Mesoscale weather influenced by auroral gravity waves contributing to conditional symmetric instability release?

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Received: 23 January 2024 – Revised: 2 April 2024 – Accepted: 10 June 2024 – Published: 15 July 2024

Abstract. We consider possible influence on severe weather occurrence in the context of solar wind coupling to the magnetosphere–ionosphere–atmosphere system, mediated by aurorally excited atmospheric gravity waves. Solar wind high-speed streams from coronal holes cause intensifications of ionospheric currents at high latitudes launching gravity waves propagating in the upper and lower atmosphere. While these gravity waves reach the troposphere with much attenuated amplitudes, they can contribute to conditional symmetric instability release and intensification of storms. Severe weather events, including winter storms and heavy rainfall causing floods and flash floods, show a tendency to follow arrivals of solar wind high-speed streams from coronal holes. The ERA5 re-analysis is used to evaluate slantwise convective available potential energy and vertically integrated extent of realizable symmetric instability to assess the likelihood of slantwise convection in frontal zones of extratropical cyclones during severe snowstorms and flash floods. The observed low-level southerly winds and high wind shears in these regions are favorable conditions for over-reflection of down-going aurorally excited gravity waves potentially contributing to conditional symmetric instability release leading to slantwise convection and high-rate precipitation.

1 Introduction

Forecasting weather has significantly improved but continues to present challenges, such as prediction of flash floods (Ferraris et al., 2002; Gourley et al., 2012; Terti et al., 2019), tornado outbreaks (Schultz et al., 2019; Gensini et al., 2019; Mercer and Bates, 2019; Chernokulsky et al., 2020; Miller et al., 2020), explosive extratropical cyclones (Sanders 1987; Gyakum et al., 1996; Kuwano-Yoshida and Enomoto, 2013; Schultz et al., 2019), and rapid intensification of tropical cyclones (Rozoff and Kossin, 2011; DeMaria et al., 2021; Lu et al., 2023).

It has been shown (Prikryl et al., 2009a, 2016, 2018, 2019, 2021a, b; Prikryl and Rušin, 2023) that severe weather events tend to occur following the arrivals of co-rotating interaction regions (CIRs) (Smith and Wolfe, 1976) at the leading edge of solar wind high-speed streams (HSSs) from coronal holes (Krieger et al., 1973; Tsurutani et al., 1995), or impacts of interplanetary coronal mass ejections (ICMEs) (Burlaga et al., 1981; Gopalswamy, 2016). It is the southward component of the interplanetary magnetic field, often due to solar wind Alfvén waves (Tsurutani et al., 2018), that cause magnetic reconnection (Dungey, 1961, 1995) and solar wind energy input into the magnetosphere and ionosphere. The solar wind coupling extends to the neutral atmosphere because it is a major source of large-amplitude aurorally excited atmospheric gravity waves (Hines, 1960) propagating globally in the atmosphere that can reach the troposphere (Mayr et al., 1984a, b).

It has been proposed that aurorally excited atmospheric gravity waves (AGWs) may play a role in influencing storm development (Prikryl et al., 2009b) by contributing to the release of conditional symmetric instability (CSI) (Schultz and Schumacher, 1999; Chen et al., 2018). Particularly when down-going AGWs over-reflect in regions of opposing winds and wind shears in the warm frontal zone of extratropical cyclones, where CSI is often present, and can be released by even a very small displacement of a moist air parcel provided by the AGWs. While these AGWs reach the troposphere with much attenuated amplitudes, they are subject to amplification
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(https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDF_06/summary?keywords=IMERG, last access: 10 July 2024).

A browser archive of global satellite images of clouds at 3-hourly intervals is provided by the International Satellite Cloud Climatology Project Global ISCCP B1 Browse System (GIBBS) (Knap, 2008).

The Northeast Snowfall Impact Scale (NESIS) was developed by the National Weather Service (Kocin and Uccellini, 2004a; https://www.ncdc.noaa.gov/snow-and-ice/rsi, last access: 10 July 2024) to consider the societal impacts of these snowstorms, in particular the impact on transportation and economy. NESIS characterizes and ranks high impact of the snowstorms in the north-eastern US into five categories: Extreme, Crippling, Major, Significant, and Notable. The index uses population information in addition to meteorological measurements. Similar, but not identical with the NESIS, is the Regional Snowfall Index (RSI) (https://www.ncdc.noaa.gov/snow-and-ice/rsi/, last access: 10 July 2024) for significant snowstorms that impact the eastern two thirds of the US. The RSI is an evolution of NESIS index that ranks snowstorm impacts on a scale from 1 to 5 by including population information to estimate the societal impacts. For details on how RSI is calculated, see Squires et al. (2014).

The solar wind data are provided by the National Space Science Data Center (NSSDC) OMNIWeb (King and Papitashvili, 2005; http://omniweb.gsfc.nasa.gov, last access: 10 July 2024). The hourly averages of solar wind velocity (V), the interplanetary magnetic field (IMF) magnitude (|B|), the standard deviation of IMF B_z (σB_z), and the proton density (n_p) are used to identify co-rotating interaction regions (CIRs), which are the interfaces between the fast and slow solar wind at the leading edge of HSSs from coronal holes (Tsurutani et al., 1995, 2006). The highly fluctuating IMF B_z component in CIRs and high-density plasma adjacent to the heliospheric current sheet and CIR (Tsurutani et al., 1995, 2006, 2016) cause recurring geomagnetic storms (Tsurutani et al., 2006). The IMF sector boundaries, where the IMF reverses its polarity, have been identified as heliospheric current sheets (HCSs) (Smith et al., 1978; Hoeksema et al., 1983) that usually closely precede, or coincide (Huang et al., 2016a, b), with stream interfaces. In the absence of the IMF data, magnetic sector boundary crossings (SBCs), which are now generally referred to as HCS crossings, can be estimated from ground-based magnetograms (Svalgaard, 1975). In the present paper we use an updated list of SBCs/HCSs (Prikryl et al., 2009a).

Measurements of the intensity of the green coronal emission line (Fe XIV, 530.3 nm) by ground-based coronagraphs from 1939 to 2008 are available in a homogeneous coronal dataset (Rybník, 1975; Rybník et al., 2001, 2005; Dorotovič et al., 2014; https://www.kozmos-online.sk/, last access: 10 July 2024). The coronal intensities are expressed in absolute coronal units (ACU) representing the intensity of the continuous spectrum from the center of the solar disk

2 Data and methods

For the analysis of conditional instability in the troposphere, the latest hourly climate reanalysis produced by ECMWF, ERA5, at 0.25° × 0.25° is utilized (Hersbach et al., 2020). Following Chen et al. (2018; their Sect. 2), indices including convective available potential energy (CAPE), slantwise CAPE (CAPE), and vertically integrated extent of realiz-able symmetric instability (VRS; a measure to quantify the “releasable” CSI) are diagnosed, to assess the likelihood of slantwise convection during severe snowstorms storms and flash floods.

The Integrated Multi-satellE Retrievals for GPM (IMERG) Final Precipitation L3 at daily resolution, at spatial scale of 0.1° × 0.1° V06 (GPM_3IMERGDF) dataset (Huffman et al., 2019) is provided by the Goddard Earth Sciences Data and Information Services Center


https://doi.org/10.5194/asr-21-1-2024
with a width of 1 Å at the same wavelength as the observa-
tional spectral line (1 ACU = 3.89 W m⁻² sr⁻¹ at 530.3 nm).
The intensity depletions, called coronal holes, are sources of
HSSs. The green corona intensity for the solar central merid-
ian is computed by averaging the intensities measured at the
east and west limbs 14 d apart (Prikryl et al., 2009a).

3 Assessment of conditional symmetric instability
and slantwise convection in frontal zones of
extratropical cyclones

Prikryl et al. (2009b) observed travelling ionospheric disturb-
bances (TIDs) caused by AGWs from auroral sources that
also propagated in the lower atmosphere and reached the
troposphere (Prikryl et al., 2005; and references therein).
They suggested that down-going aurorally-excited AGWs
that over-reflect in the warm frontal zone of extratropical
cyclones contribute to CSI release, resulting in slantwise con-
vection and series of cloud/rain bands. The cloud/rain bands
were correlated with AGWs that were observed in the up-
per atmosphere even if ray tracing of the AGWs from auroral
sources showed that they can also propagate in the lower at-
mosphere and reach the troposphere (Prikryl et al., 2009b;
2018). This mechanism offers a plausible explanation for
the statistical findings mentioned in Introduction, which es-
tablish a connection between severe weather events and the
coupling of solar wind to the magnetosphere–ionosphere–
atmosphere (MIA), thereby triggering the generation of au-
orally excited atmospheric gravity waves.

In this section, the presence of CSI and slantwise con-
vection in frontal zones of extratropical cyclones is assessed
using the method by Chen et al. (2018), who investigated
the evolution of slantwise convective available potential en-
ergy (SCAPE) in explosive and nonexplosive cyclones. They
found that SCAPE exceeded values of CAPE prior to the on-
set of the rapid intensification of explosive cyclones point-
ing to the importance of CSI in the development of storms.
Using this method in combination with the ERA5 reana-
lysis data we want to further confirm the hypothesis of Prikryl
et al. (2009b) and assess the presence of CSI and slantwise con-
vection for the case study of the extratropical cyclone on
2 November 1999 investigated previously.

3.1 Extratropical cyclone on 2 November 1999

3.1.1 Brief review of the event

Following the arrival of a moderate HSSs on 31 Octo-
ber 1999 the coupling of solar wind Alfvén waves modulated
the dayside ionospheric currents launching AGWs that were
observed as TIDs on 2 November from 15:00 UTC (Prikryl et
al., 2009b; their Fig. 2). With a delay of 4.6 h determined by
a cross-correlation of time series of TIDs and cloud/rain bands
(Prikryl et al., 2009b; their Fig. 6), a series of mesoscale
cloud/rain bands in the extratropical cyclone that were ob-
served by a radiometer showed a striking similarity with the
TIDs and their sources – quasiperiodic ionospheric currents
observed at high latitudes. The GOES-8 satellite infrared im-
age of this mid-latitude cyclone (Prikryl et al., 2009b; their
Fig. 7) showed cloud bands in the warm frontal zone where
CSI is known to be often present. The moist air parcels may
rise naturally over the colder air masses ahead of the warm
front but an additional lift could be provided by aurorally
forced AGWs (Prikryl et al., 2009b; their Fig. 9).

3.1.2 The cyclone track and assessment of CSI

We now provide further evidence for the presence of CSI
and slantwise convection in this case using the ERA5 re-
analysis. Chen et al. (2022a) identified cyclone tracks with
a storm tracking algorithm performed in a region covering
North America and part of the Pacific and Atlantic Oceans
(20–80° N, 180–0° W) using ERA5 reanalysis data. We used
the North America Extratropical Cyclone (NAEC) Cata-
logue (1979–2020) (Chen et al., 2022b) to compute the deep-
ening rate of the NAEC cyclone #12143 from 6 h time series
of MSLP values. Using the criterion introduced by Sanders
and Gyakum (1980), the maximum normalized 24 h deepen-
ing rate (Lim and Simmonds, 2002; their Eq. 1) is found to
be NDRc = 0.67 Bergerons at 12:00 UTC on 2 November.
The central pressure of this cyclone deepened to a minimum
of 980 hPa on 3 November at 03:00 UTC.

To evaluate the likelihood of slantwise convection sev-
eral indices are calculated using the ERA5 reanalysis. These
indices include SCAPE, fractional SCAPE residual \( f_s =
(SCAPE – CAPE)/SCAPE \), and vertically integrated extent
of realizable symmetric instability (Glinton et al., 2017; Chen
et al., 2018). A high SCAPE, indicating high convective
available potential energy for a slantwise ascending air par-
cel from low levels, is found in the warm sector of the cy-
clone (Fig. 1a). A closer-to-one \( f_s \) indicates the relative domi-
nance of slantwise over updraft convection (Fig. 1b). VRS
shows the thickness of the air layer (measured in pressure),
where CSI, high relative humidity, and vertical motion coex-
ist (Chen et al., 2018). Figure 1c shows that cloud/rain bands
in the warm front produced high-rate precipitation co-located
with high VRS values of above 100 hPa, a strong indication
that CSI was released actively there (Fig. 1b) that persisted
for several hours. Figure 1d shows low-level southerly winds
and the wind shear evaluated between 900 and 1000 hPa lev-
els, which further supports the proposition that AGWs could
have contributed to CSI release and formation of the ob-
served rain bands (Prikryl et al., 2009b).

3.2 Winter storms in the eastern US

The Northeast Snowfall Impact Scale (NESIS) developed by
the National Weather Service (Kocin and Uccellini, 2004a;
https://www.ncdc.noaa.gov/snow-and-ice/rsi/nesis, last ac-
cess: 10 July 2024) consider the societal impacts of snow-
storms, in particular the impact on transportation and economy. It characterizes and ranks the impact of snowstorms in the north-eastern US into five categories: Extreme, Crippling, Major, Significant, and Notable. The index uses population information in addition to meteorological measurements. Prikryl et al. (2018) performed the superposed epoch (SPE) analysis of solar wind variables keyed to start dates of the NESIS storms of category 2 or higher (Significant to Extreme) to show a tendency of severe snowstorms to occur following arrivals of HSS/CIRs.

It is noted that the start dates of the NESIS snowstorms do not necessarily relate to a particular phase in the development of extratropical cyclones which resulted in snowstorms in the north-eastern US. Furthermore, there are other causes of heavy snowfall, including the lake effect over the Great Lakes. Because we are aiming at snowstorm-causing cyclones to be potentially impacted by aurorally excited AGWs, it is more appropriate to use the days of the intensification of these cyclones, ideally the maximum deepening rate of the low-pressure systems, as key times in the SPE analysis.

As discussed previously (Prikryl et al., 2018; their supplementary material), in some cases the start days of NESIS storms were adjusted by estimating the relevant cyclone intensifications. Kocin and Uccellini (2004b) provided meteorological maps and satellite images of the NESIS snowstorms up to 2003. To determine approximate times of the cyclone deepening we have examined sequences of the published surface weather maps, or maps available online (http://www.wpc.ncep.noaa.gov/archives, last access: 10 July 2024), as well as sequences of images from a browser archive of global satellite IR images of clouds at 3-hourly intervals that is provided by the International Satellite Cloud Climatology Project Global ISCCP B1 Browse System (GIBBS) (Knapp, 2008). As a guiding criterion, a deepening to central pressure level of 1000 hPa, or less, estimated from available surface maps, and/or a visual appearance of cyclone intensification/cyclogenesis in IR images, was used to determine approximate start time of cyclonic development that likely led to, or was associated with, a snowstorm.

For example, the snowstorm on 25–28 January 2015 (Case 1 discussed further below) included a Colorado Low that was already weakening as it was passing by Great Lakes prior the rapid cyclogenesis that occurred over the east coast and resulted in the heaviest snowfall there on 26 January, which we used as the key date in the SPE analysis. Most of the NESIS start dates are used unadjusted as key dates, including those when no intensifying cyclone was identified. Only a few adjustments of the key dates by 1–2 d relative to the start dates of the NESIS snowstorms were made. An exception was the case of a significant snowstorm in 30 December 2013–3 January 2014 that was mostly caused by an intense lake effect before a cyclogenesis occurred over the south-east on 3 January, leading to a snowstorms in the north-eastern US, which contributed to heavy snowfall in the north-east, and this date is used as the key date in the SPE analysis.

We now extend the analysis by Prikryl et al. (2018; their Fig. 1) of NESIS storms of categories 2 to 5 and include the IMERG precipitation data for support. Figure 2a and b shows the results of the SPE analysis of green corona intensity and solar wind variables keyed to start days of 50 NESIS storms. The mean solar wind velocity \( V \) increases to an overall maximum after the key time. The mean solar wind density \( n_p \), magnetic field \( |B| \), and the standard deviation \( \sigma_B \) peak around the key time. The broad enhancements of the mean parameters are due to superposition of...
misaligned CIRs. This pattern is similar to those obtained previously for several groups of storms (Prikryl et al., 2009a, 2018). The pattern indicates that severe snowstorms do not occur randomly relative to HSS/CIRs but tend to occur following the arrival of HSS/CIRs. The observed pattern is the result of the superposition of solar wind HSSs from coronal holes. The minimum of the green corona intensity around the epoch day $-3$ (Fig. 2a) is due to the superposition of coronal holes that are sources of HSSs. Figure 2c shows, for each epoch day, the cumulative number of the IMERG grid cells over the northeast region with daily precipitation rates exceeding thresholds of 60, 80, 100, and 120 mm. The IMERG data, while covering only years 2000–2020, show a peak in the occurrence of high precipitation rates following the key time.

To further support the SPE analysis results for the NESIS storms several cases of winter storms, some of which are not included among the NESIS storm, are discussed in the next sections. Greybush et al. (2017, 2023) assessed the ensemble predictability of the East Coast winter storms on 25–28 January 2015, 22–24 January 2016, 7 February 2020, and 16 January 2022. We decided to investigate these winter storms, as well as another winter storm on 30 January–3 February 2021, and one oceanic explosive extratropical cyclone on 6–7 February 2023, in the context of solar wind – MIA coupling following arrivals of HSSs from coronal holes. Figure 3 shows the solar wind plasma parameters for 12 d periods with the days of the above listed winter storms highlighted in yellow colour. The CIR interfaces between the fast and slow solar wind at the leading edge of the HSSs, and HCSs, are shown by vertical solid and dashed lines, respectively. In the next sections, the CSI and slantwise convection is assessed for four events on 25–28 January 2015, 22–24 January 2016, 7 February 2020, and 6–7 February 2023. The other two storms shown in Fig. 3d and e can be viewed in the Supplement.

### 3.2.1 Case 1: 25–28 January 2015

The snowstorm on 25–28 January is ranked as category 2 on the NESIS scale and as category 3 on the RSI scale. It developed during the arrival of HSS/CIR on 26 January (Fig. 3a). The NAEC cyclone track of storm #21149 (overlaid in Fig. 5d) showed a rapid intensification with the maximum rate of 0.75 Bergeron at 00:00 UTC on 27 January, reaching a minimum central pressure of 970 hPa. During the intensification a striated delta cloud (Feren, 1995) and convective bands developed in the frontal zones of the cyclone (Fig. 4a; GOES-13 IR image on the right). High values of SCAPE are found in the warm sector and the cold front area (Fig. 5a) with a closer-to-one $f_{\phi}$ indicating the relative dominance of slantwise over upright convection. The VRS (Fig. 5c) shows highest values in the warm sector, an indication that CSI was released resulting in high-rate precipitation derived from ERA5 (Fig. 5b). The striated delta cloud and warm frontal zone were co-located with low-level southerly winds and wind shears (Fig. 5d), the conditions that are favorable for over-reflection of AGWs.

It is noted that following the arrival of a strong HSS/CIR on 21 January (Fig. 3a) another extratropical cyclone (NAEC storm #21143) intensified off the east coast starting on 22 January with the central pressure deepening to 970 hPa at a rate of 0.78 Bergeron. As in the case of the snowstorm a week later, this storm displayed similar banded clouds (Fig. 4a; GOES-13 IR image on the left) that were co-located with high values of SCAPE, low-level...
southerly winds, and wind shears, in the warm frontal zone. A major snowstorm affected Atlantic Canada with heavy snow and high winds (https://www.ctvnews.ca/canada/high-winds-heavy-snow-hammer-atlantic-canada-1.1650354/comments-7.476981, last access: 10 July 2024).

### 3.2.2 Case 2: 22–24 January 2016

The snowstorm on 22–24 January is ranked as category 4 (Crippling) in the NESIS scale. As already shown in the previous study (Prikryl et al., 2018; their Fig. 2a), the present Fig. 3b shows that this winter storm developed following the arrival of a strong HSS/CIR from a recurrent coronal hole (recurring with solar rotation period of 27 d). Separated by about 27 d, two other winter storms on 15–16 February and 15–16 March 2016 were closely associated with the same recurrent HSS/CIR (Prikryl et al., 2018; their Figs. 2–4) that caused recurrent geomagnetic storms.

The snowstorm in January was caused by a cyclone intensifying over the east coast. The track of the NAEC storm #21733 (Chen et al., 2022b) shows the cyclone’s central pressure reaching the minimum of 985 hPa following the 24 h deepening rate of 0.42 Bergeron at 18:00 UTC on 22 January. During the deepening phase the extratropical cyclone developed a striated delta cloud that can be seen in Fig. 4b. Prikryl et al. (2018; their supplementary material) examined a series of the GOES-13 IR images and suggested that AGWs launched by ionospheric currents at auroral latitudes could have played a role in the formation of the striated delta cloud that caused high-rate precipitation derived from ERA5 (Fig. 6b). The striated delta cloud was colocated with low-level southerly winds and wind shears evaluated between 900 and 1000 hPa levels (Fig. 6d), the conditions favorable for over-reflection of equatorward propagating down-going AGWs.
Similarly to the case discussed in Sect. 3.1 the high values of SCAPE were present in the warm sector of the cyclone (Fig. 6a). A closer-to-one $f_s$ indicates the relative dominance of slantwise over upright convection. The VRS (Fig. 6c) shows the thickness of the air layer (measured in pressure), where CSI, high relative humidity, and vertical motion co-exist (Chen et al., 2018). It shows the highest values co-located with the striated delta (Fig. 6c), a strong indication that CSI was being released actively there, with high VRS values matching the high-rate precipitation (Fig. 6b) that persisted for several hours.

### 3.2.3 Case 3: 7 February 2020

This snowstorm that is not included among the NE-SIS snowstorms was discussed by Greybush et al. (2017, 2023). The storm developed following the arrival of HSS/CIR on 6 February (Fig. 3c). Heavy precipitation started already on 5 February during a period of strong northwest flow of a decaying atmospheric river bringing significant moisture (https://www.weather.gov/gjt/WinterStormSummary_Feb04-07_2020, last access: 10 July 2024). On 7 February, the central pressure of the cyclone (NAEC storm #24075) deepened at a rate 0.65 Bergeron to 968 hPa. The rapid cyclogenesis over the east coast further intensified the snowstorm that affected the US and Canada with heavy snowfall and widespread wind damage (https://www.weather.gov/phi/EventReview20200207, last access: 10 July 2024). The cyclone developed a cloud head (Fig. 4c) exhibiting mesoscale snow bands (Varcie et al., 2023; Colle et al., 2023). The frontal zones show high values of SCAPE (Fig. 7a) indicat-

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**Figure 4.** The GOES-13 infrared images during winter storms in (a) January 2015, (b) January 2016, and (c) February 2020 (https://www.ncdc.noaa.gov/gibbs/, last access: 10 July 2024).
ing the relative dominance of slantwise convection, where the VRS (Fig. 7c) shows the highest values, an indication that CSI was released resulting in high-rate precipitation derived from ERA5 (Fig. 7b). As in the other cases, the frontal zones were co-located with high low-level southerly winds and wind shears (Fig. 7d).

3.2.4 Case 4: 6–7 February 2023

While this oceanic explosive extratropical cyclone developed off the US east coast and only marginally affected the east coast of Canada with strong winds, this occurred following the arrival of HSS/CIR (Fig. 3f). The cyclone would have likely caused a severe winter storm if it developed over the US coast. It explosively intensified on 6 February from a low of 1015 hPa just east of Florida deepening to 978 hPa in 24 h, with the IR images displaying banded structures in the cloud head and the warm frontal sector (Fig. 8). In these regions, high values of SCAPE, VRS, precipitation rates, as well as low-level southerly winds and wind shears are found (Fig. 9). As was the case for the event discussed in Sect. 3.1, the solar wind coupling to the MIA system modulated the dayside ionospheric currents generating AGWs that could have contributed to CSI release leading to intensification of cyclones and high precipitation.

3.3 High-rate precipitation flash floods

High intensity storms producing flash floods are common to the continental United States (CONUS), particularly to the Mississippi River Basin (MRB), where there is also the highest average rainfall accumulation (Dougherty, 2020; Dougherty and Rasmussen, 2019, 2020). The previously published results of the SPE analysis of solar wind variables keyed to start days of heavy precipitation events leading to floods and flash floods have shown that such events tend to occur following arrivals of solar wind HSSs (Prikryl et al., 2018, 2021a, b; Prikryl and Rušin, 2023). This was also

Figure 5. The same as Fig. 1, but for the winter storm on 27 January 2015 with the track of the NAEC storm #21149 overlaid.

Figure 6. The same as Fig. 1, but for the winter storm on 23 January 2016, with the track of the NAEC storm #21733 overlaid.
demonstrated, using the SPE analysis, in the case of flash flood events in MRB for a period of 1998–2019 obtained from the NOAA/NWS storm database records of flash flood reports using the SPE analysis (Prikryl et al., 2021b; their Fig. 3g–i).

In the present analysis that is extended to ±12 epoch days from the key time and uses the IMERG precipitation database, Fig. 10a ($n = 516$; 1998–2019 NOAA/NWS storm database; Prikryl et al., 2021b), Fig. 10b ($n = 484$; 2002–2013 MRB dataset; Dougherty, 2020), and Fig. 10c ($n = 584$; CONUS dataset; Dougherty and Rasmussen, 2020) show the SPE analysis for different flash flood datasets. Similar to winter storms (Fig. 2) but for much larger number of events, the mean solar wind variables for all three cases in Fig. 10 show familiar patterns indicating that flash floods do not occur randomly relative to HSS/CIRs but tend to occur with the arrival of HSS/CIRs. As examples, we briefly discuss cases of flash floods on 19–22 May 2017, 1–2 May 2011, and 11–12 November 2020.

Following the arrival of a strong HSS/CIR on 19 May 2017 (Fig. 11a) that triggered a minor geomagnetic storm (Fig. 11c) flash floods caused by extreme rainfall occurred.
in Indiana, Kentucky, and Tennessee (https://floodlist.com/america/usa/indiana-kentucky-tennessee-may-2017, last access: 10 July 2024). The maximum daily precipitation rate reached 500 mm (red dotted line in Fig. 11b). One week later, after exiting from the HSS, the Earth’s magnetosphere was impacted by a strong ICME (Fig. 11a) causing a major geomagnetic storm. This was associated with high-rate precipitation that affected central and southern states on 28 and 29 May 2017. Top panels in Fig. 12 show high values of SCAPE in the frontal zones of the cyclone, a closer-to-one $f_s$, indicating the relative dominance of slantwise over upright convection, and high VRS values that are a strong indication that CSI was being released actively. High VRS match the high-rate precipitation that persisted for several hours. The high wind shears and low-level southerly winds opposing the equatorward propagating down-going AGWs are favorable conditions for over-reflection of AGWs.

The GOES-13 infrared image (Fig. 13a) shows an intense convection in the frontal zones of a cyclone that formed on 19 May 2017. The cyclone maintained relatively constant
central pressure just above 1000 hPa with only a mild deepening rate of 0.11 Bergeron (NAEC storm track #22481). However, the cyclone rapidly grew large with the central pressure moving north over Canada, while the intense convective activity in the South and over the Gulf continued for several days.

Dougherty and Rasmussen (2020) examined a flash flood in the south-central United States that occurred from 1 May 07:00 UTC to 21:00 UTC on 2 May 2011. The intense convection causing the heavy precipitation developed in the tail of a cold front of a large cyclone with its central pressure over the Midwest and central Canada. In the context of solar wind, the flash flood occurred after the arrival of a strong HSS/CIR that caused a minor geomagnetic storm (Fig. 11e and f). The assessment of conditional symmetric instability and slantwise convection (Fig. 12; middle panels) indicates conditions that are favorable for over-reflection of down-going AGWs to contribute to CSI release.

Catastrophic flash floods across North Carolina that occurred on 11–12 November 2020 (https://floodlist.com/america/usa/north-carolina-floods-november-2020, last access: 10 July 2024) were closely associated with a HSS/CIR (Fig. 11g). Figure 13c shows the GOES-13 IR image of a mesoscale system displaying a string of convective cells extending over the western edge of North Carolina. Figure 11h shows the number of IMERG grid cells over the CONUS area with precipitation rates exceeding given thresholds and the maximum daily precipitation with a peak on 12 November. The assessment of CSI and slantwise convection (Fig. 12; bottom panels) show high values of SCAPE, VRS, and precipitation rate derived from ERA5. In the same region low-level southerly winds and high wind shears are present.

It is noted that during this flash flood event there was also a tropical cyclone Eta that briefly re-intensified into a hurricane before landing in Florida. Figure 13b shows that the hurricane Eta produced heavy precipitation associated with high SCAPE, VRS, and low-level southerly winds and wind shears, which potentially can make a case for the AGWs contribution to CSI release. Prikryl et al. (2019) observed that rapid intensification of tropical cyclones often occurs following arrivals of HSS/CIR or ICMEs. They found that this is
most likely for tropical cyclones displaying convective bursts (Prikryl et al., 2019; their Fig. 19).

4 Discussion

In support of previously published results (Prikryl et al., 2018, 2021a, b; Prikryl and Rušín, 2023), the SPE analysis of solar wind variables keyed to start dates of severe snowstorms (Sect. 3.2) and flash floods (Sect. 3.3), shows a ten-
Figure 13. The GOES-13 infrared images for flash floods on (a) 20 May 2017, (b) 1 May 2011, and (c) 11 November 2020 (https://www.ncdc.noaa.gov/gibbs/, last access: 10 July 2024).

dency of these weather events to occur following arrivals of HSS/CIRs. In a supplementary analysis for cases of winter storms and flash floods, high values of SCAPE are found in the warm and cold frontal zones with a closer-to-one $f_s$ indicating the relative dominance of slantwise over upright convection, which is an indication that CSI is being released resulting in slantwise convection and high-rate precipitation. In these regions, high wind shears and low-level southerly winds opposing the incoming AGWs are found. In the context of the solar wind–MIA coupling generating equatorward propagating AGWs, these are the conditions favorable for over-reflection of down-going AGWs potentially contributing to CSI release.

The cases of winter storms and flash floods investigated in this paper are associated with arrival of HSS/CIRs when large-amplitude solar wind Alfvén waves generate high-intensity auroral electrojet activity (Tsurutani and Gonzalez, 1987; Tsurutani et al., 1990, 1995). Auroral electrojets are known as sources of atmospheric AGWs (Chimonas and Hines, 1970) propagating globally in the neutral atmosphere (Richmond, 1978; Hunsucker, 1982), both upward and downward (Mayr et al., 1984a, b, 2013). The solar wind–MIA coupling generates aurally excited AGWs that are observed in the ionosphere as travelling ionospheric disturbances (TIDs) using various techniques (e.g., Prikryl et al., 2022; and references therein). But ray tracing of AGWs (Prikryl et al., 2018; Prikryl and Rušín, 2023) can show that down-going AGWs can reach the troposphere, where they can contribute to the CSI release leading to slantwise convection and heavy precipitation.

Studies that are referenced in Introduction found that striated delta clouds, striated cloud heads, and strings of “back building” convection cells in cold fronts, tend to occur following arrivals of HSSs or ICMEs. As discussed in Sect. 3.2, aurorally generated AGWs could have played a role in the formation of the striated delta clouds (Fig. 4a and b) in Case 1 and 2, and striated cloud heads (Fig. 8) in Case 4. In Sect. 3.3, a string of “back building” mesoscale convective cells (Fig. 13c), could have also been triggered by equatorward propagating AGWs as previously suggested for other cases (Prikryl et al., 2021a; Prikryl and Rušín, 2023). High values of SCAPE, VRS, precipitation rates, as well as low-level southerly winds and wind shears are found associated with these phenomena (Figs. 5, 6, 9, and 12), which are favorable conditions for down-going AGWs to over-reflected contribute to CSI release. The occurrence of striated delta clouds identified by Feren (1995), and several cases of cloud heads that were discussed by Dixon et al. (2002) and Browning and Wang (2002), are shown in the context of solar wind in the Supplementary material. All these cases were associated with arrivals of HSS/HCS/CIRs or ICMEs, when solar wind–MIA coupling generates large-amplitude globally propagating AGWs.

5 Conclusions

It is observed that severe winter storms in the northeast United States, and flash floods in the continental US and the Mississippi River Basin, tend to occur following arrivals of solar wind high-speed streams from coronal holes. This link points to solar wind–magnetosphere–ionosphere–atmosphere coupling, mediated by aurorally excited globally propagating atmospheric gravity waves that can reach the troposphere and influence the weather development. Assessment of slantwise convective available potential energy and the vertically integrated extent of realizal symmetric instability using the ERA5 reanalysis dataset indicates the likelihood of slantwise convection in frontal zones of extratropical cyclones. The results also show the presence of low-level southerly winds and high wind shears. These are the conditions favorable for over-reflection of down-going aurorally excited gravity waves, which can potentially contribute to conditional symmetric instability release, slantwise convection, cloud bands and high-rate precipitation. Aurorally generated gravity waves can also play a role in cases of striated delta clouds and cloud heads.
**Data availability.** The solar wind data can be obtained from the NSSDC OMNIWeb http://omniweb.gsfc.nasa.gov (NASA, 2024; King and Papitashvili, 2005). The Modified Homogeneous Data Set of Coronal Intensities can be obtained at https://www.kozmos-online.sk/slnko/modifikovany-homogeneny-rad-modified-homogeneous-data-set/(KOZMOS-online.sk, 2024; Dorotovič et al., 2014).

The ERA5 reanalysis dataset https://doi.org/10.24381/cds.143582cf (Hersbach et al., 2017). The Integrated Multi-satellitE Retrievals for GPM (IMERG) Final Precipitation L3 1d 0.1° × 0.1° V06 (GPM_3IMERGDF) dataset (Huffman et al., 2019) is provided by the Goddard Earth Sciences Data and Information Services Center (https://doi.org/10.5067/GPM/IMERGDL/DAY/06).

**Supplement.** The supplement related to this article is available online at: https://doi.org/10.5194/asr-21-1-2024-supplement.

**Competing interests.** The author has declared that there are no competing interests.

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**Special issue statement.** This article is part of the special issue “EMS Annual Meeting: European Conference for Applied Meteorology and Climatology 2023”. It is a result of the EMS Annual Meeting: European Conference for Applied Meteorology and Climatology 2023, Bratislava, Slovakia, 3–8 September 2023.

**Acknowledgements.** The author would like to thank Ting-Chen Chen at the Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, for sharing the computer code for the analysis of conditional symmetric instability, and to Erin Dougherty at Department of Atmospheric Science, Colorado State University, for providing lists of MRB and CONUS flash floods. The IMERG dataset is provided by the Goddard Earth Sciences Data and Information Services Center. The reanalysis dataset ERA5 is a product of the European Centre for Medium-Range Weather Forecasts (ECMWF). The contributions by ACE, Geotail, IMP-8, SOHO, and Wind spacecraft teams; the NSSDC OMNIWeb; and the SuperDARN project are acknowledged.

**Review statement.** This paper was edited by Dario Giaiotti and reviewed by two anonymous referees.

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https://doi.org/10.5194/asr-21-1-2024


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