Response of California temperature to regional anthropogenic aerosol changes

T. Novakov, T.W. Kirchstetter, S. Menon & J. Aguiar
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Abstract. In this paper, we compare constructed records of concentrations of black carbon (BC) – an indicator of anthropogenic aerosols – with observed surface temperature trends in California. Annual average BC concentrations in major air basins in California significantly decreased after about 1990, coincident with an observed statewide surface temperature increase. Seasonal aerosol concentration trends are consistent with observed seasonal temperature trends. These data suggest that the reduction in anthropogenic aerosol concentrations contributed to the observed surface temperature increase. Conversely, high aerosol concentrations may lower surface temperature and partially offset the temperature increase of greenhouse gases.

1. Introduction

Greenhouse gases warm the Earth's surface and the lower and middle troposphere. Light-scattering aerosols, such as sulfate, nitrate and organics cool the surface. Light-absorbing aerosols, such as black carbon (BC), warm the atmospheric layer but cool the surface. However, despite this differential heating profile for black carbon, all aerosols in general cool the surface.

It has been suggested that decreasing global atmospheric aerosol concentrations [*Streets et al*, 2006; *Mishchenko et al*., 2007] after about 1990 caused increases in observed global solar radiation intensity [*Pinker et al*., 2005; *Wild et al.*, 2005] and global surface temperatures [*Wild, Ohmura, and Makowski*, 2007]. *Nazarenko and Menon* [2007] used transient climate model simulations to show that surface temperature and

radiation trends that were observed between 1960 and 2000 by *Wild et al.* [2005] are predicted only when the effects of anthropogenic aerosols are included in the model.

Previous results pertain to effects on global or hemispheric scales. Observational evidence of aerosol-mediated surface temperature change on regional scales, however, has not been demonstrated. The California temperature record shows that surface temperature increased about 2ºC during 1950–1999, with the largest increase occurring after about 1990 [*Duffy, Bonfils, and Lobell*, 2007]. Here we show that anthropogenic aerosol concentrations measured over the past two to three decades in major air basins in California substantially decreased after about 1990. This concentration decrease coincided with a significant increase in regional surface temperatures, consistent with the notion that lower aerosol concentrations allow more solar radiation to reach the ground. Our analysis further shows that average seasonal aerosol concentration trends mirror the observed [*Duffy, Bonfils, and Lobell*, 2007] seasonal temperature trends. These authors noted that all model simulations for California show warming, however, none reproduce the observed seasonal temperature differences.

2. Results and discussion

To ascertain the effect of attenuation solar radiation by anthropogenic aerosols on surface temperature, data on fine aerosol mass and its optical properties measured at locations throughout the State over the past decades would be needed. Such data, however, do not exist. Instead we made use of existing aerosol data from monitoring sites in three major air basins for which uninterrupted record exist: from 1970 for the sites in the San Francisco Bay air basin and from 1980 for sites in the San Joaquin Valley and Sacramento Valley air basins. The data include coefficient of haze (COH) monitored at sites throughout the three air basins obtained by the California Air Resources Board and are available at [*http://www.arb.ca.gov/aqd/aqdcd/aqdcddld.htm*]. BC concentrations were derived from COH as described in *Kirchstetter et al.* [2008]. Light scattering coefficient (Bsc) data are also available, mostly for Sacramento Valley sites.

Black carbon is a unique tracer for combustion aerosol and its concentration trend may be used as an approximate surrogate for the trend of fine anthropogenic aerosol mass, at least at locations considered here**.** We base this inference on the Bsc - $PM_{2.5}$

proportionality derived at sites in San Joaquin Valley [*Chow et al.* 2006a] and the generally linear relationship that exists between concomitantly measured BC and Bsc, as illustrated by a plot of Bsc vs. BC monthly values in Fresno, California for the February 2000 to December 2002 period (Fig.1a). This conclusion is not unexpected because, at the locations considered, both the light-absorbing BC and much of light scattering aerosol, such as organic carbon and aerosol nitrates, are derived from motor vehicle emissions **[***Watson and Chow*, 2002; *Chow et al.* 2006b **].** SO_2 concentrations and emissions in the State have been steadily decreasing [*http://www.arb.ca.gov/aqd/almanac/almanac07/chap307.htm*]

In this paper we emphasize changes in annual BC concentrations derived from monthly average values. These exhibit strong seasonal variations with concentration maxima in winter and minima in summer. The seasonal cycle in BC concentrations is due to reduced pollutant dispersion – mixing height and wind speed – during winter months [*Cass et al.* 1984]. This seasonality is seen in data from the three air basins and other locations in California. This seasonal pattern persisted in the San Francisco Bay Area throughout a 37-year period of observation [*Kirchstetter et al*. 2008]. An example is shown in Fig. 1b, where monthly and annual average BC concentrations measured from 1980 to 2000 in the Bay Area are displayed. As it is seen in Fig 1b, monthly and annual BC concentrations show a pronounced decrease after 1991, evident in both peak maxima and minima.

Similar decrease is evident in average annual BC concentrations in all three air basins (Fig. 2a). Annual BC levels decreased from late the 1960s until 1975, remained practically unchanged till 1990, and steadily decreased thereafter. (In these plots we only show yearly average values; we do not indicate the standard deviations because these would be governed almost entirely by the spread in seasonal concentration shown in Fig. 1b.) This decrease in BC coincides with the onset of accelerated heating [*Duffy, Bonfils, and Lobell*, 2007]. We recognize that the cited temperature record is for the whole State whereas our analyses of aerosol data are for three air basins. Nevertheless, our comparison appears justified because when warming has occurred, the entire state has felt temperature increases [*Duffy, Bonfils, and Lobell*, 2007].

Further support for the role of aerosols in the post 1990 warming in California is suggested by seasonal temperature and aerosol trends. In Fig. 2b and Fig. 2c we show summer and winter BC concentrations and summer and winter temperature taken from Fig 1 in [*Duffy, Bonfils, and Lobell*, 2007]. In Figures 2b and 2c BC concentrations are shown on inverted concentration scale so a reduction in aerosol concentration (trending upward) would be suggestive of warming. The data in Fig. 2b and 2c show that the BC decrease is larger in winter than in summer. This is consistent with observed warming being higher in winter than in summer. The agreement between the observed temperature change and the change in BC concentration for summer for the entire 1970 – 2000 period and for winter from about 1980 to 2000 is remarkably good. The reason for the large scatter in the pre-1980 winter data remains unknown at present.

That attenuation of sunlight by anthropogenic aerosols has an effect on the surface temperature in California is suggested by the relationship between aerosol optical thickness (AOT) and aerosol concentrations in Fresno, California, the only site in one of air basins discussed here where AOT is measured since 2000. AOT (at 870nm) data are from NASA's AERONET network [*http://aeronet.gsfc.nasa.gov/index.html*]). Hourly AOT plotted against corresponding Bsc averages for May 2002 through October 2002 period are presented in Fig. 3. The close correspondence among these short- term values suggests that AOT and Bsc changes occur synchronously.

In a separate study (unpublished) we examined the relationships between seasonal, daily, and hourly diurnal variations in ground level aerosol scattering coefficient Bsc, and aerosol optical thickness at 870 nm in Fresno. We found that from May through November 2002 the hour by hour diurnal variations of simultaneously measured Bsc and AOT were well correlated when Bsc was above ~70 to 80 Mm^{-1}. These results demonstrate that short-term changes in aerosol concentrations (BC or Bsc) occur synchronously with AOT values and consequently influence the changes in the surface solar flux, which in turn influences the surface temperature.

3. Conclusions

We have shown that: 1) annual and seasonal ambient anthropogenic aerosol concentrations in three major air basins in California show a distinct decrease after about

1990; 2) this aerosol decrease (exemplified by BC) coincides with the observed temperature increase in the State; 3) short-term changes in aerosol concentrations (BC or Bsc) occur synchronously with changes in aerosol optical thickness values; 4) observed seasonal temperature trends are mirrored in winter and summer aerosol trends. These observational results suggest that anthropogenic aerosols play a role in modifying the greenhouse gas related temperature increase in California over the past three decades.

Acknowledgment

Work supported by Director, Office of Science, Office of Biological and Environmental Research, U.S. Department of Energy

References

Cass, G.R., M. H. Conklin, J. J. Shah, J. J. Huntzicker, and E. S. Macias (1984), Elemental carbon concentrations: Estimationof an historical data base, *Atmos. Environ*., *18*, 153-162.

Chow, J.C., J.G. Watson, D. H. Lowenthal, L.-W. Antony, L.W. Chen , and K. L. Magliano (2006a), Particulate carbon measurements in California's San Joaquin Valley. *Chemosphere 62*, 337–348.

Chow, J.C., J.G. Watson, K. Park, D.H. Lowenthal, N.F. Robonson and K.A. Magliano (2006b), Comparison of article lihjt scattering and fine particulate matter mass in central California, *J. Air Waste Manage Assoc. 56*, 398-410.

Duffy, P. B., C. Bonfils, and D. Lobell (2007), Interpreting recent temperature trends in California, *Eos 88*, 409 - 410.

Kirchstetter, T.W., J. Aguiar, S.Tonse, D. Fairley, and T. Novakov (2008), Black carbon concentrations and diesel vehicle emission factorsderived from coefficient of haze measurements in California: 1967 - 2003, *Atmos. Environ., 42*, 480 - 491.

Mishchenko, M.I., I. V. Geogdzhayev, W. B. Rossow, B. Cairns, B. E. Carlson, A. A. Lacis, L. Liu, and L. D. Travis (2007), Long-term satellite record reveals likely recent aerosol trend, *Science 315,* 1543 - 1543.

Nazarenko, L., and S. Menon (2005): Varying trends in surface energy fluxes and associated climate between 1960 and 2002 based on transient climate simulations, *Geophys. Res. Lett*., *32,* L22704, doi:10.1029/2005GL024089.

155 Pinker, R. T., B. Zhang, and E. G. Dutton (2005), Do satellites detect trends in surface
156 solar radiation? *Science 308*, 850 - 854.
157 Streets, D.G., Y. Wu, and M. Chin (2006),Two-decadal aerosol trends as a likely
158 explanation of the global dimming/brightening transition, *Geophys. Res. Letters*,
159 VOL. *33*, L15806, doi:10.1029/2006GL026471.
160 Watson, J.G. and J.C. Chow (2002), A wintertime PM2.5 episode at the Fresno, CA
161 Supersite , *Atmos. Environ., 36,* 465–475.
162 Wild, M., H. Gilgen, A. Roesch, A. Ohmura, C. N. Long, E. G. Dutton, B. Forgan, A.
163 Kallis, V. Russak, and A. Tsvetkov (2005),From Dimming to Brightening:
164 Decadal Changes in Solar Radiation at Earth's Surface, *Science 308,* 847 - 850.
165 Wild, M., A. Ohmura, and K. Makowski (2007), Impact of global dimming and
166 brightening on global warming, *Geophys. Res. Letters*, VOL. *34*, L04702,
167 doi:10.1029/2006GL028031.
168
169
170 **Figure caption**
171 Figure 1. a) A plot of Bsc vs. BC monthly values in Fresno, California for the
172 February 2000 to December 2002 period. b) Monthly and annual average BC
173 concentrations measured from 1980 to 2000 in the Bay Area sites.
174 Figure 2. a) Time series of BC concentrations in San Francisco Bay Area (SFBA),
175 San Joaquin (SJV) and Sacramento Valleys (SACV) and average (AVG) values for the
176 three air basins. b) Comparison of observed summer temperature relative to 1961-1990
177 base and non-winter (Jun – August) BC concentrations. BC values (solid line) are annual
178 averages for each individual year, temperature values (open circles) are for every second
179 year. c) Similar to (b) but for winter months (December – February). Note that the
180 vertical scale in (b) and (c) differ.
181

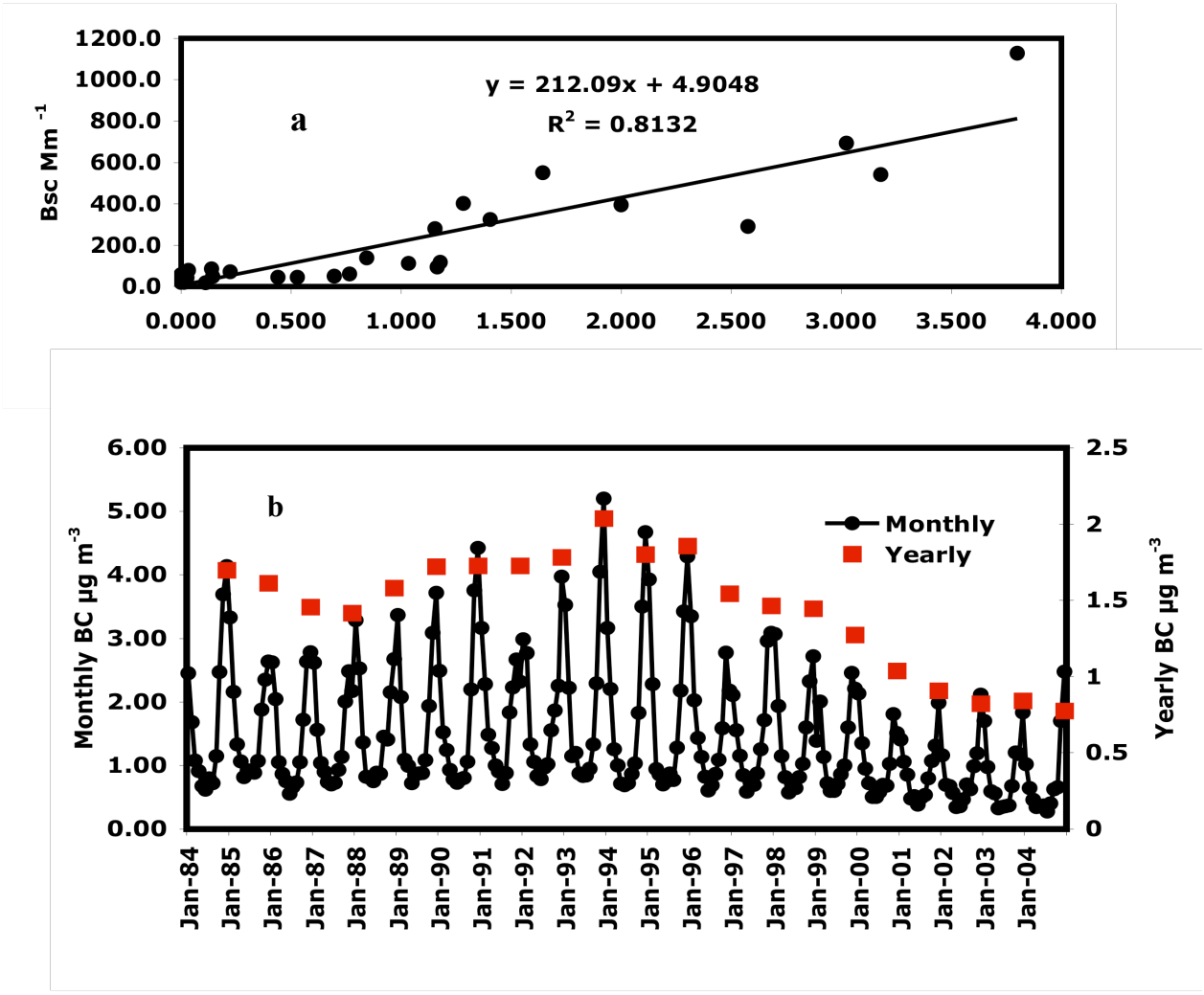
a
y = 212.09x + 4.9048
R2 = 0.8132
Bsc Mm -1
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
b
Monthly
Yearly
Monthly BC µg m-3
Yearly BC µg m-3
6.00
5.00
4.00
3.00
2.00
1.00
0.00
2.5
2
1.5
1
0.5
0
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03
Jan-04

Fig.1

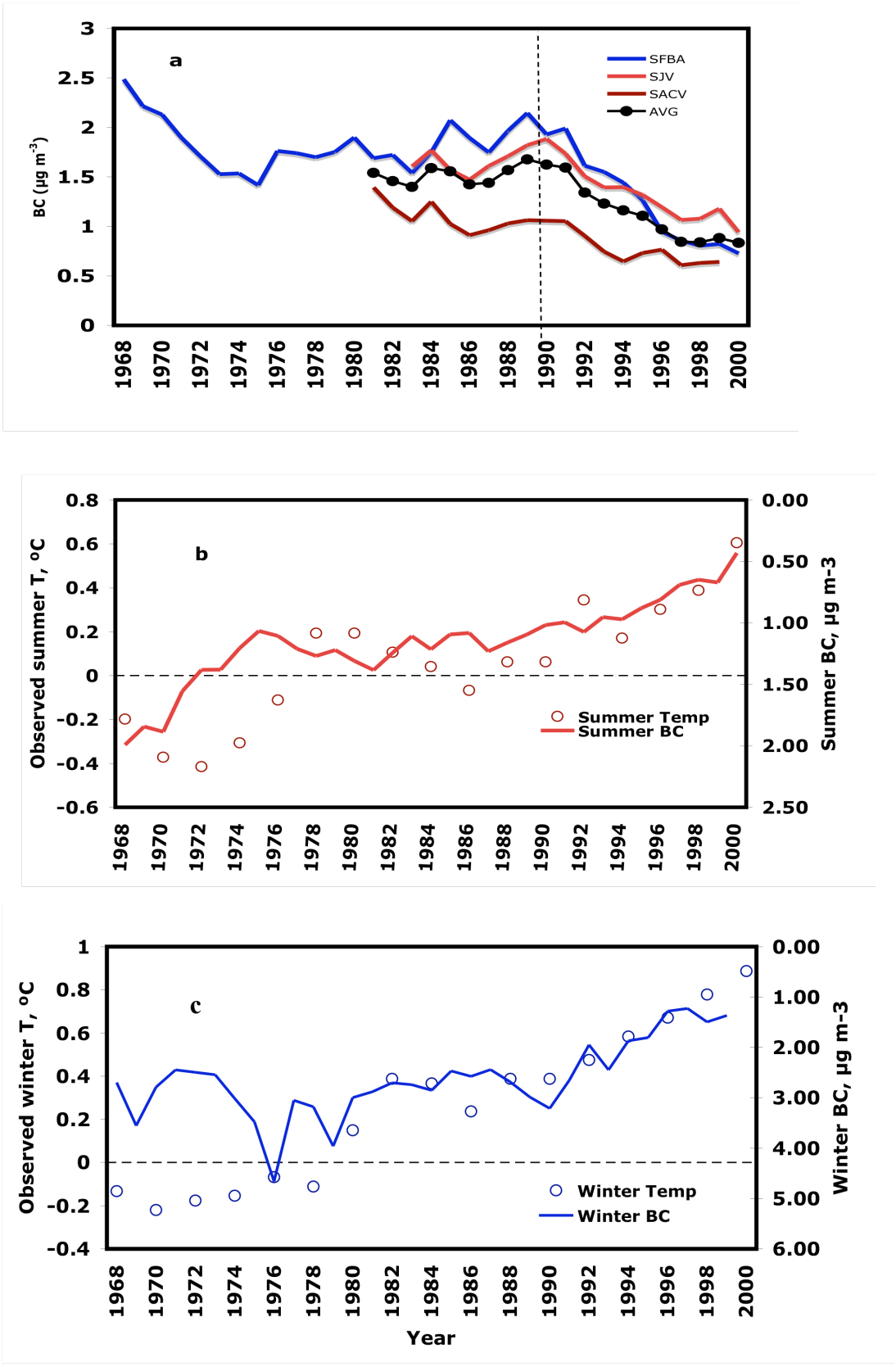
a
SFBA
SJV
SACV
AVG
BC (μg m-3)
b
Observed summer T, °C
Summer BC, μg m-3
Summer Temp
Summer BC
c
Observed winter T, °C
Winter BC, μg m-3
Winter Temp
Winter BC
Year

Fig. 2

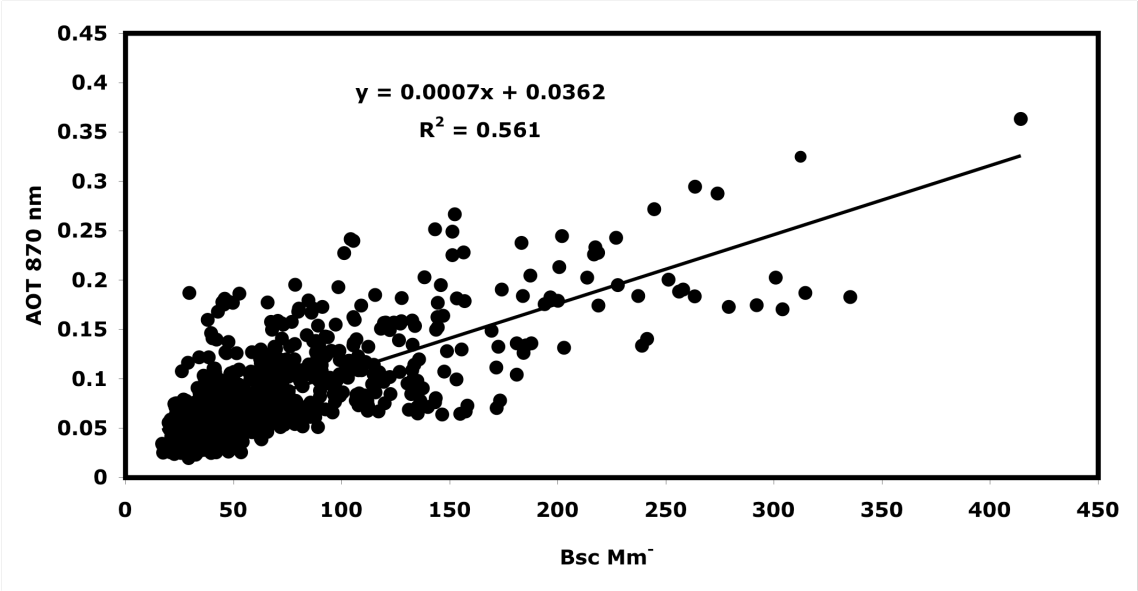
y = 0.0007x + 0.0362
R2 = 0.561
AOT 870 nm
Bsc Mm-
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450

Fig. 3