Ninth Workshop
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Comparative analysis of short-term effects of solar and galactic cosmic rays on the lower atmosphere circulation in the Northern hemisphere

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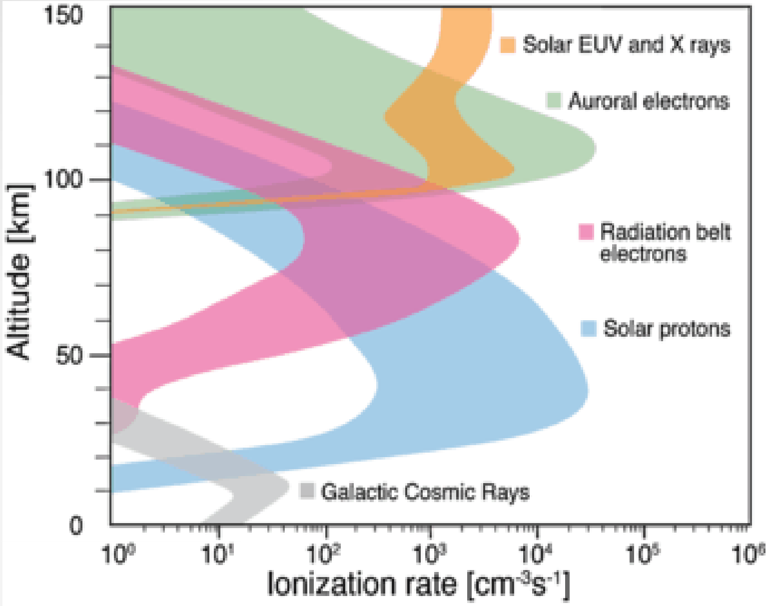
Cosmic ray variations as one of the links between solar activity and the lower atmosphere circulation

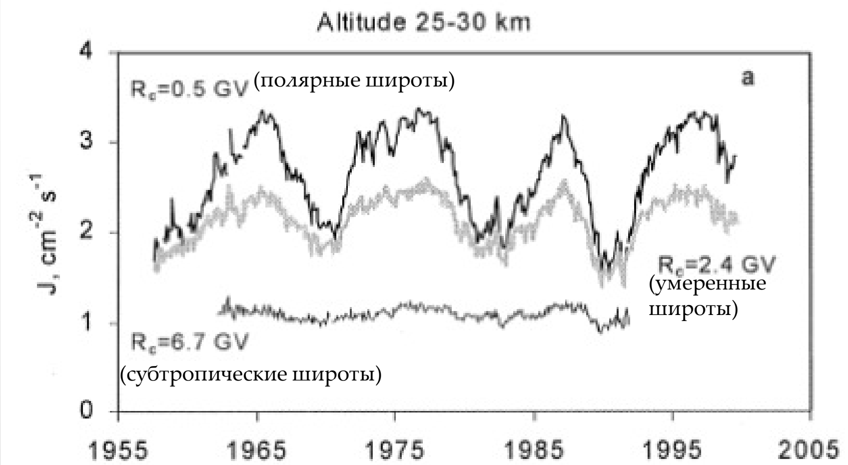


[Baker et al., 2012; Mironova et al., 2015]

Fluxes of energetic charged particles are now considered as an important link between processes on the Sun and the lower atmosphere dynamics.

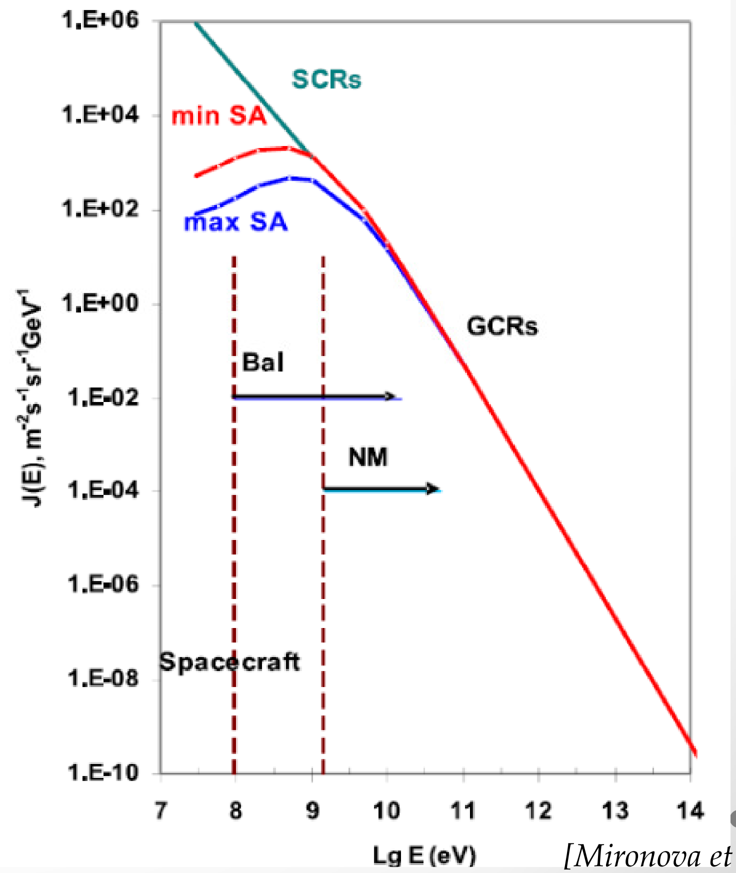
Ionization of the atmosphere below 50 km is due to **solar and galactic cosmic rays.**

Latitudinal dependence of GCR fluxes



[Bazilevskaya et al., 2000]

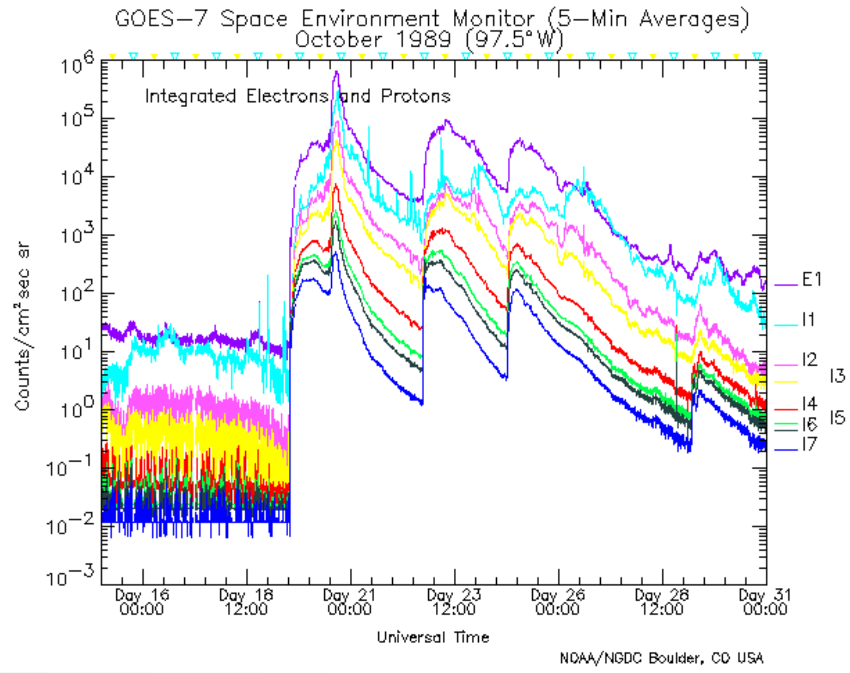
Cosmic ray variations in the 11-yr cycle



[Mironova et al., 2015]

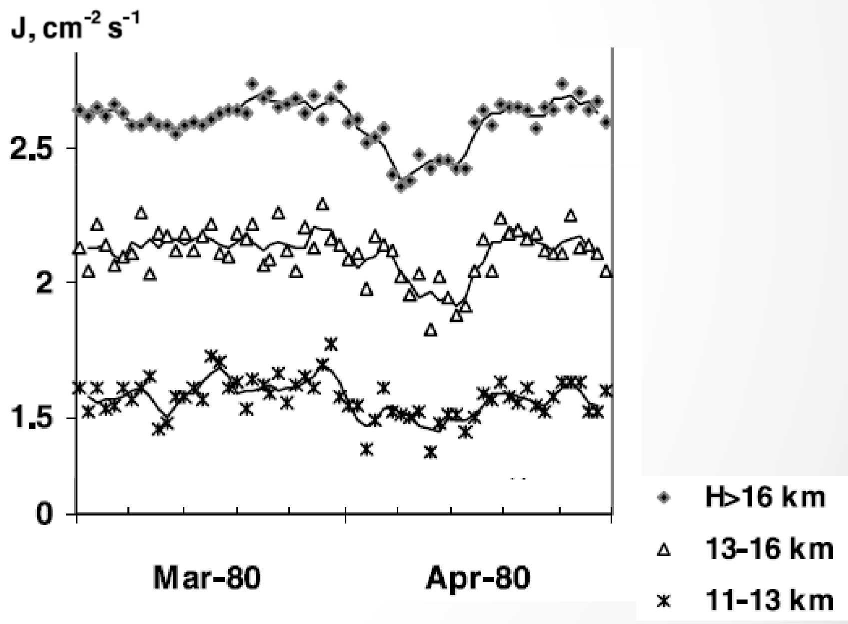
Short-term variations of cosmic rays

- Solar proton events (SPE)



Series of SPEs started on 19 October 1989 (according to GOES-7).

- Forbush decreases of galactic cosmic rays (GCR)

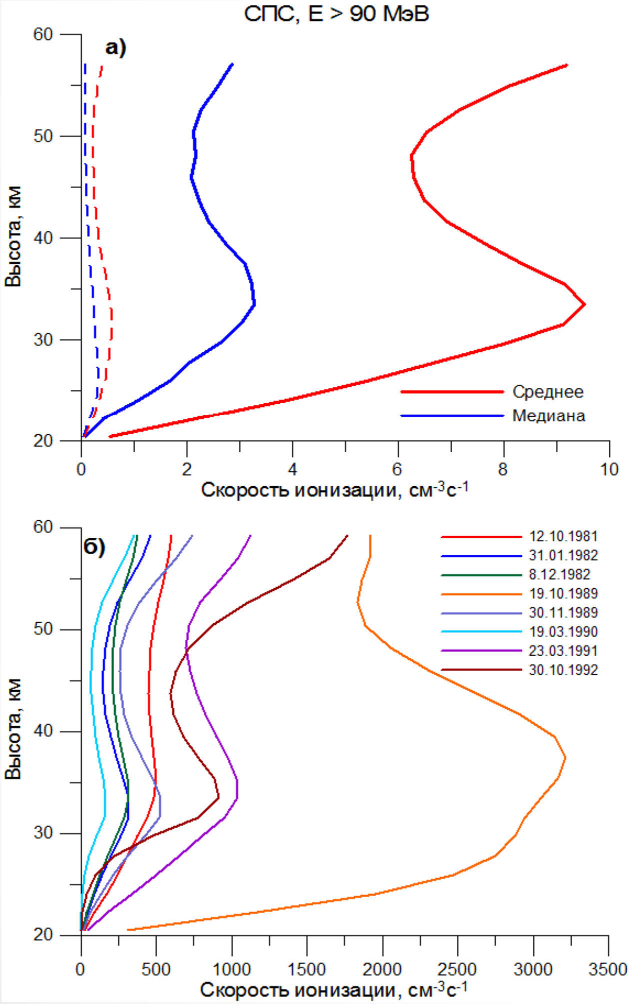


Forbush decrease of GCR started on 31 March 1980 (Murmansk)

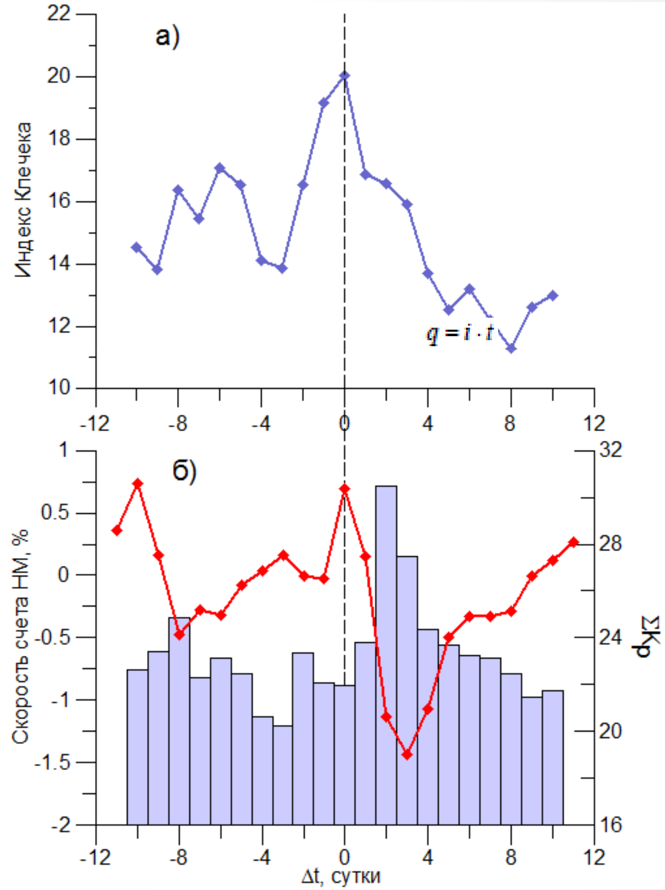
[Bazilevskaya et al., 2008]

Solar Proton Events: data used

- **48** isolated **SPEs** with energies **>90 MeV**, cold half of year (October-March) 1980-1996 according to Catalogues of SPEs 1990, 1998 (Ed. Logachev Yu.I.)
- Geopotential heights of the isobaric level 500 hPa (GPH500) according to reanalysis data NCEP/NCAR [Kalnay et al., 1996]

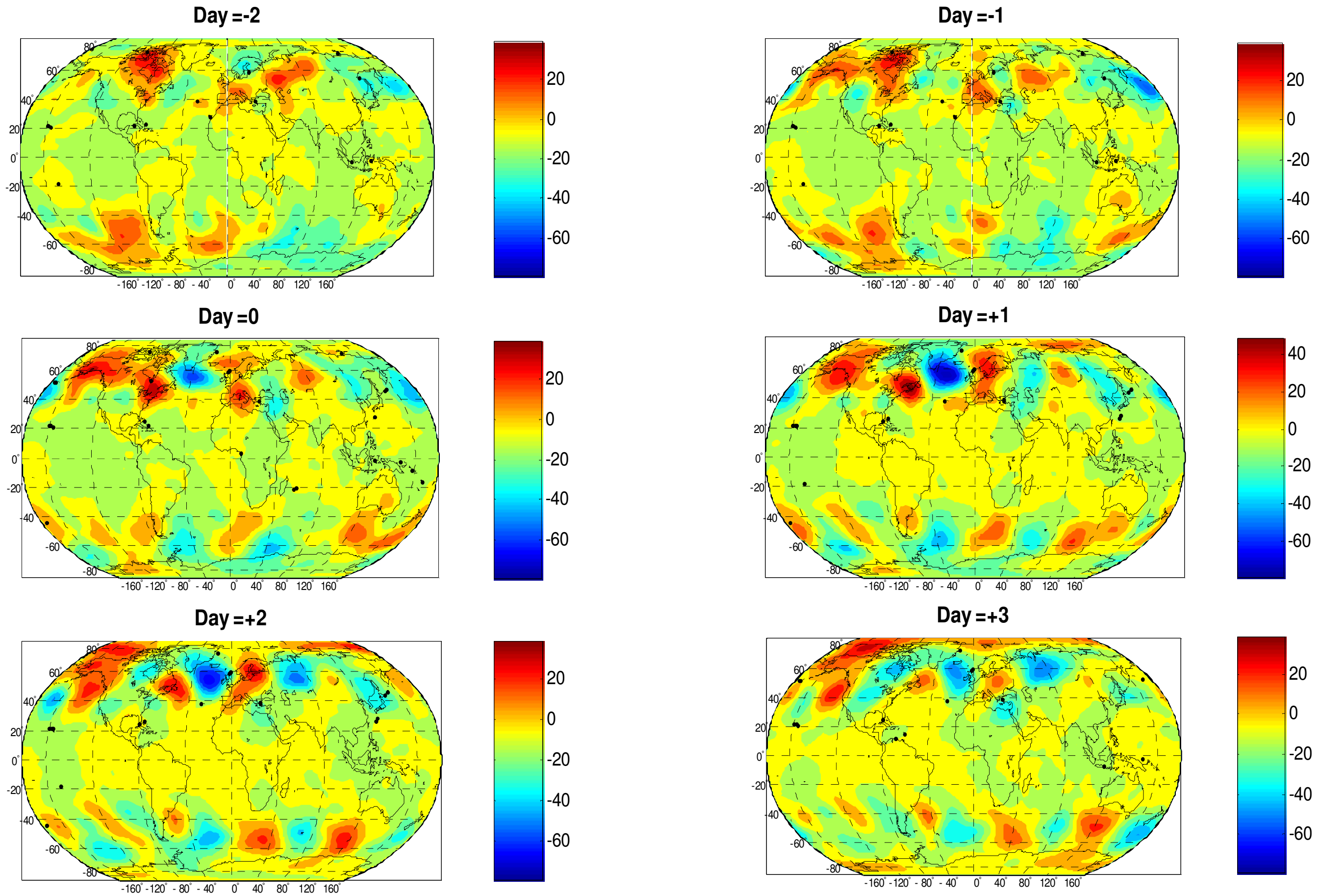


Daily values of ionization rate in the polar cap (Φ= 60-90º) during the SPEs under study according to the data SOLARIS-HEPPA.



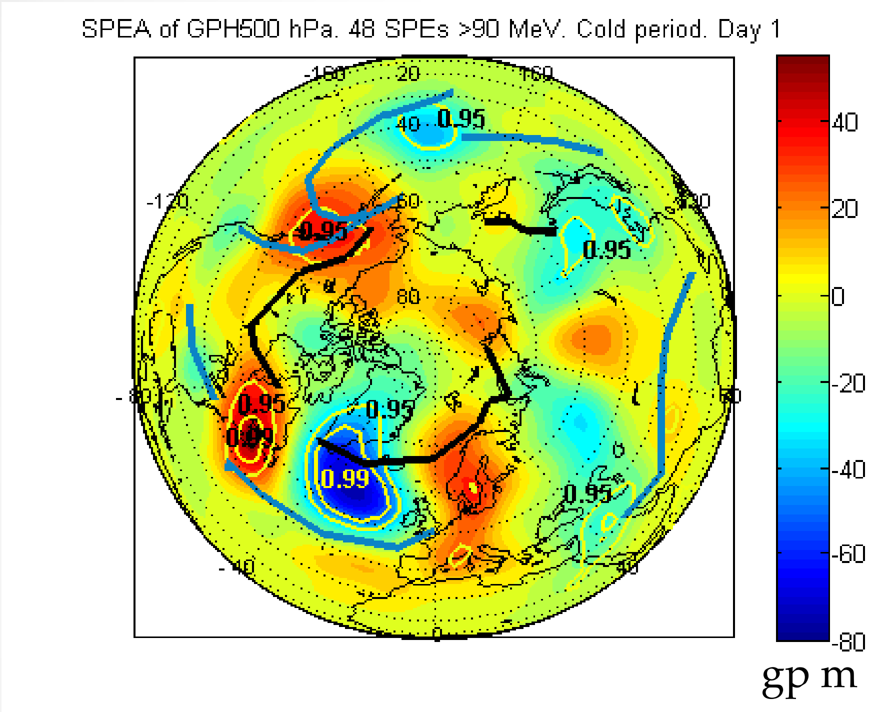
Distribution of solar-geophysical indices relative to the key days (days of SPE onsets)

Mean changes of troposphere pressure (GPH500) associated with energetic SPEs



Superposed epoch analysis of GPH500 deviations from the mean level over the period ±10 days relative to the event onsets for 48 SPEs (October-March, 1980-1996).

Spatial distribution of pressure variations in the Northern hemisphere after the SPE onsets and climatic positions of the main atmospheric fronts



Mean changes of GPH500 on the next day after the SPE onset (Δt=+1 day) . Number of events N=48, cold months.

Climatic position main atmospheric fronts according to [Khromov and Petrociants, 1994] is shown:

Arctic fronts – black lines, Polar fronts – blue lines

Yellow lines show areas of statistical significance of pressure variations estimated according to Monte-Carlo methods.

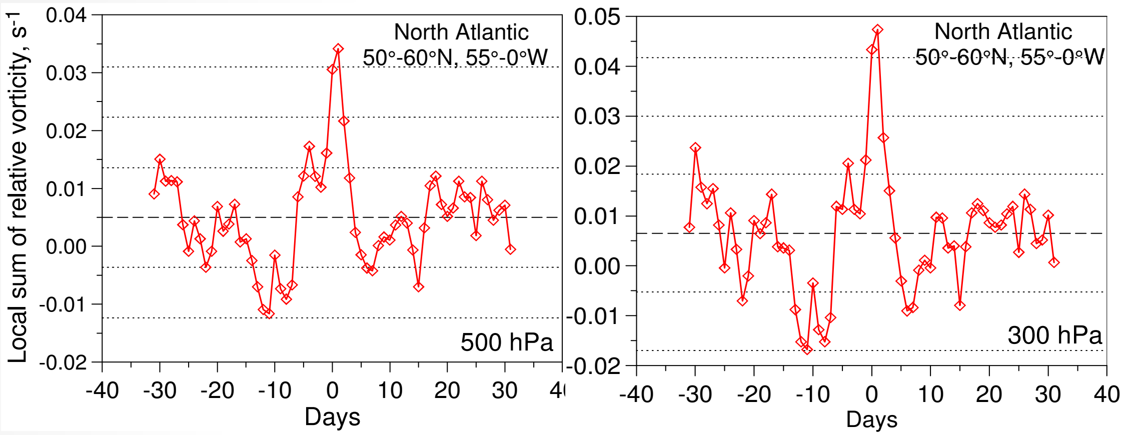
Most statistically significant pressure variations associated with SPEs are observed in **the North Atlantic region**.

Maximum pressure decrease takes place near the south-eastern coasts of Greenland where high-latitudinal **Arctic fronts** are formed.
Arctic fronts separate cold Arctic air from warmer air of middle latitudes.

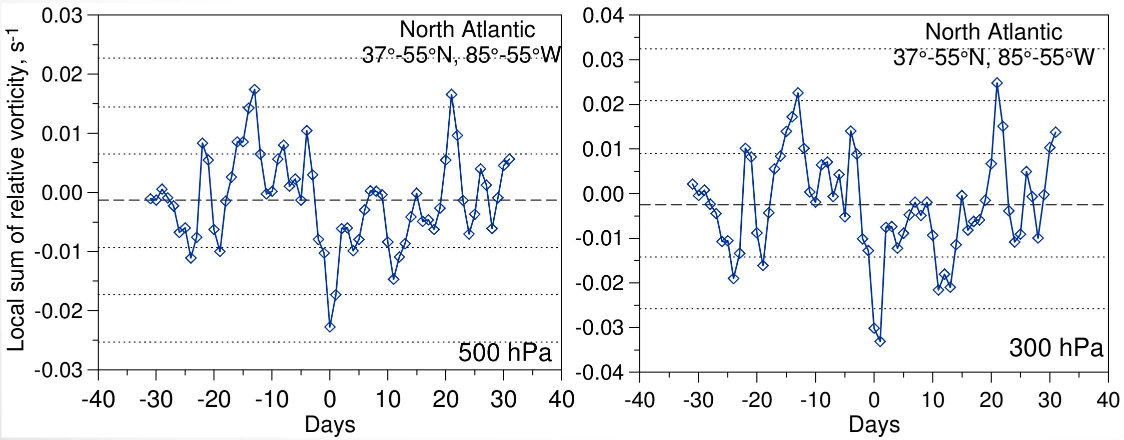
Pressure decrease over the North Atlantic is accompanied by the formation of high-pressure crest over Northern and Central Europe, as well as high-pressure area near the coasts of North America.

Relative vorticity changes in the areas of most pronounced pressure variations

South-eastern coasts of Greenland and Island low



Eastern coasts of North America



To characterize vortices in the atmosphere a vortex of wind velocity is used

$$\vec{\Omega} = \nabla \times \vec{V}$$

Relative vorticity (vertical component of the velocity vortex)

$$\Omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

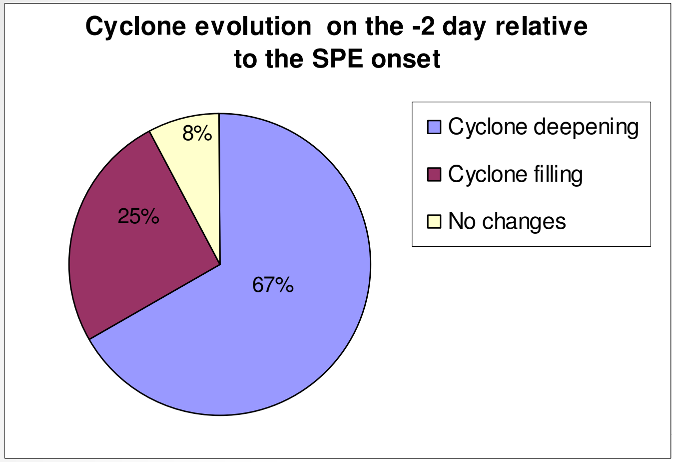
characterizes air movements in the horizontal plane.

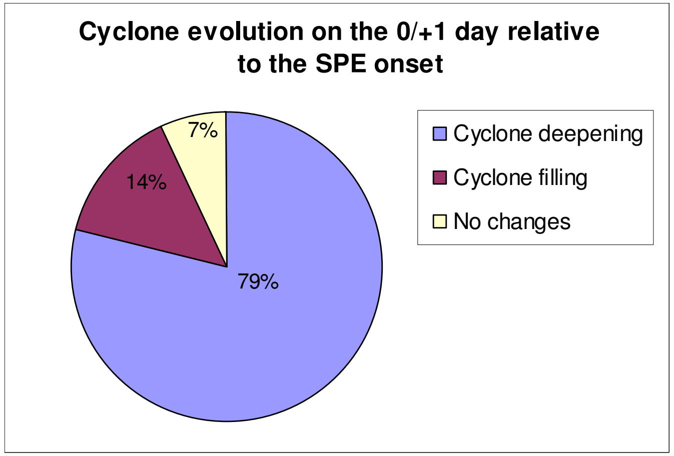
Relative vorticity in the course of energetic SPEs :

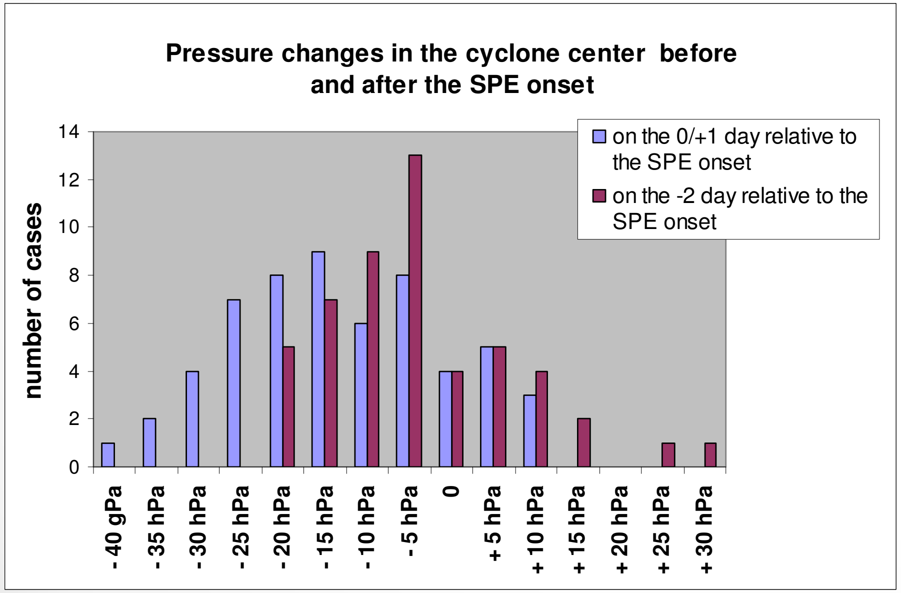
- **increases** in the area of the south-eastern coasts of Greenland (**strengthening of cyclonic processes**)

- **decreases** (negative values) near the coasts of North America (**strengthening of anticyclonic processes**)

Changes of cyclone evolution associated with energetic SPEs according to the weather chart analysis





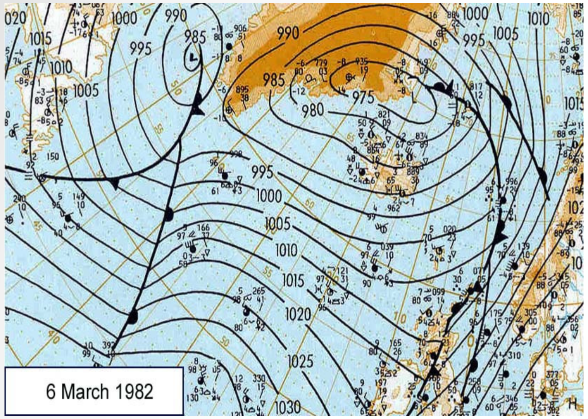


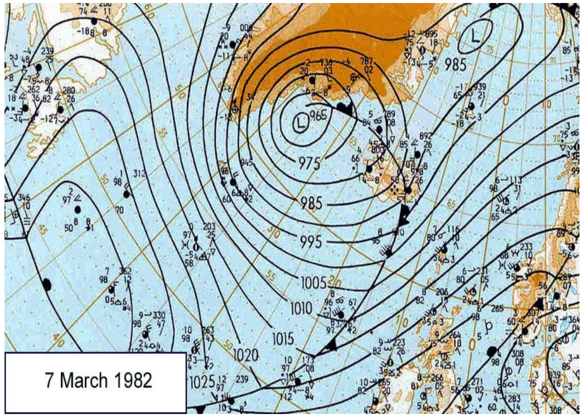
The weather chats analysis indicates **an intensification of cyclone deepening** in the North Atlantic (45-65°N) after energetic SPE :

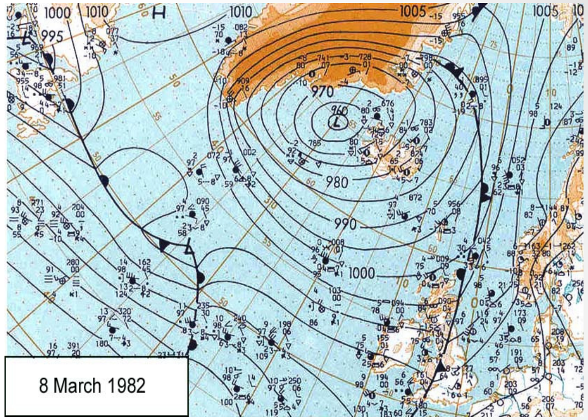
- cyclones deepen more frequently
- pressure in their center drops by greater values compared with undisturbed conditions.

Examples of cyclone deepening associated with energetic Solar Proton Events

SPE 7 March 1982 (>90 MeV)

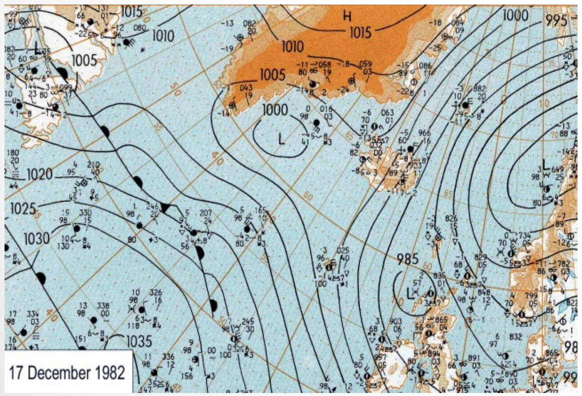


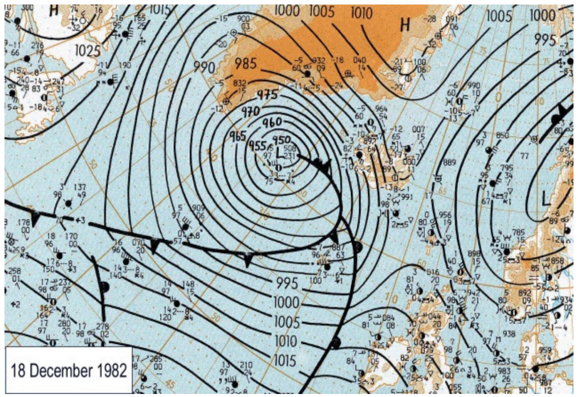


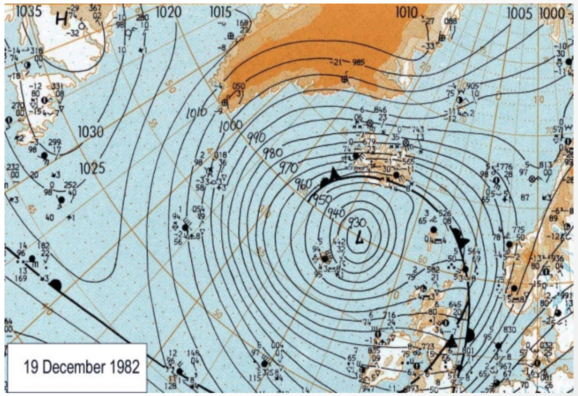


8 hours after the SPE onset

SPE 17 December 1982 (>600 MeV)





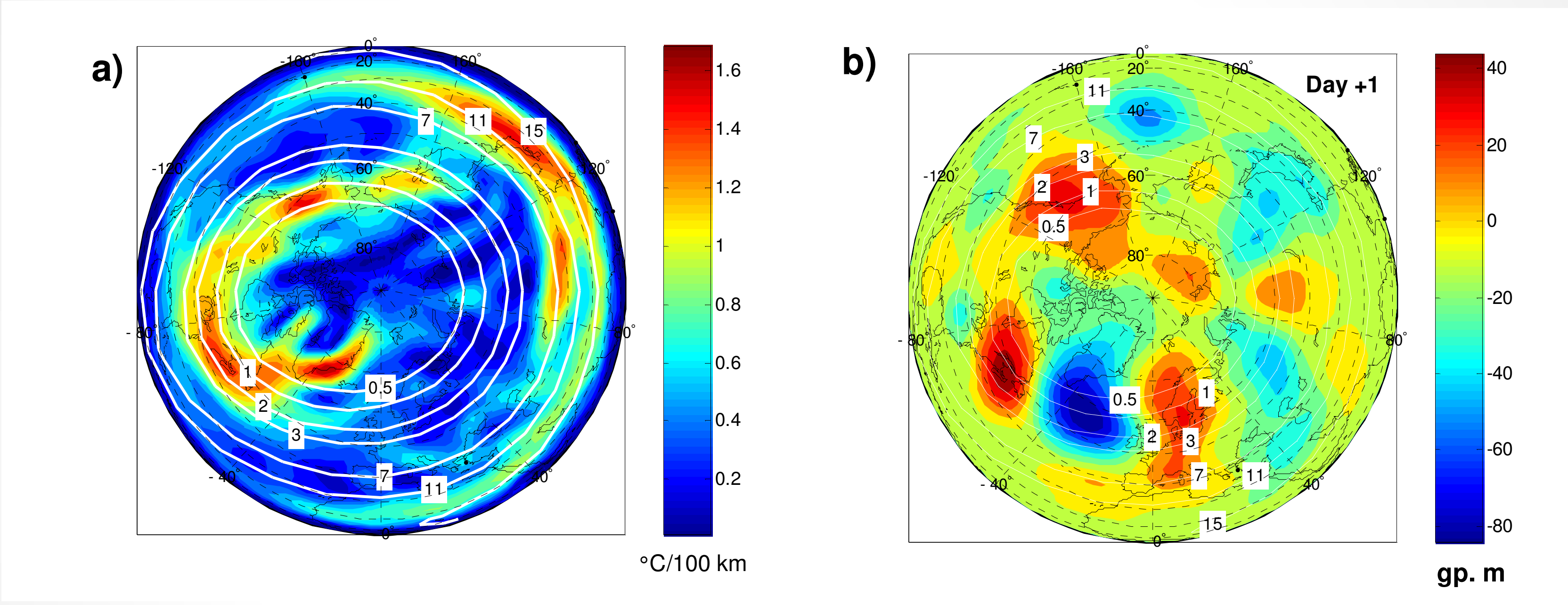


16 hours after the SPE onset

In most cases cyclones deepening near the Greenland coasts after SPEs were occluded (i.e., they reached **the stage of maximum development** and had to start filling).

A secondary deepening of cyclones is called “regeneration” and requires an input of cold air (cold advection). After SPEs cyclone regeneration was intensified.

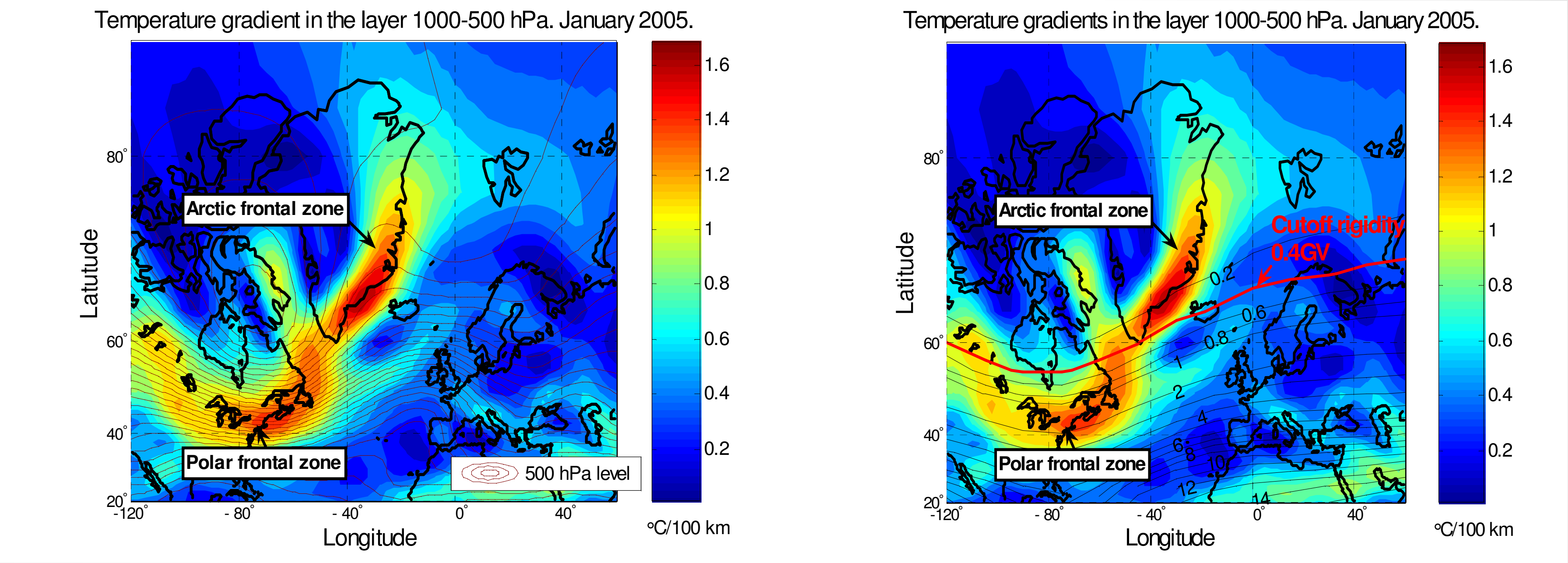
Geomagnetic cutoff rigidities [Shea and Smart, 1983] in the area of most pronounced SPE effects



Charged particle movement in the magnetic field of the Earth is determined by its rigidity $R = Pc/Ze$, where P and Ze are particle impulse and charge, c is the light velocity. To reach any point at the Earth at geomagnetic latitude λ, a particle must have some minimal (cutoff) rigidity $R_c = 14.9 \cdot \cos^4 \lambda \cdot 10^9$

The North Atlantic area where the SPE effects are most pronounced is characterized by **low thresholds of geomagnetic cutoff** **$R_c \leq 0.5$–2 GV** (i.e. minimal energies of precipitating protons **$E_{min} < 0.1$–1 GeV**). **In the North Pacific cyclogenetic area** threshold rigidities are sustantially higher $R_c \sim 7$–15 GV ($E_{min} > 6$–14 GeV) and SPE effects are observed.

Peculiarities of the North Atlantic region



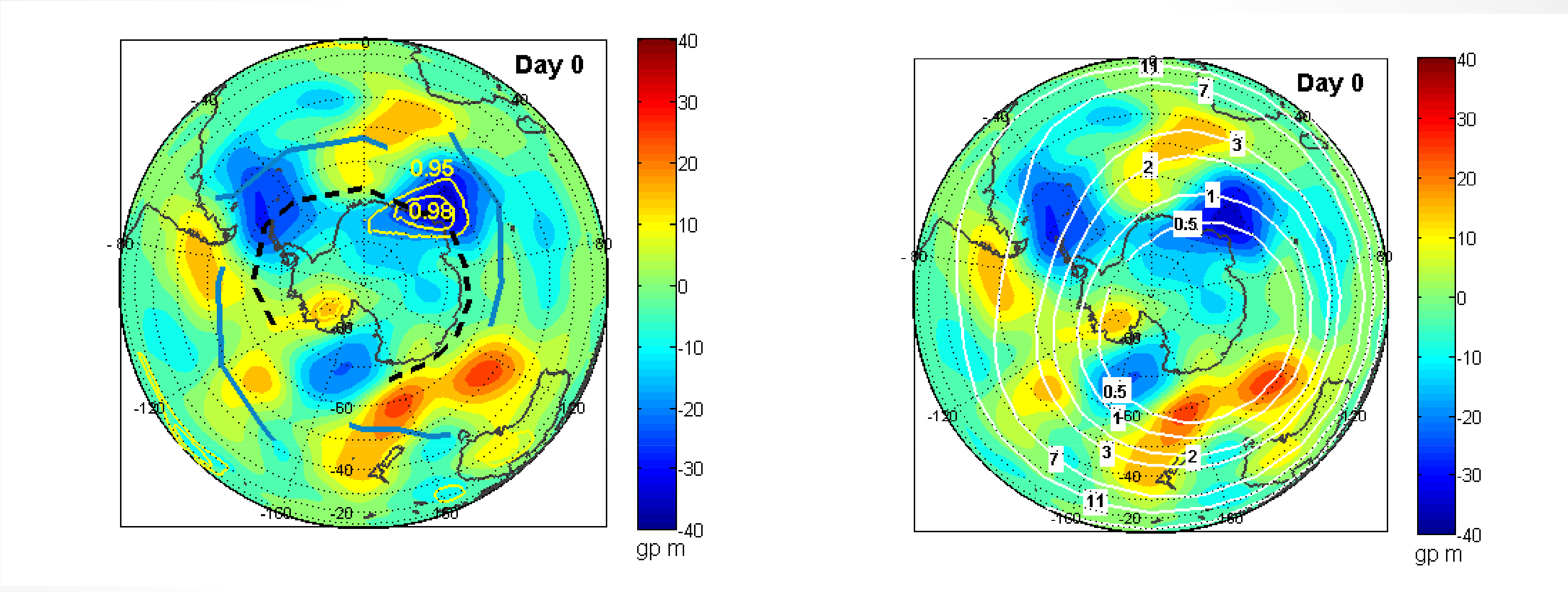
The North Atlantic region is characterized by **a favorable structure of the thermo-baric field** for cyclone deepening:

- **Divergence of isohypses** in the middle troposphere contributing to air outflow
- **High temperature contrasts** near the Greenland coasts creating conditions for **cold advection.** Cold advection is known to intensify cyclonic vortices.

The North Atlantic region are characterized by **low geomagnetic cutoff rigidities**, contributing to cosmic particle precipitation, with energies being ~ 90 MeV.

Effects of Solar Proton Events in the Southern hemisphere

500 hPa



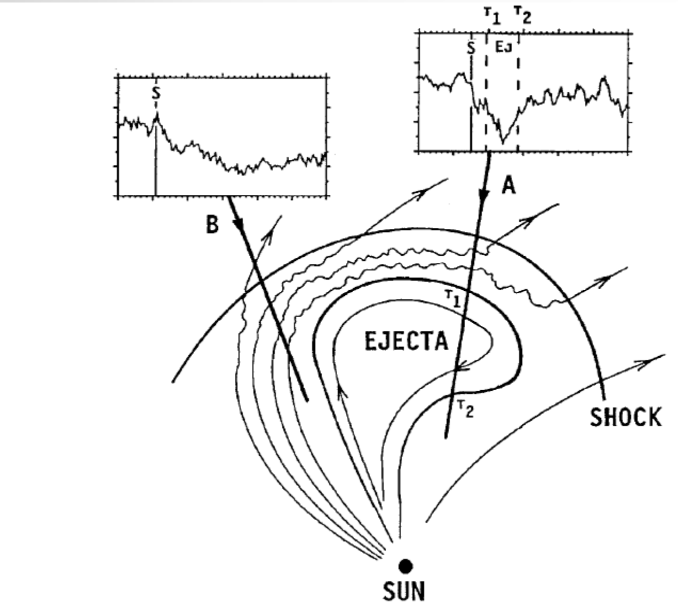
In the Southern hemisphere SPEs under study occur in a warm half of year. However, effects of SPEs were detected, but with a smaller amplitude.

A sharp **pressure decrease (GPH500 lowering)** was observed on the day of the SPE onsets near the coasts of Queen Maud Land in the climatic low area, which is formed due to **regeneration of cyclones at Antarctic fronts**.

The area of most pronounced effects of SPEs in the Southern hemisphere is also characterized by low thresholds of geomagnetic cutoff **$R_c \leq 0.5–2$ GV.**

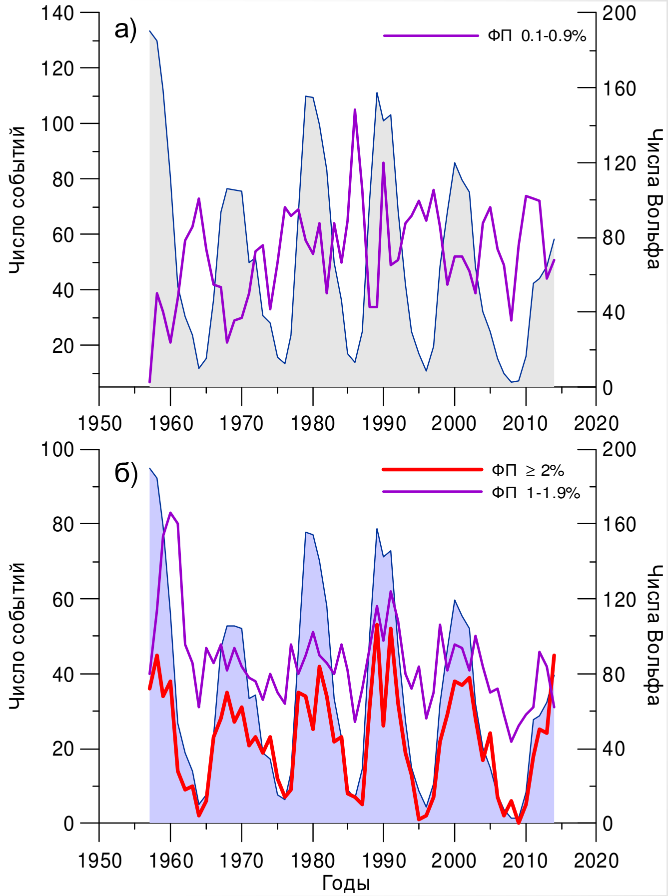
SPE effects on cyclone regeneration are similar in the Northern and Southern hemispheres

Forbush decreases of galactic cosmic rays

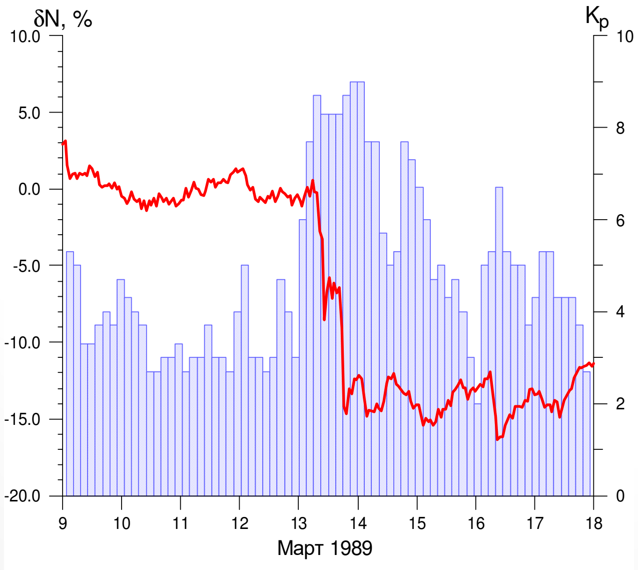


Forbush decreases of GCR are associated with propagating solar wind disturbances.

Scheme of GCR Forbush decrease [Cane, 2000]



Frequency of occurrence of Forbush decreases of GCR depending on the solar activity level (on the base of the IZMIRAN data [Belov, 2009])

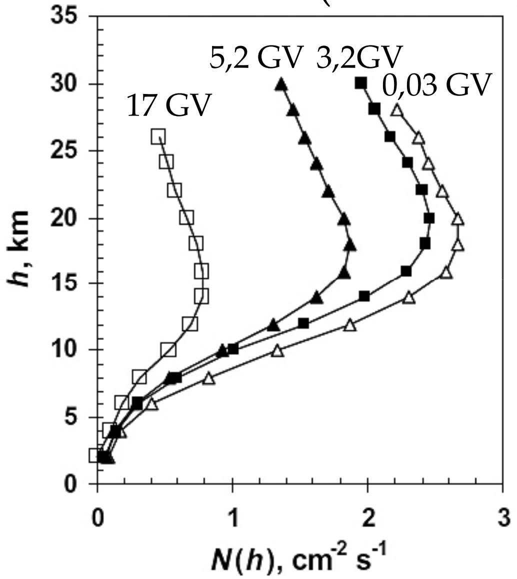


Forbush decrease of GCR during the magnetic storm started on 13 March 1989

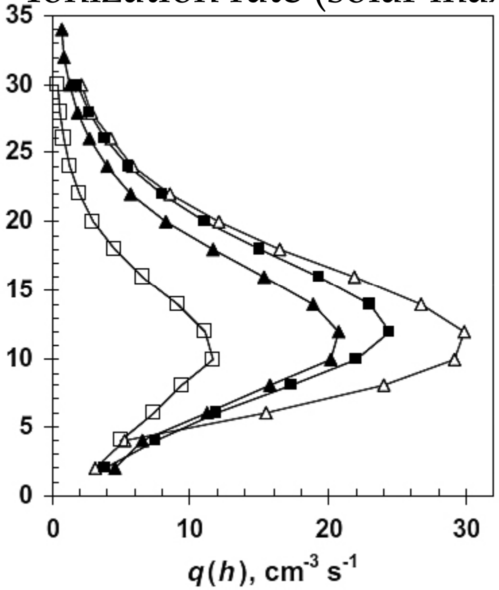
Forbush decreases of GCR: data used

- **48 Forbush decreases** (FD) of GCR, with the amplitude **>2.5%** according to the neutron monitor data in Apatity (geomagnetic cutoff rigidity R=0.65 ГВ) in cold months (October-Mach) 1980-2006
- Geopotential heights of the 1000 hPa pressure level according to reanalisis data NCEP/NCAR (Kalnay et al., 1996)

CR fluxes (solar max)



Ionization rate (solar max)



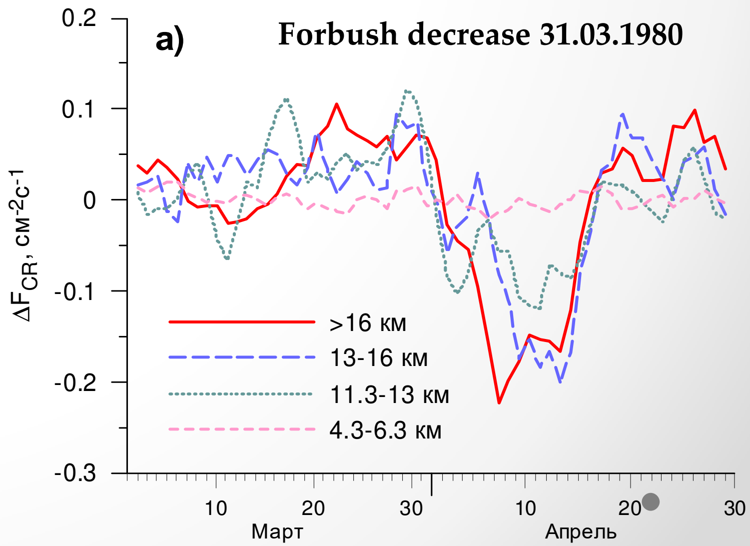
[Stozhkov et al., 2009]

Relation of ionization rate **q** to particle flux **J** [Bazilevskaya et. al., 2008]

$$q / J = A \cdot \exp(-B \cdot H)$$

Middle and high latitudes (R_c = 0.5–3 ГВ):

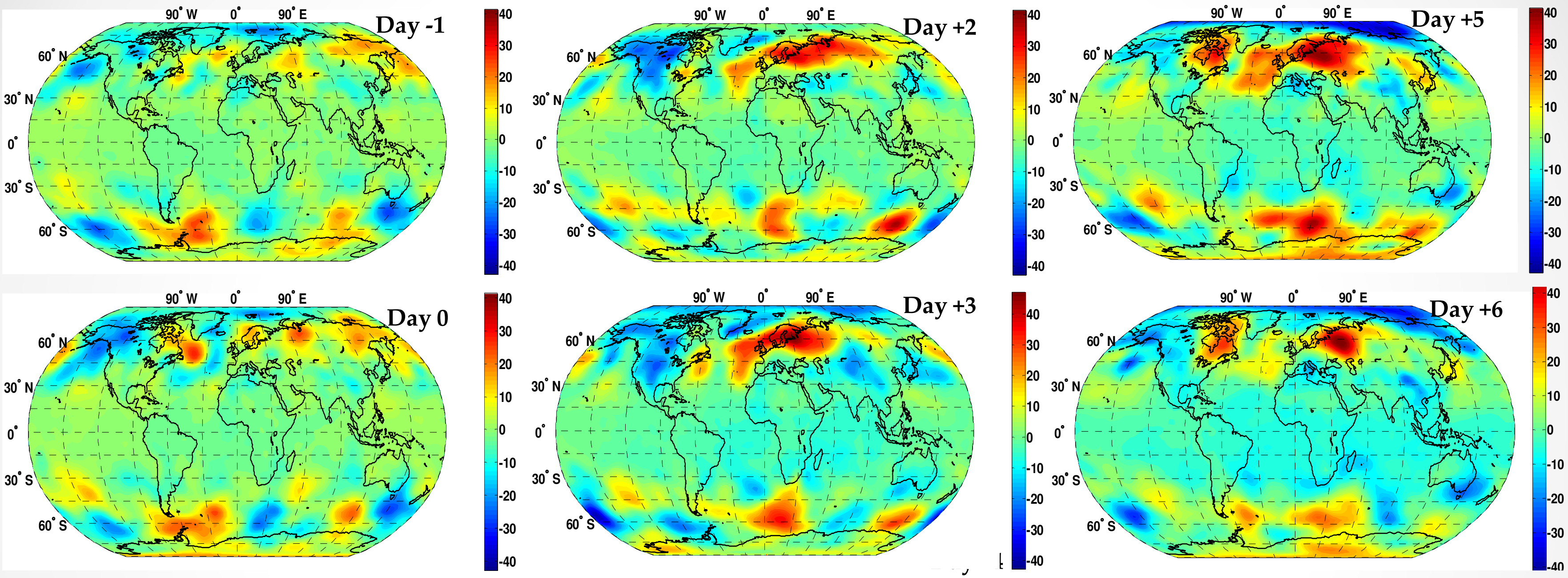
q ~25-30 cm^{-3}·s^{-1} (solar maximum)
q ~30-40 cm^{-3}·s^{-1} (solar minimum)

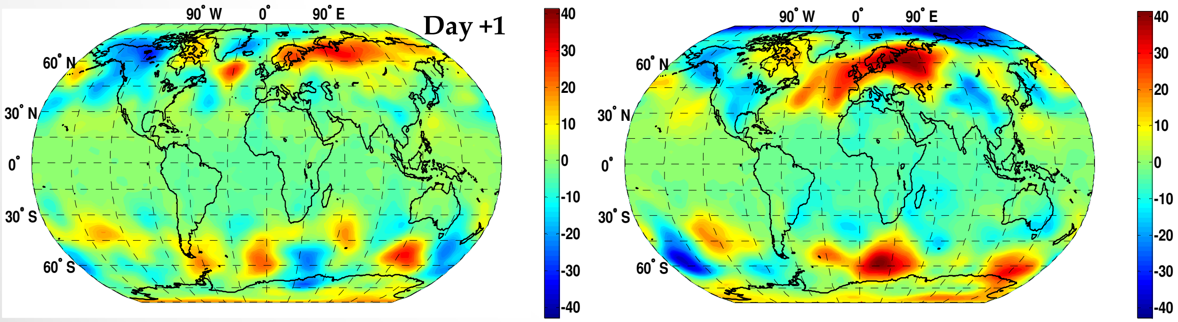


Forbush decrease started on 31 March 1980 (Murmansk)
ΔNM =6% ΔJ ~0.2-0.25 cm^{-3}·s^{-1} Δ q ~2.5–3 cm^{-3}·s^{-1}

For studied events ΔNM =**2.5–6.5%** Δ q ~ **1–3** cm^{-3}·s^{-1}

Mean changes of troposphere pressure (GPH1000) during Forbush decreases of GCR

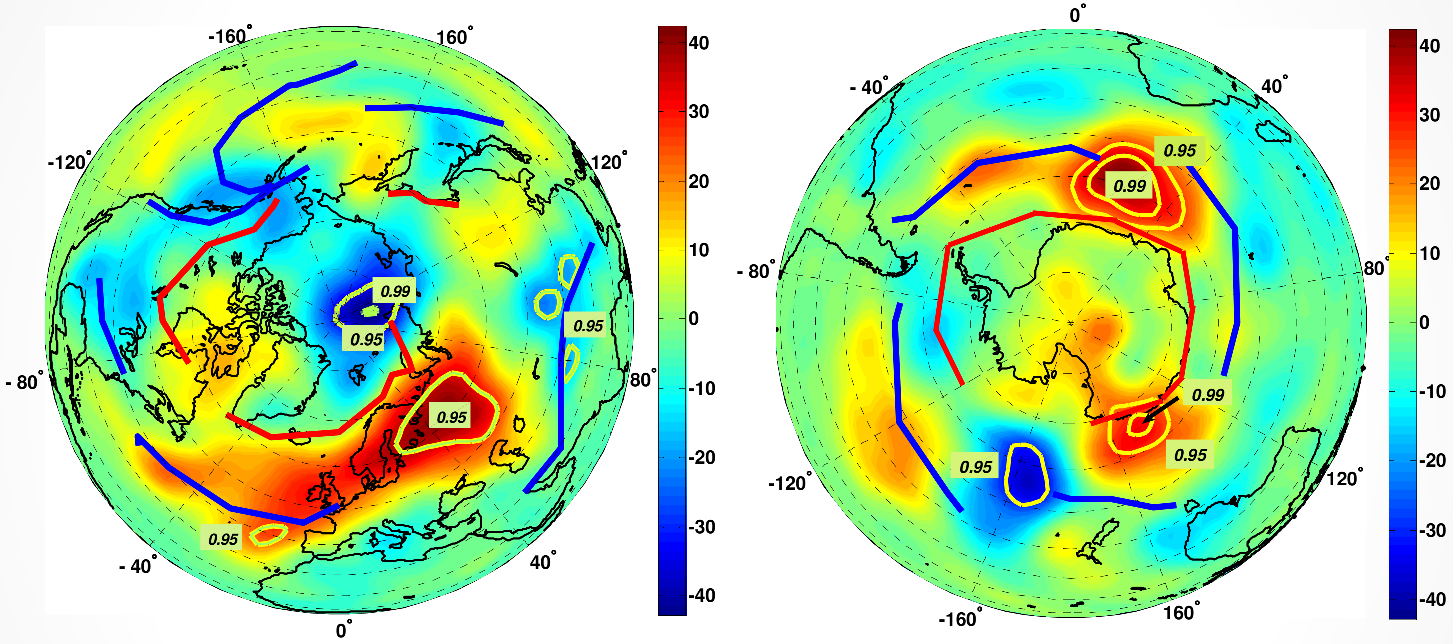




Superposed epoch analysis of GPH1000 variations for 48 Forbush decreases (October-March, 1980-2006).

Forbush decrease effects on pressure variations are most pronounced at middle latitudes, similarly SPE effects. No FD effects were observed at low latitudes.

Spatial distribution of pressure variations associated with GCR Forbush decreases and climatic positions of the main atmospheric fronts

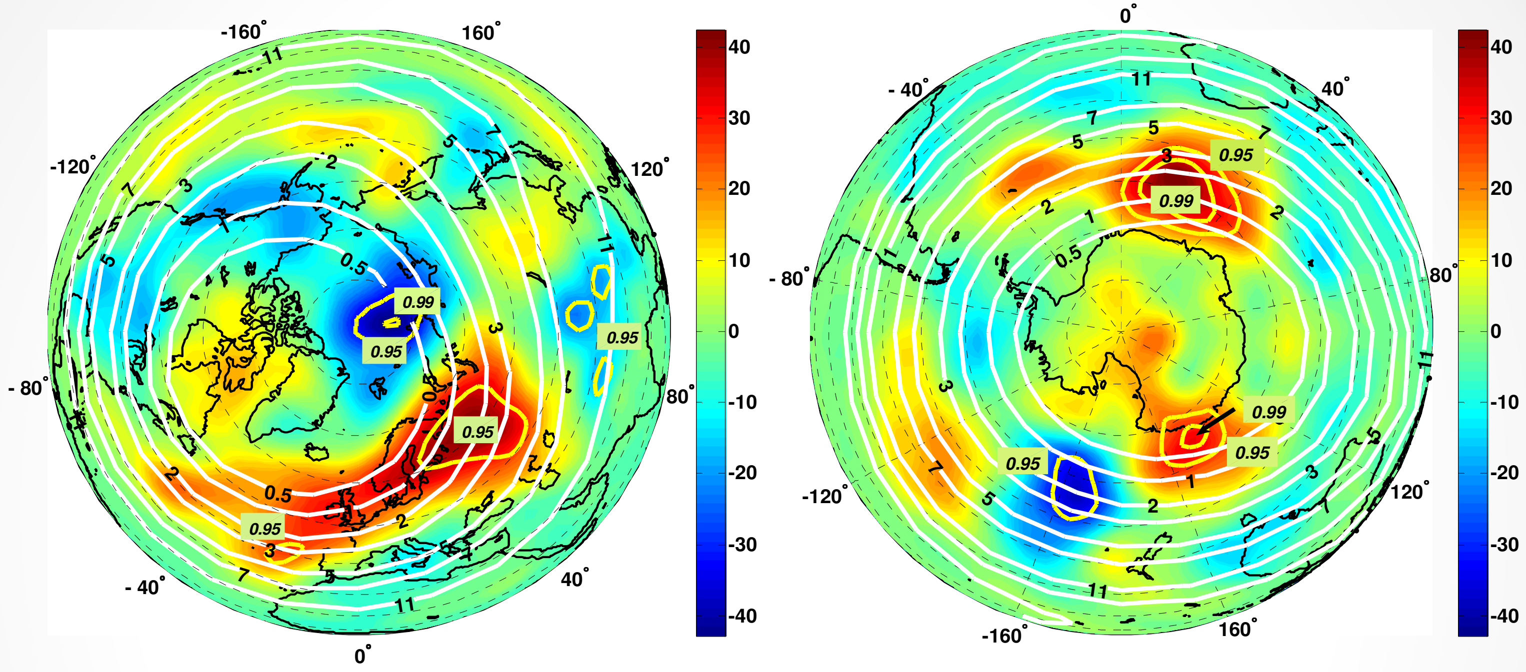


The areas of most statistically significant effects of Forbush decreases (pressure growth) at middle latitudes is closely related to climatic positions of the main atmospheric fronts.

In the Northern hemisphere the **area of pressure increase** stretches along **the North Atlantic branch of Polar fronts** and covers the eastern part of the North Atlantic, Northern Europe and European territory of Russia.

In the Southern hemisphere pressure increases along **the South Atlantic branch of Polar fronts** and over the d'Urville Sea.

Geomagnetic cutoff rigidities in the area of most pronounced effects of Forbush decreases



Most significant pressure increases in the course of GCR Forbush decreases were detected in those areas of the Northern and Southern hemispheres where geomagnetic cutoff rigidities amount to about **R_c ~ 0.5–3 GV** (i.e. minimal energies of precipitating particles **E_{min}~ 120 MeV - 2 GeV**).

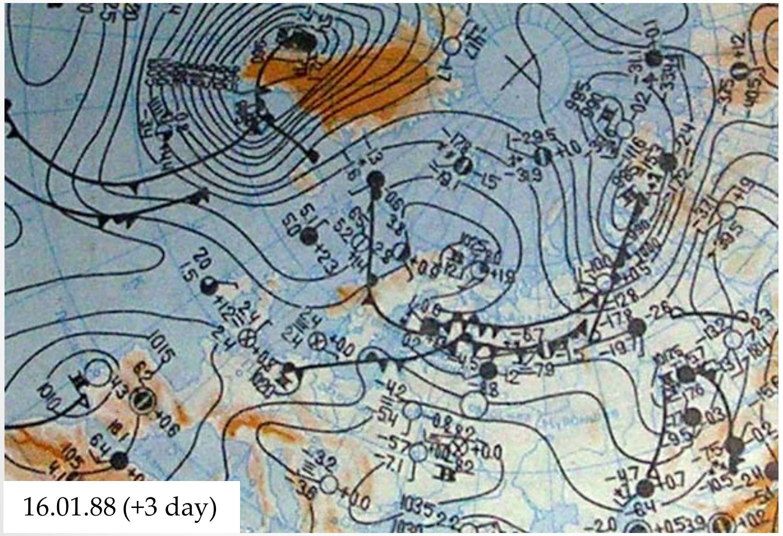
Effects of Forbush decreases were not detected in the North Pacific; this may be due to higher thresholds of geomagnetic cutoff in this area (**R_c ~4–9 GV**; **E_{min} ~3–6 GeV**).

Reasons for pressure growth associated with Forbush decreases according to the weather chart analysis

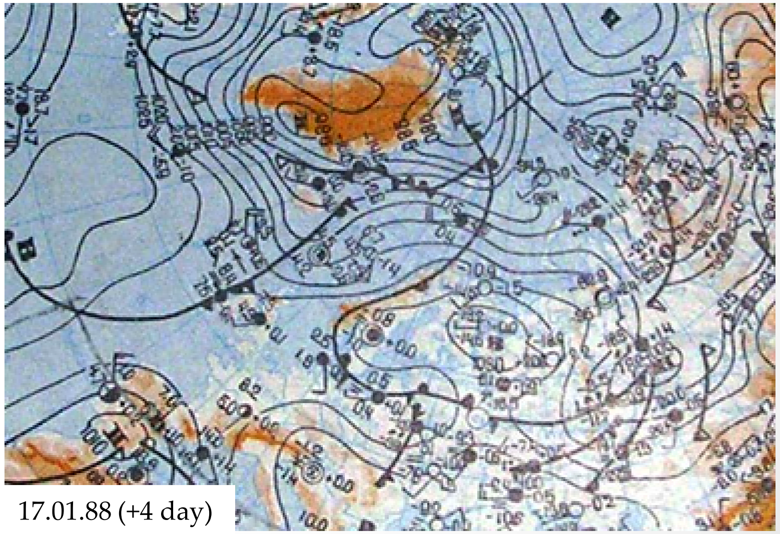
The main reason for the pressure growth in the North Atlantic region is an intensification of formation of blocking anticyclones – more intensive transformation of mobile cold anticyclones into slowly moving or stationary anticyclones which 'block' the zonal air flow at middle latitudes. Formation of blocking anticyclones was observed in **67%** of Forbush decreases which is 1.5 more often than under undisturbed conditions).

In the Southern hemisphere pressure growth during Forbush decreases was due to cyclone weakening in the areas of climatic depression (near the coasts of Queen Maud Land) and the displacement of high pressure crests from subtropical latitudes.

Forbush decrease of GCR started on 13 January 1988.



16.01.88 (+3 day)



17.01.88 (+4 day)

Comparative analysis of short-term effects of cosmic rays on the circulation of the Northern hemisphere

	Solar Proton Events	Forbush-decreases of GCR
Particle energies	> 90 MeV	≥ 200 MeV
Altitudes reached by cosmic particles	~ 35–40 km	~ 10–15 km
Changes of ionization rate	**Increase** by ≤ 10 – several hundred $cm^{-3}\cdot s^{-1}$	**Decrease** by ~1–3 $cm^{-3}\cdot s^{-1}$
Most significant pressure changes at middle latitudes	Pressure **decrease**	Pressure **increase**
Maximal values of pressure changes (ΔGPH) and their altitudinal range	–80…–100 gp m 300–500 hPa (5–9 km)	+50 gp m 1000 hPa (~sea level)
Localization of most significant pressure changes	North Atlantic, the south-eastern coasts of Greenland	Eastern part of the North Atlantic, Scandinavia, northern part of the European territory of Russia
Characteristic time of the circulation response	≤ 1–2 days	~3–4 days
Typical synoptic processes	Regeneration of cyclones at Arctic fronts	Formation of blocking anticyclones at Polar fronts
Atmosphere conditions in the areas of maximal CR effects	High temperature contrasts between the icy surface of Greenland and the warmer ocean, divergence of isohypses over the ocean	Heated atmosphere over the warm North-Atlantic current, convergence of isohypses over Eurasian continent
Vertical geomagnetic cutoff rigidity in the areas of maximal effects of CR variations	~0.4–1 GV	~1–3 GV

Conclusions

- **Most statistically significant effects** of cosmic ray (CR) variations on the baric system evolution are observed in **the North Atlantic region** where **low thresholds** of geomagnetic cutoff take place allowing precipitation of particles with minimal energies from ~100 MeV to ~2-3 GeV. Depending on precipitating particle energies, intensification of atmospheric processes occurs at **high-latitudinal Arctic fronts** or **Polar fronts of middle latitudes**.
- **Solar Proton Events** (SPEs) with energies enough to penetrate to the stratosphere ($E > 90$ MeV) are accompanied by **pressure decrease** over the North Atlantic due to the **intensification of secondary deepening (regeneration) of cyclones** near the south-eastern coasts of Greenland (the region of the formation of Arctic fronts).
- **Forbush decreases of galactic cosmic rays** are accompanied by **pressure increase** over the eastern part of the North Atlantic, Scandinavia and European territory of Russia due to **more intensive formation of blocking anticyclones** at Polar fronts of middle latitudes.
- **The North Atlantic is a special region for the formation of CR effects** on short time scales (about several days). The **structure of the thermobaric field** is favorable for cyclone development near the Greenland coasts (high temperature contrasts, divergence of isohypses over the ocean) and for anticyclone development in the eastern North Atlantic (warmed atmosphere over the North-Atlantic current, convergence of isohypses over the continent). The favorable thermobaric field structure is combined with **low thresholds of geomagnetic cutoff** allowing precipitation of cosmic particles strongly modulated by solar activity.