Evidence of Clear-Sky Daylight Whitening: Are we already conducting geoengineering?

Chuck Long, Jim Barnard, Connor Flynn
Original US Brightening paper:


- Used data from ARM SGP and 6 SURFRAD sites

- Showed:
  - All-sky brightening average of 8 Wm$^{-2}$/decade
  - All-sky brightening associated with average 2.3%/decade decrease in daylight cloud amount
US Sites All-Sky Brightening

Average = +8 Wm$^{-2}$/decade

- Fort Peck, MT
- Boulder, CO
- Desert Rock, NV
- Bondville, IL
- Goodwin Creek, MS
- Penn State, PA
- ARM SGP

Pacific Northwest National Laboratory
Proudly Operated by Battelle Since 1965
Correlation of All-Sky Brightening with Sky Cover Anomalies

US Sites Seasonal Sky Cover vs All-sky SWdn Anomalies

Slope = -13.5 Wm\(^{-2}\)/10\% Scv

\( R^2 = 0.62 \)
US Clear-Sky Brightening

- US average total SW increase of 4.6 Wm$^{-2}$/decade
  - Not correlated with aerosol optical depth changes!
- Direct SW did not change over the years
- Change in clear-sky total SW was virtually all in the diffuse SW

- This is NOT what is expected for aerosol direct effect!
  - Expect increase in direct SW, decrease in diffuse SW

- What’s going on?
Clear-Sky Total Brightening

US Sites Yearly Clear-Sky SWdn Anomalies

Clear-sky SWdn slope: 4.6 Wm²/decade
Correlation of Aerosol versus Clear-sky SW

US Sites Seasonal AOD vs Clear-sky SWdn Anomalies

Slope = -40 Wm\(^{-2}\)/unit_AOD

\(R^2 = 0.05\)
The clear-sky total SW increased

Documented aerosol optical depths decreased


But clear-sky direct and diffuse components did not change as expected for direct aerosol effect…
Why is the sky blue and a cloud white?

Molecular scattering

Blue light scattered
4X more than red light

Sky Imager classification of cloud and cloud-free pixels uses a ratio of red over blue:
Ratio is small for blue sky, but approaches 1 for cloud.
So the red/blue ratio increases for increasing “whiteness”…
Scattering phase function

**Molecular Scattering**

Backward direction | Forward direction

**Large Particle Scattering**

When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.

**Rayleigh Scattering**

From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.

**Mie Scattering**
The Hypothesis

- Decreasing aerosol optical depth increased downwelling clear-sky SW.
- But at the same time there was a shift from small mode somewhat absorbing scatterers to a large mode mostly non-absorbing scatterers.
- This resulted in the increased direct SW being scattered out of the direct component into the diffuse.
  - Large mode scattering still in forward direction, but less backscatter.

Also scattering more of the longer wavelengths!
So where did the large mode come from?

- Radiative transfer modeling shows the hypothesis is feasible for small ice crystals loading increasing while aerosols decreasing.
- Records show that US commercial air traffic increased over the study period.
- Jet exhaust includes aerosol particles and water vapor → contrails → moistening → contrail cirrus → cirrus haze.
Clear-sky Whitening

- We allow some amount of condensed water in the column still to be called “clear-sky”
  - Dupont et al. (2008) show up to 0.15-0.2 optical depth of typically ice haze to be classified as “clear-sky” in the traditional definition
- So the “clear-sky” brightening results could be due to a “whitening” of the conditions we classify as “cloud-free”
- Indicated in Long et al. (2009) by increase in the diffuse over direct ratio which is related to increased turbidity

- How can we test this?

Diffuse Over Direct SW ratio

US Sites Yearly Clear-sky Diffuse/Direct Ratio Anomalies

Clear-sky Dif/Dir slope: 0.021/decade

Year
MFRSR diffuse spectral SW Measurements

- The ARM and SURFRAD sites all have collocated Multi-Frequency Rotating Shadowband Radiometers (MFRSRs)
- Include spectral channels at 415, 500, 615, 673, 870, 940 nm
- Use 870 nm as “red”, and 415 nm as “blue”
- Use detected clear-sky periods from RFA and fit functions for the MFRSR spectral channels, interpolate coefficients for cloudy periods same as broadband in original study
- Produce yearly averages of clear-sky diffuse 870 nm and 415 nm using same averaging methodology as original study
- If clear-sky whitening is occurring, there should be an increasing tendency in the 870/415 nm ratio through the study years
Yearly Average 870/415 nm Ratio

Yearly Avg Ratio of 870/415 nm Clear-Sky MFR Diffuse Irradiance

\[ y = 0.0011x + 0.151 \]

\[ R^2 = 0.362 \]

95% Conf Level Slope Interval: 0.0003, 0.0019
Summary

- Long et al study showed increasing clear-sky SW over US
- Augustine et al. showed decreasing aerosol optical depths during same period
- However examination of clear-sky direct and diffuse SW components did not behave as expected for aerosol direct effects
  - Direct SW didn’t change appreciably
  - The increase in total SW was in the diffuse SW component
- The above is possible if an increase in large mode scatterers under “clear skies” at same time as decrease in “dry” aerosol loading
- Tendency of dif/dir and 870/415 nm ratios compatible with hypothesis
- Increased “ice haze” from increased jet air traffic?

Thank You…

Chuck.Long@pnnl.gov
Ice crystals are not spherical...