The Recent Solar Minimum:
How Low Was It?
What Were The Consequences?

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Space Weather Workshop

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Outline

Part 1: The recent solar minimum…. How low did it go? How does it compare? Are we headed for another Maunder Minimum?

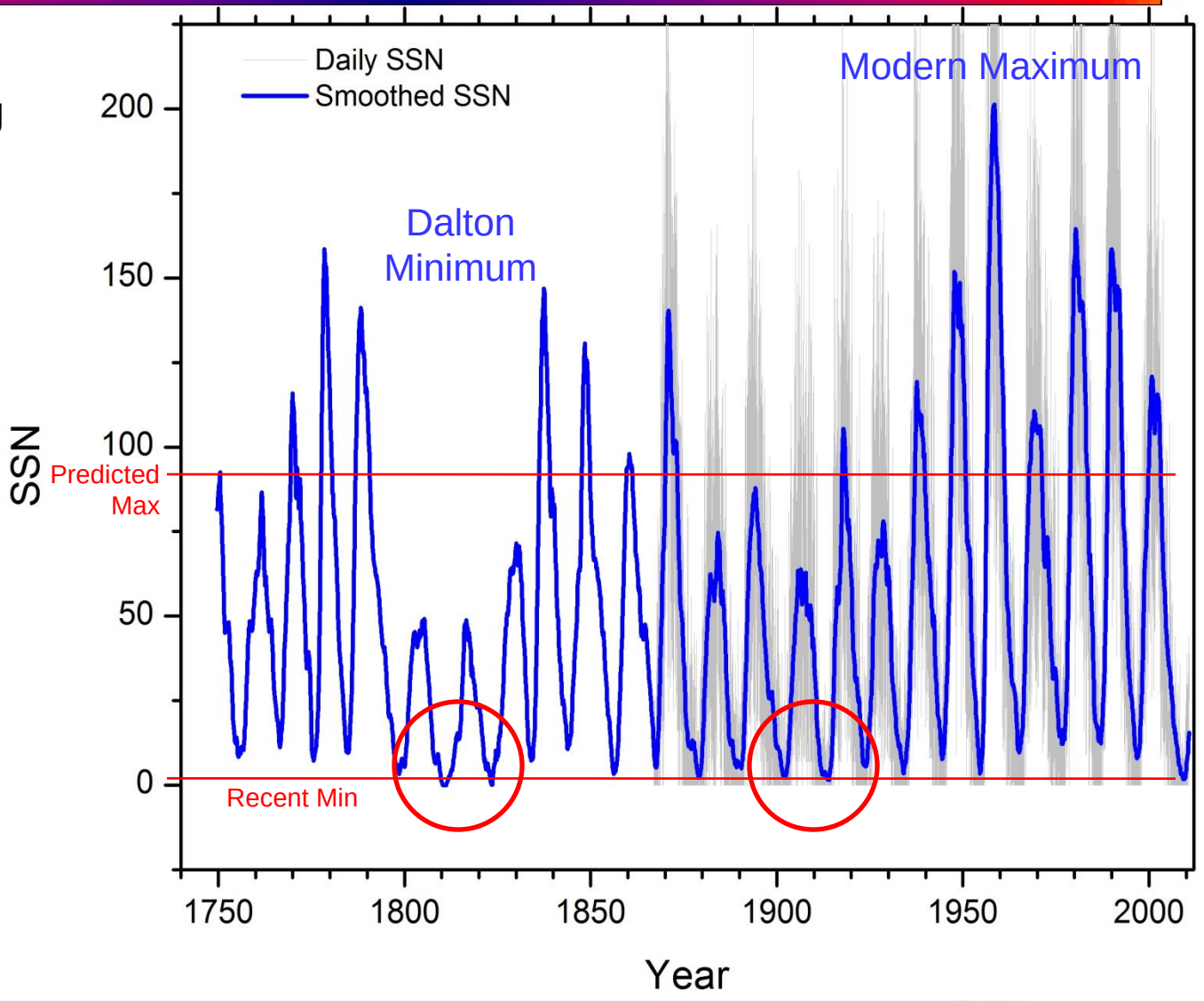
- Smoothed Sunspot Number
- Geomagnetic Indices
- F10.7
- Space Weather: Will we have any this coming solar cycle?

Part 2: What were some of the consequences of this recent minimum?

- Impact on neutral density and satellite drag
- Impact on TEC and the ionosphere
- Impact on climate

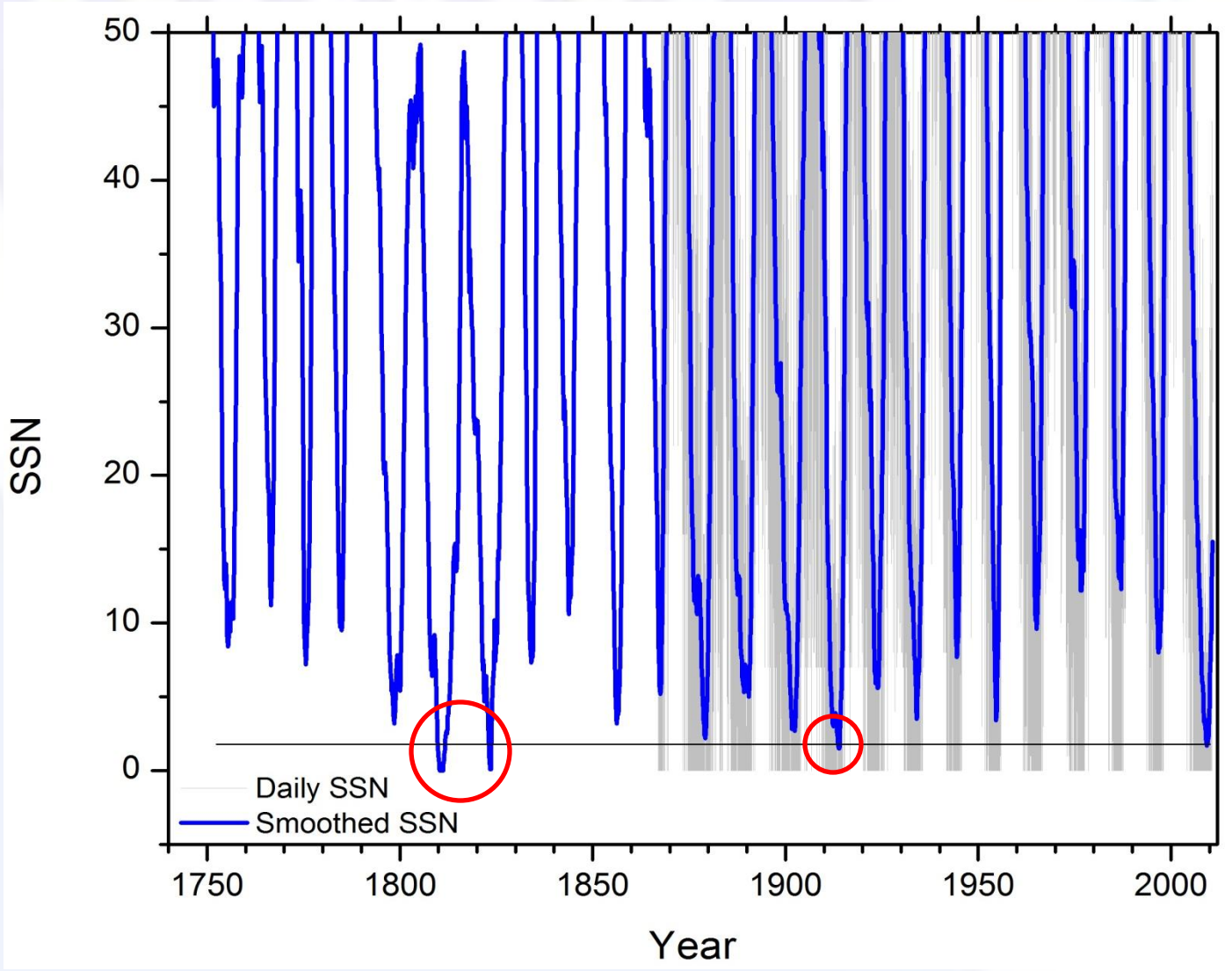
Smoothed Sunspot Number

- **13 Month Running Average**
- **Note the two previous periods of low solar cycles…**
  - **1825**
  - **1900**
- **Predicted Maximum for next cycle = 90**

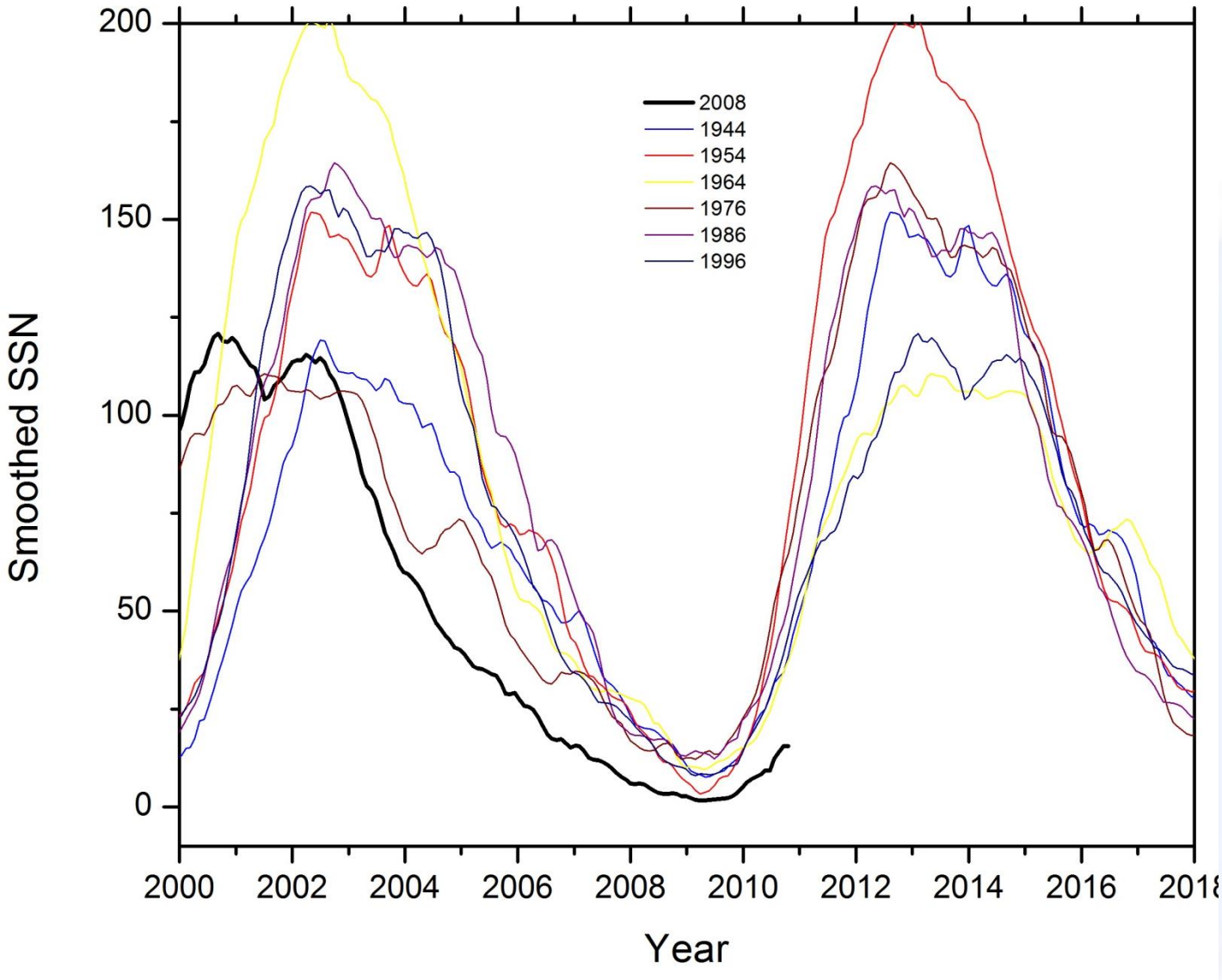


Smoothed SSN

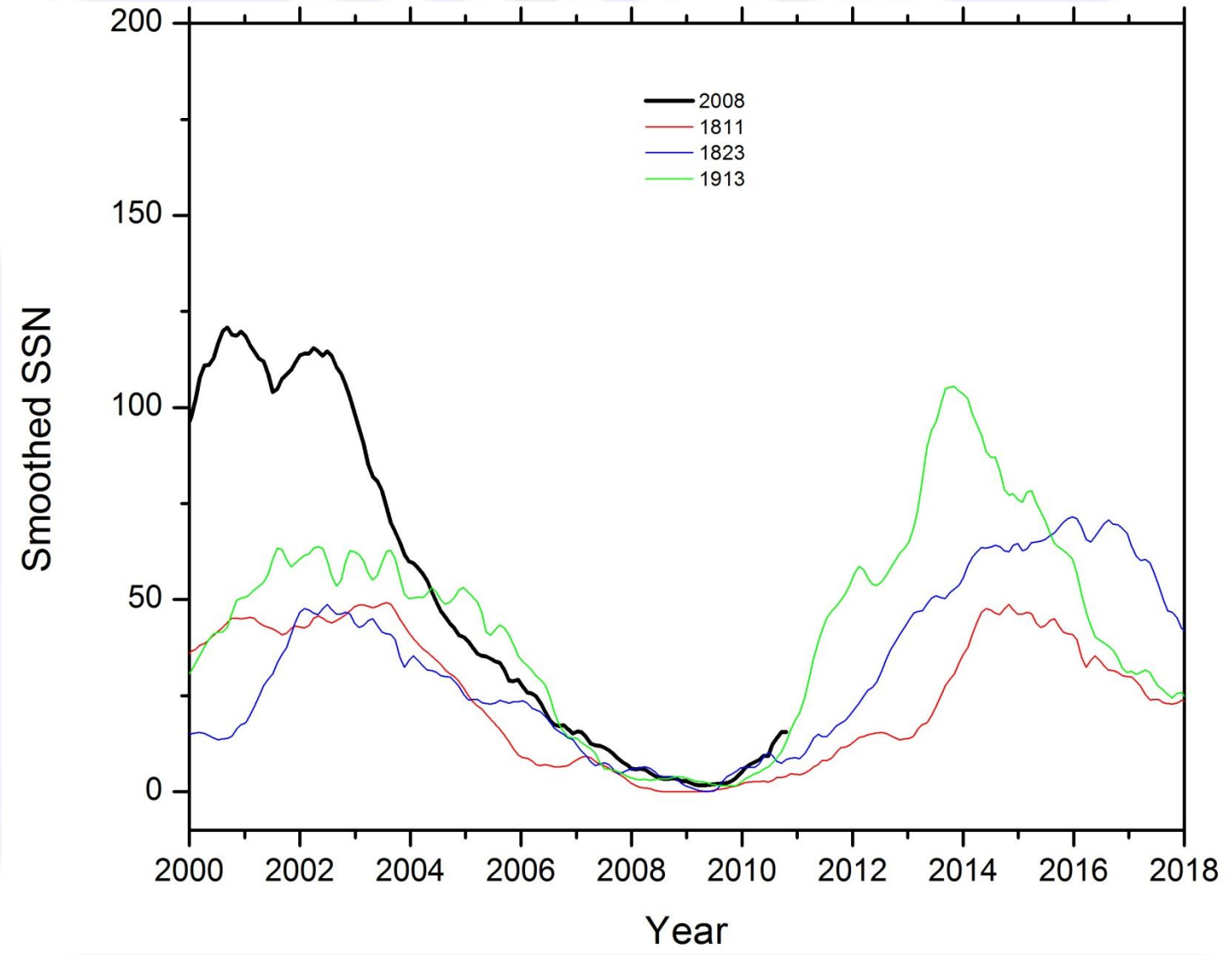
- **Solar minima have significant variability.**
- **Recent minimum was lowest since 1913.**
- **Two minima in the early 1800s were lower than the current minimum.**



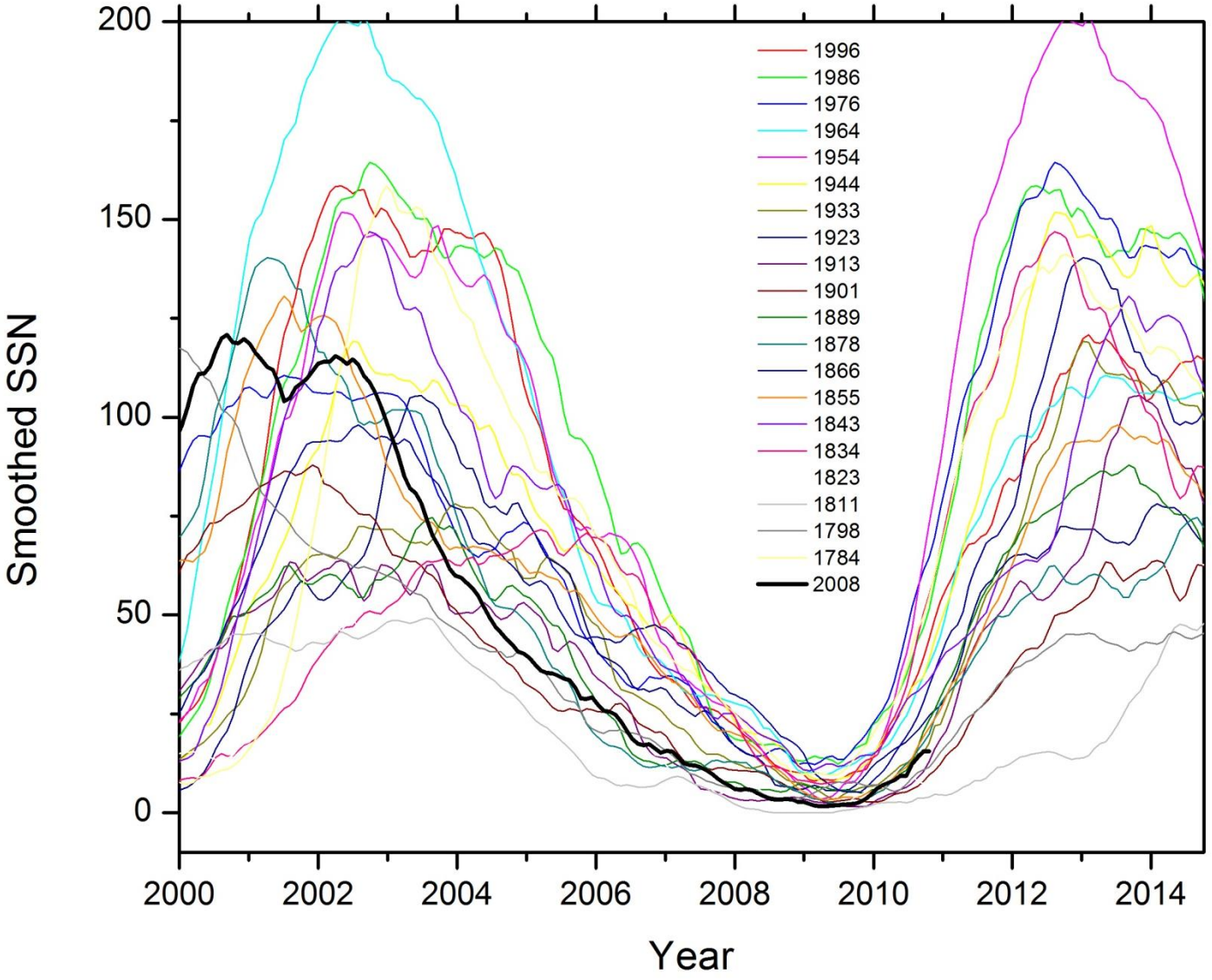
Current Min. Compared to the Previous Six



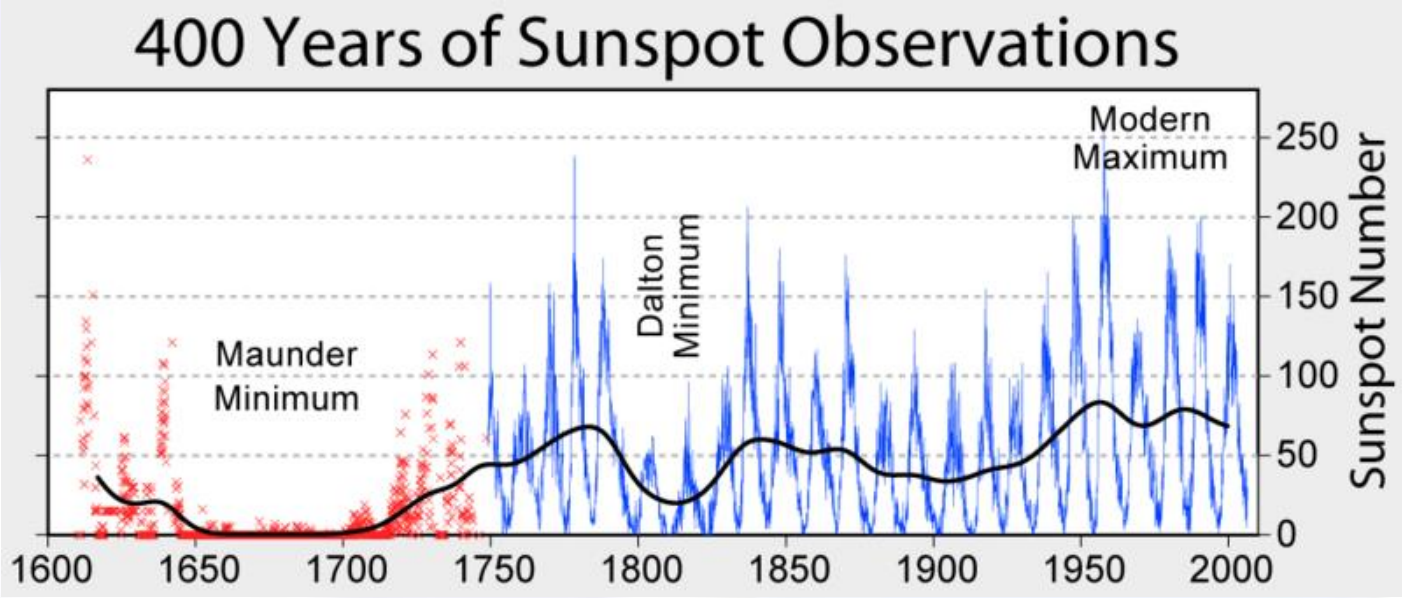
Current Min. Compared to the Lowest Three

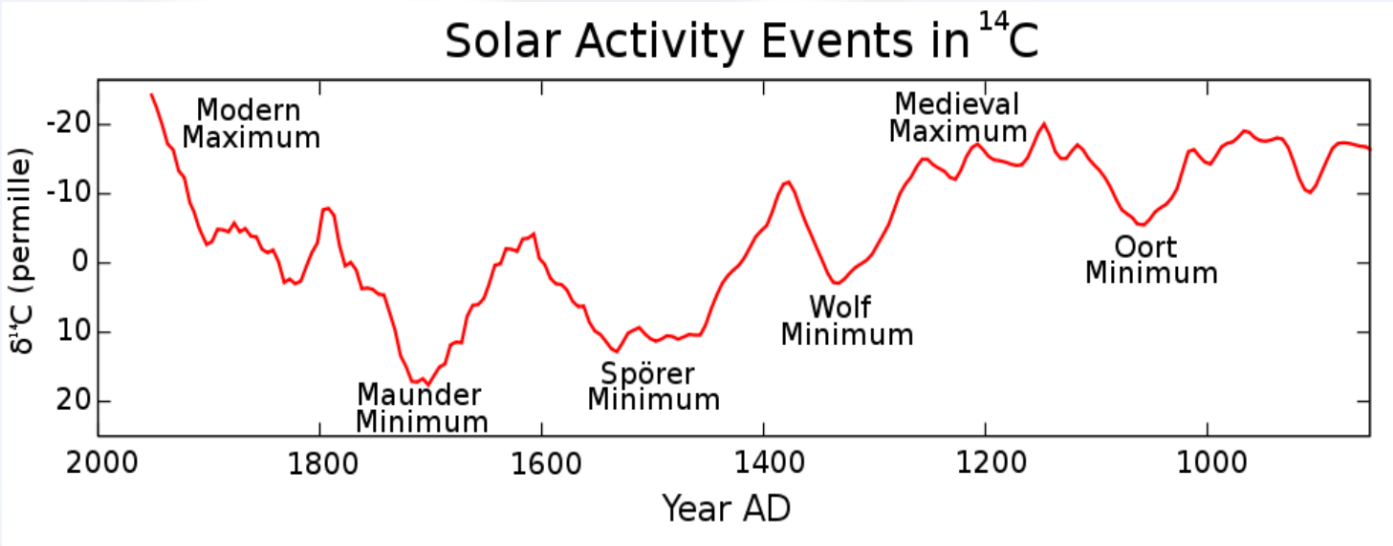


All of the Last 21 Solar Cycles



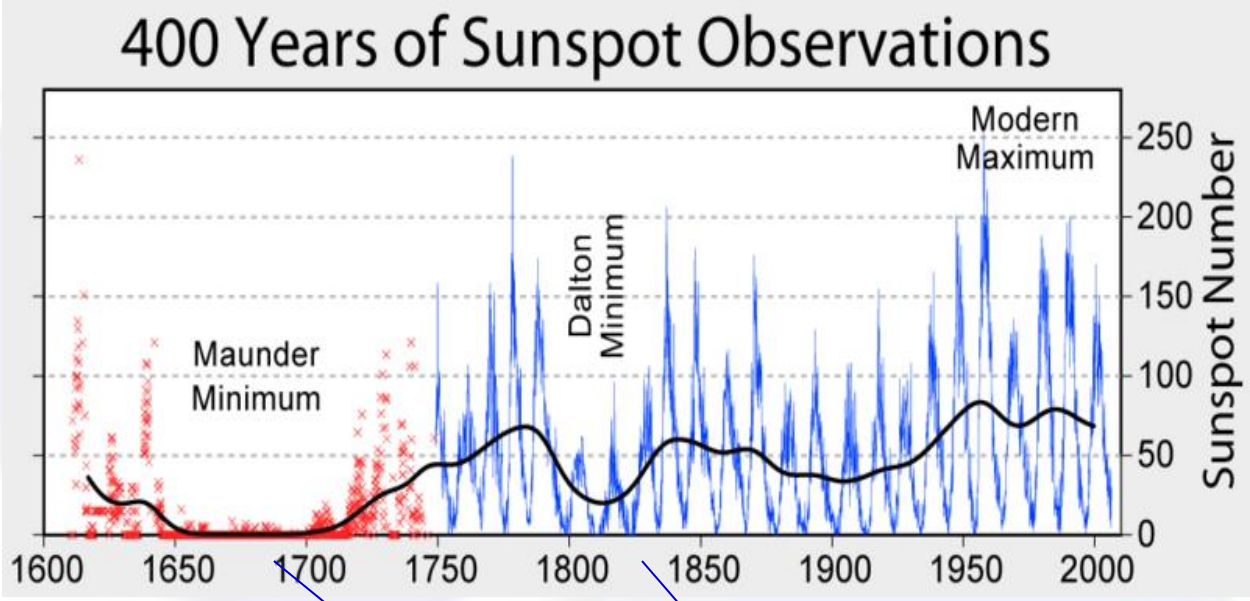
Longer SSN Record

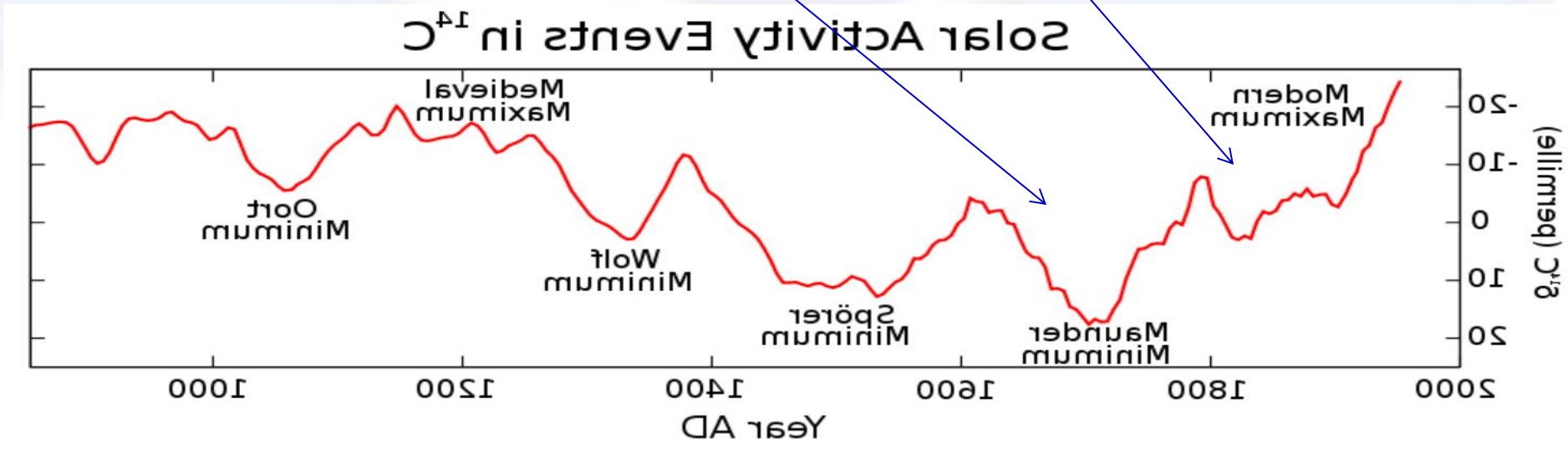




Longer SSN Record

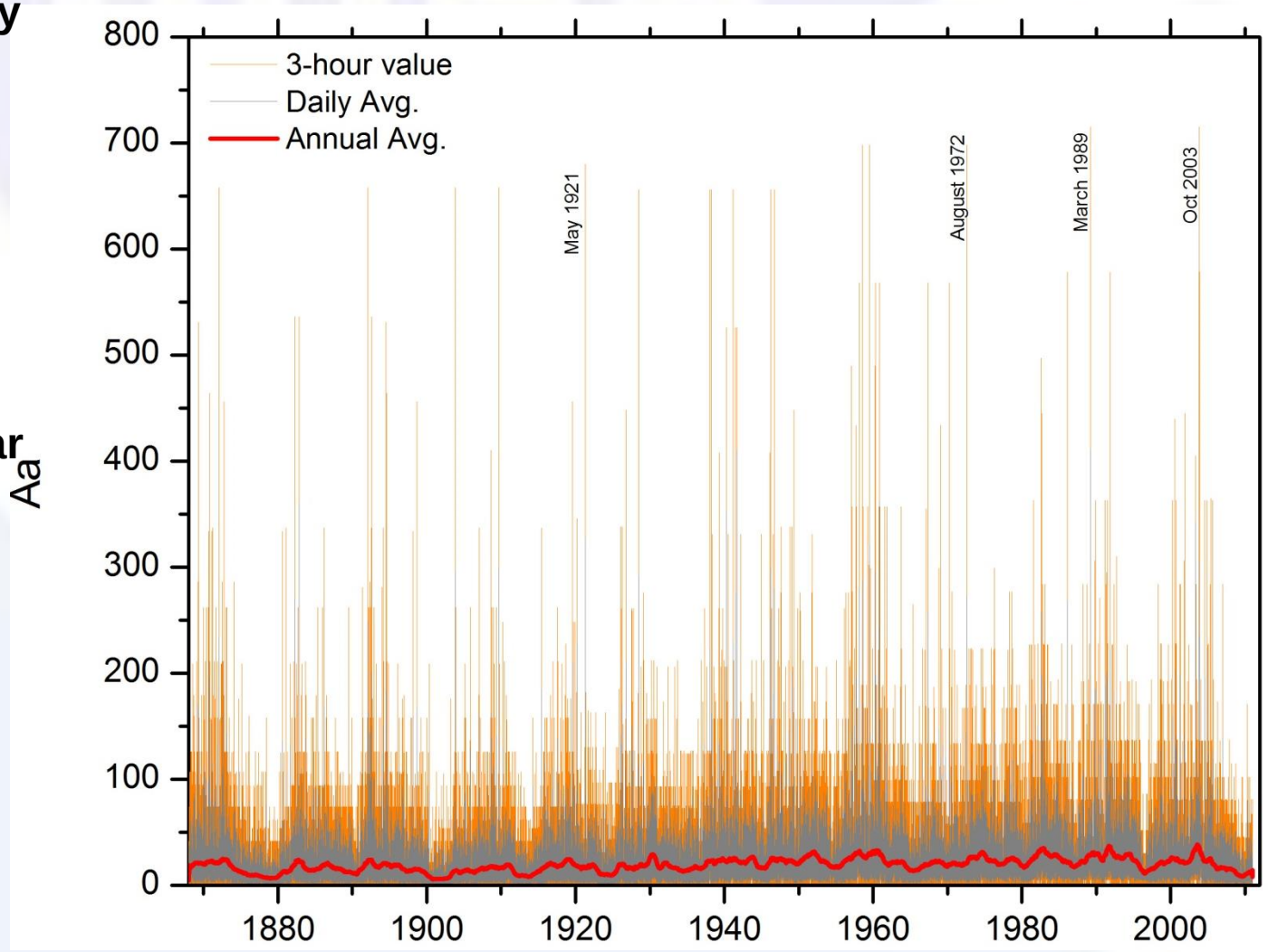
- **Current minimum not as low as Dalton minimum**
- **Maunder and Spörer minima are lower than Dalton minimum**
- **Modern Maximum is larger than any maximum in 1200 years**





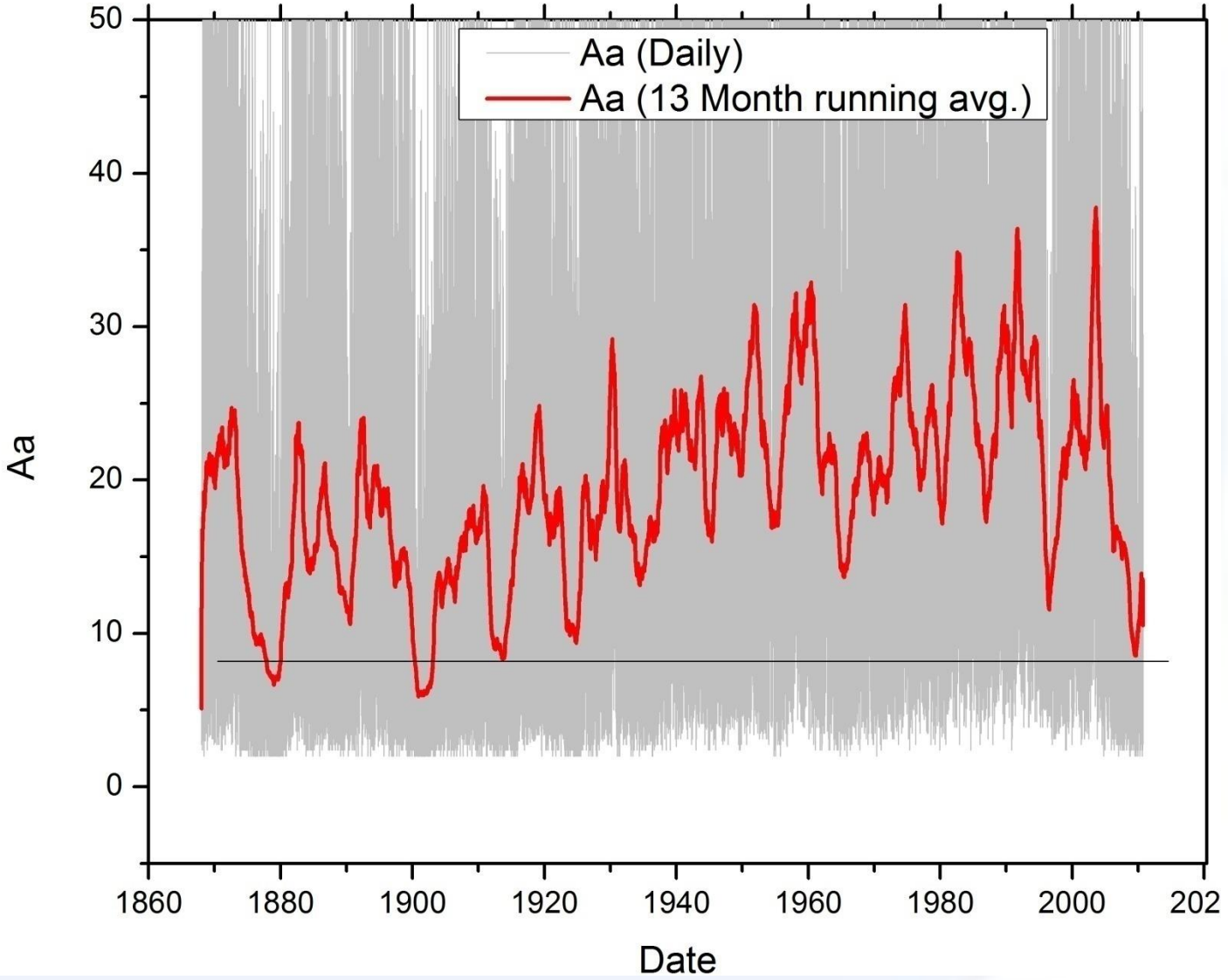
Aa Geomagnetic Record

- Derived from only two ground magnetometer stations
  - England
  - Australia
- Longer record than Ap or Kp
- Not a strong solar cycle signal
  - CME driven geomagnetic storms during solar max
  - Coronal hole geomagnetic storms during solar min



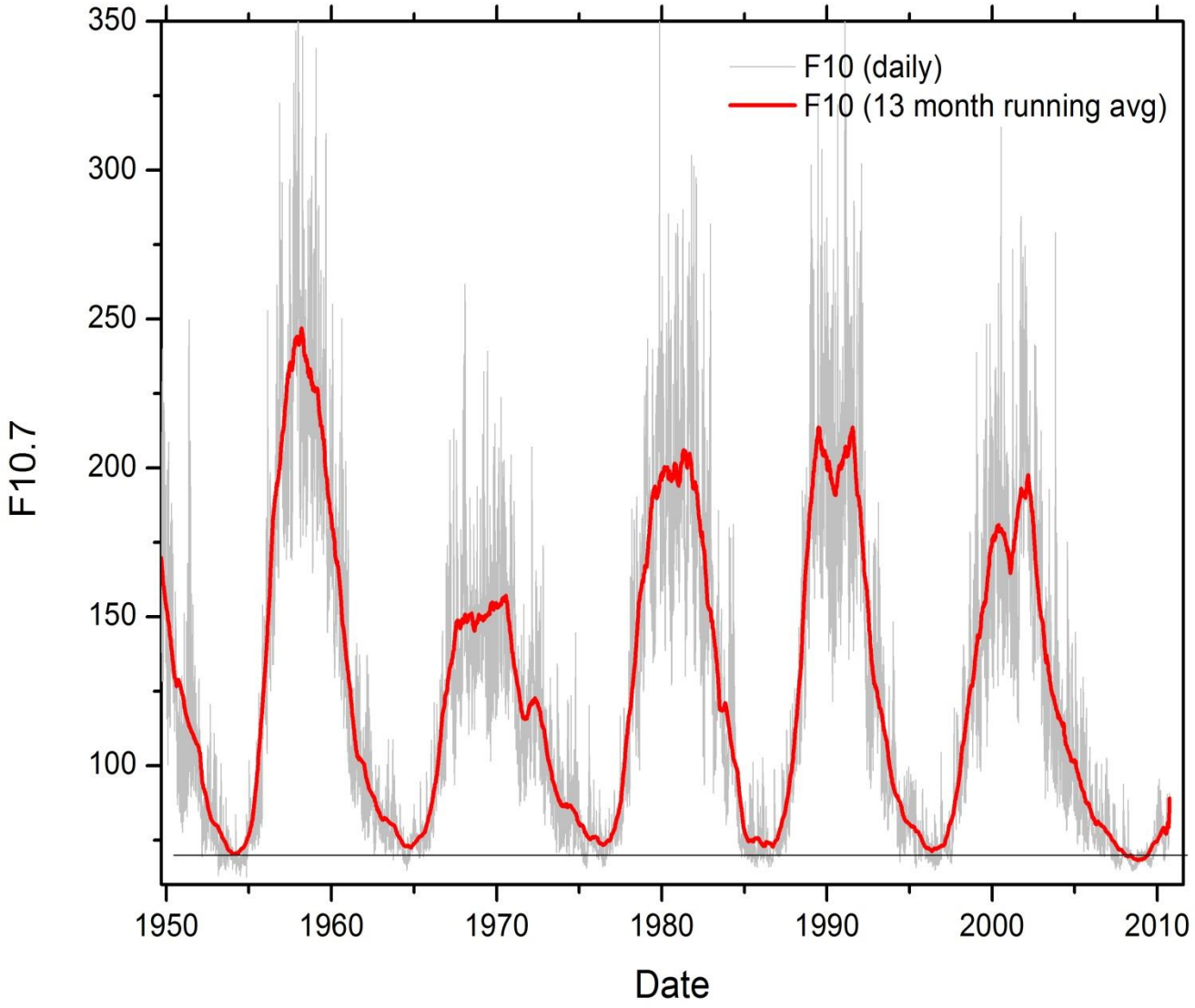
Smoothed Aa Index

- **Recent minimum shows a significant departure from the trends of the last 80 years.**
- **Recent minimum is the lowest since 1913**
- **There have been lower minima**



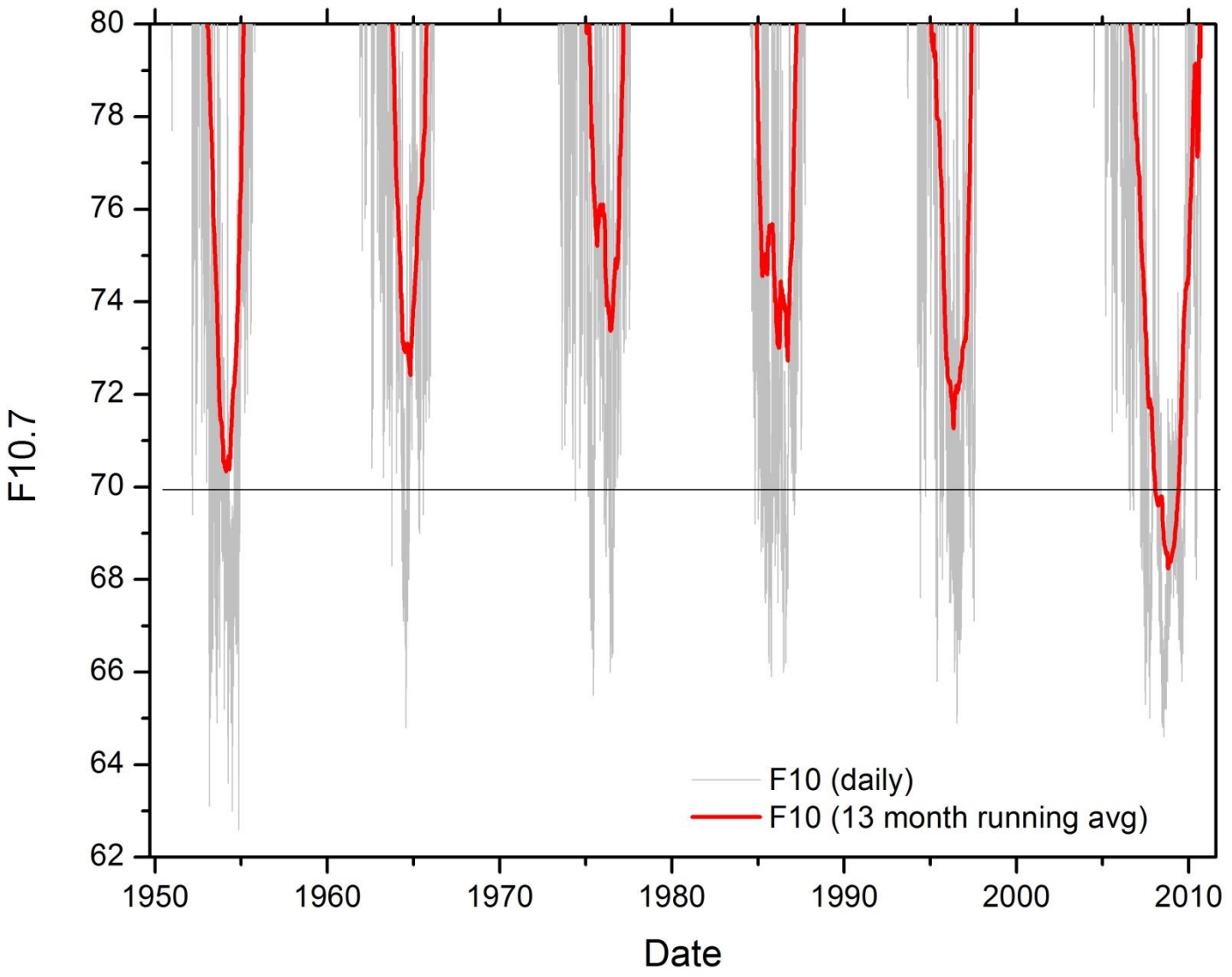
F10.7

- **F10.7 is a solar radio emission used as a proxy for solar EUV irradiance**
- **Shows strong solar cycle signal**
- **Reaches similar minimum values during each solar min.**



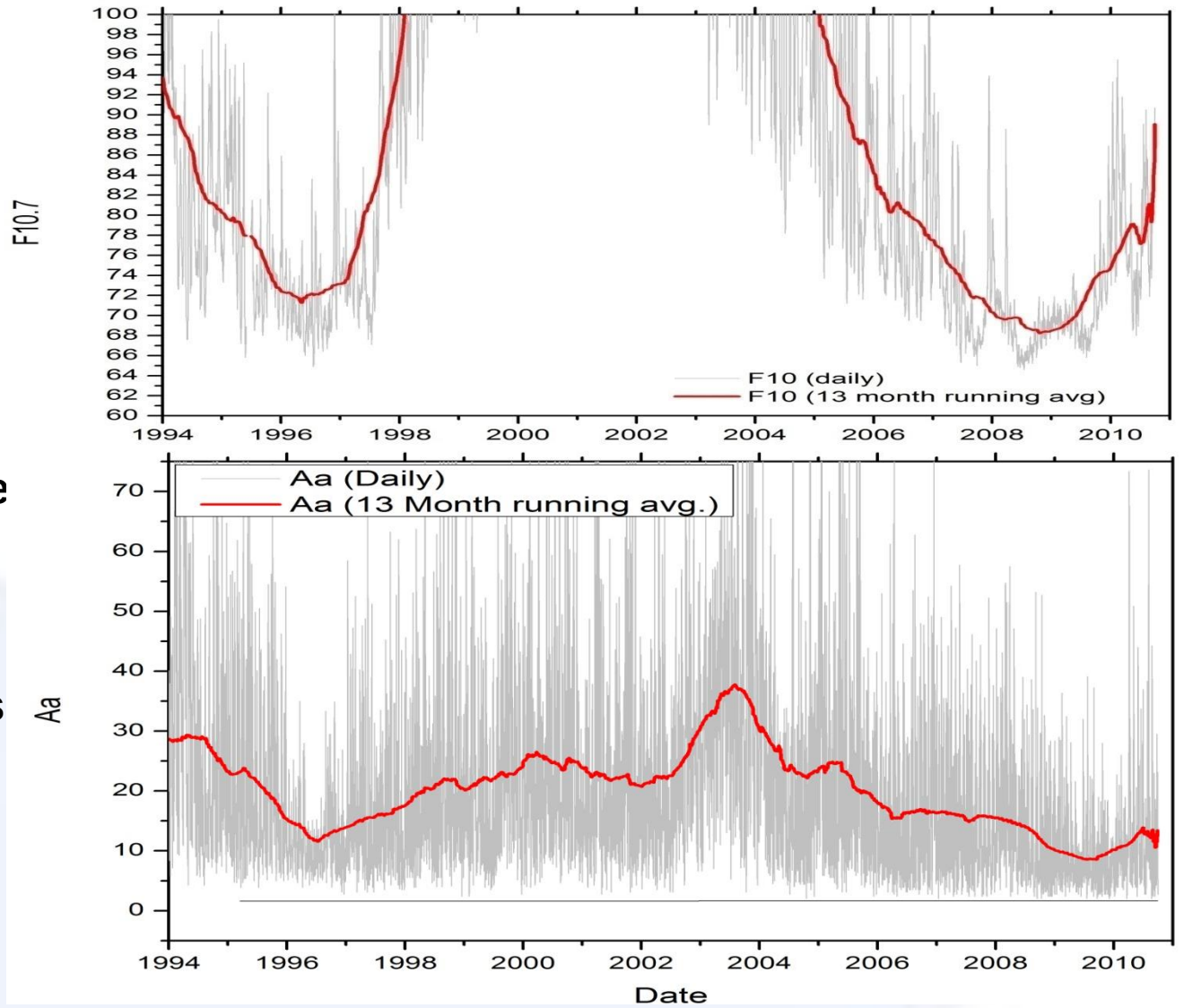
Details of F10.7

- **Lower daily values were observed in the late 1950s**
- **The 13 month running average values have never been observed as low as the recent cycle**



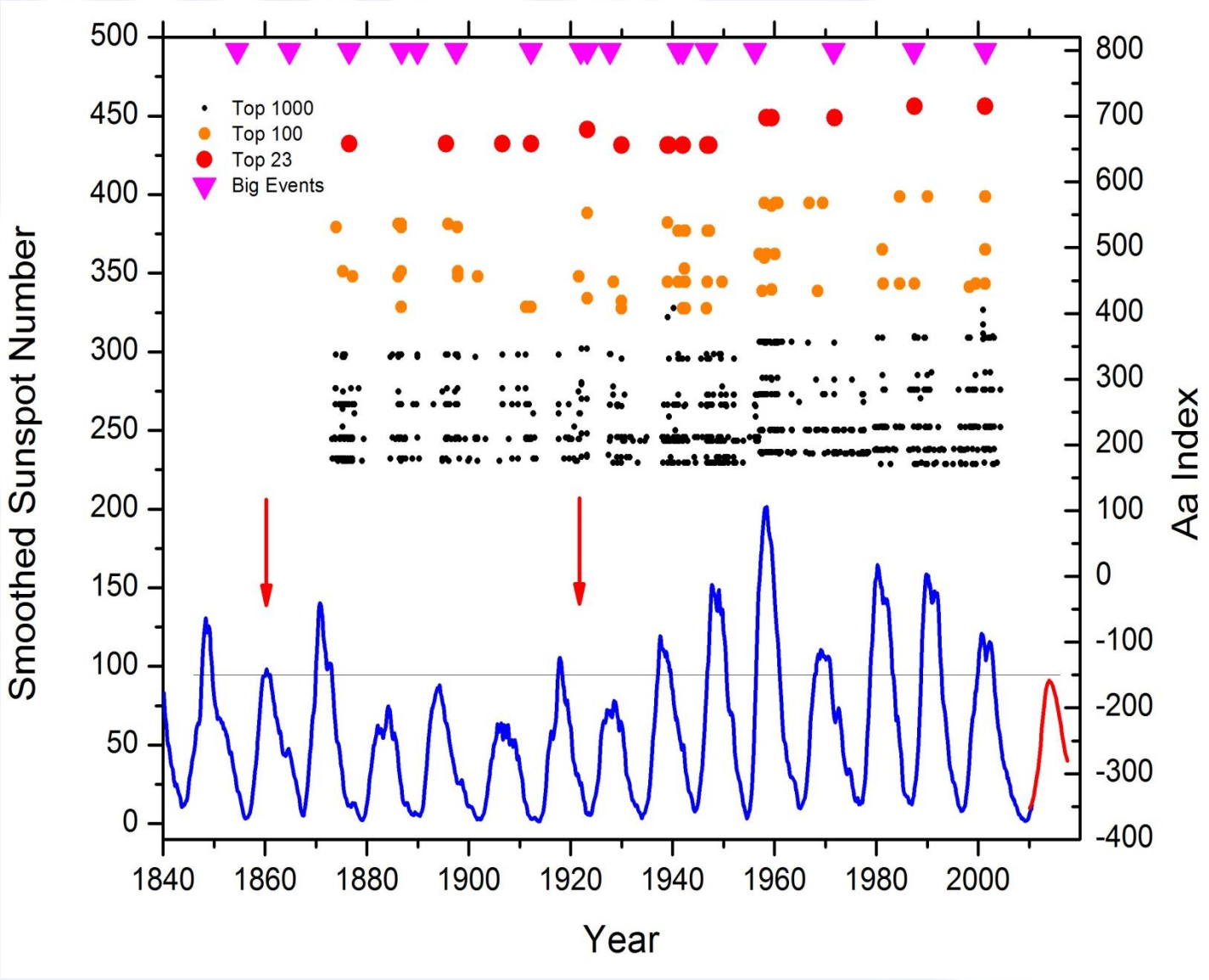
Why Was This Recent Solar Minimum so Low?

- In F10, previous solar minimum (1996) had similar low values but also had 27-day variations
- Recent solar minimum had nearly two years with little or no 27-day modulation making the the 13 month running average values significantly lower.
- In Aa the opposite was true… less 27 day modulation but lower values



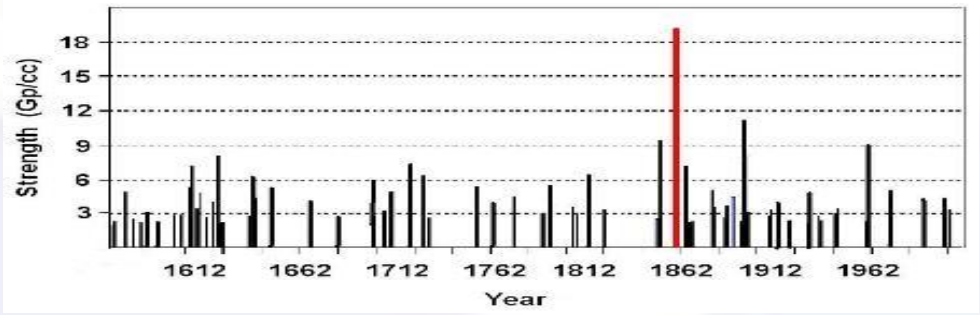
Geomagnetic Activity

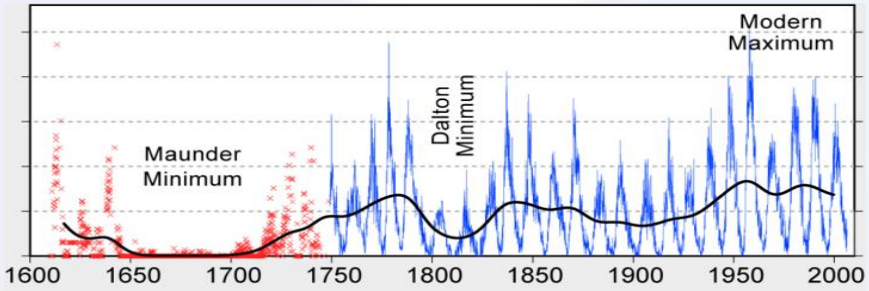
- **Really big storms can occur during any size solar cycle.**
- **Even big storms don't show strong correlation with sunspot number**
- **Two of the biggest on record occurred during moderate sized solar cycles**
- **The next solar cycle is expected to be of moderate size.**

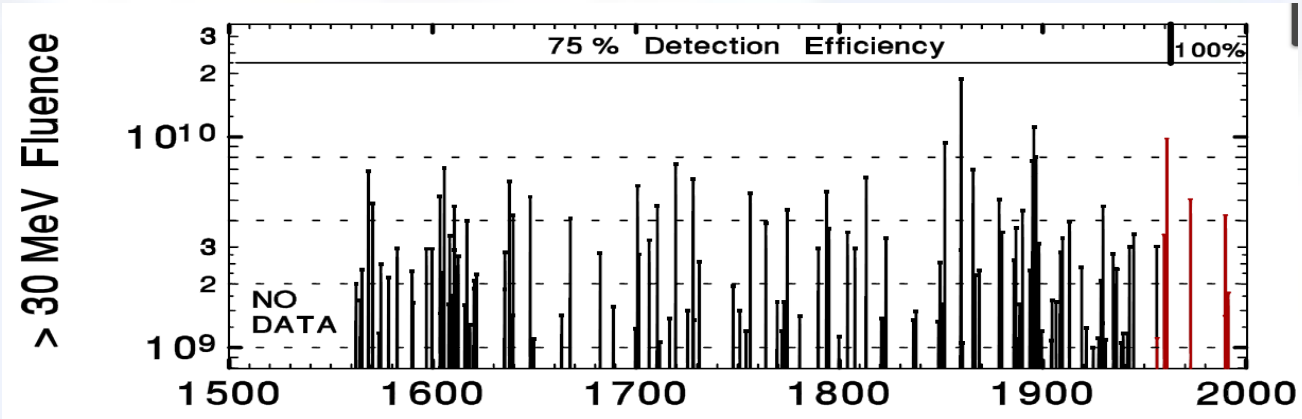


Other Space Weather: Proton/Particle Events

Ice core data shows a strong spike (red bar) in the atmospheric nitrate (NOx) abundances during the 1859 storm, along with lesser spikes for many other storms since 1500







D. F. Smart, M. A. Shea, G. A. M. Dreschhoff, H. E. Spence, and L. Kepkoc, 2009
McCracken et al., 2001

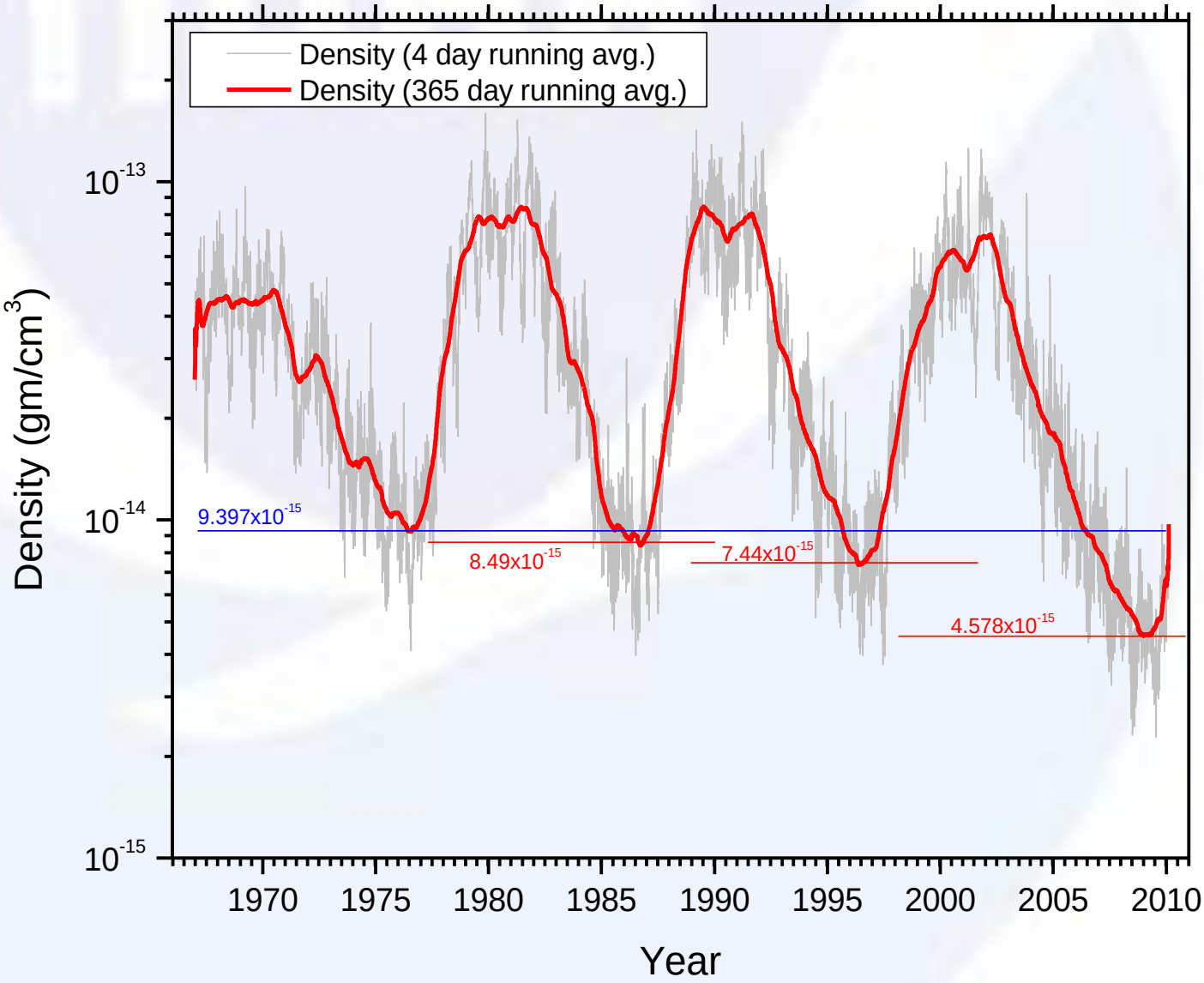
Part 1: Summary

- Recent solar minimum was the lowest in nearly 100 years
  - Lowest smoothed sunspot min since 1913
  - Lowest smoothed geomag min since 1913
  - Lowest smoothed F10.7 on record (since 1947)
- There have been lower and longer minima as recorded in the sunspot record.
  - Dalton minimum (two minima) in the 1800s was lower
  - Maunder minimum was probably much lower
- Even if this Cycle is Small, Space Weather Will Continue
  - Geomagnetic Storms will still occur
    - Maybe less frequent but likely as large
  - Particle Events will still occur
    - Seem to be less correlated with SSN

Part 2: Response of the Terrestrial System

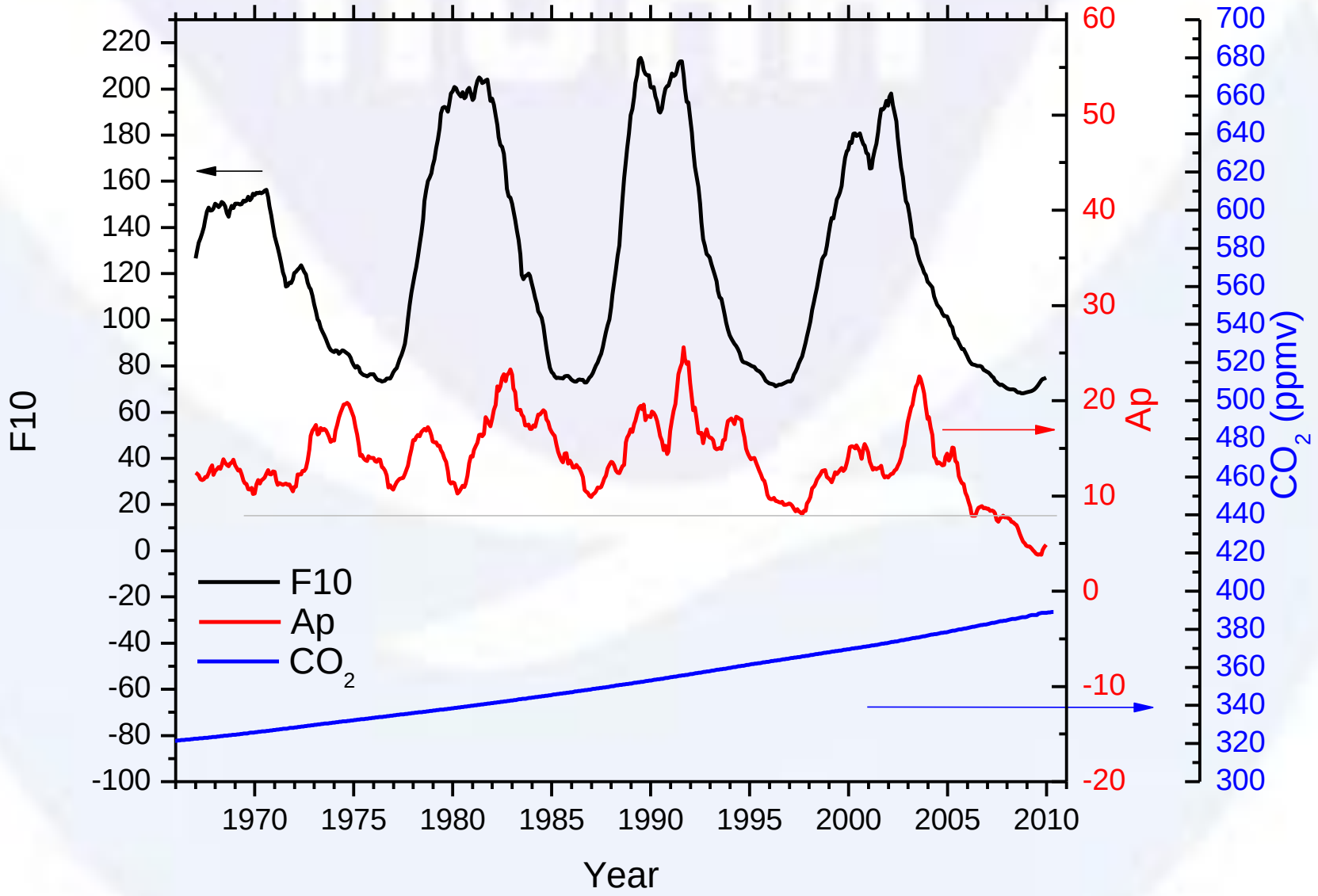
400 km Neutral Density Derived from Satellite Drag
(thanks to John Emmert, NRL)

- **Density has been getting lower each solar min**
- **The change from each successive min to min…**
  - **10% Drop**
  - **12% Drop**
  - **38% Drop**
- **Recent minimum is much lower.**

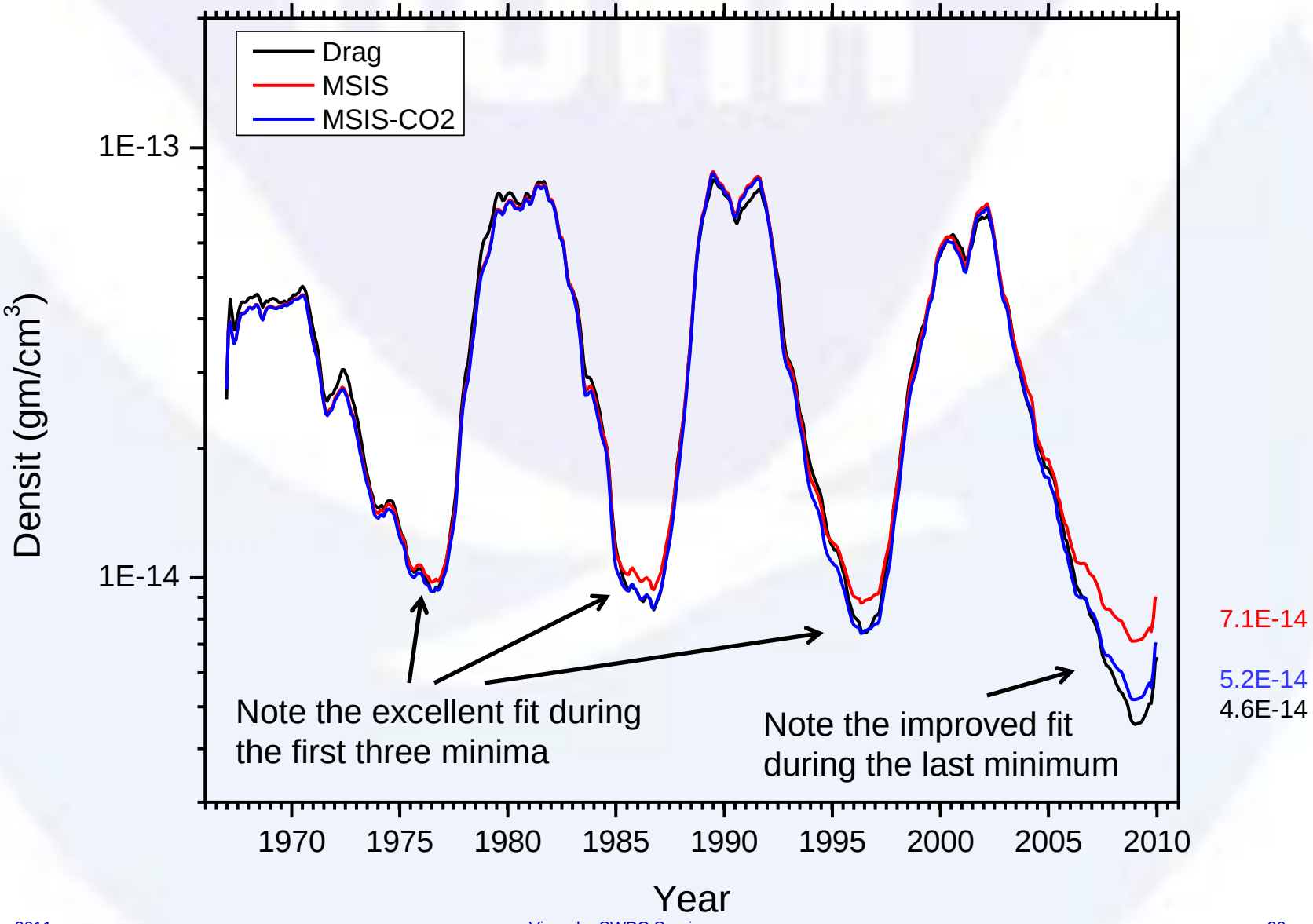


Thermospheric Drivers

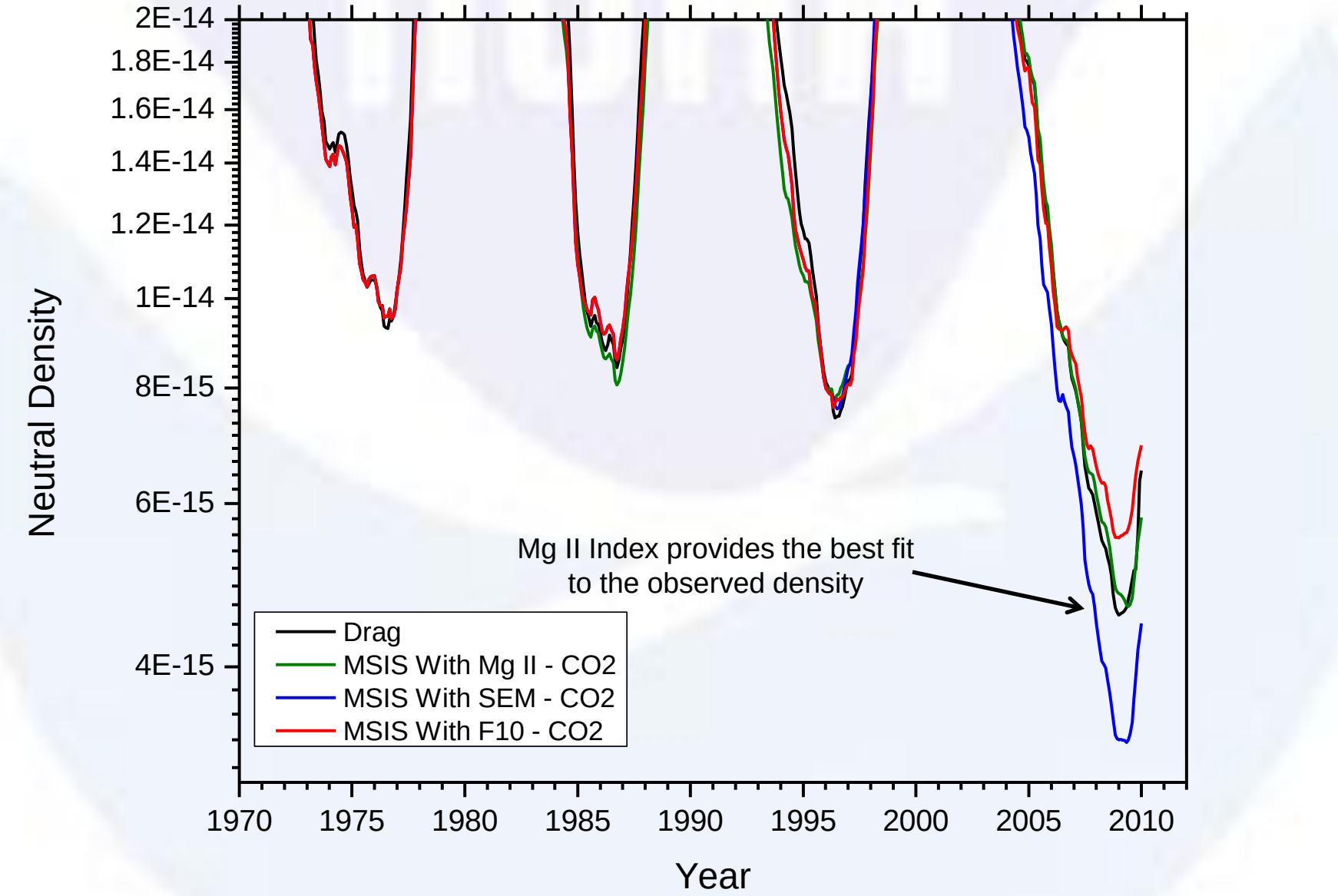
Solar EUV (F10), Geomagnetic Storms (Ap), Climate Change(CO_2)



Subtracting the Anthropogenic Correction

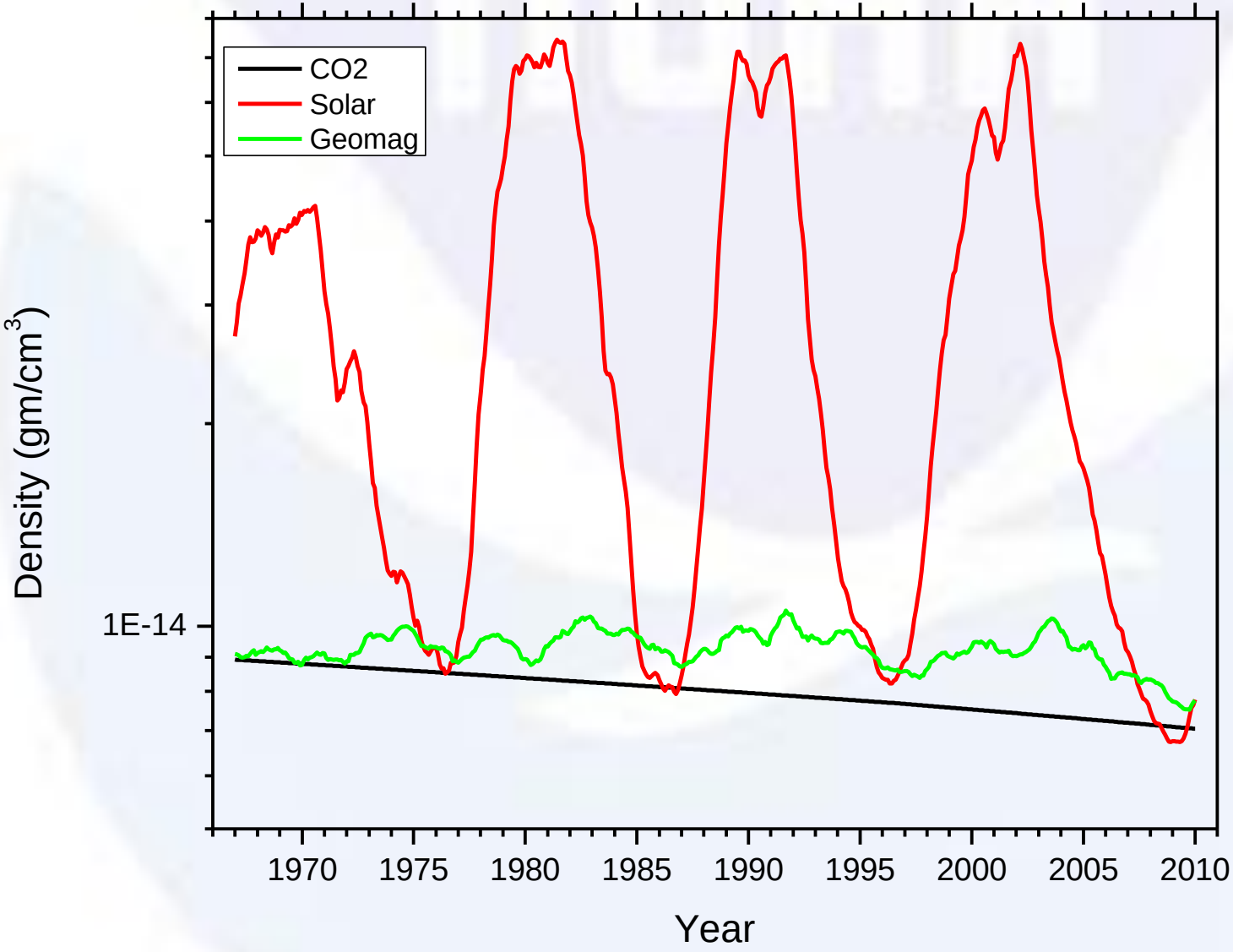


MSIS Results Using the Three Solar Inputs
(Details)



Relative Magnitude of the Density Changes

Modeled density changes for each input while holding the other two constant



Relative Contributions of the change from (1996 to 2009)

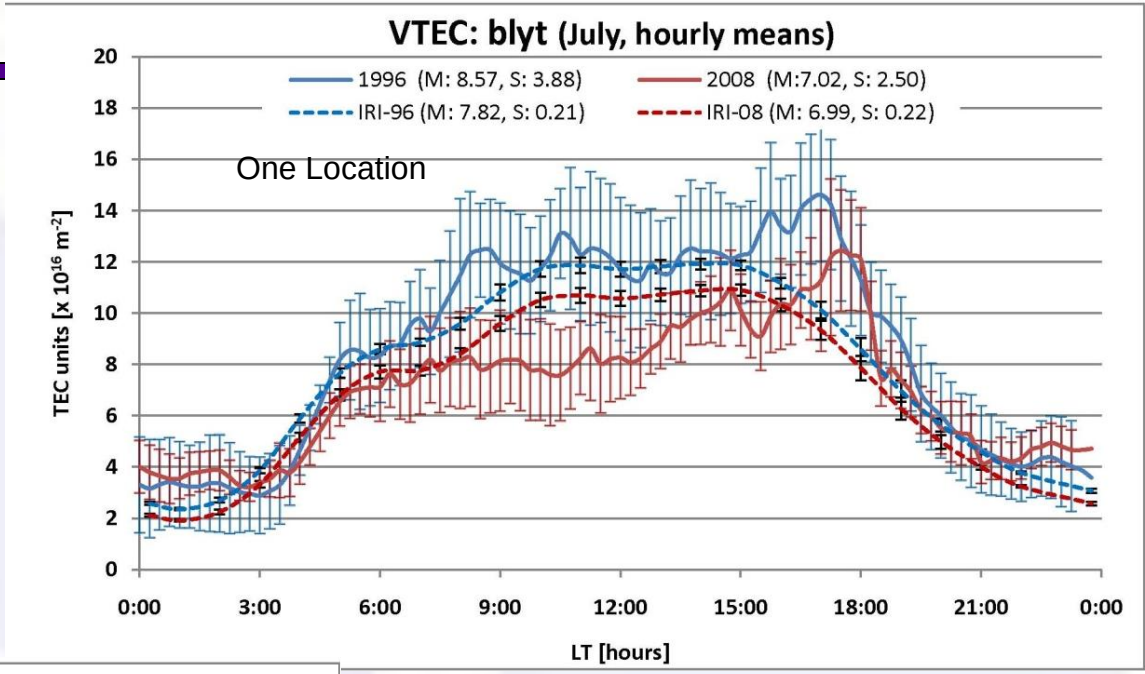
Solar 1.49E-15 = 48%

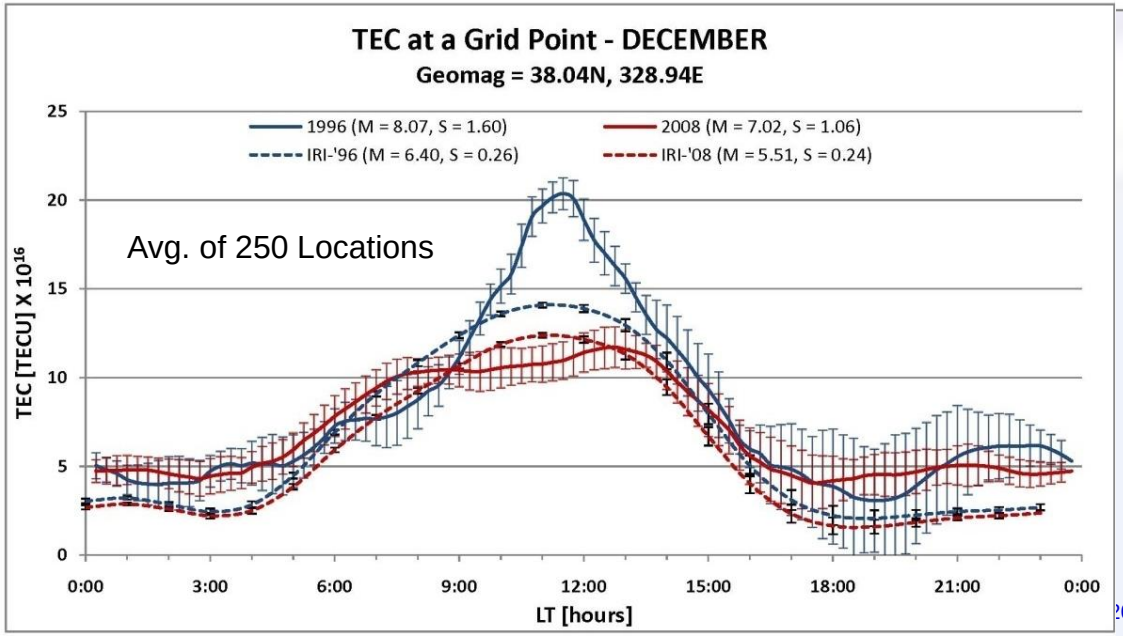
Geomag 1.03E-15 = 33%

Anthro 0.61E-15 = 19%

Response of the Ionosphere

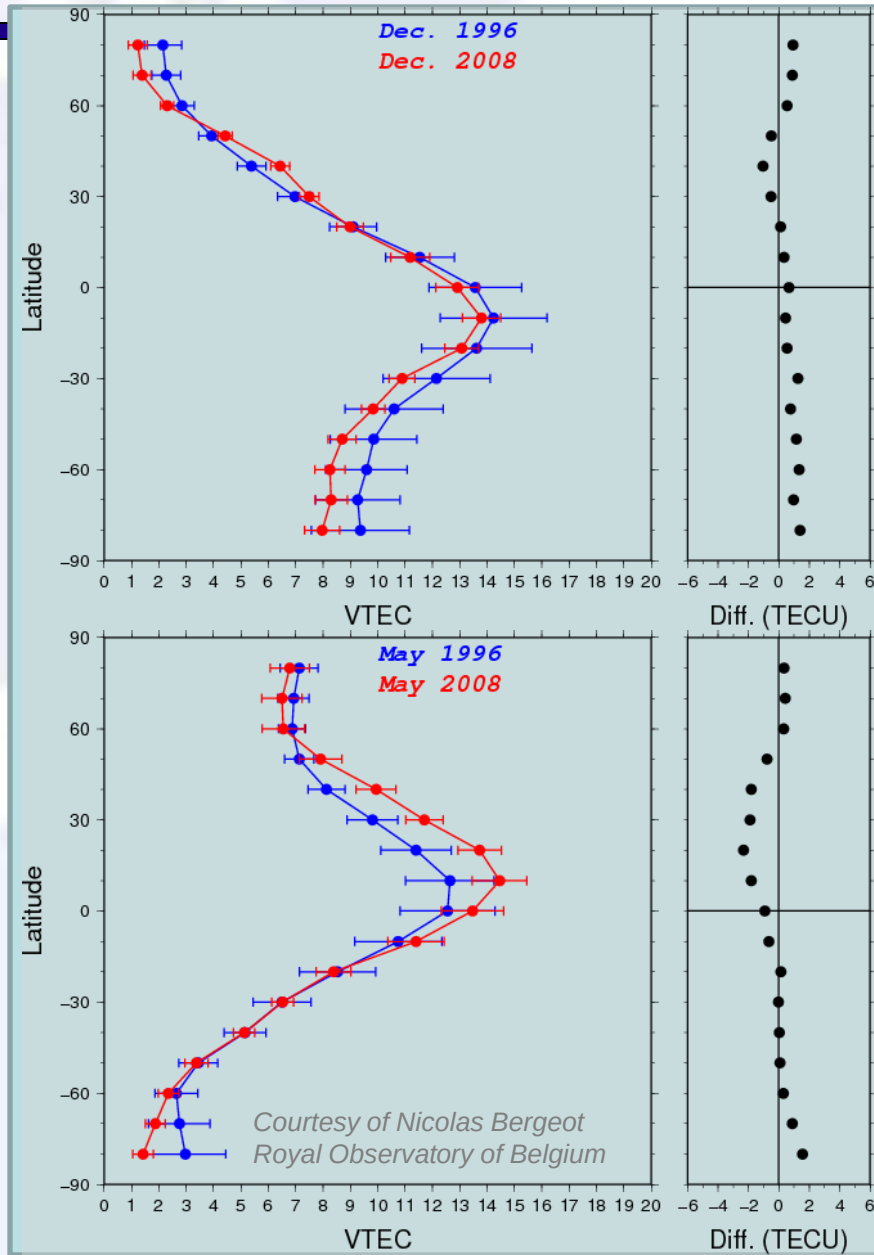
- **Total Electron Content shows significant changes from last minimum to the most recent minimum…**
  - **At some local times**





Response of the Ionosphere

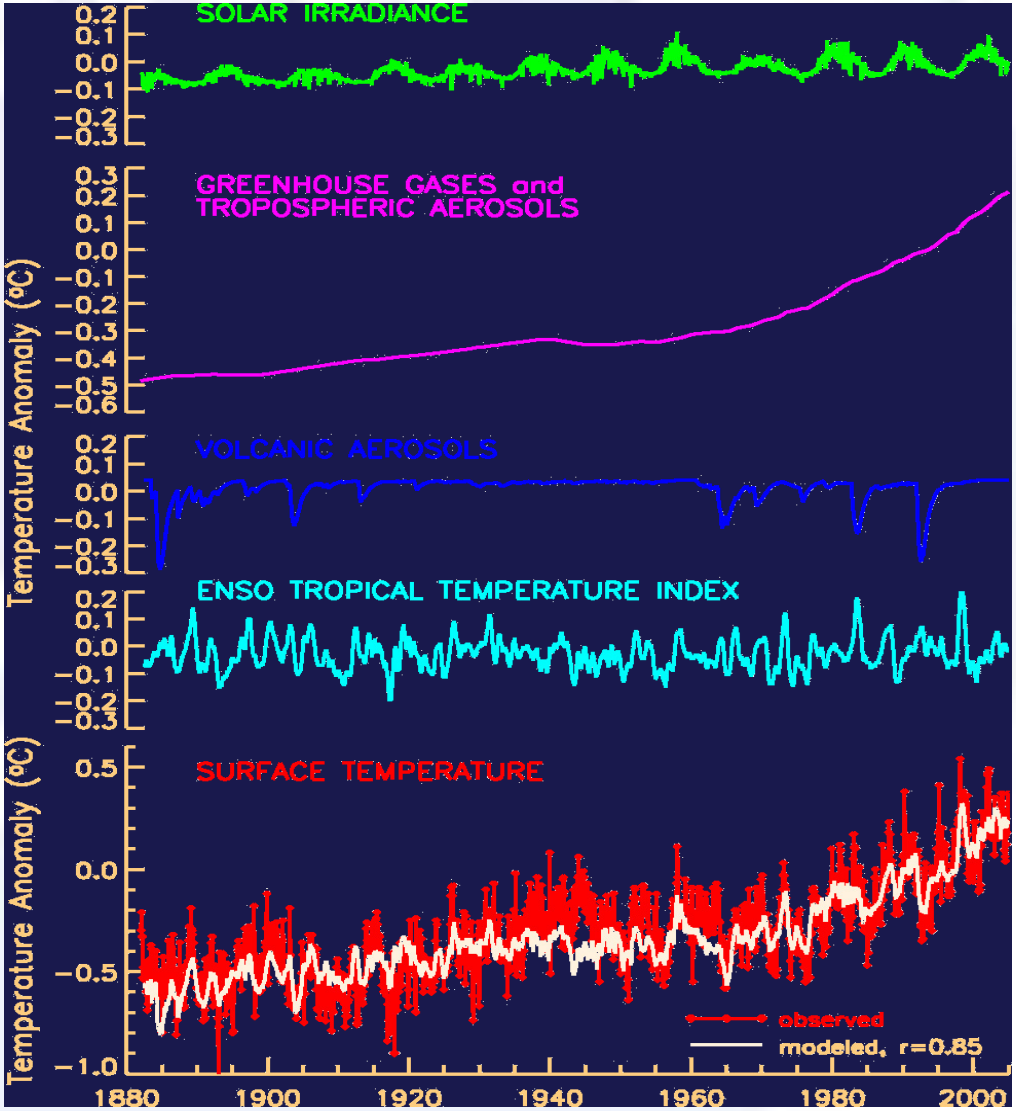
- **Total Electron Content shows changes from last minimum to the most recent minimum…**
  - **But only during some seasons**
  - **And only at some latitudes**
- **Sometimes the response is the opposite of what is expected.**



Extracted from CODE Global Ionospheric maps (GIMs IONEX format)

Response of the Climate

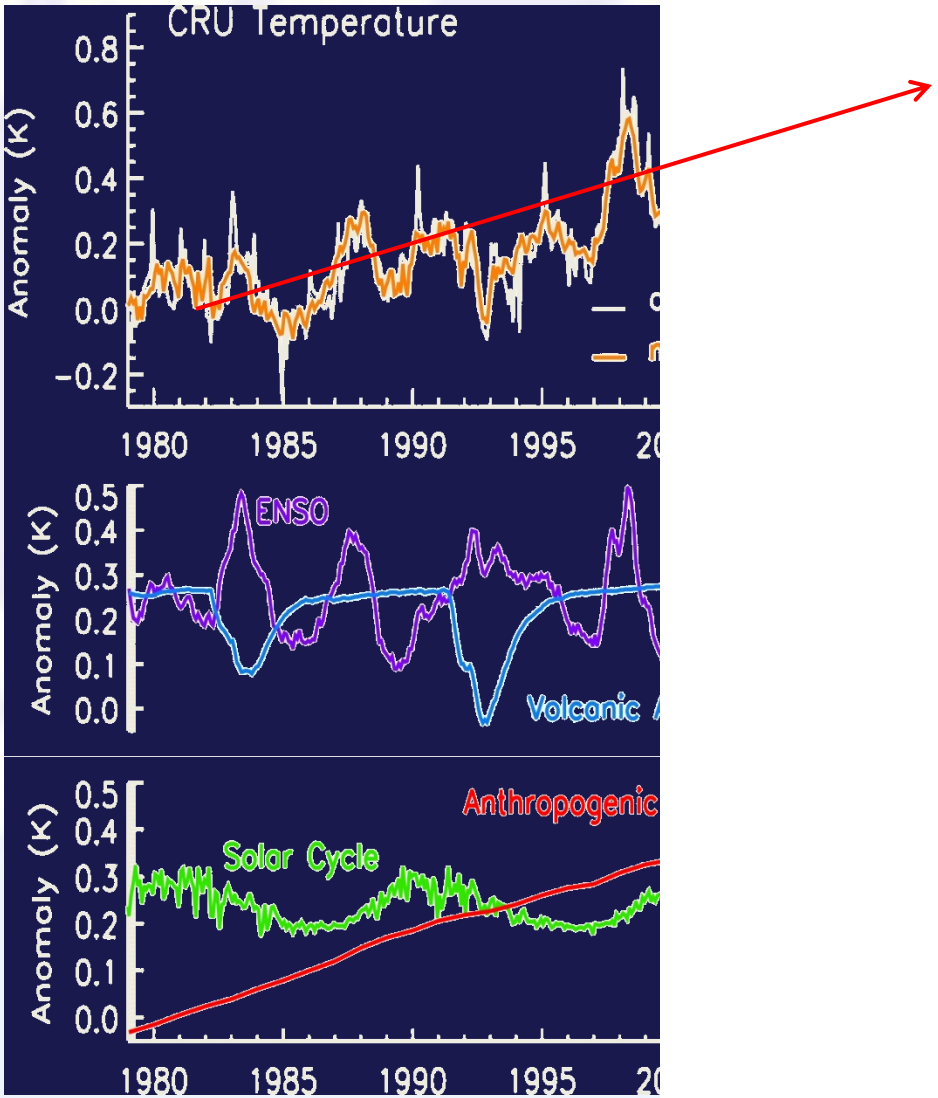
- **Globally-averaged surface temperature**
  - **130 Year record showing general warming of ~1°C**
- **Four primary contributors to global climate change**
  - **Solar**
  - **Anthropogenic**
  - **Volcanoes**
  - **El Nino/La Nina**
- **Simple empirical model can reproduce much of the observed climate change.**



Lean, NRL

Climate During the Recent Solar Minimum

- **Up to 1998 Global climate was on a steady rise.**



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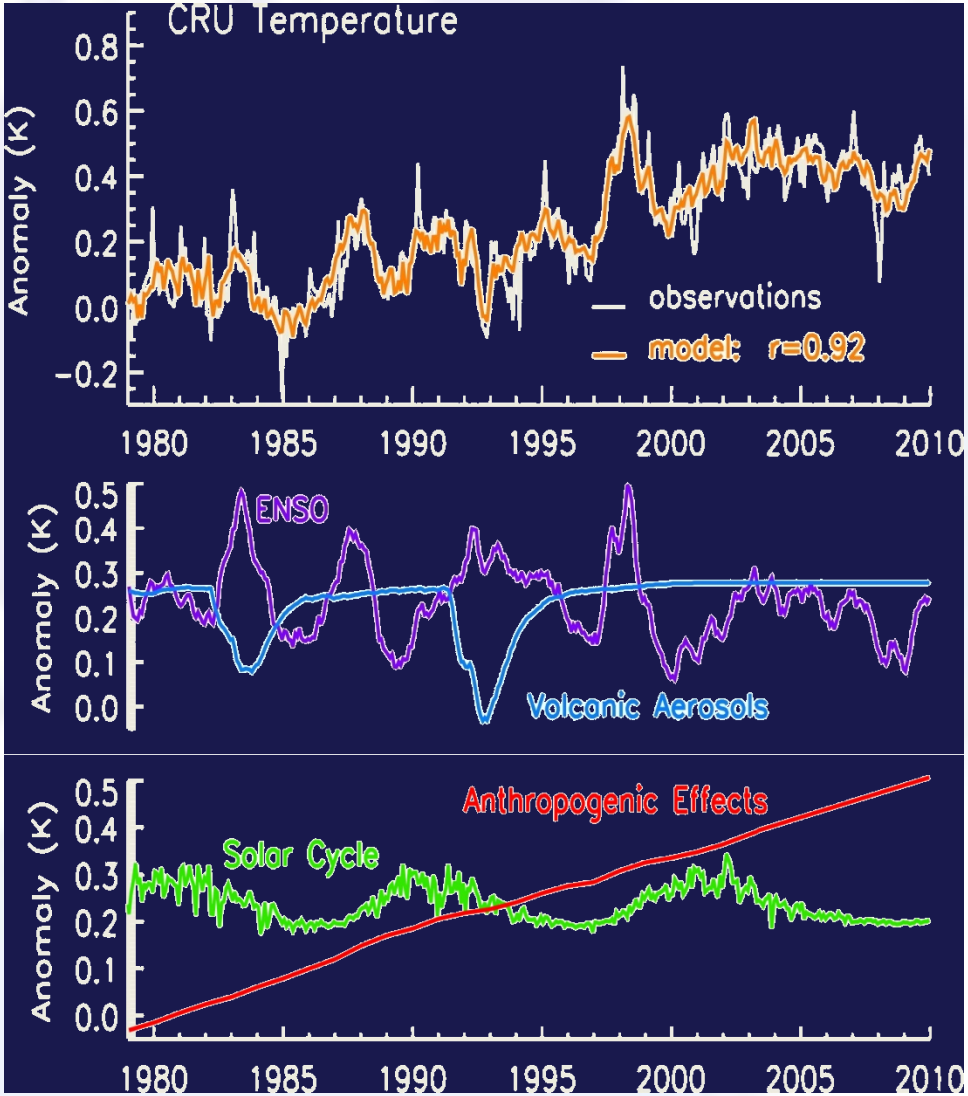
Climate During the Recent Solar Minimum

- **After 1998 global climate did not rise**
  - **Anthropogenic forcing continued to rise during this period**
  - **Global temperatures did not follow predictions made in 2000.**
- **Recent climate trends are driven by three of the four**
  - **Anthropogenic forcing has warmed the climate**
  - **Solar and ENSO have been cooling the climate**
  - **The result was a flat global temperature for the last 6-8 years.**



Lean, NRL

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- There have been lower and longer minima as recorded in the sunspot record.
  - Dalton minimum (two minima) in the 1800s was lower
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- Even if this Cycle is Small, Space Weather Will Continue
  - Geomagnetic Storms will still occur
    - Maybe less frequent but likely as large
  - Particle Events will still occur
    - Seem to be less correlated with SSN
- The response of the thermosphere was significant
  - 38% reduction in the neutral density at 400 km
- The response of the ionosphere was more subtle
  - Generally lower TEC but not uniform across space and time
- The response of the climate was measureable
  - Contributed to the lower than expected temperatures from 2005-2011