Final Technical Report:

The Radiative Properties of Small Clouds: Multi-Scale Observations and Modeling

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Warm, liquid clouds and their representation in climate models continue to represent one of the most significant unknowns in climate sensitivity and climate change. Our project combines ARM observations, LES modeling, and satellite imagery to characterize shallow clouds and the role of aerosol in modifying their radiative effects.

We are pleased to report major advances on the following aspects of this work:

1. Metrics for the albedo effect

What exactly do metrics for aerosol-cloud interactions represent?

The interaction of aerosols and clouds engenders a large measure of uncertainty in climate sensitivity and climate change. Metrics that quantify these interactions and associated radiative forcing estimates span a range that is too wide to be definitive for climate studies. Our work has argued that a component of this uncertainty derives from the use of a wide range of observational scales and platforms. A common metric used to quantify the first aerosol indirect effect, or albedo effect, is *ACI*, the change in cloud microphysical properties with a change in aerosol concentration. This metric was intended to describe the microphysical processes that are the underlying mechanism for the albedo effect and require inputs from observations made at the "process scale". However, observations from which *ACI* is calculated are often made of bulk properties (e.g., cloud optical depth) over a wide range of resolutions, or "analysis scales." By addressing this scale dependence (see below), this work eliminates some confusion over the existing range of values that have been published and raises the question: what does *ACI* represent? At the core, process level, *ACI* represents the activation process. However, when calculated using bulk properties measured over larger scales (e.g., global-scale satellite products or 1° GCM grid cells) it must, *ipso facto*, include other cloud microphysical processes whose contributions vary from one cloud regime to another (Stevens and Feingold 2009). We argue that many of these values labeled *ACI* are in fact more representative of the full range of aerosol-cloud interactions and their associated feedbacks. Since the albedo effect only attempts to address instantaneous impacts of aerosol on cloud albedo without the complications of feedbacks to cloud fraction or *L*, it becomes particularly hard to justify continued use of empirical measures of *ACI* as a means of assessing the albedo effect over large scales. Instead, the full range of aerosol effects on cloud microphysics should be addressed using process-scale measures of *ACI*, unconstrained by *L*, that have been aggregated to the climate model scale. Moreover, if the measures of *ACI* have been aggregated appropriately then they are more likely to embody causality rather than unphysical correlation induced by large-scale averaging.

2. Scale dependence of the albedo effect

Previous work on quantifying aerosol-cloud interactions raised questions concerning the effects of observational platform and scale (e.g., ground-based versus space-based remote sensing) on analyses of shallow clouds (McComiskey and Feingold 2008; McComiskey et al. 2009). A survey of the literature revealed a scale-dependent bias in the quantity ACI (the change in cloud microphysical properties with a change in aerosol concentration), which is typically used to quantify the cloud-albedo or Twomey Effect and sometimes used in GCM parameterizations. We published a study examining the impacts of observational scale on quantifying ACI using test cases from the WRF model, run in LES mode, AMF data, and MODIS imagery in the region of coastal California and the eastern Pacific Ocean (McComiskey and Feingold 2012). We show that as observations become coarser in resolution, variance in the property being measured is lost. This loss of variance can have an appreciable impact on the statistics that are used to represent ACI. Therefore, maintaining statistics of the variability in the observations becomes more important as coarser resolution measurements are employed. This is especially true when considering the fact that aerosol and cloud properties have different inherent scales of variability and that averaging will have different effects on each, as well as the magnitude of regression slopes between the two. The study identifies two additional factors that compromise accuracy in quantifying the cloud-albedo effect typically occurring with coarse scale modes of analysis and relates these factors to the scale-dependent bias in ACI.

3. Evaluation of aerosol-cloud interactions during the AMF deployment at Graciosa

To continue with these findings we engaged in a comprehensive evaluation of aerosol-cloud interactions at Graciosa during the AMF deployment there, following methodology developed in McComiskey et al. (2009). Together with colleagues, aerosol and cloud properties have been critically examined and collated to a regular time grid to facilitate subsequent analysis. Graciosa offers the possibility of examining different cloud types (cumulus, stratocumulus and stratus) with a comprehensive set of measurements. Our closure analysis shows that a simple parcel model of activation (with surface aerosol, updraft and L observations as constraints) succeed in capturing much of the observed variability in cloud optical depth, even when the boundary layer is decoupled (McComiskey and Feingold ICCP 2012), but closer examination reveals compensation of errors in drop size and drop concentration that enter the optical depth calculation. A complete understanding of the system requires concurrent, consistently accurate closure of each of these variables. We continue to explore sources of both model and measurement error that contribute to this compensation.

4. A methodology for observationally-based assessments of the albedo effect

While point-based measurements such as those at Pt. Reyes or Graciosa provide process-level information needed to understand aerosol-cloud interactions, coarser resolution modes of analysis such as GCMs and satellite imagery are needed to provide a global view. As part of the work addressing scale issues described above, we developed an observationally-based approach to global assessment of the albedo effect. This involves using PDFs that represent the variability of aerosol and cloud properties across coarser scales of observation or a larger model grid cell. We are compiling these PDFs using surface measurements at AMF sites (Pt. Reyes and Graciosa) but they could ultimately be derived from global-scale satellite observations. In the specific case of calculating ACI, a joint PDF between the cloud liquid water and vertical velocity is important for representing the physical processes accurately. Using these PDFs for different regions and cloud regimes, the approach is to (i) statistically sample the joint PDFs; (ii) use the samples as input to a (process-level) cloud model containing the regime-appropriate physics; (iii) based on this model output, generate a set of regional estimates of radiative forcing, from which a global estimate can be derived. These observations would also be a significant contribution to the modeling community for corroborating the statistics produced by models or as parameterizations.

5. Precipitation Susceptibility

The concept of precipitation susceptibility S_o, or the extent to which the rain rate from shallow, liquid-phase clouds is microphysically influenced by aerosol, and therefore drop concentration N_d was first introduced by Feingold and Siebert (2009) and soon after by Sorooshian et al. (2009) Wood et al. (2009) and others. Our recent work under this project addresses an apparent contradiction between the trends in precipitation susceptibility with increasing liquid water path. Two primary responses have emerged: (i) S_o decreases monotonically with increasing L and (ii) S_o increases with L, reaches a maximum, and decreases thereafter. We used a variety of modeling frameworks ranging from box models of (size-resolved) collision-coalescence, to trajectory ensembles based on large eddy simulation to explore the role of time available for collision-coalescence t_c in determining the S_o response. The analysis shows that an increase in t_c shifts the balance of rain production from autoconversion (a N_d-dependent process) to accretion (roughly independent of N_d), all else (e.g., L) equal. Thus with increasing cloud contact time warm rain production becomes progressively less sensitive to aerosol, all else equal. When the time available for collision-coalescence is a limiting factor, S_o increases with increasing L whereas when there is ample time available, S_o decreases with increasing L. The analysis therefore explains the differences between extant studies in terms of an important precipitation-controlling parameter, namely the integrated liquid water history over the course of an air parcel's contact with a cloud.

Impact

1. The scale-oriented work has eliminated confusion over the existing range of values that have been published for ACI and what type of useful information can be inferred from values obtained at each particular range of scales (e.g., airborne in situ observations versus satellite imagery). It will have direct impact on GCMs that use ACI to quantify the albedo effect for IPCC AR5.
2. The clear distinction of scale-dependence provides clarity on what ACI represents. Although it has traditionally been used to represent droplet nucleation, this is only true at small scales. At larger spatiotemporal scales it must include a range of cloud microphysical processes including collision-coalescence, entrainment and sedimentation.
3. Analysis of aerosol and cloud data at Graciosa provides a test of cloud optical depth closure (the ability of a model to replicate observed optical depth).
4. The proposed PDF approach provides an observationally-based approach to assessment of aerosol-cloud forcing that can be used to constrain uncertainty in global estimates and provide important data for evaluation of GCM cloud properties and their variability.

5. The behavior of precipitation susceptibility is a reflection of the relative importance of autoconversion (a drop concentration-dependent process) and accretion (independent of drop concentration) and the research performed here thus provides important information on this balance in different cloud regimes. An understanding of the role of cloud contact time places significant emphasis on the importance of resolving convection and characteristic cloud lifetimes in climate models if treatment of aerosol influences on precipitation is to be improved.

Products directly related to this project

Feingold, G., and A. McComiskey, 2013: Aerosol-Cloud Precipitation Research (Aerosol Indirect Effects), Invited chapter for AMS Monograph celebrating 20 years of the ARM program.

Feingold, G., A. McComiskey, D. Rosenfeld, and A. Sorooshian, 2013: On the relationship between cloud contact time and precipitation susceptibility to aerosol. J. Geophys. Res., in press.

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