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

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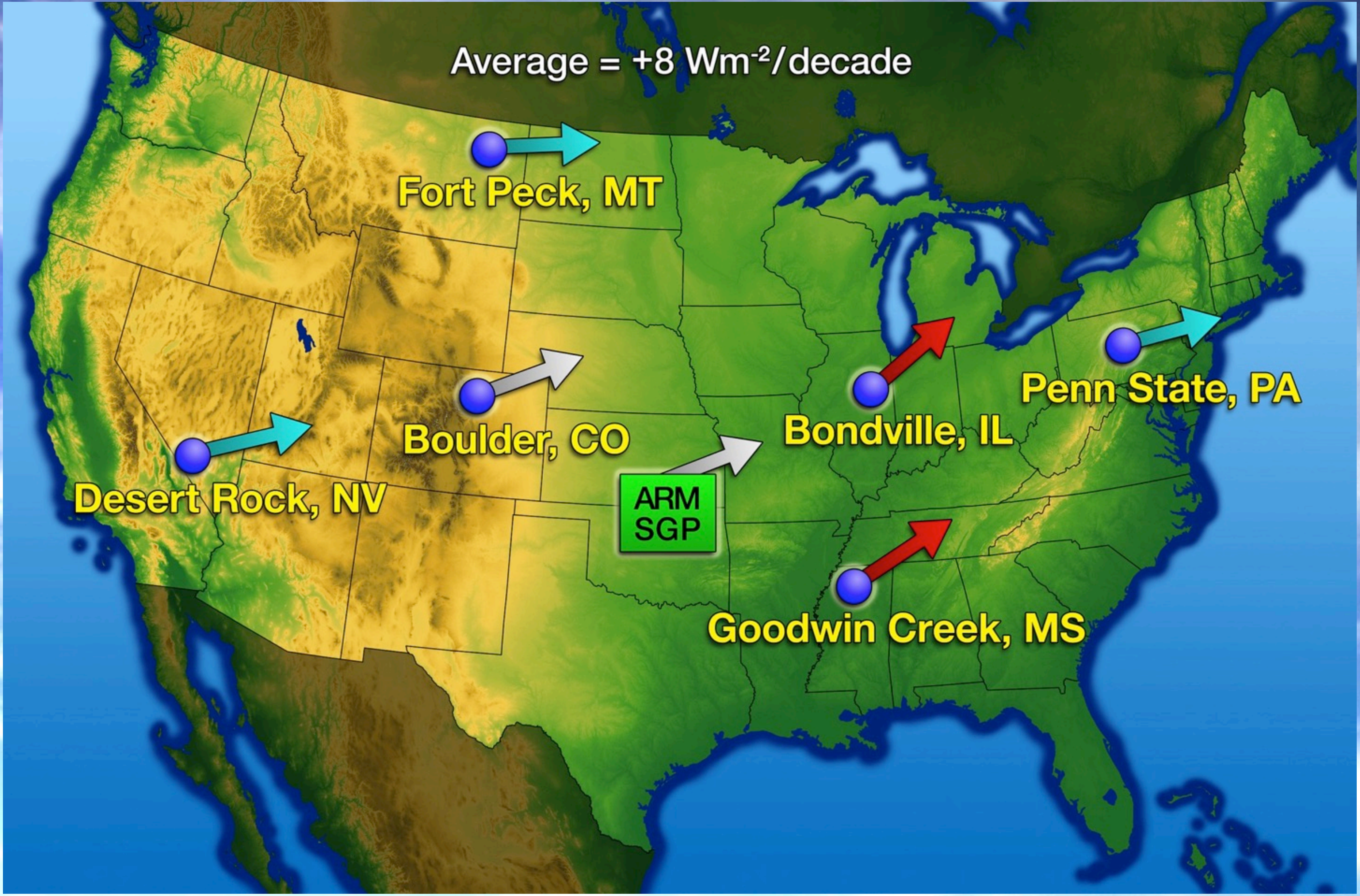
Original US Brightening paper:

- Long, C. N., E. G. Dutton, J. A. Augustine, W. Wiscombe, M. Wild, S. A. McFarlane, and C. J. Flynn (2009): Significant Decadal Brightening of Downwelling Shortwave in the Continental US, Journal of Geophysical Res, 114, D00D06, doi:10.1029/2008JD011263.

- Used data from 6 SURFRAD sites and ARM SGP
  - 1996 - 2007

US Sites All-Sky Brightening

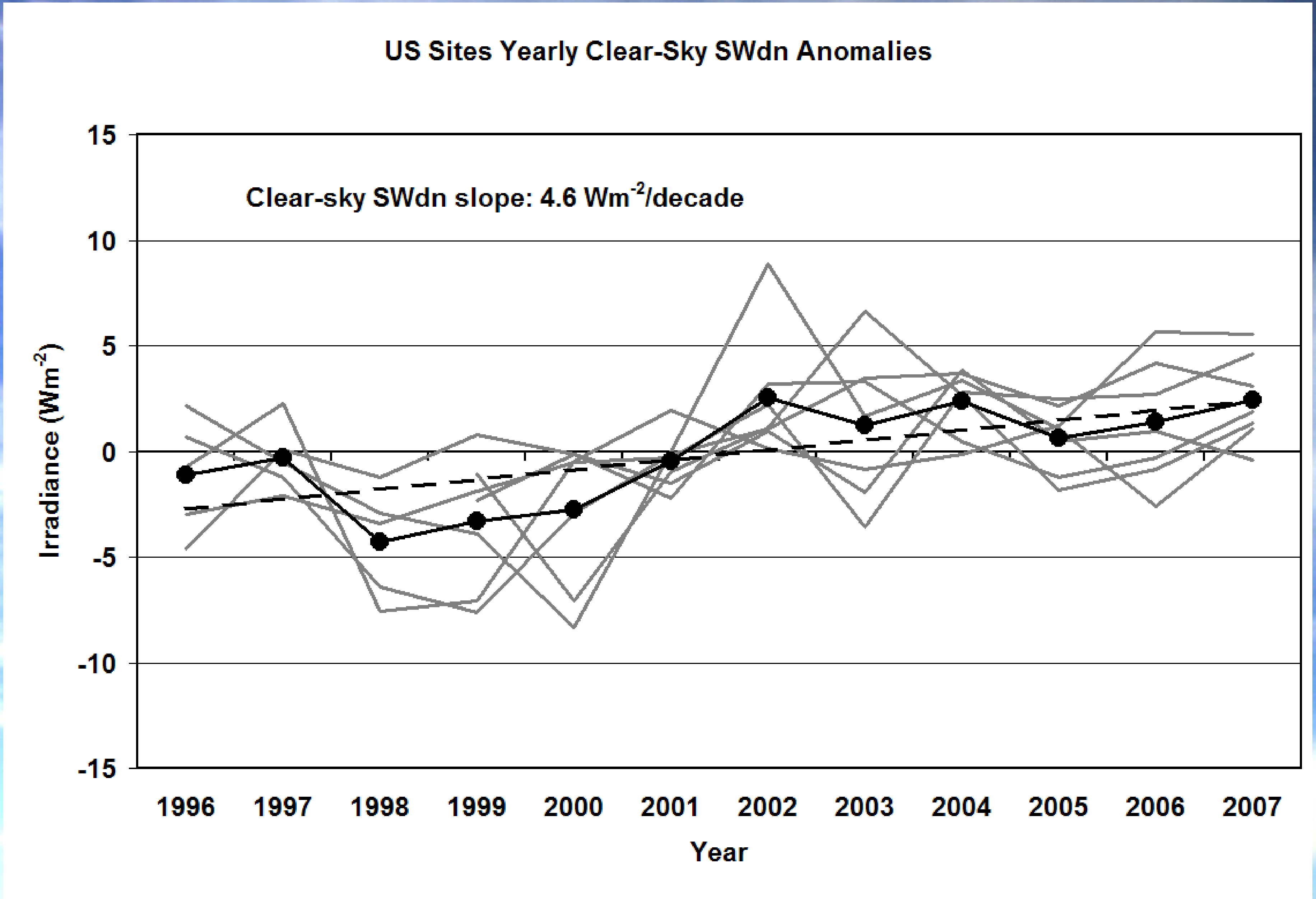


US <u>Clear-Sky</u> Brightening

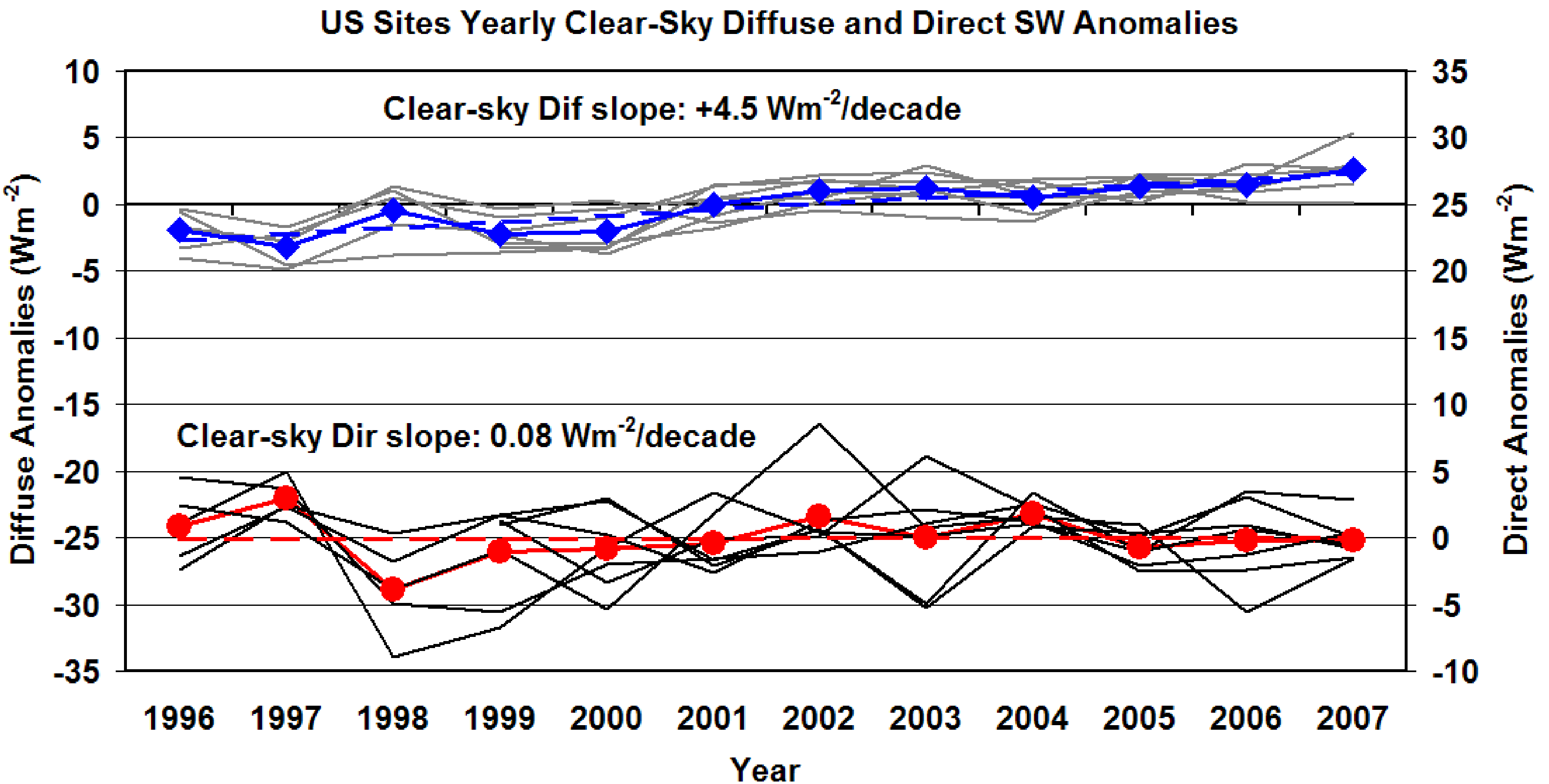
- **US average total SW increase of 4.6 Wm^{-2}/decade**
- **<u>Direct SW shows no trend</u> over the study years**
- **Trend in clear-sky total SW was virtually <u>all in the diffuse SW</u>**

- **This is NOT what is expected for aerosol direct effect!**
  - **For decreased aerosols: Expect increase in direct SW (less attenuation), decrease in diffuse SW (less scattering)**
- **Total SW changes not correlated with aerosol optical depth changes!**

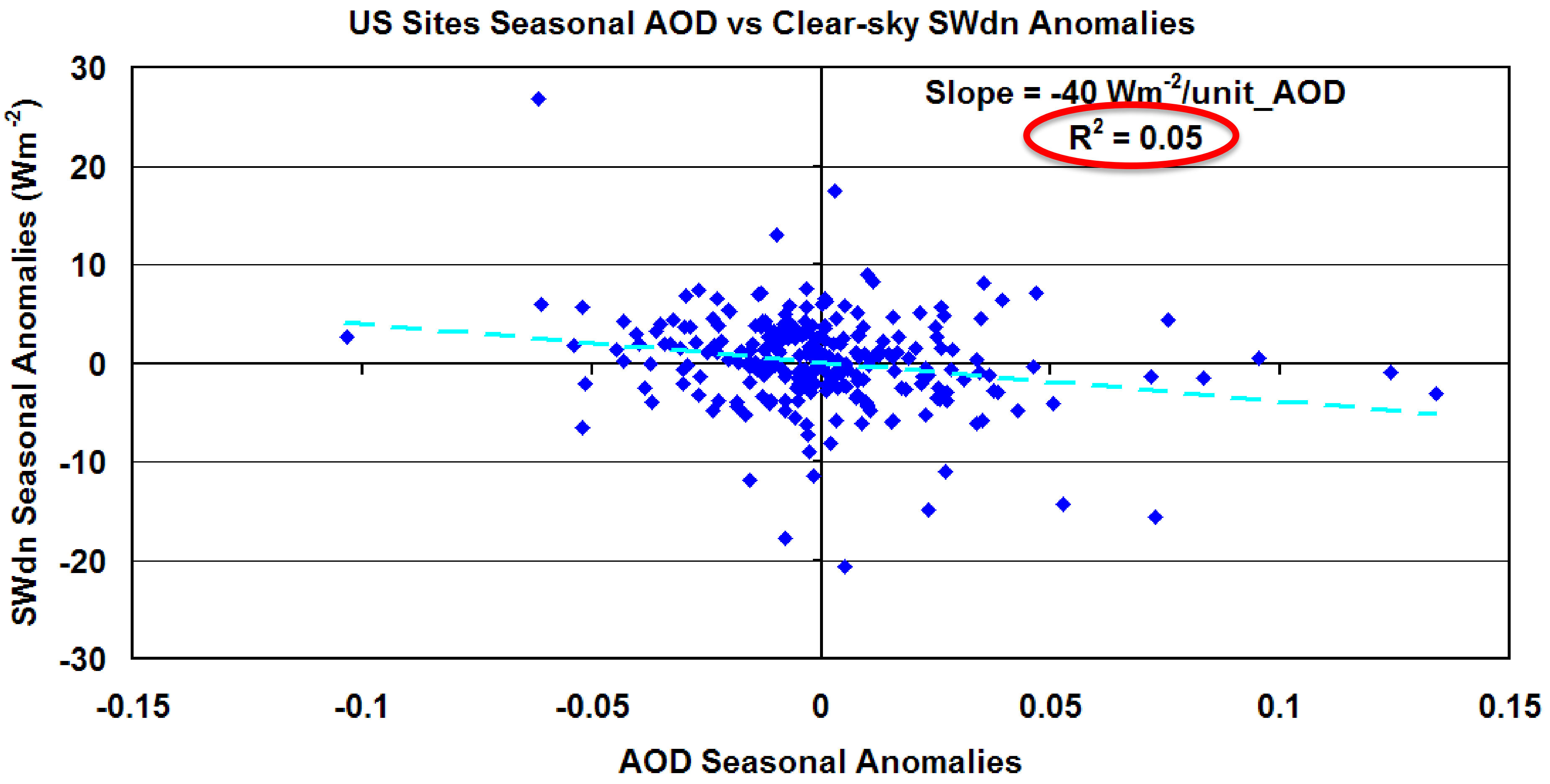
Clear-Sky Total Brightening



Clear-Sky SW Components



Correlation of Aerosol versus Clear-sky SW Anomalies

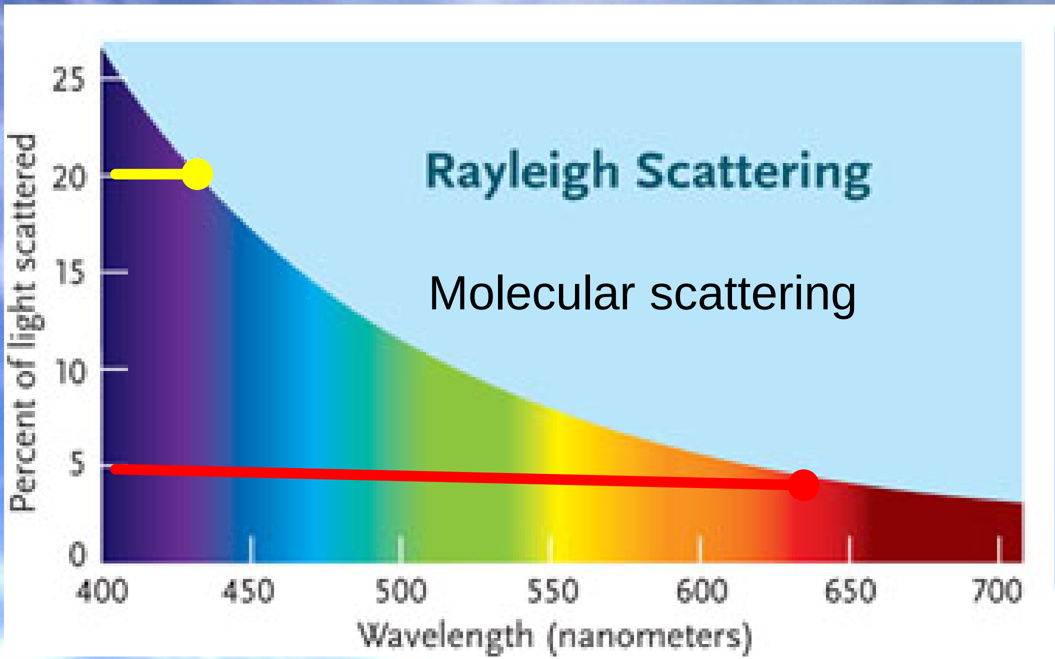


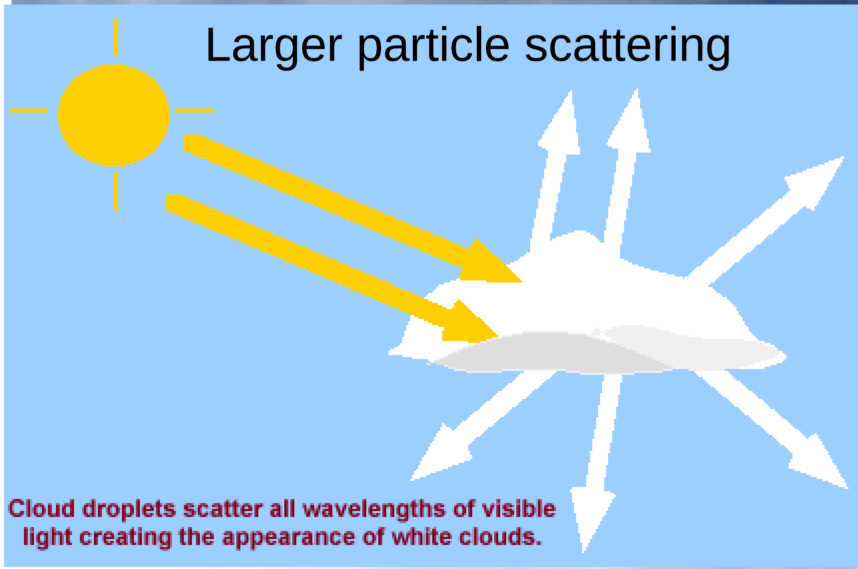
Puzzling!

- The clear-sky total SW increased
- Documented aerosol optical depths decreased
  - Augustine, J. A., G. B. Hodges, E. G. Dutton, J. J. Michalsky, and C. R. Cornwall (2008), An aerosol optical depth climatology for NOAA's national surface radiation budget network (SURFRAD), J. Geophys. Res., 113, D11204, doi:10.1029/2007JD009504.
- But clear-sky direct and diffuse components did not change as expected for direct aerosol effect…
- All confirmed by more recent study spanning 1995-2010
  - Gan, C.-M., Pleim, J., Mathur, R., Hogrefe, C., Long, C. N., Xing, J., Roselle, S., and Wei, C. (2014): Assessment of the effect of air pollution controls on trends in shortwave radiation over the United States from 1995 through 2010 from multiple observation networks, Atmos. Chem. Phys., 14, 1701-1715, doi:10.5194/acp-14-1701-2014.

????????

Why is the sky blue and a cloud white?





Blue light scattered 4X more than red light

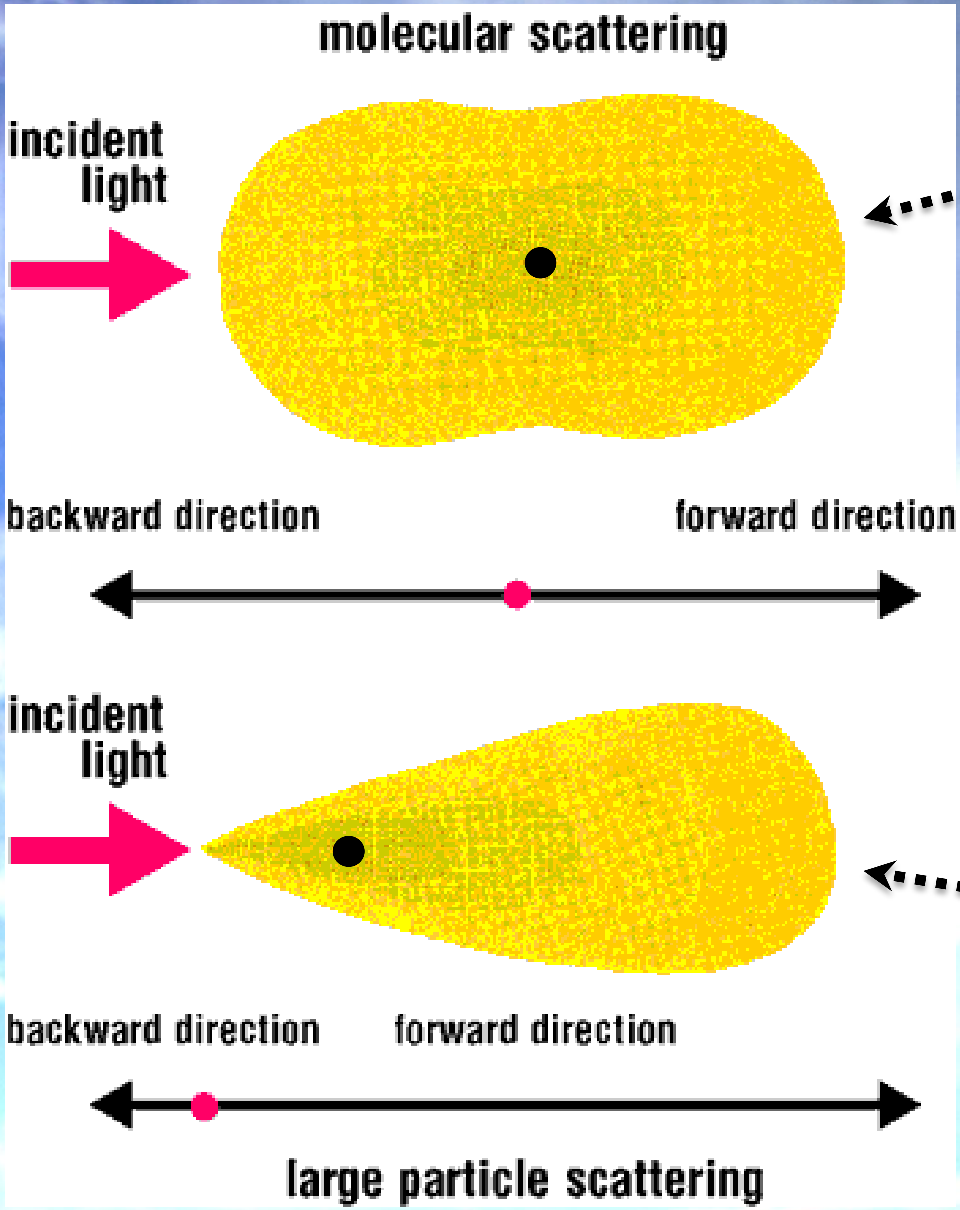
Visible light scattered about equally

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.

<u>So the red/blue ratio increases for increasing "whiteness"…</u>

Scattering phase function

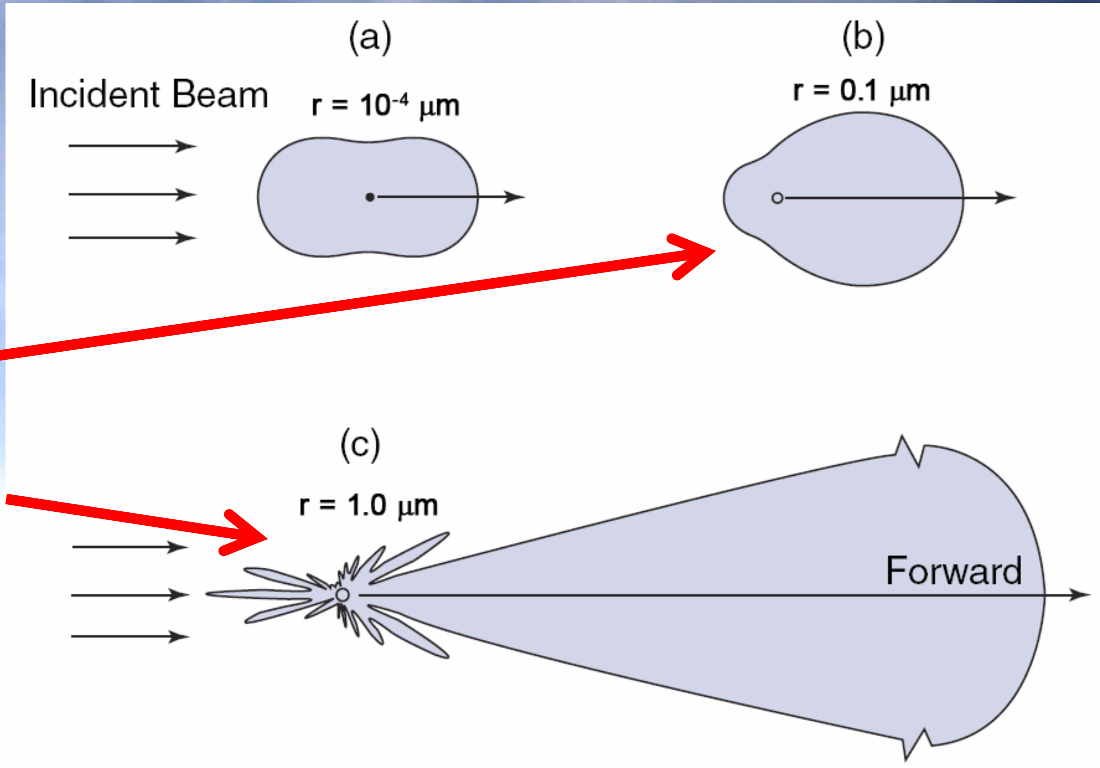


Molecules scatter equally forward and backward

Larger particles scatter more in forward direction

The Hypothesis

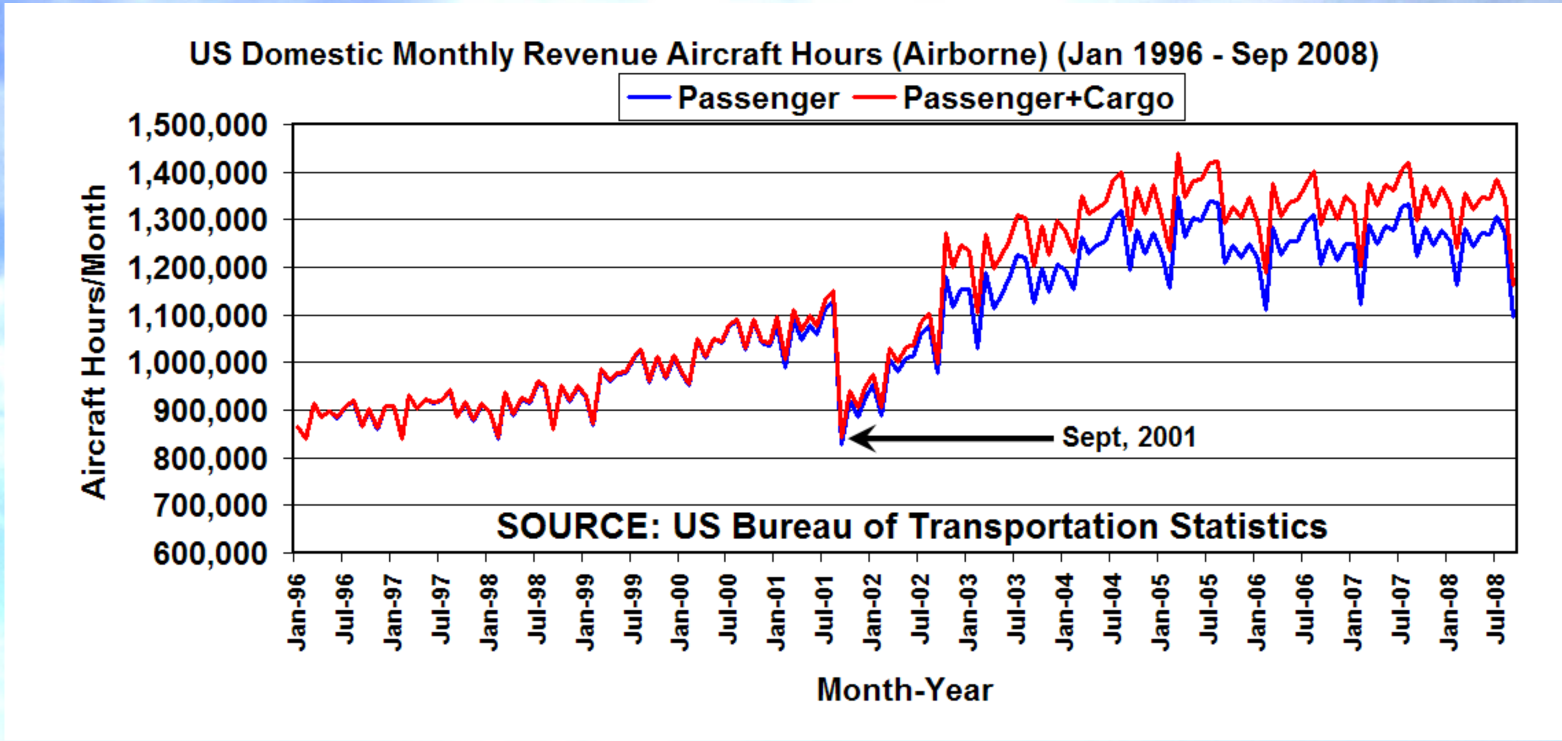
- Decreasing aerosol optical depth increased the downwelling clear-sky SW
- But at the same time there was a shift from smaller mode somewhat absorbing scatterers to a larger mode mostly non-absorbing scatterers
- This resulted in the increased direct SW being scattered out of the direct component into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



Also scattering more of the longer wavelengths!

So where did the larger mode come from?

- **Radiative transfer modeling shows the hypothesis is feasible for small sized ice crystal amounts increasing while aerosols loading is decreasing**
- **Records show that US commercial air traffic increased over the study period**
- **Jet exhaust results in 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 traditionally classified as "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 clear-sky diffuse over direct SW ratio, which is related to increased atmospheric turbidity**

- **How can we further test this "whitening" hypothesis?**

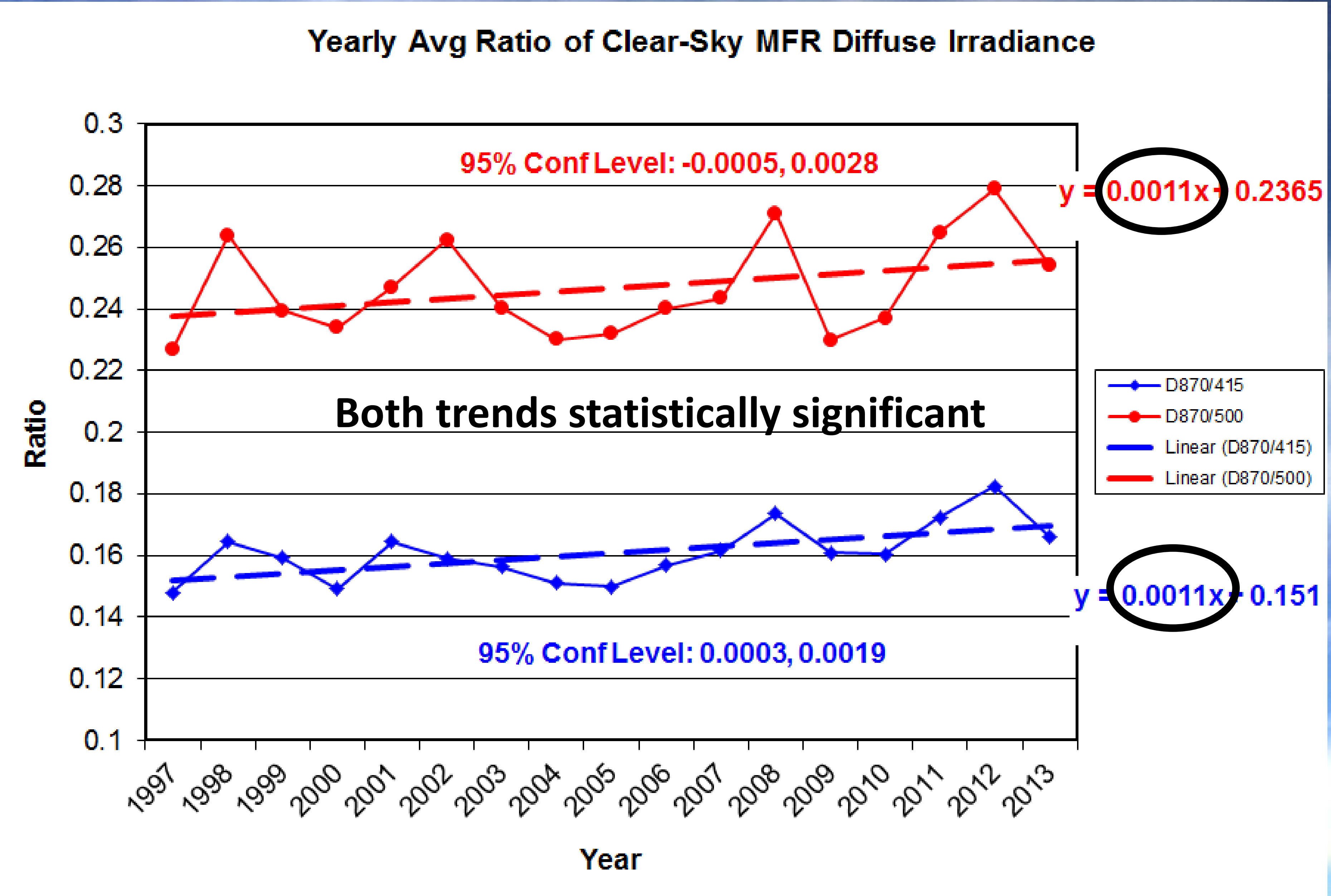
MFRSR diffuse spectral SW Measurements

- The SURFRAD and ARM sites all have collocated Multi-Frequency Rotating Shadowband Radiometers (MFRSRs)
  - Include spectral channels at 415, 500, 615, 673, 870, 940 nm
  - Spectral total, direct, and diffuse components

- Use diffuse 870 nm as “red”, and 415/500 nm as “blue”
- Use same methodology as for broadband SW in original study
  - Use SW detected clear-sky periods 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, 500, 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 and 870/500 nm ratio (red/blue like TSI) through the study years

Yearly Average 870/415 & 870/500 nm Ratio for ARM SGP



Questions!

- Tendency of Diffuse/Direct and 870/415 and 870/500 nm ratios compatible with hypothesis of clear-sky whitening…for SGP
  – Is this due to increased “ice haze” from increased jet air traffic?
  – Are the results that same for other (SURFRAD) sites? Are the 870/415 nm ratio slopes greater for the sites with greater clear-sky trends as one would expect?
  – Is the “whitening” occurring with same magnitude but more frequently, or as often but greater whitening?
- Long et al. (2009) study showed greater SGP clear-sky brightening Summer and Fall, very little for Winter and Spring
  – What are the seasonal differences causing these trend differences?
  – Are these seasonal trends the same for other geographic areas?
- If indeed caused by air traffic moistening and adding IN to the upper troposphere, then there should be a diurnal signature with increased whitening in the afternoon. Is there?

Thank You…

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Ice crystals are not spherical…

Extra info

- SGP 1996-2007 clear-sky SW slope 3 W/m^2/decade
  - Clear-sky direct SW slope -0.3 W/m^2/decade
  - Clear-sky diffuse SW slope 3.2 W/m^2/decade

- Model sensitivity test: SHDOM radiative transfer model [Evans, 1998] in 1D mode, and average the SW over a 24-h period

- Hofmann et al (1998) Wyoming study of thin aerosol layers from jet exhaust, not spread over 1-2 km model layers!
    - 8.6 - 12.7 km (29 to 41 kft), 1973-1997
    - Thin layers of highly concentrated CN.
    - Frequency of occurrence of the CN layers approximately doubled from 1980 to 1992.

Hofmann, DJ, R. Stone, ME Wood, T Deshler, and JM Harris (1998): An analysis of 25 years of balloon borne aerosol data in search of a signature of the subsonic commercial aircraft fleet. GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.13, PAGES 2433-2436.

Correlation of All-Sky Brightening with Sky Cover Anomalies