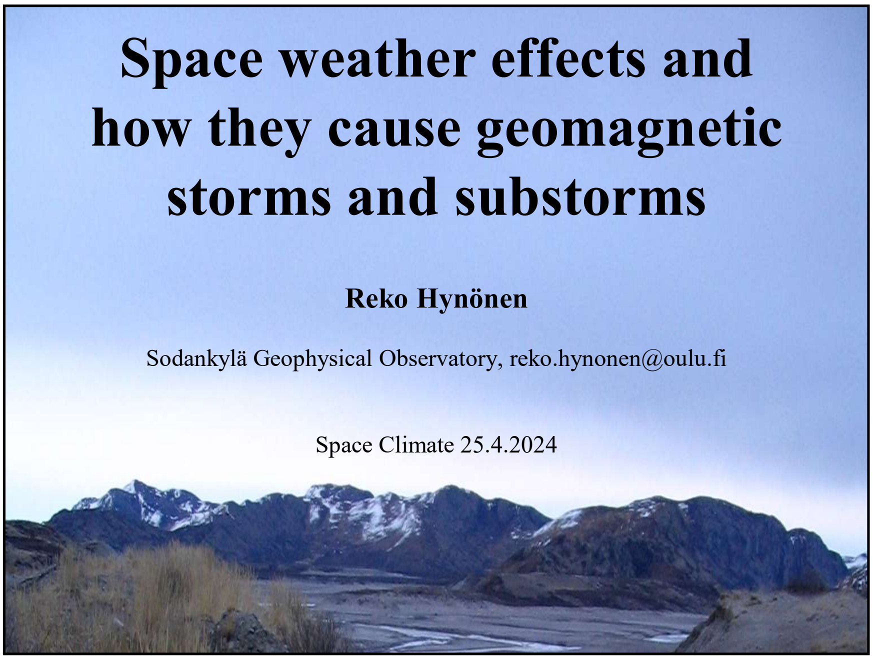
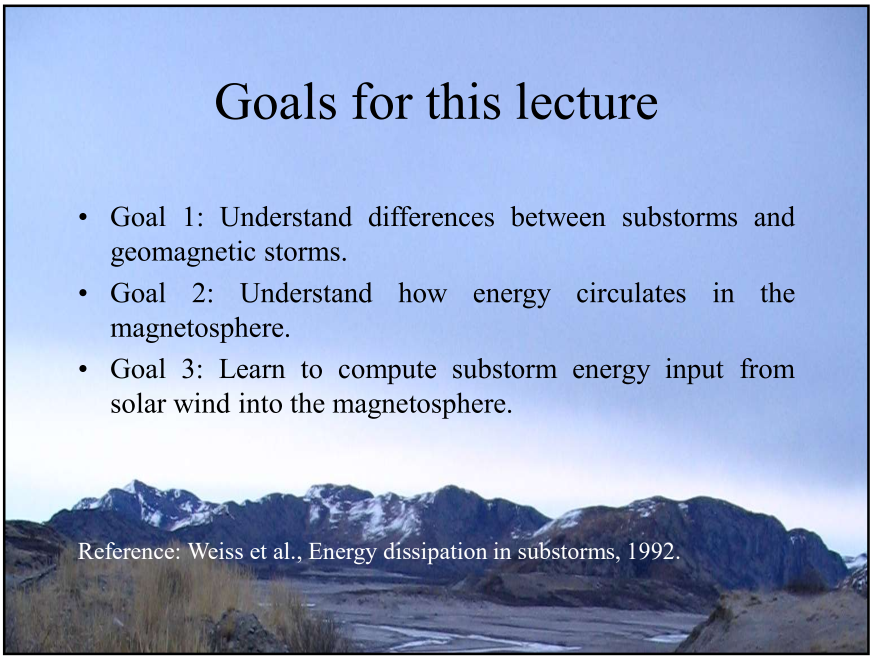
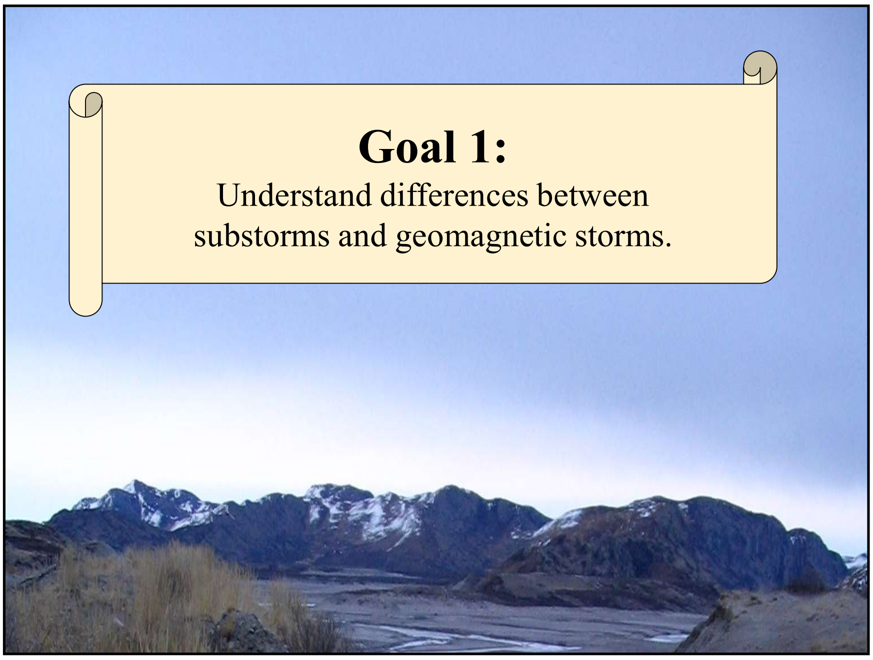
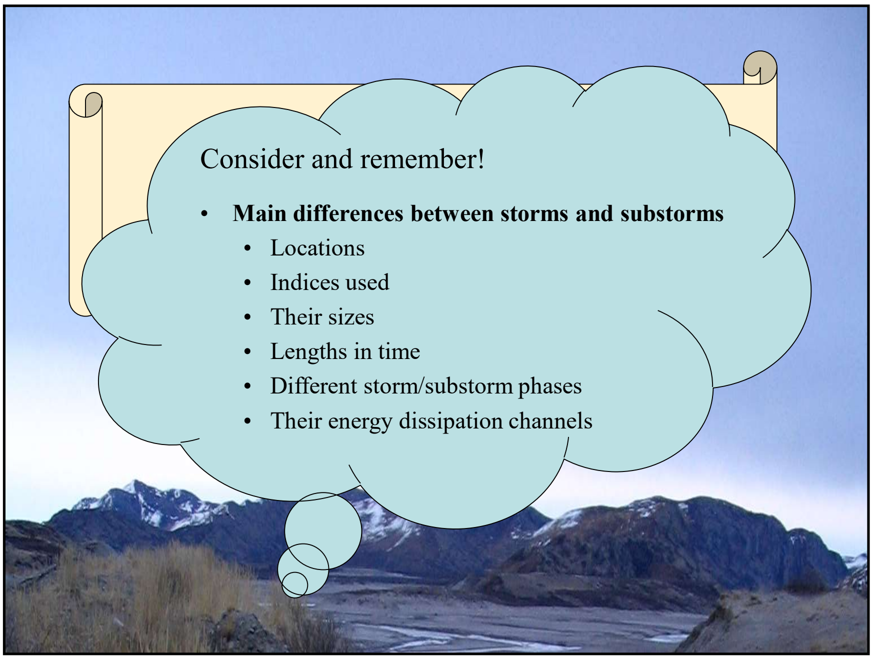


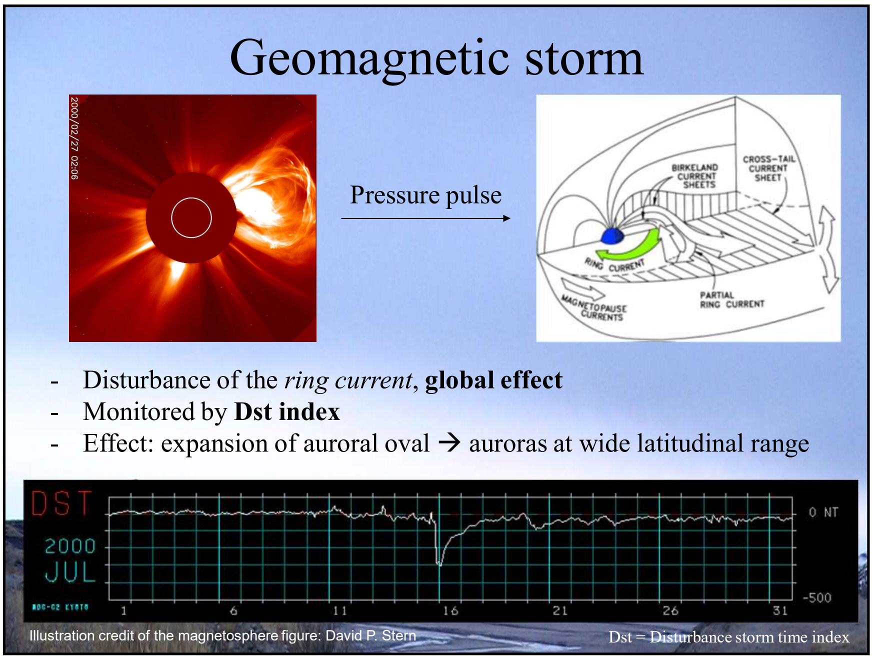
- Particularly we look into energy of these events



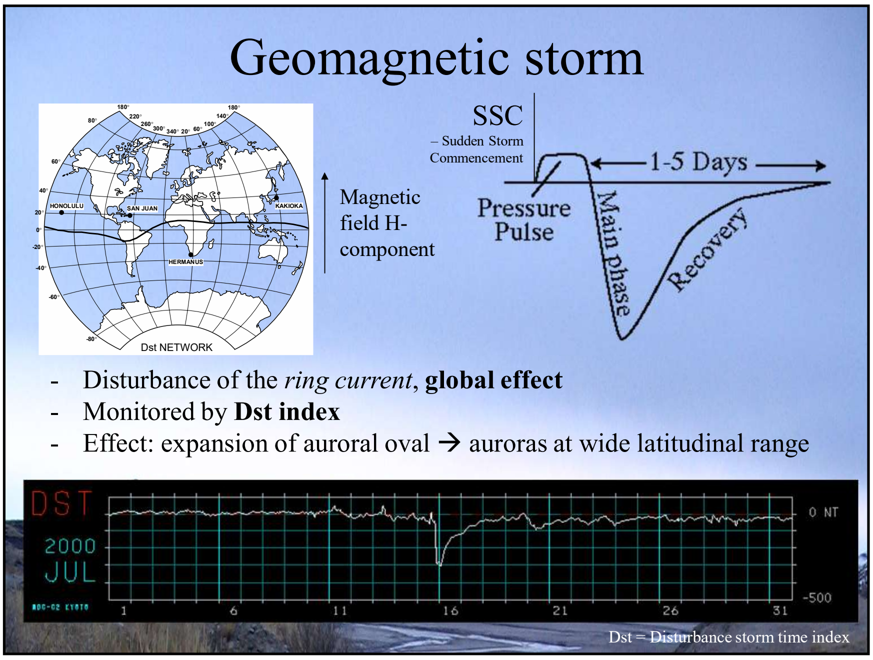
- We always ask about these things in the oral exam.
- It is important to know:
    1. Where the storms and substorms are observed, how long they last and how they are measured
    2. Where does the energy come from and where does it go.
    3. Some empirical and theoretical formulas about how we can estimate this, as well as some typical values of these energies/powers.


Goal 1:
Understand differences between
substorms and geomagnetic storms.

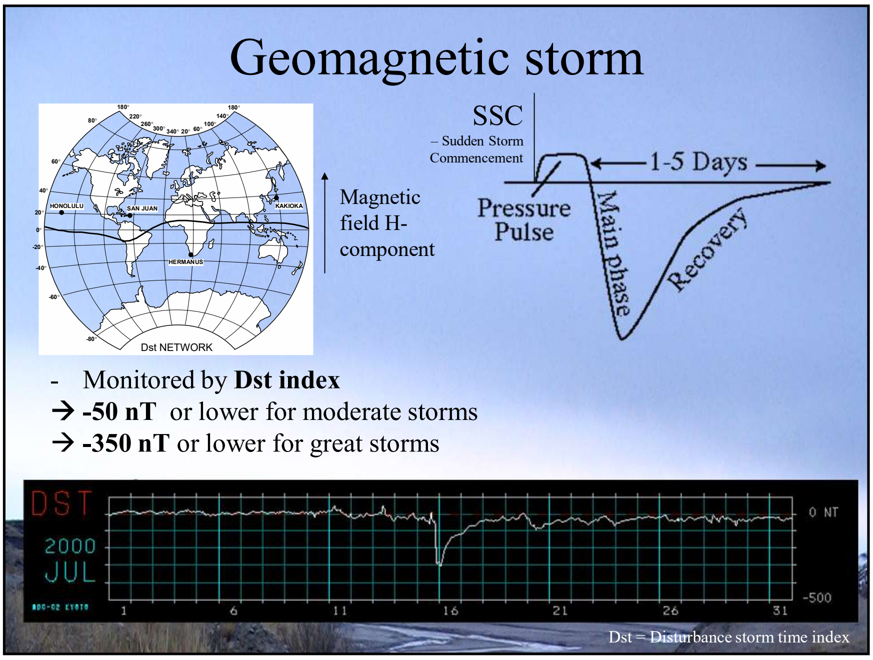

Consider and remember!
Main differences between storms and substorms
Locations
Indices used
Their sizes
Lengths in time
Different storm/substorm phases
Their energy dissipation channels



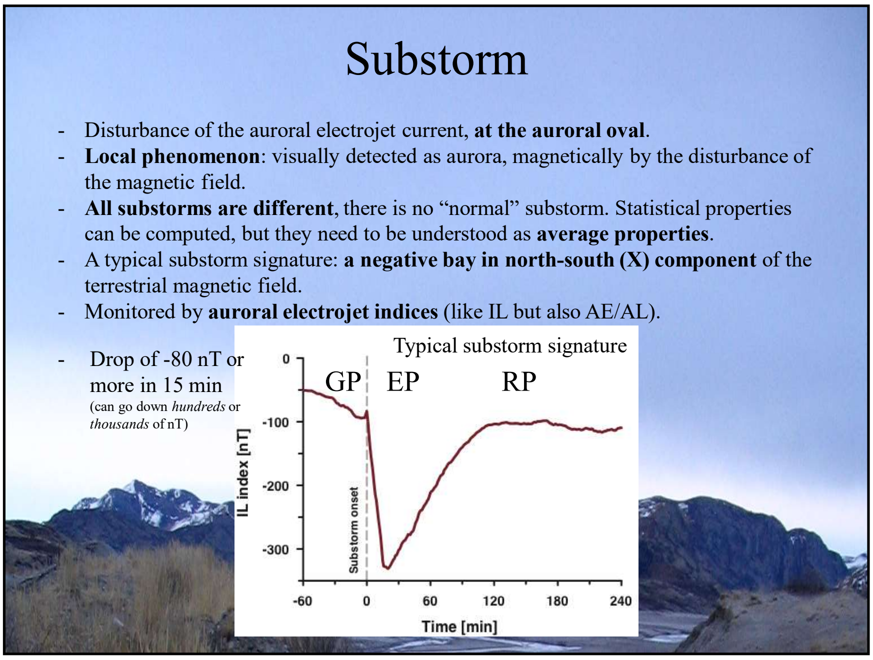
- Typically occurs when a solar wind pressure pulse (e.g. from a coronal mass ejection, or CME) compresses the magnetosphere.
- Normally the edge, magnetopause, is at about 10 Earth radii but it changes dynamically with the incoming solar wind.
- Storms are detected by monitoring the ring current.
- Ring current is a westward current flowing at several (~3-8) Earth radii. In the ring current, protons flow westward and electrons eastward, resulting in a net westward electric current.
- By the right-hand rule, the magnetic field from the ring current points southward, so the effect on the ground is a magnetic field decrease in the north-south direction.



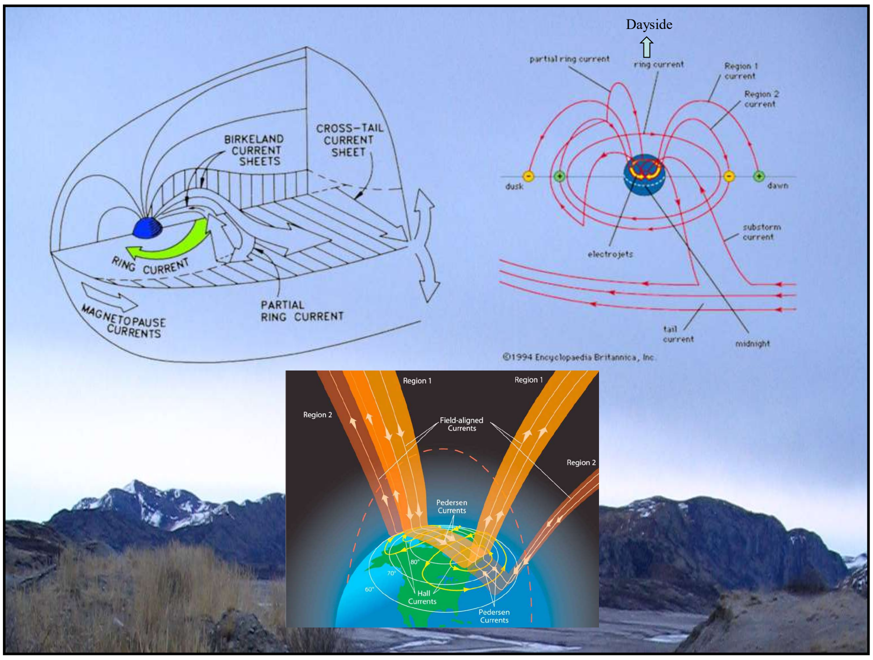
- Measured by Dst index, for **D**isturbance **s**torm **t**ime.
- Four magnetic stations around the equator, compute Dst index from north-south component of the equatorial magnetic field.
- First, when e.g. a coronal mass ejection hits, it triggers a Sudden Storm Commencement, SSC. This is indicated by a pressure pulse that **causes the magnetosphere to squeeze** → This strengthens the equatorial geomagnetic field (which points northward), so Dst goes up.
- At the same time the ring current begins to intensify. **Ring current also expands** farther from the ground, thus further contributing to the field increase in the pressure pulse.
- Geomagnetic storm usually (but not always) starts with a pressure pulse. This is also called the **Initial Phase.**
- During the **main phase**, the ring current intensifies further. This causes the Dst to go down.
- After the short main phase, typically of about a few hours, long **recovery phase** when the ring current stabilises lasts for days
- Causes substorms, called storm-time substorms. This is the original reason why substorms were named such, but nowadays we know that substorms occur frequently without an associated geomagnetic storm.



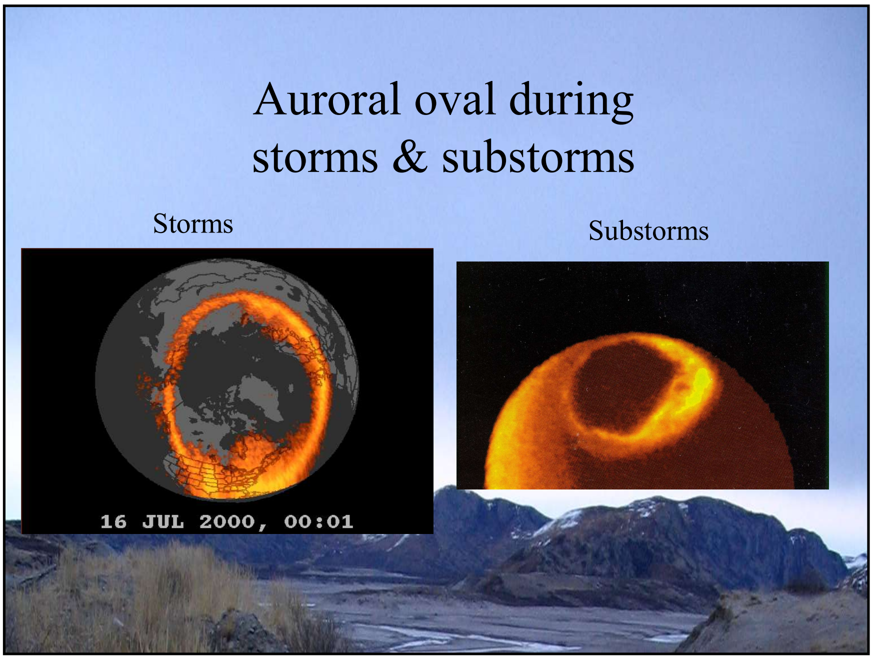
- Storms are classified by the value of Dst into classes.
- Important bits: -50 for moderate, -350 or less (more negative) for great
- Weak is -30 - -50, strong is -100 - -200, severe is -200 - -350.
- Some famous storms: Halloween storm 2003, Carrington storm 1859



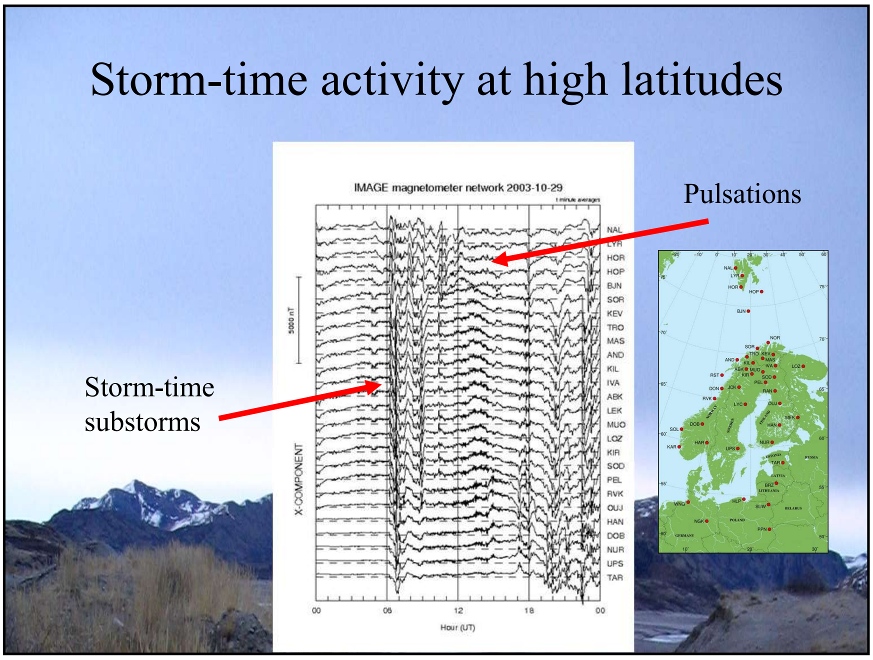
- A different creature that just looks similar in a magnetograph.
- All substorms are different but they have some common statistical properties
- Substorms are a local phenomenon, situated at either or both auroral regions.
- Visually observed as aurora and as the enhancement of the **auroral electrojet**, detected as a fall of the north-south (X) component of the magnetic field. Monitored by auroral electrojet (AE) indices like AL (the lowest fall from quiet levels over the measuring network) or IL (the same as AL but measured from IMAGE network)
- Phases: Growth phase, expansion phase, and recovery phase. Time estimates are given for a typical substorm but these vary wildly.
    - GP: electrojet starts primes for the substorm over 30-60 minutes with a small-ish drop of few tens of nT
    - EP: a sudden drop of magnetic field as the substorm onsets (indicated visually by bright aurora), lasts typically only half an hour.
    - RP: the field recovers over a couple of hours to the quiet level.
- Last from half hour and up to several hours.



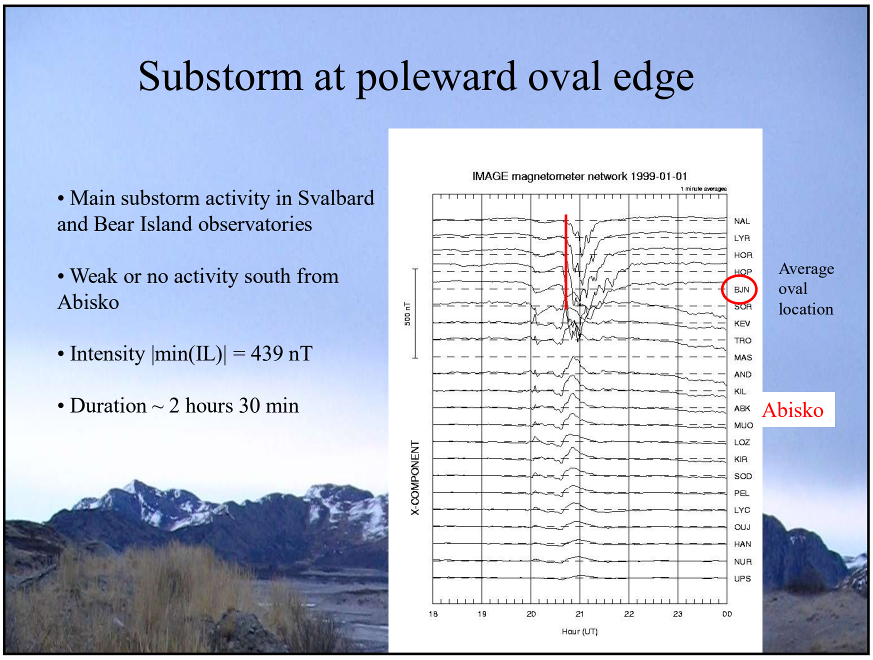
- Let's look at the big picture.
- Top-left: Magnetosphere and locations within it are connected through various currents. Particularly, Birkeland currents connect the magnetic tail to the high-latitude ionosphere, at the auroral zone.
- Top-right: Birkeland currents are field-aligned currents, or FACs. They can be divided into two current systems known as Region 1 current and Region 2 current.
- Region 1 current connects to the dayside, while the Region 2 current connects to the nightside. Between the foot points there are two electrojets, known as auroral electrojets.
- During a geomagnetic storm the ring current intensifies.
- During a substorm, the Birkeland current intensifies and the substorm current forms. Then the auroral electrojets in the ionosphere intensify, and particularly the westward auroral electrojet (causing the drop in magnetic field, according to right-hand rule) moves southward with the auroral expansion.



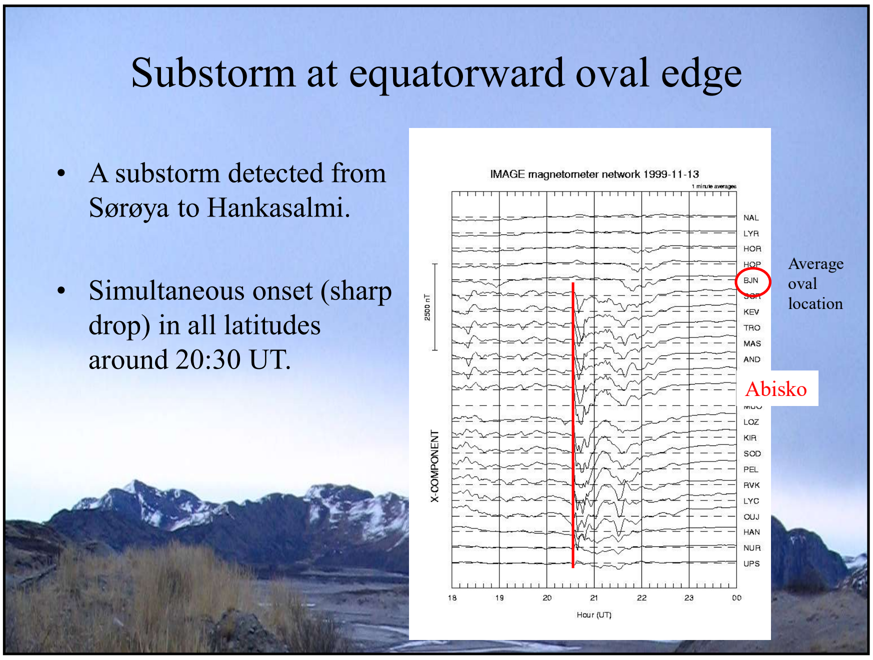
- Left: Note how widely the auroral oval has expanded during this storm.
- Right: in comparison, substorm can only be seen in this relatively small area, in this particular time sector.
- Let’s review how these two look in the magnetogram in the next slide.



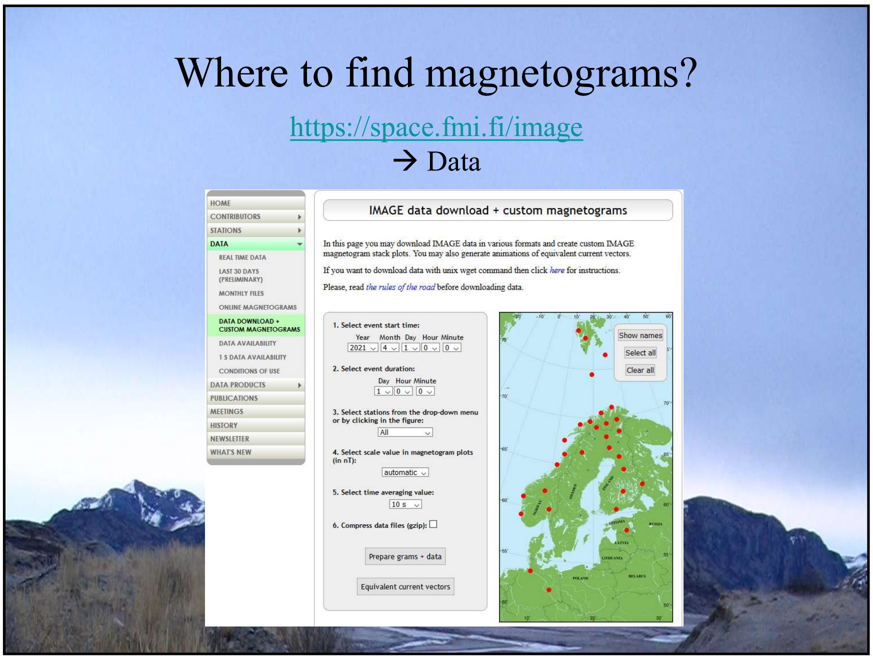
- Here: each plot is a magnetogram from a different magnetic station in the IMAGE network.
- The figure is from the famous Halloween storm 2003.
- The disturbance of the geomagnetic storm can be seen in virtually all of them.
- There are also some associated geomagnetic pulsations on the dayside.



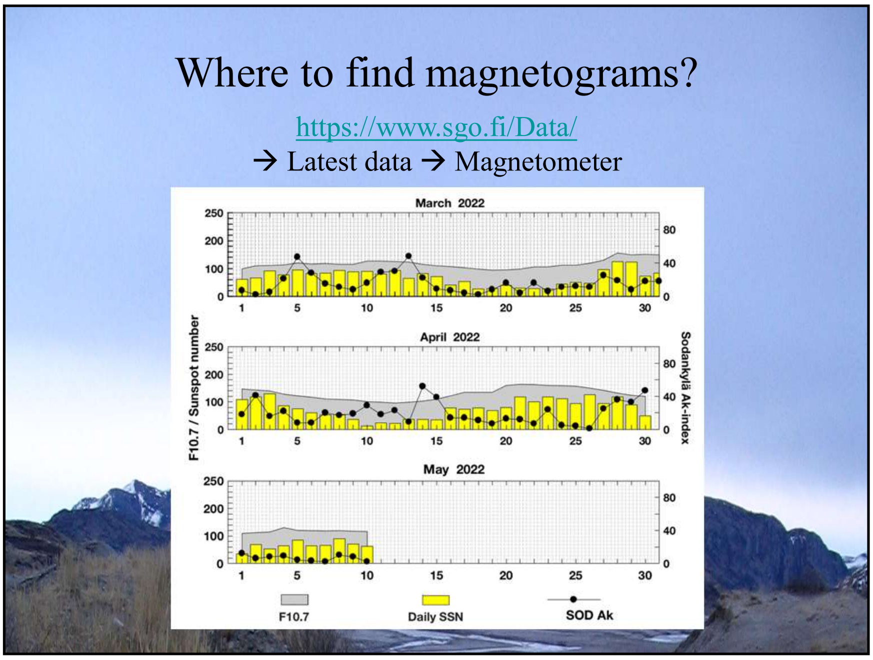
- In comparison, here's a substorm around the poleward auroral oval edge.
- Activity in Svalbard and Bear Island.
- There is no drop in Abisko or southern stations, although there is a curious increase.



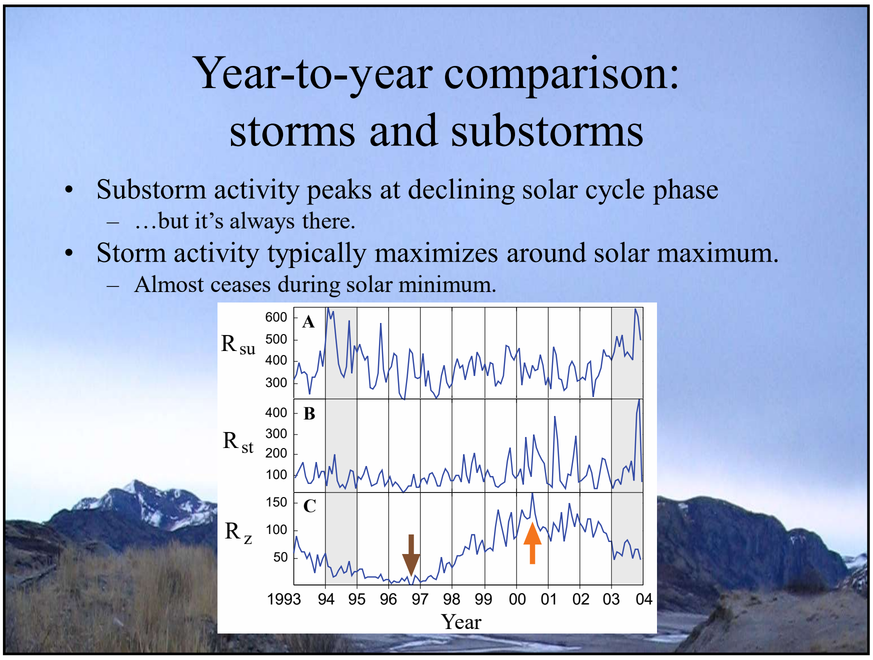
- Another one, now on the equatorward oval edge.
- This time, most activity is around Norway and Finland.
- No activity in Svalbard and Bear Island.



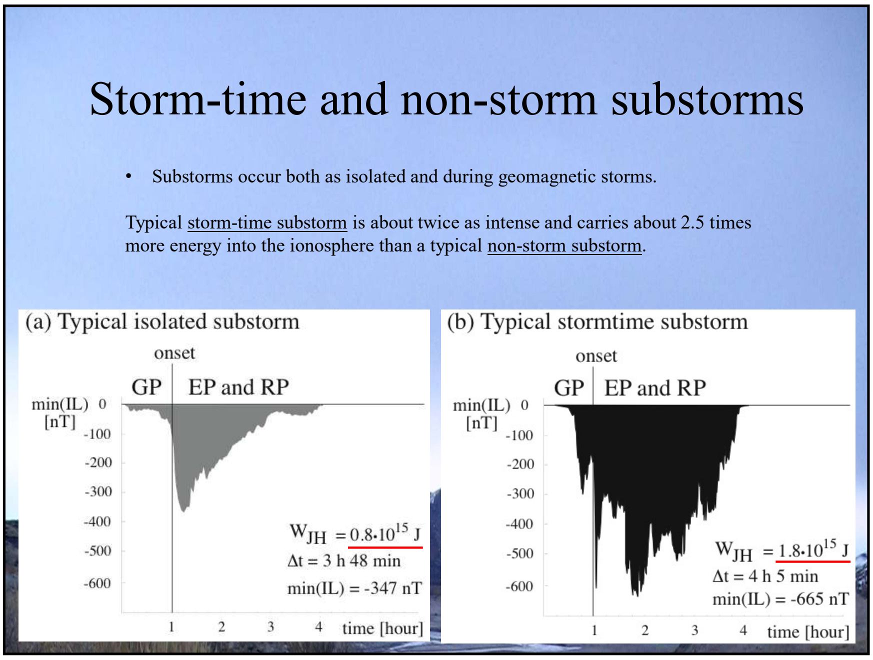
- This is the website where to find magnetic data related to Finland.
- https://space.fmi.fi/image



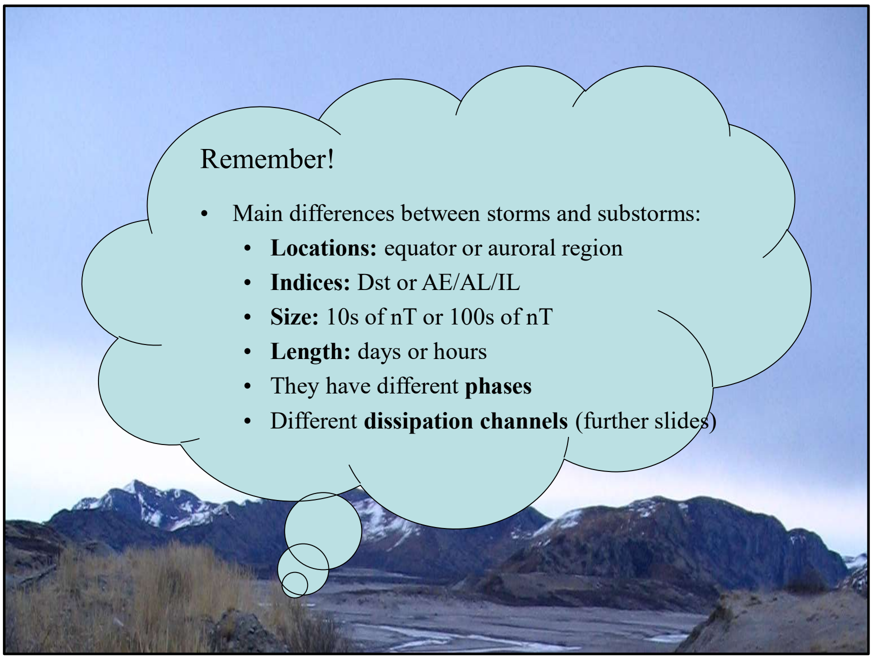
- More data available at the website of Sodankylä Geophysical Observatory
- https://www.sgo.fi/Data/

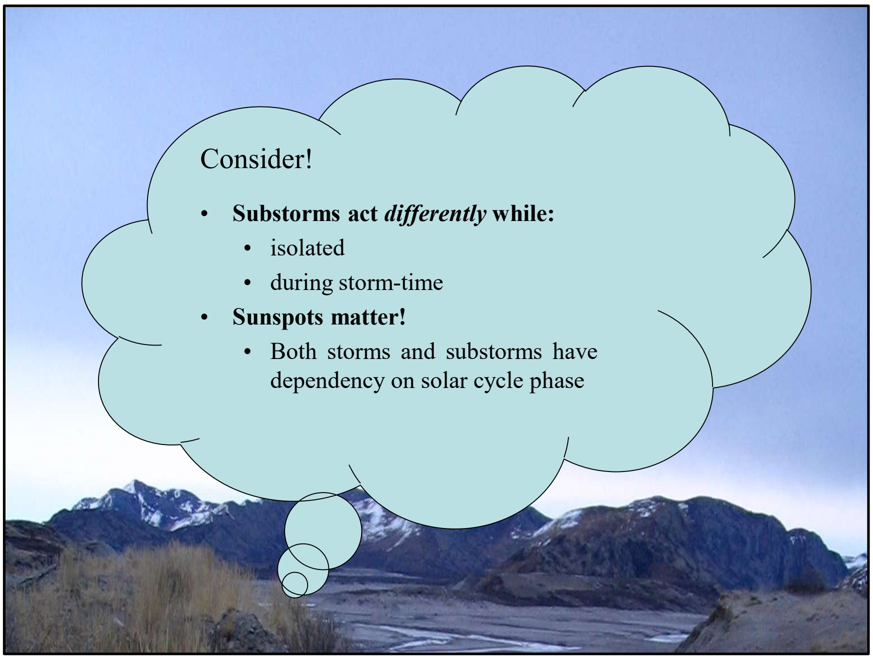


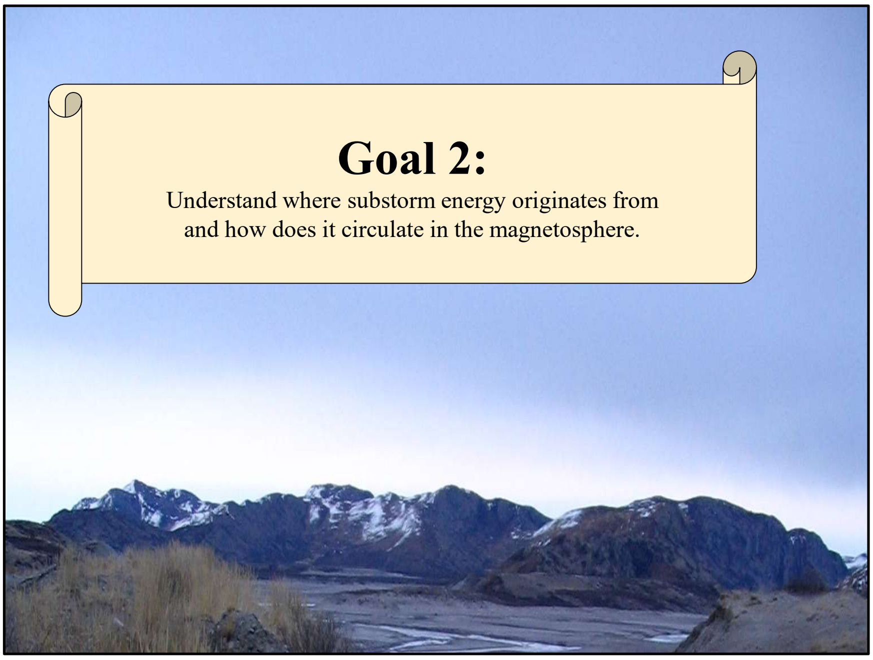
- Typical: Substorm activity (R_su) peaks at declining phase of the sunspot activity. Driven by solar wind streams that are prominent during that time.
- Storms (R_st) peak at maximum. Driven by flares and CMEs.
- Storms correlate somewhat with the number of sunspots (R_Z).
- Note the y-scale of substorms: are virtually ubiquitous and exist at all phases of the solar cycle.

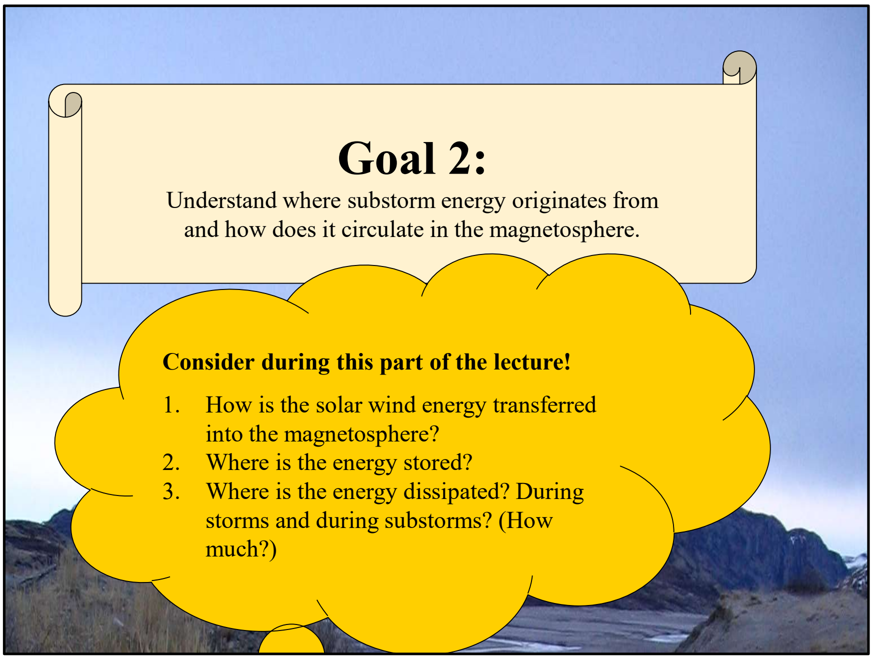


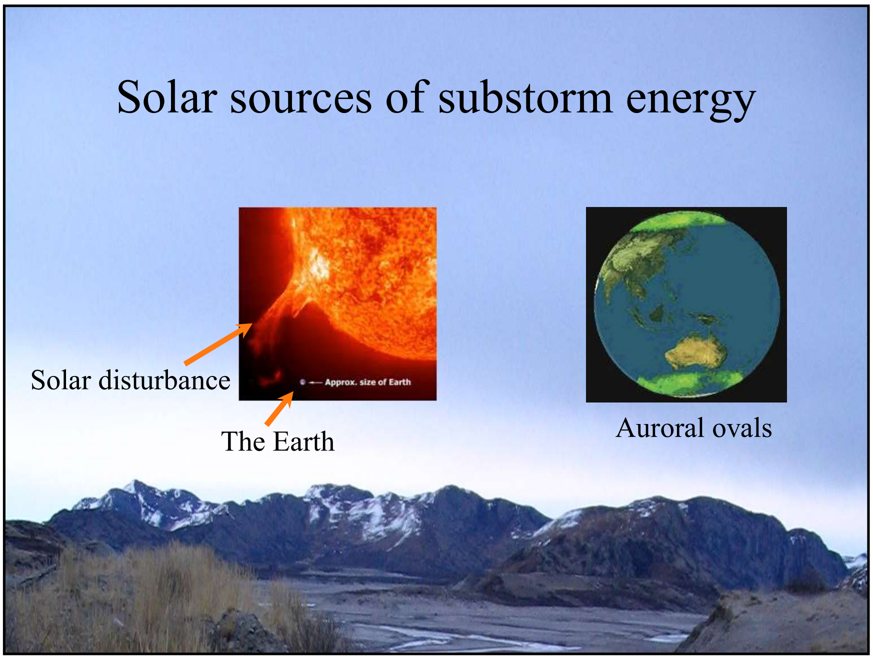
- Isolated: smaller, cleaner, effectively shorter.
- Storm-time: more intense, more complicated structure. Multiple expansion phases.
- Note the energy: of the order of 10^15 J.
- Around 1 peta Joule. Remember that, we often ask about it in the oral exam.


Remember!
• Main differences between storms and substorms:
• Locations: equator or auroral region
• Indices: Dst or AE/AL/IL
• Size: 10s of nT or 100s of nT
• Length: days or hours
• They have different phases
• Different dissipation channels (further slides)

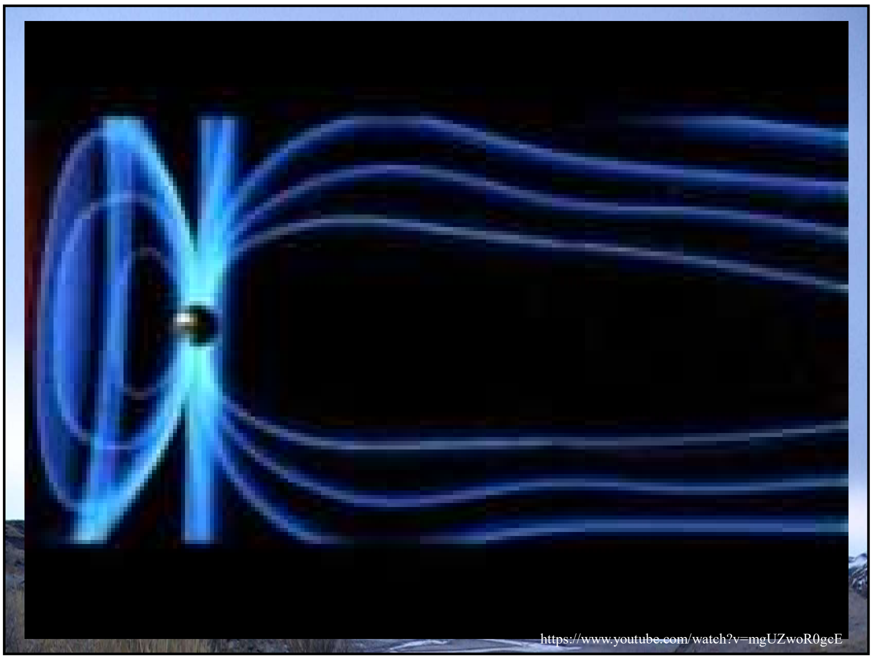

Consider!
• Substorms act differently while:
• isolated
• during storm-time
• Sunspots matter!
• Both storms and substorms have dependency on solar cycle phase


Goal 2:
Understand where substorm energy originates from
and how does it circulate in the magnetosphere.


Goal 2:
Understand where substorm energy originates from and how does it circulate in the magnetosphere.
Consider during this part of the lecture!
1. How is the solar wind energy transferred into the magnetosphere?
2. Where is the energy stored?
3. Where is the energy dissipated? During storms and during substorms? (How much?)

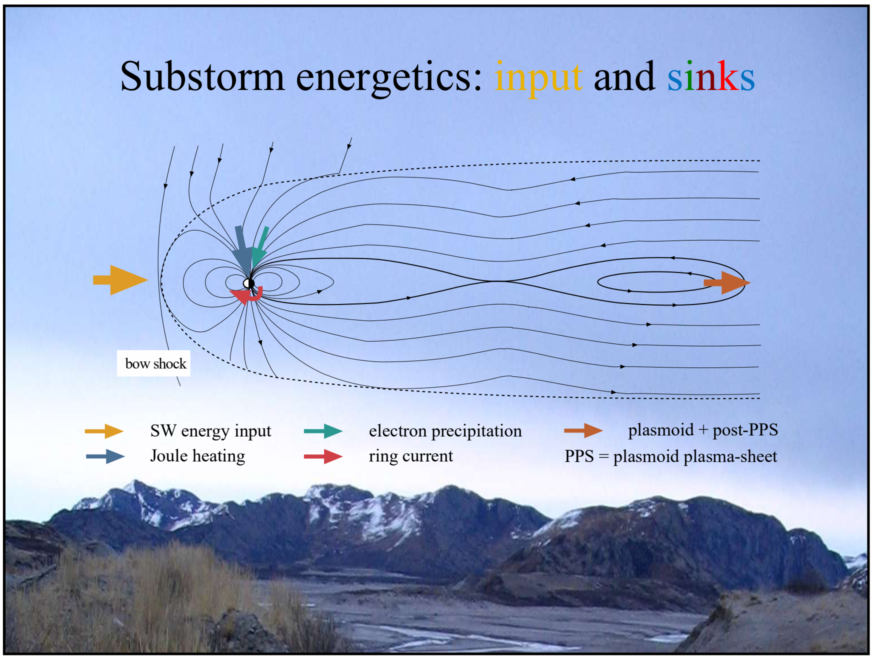


- Energy comes mainly from the Sun.
- Important solar wind quantities for the energy include: Solar wind speed, pressure, and magnetic flux.
- Now we know where the energy comes from. Where does it go?

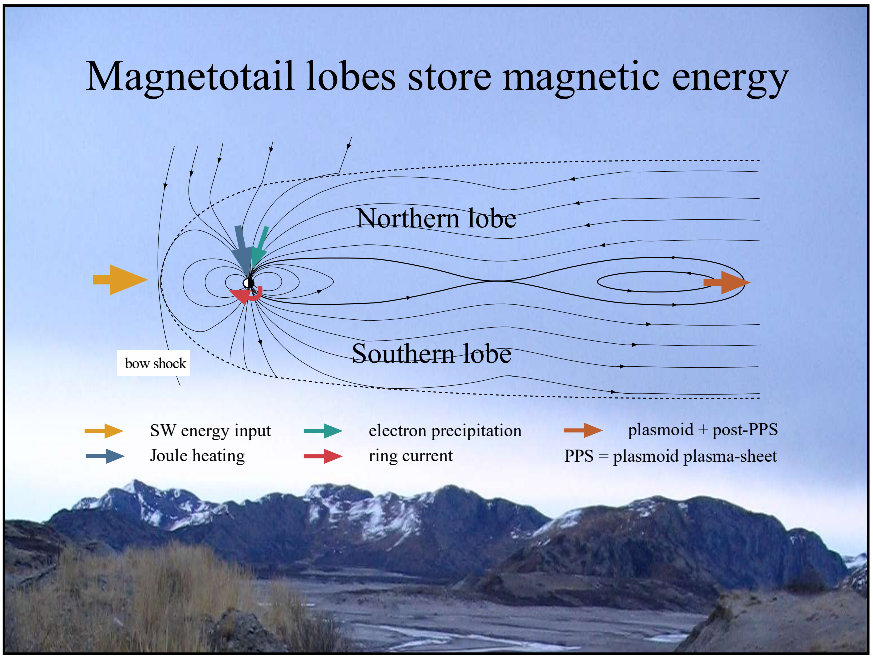


https://www.youtube.com/watch?v=mgUZwoR0gcE

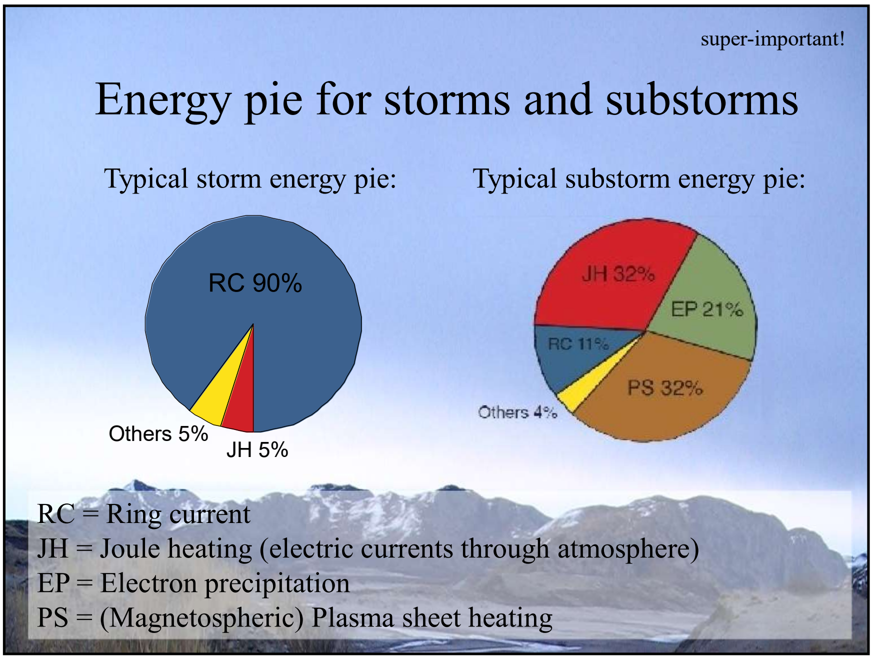
- Note also the plasmoid at 00:34 as the tail field "snaps" and it disappears towards the right
- "Snap" is an example of magnetic reconnection and releases a lot of energy stored in the magnetic field. The energy releases by accelerating particles that end up in the auroral zones by moving along the field lines.



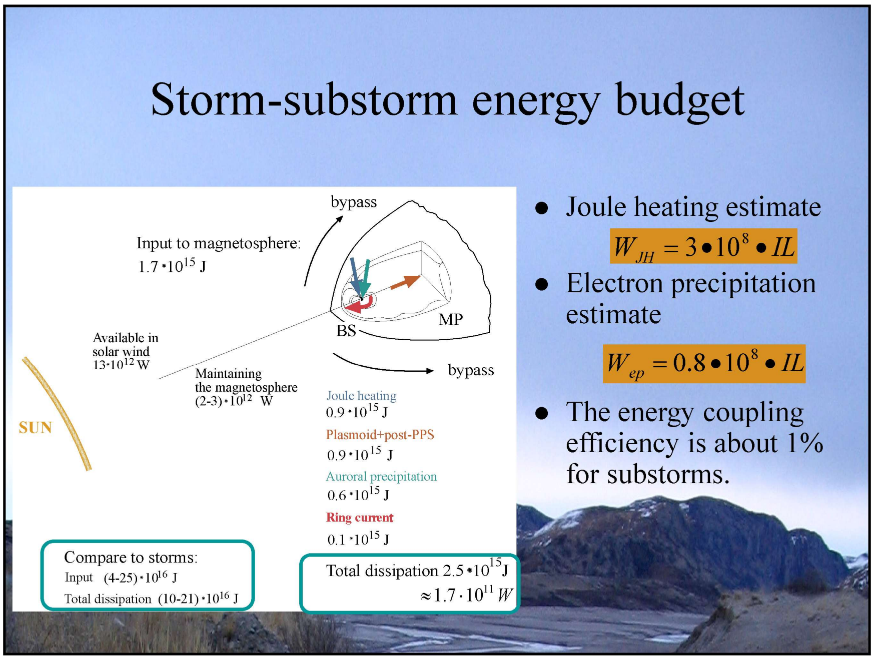
- Energy comes from the solar wind.
- It goes into:
  - Joule heating: when the current goes through a conductor (like atmosphere)
  - Electron precipitation: Electrons get trapped in the magnetic field lines and under certain conditions can precipitate into the atmosphere.
  - Ring current (energetic particles).
  - Plasmoid and plasma sheet heating: the ball of plasma at the back of the magnetotail escaping back into the solar wind.



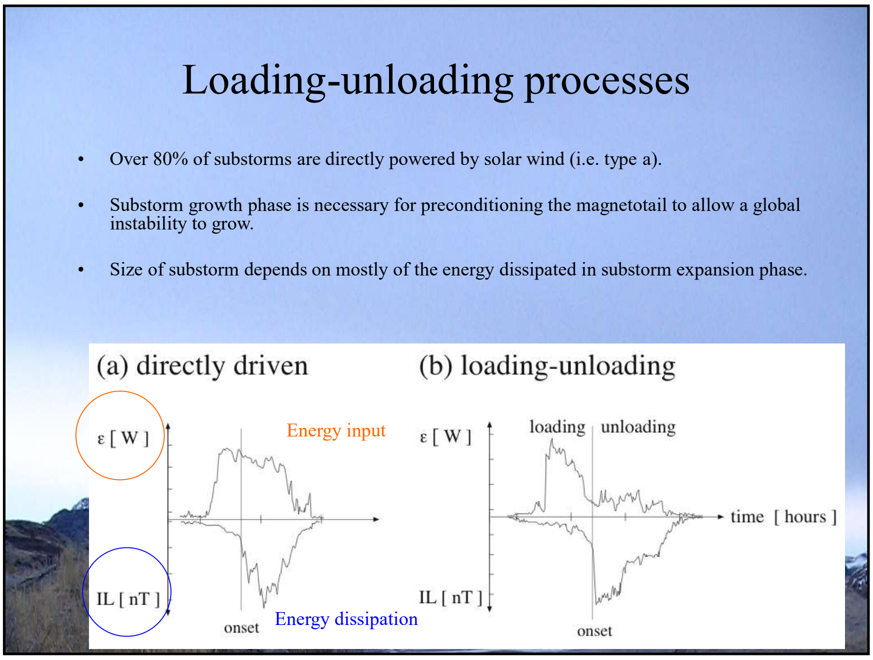
- In the video you saw the energy comes from the solar wind.
- Field lines get convected and pushed back, storing particles and thus **energy into the magnetic lobes**. Important!
- Between the lobes there's plasma sheet. Some heat goes there as well.



- This is important!
- How is the energy distributed in the storms and substorms? Where does the energy end up?
- Storm energy is almost completely ring current. Small part comes from Joule heating, and the rest is other stuff.
- Substorm energy, a completely different animal.
  - About 1/3 Joule heating
  - About 1/3 plasma sheet heating
  - About 1/5 electron precipitation
  - Just 1/9 ring current
  - Some other things like the plasmoid leaving

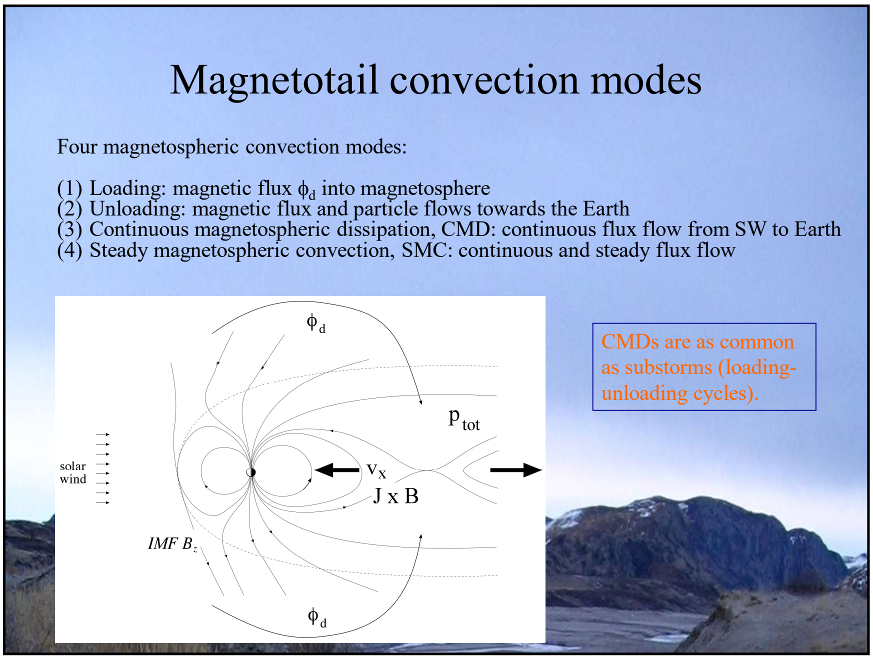


- Energy is input from the solar wind
- Take a while to note these numbers and remember them.
- Also consider the empirical equations here. They give an estimate of the power (i.e. Instantaneous energy input in Watts) computed from an auroral electrojet index IL.

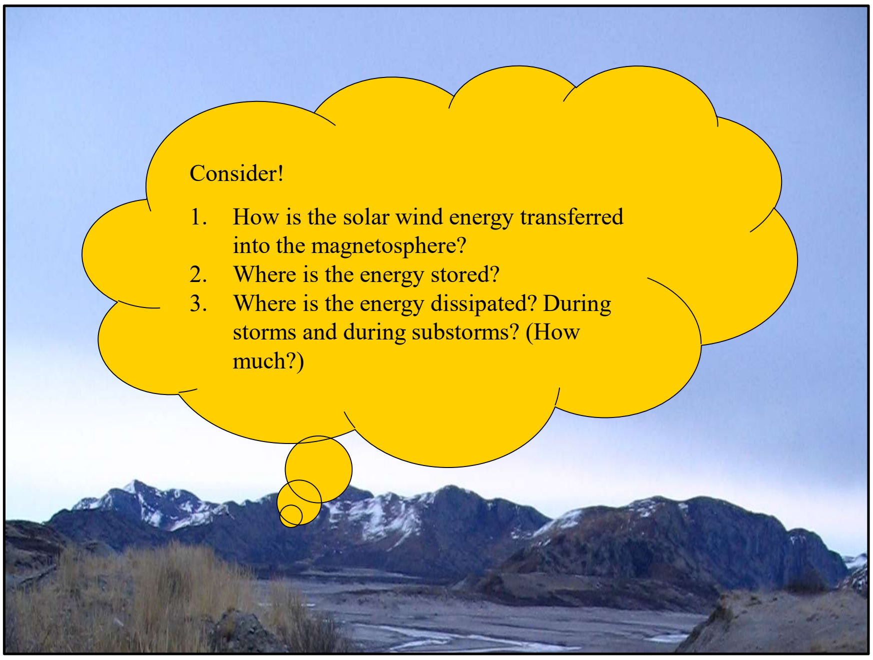


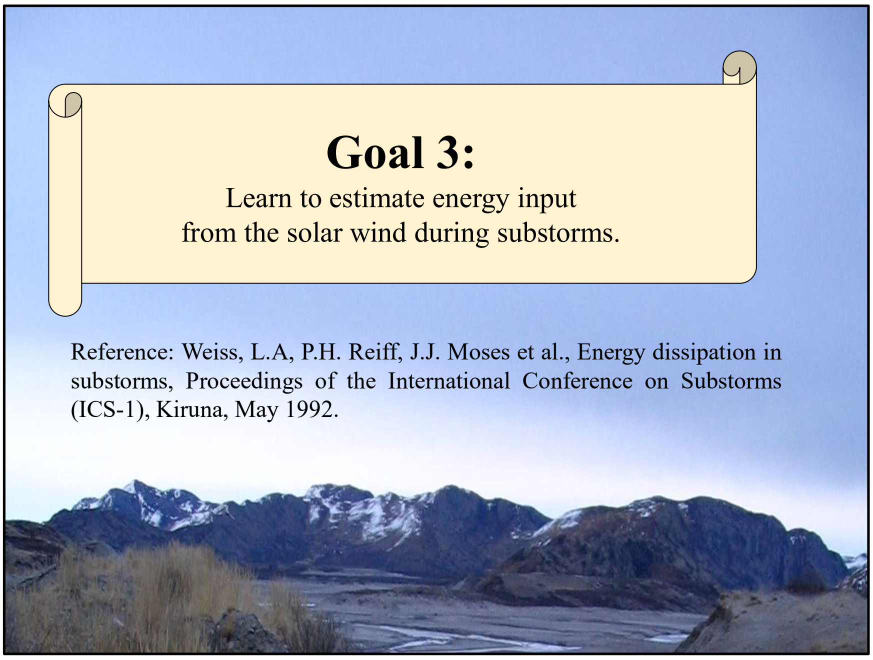
Final notes about the goal 2: two types of substorms energizing. Epsilon is defined few slides later.

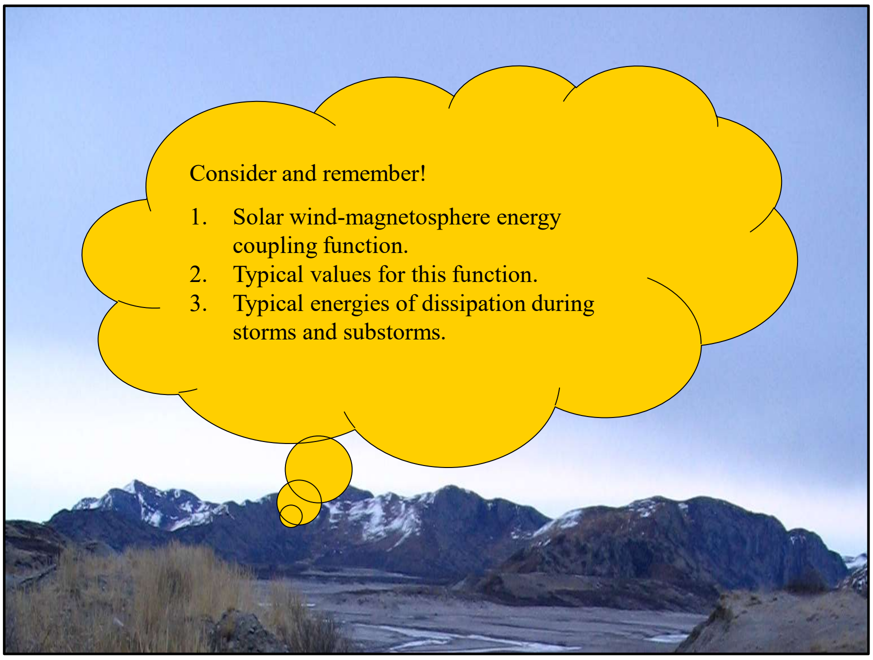
- Directly driven: Solar wind energy goes almost immediately into driving the substorm
- Loading-unloading: Solar wind energy is stored in the magnetic lobes for some time, before something triggers the substorm and releases the energy



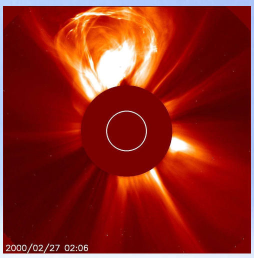
1+2 – Loading and unloading go hand in hand
3 – Solar wind can directly dissipate into the magnetosphere
4 – Flux and particles convect steadily and there’s no associated substorm.


Consider!
1. How is the solar wind energy transferred into the magnetosphere?
2. Where is the energy stored?
3. Where is the energy dissipated? During storms and during substorms? (How much?)

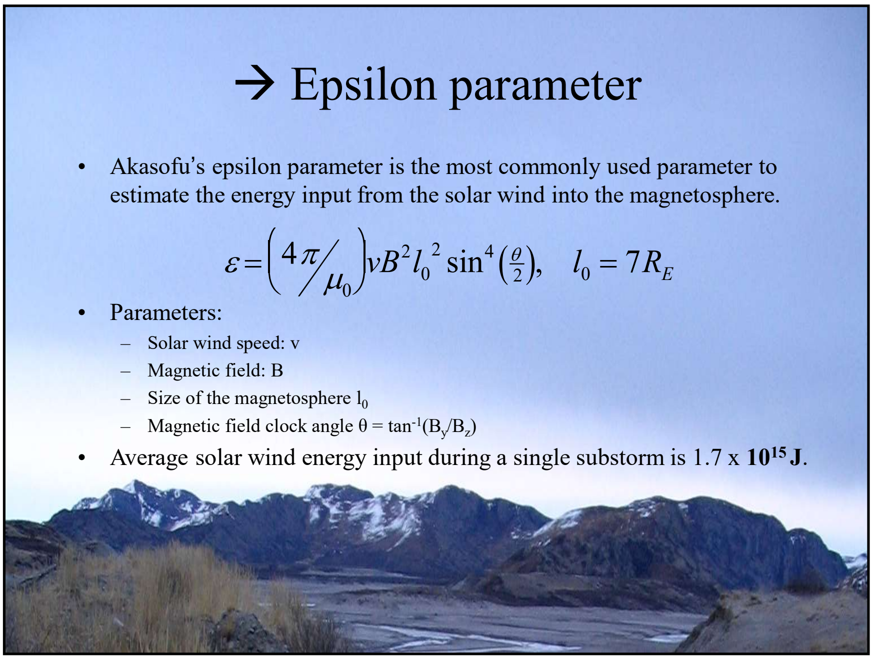

Goal 3:
Learn to estimate energy input
from the solar wind during substorms.
Reference: Weiss, L.A, P.H. Reiff, J.J. Moses et al., Energy dissipation in substorms, Proceedings of the International Conference on Substorms (ICS-1), Kiruna, May 1992.


Consider and remember!
1. Solar wind-magnetosphere energy coupling function.
2. Typical values for this function.
3. Typical energies of dissipation during storms and substorms.

Energy coupling function



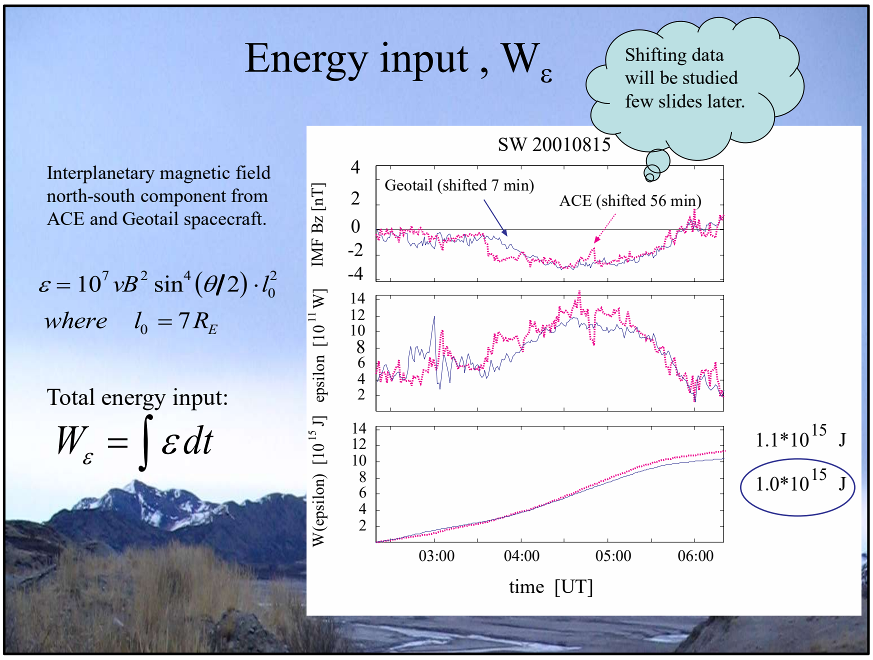
- How much energy is in the solar wind? How much is bestowed upon magnetosphere?
- Interesting parameters:
  - Solar wind speed: v → Kinetic energy
  - Magnetic field: B → Magnetic energy
  - Size of the magnetosphere l_0
    → Cross-section for energy channels
  - Magnetic field clock angle $\theta = \tan^{-1}(B_y/B_z)$
    → Effect of the magnetic field southward component



Theoretical parameter that gives an estimate of the energy input (power) into the magnetosphere.

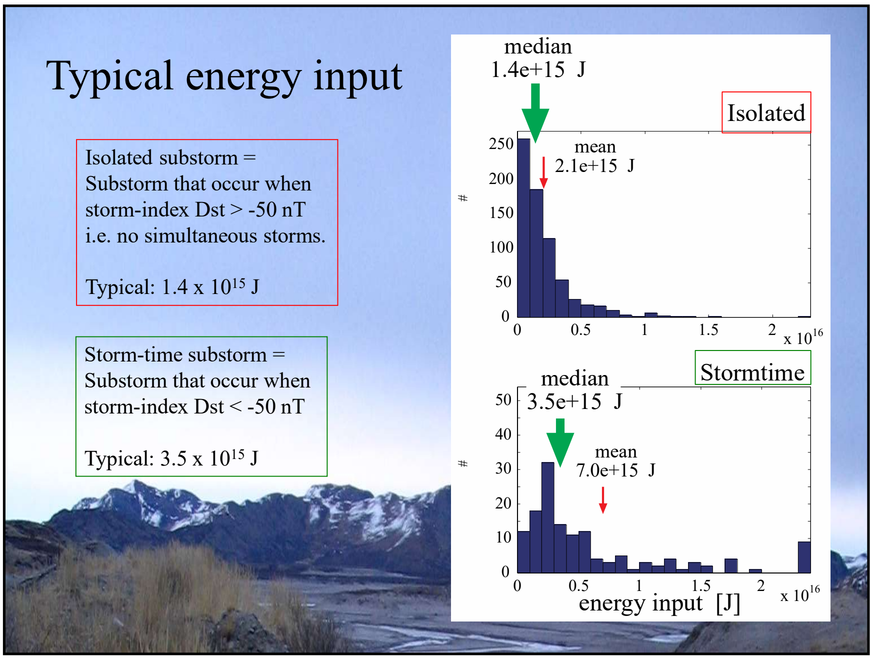
Look at its parameters:

- Speed v
- Magnetic field B^2
- Magnetospheric size l_0
    - Can be varied to get better estimates
- Theta that is the clock angle of the solar wind, depends on the magnetic field.

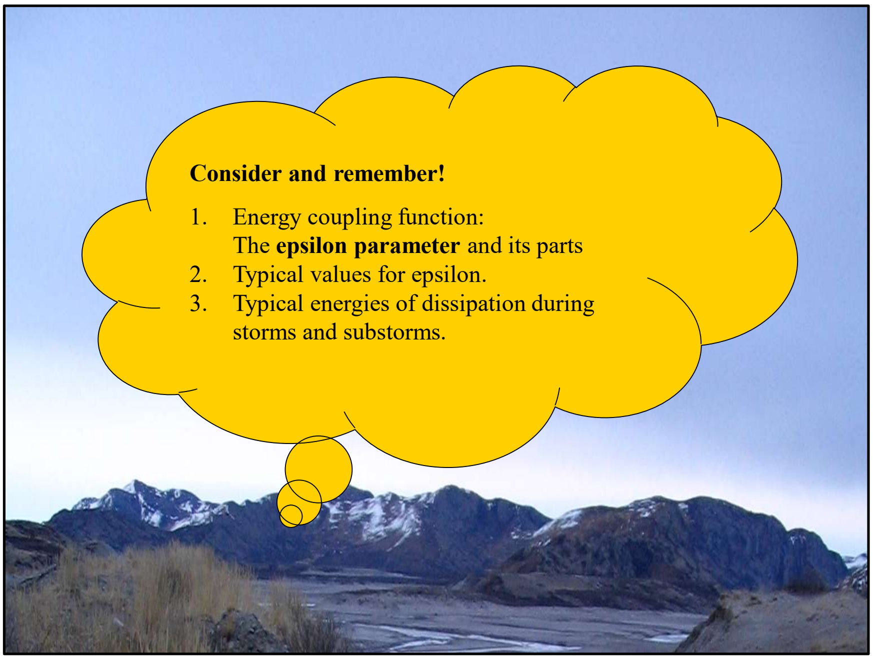


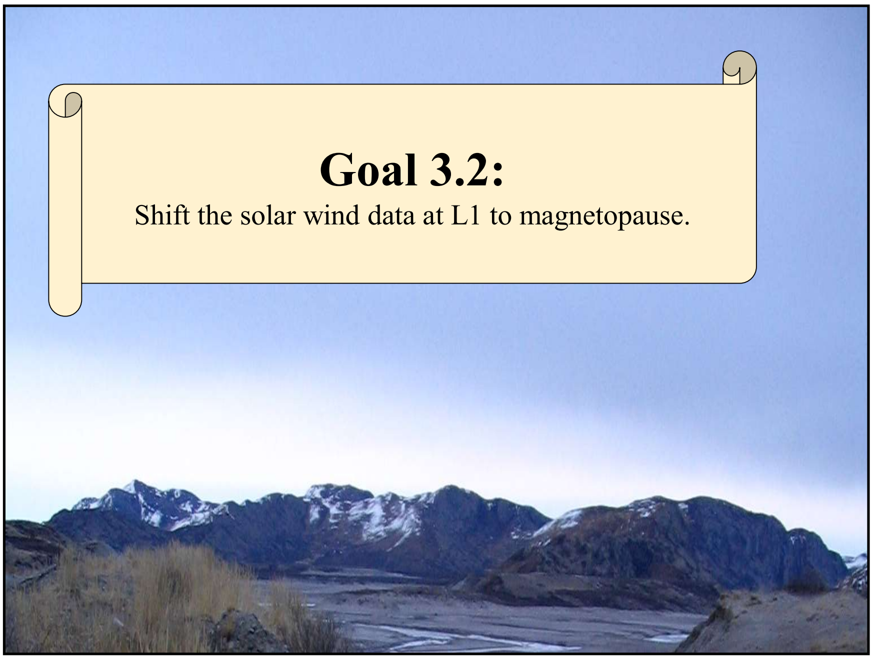
An example.

Energy of an event like substorm or storm can be acquired by integrating the power over time.

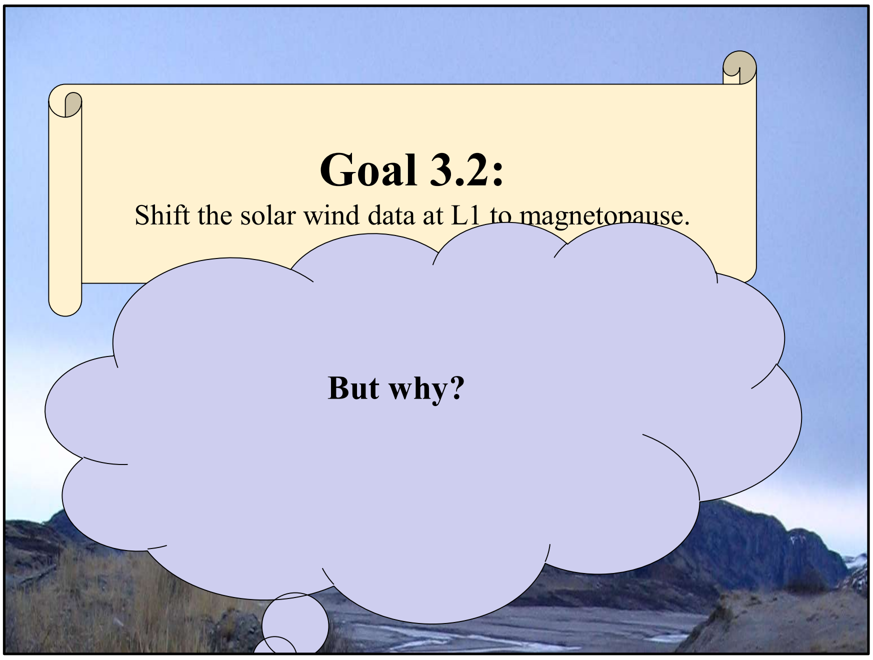


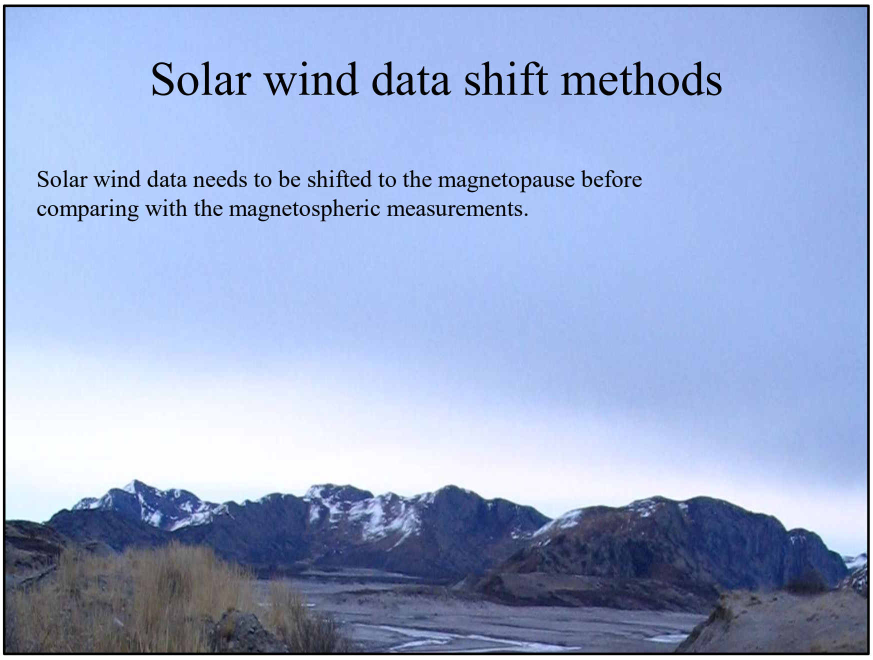
- Some statistics:
  This is the number of substorms that have such energy input. X-axis is the energy and y-axis shows how many substorms have that energy.
Note the y-scales: stormtime substorms are rarer than isolated substorms, mainly because storms are relatively rare.


Consider and remember!
1. Energy coupling function:
The epsilon parameter and its parts
2. Typical values for epsilon.
3. Typical energies of dissipation during
storms and substorms.



- Final part


Goal 3.2:
Shift the solar wind data at L1 to magnetopause.
But why?

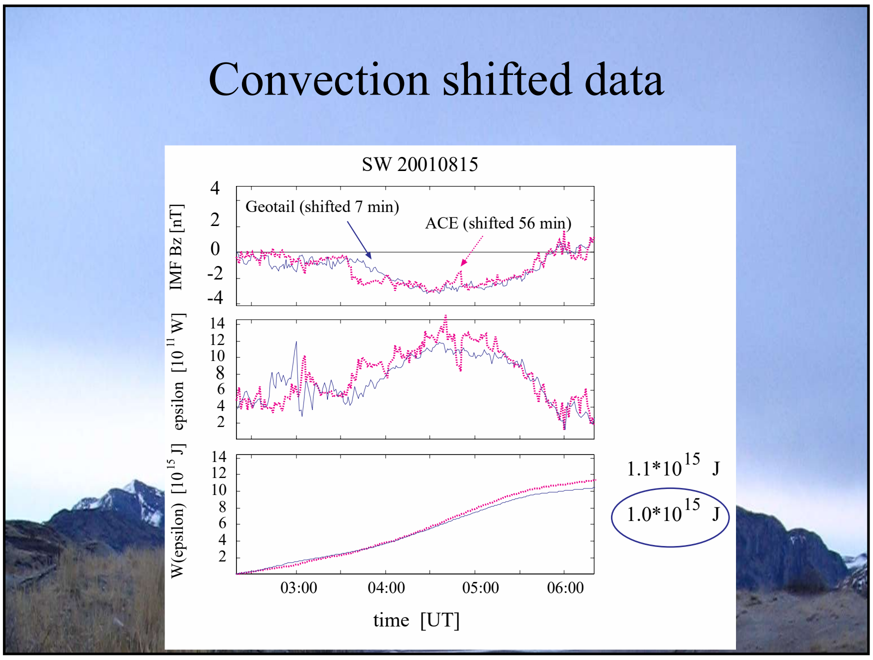


- Solar wind measurements are typically done in L1 or within the solar wind itself. It takes time for the solar wind structure to reach magnetopause, and only then can it interact with Earth’s magnetic field.

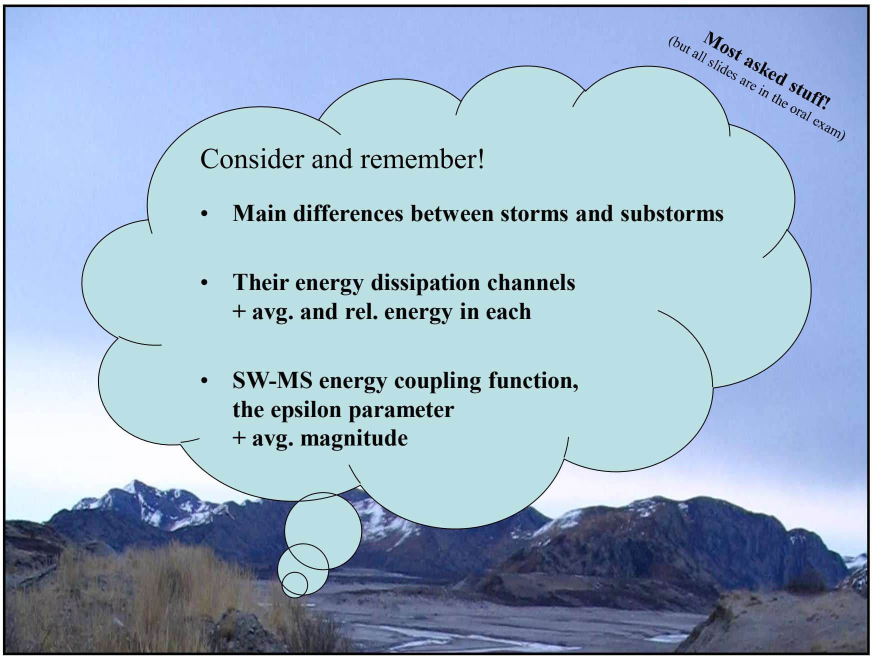
Solar wind data shift methods

Solar wind data needs to be shifted to the magnetopause before comparing with the magnetospheric measurements.

Most typical methods are:
(1) Convection shift by an **average velocity** during the event of interest. MOSTLY USED
(2) Convection shift + **disturbance orientation correction**. Needs data from multiple spacecraft or modeling efforts. NEEDS MULTIPLE SPACECRAFT
(3) Shifting each data point **separately** → causes non-continuous data. NOT GOOD.
(4) **Finding signatures** on same structures in other measurements and **estimating the time shift** based on the structures seen. WORKS FOR SINGULAR EVENTS



- Example using the method 1.


Most asked stuff!
(but all slides are in the oral exam)
Consider and remember!
• Main differences between storms and substorms
• Their energy dissipation channels
+ avg. and rel. energy in each
• SW-MS energy coupling function,
the epsilon parameter
+ avg. magnitude