The annual European Meteorological Society meeting, 4-9 September 2022, University of Bonn
UP2.5 The interconnection between the sun, space weather and the atmosphere

Tropospheric weather influenced by solar wind coupling to the magnetosphere-ionosphere-atmosphere system

Paul Prikryl[1], Vojto Rušin[2]

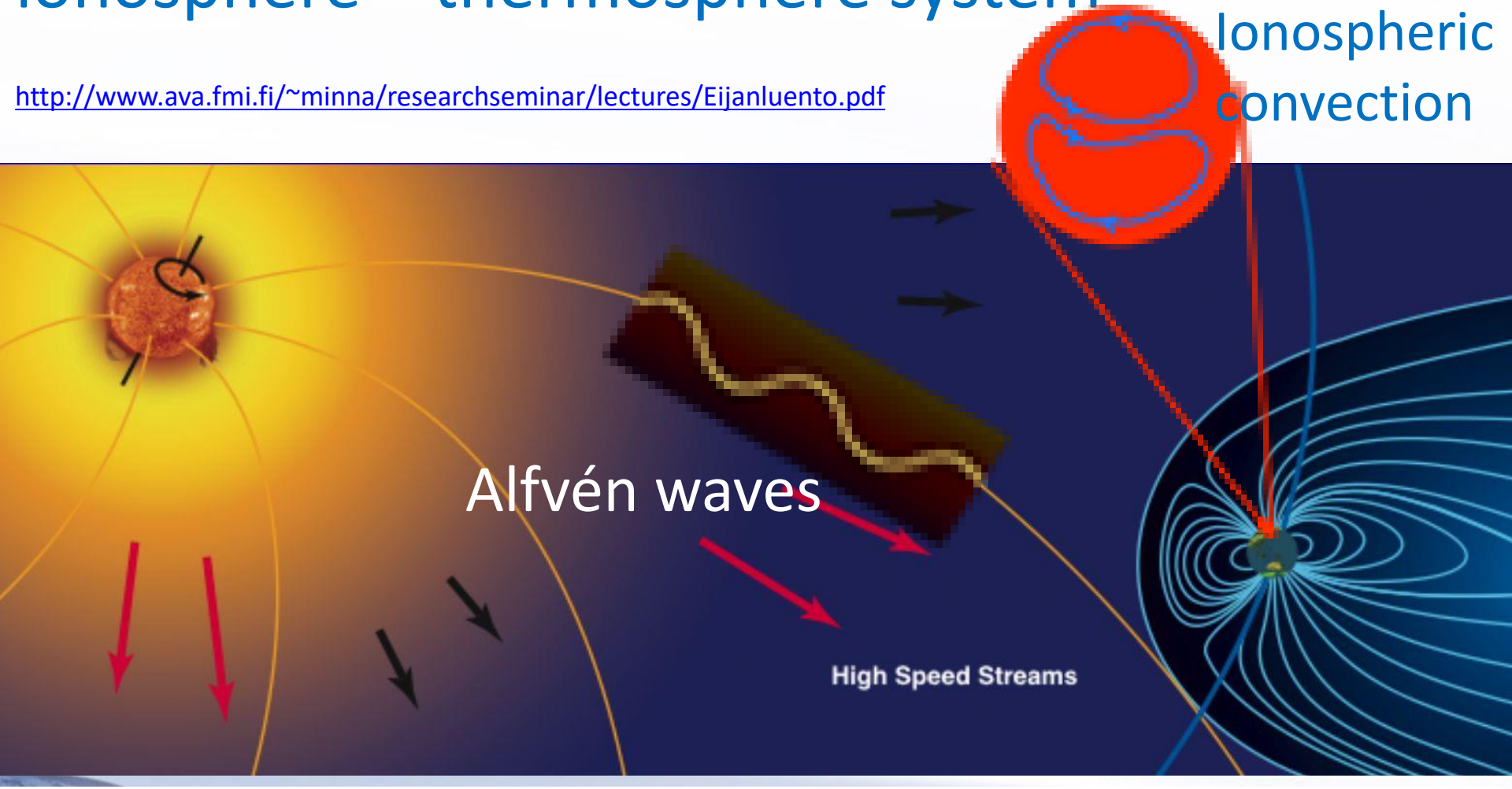
[1]Physics Department, University of New Brunswick, Fredericton, NB, Canada
[2]Astronomical Institute, Slovak Academy of Sciences, Tatranská Lomnica, Slovakia

Outline

- Introduction & Motivation
- Statistical results
  - Extratropical cyclones
  - Tropical cyclones
  - Heavy rainfall & Flash floods
  - Tornado outbreaks
- Interpretation
- Summary & Conclusions

Solar wind coupling to the magnetosphere – ionosphere – thermosphere system

http://www.ava.fmi.fi/~minna/researchseminar/lectures/Eijanluento.pdf



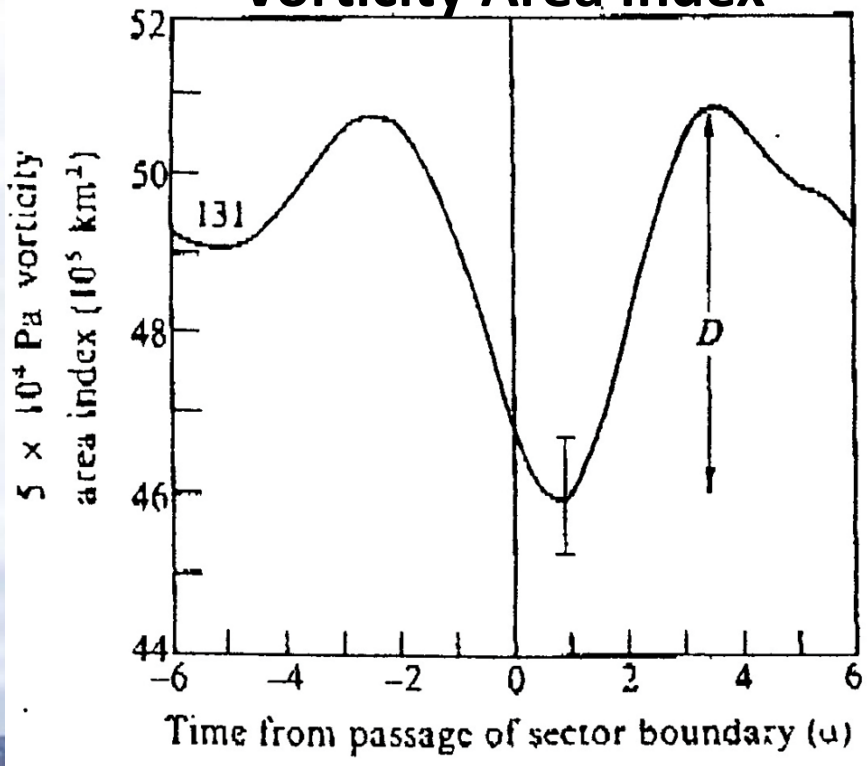
This diagram illustrates the solar wind - magnetosphere coupling process. The expanding atmosphere of the Sun – the solar wind, draws out magnetic fields from the Sun that couple to the Earth's magnetosphere, connecting it to the ionosphere and thermosphere. In this the context we examine severe weather and possible influences by solar wind.

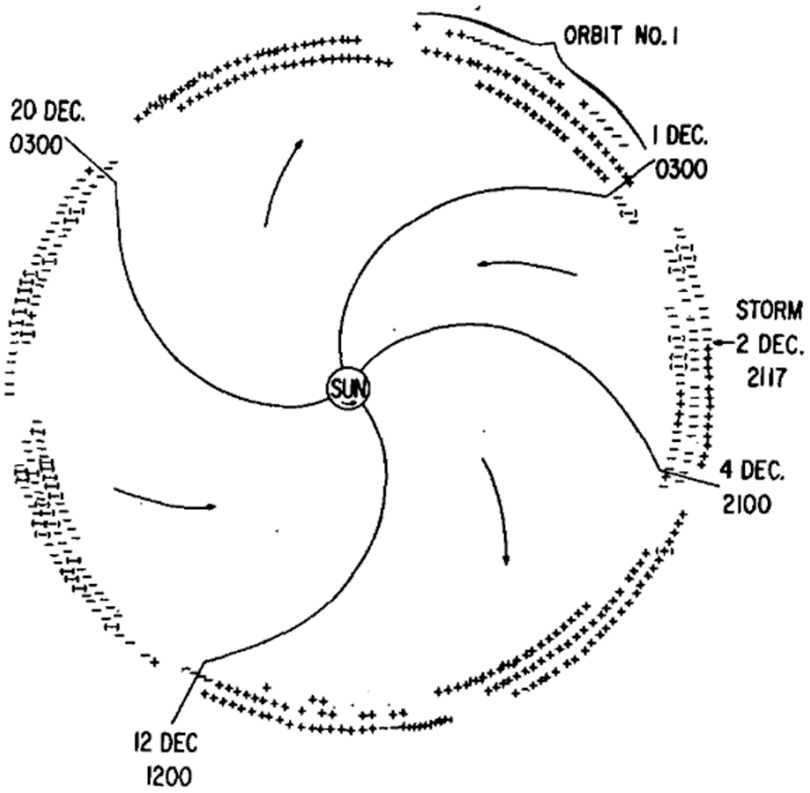
Motivation & Introduction

- "Wilcox effect" (Wilcox J. M., et al., Science, 180, 185-186, 1973; Wilcox et al., J. Atmos. Sci, Vol. 31, 581-588, 1974)

Nov-Mar 1963-1973

Vorticity Area Index



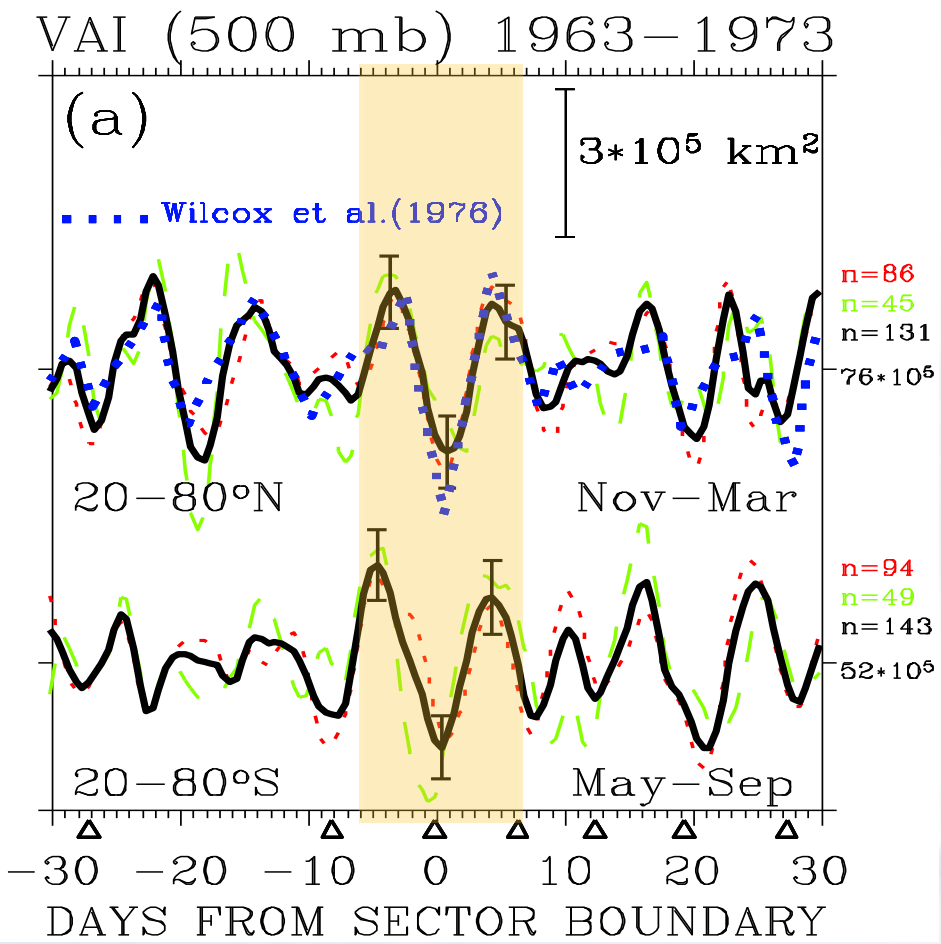


Ness, N.F. and J.M. Wilcox, Phys. Rev. Lett., 1964, 13, 461.

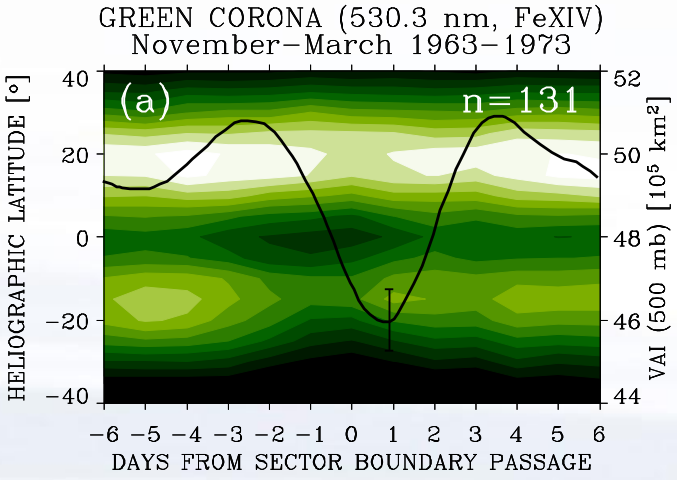
In 1970's a solar physicist John Wilcox discovered a connection between the sector boundaries in the IMF and upper-level vorticity in the troposphere. Vorticity area index (VAI) was defined as the sum of the area (km^2) over which the absolute vorticity exceeded $20x10^{-5}$ s^{-1} plus the area over which vorticity exceeded $24x10^{-5}$ s^{-1} (Roberts and Olson, 1973). In mid latitudes in winter, when the extra-tropical cyclones are most active, they found a statistically significant dip in VAI just after the IMF sector boundary crossings (SBCs). They used the superposed epoch (SPE) analysis method.

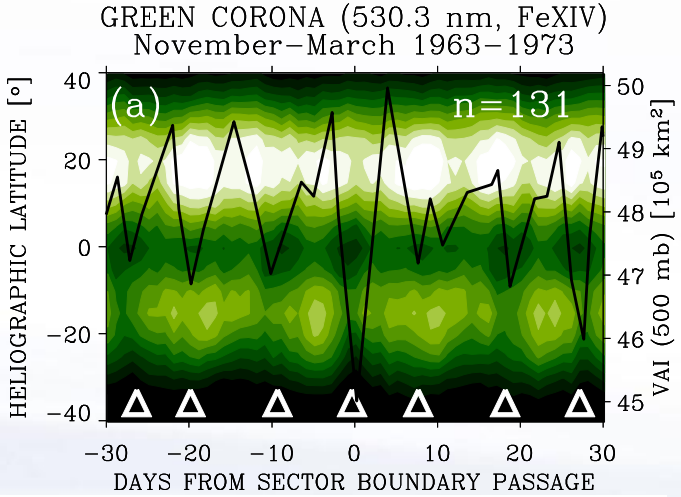
Motivation & Introduction

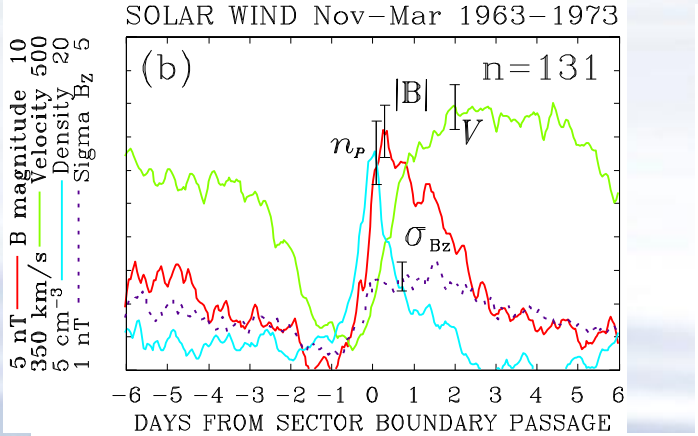
- "Wilcox effect" confirmed using the ERA40 reanalysis in the Northern and Southern Hemispheres (Prikryl et al., Ann. Geophys., 27, 1–30, 2009).

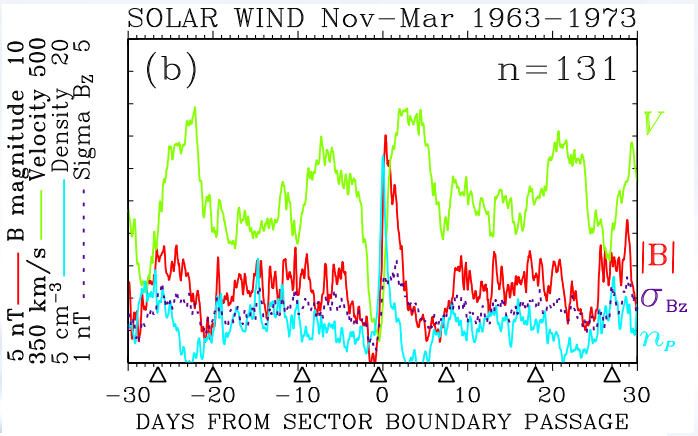


Superposed epoch (SPE) analysis of green corona, solar wind parameters, and VAI ("Wilcox effect")









The SPE analysis keyed to 131 interplanetary magnetic field (IMF) sector boundary crossings (Prikryl et al., Ann. Geophys., 27, 1–30, 2009).

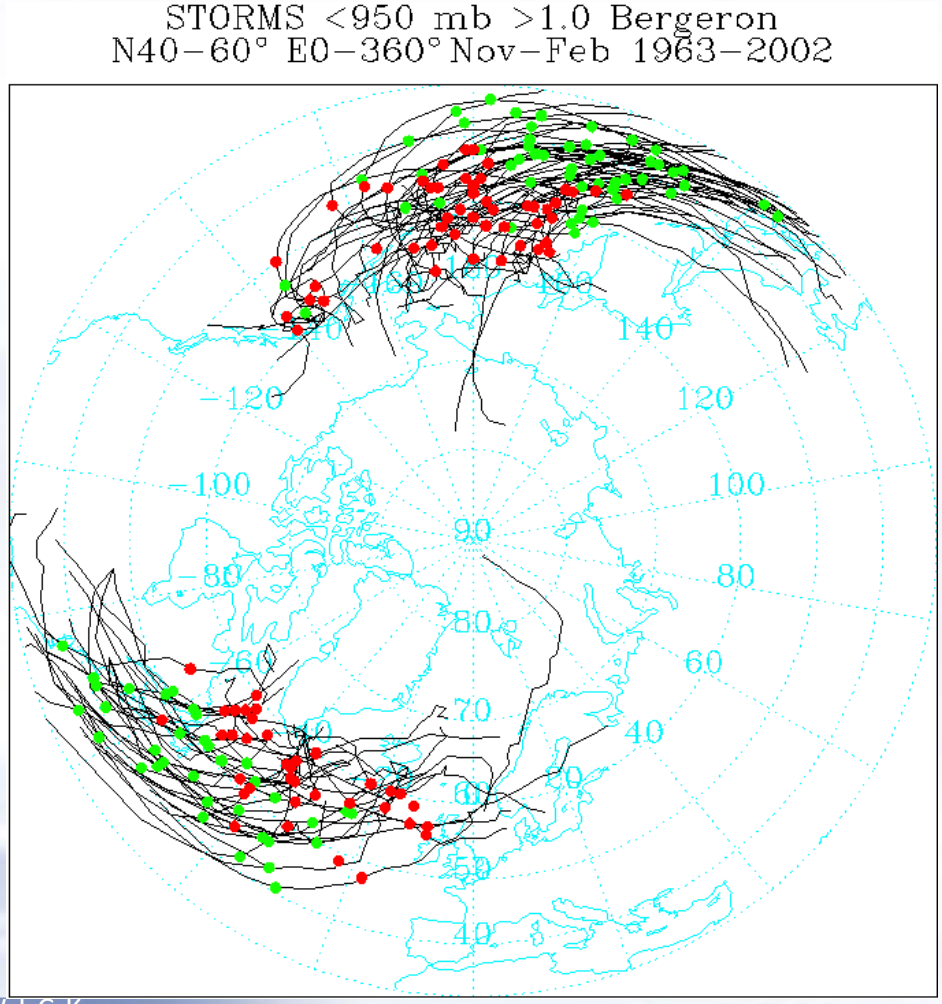
The IMF sector boundaries are markers in solar wind signalling the arrivals of high-speed streams (HSSs) from coronal holes. The SPE analysis of solar wind parameters (proton density n_p, magnetic field magnitude B, and the standard deviation of the magnetic field north-south component σ_{Bz}) and solar corona intensity, keyed to SBCs, shows the expected result, a superposition of co-rotating interaction regions (CIRs) on the leading edge of HSSs. The "Wilcox effect" is shown over the mean corona intensity.

Explosive extratropical cyclones

Storm tracks obtained from the ERA-40 reanalysis

Prikryl et al., J. Atmos. Sol.-Terr. Phys., 149, 219–231, 2016.

Vorticity is a measure of storminess, representing the growth and decay of extratropical cyclones. These are the storm tracks of explosive extratropical cyclones, with the maximum growth rate indicated by green dots; red dots showing minima in the central seal level pressure (SLP).



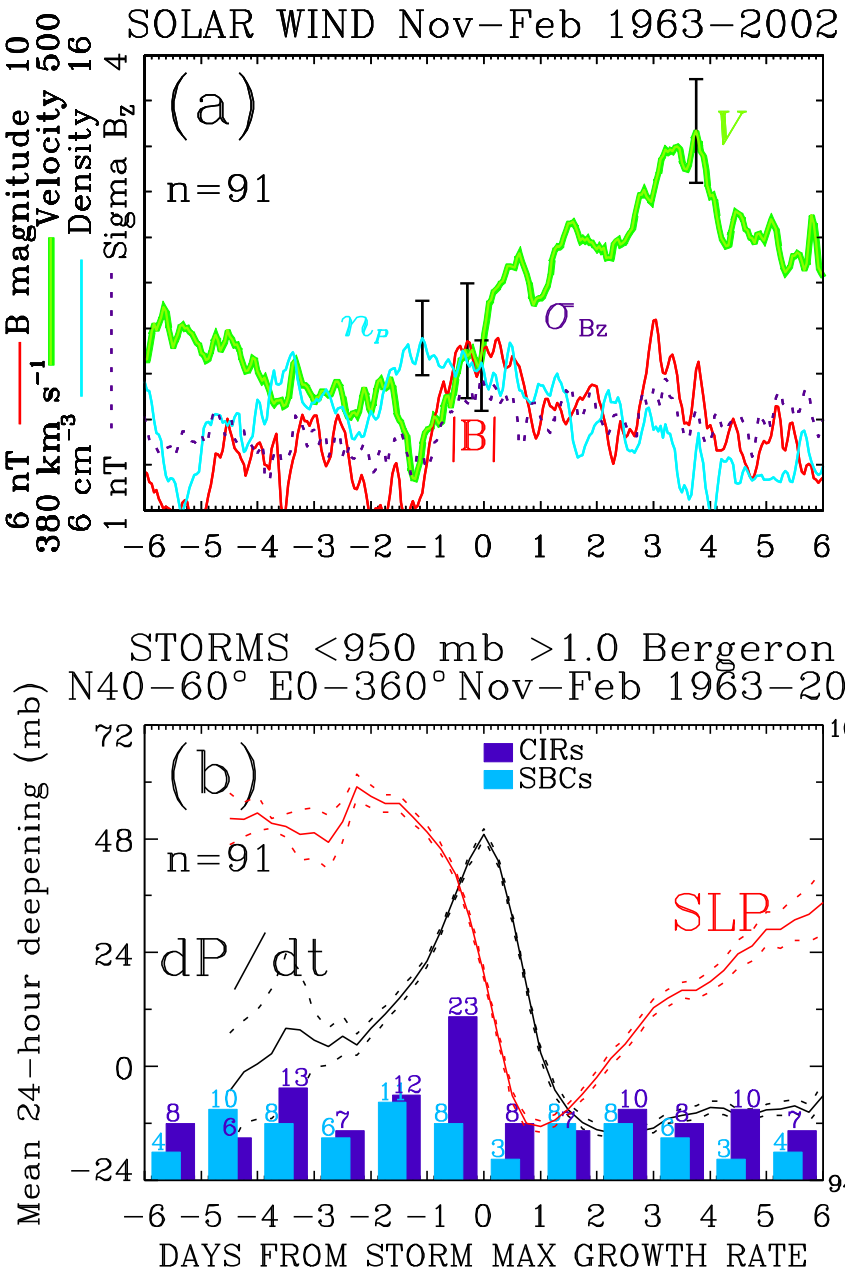
The SPE analysis keyed to the maximum growth rate of 91 explosive extratropical cyclones in the Atlantic and Pacific

Prikryl et al., J. Atmos. Sol.-Terr. Phys., 149, 219–231, 2016.

The maximum growth rate (dP/dt), deepening of the central SLP, defines the key times for the SPE analysis shown for ±6 days from the key time.

The results show an increase in the mean solar wind velocity *V*, from a minimum before, to a maximum after, the key day, while the other solar wind parameters peak around the key time, which is a result of superposition of HSS/CIRs (cumulative numbers of CIRs and SBCs are shown in the bottom panel).

These results indicate **a tendency of explosive cyclones to follow arrivals of high-speed solar wind streams (HSS) from coronal holes**, suggesting a link between the space weather and the tropospheric weather.



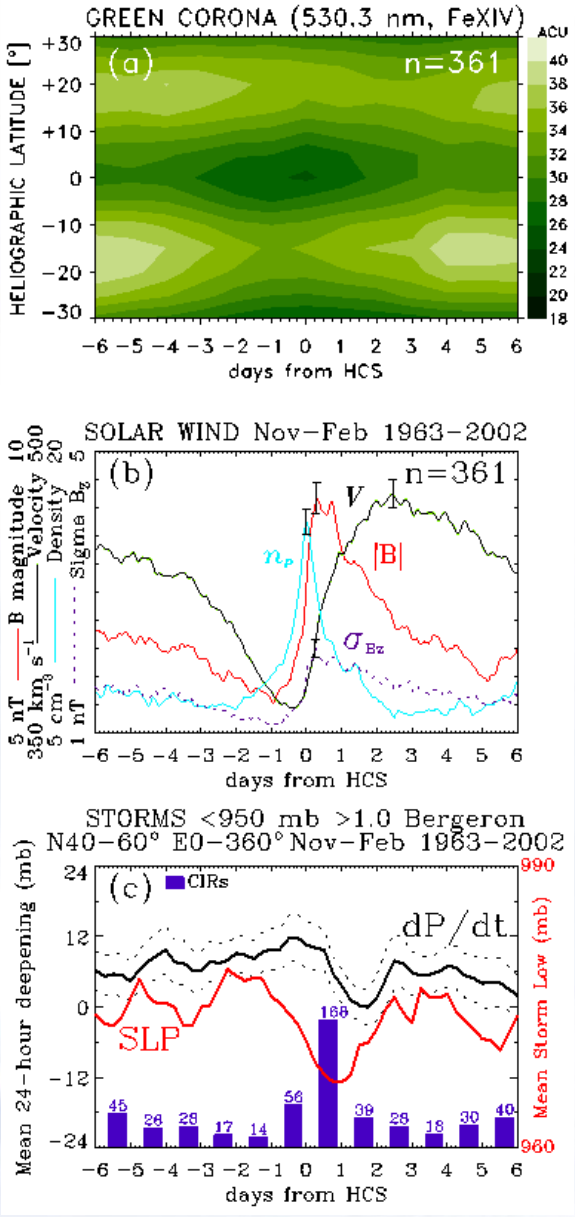
CIR: Co-rotating Interaction Region

SBC: IMF Sector Boundary Crossing

The SPE analysis keyed to sector boundary crossings

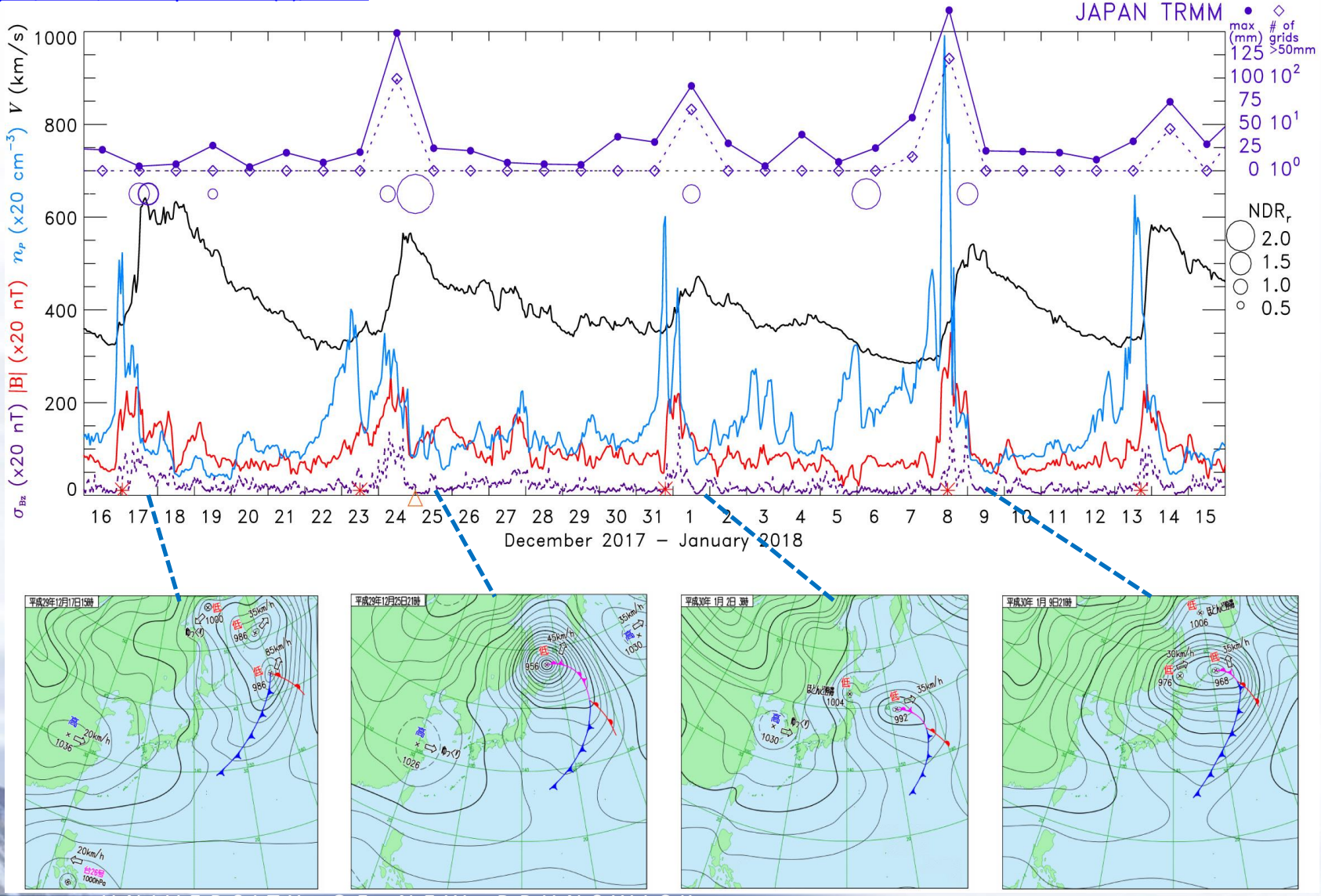
Another approach is to define the key times by solar wind events. The SPE analysis is keyed to magnetic sector boundaries that are now known as the heliospheric current sheet (HCS). The results for the green corona intensity and solar wind parameters show the familiar pattern but of larger amplitudes.

(c) The mean deepening rate dP/dt and central sea-level pressure SLP of explosive extratropical cyclones that occurred within ±6 days from the key time. The histogram shows the cumulative numbers of CIRs.



Explosive extratropical cyclones & heavy precipitation

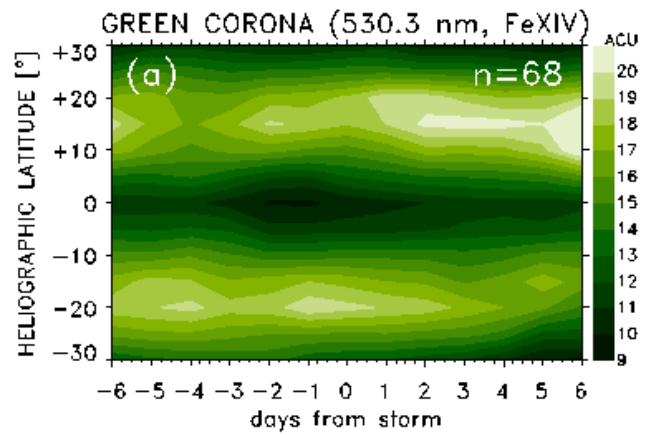
Prikryl P., et al., Atmosphere 12 (9), 2021.

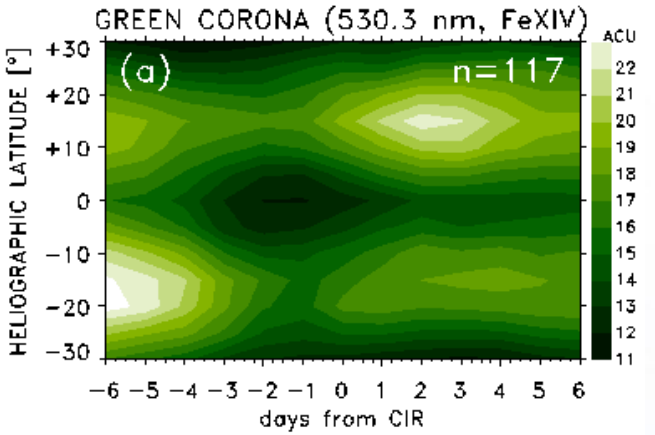


The SPE analysis

of time series of **(a)** green corona 530.3-nm (FeXIV) intensity

Prikryl P., et al., Atmosphere 12 (9), 2021.



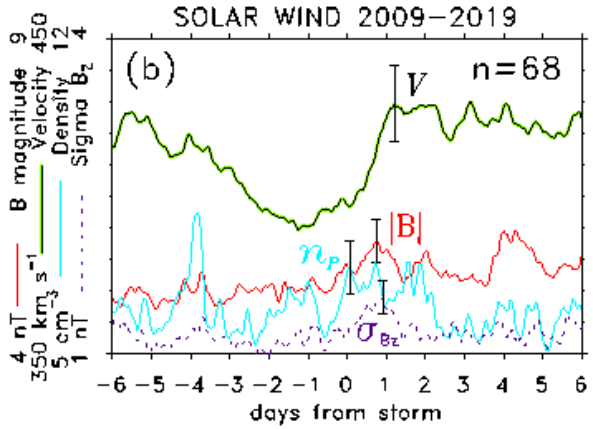


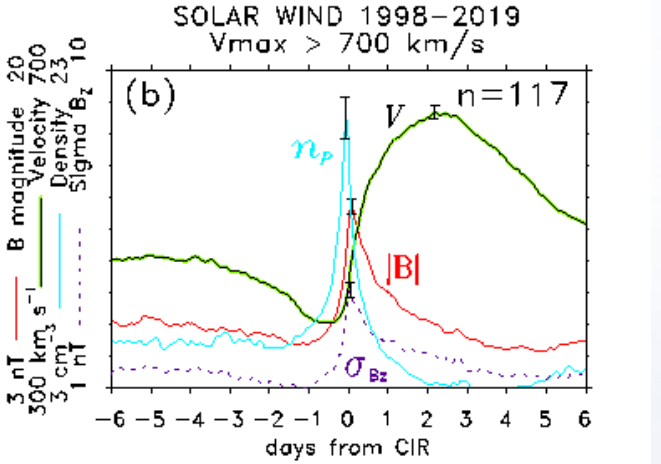
(b) solar wind variables keyed to

← heavy rainfall events in Japan

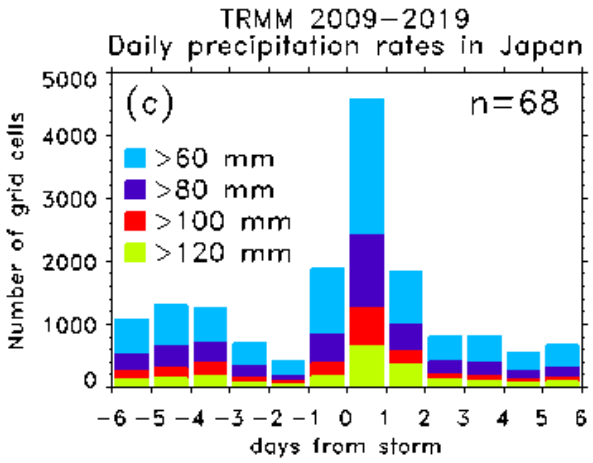
and

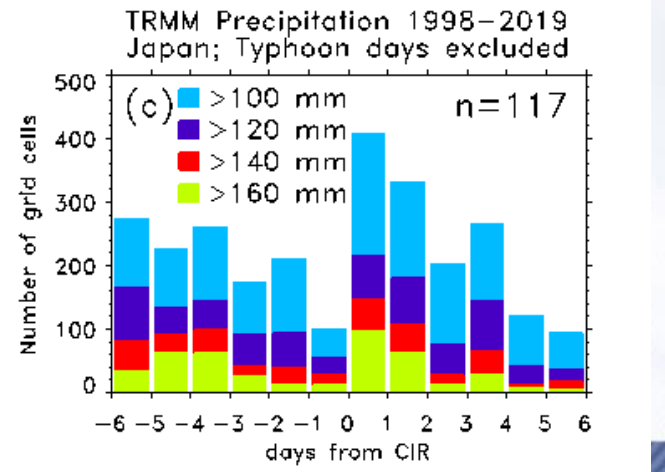
arrivals of major HSS/CIRs →





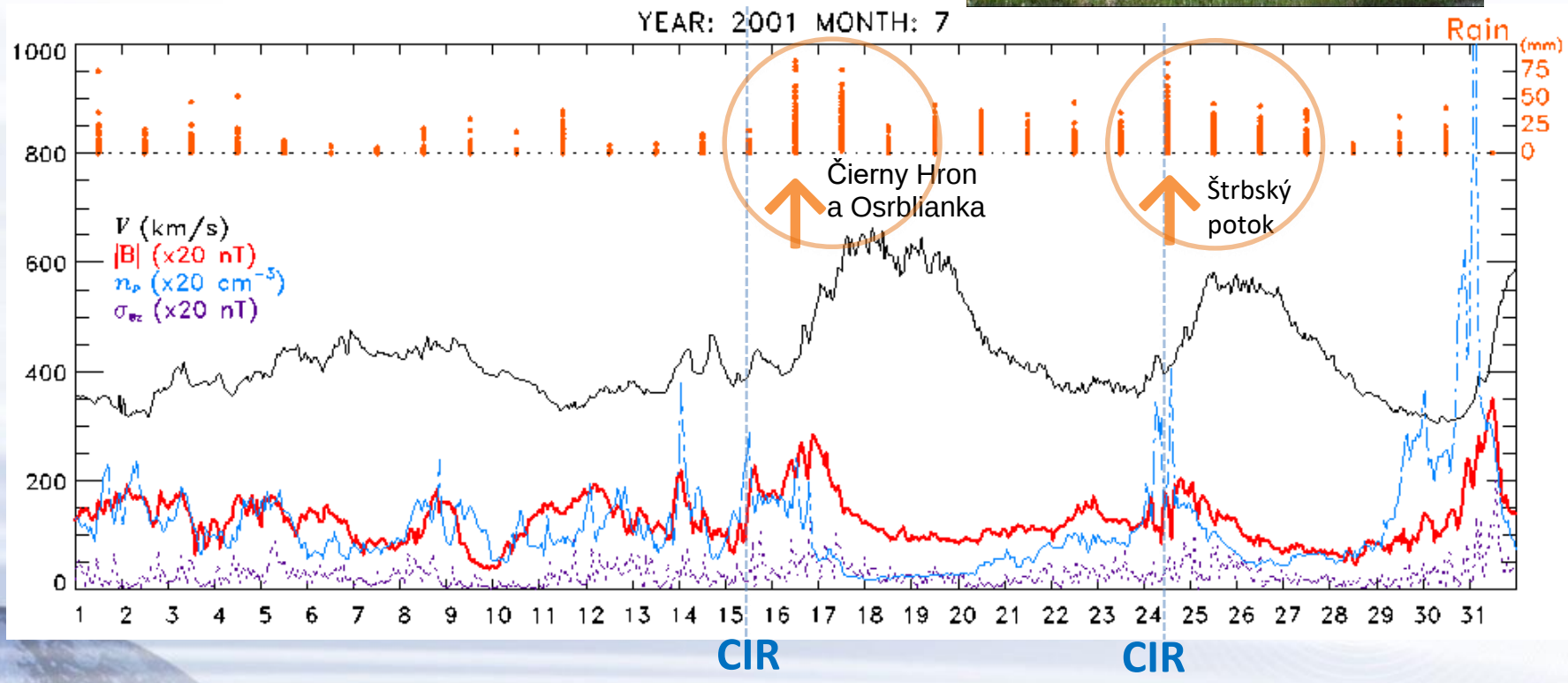
(c) The cumulative number of TRMM grid cells over Japan with above-threshold daily precipitation rates (days of typhoon impacts are excluded).





Heavy rainfall and flash floods in Slovakia in July 2001

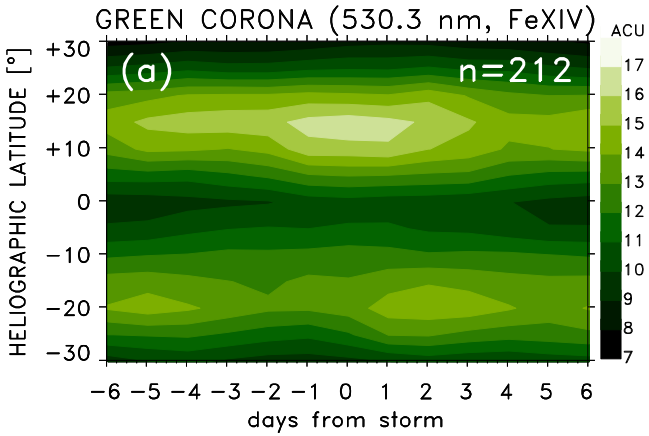


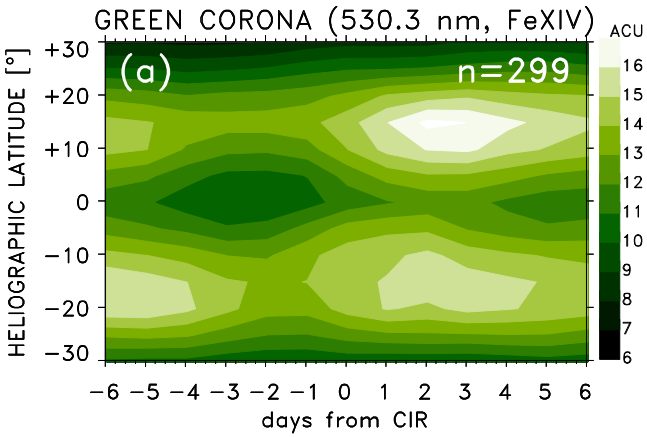


Prikryl et al., J. Atmos. Sol.-Terr. Phys., 171, 94–110, 2018.

The SPE analysis

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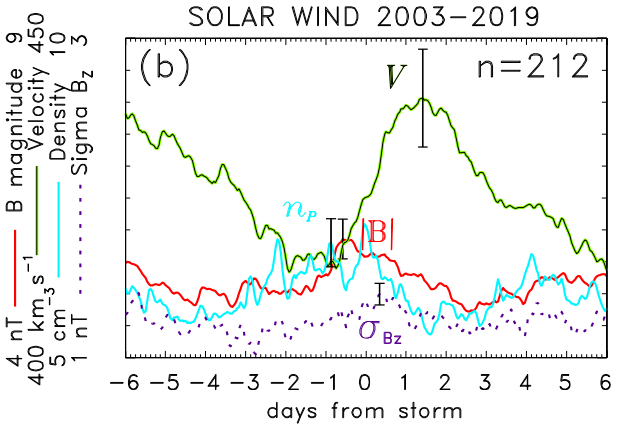
Prikryl P., et al., Ann. Geophys. 39 (4), 769–793, 2021.

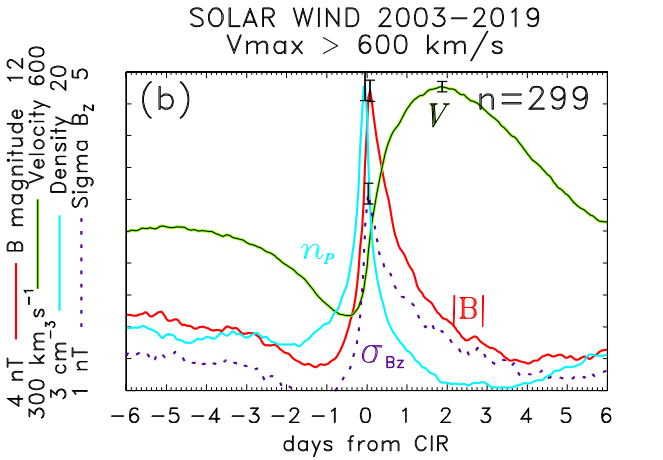
(b) solar wind plasma variables keyed to

← heavy rain storms

and

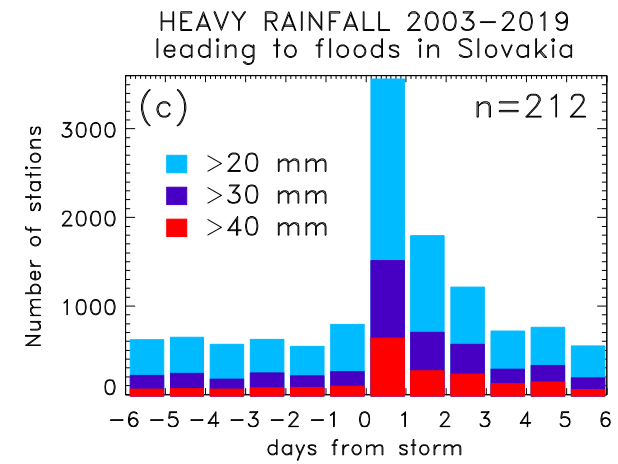
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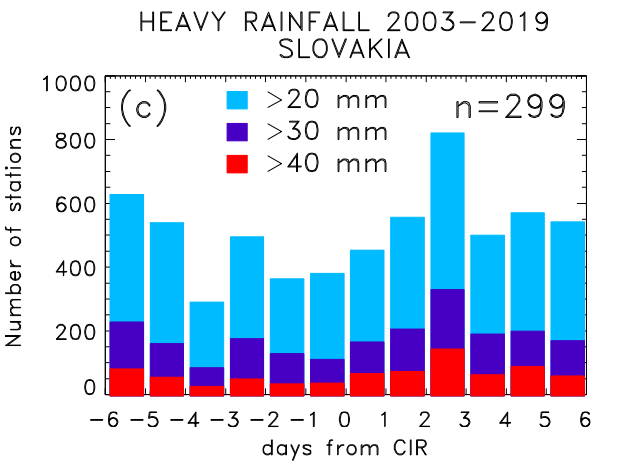




Slovakia

(c) The cumulative number of rain-gauge stations in Slovakia with above-threshold daily precipitation rates





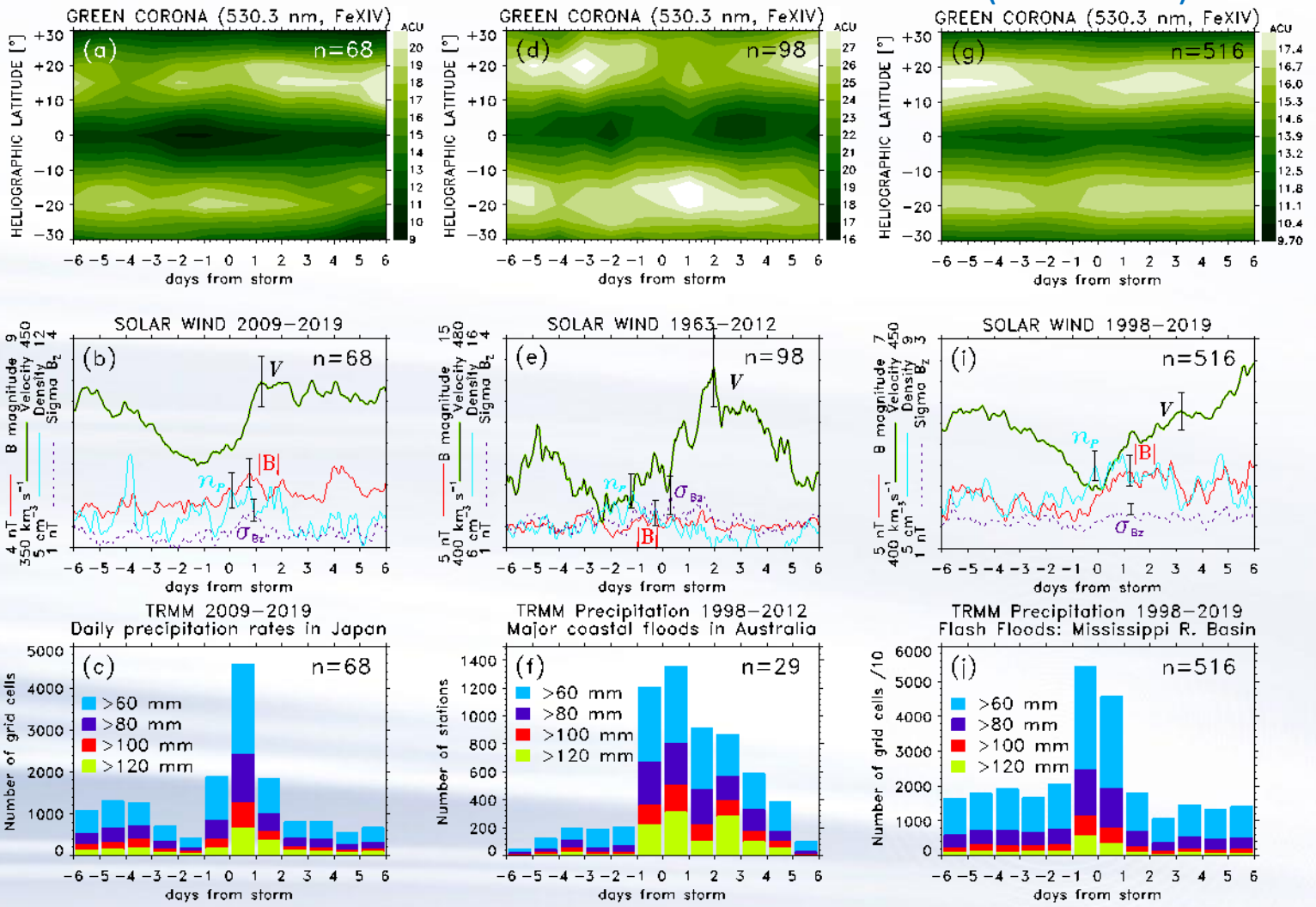
Heavy rainfall events in Japan (2009-2019)

Major coastal flooding in southeastern Australia (1963-2012)

Flash floods in the Mississippi River Basin, U. S. (1998-2019)

SPE analysis of green corona & solar wind parameters **keyed to start dates of heavy rainfall, major floods, and flash floods**

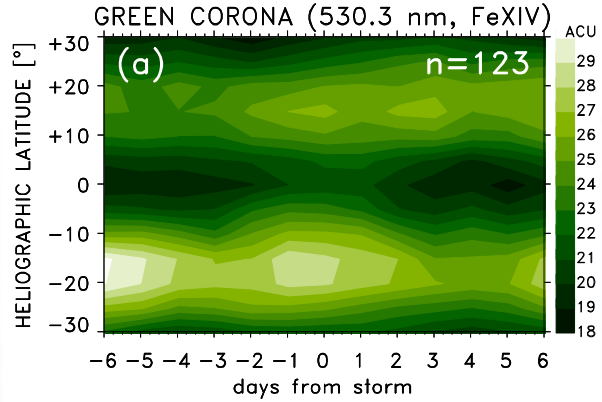
Cumulative number of TRMM grid cells with above-threshold daily precipitation rates



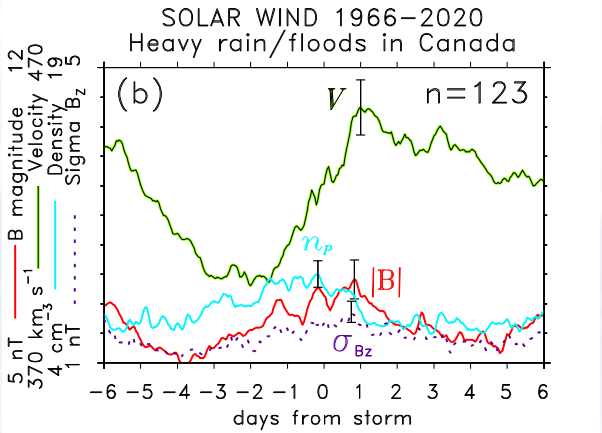
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The SPE analysis

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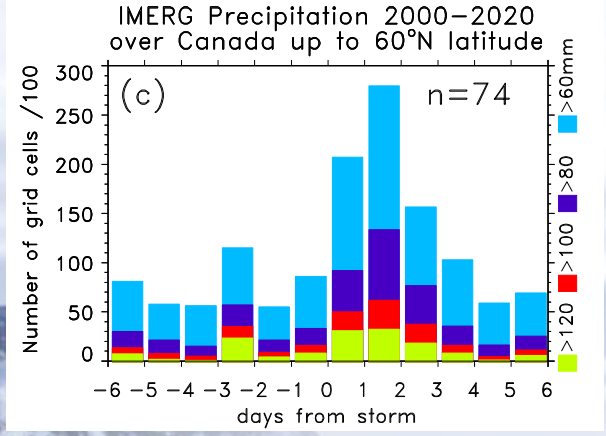


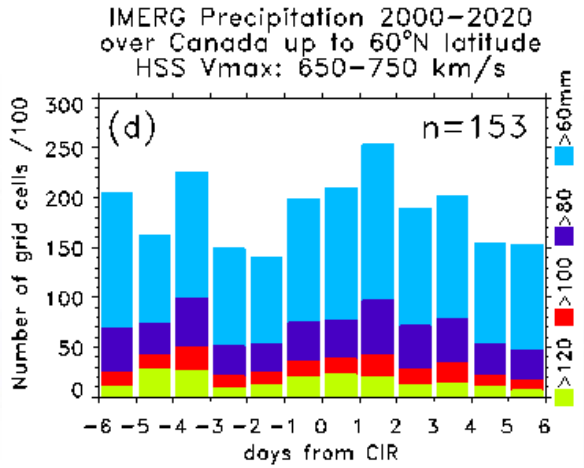
(b) solar wind plasma variables keyed to **← heavy rain / floods** and **arrivals of major HSS/CIRs (d, e, f) →**

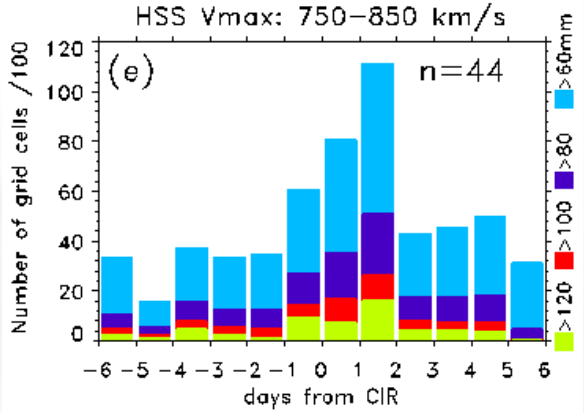


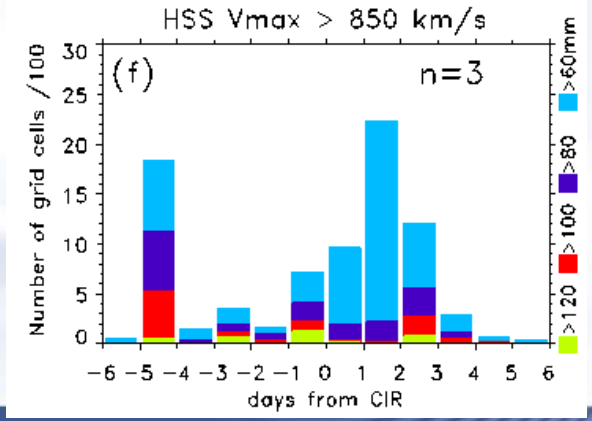
Canada

(c) The cumulative number of IMERG grid cells with above-threshold daily precipitation rates









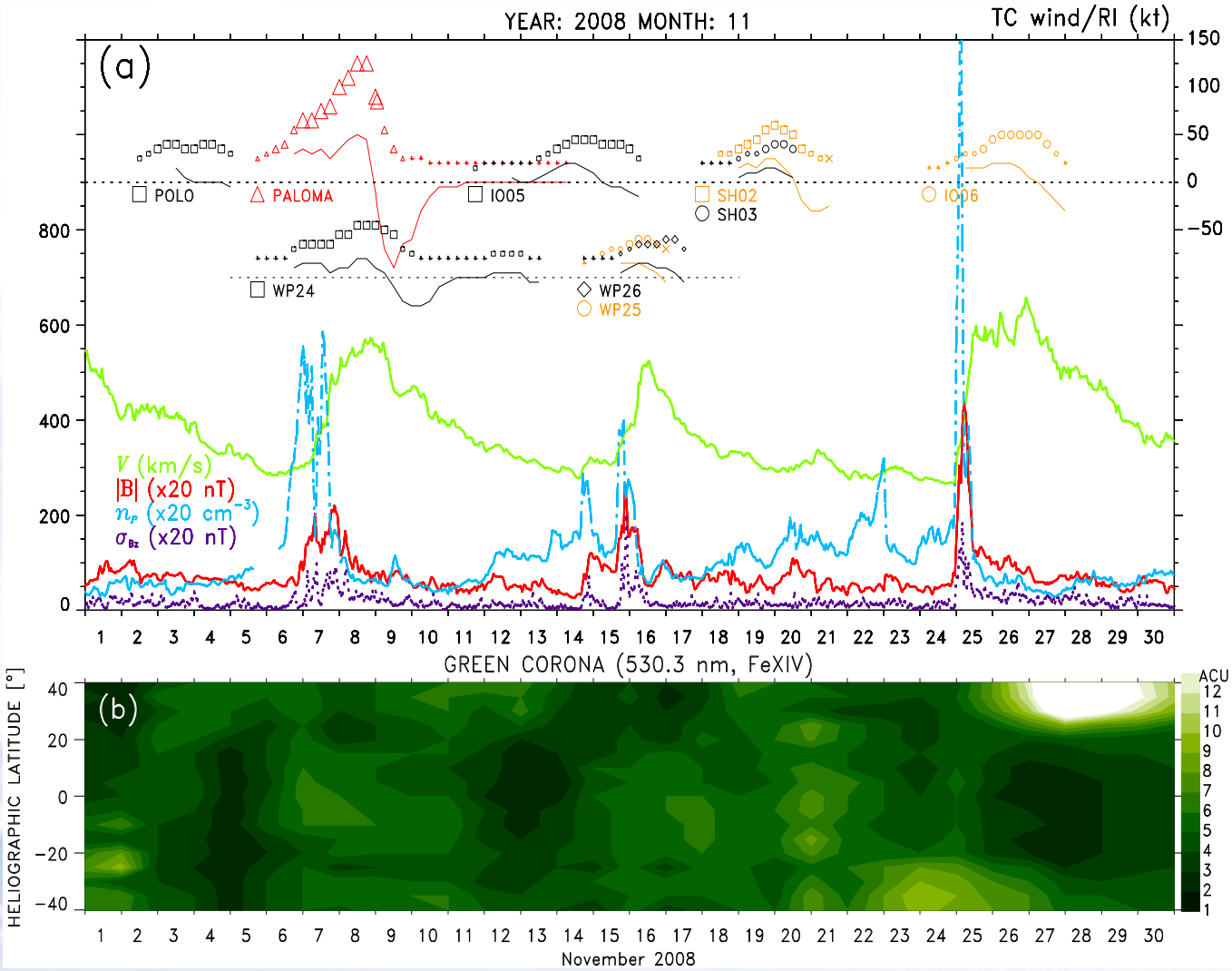
Rapid intensification (RI) of tropical cyclones

(Prikryl P., et al., J. Atmos. Sol.-Terr. Phys. 183, 36-60, 2019)

The “best track” data for tropical cyclones in the northern and southern hemispheres in November 2008: The maximum sustained wind (MSW) and RI in 24 h (thin solid lines).

Solar wind parameters

(b) Synoptic map of green corona intensity interpolated to the central solar meridian

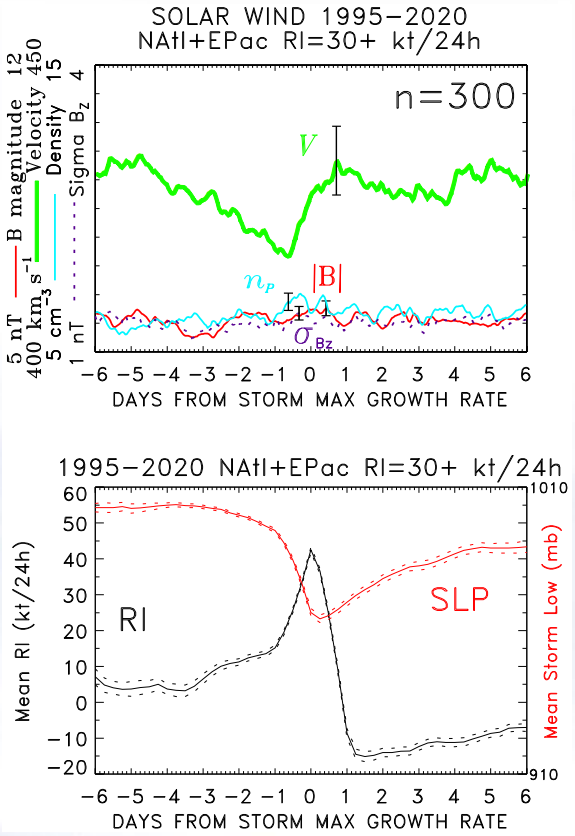


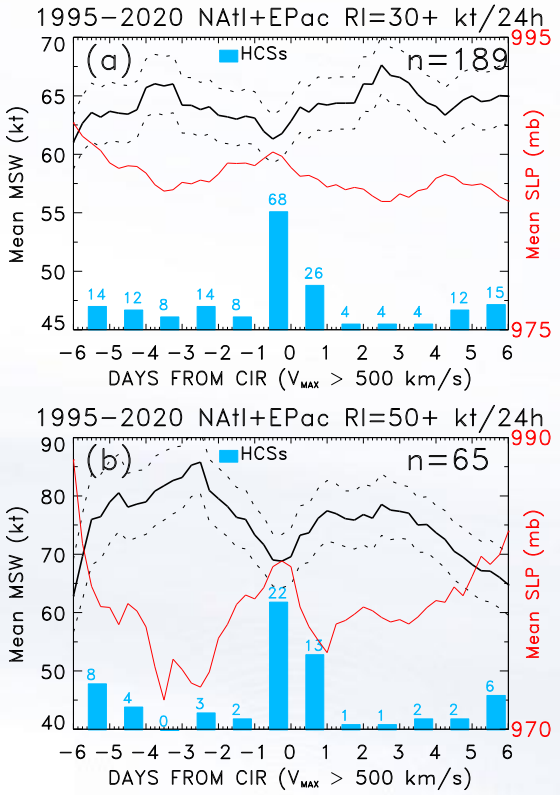
Rapid intensification of hurricanes

(Prikryl P., et al., J. Atmos. Sol.-Terr. Phys. 183, 36-60, 2019)

(left) The SPE analysis of solar wind variables keyed to the first maximum rapid intensification (RI) that exceeded maximum sustained wind (MSW) of 30 kt shows a pattern that suggests a tendency of RIs to follow arrivals of HSS/CIRs.

(right) The SPE analysis of the mean MSW and the mean SLP for hurricanes that exceeded given RI thresholds within the period ±6 days from the key time defined by the arrivals of major HSS/CIRs. The mean RI increases as the SLP deepens following the arrival of major HSS/CIRs.



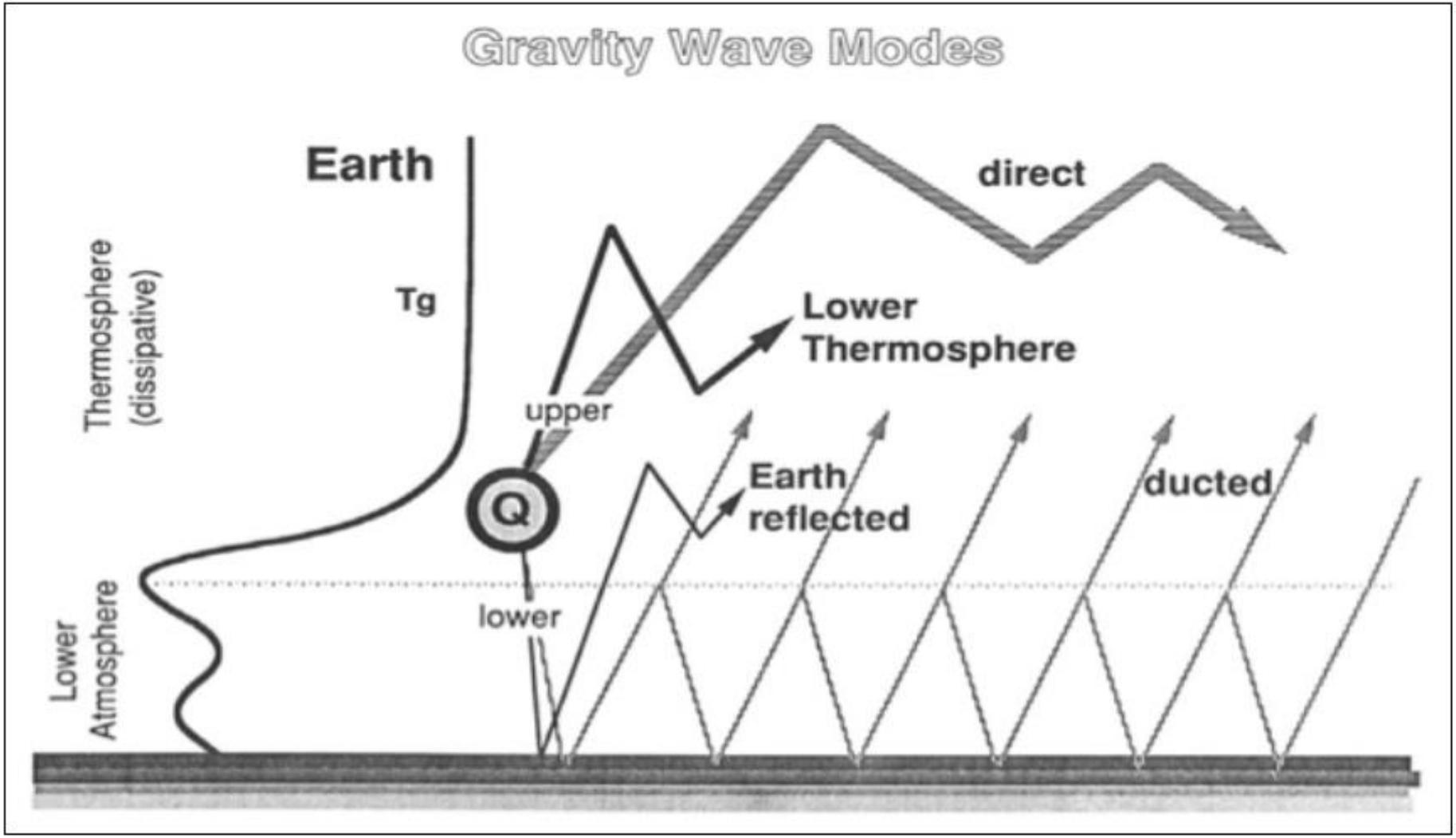


HURDAT2 database of “best tracks” of TCs for the Atlantic and East Pacific basins is provided by the National Hurricane Center (NHC).

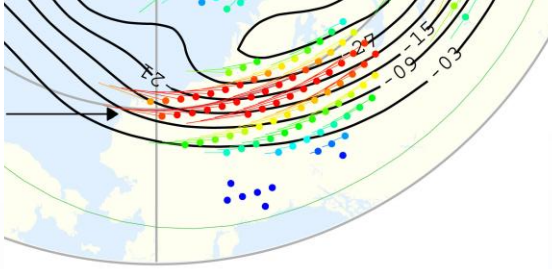
Can convection in the troposphere be triggered/initiated by aurorally-generated atmospheric gravity waves?

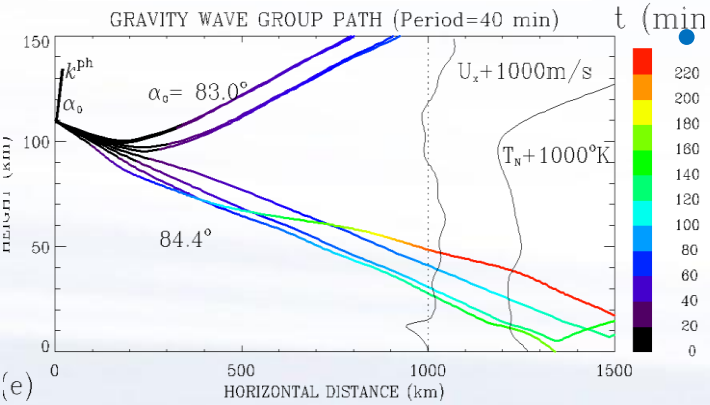
Possible sources of AGWs:

Joule heating, Lorentz force, or energetic particle precipitation in the high-latitude lower thermosphere. (Chimonas and Hines, 1970; Chimonas, 1970; Testud, 1970; Richmond, 1978)



Mayr et al. (1990), Thermospheric gravity waves: Observations and interpretation using the transfer function model. Space Science Reviews 54, 297–375.





Ray tracing gravity waves

- Solar wind pressure pulses modulate ionospheric convection – a source of TIDs
- Ray tracing gravity wave energy using dispersion relation by Hines (1960)

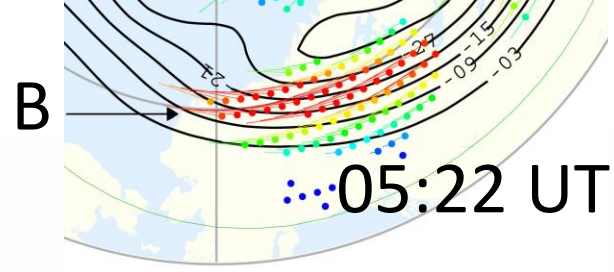
Prikryl P., et al., Ann. Geophys., 27, 31-57, 2009.

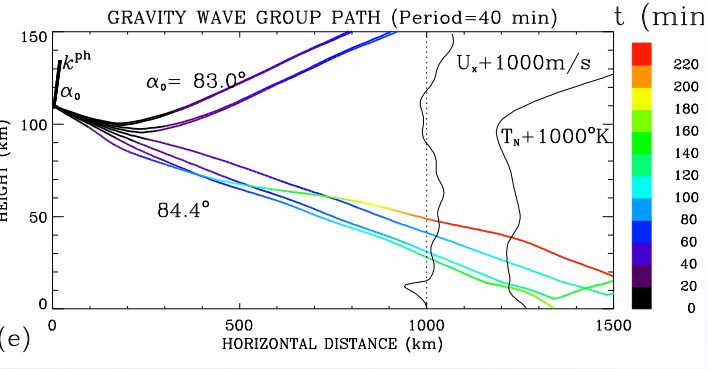
$$(\omega^2 - \omega_a^2)\,\omega^2 / C^2 - \omega^2 (k_x^2 + k_z^2) + \omega_b^2 k_x^2 = 0$$

$\omega_a = \gamma g/2C$ is the acoustic cutoff frequency,
γ, C, g are the ratio of specific heats, speed of sound, and acceleration due to gravity,
k_x and k_z are the components of the wave vector **k**.

Brunt-Väisälä (buoyancy) frequency ω_b is defined as

$$\omega_b^2 = (\gamma\text{-}1) g^2 / C^2 + (g / C^2)\,(dC^2 / dz)$$





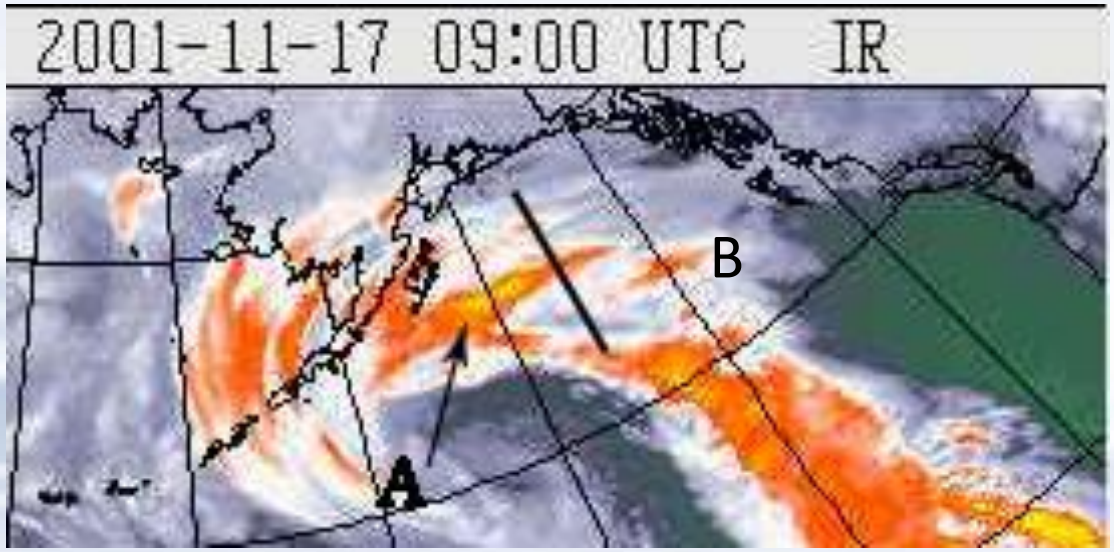
Gravity waves initiate convection

- Solar wind pressure pulses modulate ionospheric convection – a source of TIDs

Ray tracing of gravity wave energy

using dispersion relation by Hines (1960)

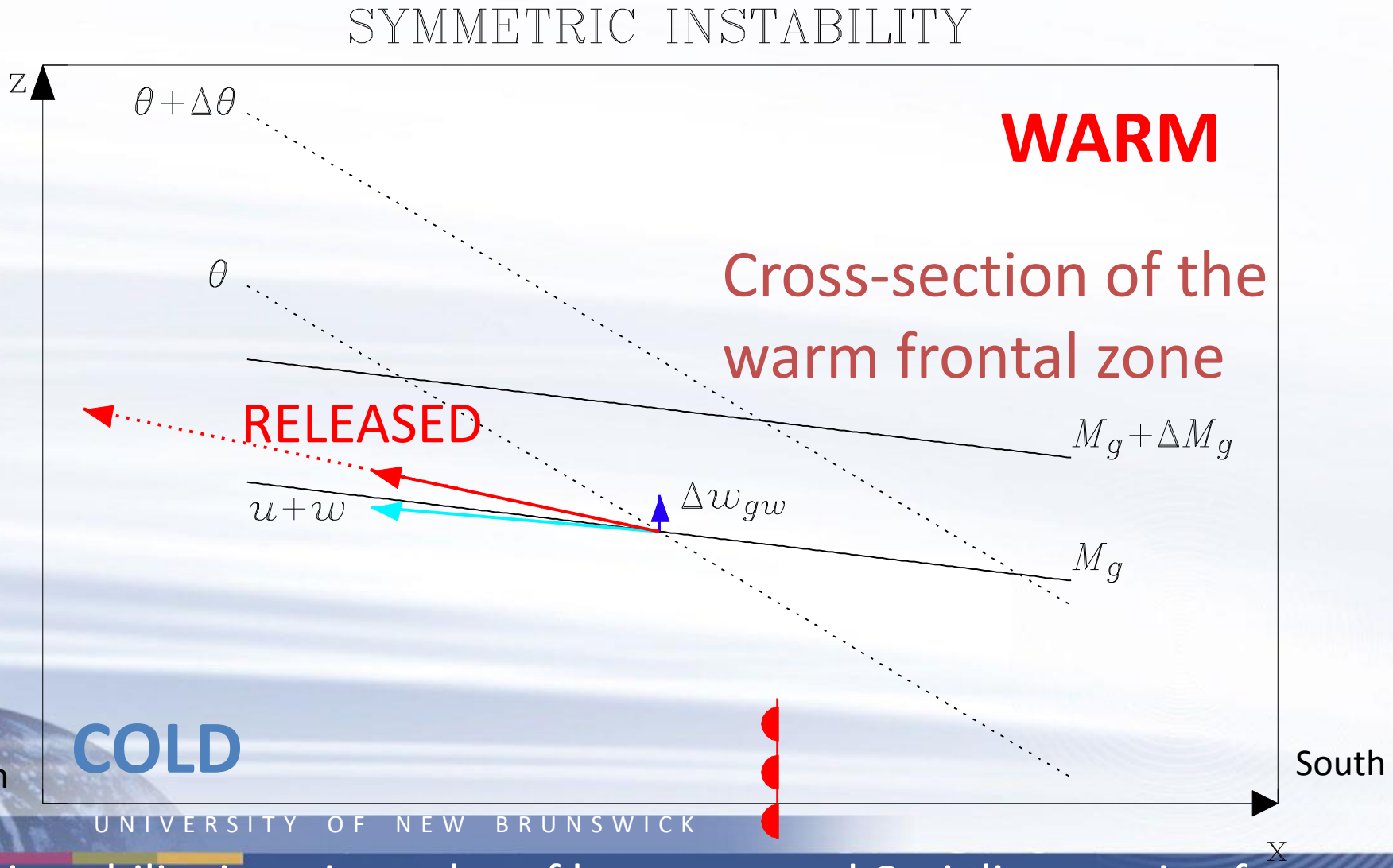
Down-going GWs that can reach troposphere may initiate convection forming cloud bands in extratropical cyclones.



Prikryl P., et al., Ann. Geophys., 27, 31-57, 2009

Slantwise convection initiated by AGWs

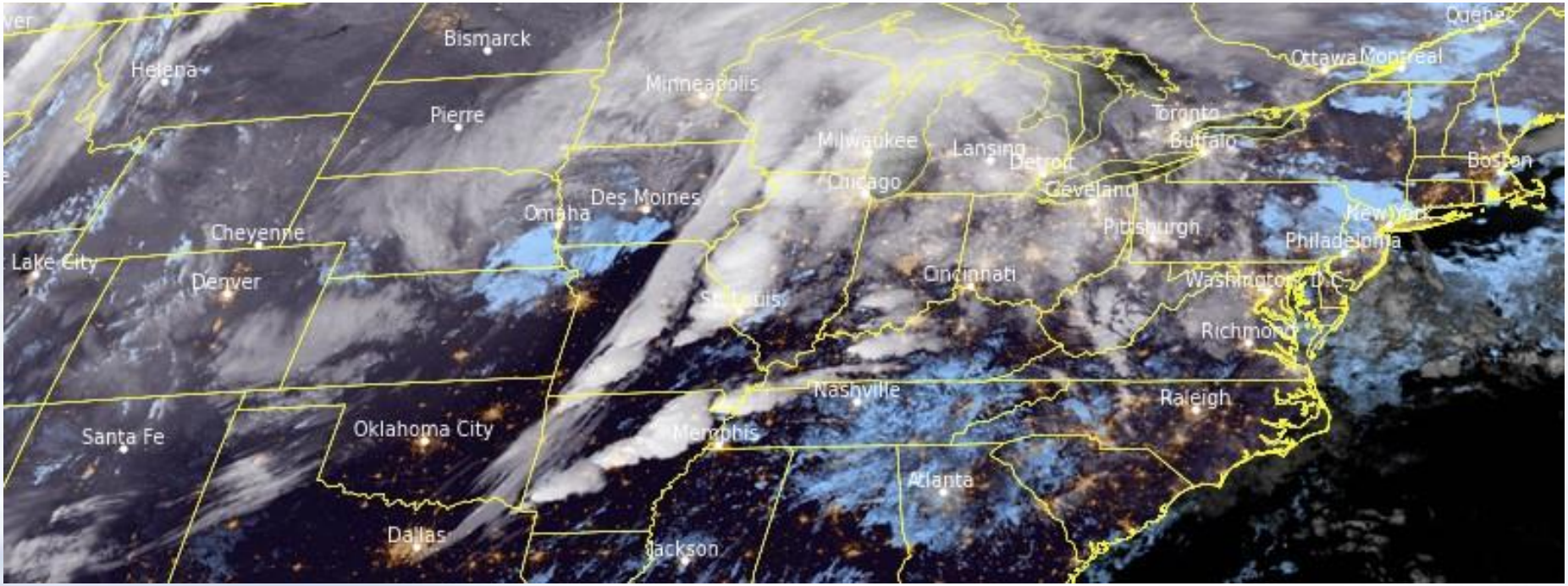
The slopes of isolines of potential temperature θ and geostrophic momentum Mg in the x-z plane are such that ∂θ/∂z > 0 and ∂Mg/∂x > 0, meaning that the atmosphere is stable to purely vertical and horizontal displacements.



The instability is an interplay of buoyancy and Coriolis restoring forces.

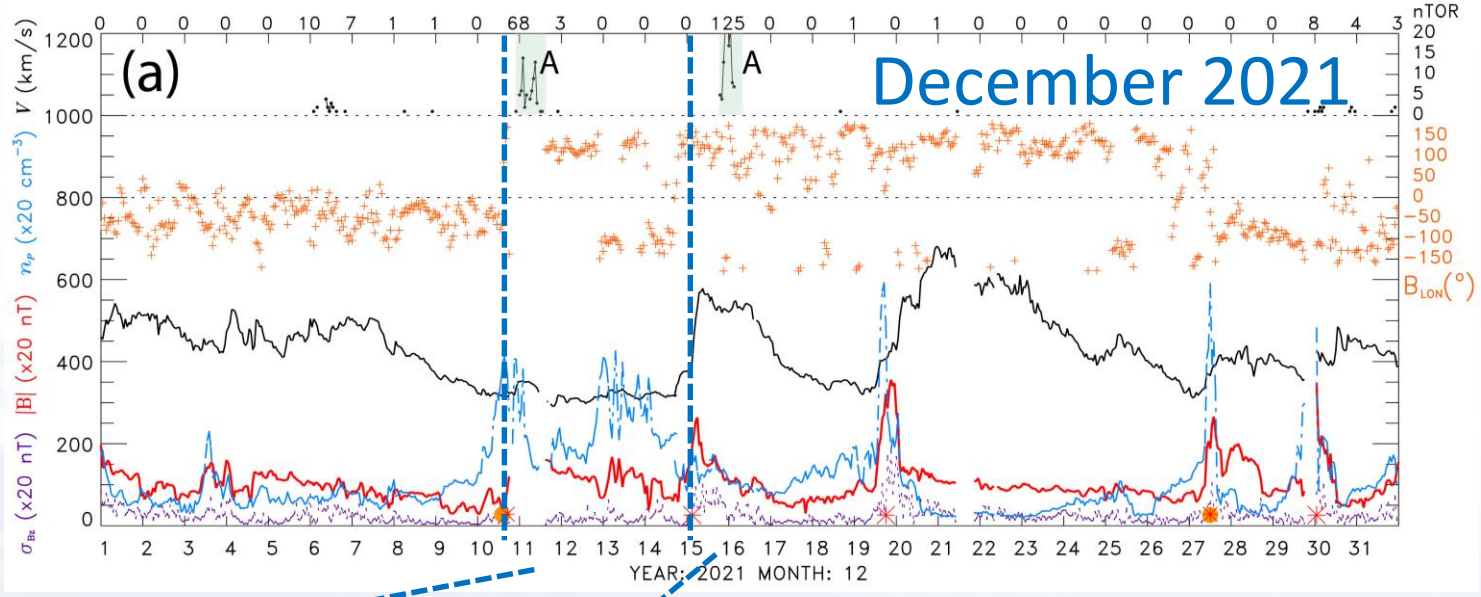
Tornado outbreak hits U.S. South and Midwest

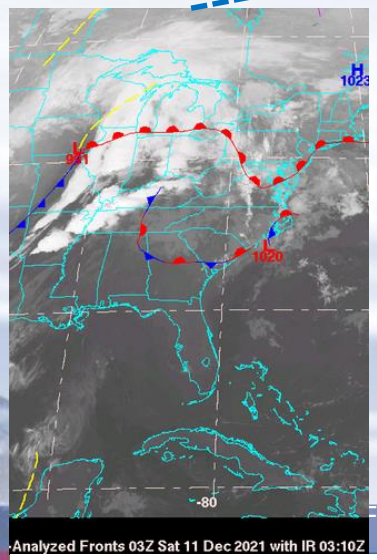
December 11, 2021

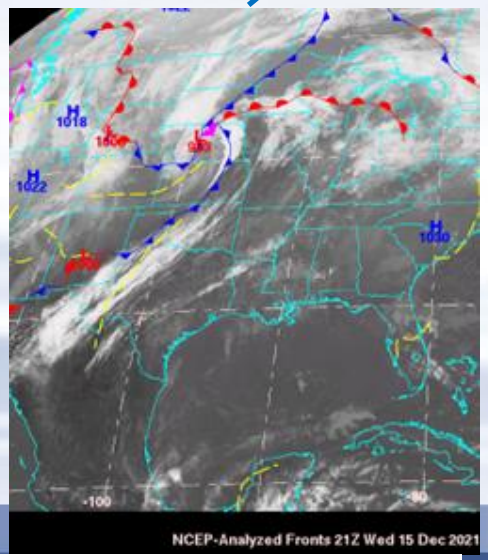


Such instabilities are likely present when violent tornado outbreaks occur. This large tornado outbreak in December 2021 occurred in the frontal regions of an intensifying extratropical cyclone following arrival of HCS and CIR at the leading edge of a minor HSS.

Recent tornado outbreaks in the context of solar wind

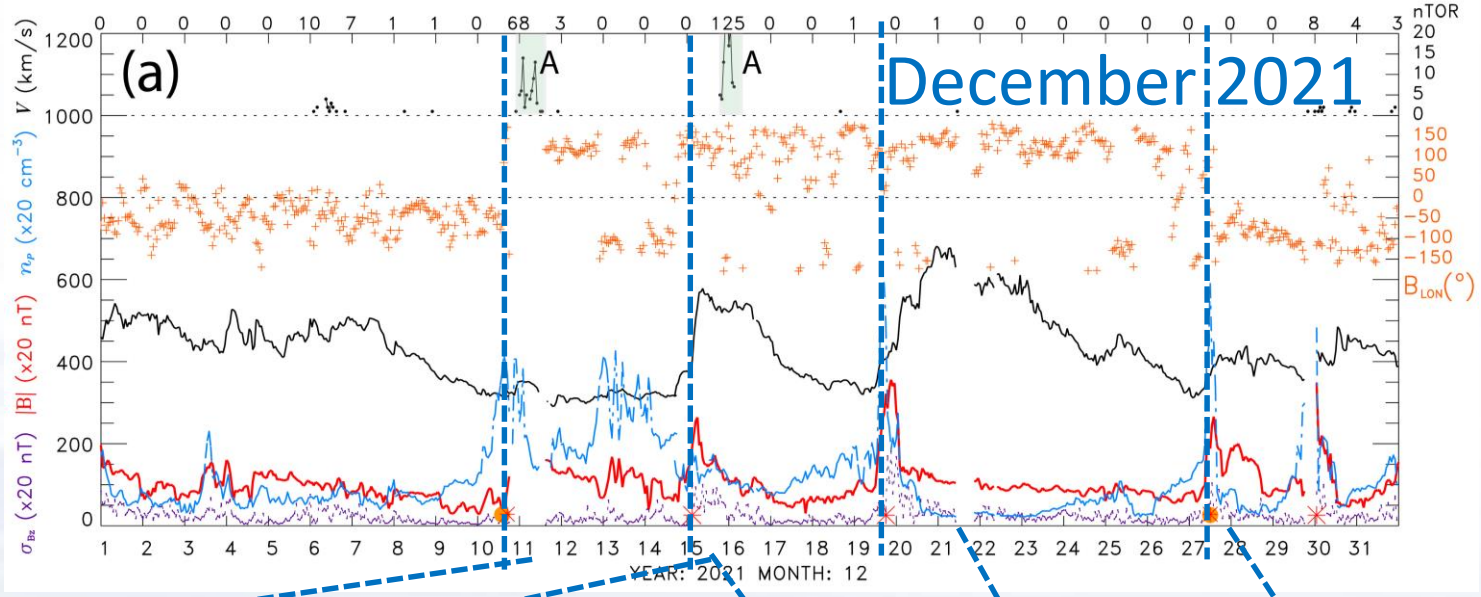


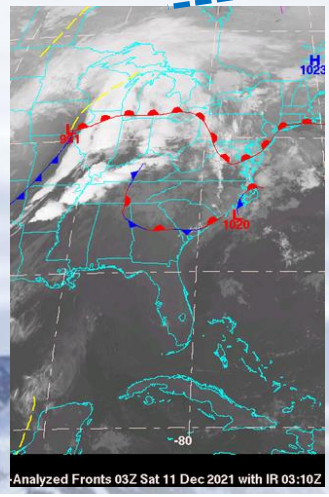


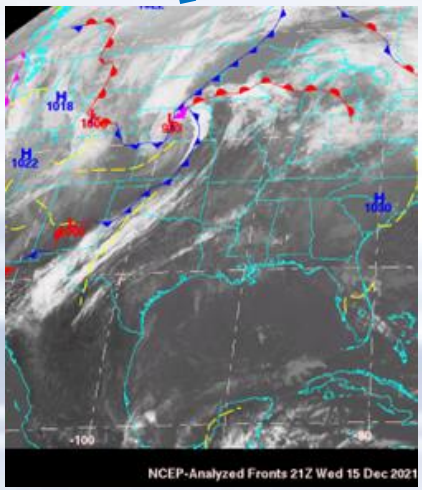


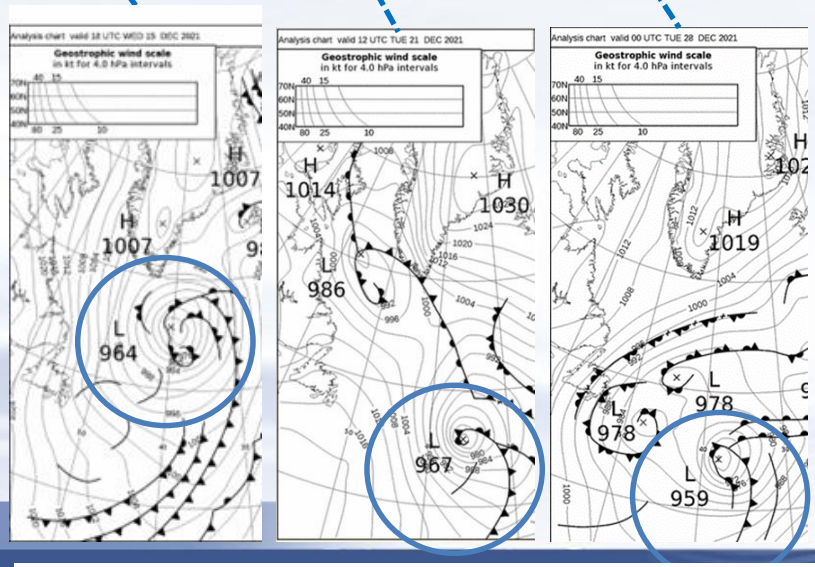
https://a.atmos.washington.edu/data/data.php?loc=satellite

Recent tornado outbreaks & intensifying cyclones





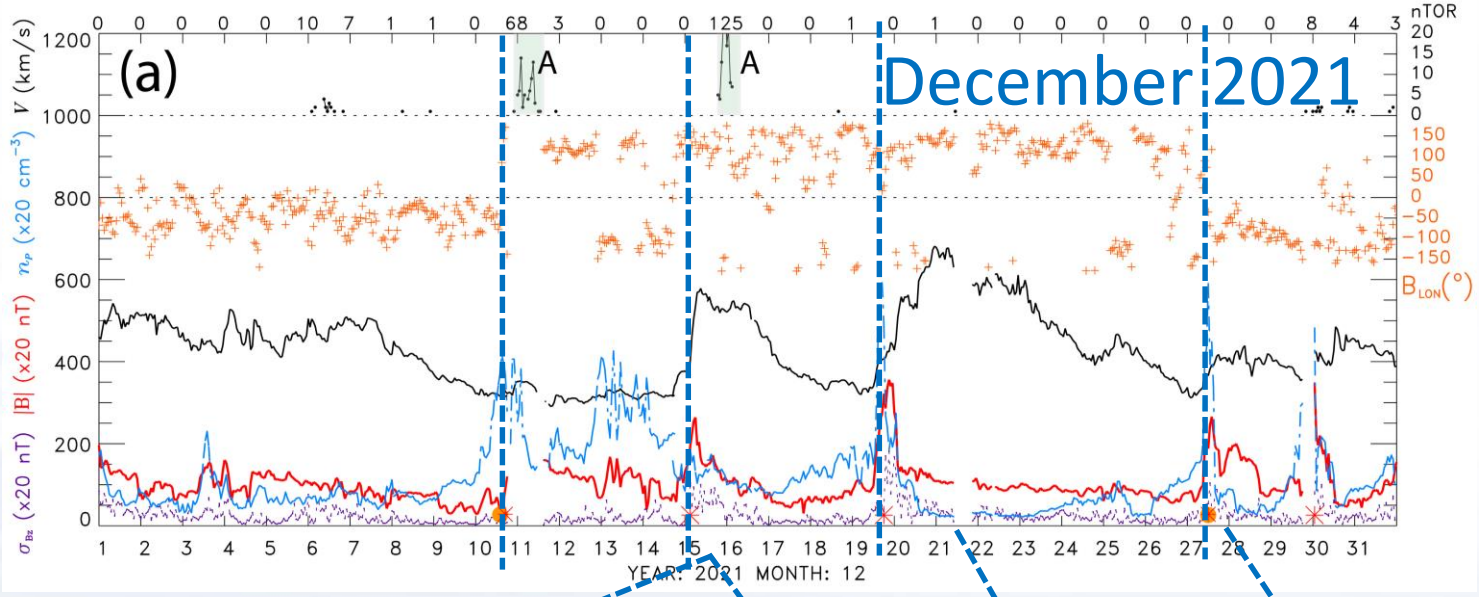


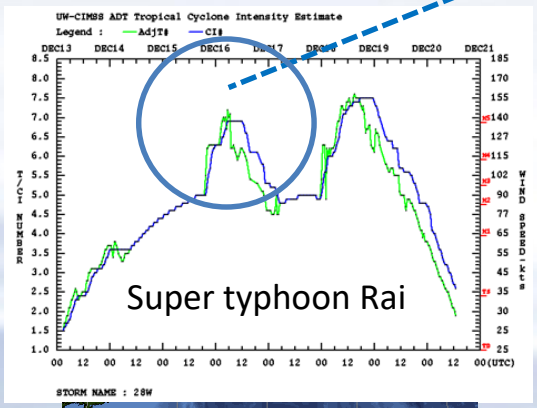


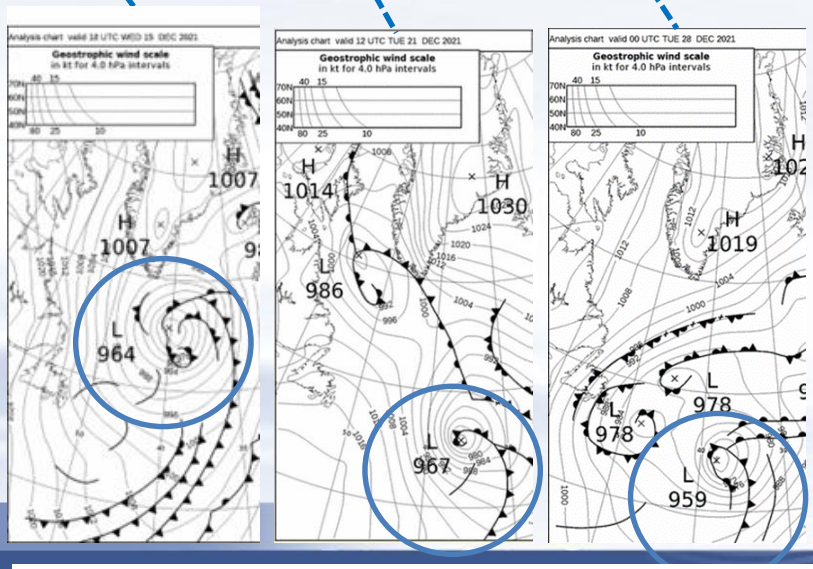
https://a.atmos.washington.edu/data/data.php?loc=satellite

https://www1.wetter3.de/Archiv/archiv_ukmet.html

Recent tornado outbreaks & intensifying cyclones







https://tropic.ssec.wisc.edu/tropic.php#

https://www1.wetter3.de/Archiv/archiv_ukmet.html

Summary and Conclusions

- **Severe weather events** including
  - explosive extratropical cyclones (Prikryl et al., 2009, 2016)
  - rapid intensification of tropical cyclones (Prikryl et al., 2019)
  - heavy rainfall and flash floods (Prikryl et al., 2018, 2021)

  tend to follow arrivals of high-speed solar wind streams - HSS/CIRs.
- Large tornado outbreaks are frequently associated with high-density solar wind adjacent to HCSs, or tend to follow HSS/CIRs or ICMEs (subject of a study).

Proposed interpretation:

- Solar wind coupling to the magnetosphere-ionosphere-atmosphere system generates atmospheric gravity waves (AGWs).
- AGWs propagate globally from lower thermosphere at high latitudes upward & downward, and can reach troposphere
- AGWs can trigger/release moist instabilities to initiate convection leading to latent heat release that provides energy to intensify storms.