Take home messages

1. Clouds, clouds, clouds

2. Satellite observations provide a wide range of useful information for understanding particulates role in climate
Particles affect energy balance of the Earth

Kiehl and Trenberth, 1997
Particulate effects on climate depend on the amount and distribution of the particles, but also their physical and optical properties.
Seasonal, regional mean AOD over clear-sky ocean from MODIS

Seasonal, regional mean aerosol radiative effect over clear-sky ocean from MODIS

AOD = aerosol optical depth

DJF  MAM  JJA  SON

Remer & Kaufman 2006
Not all particles are pollution (sea salt, dust).

But we can estimate the pollution portion from the size of the observed particles

\[
\tau_p = \frac{(f - f_d)\tau - (f_m - f_d)\tau_m}{(f_p - f_d)}
\]

Note that not all fine particles are pollution

Yu et al. 2008; Kaufman et al., 2005
Particulate pollution across the Pacific

The radiative effect of these particles will be an anthropogenic forcing on climate

Yu et al 2008
Estimate of total radiative effect of all particles over clear-sky global oceans is -5.5 ±0.5 Wm\(^{-2}\)

Estimate of anthropogenic radiative forcing over clear-sky global oceans is -1.4 ± 0.4 Wm\(^{-2}\)

By the way, the satellite estimates are closer to model estimates for the anthropogenic forcing than for radiative effect.
Particulate pollution over clouds changes forcing from cooling (negative) to warming (positive)

Remer 2009
CALIOP on CALIPSO permits analysis of aerosols above clouds

August 13, 2006 (Night Time)

Chand et al. 2009

Chand et al. 2009
Entire region shows positive effect

Switch to positive effect is a function of cloud fraction

Chand et al., 2009
Global mean clear-sky particle radiative climatic effects are negative \((-5.5 \pm 0.5 \text{ Wm}^{-2}\))

But the total sky effect can be positive (warming)

Only the combination of two satellite sensors: MODIS on Aqua and CALIOP on CALIPSO could provide the quantitative illustration of how widespread this positive effect could be.
Particles affect energy balance of the Earth

Kiehl and Trenberth, 1997
Clouds exert significant radiative effect, much larger than any direct aerosol effect.

But cloud changes are either natural, or a feedback induced by climatic temperature changes.

Unless, an independent forcing agent (particulate pollution) is responsible for the changes to clouds.
We find associations between aerosol and cloud products in the MODIS-derived data sets.

Aerosols are associated with changes in cloud microphysics, cloud cover, cloud height, intensity of convection.

Kaufman et al. (2005)
Koren et al. (2005)
Yuan et al. (submitted Science)

MODIS AOD Time Series

- MODIS AOD
- MODIS AOD Time Series

TRMM–LIS Flash counts

- Lightning

OMI percent increase in 2005

MODIS Multiyear T-PS Profiles

- Crystal Effective Radius (μm)
- Brightness Temperature (K)

Cloud microphysics

Lightning

Ozone
At low AOD, increasing aerosol increases cloud fraction via a microphysical pathway. At high AOD, increasing aerosol decreases cloud fraction via a radiative pathway.

Koren et al. (2008) Science
Here we see change in atmos stability with changes in AOD and clouds.
Conclusions

Clouds… Clouds… CLOUDS! (a highly complex system)

Satellite observations provide:
- a large regional or global perspective (large statistics)
- constraints on ambient particle properties, amounts and distributions.
- insight into associations between particles and clouds, lightning, ozone, and atmospheric stability

Combinations of satellite sensors are more powerful than a single instrument. (Here I showed MODIS, CALIOP, OMI, TRMM and AIRS, but there are many more)