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Cosmic rays and clouds:
an important climate factor?

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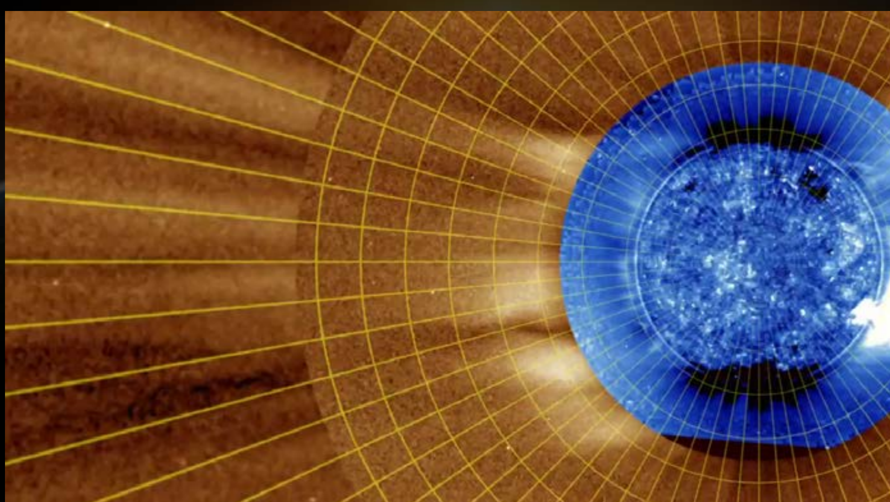
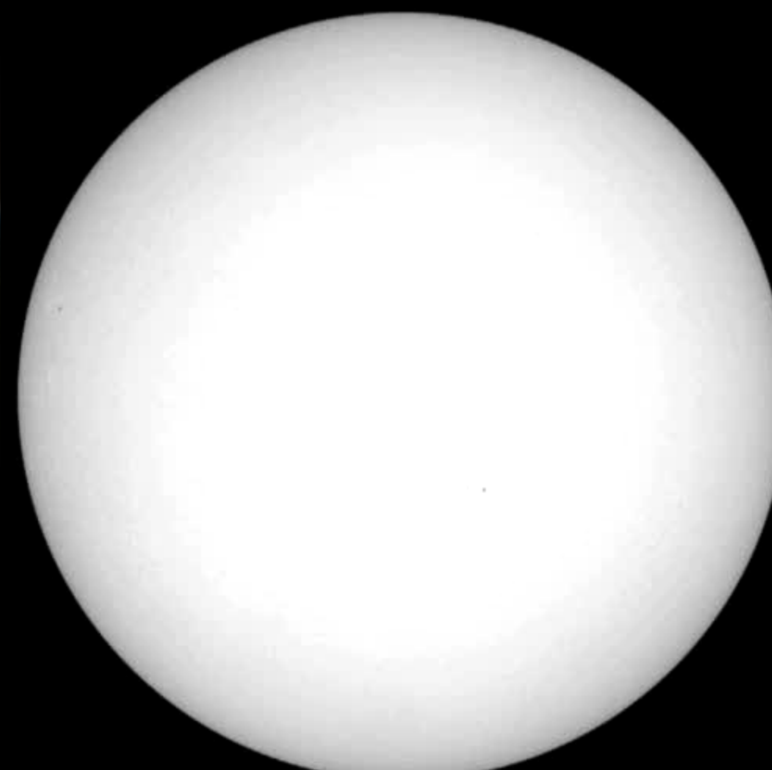
Influence of solar variability on the Earth's climate requires knowledge of

1. Short- and long-term solar variability
2. Solar-terrestrial interactions
3. Mechanisms determining the response of the Earth's climate system to these interactions

Rind, 2002



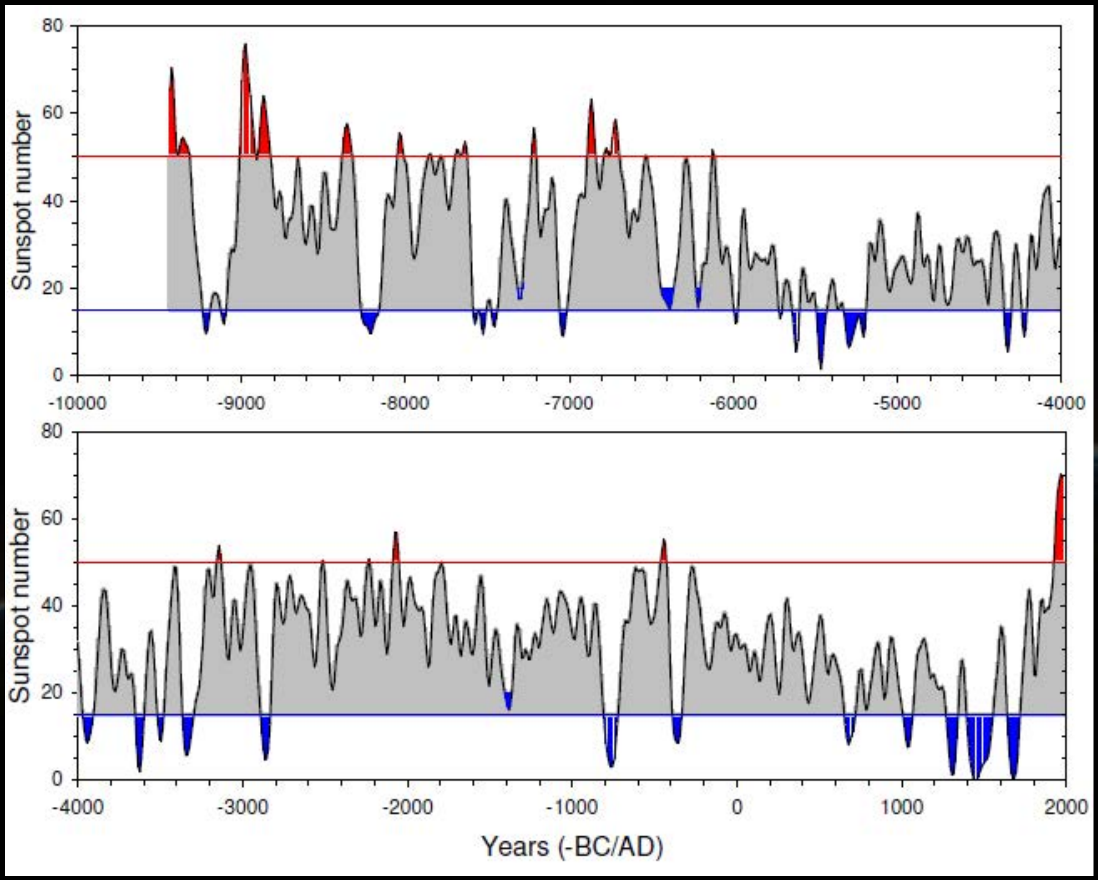


Solar activity and climate in the past

- Global temperature changes in the past show a coincidence with the major changes in the solar activity (based on sunspot, ^{10}Be and ^{14}C isotope measurements), however there are exceptions due to other climate forcings and oscillations
- Little ice age period (16th to 19th century) corresponds to the periods of low solar activity (e.g. Eddy, 1976).

Pieter Bruegel the Elder (1565 g.)

Cosmogenic radionuclides allow to reconstruct solar activity thousands of years in the past



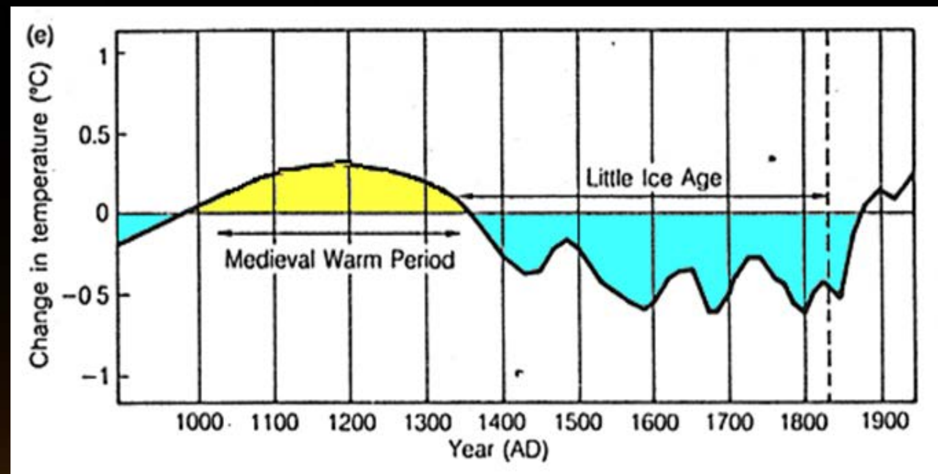
Usoskin, 2007

- ^{14}C and ^{10}Be are produced by cosmic rays in the Earth's atmosphere and stored in natural archives (ice, trees, sediments)
- Proxies for solar activity

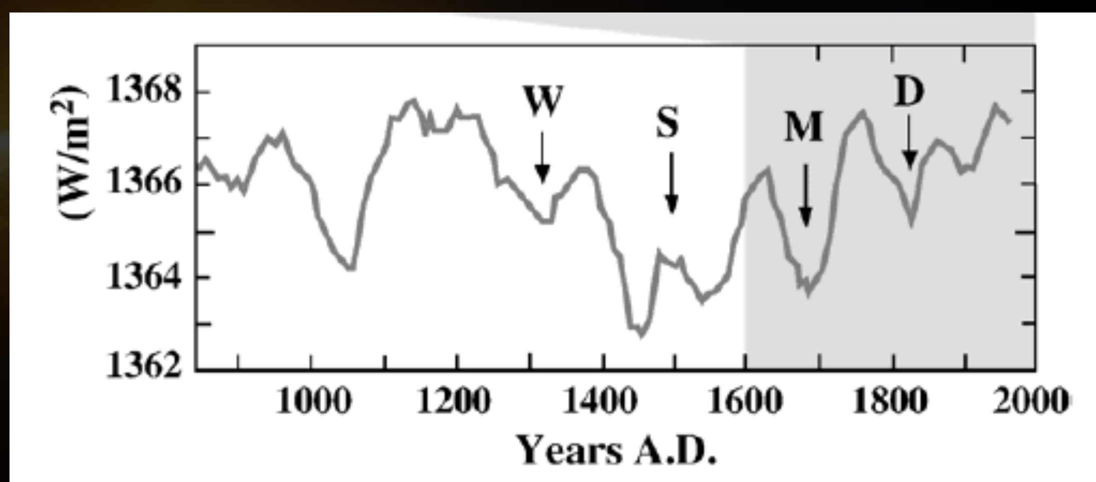
Drilling of ice cores to obtain ^{10}Be measurements

Solar activity and climate

Global temperature



Solar activity

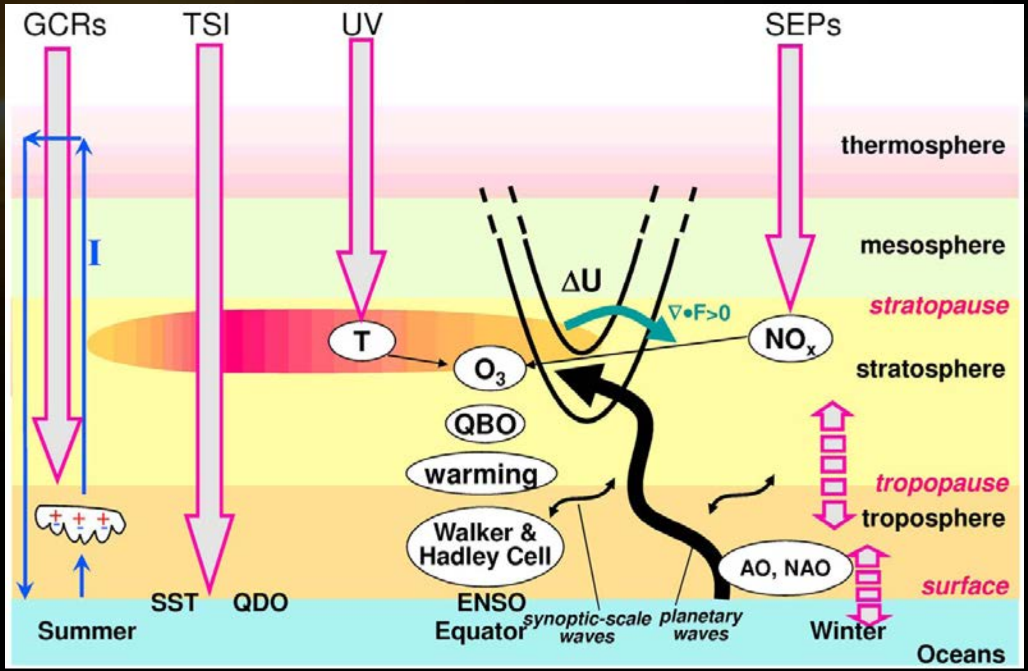


Solar irradiance reconstruction (based on ^{10}Be measurements in ice), Bard et. al. 2000

Solar Minimums: Wolf (W), Spörer (S), Maunder (M), Dalton (D)

Mechanisms of solar influences on climate

- **Total solar irradiance (TSI)** → sea surface temperature (SST) → modifications of synoptic circulation patterns (Meehl et al., 2009)
- **Ultraviolet (UV)** spectral irradiance → ozone - stratospheric temperatures (Austin et al., 2008) → may impact large scale tropospheric variability via dynamic stratosphere-troposphere couplings (Haigh, 1996)
- **Solar proton events (SEP)** → atmospheric chemistry → ozone
- Galactic cosmic ray (GCR) flux → cloud amount and properties



Kodera and Kuroda (2002)

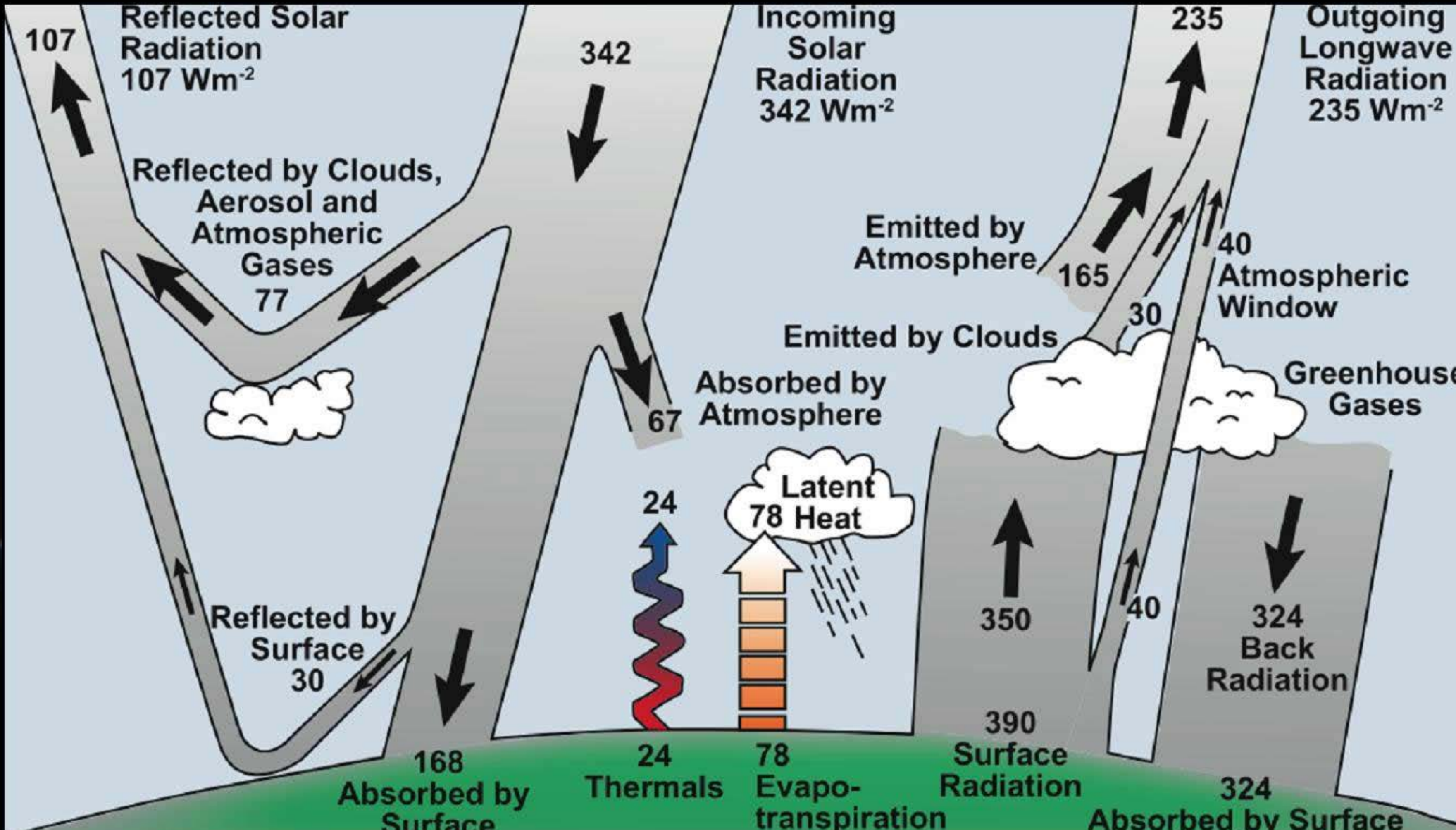
Amplification mechanisms!?

Cosmic ray shower (cascade)

Cosmic ray total energy flux on earth is **10^9 times smaller** than solar irradiation (~ 10^{-5} W/m^2).

How such small energy can influence our climate system?

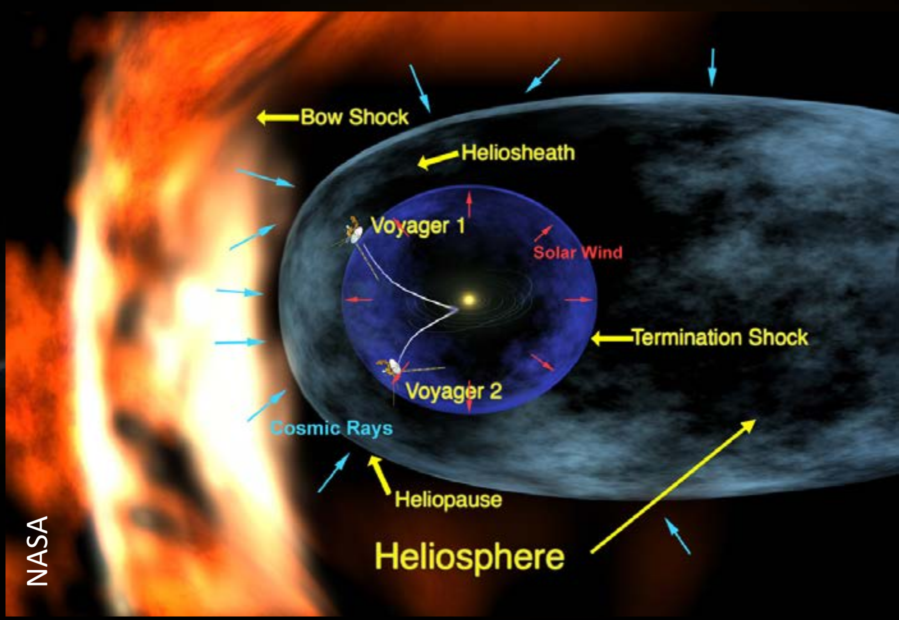
Earth's radiative balance and clouds

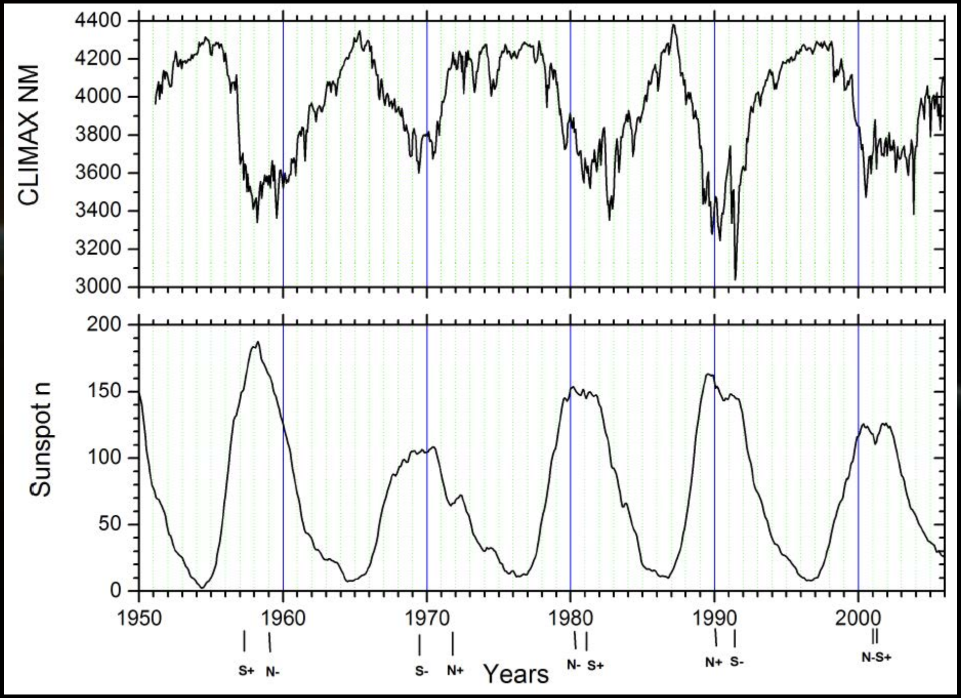


Houghton et al., 1996

Solar activity modulates cosmic rays

- Cosmic rays (CR) consist of high-energy particles (mainly protons)
- CR flux of low energy particles is greater than flux of high energy particles ($E^{-\gamma}$)
- Particles with less energy are more influenced by the Sun

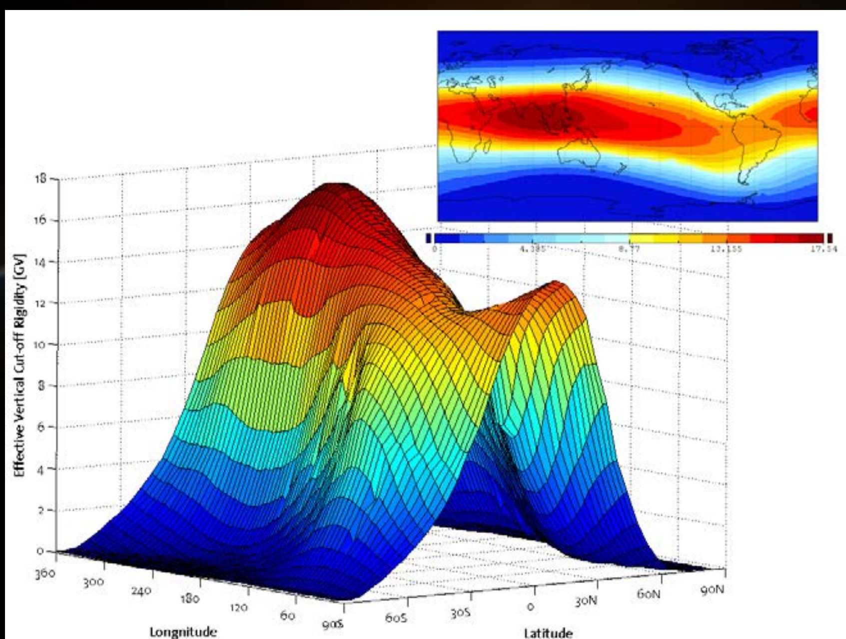




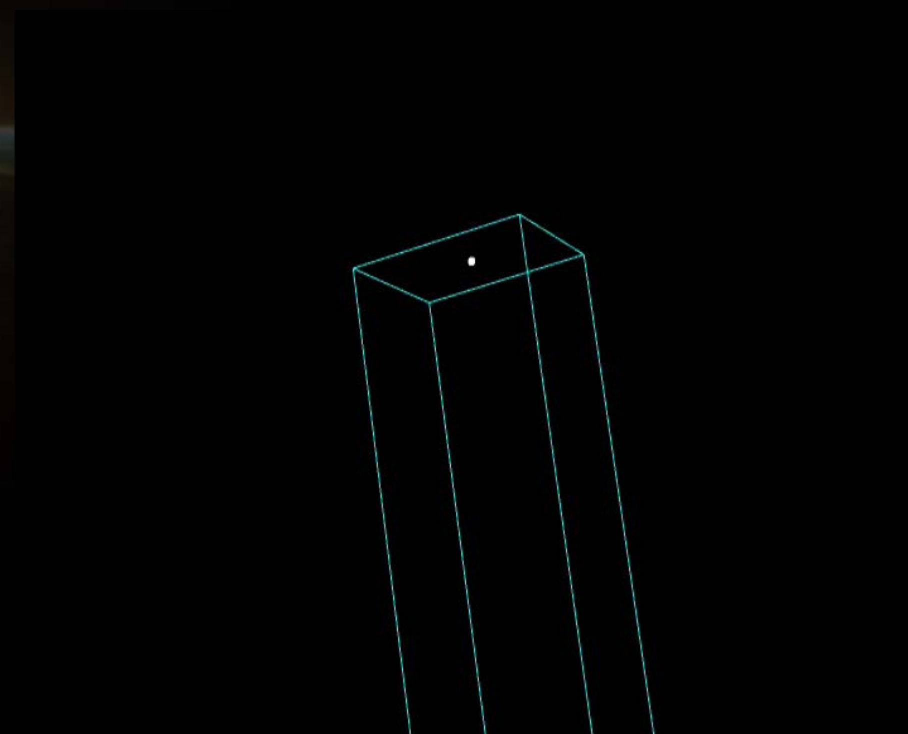
Cosmic ray flux on Earth depends on

- Solar magnetic field and Solar wind
- Geomagnetic field (vertical cutoff rigidity)
- Earth's atmosphere

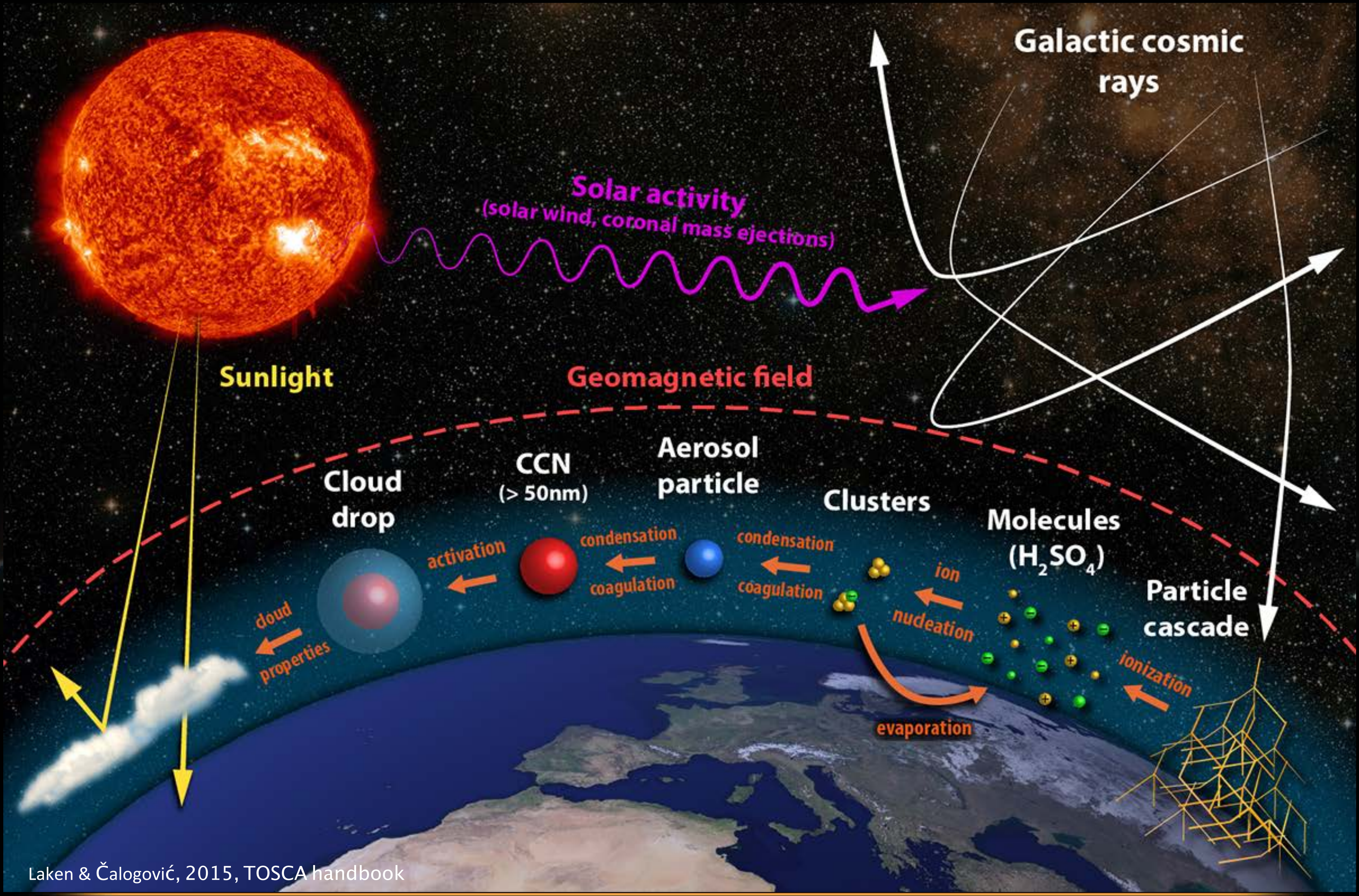
Example of vertical cutoff rigidity for 20 km altitude, 19.3.1991. 00:00h



Cosmic ray showers (cascade) → ionization in the atmosphere



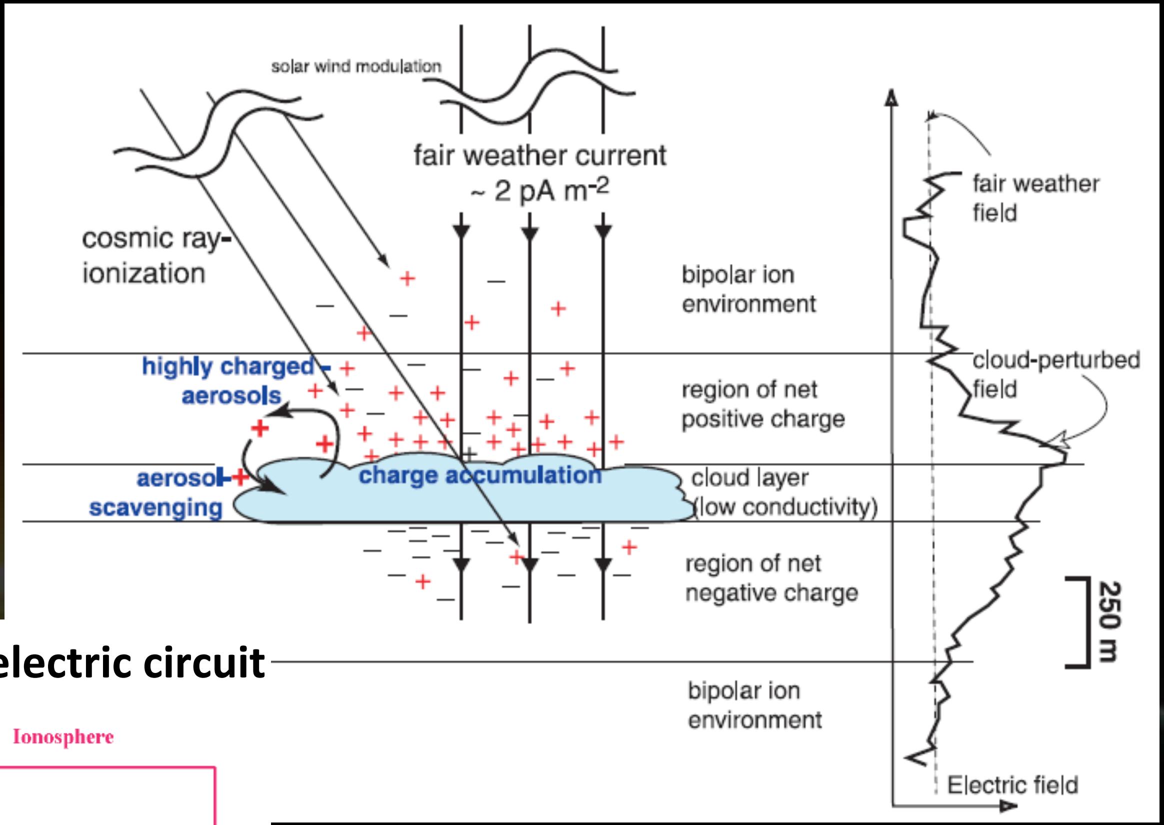
"Clear-air" mechanism



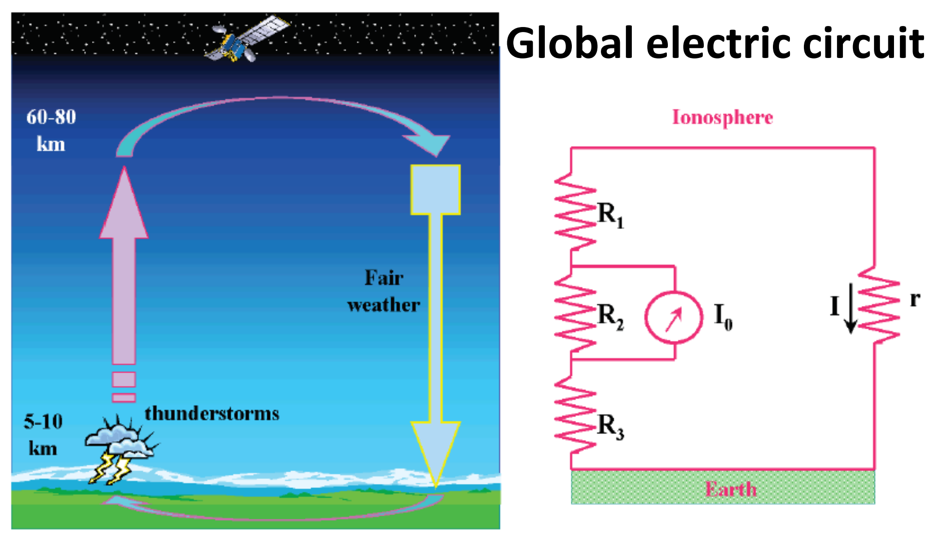
Laken & Čalogović, 2015, TOSCA handbook

"Near-cloud" mechanism

Charges at cloud boundaries and its attachment to aerosols and cloud droplets impact the microphysics of clouds – cloud droplet formation, droplet-to-droplet collision efficiency, droplet-to-aerosol particle collisions and so-called electroprotection and electroscavenging processes.



Carslaw, Harrison et al., 2002

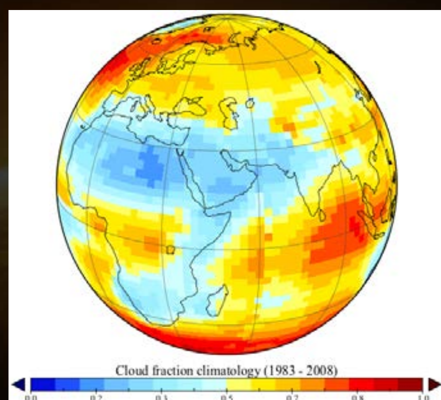


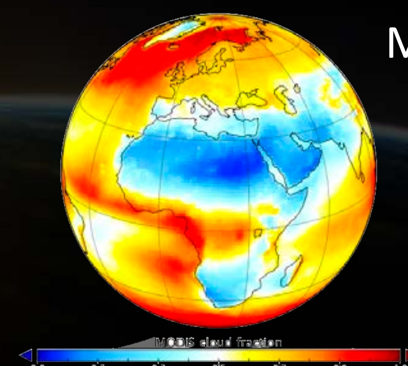
Makino and Ogawa, 1984

Cloud datasets

ISCCP (International Satellite Cloud Climatology Project)

- D1 dataset (from 1983), intercalibrated radiance measurements from a fleet of polar and geostationary satellites
- temporal resolution: 3h (IR data)
- spatial resolution: 2.5° x2.5° (280 x 280km^2)
- distinguishes clouds at different altitude levels: e.g. high (>6.5km), middle (3.2 – 6.5km) and low (0 – 3.2km)





MODIS

MODIS (MODerate Resolution Imaging Spectroradiometer)

- views in 36 channels from Visible to thermal IR, on board two polar orbiting satellites Aqua, and Terra, operational since 2000
- temporal resolution: 12h, spatial resolution: 1° x 1°

The hypothesized link between cosmic ray flux and cloud cover

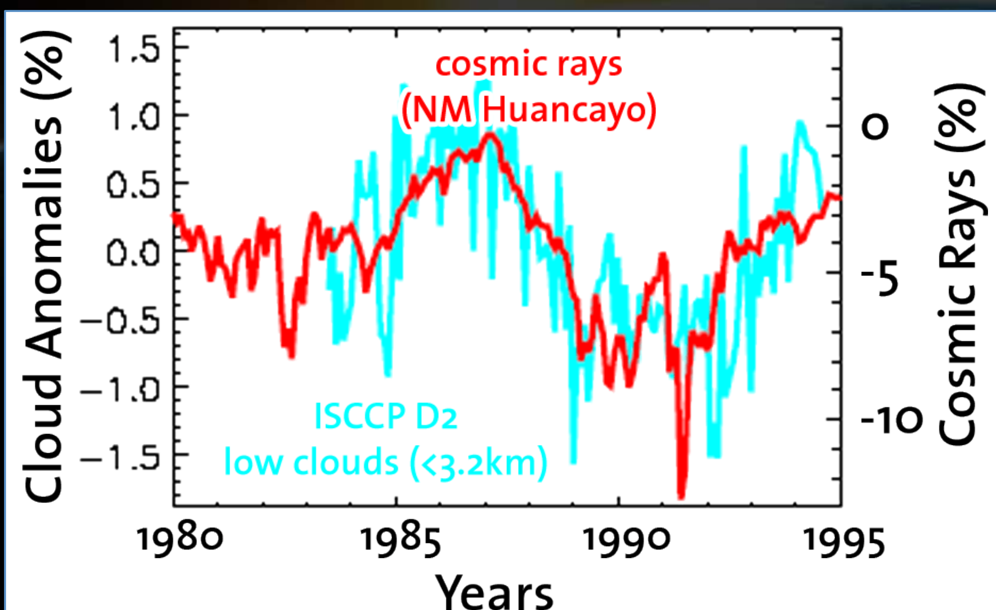
Long-term studies

Svensmark and Friis-Chistensen (1997)

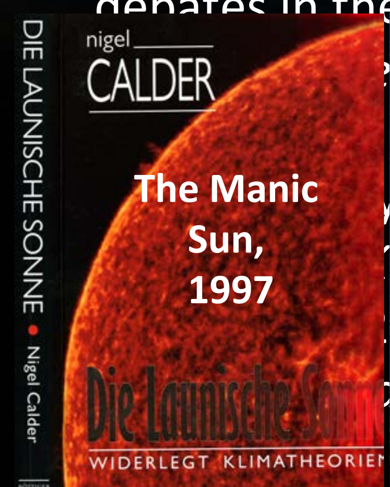
- analyzed one solar cycle and reported that global cloud cover changed in phase with the GCR flux by 2-3% → radiative forcing (0.8 – 1.7 W/m^2) is comparable with greenhouse gases forcing

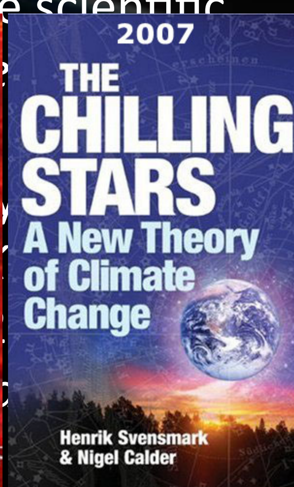
Marsh and Svensmark, 2000

low clouds (0-3.2km)

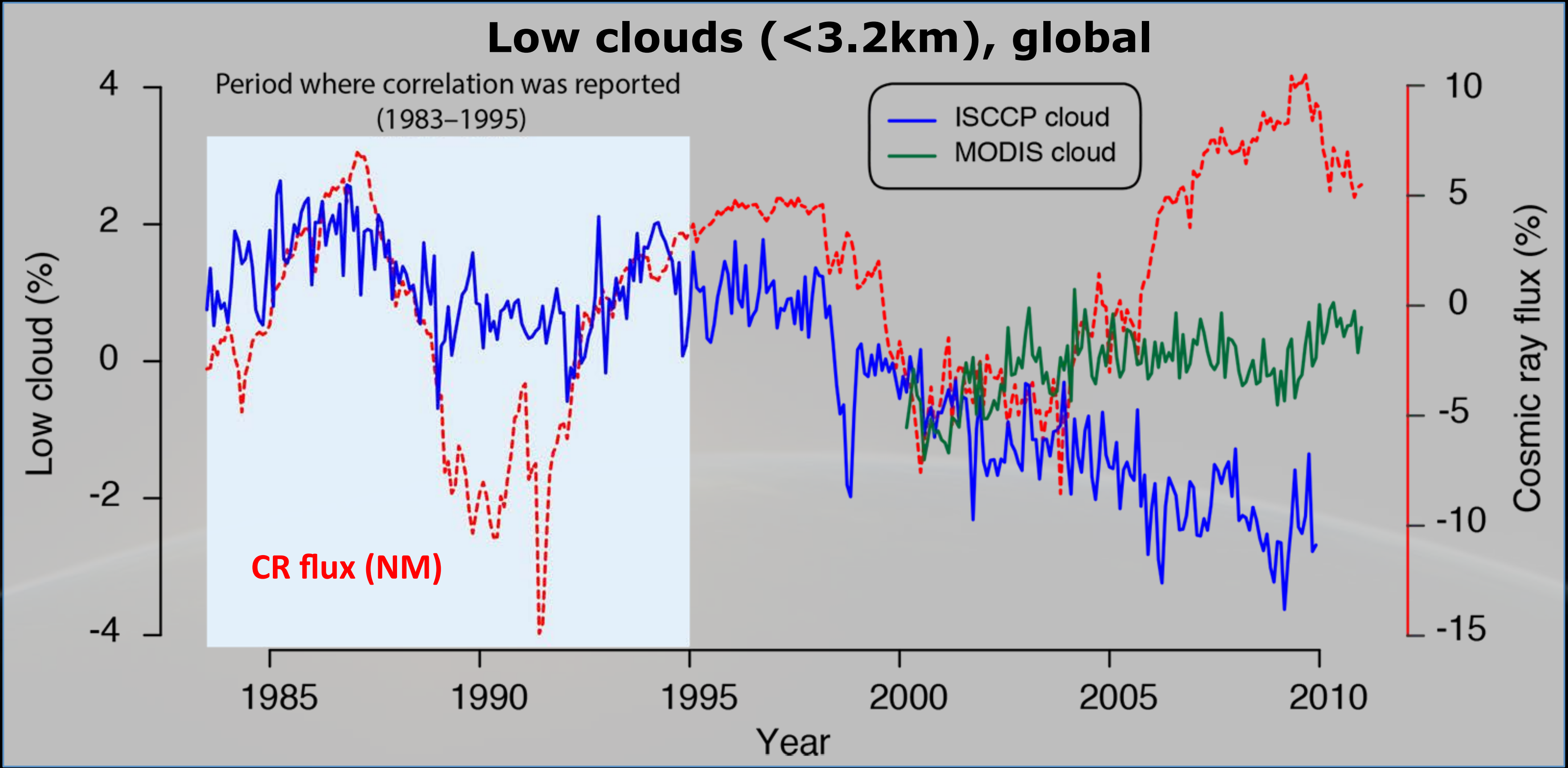


Climate sceptics still use these (incorrect) arguments





Long-term cloud data doesn't support GCR-cloud link



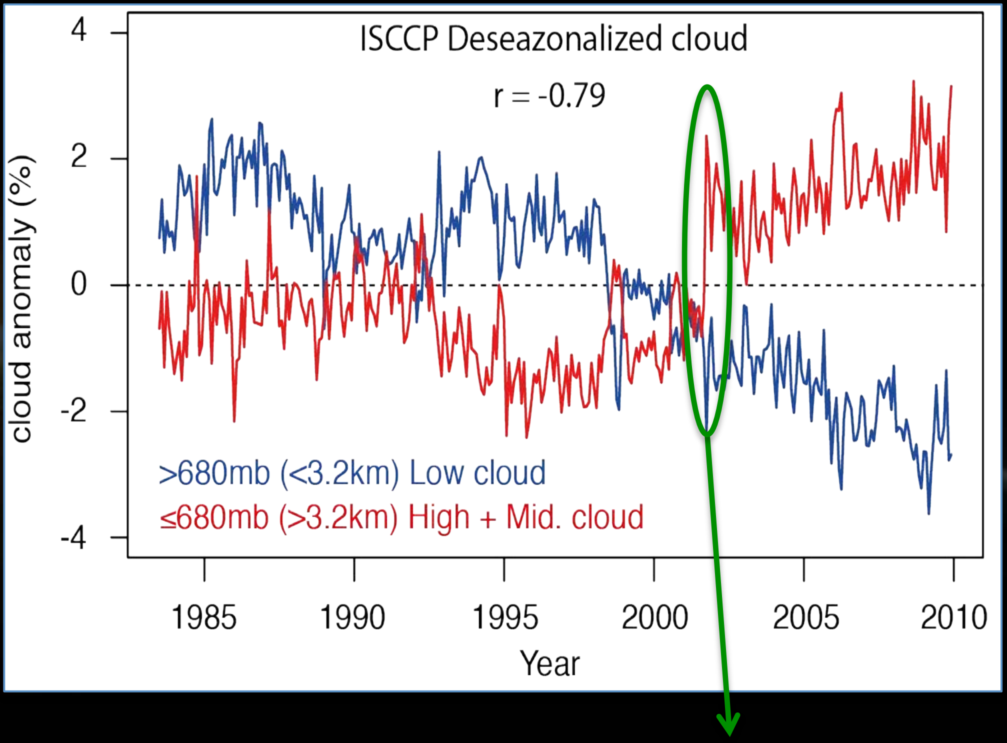
- Correlation only in low (<3.2km) ISCCP cloud (1983–1995)
- High correlation from 12-month smoothed data (df=4)
- Low (non-significant) correlation from unsmoothed data

Laken, Pallé, Čalogović & Dunne, 2012, SWSC

Artificial anti-correlation exists between low and high/middle troposphere cloud

- Low cloud obscured by overlying cloud (**measurements are non-cloud penetrating**).
- Number of geostationary satellites increased over time → artificial drop in low cloud
- Errors in identifying cloud height can contribute to shifts between low and high cloud.
- Satellite cloud issues well known: e.g. Hughes, 1984; Minnis, 1989, Tian & Curry, 1989; Rozendall et al. 1995; Loeb & Davies, 1996; Salby & Callaghan, 1997, Campbell, 2004

Evidence for CR – cloud link is based on low level clouds:
these data are not reliable!

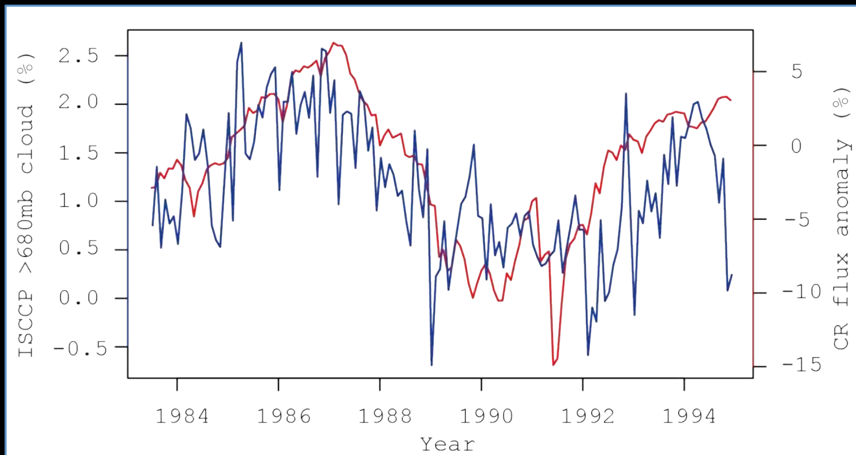


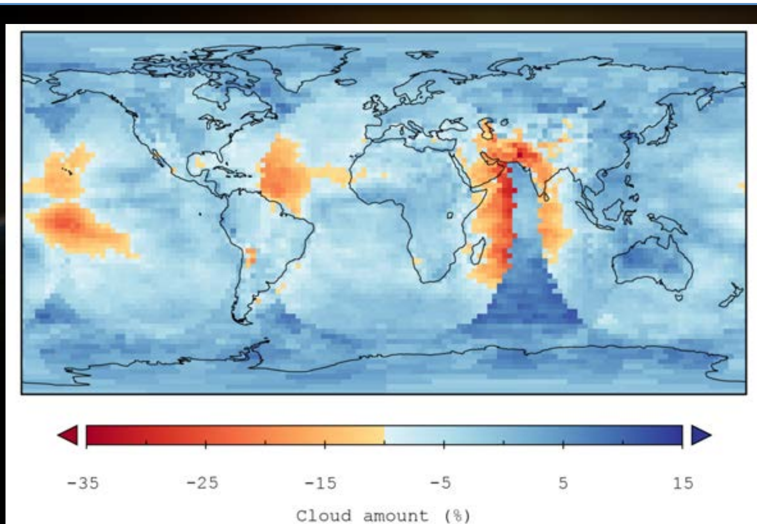
changes in the satellite constellation

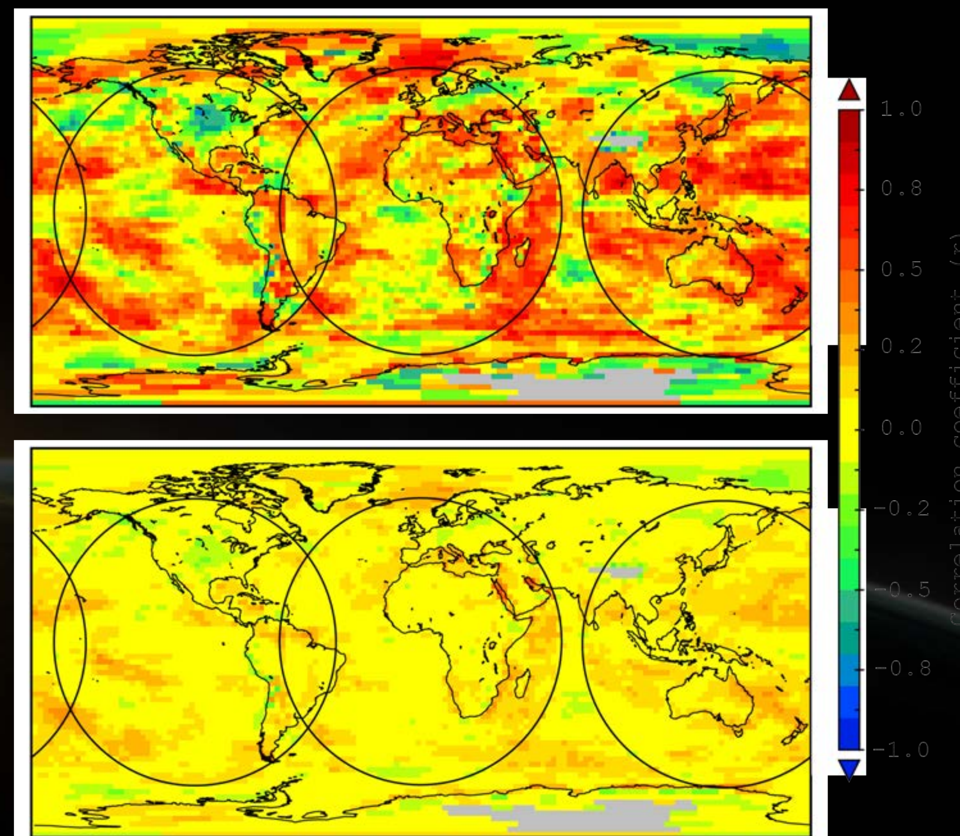
Laken, Pallé, Čalogović & Dunne, 2012, SWSC

Many additional problems of long-term analysis (e.g. signal attribution - ENSO, volcanic eruptions...)

Correlations between CR flux and clouds are artificial



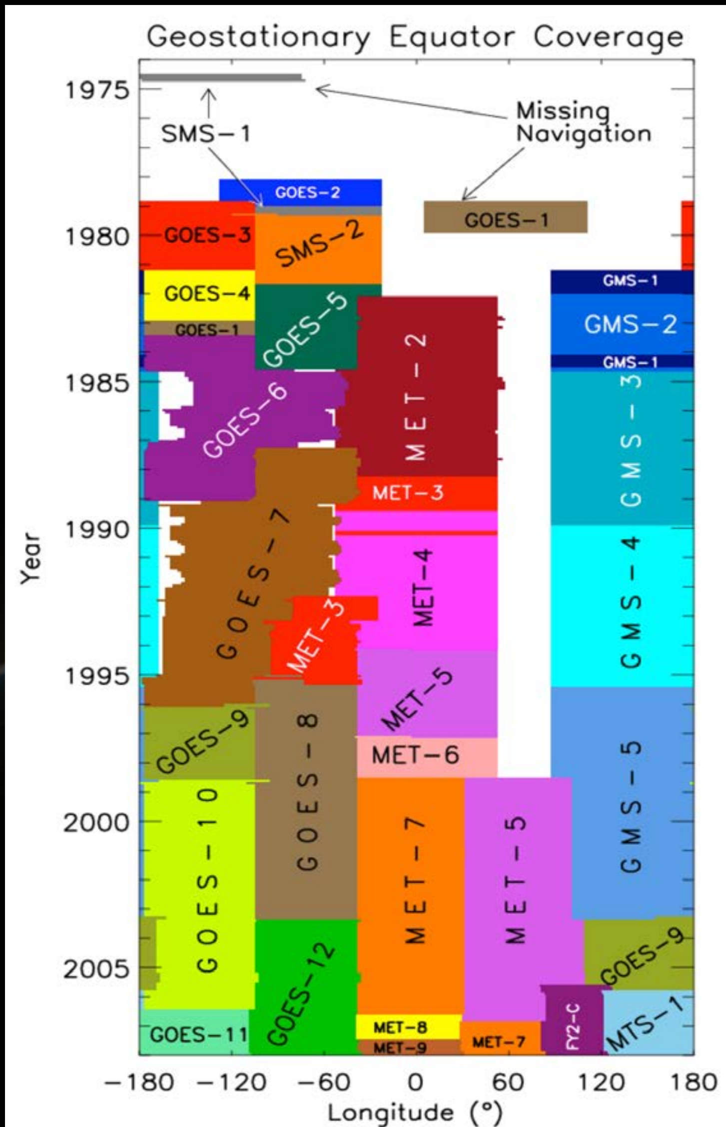


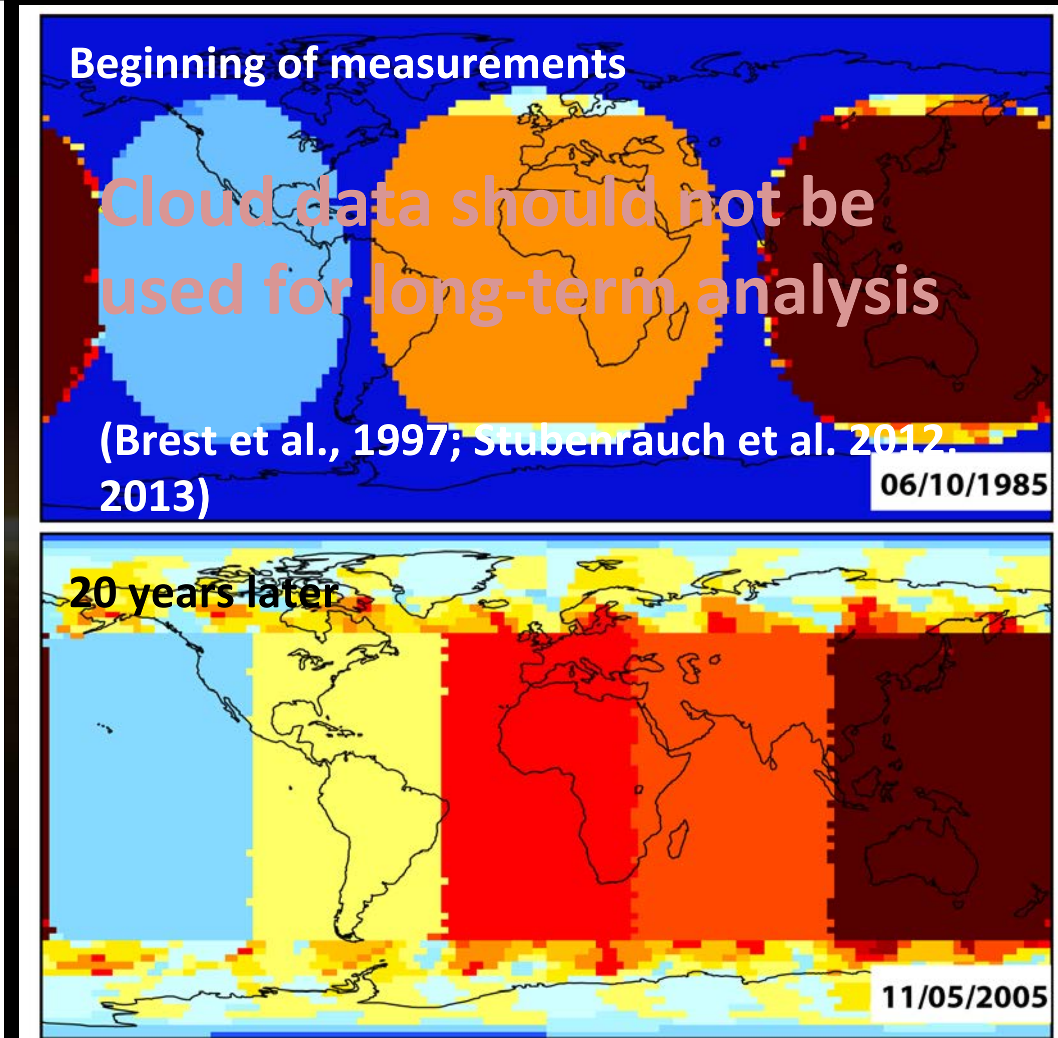


Laken, Pallé, Čalogović i Dunne, 2012, SWSC

If linear trends in CR and cloud data are removed correlation becomes weak

Timeline of geostationary satellite operation at equator over ISCCP observation period





CERN CLOUD experiment

- **C**osmics **L**eaving **OU**tdoor **D**roplets

Laboratory experiment with a special cloud chamber to study the possible link between galactic cosmic rays and cloud formation.

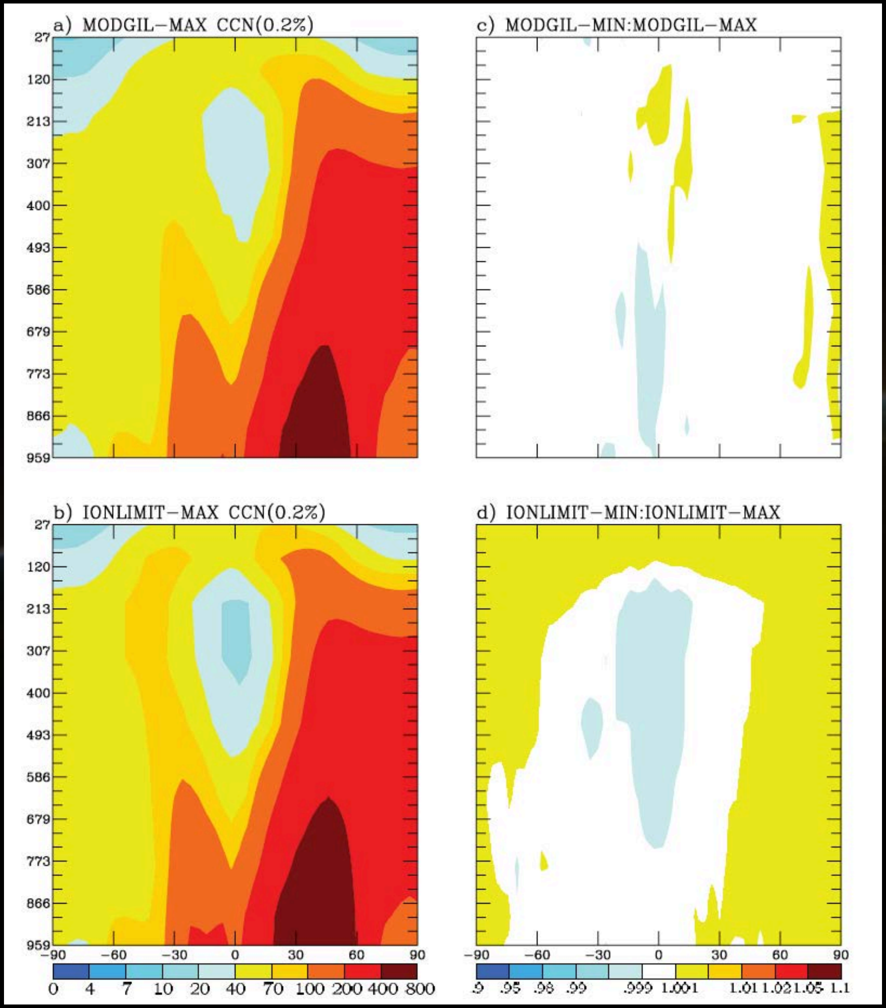
- **Ion-induced aerosol nucleation 10x faster than binary homogeneous nucleation**
- Nucleation in presence of ammonia → **100 do 1000x** faster than ion-induced nucleation
- Nucleation with acid-amines → **1000x** faster than nucleation with ammonia (explains observed particle formation rates in the atmosphere)

Almeida et al., 2013, Nature

Model studies show minor impact to alter CCN populations

CCN concentrations during solar max

Difference (solar max – solar min)

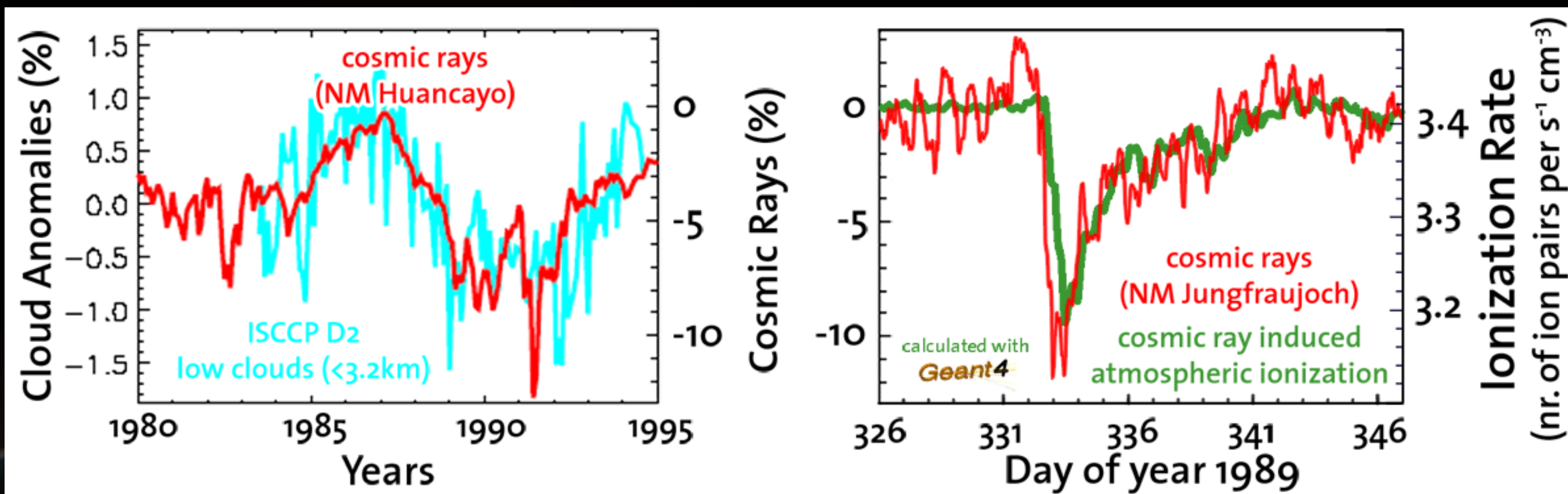


Pierce and Adams, 2009

- Used general circulation model (GCM) with aerosol microphysics (TOMAS)
- Changes in the nucleation rate due to cosmic rays (ion-induced nucleation) are very small
- Ionisation increases growth od small particles, but these particles remain at small sizes for long time – unlikely to survive and grow to CCN sizes.
- Model calculations show change of approx. 0.2% for aerosols >80 nm in diameter over the solar cycle

Short-term studies - opportunity to test GCR-cloud hypothesis

• Short-term changes in cosmic rays (Forbush decreases) are comparable to variations during the solar cycle.

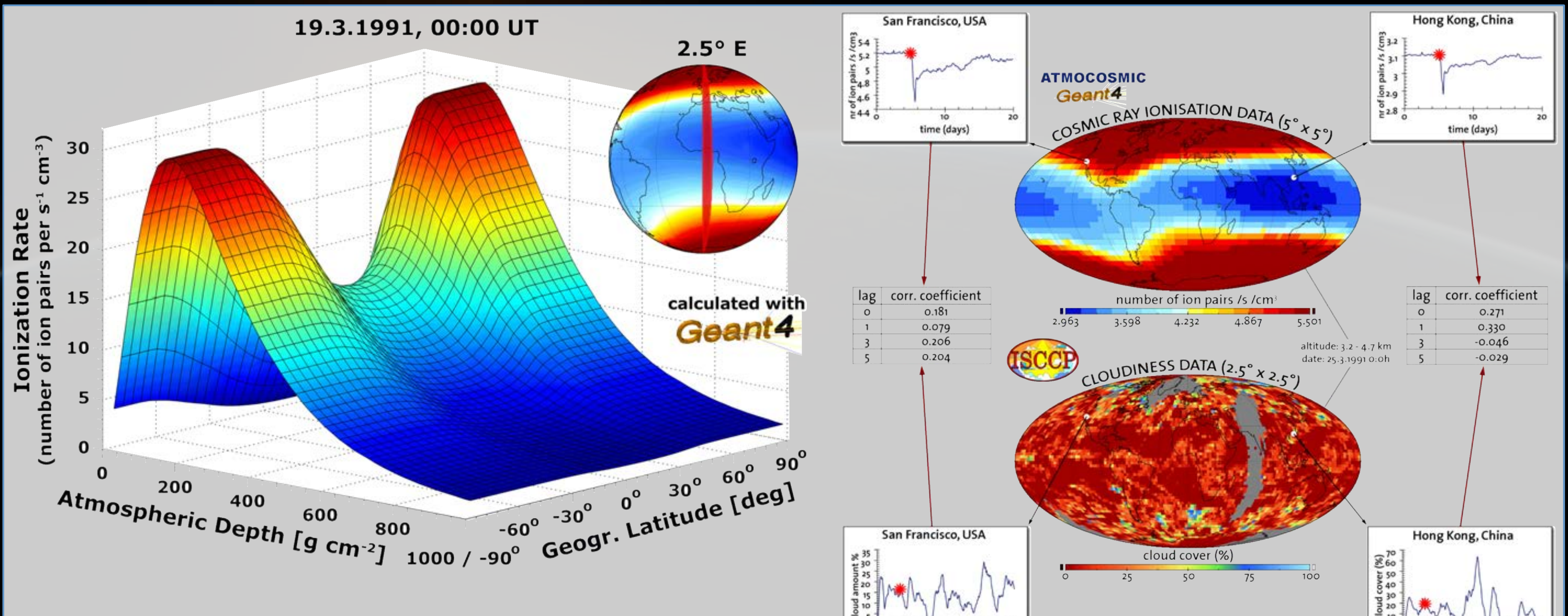


Advantages: some important unwanted factors that influence long-therm studies are removed (ENSO, vulcanic eruptions, satellite calibration errors)

Disadvantages Meteorological variability (noise) in clouds has to be **reduced** to be able to detect the solar-related changes (signal), **limited** number of high-magnitude Forbush decreases (several pro cycle)

Analysis of ISCCP cloud cover during 6 biggest Forbush decreases (1989-1998)

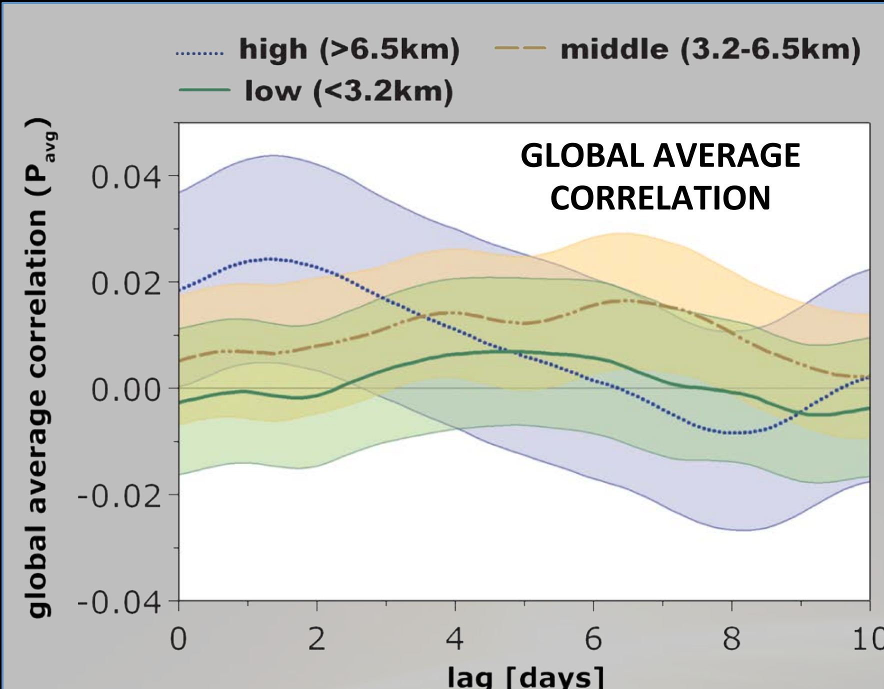
- Forbush events with decreases in CR flux > 9 %
- calculated cosmic ray induced ionization rate (GEANT4, 2.5°x2.5°)
- independent correlation analysis of all grid cells for each lag (10 days)
- in total 8.6 milion correlations calculated

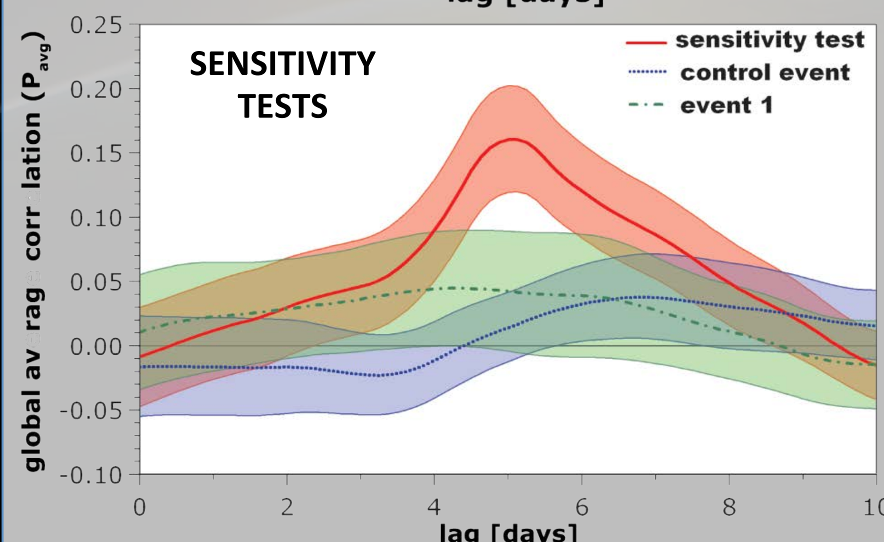


Čalogović et al. 2010, GRL

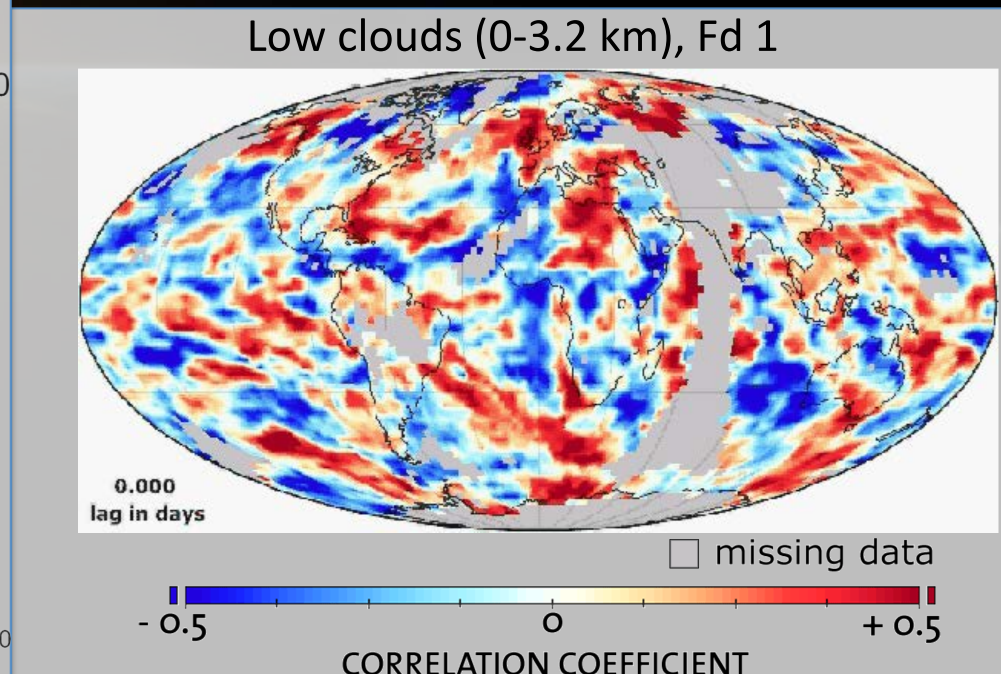
Results

Čalogović et al., 2010, GRL





- No siginificant corrleations found in all 6 Forbush events together, in analysis of individual events or cloud layers (low, middle, high cloud cover)
- No significant diferences for obtained correlations in different areas (low and high latitudes, land, oceans)
- Method is enough sensitive to detect global cloud changes



Short-term studies using Forbush decreases show conflicting results

- **positive correlations:**

Tinsley & Deen, 1991; Pudovkin & Vertenenko, 1995; Todd & Kniveton, 2001; 2004; Kniveton, 2004; Harrison & Stephenson, 2006; Svensmark *et al.*, 2009; Solovyev & Kozlov, 2009; Harrison & Ambaum, 2010; Harrison et al. 2011; Okike & Collier, 2011; Dragić et al. 2011; 2013; Svensmark et al., 2012; Zhou et al. 2013; Aslam & Badruddin, 2015

- **negative correlations:**

Wang *et al.*, 2006; Troshichev *et al.*, 2008

- **no correlations or inconclusive results:**

Pallé & Butler, 2001; Lam & Rodger, 2002 ; Kristjánsson *et al.*, 2008 ; Sloan & Wolfendale, 2008; Laken *et al.*, 2009; Čalogović *et al.*, 2010; Laken & Kniveton 2011; Laken et al., 2012; Erlykin and Wolfendale, 2013

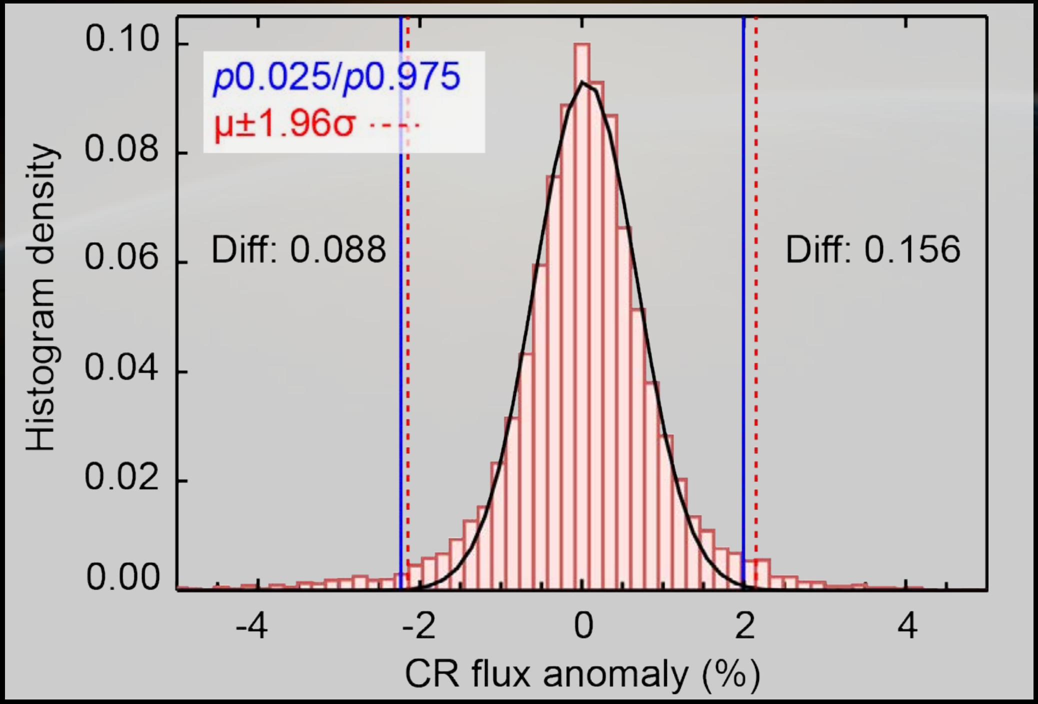
Why?

- Improper use of statistical tools / wrong statistical assumptions
- "quality" and properties of cloud datasets

Calculate thresholds for statistical significance with Monte Carlo approach

By generating large populations of random events identical in design to a composite with real events, the probability (p) of obtaining a given value by chance in a composite with real events can be accurately known.

Distribution of daily anomalies



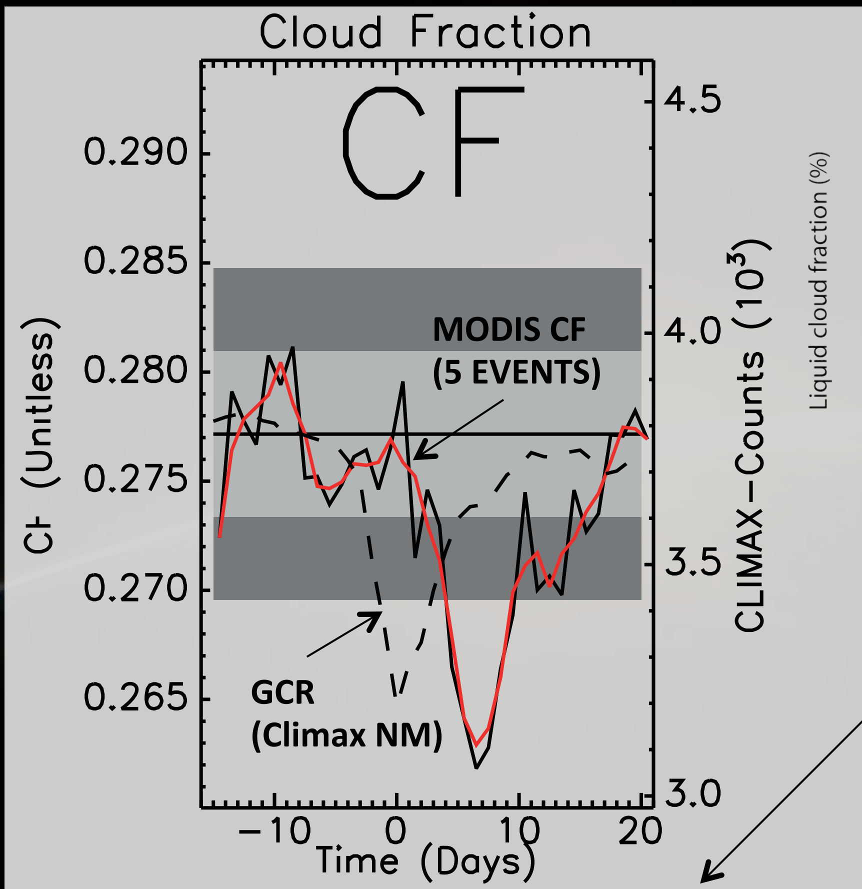
This has advantages over traditional tests (e.g. T/U tests), as it requires no minimum sample size or specific distribution, and it doesn't need adjustment for autocorrelation.

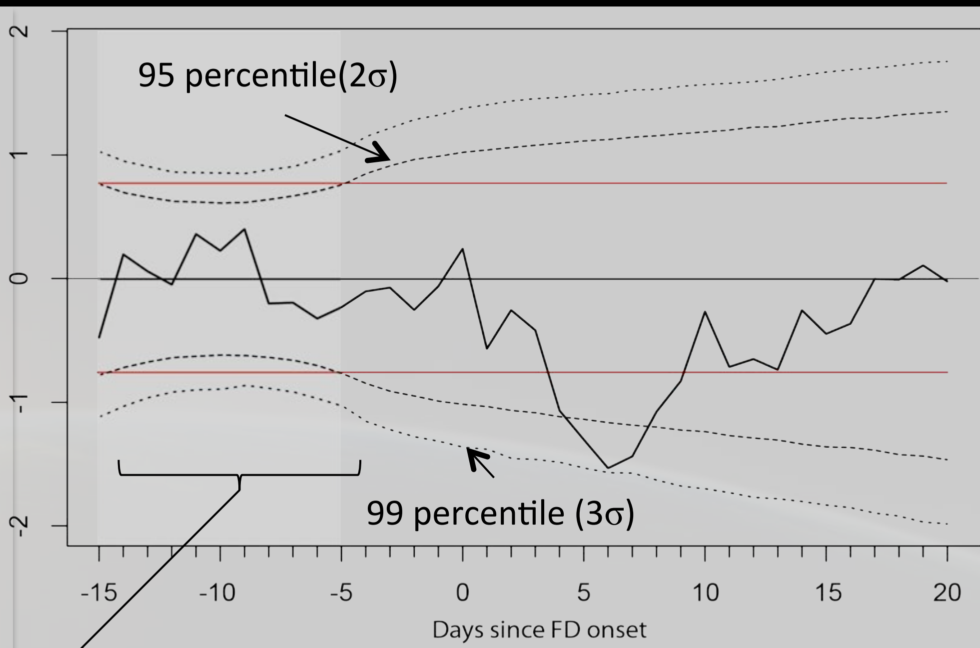
Laken & Čalogović, SWSC, 2013

Big variability in the clouds can be often mixed with the expected signal!

Svensmark et al. 2012, ACPD

Laken, Čalogović, Beer and Pallé (2012), *ACPD*





Dashed/dotted lines show **correctly** adjusted 2 and 3σ level – calculated from 10,000 MC simulations

Data NORMALIZED between period of day -15 and day -5

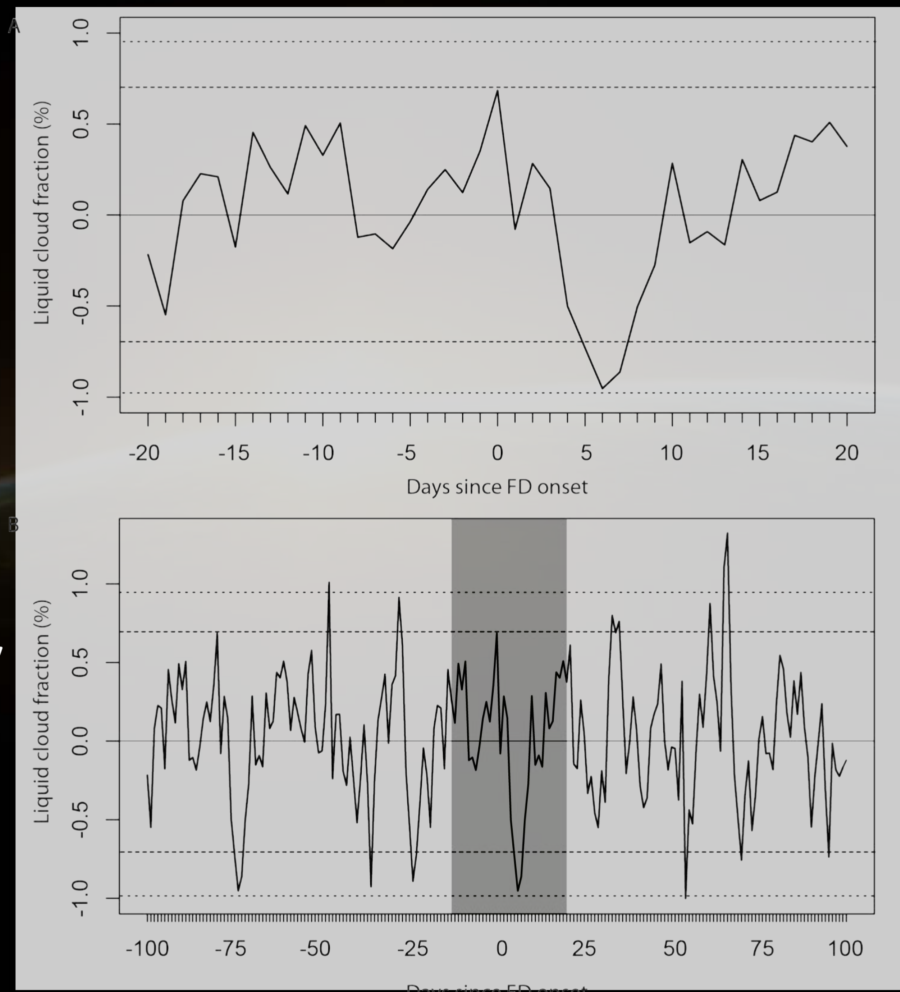
Proper statistical tests (MC simulations) are needed to asses the correct statistical significance!

Extension to longer analysis periods reveals no unusual variability in clouds during Fd events

MODIS Liquid cloud fraction changes using 5 biggest Fd events from Svensmark et al. (2012)

±20 day analysis period

±100 day analysis period

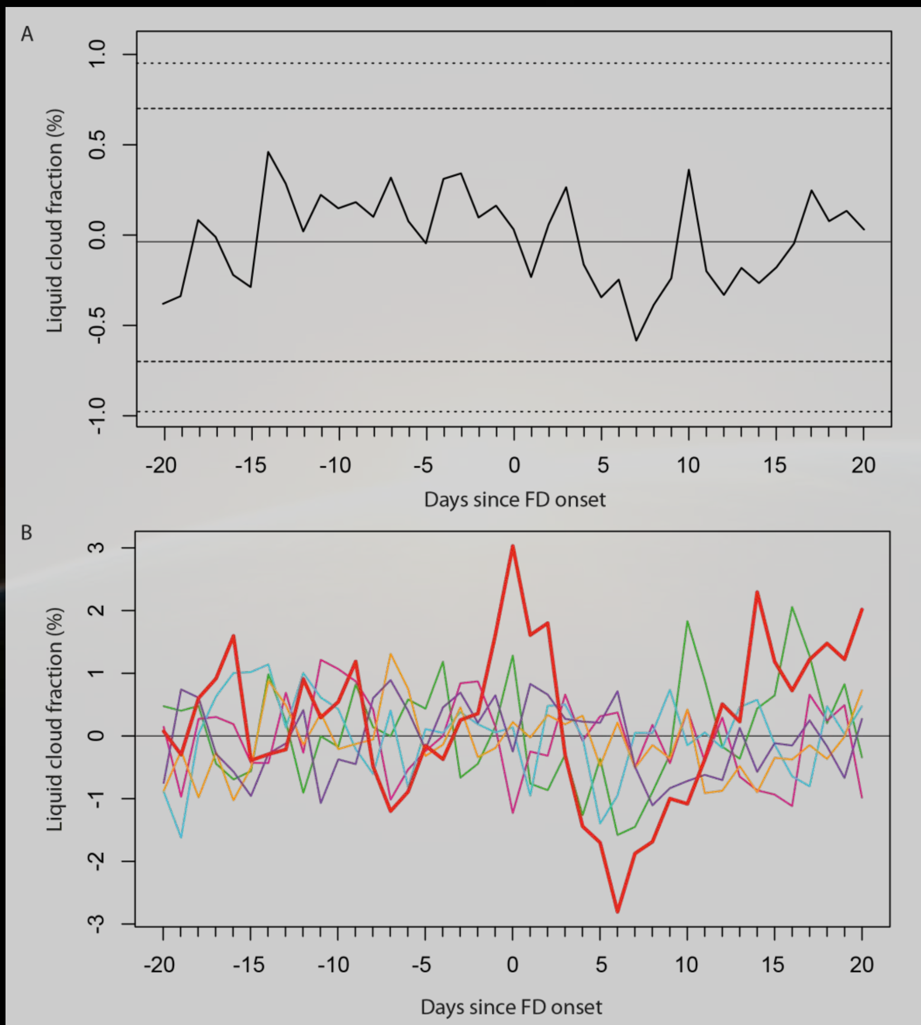


Values are anomalies from 21-day moving averages (i.e. mean of each day subtracted from 21-day moving average).

Dashed and dotted lines indicate the 95th and 99th (two-tailed) percentile confidence intervals respectively calculated from 100,000 Monte Carlo simulations.

Laken, Čalogović, Beer and Pallé (2012), *ACPD*

Just one event (and eventually outlier) can influence the whole composite



MODIS cloud fraction composite for Fd events 1, 3, 4, 5, 6 ranked by Svensmark et al. 2012

By replacing the event 2 with event 6 there are no significant changes in the composite!

Individual 5 Fd events plotted against event 2 (19.1.2005) where is clear that all significance in Svensmark composite comes from event 2.

Laken, Čalogović, Beer and Pallé (2012), *ACPD*

DTR shows response to Fd events?

- Surface level Diurnal Temperature Range (DTR) → effective proxy for cloud cover (indirect cloud data)
- DTR has longer time span than satellite cloud observations → allows to use the larger number of Forbush events

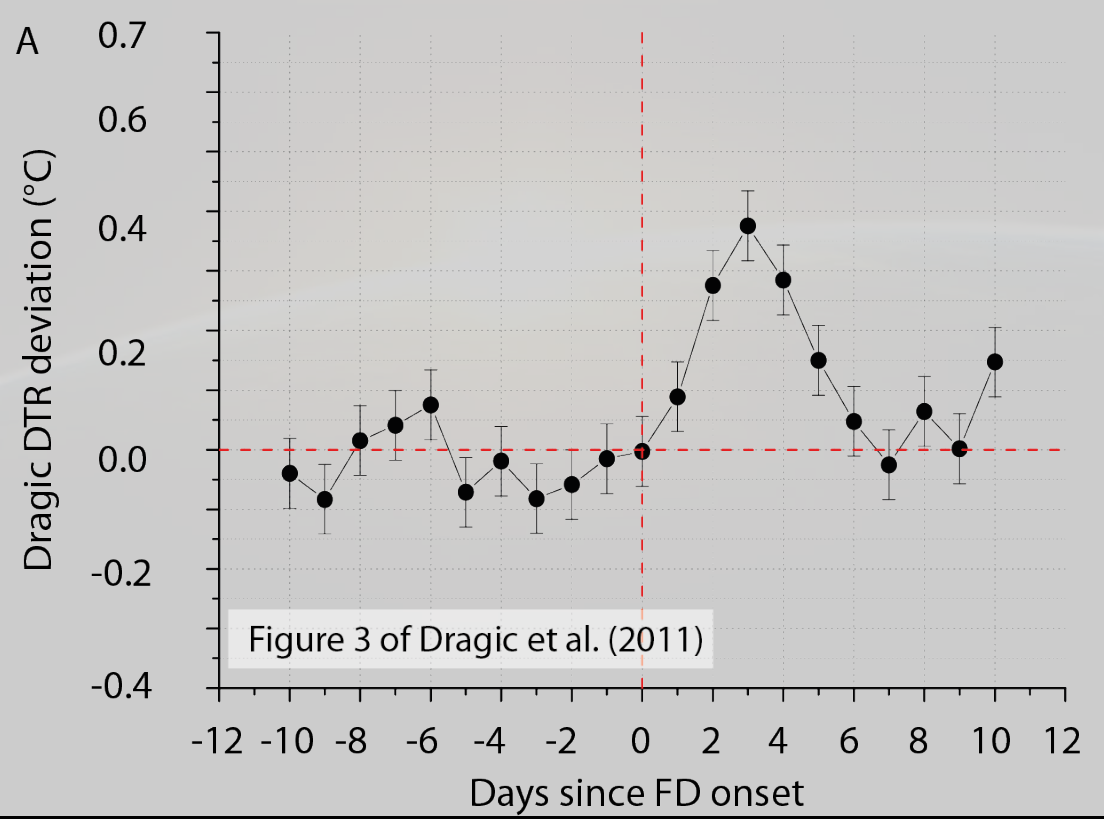
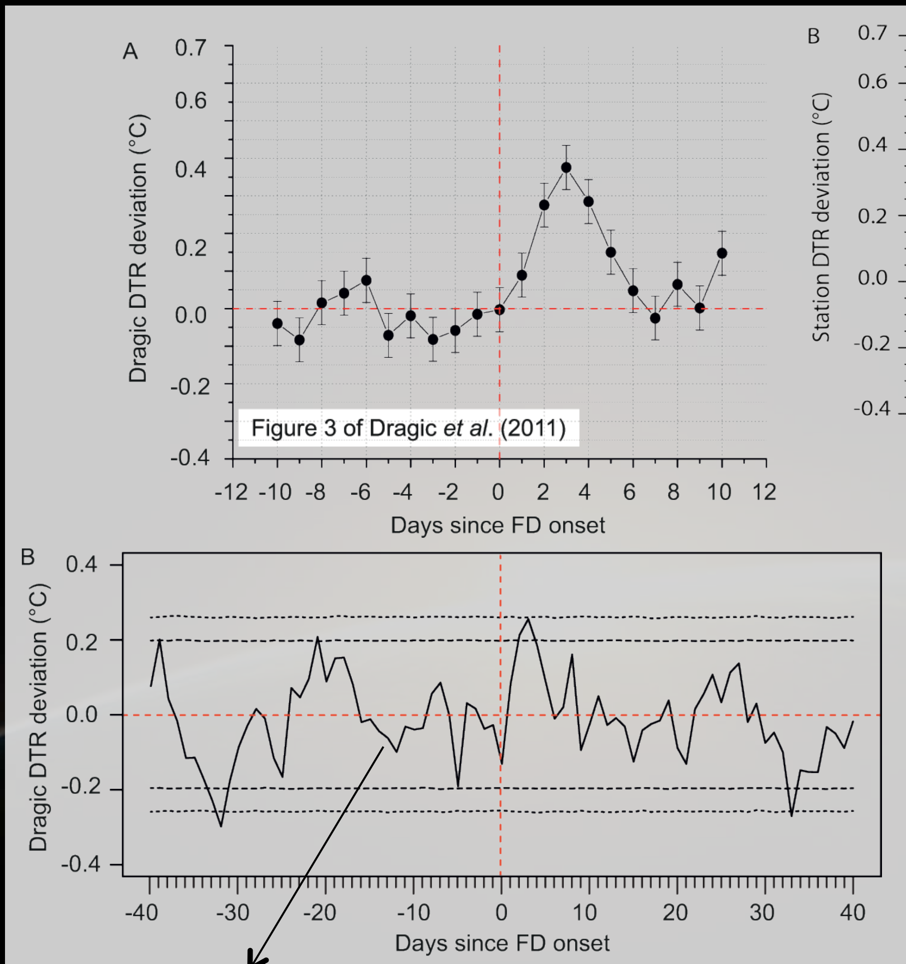
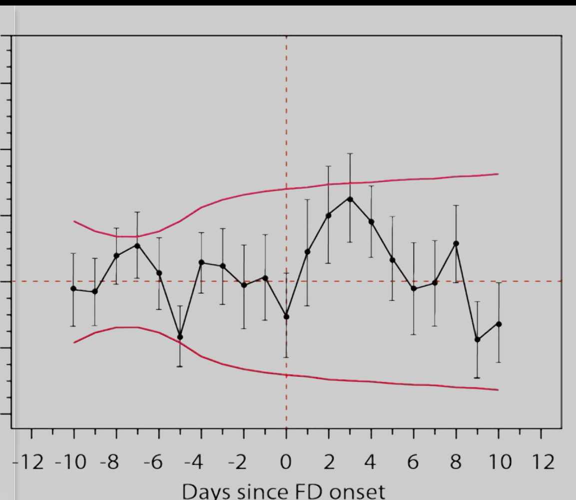


Figure 3 of Dragic et al. (2011)

- Dragić et al. (2011) uses composite of 37 Fd events (>7%) that show significant increase in DTR → support for GCR-cloud hypothesis

Analysis of Dragić et al. (2011) results





Dragić et al. Normalization of data in period from t_{-10} to t_{-5} and 99% significance intervals

Analysis of the same data as in Dragic et al. (DTR data and 37 Forbush events) shows that authors didn't estimate correctly statistical significance using t-test and certain statistical assumptions.

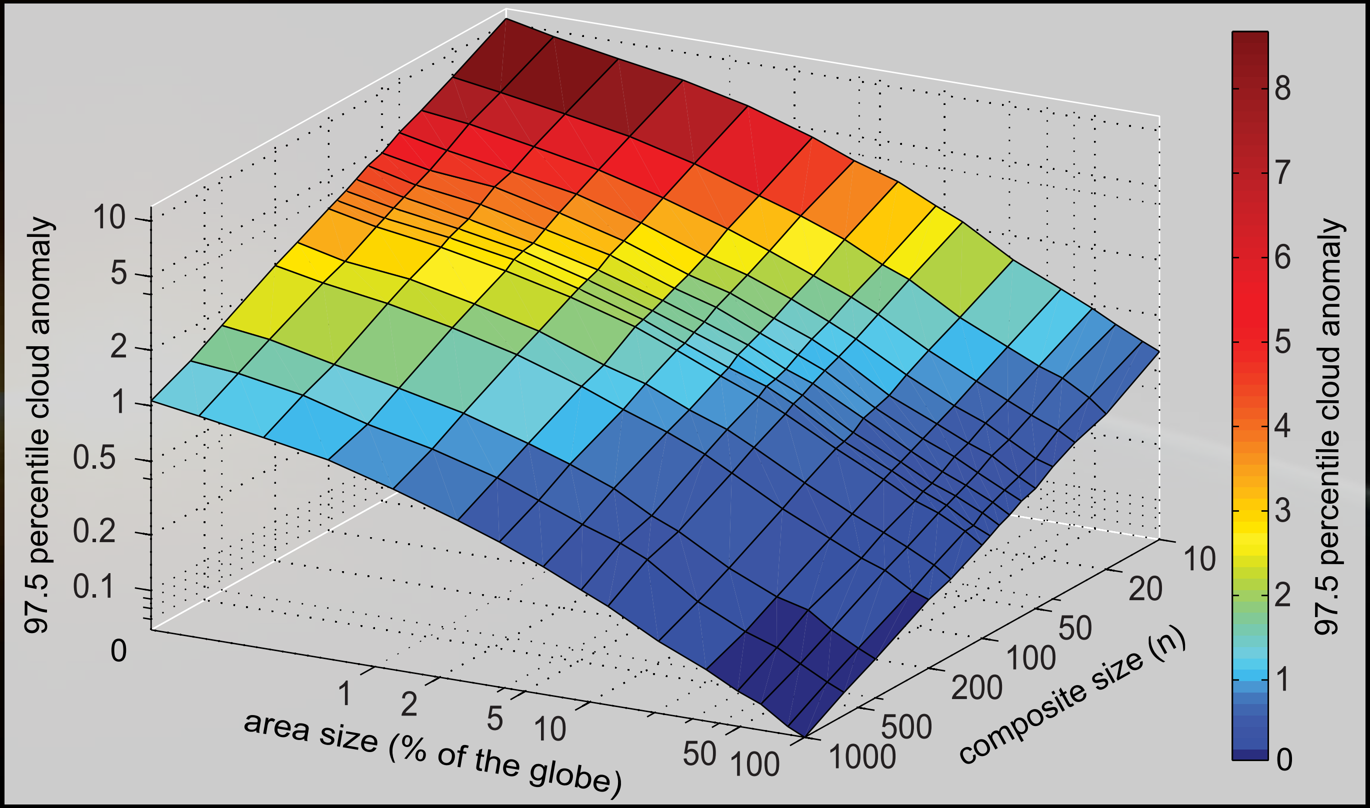
Significance intervals calculated from 100 000 Monte Carlo simulations (using 21-day running average)

Size of sample area and number of events impact the noise

Noise levels of data govern detectability of a signal. The noise varies with both the spatial area (*a*) considered by the data, and the number of composite events (*n*).

'*Noise*' indicated by <u>97.5[th] percentile values</u> from 10,000 random composites of varying *a* and *n* size.

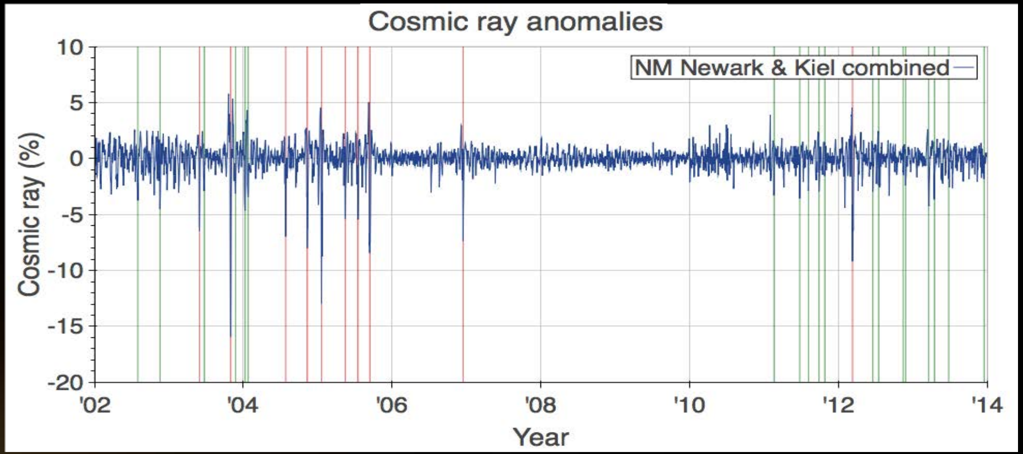
Each point of grid represents another independent set of 10,000 MC simulations



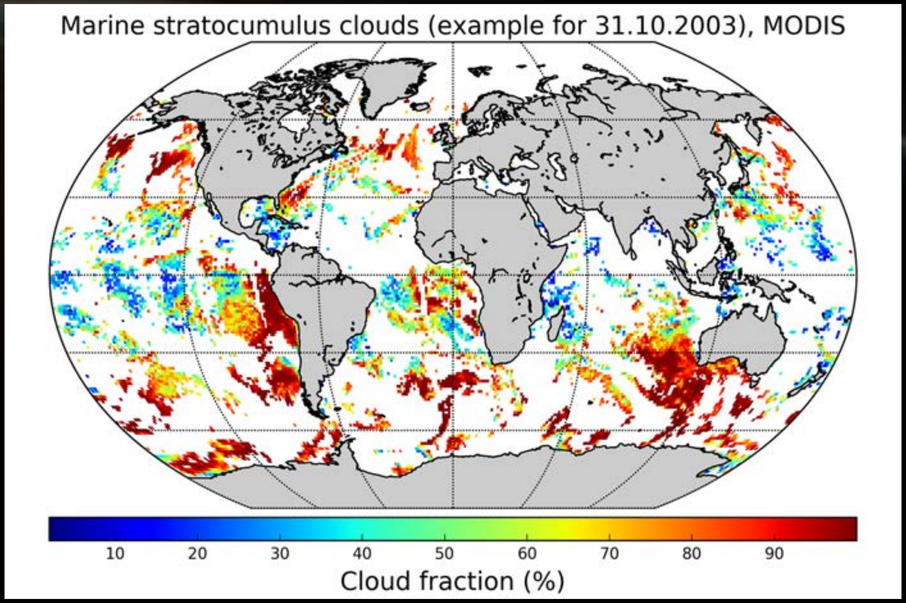
Laken & Čalogović, SWSC, 2013

possible to see how large *a* and *n* would need to be at minimum to see a hypothesized effect.

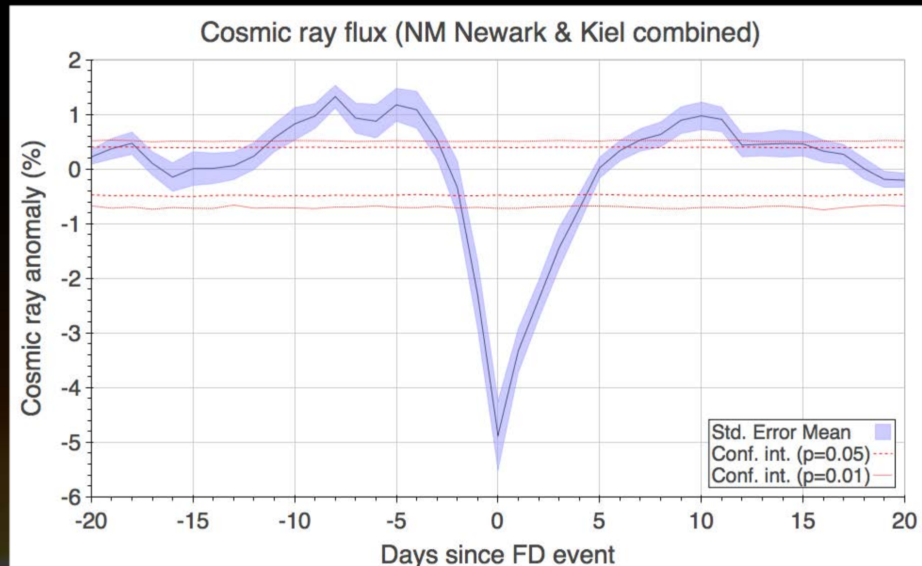
Does GCR – cloud link operate under specific conditions?

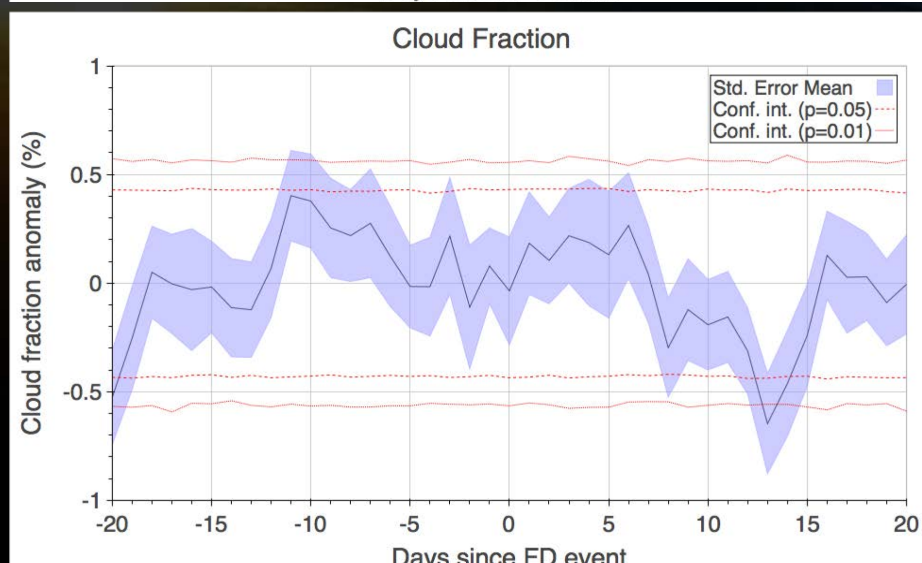


- MODIS cloud data (2002-2016)
- seven different cloud parameters (cloud fraction, cloud optical thickness, particle eff. radius…)
- 29 strongest Forbush decreases (>5%)
- Isolated Marine Stratocumulus Clouds isolated (top pressure > 800 hPa, optical thickness of 3.6–23)



Does Marine Stratocumulus Clouds show response to GCR variations?





There are numerous issues that may affect the results of solar-terrestrial studies

- Satellite cloud estimates are fraught with limitations and calibration errors, meaning long-term analysis is problematic at best, and, as in the case of commonly used ISCCP data, is fundamentally flawed.
- Co-variance of solar-related parameters (UV, TSI, CR flux, solar wind) make signal attribution difficult.
- Climate variability and volcanic activity, operating over time-scales similar to the solar cycle, make disambiguating causes of cloud cover change difficult.
- Composite analysis of FD and GLE events is often compromised by the difficulties of statistical analysis of autocorrelated data. This is compounded by the application of inappropriate and black-box statistical tests.
- Changing signal-to-noise ratios connected to spatio-temporal restrictions in composites have generally not been sufficiently taken into account in composite studies, leading to widespread type-1 (falsepositive) statistical errors.

Some of these issues already discussed by Pittock (1978, 1979)

Conclusions

- Methodological differences and inappropriate statistics in composite analysis can produce conflicting results. These are the likely source of discrepancies between cosmic ray – cloud composite studies.

- Present cloud datasets are limited to detect a small changes in cloud cover as well to detect the regional cloud changes (<several thousand km) due to the big natural cloud variability (noise). Thus, localized and small effect on cloud cover can't be completely excluded.

- **No compelling evidence** to support a cosmic ray cloud connection hypothesis using the satellite cloud data (ISCCP, MODIS) with long- or short-term (Fd) studies.

- Cosmic rays doesn't influence the **global** cloud cover and it is not a major factor in climate change or global warming! (opposite to believing of climate sceptics)

Thank you for your attention!

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