Long Term Trends in Radiation "Brightening" in United States During 1995 – 2010

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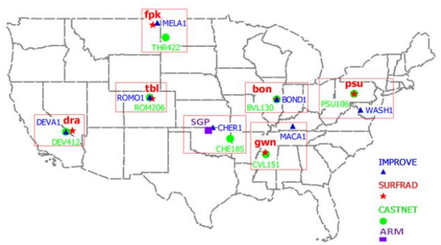
Overview

•In this study, we analyze long term (approximately 10-15 years depending on the site) observational records of total downwelling shortwave (SW) radiation, clear-sky downwelling SW radiation, cloud cover (CVR) fraction, clear-sky diffuse ratio (DF), and aerosol optical depth (AOD) together with aerosol concentrations from several networks (e.g. SURFRAD, CASTNET, IMPROVE and ARM) in the United States (US).

•Observations from seven states (i.e. Illinois, Montana, Mississippi, Colorado, Pennsylvania, Nevada and Oklahoma) with different climatology are selected in this assessment to better understand the spatial and temporal distributions of aerosols and clouds in conjunction with their direct, semi-direct, and indirect effects.

•This analysis aims to test the hypothesis that the reductions in anthropogenic aerosol burden resulting from substantial reductions in emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) over the past 15 years has caused an increase in SW radiation near the surface.

•The results from the assessments are presented in two parts. The first part examines the "brightening" trend by using SW radiation and cloud cover observations. The second part examines the effect of the reduction of SO_2 and NO_x emissions on the radiation budget by using AOD and aerosol concentration measurements.



Map of continental United States showing the locations of various sites of SURFRAD, ARM, CASTNET and IMPROVE.

Table 1: Listing of site identification of each site for different networks and their measurement period.

SURFRAD / ARM	SW Radiation	AOD	CASTNET	Aerosol Concentration	IMPROVE	Aerosol Concentration	SeaWiFS (grid cell: 0.5° x 0.5°)	AOD
BON [Bondville, IL] Elevation:230 m	1995-2010	1997-2010	BVL130 [Bondville, IL]	1990-2010	BONL1 [Bondville, IL]	2001-2010	Bondville, IL Lat: 40.05° Lon: -88.37°	1998-2010
TBL [Table Mountain, CO] Elevation: 1689 m	1996-2010	1997-2010	ROM406 [Rocky Mtn NP, CO]	1994-2010	ROMO1 [Rocky Mountain NP, CO]	1991-2008	Table Mountain, CO Lat: 40.05° Lon: -88.37°	1998-2010
GWN [Goodwin Creek, MS] Elevation: 98 m	1995-2010	1997-2010	CVL151 [Coffeeville, MS]	1990-2010	MACA1 [Mammoth Cave NP, KY]	1992-2010	Goodwin Creek, MS Lat: 40.05° Lon: -88.37°	1998-2010
FPK [Fort Peck, MT] Elevation: 634 m	1996-2010	1997-2010	THR422 [Theodore, ND]	1998-2010	MELA1 [Midicine Lake, MT]	2000-2010	Fort Peck, MT Lat: 40.05° Lon: -88.37°	1998-2010
DRA [Desert Rock, NV] Elevation: 1007 m	1999-2010	1999-2010	DEV412 [Death Valley, CA]	1995-2007	DEVA1 [Death Valley NP, CA]	2000-2010	Desert Rock, NV Lat: 40.05° Lon: -88.37°	1998-2010
PSU [Penn State, PA] Elevation: 376 m	1999-2010	1999-2009	PSU106 [Penn State, PA]	1990-2010	WASH1 [Washington DC]	1990-2010	Penn State, PA Lat: 40.05° Lon: -88.37°	1998-2010
SGP [South Great Plain, OK] Elevation: 314 m	1997-2010	1996-2007	CHE185 [Cherokee, OK]	2002-2010	CHER1 [Cherokee Nation, OK]	2003-2010	South Great Plain, OK Lat: 40.05° Lon: -88.37°	1998-2010

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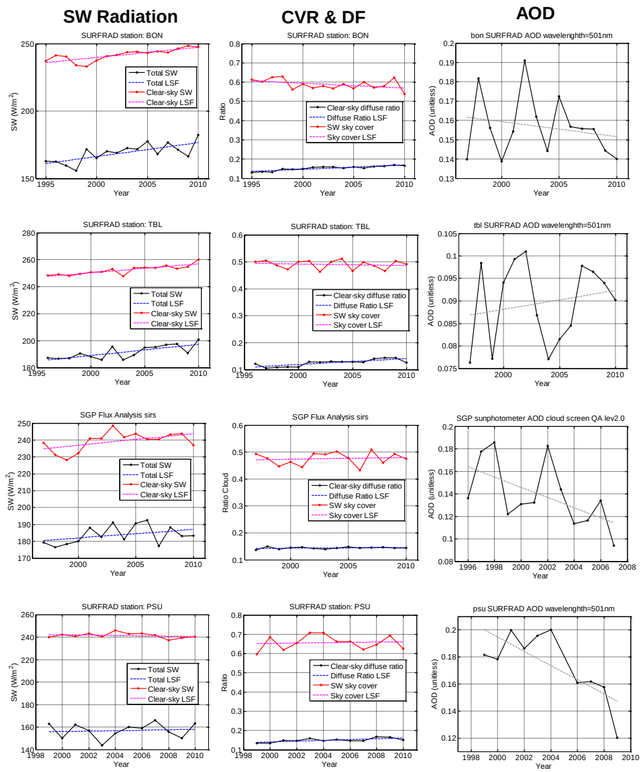
Results and Discussion



BON (eastern US)

- The trends in total SW and clear-sky SW radiation are 1.04 and 0.76 W/m^2/year respectively while the AOD trends for SURFRAD and SeaWiFS are -0.0008 and -0.0039 per year respectively.
- The association between trends in clear-sky SW radiation and aerosol loading is also supported by the trend in the near surface aerosol concentrations from CASTNET (SO_4: -0.14 µgm^{-3}/year, SO_2: -0.25 µgm^{-3}/year and NO_3: -0.09 µgm^{-3}/year) and IMPROVE (NH_4NO_3: -0.03 µgm^{-3}/year, $(NH_4)_2SO_4$: -0.17 µgm^{-3}/year and OMC: -0.07µgm^{-3}/year).
- However, the increasing trend in clear-sky diffuse ratio is contradictory to trends in aerosol burden (i.e. should be decreasing as anthropogenic aerosol concentrations decrease). Possible factors influencing the trends in diffuse ratio:
  - heavier air traffic in the eastern US can enhance the cirrus coverage
  - the classification of "clear-sky" conditions in the radiation retrieval methodology which can potentially influence the "clear-sky" radiation estimate.

*GWN site has similar trends (e.g. SW radiation, AOD and aerosol concentration) as BON site.

TBL (western US)

- The trends in total SW and clear-sky SW radiation are 0.83 and 0.66 W/m^2/year respectively while the AOD trends for SURFRAD and SeaWiFS are 0.0004 and -0.0006 per year respectively.
- The trend in clear-sky SW radiation and aerosol loading do not agree with the hypothesis and the trend in the near surface aerosol concentrations from CASTNET (SO_4: -0.0003 µgm^{-3}/year, SO_2: -0.02 µgm^{-3}/year and NO_3: -0.002 µgm^{-3}/year) and IMPROVE (NH_4NO_3: 0.005 µgm^{-3}/year, $(NH_4)_2SO_4$: -0.009 µgm^{-3}/year and OMC: -0.002µgm^{-3}/year) are a mixture of increasing and decreasing trends for different species.
- One of the causes is because the CAA (Clean Air Act) controls did not substantially reduce pollutant emission in the western US and hence the "brightening" effect is less pronounce here.
- At this location the increase in clear-sky diffuse ratio is consistent with increasing aerosol burden.

*FPK and DRA sites illustrate similar trends (e.g. SW radiation, AOD and aerosol concentration) with TBL site.

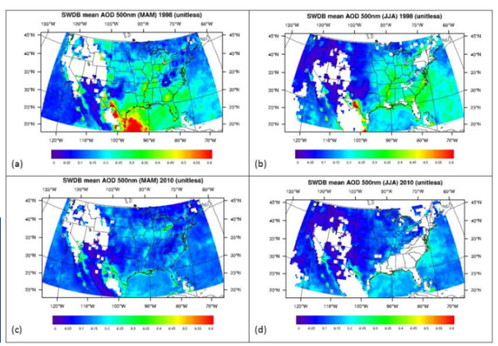
SGP (central US)

- The trends in total SW and clear-sky SW radiation are 0.5 and 0.7 W/m^2/year respectively while the AOD trends for SURFRAD and SeaWiFS are -0.005 and -0.0005 per year respectively.
- The association between trends in clear-sky SW radiation and aerosol loading is also supported by the trend in the near surface aerosol concentrations from CASTNET (SO_4: -0.17 µgm^{-3}/year, SO_2: -0.08 µgm^{-3}/year and NO_3: -0.11 µgm^{-3}/year) and IMPROVE (NH_4NO_3: -0.09 µgm^{-3}/year, $(NH_4)_2SO_4$: -0.09 µgm^{-3}/year and OMC: -0.14 µgm^{-3}/year).
- Although the clear-sky diffuse ratio again contradicts the hypothesis, this increasing trend may caused by the occurances of sub-visual cirrus and the classification of "clear-sky" condition in the radiation retrieval methodology.

PSU (special case)

- The trends in total SW and clear-sky SW radiation are 0.2 and -0.16 W/m^2/year respectively while the AOD trends for SURFRAD and SeaWiFS are -0.005 and -0.001 per year respectively.
- Even though the clear-sky SW radiation trend is decreasing weakly, the aerosol loading is consistent with the decreasing trend of surface aerosol concentrations from CASTNET (SO_4: -0.14 µgm^{-3}/year, SO_2: -0.43 µgm^{-3}/year and NO_3: -0.08 µgm^{-3}/year) and IMPROVE (NH_4NO_3: -0.04 µgm^{-3}/year, $(NH_4)_2SO_4$: -0.18 µgm^{-3}/year and OMC: -0.13 µgm^{-3}/year).
- Although the clear-sky diffuse ratio also exhibits an increasing trend, this may be caused by heavy air traffic at cruise altitude (leading to the frequent formation of cirrus clouds), long range transported plume events and increasing cloud cover trend at this site.

Acronym: least-square fit (LSF)



Average AOD of SeaWiFS measurement for spring & summer of 1998 & 2010.

- As shown in the figure, across the eastern U.S, the AOD values (0.2-0.4) during1998 were much higher than those during 2010 (<0.2). AOD values across the western U.S. were similar for both years.
- Considerable reductions in AOD are noted over the past decade further illustrating the large-scale reductions in aerosol burden over the eastern US.

Summary

- The total downwelling SW radiation and clear-sky SW radiation at majority of the sites across the eastern U.S. exhibit an increasing trend over the 15 years.
- At locations where discrepancies in trends were noted, the apparent dimming can be explained by the site location, heavy air traffic, increasing cloud cover fraction.
- Trends in AOD retrievals from SeaWiFS at locations of the SURFRAD sites agree with the in-situ AOD measurements at these locations (except at TBL). However, the difference (SURFRAD: 0.0004; SeaWiFS: -0.0006) in TBL is very small and may due to the larger spatial averaging (0.5° x 0.5°) of SeaWiFS.
- The analyzed trends of SW radiation, AOD, and aerosol concentration from three of the seven sites (i.e. BON,GWN and SGP) show a clear association between increasing clear-sky SW and decreasing surface and tropospheric (inferred from AOD) aerosol burden.
- Three sites (i.e. TBL, FPK and DRA) show increasing AOD associated with mostly increasing trends in aerosol concentration at surface. At these sites, the changes in aerosol burden and/or direct aerosol effects alone cannot explain the observed changes in surface SW radiation, but other factors also need to be considered such as cloud cover, aerosol vertical profiles and elevated plumes.
- Trends in clear-sky diffuse ratio are often confounded by other factors and did not show a clear association with trends in aerosol burden.

  There are several possible interpretations to resolve this seeming contradiction such as heavier air traffic in the eastern US which can enhance the cirrus coverage and the classification of "clear-sky" conditions in the radiation retrieval methodology which can potentially influence the "clear-sky" radiation estimate.
- *Future work*: Multi-decadal model calculations with the coupled WRF-CMAQ model (Wong et al., 2012) are being set up for the 1990-2010 period to test the ability of the model to simulate not only the changes in aerosol burden over the US arising from the implementation of the CAA, but also the associated radiation brightening as analyzed in the present analysis.