Abstract

In a changing climate, clouds are perturbed by large scale changes of the general circulation induced by both the greenhouse gases and the aerosols. Some of the aerosols, however, also perturb cloud microphysical properties. The challenge for today micro- and meso-scale observational studies of perturbed clouds is therefore to establish the links between these two contrasting forcings: to understand how clouds respond to changes in the general circulation in order to quantify how this response might be modulated by changes in their microphysical properties. The two generic classes of micro- to meso-scale observational strategies, the Eulerian column closure and the Lagrangian cloud system evolution approaches are described using examples of low level cloud studies, and recommendations are made on how they should now be combined with large scale information to address this issue.

1. Introduction

There is an apparent paradox in cloud physics: clouds are very diverse, in terms of morphology, depth, cloud base and top heights, horizontal extent, dynamics and microphysics; they have very diverse radiative impacts in term of the balance between their albedo and their greenhouse effects, as well as very diverse dynamical impacts in term of how they contribute to the redistribution of water vapor, sensible, and latent heat in the atmosphere. Cloud spatial and temporal distributions are very heterogeneous, with large regions void of clouds, while others are overcast almost all year long. The lifetimes of cloud systems vary enormously from those that are almost stationary for days to others that are fleeting. Nevertheless, and herein lies the paradox, together they manage to maintain a fairly constant Earth albedo close to 0.3, and a fairly constant balance between their albedo and greenhouse contributions to the climate system.

Such a large-scale equilibrium would call for observational approaches starting from the global scale down to the microscale to first capture the processes responsible for the regulation of the hydrological cycle. In contrast, most observational studies of clouds to date have focused on the microscale up to the mesoscale. Such studies have been our fundamental tools for constructing, from the bottom-up, the current cloud models we use to simulate the climate system, but model comparison exercises, such as in the IPCC, clearly show that some key feedback processes are still poorly accounted for. Moreover, while the models predict a mean cloud radiative forcing in agreement with observations, they also exhibit noticeable biases, with a consistent over-prediction of optically thick clouds and an under-prediction of optically thin low and middle-top clouds (Zhang et al., 2005). This led to the conclusion that differences in cloud response are the primary source of inter-model differences in climate sensitivity (AR4, Sec. 8.6.2.3).

Better understanding of how clouds react to anthropogenic forcings is therefore a priority for improving the accuracy of climate change projections. Anthropogenic forcings, however, can produce
very diverse impacts on the general circulation. The greenhouse gases have a long residence time (century) and are homogeneously distributed. Anthropogenic aerosols in contrast have a short residence time (weeks) and consequently, their spatial distribution is heterogeneous, mainly concentrated at the vicinity of the sources. Greenhouse gases interact primarily with the longwave radiation. The net radiative impact of aerosols in contrast depends on their chemical composition, and the balance between their light scattering and absorbing contributions. Impacts of greenhouse gases on clouds can therefore be explored from a global perspective to examine for instance how the increase in the column water vapor might be compensated by a damping of the convective mass flux to reduce the fractional increase in precipitation (Held and Soden 2006). In contrast, aerosol impacts must also be considered at the regional scale, where they are concentrated. The hypothesized “Elevated Heat Pump” effect (Lau et al. 2006), is an example of a plausible, but currently unverified, regional scale aerosol effect which may impact the Indian monsoon at the Himalaya foothills.

This perspective suggests that anthropogenic forcings might only perturb clouds by modifying the general circulation, i.e. from the global scale down to the cloud scale. However, aerosols also impact cloud microphysics, since some act as droplet or ice crystal nuclei. Such microphysical changes can propagate up to the cloud scale. The first order response to changing nucleus concentration is an effect upon the cloud albedo by changing the surface area of the droplets, but feedbacks on cloud-scale dynamics must also be considered to fully understand the response. By modifying cloud microphysical and optical properties, aerosol thus perturb clouds not only from the global scale down, via their direct and semi-direct effect, but also from the micro-scale up (the aerosol indirect effects). Parameterizations of these processes in GCM are very crude, partly because they involve nonlinear processes at scales that are not accessible to such models, but also because our knowledge of the various feedbacks of cloud microphysics on cloud dynamics is still limited. For example, high resolution cloud models suggest that the aerosol impacts result in non-trivial effects, inducing either a decrease or an increase of the cloud liquid water path (LWP) with the sign of the response depending upon poorly understood factors. Hence, the aerosol impacts on clouds remain the most uncertain of the climate forcings in term of efficacy (IPCC-AR4, Fig. 2.19).

To improve climate change projections, it is thus crucial to understand how climate change might impact the spatio-temporal distribution, hence radiative forcing of clouds (from the global scale down). But we also have to find out if clouds only respond to changes in the large scale dynamical forcings, or if microphysical processes might also modulate their response, thereby impacting the hydrological cycle and the general circulation, i.e. from the bottom up.

Because of the very large range of scales involved however, it has been difficult to connect the large scale observational studies of the hydrological cycle with the micro- and mesoscale observations of cloud physics. Here, using examples from existing and future field studies, we will show how effective the micro to mesoscale approach was for understanding cloud dynamics and microphysics, but also suggest that it now needs to evolve to progressively larger scales. This mandates a greater degree of multidisciplinarity in the design of future observational studies in order to clarify the interactions between aerosol physics and chemistry, small-scale turbulent dynamics, radiation, and the hydrological cycle at the global scale.

2. The Ingredients of an Observational Strategy

To begin to determine the magnitudes of the aforementioned potential cloud perturbations, the overall objective of the observational approach must be to quantify the respective susceptibilities of cloudiness, or more specifically cloud radiative properties, \( \delta c \) to changes in the general circulation and to internal microphysical changes induced by the aerosol. This has been laid out in Stevens and Brenguier (this issue) as:

\[
\delta c = \left( \frac{\partial c}{\partial M} \right)_A \left( \frac{\partial M}{\partial A} \right)_G \delta A + \left( \frac{\partial M}{\partial G} \right)_A \delta G + \left( \frac{\partial c}{\partial A} \right)_M \delta A
\]

[1]

where \( c \) represents cloudiness, \( M \) is the large-scale meteorology, \( G \) are the greenhouse gases and \( A \) the aerosols. \( A_\mu \) specifically refers to the subset of the aerosols that may impact cloud microphysical
properties, namely cloud and ice condensation nuclei (CCN, IN) and absorbing aerosol particles scavenged in hydrometeors.

The term in the braces is the large scale meteorological forcing $\delta M$ related to the aerosol and greenhouse gases forcings, both of which are the result of integrated radiative forcings on large spatial scales. Thus, from [1] we can write cloud perturbations

$$\delta c = \left( \frac{\partial c}{\partial A_\mu} \right)_M \delta A_\mu + \left( \frac{\partial c}{\partial M} \right)_A \delta M$$

and

$$\delta c = \lambda_{A_\mu} \delta A_\mu + \lambda_M \delta M$$

where $\lambda_{A_\mu}$ and $\lambda_M$ are the sensitivities (susceptibilities) of clouds to perturbations in $A_\mu$ and $M$ respectively.

In designing a strategy for an observational program to assess the impacts of aerosols upon clouds, it is essential therefore to ask whether variability in observed cloud radiative properties $\delta c$ will be dominated by variability in aerosols or by the varying meteorological forcing. Equation [2] clearly shows that in order to determine, using observations, the sensitivity of clouds to aerosol perturbations $\lambda_{A_\mu}$ we must first understand the impacts of meteorology upon the cloud system, as expressed by $\lambda_M$.

The meteorological sensitivity $\lambda_M$ is poorly known in many cases, and so it is a major challenge to use observations to determine it. For marine stratocumulus clouds, there has been considerable success in relating cloud properties (e.g. cloud fractional coverage) to the large scale meteorology using observations (e.g. Klein and Hartmann 1993, Klein et al. 1995, Wood and Bretherton 2006). As is demonstrated in Stevens and Brenguier (this issue), the meteorological sensitivity is very high in many cases, which will limit our ability to attribute perturbations in clouds to those in aerosols.

We can further quantify the uncertainties in determining the sensitivity to aerosols by considering the variability across a set of measurements that would be made in a particular observational campaign. If we define $\sigma^2_x$ as the observed variance in parameter $x$ across this set of measurements, then equation [2] can be used to show that

$$\sigma^2_c = \lambda_{A_\mu}^2 \sigma^2_{A_\mu} + \lambda_M^2 \sigma^2_M + 2 \lambda_{A_\mu} \lambda_M \sigma_{A_\mu} \sigma_M r,$$

where $r$ is the correlation coefficient between the $A_\mu$ and $M$. Equation [3] tells us that not only do we need to understand the meteorological variability and its impact on the clouds, but we also need to understand to what extent the meteorological variability covaries with the aerosol variability. In other words, even accounting for the meteorological variability in a dataset (i.e. the second term in [3], through knowledge of $\lambda_M$) is insufficient to determine fully the aerosol sensitivity without understanding how the aerosol properties are tied to the large scale flow. Note also that such a formulation that assumes a one way cause and effect relationship, at least on short time scales, between aerosols and clouds is a simplistic representation of a tightly coupled system in which clouds and aerosols interact at all scales. For instance, clouds can significantly impact aerosols via scavenging by precipitation, hence contributing to the covariance between aerosol and the meteorology. These mutual interactions raise serious concerns about the numerous and contrasting satellite studies showing correlations between aerosols and clouds that are generally interpreted as evidence of aerosols impacting clouds, while in fact the opposite may be true.

To optimize the chances of detecting an aerosol signal in the backdrop meteorological noise, the first step is therefore to select a place where the variability of the aerosol is significant, while the variability of the meteorology is minimized. The covariance between the two, however, sets a limit to this strategy when reducing the meteorological variability (by selecting specific weather situations for instance), necessarily reduces the aerosol one. The Second Aerosol Characterization Experiment (ACE-2), which took place in the North-Atlantic in June 1997, illustrates this impediment. Within ACE-2, the Cloudy-Column experiment was designed to test the Twomey hypothesis, namely that the cloud optical thickness $\tau$ scales with the liquid water path $W$ and the droplet number concentration $N$
as $\tau \propto W^{5/6} N^{1/3}$. The ocean, north of the Canary Islands, offers opportunities to sample air masses flowing around the Azores high that are generally pristine, except when they skim along the European continent where they are polluted by anthropogenic aerosol. Droplet concentrations observed during the eight case studies ranged from less than 50 cm\(^{-3}\) in pristine air masses up to more than 250 cm\(^{-3}\) in the most polluted ones, i.e. a factor of five, while the LWP ranged from 33 g m\(^{-2}\) to 77 g m\(^{-2}\), i.e. a factor of only two. Such a gap between the aerosol and the LWP variability allowed to precisely validate the Twomey hypothesis (see Sec. 3.1.4 hereafter), but the data set didn’t provide any evidence of an aerosol impact on the cloud life cycle. Indeed, aerosol and meteorology were closely correlated because polluted air masses had flown over the continent, hence had experienced greater sensible and lower latent heat fluxes than the pristine oceanic air masses. Overall, the most polluted cases exhibited thinner LWP than their pristine counterpart (Brenguier et al., 2003), and it was not feasible to determine if clouds were thinner because of the reduced latent heat fluxes two days ahead over the continent, because of direct or semi direct aerosol effects on the air mass when it moved over the ocean, from the continent to the sampling area, or because of an indirect aerosol effect on the cloud layer.

Similarly attempts were made to examine the climatology of precipitation downwind of big cities such as Saint-Louis (Changnon et al., 1971), but careful analysis of the observations with a detailed numerical model indicated that urban land-use forced convergence downwind of the city, rather than the presence of greater aerosol concentrations, is the dominant control on the locations and amounts of precipitation in the vicinity of an urban complex (van den Heever and Cotton 2008).

An attractive alternative approach is to select situations were aerosol and meteorological variations are uncorrelated, which has been the basis of weather modification control experiments over many years. Accidental biomass burning events offer such opportunities, but they are generally not frequent enough to build significant statistics. To improve the statistics, week-end effects have been examined climatologically (Forster and Solomon, 2003; Gong et al., 2006). A detectable weekly cycle of the diurnal temperature range has been evidenced, as well as the anthropogenic origin of this cycle, but a potential aerosol effect on clouds has not been demonstrated because of other atmospheric parameter changes (e.g. heat island effect) that are also correlated to the weekly cycle of anthropogenic activities. The identification of situations where aerosol variability is uncorrelated with meteorology thus remains open.

For shallow clouds, the issue of sensitivity is particularly acute. Indeed, their liquid water content is typically a few hundredths of the total water content. That explains why deriving their LWP and its temporal evolution from field observations of the thermodynamic fields (i.e. temperature and water vapor) remains beyond our grasp. The magnitude of the energy fluxes that govern the evolution of a cloud-topped boundary layer (CTBL), such as surface fluxes including precipitation, cloud top entrainment, and the flux divergences of SW and LW radiation ($\lambda_{\text{d}}$) are comparable in magnitude to their potential modulation by the aerosol for example by suppressing precipitation ($\lambda_{\text{A}}$). The susceptibility of marine stratocumulus clouds to aerosol is therefore noticeable, as demonstrated by ship tracks.

Quantifying the susceptibilities of marine stratocumulus clouds to the meteorology and to the aerosol, respectively, is a challenge in the sense that small perturbations of the boundary layer state parameters need to be precisely measured. What facilitates the observation of these clouds, however, is their long synoptic life time (although of course, the cloud element lifetime is only a few minutes), large spatial extension, relative statistical homogeneity at the mesoscale, and their reproducible diurnal cycle.

Beyond the susceptibilities, additional ingredients shall also be carefully evaluated for designing a field experiment. They include the spatial and temporal scales of interest, and the identification of all physical processes that may interfere with the observations. Here we describe two basic categories of observational approach that are particularly useful for the study of the interactions between marine stratocumulus clouds and their environment. The principles involved are, however, applicable to other cloud systems.
3. Eulerian versus Lagrangian

3.1 Closure experiments

Closure experiments aim to measure the consistency of the atmospheric state parameters with respect to models of the underlying physical processes. The methodology consists of measuring input parameters to initialize a model and derive output parameters, and concomitantly measure the control parameters for comparison with model predictions. As an example, we will describe here the observational strategy of the ACE-2 Cloudy-Column experiment (Brenguier et al. 2000a), which was the first field study entirely dedicated to the aerosol indirect effects in extended boundary layer cloud systems. The hypotheses to be tested can be summarized in the form of three key questions: (a) for specified cloud fields, is the droplet concentration consistent with the predictions of aerosol activation models? (b) do cloud radiative properties vary with the droplet concentration as anticipated by Twomey (1977)? (c) for a particular value of LWP, is the precipitation rate modulated by the droplet concentration?

3.1.1 Temporal and spatial scales

Sampling a single convective cell during its vertical ascent and measuring aerosol properties, vertical velocity and cloud droplet concentration to examine CCN activation is not feasible with existing airborne platforms. Radiative transfer also raises serious difficulties for single cells because it is three dimensional in essence, and measurements of irradiance performed from above a single convective cell will necessarily be affected by radiation from neighboring cells. Finally, the cycle of precipitation formation in a single convective cell is short (a few tens of minutes) resulting in very heterogeneous drizzle patches below cloud base.

An alternative strategy is to examine the phenomenon at a larger scale at which aerosol properties, turbulence, cloud microphysics and precipitation are statistically homogeneous (ergodic), and the three dimensional heterogeneities of the radiation and precipitation fields are smoothed over a large number of cells. Such conditions are often satisfied in boundary layer marine stratocumulus clouds at a scale of a few tens of kilometers.

3.1.2 Aerosol activation closure

This experiment aims to evaluate 0-D kinetic models of CCN activation for prediction of the cloud droplet concentration (control parameter) from the vertical velocity at cloud base and the physico-chemical properties of the aerosol (input parameters) (Guibert et al., 2003; Snider et al., 2003).

Being unable to perform a closure experiment on individual CCN activation events implies that a statistical approach to the problem must be adopted, which necessarily must encompass the spatial variability of the system being studied. Aerosol properties can, far from the aerosol sources, be reasonably assumed to be uniform over the area and the duration of the experiment. The vertical velocity, on the other hand, varies from a few cm s\(^{-1}\) up to more than 1 m s\(^{-1}\) in the most active cells. The comparison thus involves the pdf of measured droplet concentration and its comparison with the predictions of a CCN activation model initialized with the full spectrum of measured vertical velocities. Fig.1 shows the comparison of the deciles of the measured droplet concentration pdf, with the predictions of the model initialized successively with the deciles of
the measured vertical velocity distribution. This figure reveals that the range of concentration variability resulting from vertical velocity fluctuations is broader than the difference between the mean values of a pristine and a polluted case.

Therefore, a closure experiment on CCN activation will not be conclusive if the vertical velocity is not fully constrained by observations. A consistent definition of the cloud droplet concentration used here as a control parameter is also crucial. In fact, the droplet concentration that is measured in a cloud system is different from the one resulting from CCN activation, even though both are tightly related. After CCN activation is completed, additional processes, such as mixing with the environmental dry air and scavenging by precipitation, significantly dilute the droplet concentration. It is thus sensible to select, for the comparison with a CCN activation model prediction, only droplet concentration samples that are not affected by either mixing or precipitation scavenging. In ACE-2, for instance, the droplet concentration after selection was typically 30% higher than the average over all the samples (Pawlowska and Brenguier, 2000).

The main limitation of this closure experiment was the incomplete characterization of the size segregated chemical composition of the aerosols, which introduces uncertainties in the prediction of their hygroscopic properties. Since the development of airborne mass spectrometers and improved chemical analysis, the activation closure has been significantly refined (Conant et al. 2004, Fountoukis et al. 2007). However, further work needs to be done to characterize the mass accommodation coefficient for small growing aerosols, and instruments need to be designed to characterize the degree of internal vs external aerosol mixing.

3.1.3 Column closure on radiative transfer

This type of experiment aims to corroborate the Twomey hypothesis, i.e. that aerosol induced microphysical changes are reflected by changes of cloud radiative properties. The input parameter measured in situ is the vertical distribution and horizontal variability of the cloud droplet size distribution and the output parameter is the optical thickness of the cloud layer, derived as the vertical integral of extinction. The control parameter is the optical thickness derived independently from multispectral radiances measured with a second aircraft flying above the cloud layer.

In ACE-2, the statistics of all input parameters were very robust because of the long duration of sampling with two collocated aircraft, one dedicated to the microphysical fields and the second one to radiation. It thus provided the first observational evidence of the Twomey effect in extended cloud systems, e.g. the scaling of the optical thickness with LWP and droplet concentration as anticipated by Twomey (see figure 6 in Brenguier et al. 2000b). One serious limitation though was that in-situ airborne measurements do not provide information on how the microphysical fields sampled at various levels overlap in the vertical. The optical thickness used as the output parameter was derived by assuming either random or maximum overlap of the microphysical fields measured in situ. The accuracy of the prediction was thus significantly degraded by the overlap uncertainty. Since ACE-2, other closure experiments have been performed using remote sensing systems that better constrain the vertical organization of the microphysical fields (Feingold et al., 2003).

An alternative approach to radiative closure is to validate the same radiative transfer model, but in the inverse mode. Indeed inverse models are currently used to derive cloud properties from space measurements of multispectral radiances (Nakajima and King, 1990). In this approach, the radiance measurements are used to derive cloud geometrical thickness or LWP and droplet concentration, which are then compared to the ones measured in situ (Schüller et al., 2003).

3.1.4 Column closure on precipitation

This experiment contributes to the improvement of precipitation formation parameterization in GCMs. Recent field studies suggested that the precipitation rate of stratocumulus clouds, averaged over a large domain containing numerous cloud cells, scales with the mean cloud thickness or LWP and the typical droplet concentration: ACE-2 (Pawlowska and Brenguier 2003), EPIC (Comstock et al., 2004; Wood, 2005), and DYCOMS-II (VanZanten et al. 2005). The nature of such relationship is a major determinant of the magnitude of the second aerosol indirect effect. LES simulations are thus used to corroborate these observations and better quantify the empirical relationship.
Fig. 2: (a) Cloud base precipitation rates $R_{\text{CB}}$ from observational case studies in subtropical marine stratocumulus, plotted against $h^3/N_d$, where $h$ is the cloud thickness and $N_d$ the droplet concentration. The lines represent linear least-distance regressions to the case studies for each field campaign.

Comparison of model predictions (small triangles) with scaling laws derived from:

(b) ACE2 (large triangles): Precipitation rate $\langle R \rangle$ averaged over the cloud layer, cloud thickness $H_g$ derived from in situ measurements and droplet concentration $N_{\text{act}}$ derived from samples not affected by mixing or droplet scavenging.

(c) EPIC (squares): Precipitation rate at cloud base $\langle R_{\text{base}} \rangle$, LWP, and mean droplet concentration $N_c$ derived from surface remote sensing.

(d) DYCOMS-II (circles): Precipitation rate at cloud base $\langle R_{\text{base}} \rangle$ and cloud thickness $\langle H \rangle$ derived from remote sensing and mean droplet concentration $N_c$, derived from in situ measurements.

The observations are summarized in Fig. 2a. For each field campaign the precipitation rate at cloud base scales well with the cloud thickness and the cloud droplet concentration. However, each dataset appears to have offsets that mainly reflect measurement biases and differences in the methodology: precipitation rate averaged over the cloud layer (ACE-2) or at cloud base only (EPIC and DYCOMS-2), droplet concentration measured in cloud samples that are not affected by mixing or precipitation scavenging (ACE2), averaged over the cloud layer (DYCOMS-II), or extrapolated from remote sensing (EPIC), cloud thickness derived from detection of cloud base and top (ACE-2 and DYCOMS-II) or derived from remote sensing of the LWP (EPIC). These discrepancies reveal how sensitive the results can be to the definition of the physical parameters derived from diverse sources.
measurement and data processing techniques. The results also demonstrate just how sensitive the precipitation rate is to cloud macrophysical properties, with a doubling of precipitation requiring only a change of ~100 m in cloud thickness. This emphasizes the importance of controlling for meteorological variability when examining microphysical impacts.

Numerical simulations of similar cloud systems were performed with an LES model over a broad range of LWP and CCN concentration values to explore the parameter space of the measurements (Geoffroy et al., 2008). Figure 2(b-d) show the comparison of the model results with the measurements, using the same parameters and scaling laws as in each field campaign, respectively. The similarity between observations from three different areas and the results of numerical simulation suggests that the large scale relationship between LWP, droplet concentration and the precipitation rate at cloud base is robust.

3.1.5 Summary and recommendations

These three examples illustrate different types of closure experiments. Each type has clearly testable hypotheses. When the model is straightforward, like the 0-D model of CCN activation, the closure experiment closely follows the basic methodology: measured input parameters, numerical simulations, comparison of model predictions with the control parameter. In the second example, the distinction between input and control parameters is less obvious, depending on whether the model is used in the direct or in the inverse mode, such as for satellite 1-D retrieval techniques. Finally, the third example, with the 3-D model of stratocumulus clouds suggests how the technique can be extrapolated to the comparison of relationships between specified physical parameters that have been observed and further simulated with a model over the same parameter space. All, however, have in common some methodological rules which are generally not given sufficient attention in most of the closure studies. These are:

(i) Models need to be fully constrained: All parameters that might impact the prediction of the model to be tested shall be documented with an accuracy consistent with their impact (as for example for the vertical velocity in Sec. 3.1.4).

(ii) Ensure consistency in the definition of the measured and modeled parameters. The measured and model values of a parameter must be defined over the same spatial and temporal scales. For example, the droplet concentration will exhibit significant differences depending upon whether it is defined as the mean value over a cloud system or the value specifically measured in regions of CCN activation.

(iii) Redundancy in measurements is highly desirable: Single validation experiments often succeed, while redundant controls are more difficult to reconcile but allow for a higher degree of confidence. For the closure to be robust, attempts shall be made to combine redundant closures of the same process, such as combining a CCN activation spectrum and a droplet activation closures on the same data set Snider et al. (2003), or radiation closures on both transmitted and reflected light in the same cloud system (Platnick, 2000).

In general, dynamic, thermodynamic and microphysical properties all exhibit important variability and covariability on the kilometer scale (i.e. scales smaller than a typical climate model gridbox) and this variability has marked impacts upon how aerosol-cloud interaction affects the large scale properties of clouds. It is important to design a sampling strategy that further allow us to characterize these important subgrid statistical connections between variables (e.g. Illingworth and Bony, this issue; Larson et al. 2001, 2002). For instance airborne measurements in clouds are often optimized by targeting cloud cells along the flight track, but such an approach introduces a bias in the data base (overestimated cloud fraction). It is thus crucial to either adopt unbiased sampling or provide additional information to unbias the data base.

Column closure experiments are useful to validate models of physical processes and their parameterizations for general circulation models, as long as the processes have reached a steady state. They are not suited, however, for studies of the temporal evolution of the system, which call for a different approach.
3.2 Lagrangian experiments: Linking small and large scales

3.2.1 The Lagrangian Concept

The temporal and spatial scales over which cloud fields evolve and interact with the general circulation in which they are embedded are typically days and thousands of kilometers. Scales involved in the general circulation exceed those accessible to single aircraft flights, and seriously limit our ability to understand the two-way interactions between microscale processes and the general circulation.

This need to observe the evolution of meteorological fields and the processes that influence their development over long timescales led to the development of the Lagrangian observational concept, which seeks to make quasi-continuous observations of an airmass (ideally over several days although as we shall see there are considerable benefits even from flights lasting only a few hours) often by employing multiple observing platforms which overlap in time. The Lagrangian observational approach aims to study processes within a frame of reference that moves with the air, an approach necessary to study time-evolving processes in the atmosphere without resorting to making assumptions about poorly-constrained advective processes.

Despite the high costs associated with fully realizing the potential of the Lagrangian approach using in-situ aircraft observations, a number of such observational studies have been conducted over the last few decades. These studies have yielded a tremendously rich understanding of a wide variety of different processes as we discuss below.

3.2.2 Lagrangian boundary layer and cloud evolution

Lagrangian sampling of cloud-related processes on timescales of a day or more has primarily focused upon the marine boundary layer (MBL) because many of the key processes relevant to climate occur there, and because the logistics associated with conducting a Lagrangian study in the lowest level are simpler (not the least of which is the presence of a solid boundary at the base of the airmass). Although earlier Lagrangian studies had been carried out that involved balloons and tracers, the first multi-flight Lagrangian experiments devoted to understanding cloud processes were carried out during the Atlantic Stratocumulus Transition Experiment/Marine Aerosol and Gas Experiment (ASTEX/MAGE) during June 1992 (Albrecht et al. 1995, Businger et al. 2006). Two such studies were carried out, each for a period of 36-48 hours (~800 km of spatial advection). During these studies constant-density balloons floated downwind with the airmass and radioed their GPS-derived locations to a relay of three sampling aircraft. The balloons served as markers for the boundary layer airmass, which was continually being modified by chemical and energy fluxes at the surface, entrainment of free tropospheric air, wind shear within the boundary layer, horizontal dispersion, chemical reactions, and aerosol transformations. Here we will focus upon those aspects most pertinent to clouds.

The ASTEX/MAGE Lagrangian experiments were revolutionary for a number of reasons. By continuous sampling of the MBL over a period approaching two days, it was possible to make observations of the transition from a shallow, well-mixed stratocumulus-capped MBL to a much deeper decoupled MBL containing trade cumuli of less extensive coverage (Bretherton and Pincus 1995). Such air mass transitions are a critical component of the transition from the subtropical to the tropical MBL, and the physical mechanism by which the MBL undergoes this transition was deduced directly as a result of the Lagrangian observations. Previous hypotheses for the transition followed ideas based upon the work on diurnally-modulated decoupling of the boundary layer that had been carried out at fixed locations. The ASTEX Lagrangian data were able to demonstrate that although decoupling of the MBL is a key process in the transition, it is actually the increasing latent heat flux as the airmass moves over warmer water, rather than solar radiation, which is the key driver of the subtropical transition (Bretherton and Wyant 1997).
Figure 3: Flight tracks (top panel) for third Lagrangian experiment of ACE-2 (Wood et al. 2000) which sampled a polluted continental outbreak heading southward over the northeast subtropical Atlantic Ocean. Also shown in colors are back trajectories, estimated using ECMWF analyses, ending at different altitudes at the location of the start of the sampling. The three-flights allow us to build up a picture of the changing structure of the lowest 2 km of the atmosphere, the essence of which is detailed schematically (bottom panel). Reproduced from figures originally presented in Wood et al. (2000).
3.2.3 **Lagrangian entrainment rate estimates**

A second novel aspect of Lagrangian studies is the ability to derive direct estimates of the rate of MBL deepening, and thus the entrainment rate. It is now widely appreciated just how important the entrainment rate is, not only for its physical impacts upon the MBL thermodynamic and cloud climatology (Stevens 2002), but also because entrainment is a critical mediator of the response of cloud field to perturbations in atmospheric aerosols (Ackerman et al. 2004). Because microphysically induced changes (e.g. suppression of drizzle) impact the entrainment rate by changing the MBL turbulent structure, this introduces much longer timescales than the Twomey effect (Wood, 2007) which cannot be quantified observationally using measurements from fixed locations.

ASTEX allowed Lagrangian estimates of the entrainment rate over the two days of study (Bretherton et al. 1995). Recent studies have employed the Lagrangian technique using flight durations of only a few hours. For example, in DYCOMS-II (Stevens et al. 2003), single 6-hour Lagrangian flights using a C-130 aircraft were used to determine the entrainment rate by determining the observed rate of boundary layer deepening and subtracting the subsidence rate from reanalysis data (Faloona et al. 2005). This was then compared with the entrainment rate estimated using the standard flux-jump method to provide a closure on the time evolution of the entrainment rate that can be used to constrain model ability to correctly represent the entrainment process.

3.2.4 **Aerosol-cloud-chemistry interactions using Lagrangians**

Although aerosol indirect effects were not a specific focus of the ASTEX Lagrangians, the aerosol and gas phase chemistry measurements taken as part of the MAGE component of the campaign provided the first concrete demonstration of the benefits that the Lagrangian observational concept could bring to our understanding of chemical process rates in the atmosphere (Zhuang and Huebert 1996, Clarke et al. 1996), a need that had been identified since the early 1970s. It may be argued that the development of the sampling concept for the early Lagrangian studies led to the realization that aerosol particles and their precursors are themselves a fundamental component of the atmospheric general circulation, which thereby provides further possibilities for interactions between these scales that were not previously appreciated.

Lagrangian experiments that focused specifically upon aerosols and aerosol precursors were conducted as part of the First and Second Aerosol Characterization Experiments (ACE-1, ACE-2) in 1995 and 1997 respectively (Bates et al. 1998, Johnson et al. 2000) and provided a wealth of data on the coupling between aerosols, aerosol precursors, clouds, and the MBL, in both pristine and polluted MBLs. From the ACE-2 Lagrangian studies it has been possible to assemble a conceptual model for continental pollution outbreaks that serves as an invaluable basis for the planning of future sampling of the modified continental plume. Timescale analysis applied to the ACE-2 Lagrangian datasets (Hoell et al. 2000) demonstrated the importance of meteorological factors (e.g. dilution) in controlling the properties of aerosols in the MBL. The example from the third Lagrangian experiment during ACE-2 shown in Fig. 3, demonstrates the ability of Lagrangian experiments to connect microscale and mesoscale characteristics with those of the large scale flow.

3.2.5 **A strategy for future Lagrangian experiments**

The Lagrangian experiments carried out to date, whilst providing invaluable information about airmass transformations and the physical and chemical processes within them, have not yet reached their full potential as important strategies for determining how clouds will change in a perturbed climate.

(i) **Sampling limitations.** Lagrangian studies to date have sampled with one aircraft at any one time, whereas the state-of-the-art observational now use multiple aircraft (see e.g. column closure experiments above) in order to link the aerosol, thermodynamic and dynamic properties of the atmosphere measured in-situ with the column cloud radiative properties remotely sensed from above. Adopting this strategy within a Lagrangian experiment would be very powerful, especially if scanning radiometers can be used to broaden the measurements to be representative of an area. Moreover nadir-pointing remote sensing
systems (Damiani et al., 2006) provide crucial information on how the microphysical fields that are sampled horizontally by in situ aircraft overlap in the vertical.

(ii) **New sampling techniques.** Beyond piloted aircraft, new vectors are becoming available for in situ sampling of boundary layer clouds at low speed. UAV have a typical sampling speed of 30 m/s and they can now fly autonomously a predefined track (Ramanathan et al., 2007). Blimps have been used in the past, and new ones, such as the Zeppelin, might be used for Lagrangian studies, although logistics remain a serious obstacle in using blimps.

(iii) **Interdisciplinary spirit.** In order to fully characterize the evolution of the cloud layer, it is important to have a detailed characterization of all the potential factors controlling it, including the large scale meteorology, the surface and MBL top boundary conditions (both physical and chemical), in addition to the cloud microphysical, thermodynamic and turbulent information. This is a tall order for a single platform, but can be achieved provided that there is good interdisciplinary dialogue and pathways to funding support. The forthcoming EUCAARI and VOCALS experiments provide good examples of the possible connections that can be made between research communities (oceanography, atmospheric chemistry, cloud physics, and climate dynamics).

(iv) **Synergy between models and observation.** The most serious obstacle in the characterization of a boundary layer, is our inability to measure the thermodynamic conservative variables (total heat and moisture), and their budgets with an accuracy sufficient to constrain the resulting LWP. LES models which can simulate the evolution of a boundary layer, however, also suggest observable signatures of the mechanisms that drive its evolution. For instance, Sandu et al. (2008) showed that the impacts of the aerosol on the diurnal cycle of stratocumulus clouds shall be reflected by observable differences in the vertical velocity variance at cloud top, in the vertical profile of liquid water content, and in the level of turbulent kinetic energy below cloud base.

(v) **Complementary information.** With the current generation of satellite remote sensing, there is a tremendous amount of additional information that can be added from space to multi-day Lagrangian studies. Geostationary satellites, especially those with high resolution (1 km), multi-channel and high sampling frequency (15 min for SEVIRI on MSG) spectrometers can provide cloud microphysical, aerosol, and cloud top temperature information. Polar orbiting satellites with active remote sensing such as in the A-Train provide additional information, at least once a day, to better calibrate geostationary satellite observations. Promising techniques appear to derive accurate temperature, humidity and boundary layer depth information from spaceborne GPS limb sounding. A reanalysis focused upon clouds, aerosols, and the boundary layer will be an excellent way to incorporate the satellite information into a useable framework (see section 4.1 below). High resolution numerical modeling could be calibrated using the in-situ data and then used to “fill in the gaps” in rather the same way that assimilation is used in the NWP community.

In addition, aircraft observations do not provide complete information about the large-scale dynamical fields, leaving key variables such as the large-scale vertical motion field completely unknown. These fields are critically important to understanding the interactions between the small and large scales and allow a top-down assessment of the entrainment rate that can be compared with bottom-up measurements carried out by integrating over many turbulent eddies. This is currently carried out by using standard reanalysis products, but these are not generally produced with a focus upon the needs of the cloud-climate community at their heart.

4. General Recommendations and Conclusions

Understanding how clouds respond to a changing climate necessitates carefully-designed micro and mesoscale observational experiments. We have attempted to demonstrate, by giving examples, that it is a very challenging task to separate the impacts of variability in large-scale meteorology from those caused by changes in aerosol physical and chemical properties. This is because cloud and
precipitation formation is sensitive to both changes in the large-scale forcings and to microphysical aerosol induced impacts. Moreover, not only the instantaneous relationships between microphysical and macrophysical variables, but also the temporal evolution of the fields has to be documented. There is thus an important need to put the observed microphysical changes in perspective with the effects of the large scale meteorological variability.

4.1 Need for better connection between small and large scales

Acquiring a better understanding of interactions between mesoscale/microscale processes and the large scale flow requires the provision of accurate boundary conditions for mesoscale/microscale studies. In recent years this has been achieved using large scale meteorological data from reanalysis datasets (e.g. Kistler et al. 2001, Uppala et al. 2005) which have proven extremely useful because they provide gridded data at regular temporal intervals everywhere in the atmosphere.

Current reanalyses place a high value upon creating datasets that are homogeneous over a long period of time (40 years), hence preventing the use of the most advanced, but computationally expensive models, as well as limiting assimilation to data that are available over the whole reanalysis period, or at least relatively lengthy fractions of it. Aerosol processes for instance are not represented at all in current reanalyses, but given the recent advances to our observing system, this would be possible. We argue that the “one-size-fits-all” approach is not optimized to address the cloud-climate problem. Indeed, we believe that focused reanalysis systems that target key processes and assimilate new datasets, would be of major benefit to the observational community. These would not necessarily be global, but could instead be run over much smaller spatial and temporal domains at higher resolution. The regional reanalysis (e.g. the North American Regional Reanalysis) is a move in this direction, but a move towards physical process specialization in addition to geographical specialization would be beneficial. An assimilation system that focuses upon the lower troposphere including the boundary layer would greatly benefit our understanding of low cloud systems, and their relationship with large-scale meteorological and aerosol forcings.

To make the best of improved boundary conditions, the instrumental setup shall be designed to connect the meso to the microscale, relying on a combination of large scale, though limited and discontinuous sampling with instrumented aircraft, and surface (either ground or ship) stations that provide continuous sampling of the atmosphere flowing above the site.

4.2 Need for consistent multidisciplinary approaches

Clouds are perturbed in their dynamics, microphysics and radiative properties. Field experiments dedicated to this challenging issue must therefore be designed with an instrumental setup that permits the documentation of each source of perturbation and each effect with accuracies consistent with their anticipated contribution or level of response to the forcings. New airborne instruments are now available to document crucial parameters such as the size-segregated chemical composition of the aerosol. Considerable progress has been made to overcome the sampling limitation of instrumented aircraft by using airborne active remote sensing systems that provide crucial information about the vertical organization of the cloud systems sampled horizontally by the aircraft (e.g. Damiani et al., 2006). We argue that instead of running numerous separate partial studies that do not bound enough all the critical atmospheric parameters, the effort shall be concentrated on large scale multidisciplinary and multiplatform projects.

4.3 Detailed planning

Most of the surface remote sensing systems only sample two-dimensional slices of atmosphere, and instrumented aircraft samples are limited to long spaghetti of a few mm² cross-section each. Their use, over the short duration of an intensive observation period, must therefore be highly optimized, i.e. compromises must be made on where to locate surface systems and which flight tracks to allocate to each aircraft. The preparation of a field experiment thus involves preliminary studies of the expected phenomena to identify very specific and observable signatures of the physical processes and mechanisms that are supposed to express the impact of the large scale meteorological and micro-scale aerosol forcings. The use of large-scale modeling, process modeling, and theory is extremely helpful in designing testable hypotheses that observational datasets can help to refute. A clear and precise
definition of the sampling strategy is by far the most important ingredient of a micro-meso-scale observation program.

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