started during day-time hours (135°E–155°E). This suggests a great extension of the composition disturbance until low latitudes during strong geomagnetic storms.
- Significant positive storm effects occurred during the main phase at low latitudes (Ouagadougou) in the sector in which the storm onset was at night-time as well as at middle and middle-low latitudes (Point Arguello and Maui) in the sector in which the storm onset was in pre-dusk hours.
- Delayed positive effects were also observed in the night-time hours at middle latitudes during the recovery phase of the storm.

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