Results from Prior NSF Support

ATM-0082384 – 3/1/2001 to 2/28/2004 - $292,106, “Soundings, C-band radar, data synthesis and model intercomparison for the EPIC2001 stratocumulus study” (PI: Bretherton, co PI: Yuter). Radar and radiosonde data from the Oct. 2001 EPIC SE Pacific (SEP) stratocumulus cruise were analyzed, documenting a well-mixed stratocumulus-capped boundary layer with a diurnal cycle strengthened even far offshore by interactions with the Andes (Bretherton et al. 2004a). A major accomplishment was assessing the importance of precipitation in regulating cloud structure. Periods of substantial night-time drizzle with open-cell organization were observed; most drizzle evaporated above the surface (Comstock et al. 2004). A budget study showed large effects of drizzle and solar absorption on entrainment (Caldwell et al. 2003). Other EPIC contributions include LES simulations of cross-equatorial flow (de Szoeke and Bretherton 2004) and analysis of ITCZ convection (Raymond et al. 2003, 2004).

DMS-0139794 – 8/1/2002 to 7/31/2005 - $195,407, “Focused Research Group on Tropical Atmospheric Circulations” (PI: Bretherton). Idealized models of the seasonal-mean tropical circulation were mathematically analyzed (Bretherton and Sobel 2002; Sobel et al. 2004). These models couple the atmospheric circulation to an ocean mixed layer with internally predicted sea-surface temperature, deep atmospheric convection and cloud-radiation feedbacks of both deep and shallow clouds, providing insights into the current distribution of SST and precipitation in the tropics and their sensitivity to climate perturbations such as greenhouse gas enhancement. Simple relationships between tropical oceanic rainfall and troposphere-averaged relative humidity (Bretherton et al. 2004c) were observationally derived using in these models.

ATM-0336703 – 10/1/2003 to 9/30/2007 – $380,000, “Climate Process Team on Low-Latitude Cloud Feedbacks on Climate Sensitivity” (PI: Bretherton). We analyzed cloud climatologies and the diverse climate change responses of three major U.S. AGCMs (Wyant et al. 2006a) and a superparameterization (Wyant et al. 2006b), separating dynamical and thermodynamical feedbacks using vertical-velocity binning. A new single-column methodology for assessing subtropical boundary layer cloud feedbacks was introduced and applied to a mixed-layer model. It suggests that in a warmer climate, a more stable moist adiabat leads to thicker stratocumulus (Caldwell and Bretherton 2007a). Aquaplanet simulations were found to be a promising tool for low cloud feedback analysis (Meideiros et al. 2007).

DMS-0222115 – 9/1/2002-8/31/2006 – $439,742, “Wavelet-based statistical analysis of multiscale geophysical data” (co-PI: Bretherton). New wavelet-based statistical methods were developed and applied to EPIC boundary-layer turbulence data taken in a series of airborne vertical profiles (Cornish et al. 2007). 2D wavelet methods were used to provide a quantitative measure of the mesoscale cellularity of stratocumulus that varies smoothly with location.

ATM-0433712 – 11/17/2004 to 11/16/2007 - $353,816, “Observations and Modeling of Southeast Pacific Boundary Layer Clouds” (PI: Wood): Data from ongoing research cruises (2001, 2003-2006) to the SEP have been synthesized with satellite observations and modeling, building on EPIC2001 results. New results document coherent mesoscale (~20 km) circulations (cloud base inflow, cloud top outflow) critical to the dynamics of SEP stratocumuli (Comstock et al. 2005, 2007), accentuated into ‘pockets of open cells’(POCs) during periods of strong drizzle. Satellite data suggest POCs form predominantly at night (Wood et al. 2007) and coincide with dramatic CCN depletion likely due to coalescence scavenging (Wood 2006). Cloud drop concentration and LWP, which control SEP drizzle, show characteristic patterns of synoptic variability (Wood et al. 2007). Modeling work includes a mixed layer model (MLM) assessment of Sc cloud-climate feedbacks (Caldwell and Bretherton 2007a,b), MLM-based investigations of aerosol indirect effects (Wood 2007), and ongoing large eddy simulations of the diurnal cycle.

1. Scientific background and motivation

Marine boundary layer (MBL) clouds cover a large fraction of the ocean and profoundly affect the top of atmosphere and surface radiation budgets (Slingo 1990). **MBL clouds are the leading source of uncertainty in understanding the global response to increasing climate warming** (Cess et al. 1989, Bony et al. 2006, Stephens 2005, Soden and Held 2006) and **our poor knowledge of their interaction with aerosols represents a major source of uncertainty in understanding aerosol radiative forcing** (Lohmann and Feichter 2005). At the heart of both of these problems is that the physical processes that determine the thickness and coverage of MBL clouds are poorly quantified, understood, and parameterized in large scale numerical models (e.g. Randall et al. 1996).

MBL clouds are a cornerstone of the Southeast Pacific (SEP) climate system, where their presence is essential for accurately simulating strong trade winds and for producing the observed distribution of sea surface temperature (SST) (Ma et al. 1996, Gordon et al. 2000). Their persistence is aided by the Andes which form a sharp barrier to zonal flow, resulting in strong winds parallel to the coasts of Chile and Peru (Garreaud and Muñoz 2005) which drive intense oceanic upwelling. The cold surface, together with warm, dry air aloft, is ideal for the formation of extensive marine stratocumulus (Sc) clouds. The SEP supports the largest and most persistent subtropical stratocumulus deck in the world (Klein and Hartmann 1993).

Besides responding to large scale dynamics, cloud optical properties over the SEP are also affected by atmospheric aerosols (Bretherton et al. 2004a), with contributions from natural and anthropogenic sources. Cloud droplet effective radii are low off the coast of Northern Chile (Fig 4 in the VOCALS Summary), implying elevated cloud droplet concentrations directly downwind of major copper smelters whose combined sulfur emissions total 1.5 TgS yr⁻¹, comparable to the entire sulfur emissions from large industrialized nations. Smaller droplet effective radii increase cloud albedo, and estimates of the component of the TOA solar radiation due to geographic variability in effective radius alone are as high as 10-20 W m⁻² or 15% of the mean over the SEP. The magnitude of these estimates is such that the indirect effects of aerosols on clouds could lead to significant decreases in the amount of solar radiation entering the ocean, with important implications for the ocean heat budget. However, recent evidence suggests that the response of low cloud thickness and coverage to increasing aerosols requires an understanding of the complex dynamical feedbacks associated with drizzle and cloud sedimentation suppression, and increased MBL turbulence and entrainment (Ackerman et al. 2004, Bretherton et al. 2007, Wood 2007, Xue et al. 2007).

There is evidence from the recent EPIC field study (Bretherton et al. 2004a, Comstock et al. 2007) that drizzle formation, enhanced by aerosol depletion in the clean MBL, can drive rapid transitions from high to low cloud cover (Stevens et al. 2005). These transitions occur most commonly at night, as pockets of open cells (POCs) forming within fields of overcast stratocumulus over the SEP (Wood et al. 2007) and have important implications for the regional albedo (Wood and Hartmann 2006). In general, the role of precipitation in the dynamics of MBL clouds, the factors controlling its formation, and its influence upon the aerosol population are very poorly understood. **Our knowledge of clouds over the SEP region is so far limited to surface and spaceborne remote sensing. There are no in-situ observations of these clouds with which to test hypotheses concerning their physics and chemistry.**

**The VOCALS Regional Experiment (REx)**

VOCALS (VAMOS Ocean-Cloud-Atmosphere-Land Study) is an international CLIVAR program the major goal of which is to develop and promote scientific activities leading to improved understanding, model simulations, and predictions of the SEP coupled ocean-atmosphere-land system, on diurnal to interannual timescales. *The VOCALS Summary* document gives an overview of the key science goals and overall program construction and strategy. The VOCALS
Regional Experiment (REx) is a central component of VOCALS which comprises enhanced multi-platform, multi-disciplinary observations during Oct-Nov 2008 over the SEP. **VOCALS-REx will provide intensive observations of key processes contributing to the SEP climate.** The observations will be used to test a carefully coordinated set of refutable hypotheses, to evaluate our ability to model the important physical and chemical processes in the SEP, and to help evaluate the quality of satellite retrievals. REx hypotheses are organized into two categories: (1) hypotheses related to the impacts of aerosols upon the microphysical and structural properties of Sc clouds and drizzle production; (2) hypotheses related to the coupled ocean-atmosphere-land system. More scientific background is given in the VOCALS Summary.

**Specific goals of this proposal**

The overarching goal of the proposed work is a better understanding of processes, particularly those involving aerosol and precipitation interactions, which influence cloud optical and structural properties (cloud cover, thickness, and particle size) over the SEP. To achieve this, we focus primarily upon the use of the NSF C-130 aircraft, together with numerical modeling, to address the VOCALS-REx aerosol-cloud-precipitation hypotheses, viz.

[H1a] Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.

[H1b] Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.

[H1c] The small effective radii measured from space over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN).

[H1d] Depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.

The following sections describe the observational data and the models we will use (Sect 2), our hypothesis testing strategy (Sect 3), personnel/facilities (Sect 4) and a year-by-year plan (Sect 5).

**2. Data and models to be used**

We will address the hypotheses using a range of observational datasets, primarily those from the C-130 aircraft, for which a number of individual investigator PI proposals will be reviewed by the panel, but also from the NOAA research vessel Ronald H Brown (RHB). Our primary numerical modeling tool will be large eddy simulations, for which we will develop a new, simple but physically consistent, prognostic aerosol scheme which will be used to investigate aerosol-cloud-precipitation feedback processes. Use will also be made of simpler models (especially a single column version of the NCAR Community Atmosphere Model, SCAM).

**2.1 C-130 Data**

We propose to deploy the NSF Lockheed C-130Q Hercules aircraft during VOCALS-REx. The C-130 is a four-engine, medium-size utility aircraft with a long endurance (9+ hours at science speed) and sufficient instrument capacity to meet the scientific objectives in REx. To ensure a sufficient number of flights to meet these objectives we propose to deploy the C-130 for an entire month (Oct 15th-Nov 15th 2008). Given the meteorological conditions, most days will be suitable for science missions. Table 1 describes important information on location, duration, flight hours and breakdown for the proposed deployment.

The C-130 will carry an extensive payload of instrumentation to make both in-situ and remotely sensed measurements of clouds, precipitation, aerosols, and the mean and turbulent meteorological conditions. Table 2 presents the key observational datasets, organized by
measurement category, which are being proposed for the C-130. Observations from each of the categories are essential to addressing the REx hypotheses. The proposed work will primarily focus upon the links between cloud-forming aerosols, cloud, precipitation and MBL structure and dynamics in a way that is designed to integrate a wide spectrum of observations from both the standard C-130 suite and from PI user-supplied instrumentation. Individual PI groups will focus upon detailed measurements and analyses of subsets of the C-130 payload. These activities will necessarily be collaborative and workshops will be essential for efficient coordination.

**Table 1: Deployment location, dates, flight breakdown for C-130 during VOCALS-REx**

<table>
<thead>
<tr>
<th>Deployment base:</th>
<th>Either Arica (18°S, 70°W) or Iquique (20°S, 70°W), Chile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total flight hours requested:</td>
<td>120 hours + ferry from NCAR and return</td>
</tr>
<tr>
<td>Flight plan breakdown:</td>
<td>• Cross-Section Missions: 5/6 flights at 9 hrs duration (total ~50 hrs)</td>
</tr>
<tr>
<td></td>
<td>• POC-Drift Missions: 5/6 flights at 9 hrs duration (total ~50 hrs)</td>
</tr>
<tr>
<td></td>
<td>• Test/Intercomparison Flights: 4/5 flights at 4-5 hrs duration (total ~20 hrs)</td>
</tr>
</tbody>
</table>

**Table 2: Specific C-130 observations and mapping to REx hypotheses (• critical, U: useful)**

<table>
<thead>
<tr>
<th>Observations</th>
<th>1a</th>
<th>1b</th>
<th>1c</th>
<th>1d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermodynamic and dynamic in-situ measurements (high frequency winds, temperatures, water vapor, liquid water content)</td>
<td></td>
<td></td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Cloud/drizzle microphysics (FSSP, 2D-C, 2D-S)</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Radar reflectivity, precipitation rate, cloud top height, dynamics using Wyoming Cloud Radar (WCR) from below, in, or above cloud</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>Cloud base height using Wyoming Cloud Lidar (WCL) from below</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>Liquid water path (LWP), water vapor path using microwave radiometer (MWR) from below cloud</td>
<td>•</td>
<td>•</td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>Aerosol physical properties:</td>
<td></td>
<td></td>
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<tr>
<td>Size distribution (10-10,000 nm): PCASP/FSSP-300, RDMA, LDMA, Giant Nucleus Impactor, fine/ultrafine total aerosol conc. (CN)</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>Aerosol speciation:</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>High time resolution: Aerosol Mass Spectrometer. Integrative: Impactors, filters, streakers. Droplet residuals with CVI, cloud water chemistry</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
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<tr>
<td>Supersaturation activation spectra using CCN diffusion chamber</td>
<td>•</td>
<td>•</td>
<td>U</td>
<td></td>
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<tr>
<td>Video (forward and downward)</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>Gas phase measurements: CO, O₃ (EOL); SO₂, DMS (with APS)</td>
<td>•</td>
<td></td>
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</tbody>
</table>

2.2 C-130 Sampling Strategy in VOCALS-REx

2.2.1 Meteorological Context

The REx Study Region is situated to the northeast of the subtropical SEP high pressure and experiences persistent southerly and southeasterly low level winds (see Fig. 1, with REx study region highlighted by the red rectangle) which drive strong ocean upwelling along the coasts of Northern Chile and Southern Peru. This in turn maintains low SSTs over the region which, in combination with the warm free-tropospheric (FT) air aloft, is conducive to the formation of extensive marine Sc clouds. The typical cloud cover during the Austral spring is 70-80% within the VOCALS study region. Synoptic variability is associated with the passage of low pressure systems to the far south, but decreases northward, and by 20°S is quite weak.
2.2.2 Flight Plans

In this proposal we describe an experimental sampling strategy for the C-130 aircraft that involves two distinct types of flight plan: (i) **Cross-Section Missions**; (ii) **POC-Drift Missions**.

**Cross-Section Missions** (Fig. 2) will involve flying cross-sections along 20°S from the Northern Chilean coast, across strong microphysical gradients (Fig. 4 in VOCALS Summary), to the climatological maximum in Sc cloud cover at ~85°W. These missions will be used to generate, from about 5/6 flights, a quantitative picture of the mean and variability in cloud and precipitation properties in the MBL, and aerosol physical and chemical properties both in and above the MBL. These flights are designed to sample contrasts in MBL thermodynamics, chemistry, aerosols and clouds between the coast and the remote SEP. Focus will be on good sampling of aerosol characteristics, MBL structure/depth, cloud structure, microphysics, and drizzle. To avoid aliasing diurnal variability, flights will all take place at the same local time (depart 3am local, return 12 noon). This time is chosen to sample the time of peak precipitation. Efforts will be made to coordinate these missions with satellite overpasses (esp. Terra). On both outbound and return sections, the mission will comprise a set of 60 km legs below cloud (lowest flight level), in-cloud, and above cloud, with altitude changes of ~300 m minute$^{-1}$. This will give ~6 stacks of legs on each of the outbound and return portions. A number of profiles will be made up to 4 km to sample FT aerosols and meteorology. In-cloud runs will sample cloud microphysical properties, cloud droplet residual aerosol properties, and cloud chemistry. The above-cloud runs will be used to sample drizzle, cloud, and MBL structure using the Wyoming Cloud Radar (WCR), and to characterize the FT chemistry, aerosol and thermodynamic structure. Sub-cloud runs will determine physicochemical properties of aerosols, remotely sample cloud thickness, LWP, and drizzle using the microwave radiometer, the WCR and the Wyoming Cloud Lidar (WCL), and determine lower boundary conditions (SST, fluxes incl. DMS fluxes, winds). The **Cross-Section missions** present a unique opportunity to conduct a regional-scale (1000 km) aerosol-cloud microphysical closure study in marine Sc.
Cross-Section Missions will pass over the RHB which will be situated close to 20°S, and ~30 minutes will be devoted to synergistic sampling. These coordinated sections (see Fig. 3) will be used to compare instruments and will provide important in-situ context to remotely sampled cloud and drizzle properties from the RHB. In addition, these sections will be useful in helping to determine, using a C-130 and C-band radar measurements, dynamical mesoscale structures associated with POCs and other mesoscale precipitation features.

Fig. 3: Coordinated C-130/RHB Pattern. Cosampling during Cross-Section missions between C-130 (red line) and RHB (center). The region of sampling by the RHB C-band radar is shown for context. The C-130 will fly in on a low level E-W leg and, make a turn at the RHB, and continue in the upwind direction for 30-60 km. The C-130 will then climb to cloud level and make a 60-90 km run in-cloud passing over the RHB.

POC-Drift Missions (Fig. 4) will be used to study the microphysical and dynamical state and processes that occur in POCs and contrast them with surrounding overcast Sc. Broad boundaries between open and closed cellular convection may also be a focus of these missions. Of particular importance is a characterization of the aerosol and cloud microphysical properties in the two regions. When possible, these flights will be coordinated with the RHB, whose scanning C-band radar will provide mesoscale context for the C-130 data, as well as precipitation field characterization. GOES imagery will be used to locate POCs or regions prone to POC formation (using cloud microphysical retrievals to location regions of clean clouds), and missions will be targeted accordingly. Upon reaching a POC boundary, across-wind stacks of four straight and level runs 100-150 km in length will be flown below, in, and above cloud. Profiles in both regions will be obtained regularly. The aircraft will drift with the MBL mean wind (i.e. with the advecting POC) to provide Lagrangian measurements of the temporal evolution of the POC. Efforts will be made to sample the same POC on two C-130 flights, to conduct multi-aircraft Lagrangian missions with the C-130 and the BAe-146 or G-1 aircraft, or to fly in a POC region that will ultimately advect over the RHB. A flight pattern similar to the POC-drift mission will be used to conduct a contrasting multi-aircraft, multi-flight Lagrangian study originating in a polluted airmass near the Chilean coast to observe the processes affecting the aerosol and cloud evolution as the polluted MBL advects downwind from the coastal to the remote SEP.

Figure 4: POC-Drift Mission flight plan for C-130.
2.3 Integrated Datasets

To facilitate the data analysis and integration with numerical modeling component of VOCALS, we plan to develop and provide for the scientific community three integrated datasets (IDs) which synthesize observational data collected on the C-130 and the RHB. These datasets are designed to help test the REx hypotheses and to provide important constraints for both process-based and large scale numerical models. The datasets are:

i. **Combined Drizzle Integrated Dataset (CD-ID)**, a small-scale (~50 km) dataset combining vertically-representative information on the precipitation rate, cloud macrophysical and microphysical properties, and information about the coincident subcloud aerosol properties;

ii. **Cross-Section Integrated Dataset (XS-ID)** which will describe the mean state and of the MBL and lower free-troposphere (FT) along the latitude 20°S, at a resolution of 2.5° longitude. Table 3 gives more detail of the parameters we plan to include in the CD-ID and XS-ID. The IDs will also play a central role in the VOCALS model assessment that is described below. ID synthesis will be carried out in cooperation with other REx investigators: Fairall/Yuter (NOAA ESRL and NCSU respectively) will make cloud and precipitation remote sensing measurements from the RHB; Leon/Snider (U Wyoming) will produce estimates of cloud-base height, cloud thickness, precipitation rate and CCN concentration based on data from the WCR, WCL and Wyoming CCN spectrometer on the C-130; Zuidema (U Miami) will be responsible for producing liquid water path data both from the C-130 and the RHB; Huebert/Clarke (U of Hawaii) will provide physicochemical aerosol properties

iii. **Lagrangian Datasets (Lag-ID)** which will describe the time evolution of the MBL, cloud and precipitation state from multi-flight **POC-Drift Missions**. Data from all platforms involved will be synthesized as a collaborative project. The legacy of the ASTEX Lagrangian datasets (Bretherton et al. 1999) is testament to the utility of such datasets and their provision to the scientific community.

Table 3: Integrated Datasets (IDs) to be produced as part of the proposed work

<table>
<thead>
<tr>
<th>ID</th>
<th>Rationale</th>
<th>Space/Time scale; Location; Platforms</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combined Drizzle</strong></td>
<td>Collocated precipitation, aerosol and cloud micro- and</td>
<td>~50 km, 10s of mins; All flight locations; Both C-130 and RHB</td>
<td>Precipitation rate, LWP, cloud thickness, cloud droplet concentration, subcloud aerosol size distribution and chemistry</td>
</tr>
<tr>
<td><strong>Dataset (CD-ID)</strong></td>
<td>macrophysical properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cross-Section</strong></td>
<td>Data on E-W cross-section along 20°S from coast to ~1500</td>
<td>~250-1500 km, 6 hr; Along 20°S, 70-85°W; Mainly C-130 but also RHB</td>
<td>MBL depth, thermodynamic profiles, cloud base height, liquid water path, cloud fractional coverage, precipitation rate, cloud microphysics (droplet concentration and effective radius) aerosol size distribution and speciation in and above MBL, Anthropogenic indicators (SO$_2$, CO)</td>
</tr>
<tr>
<td><strong>Dataset (XS-ID)</strong></td>
<td>km offshore</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lagrangian</strong></td>
<td>MBL, aerosol, cloud, drizzle evolution for multiple POC-Drift and polluted Lagrangian flights</td>
<td>Function of time C-130 and other a/c</td>
<td>As for XS-ID, including interpolated reanalysis data</td>
</tr>
<tr>
<td><strong>Dataset (Lag-ID)</strong></td>
<td></td>
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</tbody>
</table>
2.4 Numerical Modeling strategy

A primary goal of VOCALS is to use the SEP as a testbed for better simulations of boundary-layer cloud processes and aerosol-cloud interaction with global, regional and large-eddy simulation (LES) models. These models in turn help us test the REx aerosol-cloud-precipitation hypotheses and are a vital tool to generalize REx observational findings to other Sc regions. Our proposed University of Washington (UW) modeling strategy includes the following three elements that support these overall goals using REx data from the C-130, other participating research aircraft, and the RHB together with routinely available satellite and reanalysis data:

1) LES of aerosol-cloud-precipitation interaction, to be compared with the REx-observed Lagrangian evolution of MBL air columns that start with high and low aerosol concentration. One goal of these simulations is to better understand the initiation and lifecycle of POCs.


3) Testing and refinement of moist physics parameterizations in the NCAR Community Atmosphere Model (CAM) AGCM, of which the Co-PI is a lead developer, using results from the prior two strategic elements.

2.4.1 LES of Aerosol-Cloud-Precipitation Interaction

The goal of this modeling work is to realistically simulate Sc aerosol-cloud-precipitation interaction over a 1-2 day period and its sensitivity to initial aerosol and cloud conditions vs. subsequent aerosol and cloud forcings. We will attempt to initialize and force the LES to match multi-aircraft observations of a clean and a polluted (i.e. low and high aerosol conc.) Lagrangian. LES details: We will use the System for Atmospheric Modeling (SAM 6.5) LES (Khairoutdinov and Randall 2003), which uses the anelastic equations for computational efficiency, a positive-definite advection scheme applied to adiabatically conserved thermodynamic variables, state-of-the-art surface flux and radiative transfer schemes. The Co-PI’s research group has four years of experience using and modifying SAM. For Sc, our experience is that a very fine vertical grid (5 m) is needed at the sharp MBL inversion to avoid numerical over-entrainment. For efficiency we use a stretched vertical grid with a rather coarser resolution of up to 25 min the middle of the boundary layer and in the free troposphere, while a 25-50 m horizontal resolution is adequate. For a 128 x 128 x 272 simulation on a 3 x 3 km doubly periodic horizontal domain with a depth of 2 km, our current Linux cluster can simulate 33 hours per day on 16 4-processor nodes; we also use two-dimensional simulations, which run much faster, for debugging and sensitivity tests.

SAM 6.5 supports two bulk microphysics parameterizations that we will use to simulate aerosol impacts on Sc clouds. The Khairoutdinov-Kogan (KK) scheme (Khairoutdinov and Kogan 2000) is a widely used two-moment bulk precipitation scheme with autoconversion and accretion formulations that compare favorably with observations (Wood 2005). We have added a cloud droplet sedimentation parameterization (Bretherton et al. 2007) which markedly reduces entrainment, especially when the cloud droplet concentration $N_d$ is $50 \text{ cm}^{-3}$ or less. We recently implemented the Morrison et al. (2005) two-moment scheme, which prognoses rain and cloud water mixing ratio and number concentration.

To explore feedbacks between aerosols, clouds, and precipitation, we will design and implement a simple prognostic aerosol parameterization for use in the LES and in simpler box models of the MBL (e.g. mixed layer model). The parameterization will include sinks due to drizzle collection and aggregation, a specified surface source and a specified free-tropospheric number concentration. A parameterization of this type was used in the pioneering study of Baker and Charlson (1990), henceforth BC90, to argue that given a particular aerosol source rate there are two stable CCN concentration regimes, each dominated by different sink mechanisms (coalescence scavenging over ocean, coagulation over land). In their parameterization, a constant
CCN source was assumed, which greatly simplifies the problem, but does not allow for feedbacks between CCN depletion and new particle formation and growth which observations show may be important for replenishment of the CCN population in POCs (see Fig. 5 in VOCALS Summary).

The aerosol size distribution in the LES will be represented by two prognostic variables: an accumulation mode aerosol concentration and a geometric mean radius, which are sufficient to define a CCN spectrum. The LES dynamics, in conjunction with this CCN spectrum will be used to activate cloud droplets using a Twomey-type parameterization (Abdul-Razzak et al. 1998). The geometric width of the accumulation mode will be specified using C-130 aerosol size distribution observations. The derived cloud droplet number concentration will be used to determine the autoconversion rate using the parameterization of Liu et al. (2004) modified using the observations of Wood (2005). The cloud droplet loss rate through coalescence scavenging will be parameterized following Wood (2006) and will feed back onto the aerosol concentration. In this way, the two-way interaction between aerosols and precipitation will be represented in the LES.

To determine the source rate of accumulation mode particles, we will use a number of different approaches of increasing sophistication:

1) **Specify a fixed formation rate in accordance with BC90.** Because BC90 did not allow drizzle to affect the model dynamics where we will, these simulations will be useful to revisit the ideas of bistability but with dynamically-active precipitation.

2) **Specify the formation rate as an arbitrary function of the existing aerosol surface area** by constraining the rate of sulfur mass to be equal to that produced by the ocean surface DMS flux. The number of particles over which this mass is distributed will be a free parameter and will be used to explore the sensitivity of the aerosol-cloud-precipitation system to changes in the assumptions about the pathways of accumulation particle formation.

3) **Construct a simple parameterization for the rate of formation of new accumulation mode aerosols as a function of the existing aerosol surface area and other LES prognostic variables** which will then be applied in the LES (Fig 5). We will develop a simple two-moment (number and geometric mean radius) sulfur and sea-salt aerosol model to represent aerosols in the Aitken and accumulation modes. In addition to a windspeed-dependent seasalt flux, new particle formation will be parameterized following Capaldo et al. (1999) which specifies the nucleation rate as a function of temperature, RH, and sulfuric acid concentration \([H_2SO_4]\). The latter will be predicted from DMS oxidation to SO2 and then photochemistry using Capaldo and Pandis (1997). Observations from REx will constrain atmospheric DMS concentrations. A nucleation tuner will be applied to account for ternary nucleation effects and fundamental uncertainties in our understanding of nucleation. A critical factor that will be an input in the parameterization is the existing aerosol surface area, which when depleted allows \([H_2SO_4]\) levels to build and nucleation to occur. Aerosol will grow by \([H_2SO_4]\) deposition following Pandis et al. (1994). In-cloud oxidation of \([SO_2]\) will be estimated as a function of liquid water content and residence time estimated directly from LES simulations. The new sulfate mass will be distributed evenly among those aerosols large enough to form cloud droplets (Capaldo et al. 1999), with the distribution determined stochastically from the LES-derived vertical velocity pdf, expanding upon ideas of Hegg (1990) and Kaufman and Tanre (1994).

![Figure 5. Schematic of feedback processes to be represented in LES](image-url)
Idealized high and low aerosol concentration cases will be used to understand the LES behavior. First, we will run the LES with specified aerosol concentrations, following the specifications of the GCSS DYCOMS RF02 nocturnal drizzling Sc case (A. Ackerman, GCSS web site). Following bin-resolved LES simulations of Savic-Jovcic and Stevens (2007), we will first specify aerosol concentrations that maintain $N_d$ at 100 and 25 cm$^{-3}$. They found that the low-aerosol simulation developed a pronounced mesoscale cellular structure with extensive drizzle, while the high-aerosol simulation produced a more homogeneous and much less drizzly Sc layer. Analogous results for a somewhat different case were obtained by Xue et al. (2007). Both groups used relatively large horizontal domains (12-25 km) to expose the mesoscale structure of the cloud field, but Xue et al. found the area-averaged cloud albedo to be the same for a 6 km domain.

We will test that our more computationally efficient bulk microphysics scheme behaves in a qualitatively similar way to the bin schemes. We will then add the prognostic aerosol scheme, repeat these simulations, and examine the importance of coalescence scavenging on the budget of aerosol in the high and low aerosol cases. By artificially changing the humidity of the above-inversion air as in Ackerman et al. (2004), we hypothesize that we can modify the cloud liquid water content sufficiently to strongly affect the drizzle process and aerosol feedback.

With this experience, we will move to simulations of REx-observed Lagrangian cases. We will attempt to use LES to simulate the cloud, boundary layer and aerosol evolution, starting with the first aircraft observations as initial conditions and forcing the model using measurements of time-varying SSTs, FT thermodynamic profiles and above-inversion aerosol concentrations, along with reanalyses to constrain the subsidence profile. The simulations will be compared with observed cloud macrophysical (fraction, LWP, turbulent vertical velocity variance, mesoscale structure) and microphysical properties ($N_d$, precip. rate), as well as measurements of the accumulation mode aerosol concentration. This will test the overall fidelity of the LES and constrain parameters in our aerosol model.

Next we will simulate a REx-observed low-aerosol Lagrangian case. Our first focus will be on comparing the available aircraft observations (synthesized in a Lag-ID) with our LES for conditions inside a developing or well-developed POC, where we expect substantial drizzle and a depleted accumulation mode. Using our prognostic aerosol scheme we plan to examine how the effects of precipitation upon aerosols affects the development and maintenance of POCs (i.e. the conceptual model in Fig. 6). A major scientific goal of this work is to understand what surface, FT, or nucleation aerosol source, if any, is needed to sustain the observed $N_d$ in an observed POC and thereby regulates the production of precipitation.

Our second, more speculative, clean-case modeling focus is to simulate and understand the
dynamics at the edge of a POC. REx POC-Drift and Cross-Section mission measurements will extensively sample the transition across the boundary of a POC, that radar measurements suggest is a region of locally enhanced drizzle (Comstock et al. 2007). This may suggest that the transition is the upward branch of a POC-scale circulation. One possible approach to simulating this circulation is to use a 2D simulation on a broad domain in which there is initially a moist anomaly at the center sufficient to create a drizzly patch in otherwise homogeneous Sc. Under suitable conditions, this might evolve into a POC, whose mesoscale circulations could be compared with aircraft observations. Doppler velocity retrievals from the WCR on the C-130 would be a particularly useful measurement for comparison with the model.

2.4.3 VOCALS-REx Modeling Assessment (VOCA)

Our second main modeling goal is to organize a VOCALS-REx model intercomparison ("VOCA") for regional and global atmospheric models run in a weather forecast mode. One focus will be on assessing model skill in hindcasting mean, day-to-day, and diurnal cycle of Sc properties over the SEP (70-90°W, 10-30°S). For models that include aerosol chemistry and transport modules, the second focus will be on testing model forecasts of FT and MBL aerosol concentration profiles and cloud effective radius over this same region. Models that run on a forecast-data assimilation cycle would submit a short-range (12-36 hr) forecast for each 6-hour period in the month. AGCMs, which generally must be initialized from reanalysis to make a forecast, tend to suffer a more severe initialization shock and would use a 24-36 hr forecast. Regional models would run continuously for the month, forced at the boundaries with reanalysis.

The key REx data to be used in this study will be the Cross-Section Dataset (XS-ID, Table 3 above), which will be specially constructed for model intercomparison and would complement an extensive suite of available satellite retrievals (see Table 4) and other data sources provide further important validation throughout the period.

Table 4: Ancillary datasets to be used in VOCA

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Parameters</th>
<th>Space/Time scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-Section Dataset (XS-ID)</td>
<td>See Table 3</td>
<td>Along 20°S, 70-85°W; 5/6 individual cases</td>
</tr>
<tr>
<td>GOES/ISCCP</td>
<td>Cloud cover diurnal cycle</td>
<td>70-90°W, 10-30°S; 30 mins</td>
</tr>
<tr>
<td>MODIS</td>
<td>Cloud top temperature, optical depth, N\text{\textsubscript{d}}, cloud top r\text{\textsubscript{c}}</td>
<td>70-90°W, 10-30°S; 2\times daily or daily</td>
</tr>
<tr>
<td>Quikscat</td>
<td>Surface winds, diurnal variability</td>
<td>70-90°W, 10-30°S; 2\times daily</td>
</tr>
<tr>
<td>AMSR/TMI/SSMI</td>
<td>Cloud LWP</td>
<td>70-90°W, 10-30°S, daily composite</td>
</tr>
<tr>
<td>AIRS</td>
<td>FT moisture profiles</td>
<td>70-90°W, 10-30°S; daily composite</td>
</tr>
<tr>
<td>COSMIC/GPS</td>
<td>MBL depth, FT moisture profiles</td>
<td>70-90°W, 10-30°S; monthly mean</td>
</tr>
<tr>
<td>CloudSat/CALI PSO</td>
<td>MBL depth, precipitation</td>
<td>70-90°W, 10-30°S; monthly mean</td>
</tr>
<tr>
<td>IMET Buoy</td>
<td>Surface winds/fluxes, T, RH, radiation</td>
<td>85°W-20°S; 8\times daily</td>
</tr>
</tbody>
</table>

At the June 2007 VOCALS Modeling Workshop, the Co-PI proposed a preliminary version of this intercomparison, the pre-VOCALS assessment (PreVOCA), using October 2006 as a trial month. The validation will be with satellite and buoy data, plus a week of SEP soundings from the RHB during an IMET buoy maintenance cruise. Leading global and regional modeling groups including ECMWF, NCEP, NCAR, GFDL, U. Hawaii, U. Chile and others, expressed interest in participating, and the Co-PI will shortly put out a formal protocol for PreVOCA, with model
output due December 2007. The PI has already acquired many of the needed satellite datasets and both investigators will supervise the analysis and publication of the PreVOCA model output. This will provide valuable experience with which to improve our assessment methodology for the REx-based model assessment. It is anticipated that the REx-based model assessment would be put forward to the GCSS Boundary Layer Cloud working group as a natural follow-on to the GCSS Pacific Cross-section Intercomparison currently led by Joao Teixeira.

2.4.4 USE OF VOCALS-REX ANALYSES TO IMPROVE THE CAM AGCM

The Co-PI is tightly involved in the development of improved moist physics parameterizations for the NCAR Community Atmosphere Model, the flagship US open-source AGCM. The latest model version (CAM3.5+) includes the UW moist turbulence (Grenier and Bertherton 2001) and shallow cumulus parameterizations (Bretherton et al. 2004b) as defaults. These schemes were designed to remedy model deficiencies in simulating cloud-topped MBLs, and CAM3.5+ simulates the spatial distribution, seasonality, and vertical structure of the Sc regions fairly well.

In addition, the Atmospheric Model Working Group (AMWG), which coordinates CAM improvement, is attempting to add a credible representation of the aerosol indirect effects on climate into the CAM. A new microphysical scheme including a droplet nucleation scheme (Abdul-Razzak et al. 1998) have been implemented in CAM, and a prognostic aerosol transport scheme is nearly operational.

VOCALS observations and VOCA provide exciting opportunities for testing these new parameterizations and their interactions in a controlled setting. Thus, the Co-PI will work closely with other members of the CAM microphysics development team (especially P. Rasch, S. Ghan, H. Morrison and A. Gettelman) to understand model biases in simulated clouds and aerosols seen in development versions of CAM, starting with PreVOCA results and moving on to VOCA when that data is mature. The Co-PI will work with research scientist Matt Wyant on those model improvements that directly involve the UW schemes, in particular biases in the vertical structure of the boundary layer that may be connected to turbulence, turbulence-entrainment-drizzle feedback, and transitions between turbulence and shallow cumulus convection. In this way, we aim to directly use VOCALS data to enhance a major national climate model.

3. Hypothesis testing using observations and modeling

In this section, we describe how the observational and modeling datasets and tools presented in the preceding sections will be used to critically test the VOCALS hypotheses.

3.1 Testing H1a: Variability in the physicochemical properties of aerosols has a measurable impact upon the formation of drizzle in stratocumulus clouds over the SEP.

The Combined Drizzle Integrated Dataset (CD-ID) from the C-130 and RHB measurements will first be used to examine relationships between precipitation rate at the cloud base $P_{cb}$ and cloud macrophysical properties such as cloud LWP, thickness $h$, and cloud microphysical properties such as cloud droplet concentration $N_d$. We will determine what fraction of the variance in $P_{cb}$ is explained by variability in LWP or $h$, and what fraction is controlled by microphysical variability. These estimates will be compared with results from the LES simulations described above, using different autoconversion parameterizations to examine microphysical sensitivity. The Cross-Section Integrated Dataset (XS-ID), in conjunction with mesoscale model output and satellite data collected as part of VOCA, will be used to assess the typical synoptic variability in cloud macrophysical and macrophysical properties over the SEP.

We will then attempt to determine the degree to which variability (both temporal and spatial) in $P_{cb}$ is correlated with variability in the properties of the CCN activation spectrum and the accumulation mode aerosol concentration $N_a$. If these relationships are weak, or it is clear that $P_{cb}$ is much more closely correlated with the cloud macrophysical properties ($h$ or LWP), then this would constitute a falsification of H1a.
3.2 Testing H1b: Precipitation is a necessary condition for the formation and maintenance of pockets of open cells (POCs) within stratocumulus clouds.

POC-Drift missions will be used to study the dynamical and microphysical properties of cloud and precipitation in marine Sc. Cloud and drizzle microphysics in the two regions will be contrasted. Ideally, observation of the POC formation process itself is a goal, but much will be learned about their structure by studying existing POCs over an extended time period.

**If POCs are observed that do not contain drizzle heavier than a few tenths of a mm day$^{-1}$ then we can rule out precipitation as being a necessary condition.** Based upon our findings from recent cruise data, we anticipate, but cannot be certain, that drizzle will accompany POCs. If this is the case, then a key goal is to learn the mechanisms by which precipitation affects the mesoscale cloud structure and cloud albedo.

Scanning C-band radar observations from EPIC indicate that drizzle cells frequently develop a complex layered mesoscale structure with extensive 5-10 km wide regions flowing into the center of the cells roughly at cloud base with outflow above this. It is an untested possibility that these mesoscale inflow regions are necessary to maintain the moisture supply to the cloud that would otherwise precipitate out within 30 minutes or less. The role of evaporating precipitation is also likely to be important, but evidence linking this with the mesoscale dynamics is so far lacking. The WCR on the C-130 will be used in conjunction with the aircraft-derived flight level winds to determine the mesoscale dynamics of the individual cells within the POC and help elucidate the mechanisms responsible for their maintenance and longevity. The scanning C-band radar on the RHB will also provide important information on the horizontal and vertical structure of the POCs, and we plan to obtain at least one POC case where the C-130 and RHB C-band radar will sample the same structures. LES Lagrangian simulations in clean conditions will be used to examine links between drizzle, cloud morphology and coverage as a function of the precipitation rate to further clarify the role that precipitation plays in the mesoscale dynamics. LES 2D simulations of the POC boundaries will also study whether POCs and POC growth are associated with clearly-defined mesoscale circulations.

3.3 Testing H1c: The small effective radii measured from space over the SEP are primarily controlled by anthropogenic, rather than natural, aerosol production, and entrainment of polluted air from the lower free-troposphere is an important source of cloud condensation nuclei (CCN).

Testing H1c requires a multi-step approach, involving a breakdown into separate sub-hypotheses. Here we present one such breakdown that we will test using observations from REx:

- High cloud droplet concentrations near the coast are well predicted using the accumulation mode aerosol number concentration (e.g. defined as the number concentration of aerosol particles with dry radius>0.1 μm);
- High concentrations of accumulation mode particles are clearly associated with anthropogenic indicators such as elevated carbon monoxide and sulfur dioxide levels, and the presence of free-tropospheric aerosol layers.

To assess the first sub-hypothesis, we will use the Cross-Section Integrated Dataset (XS-ID) to examine how cloud microphysical properties, such as cloud droplet concentration $N_d$ and cloud top effective radius $r_e$ change as a function of distance from the coast. Based upon evidence from MODIS and from buoy-maintenance cruises (Huneeus et al. 2006, Wood et al. 2007, Tomlinson et al. 2007) we anticipate that there will be strong microphysical gradients along 20°S. The Cross-Section missions will be used to determine the degree to which the mean and variability in the zonal gradients in $N_d$ and $r_e$ along 20°S reflect the underlying variability in subcloud aerosol physical properties such as the accumulation mode concentration, its size distribution, and the CCN spectrum. In collaboration with other C-130 REx PI groups, we will use aircraft-derived
vertical motions, together with a simple aerosol parcel model (Wood et al. 2002), to assess the degree of closure between the aerosol and cloud microphysical characteristics. In addition, detailed aerosol chemistry measurements will be made by other PI groups to assess the role of aerosol chemistry in influencing closure.

The second sub-hypothesis will be assessed using a number of anthropogenic indicators: (1) elevated carbon monoxide and SO\textsubscript{2} levels in the MBL; (2) the presence of free-tropospheric aerosol layers extending westwards to a distance commensurate with the elevated cloud droplet concentrations; (3) back-trajectory analyses from MM\textsubscript{5}/WRF simulations (being performed in collaboration with Rene Garreaud at the Universidad de Chile), and chemical transport models. The VOCA assessment will also be used to check whether observed patterns of anthropogenic influence are represented in chemical transport models over the SEP.

LES of the Lagrangian flights will be used to quantify the importance of entrainment of FT aerosols on the cloud optical properties including effective radius. Sensitivity studies where FT sources are removed will help to ascertain the importance of FT pollutant transport.

3.4 Testing H1d: Depletion of aerosols by coalescence scavenging is necessary for the maintenance of POCs.

It is becoming evident that even light precipitation can have a marked impact upon the accumulation mode aerosol concentration even if this precipitation evaporates before reaching the. Collision-coalescence of cloud and drizzle drops can remove aerosol number concentration (“coalescence scavenging”) without affecting aerosol mass, which can have a major impact upon cloud microphysics in subsequent cloud formation. Simple calculations (Wood 2006) suggest that coalescence scavenging in aerosol rich plumes in the cloud-topped MBL is independent of the CCN concentration and may deplete CCN on a timescale comparable to the timescale for dilution by entrainment of free tropospheric air if the pollution is confined to the MBL.

Our approach is to use C-130 POC-Drift and multi-flight Lagrangian observations to assess MBL aerosol budgets in regions of drizzling Sc (both POCs and surrounding unbroken cloud). Given precipitation rate and \( N_d \) estimates appropriate for the SEP (EPIC, Bretherton et al. 2004a), simple theoretical models and parameterizations indicate that CCN coalescence scavenging rates may be in the range 30-300 cm\textsuperscript{3} day\textsuperscript{-1} (Wood 2006), and will be a strong function of precipitation rate. By studying the evolution of the MBL over a period of time (from a few hours on a single flight to over 24 hours for multi-flight, or RHB/C-130 joint missions) we plan to derive estimates of the CCN loss rates. It will be important to estimate the other primary source terms, the chief one being entrainment, which will be estimated using MBL and FT aerosol measurements and entrainment rates estimated from the C-130. **Falsification of H1d would require derived CCN loss rates not to exceed 10-20 cm\textsuperscript{3} day\textsuperscript{-1} even when substantial drizzle (\( \sim 1 \) mm day\textsuperscript{-1}) is present.**

These data will be used to constrain terms in the prognostic LES aerosol parameterization described above. Specifically, we will attempt to examine, using sensitivity tests, whether coalescence scavenging followed by new particle formation and growth leads to a stable microphysical state in POCs, or whether the entrainment of FT aerosol provides a means for replenishing aerosols in POCs. The balance of processes has important implications for our understanding of the remote marine aerosol distribution and its susceptibility to precipitation.

4. Personnel and Facilities

Integrative data analysis and modeling will be carried out by PI Wood, Co-I Bretherton, a Research Scientist II Dr. Matthew Wyant (at 50%) and two graduate students. The PI, the Co-PI, and the Research Scientist are highly experienced at effective data synthesis and the proposed modeling. The PI and Co-PI have worked together in gathering and analyzing data for the EPIC 2001 cruise, and bring extensive data analysis experience from many prior field campaigns. One
graduate student is currently starting preliminary research and will be relatively experienced by the time of REx. The second student, yet to be identified, will primarily conduct the modeling work. PI Wood will lead the data processing and analysis tasks.

PI Wood, an expert in boundary cloud microphysics and remote sensing, has 15 years experience in the analysis and synthesis of atmospheric observational datasets from a large number of sources (especially aircraft, but also surface and satellite datasets). He has gained considerable field program experience, particularly in coordinating aircraft activities (during PhD work, at the UK Met. Office, and in the US). Wood is responsible for overall project supervision, and will serve as lead PI of the REx.

Co-PI Bretherton provides strong theoretical, modeling, and field experience through his work and leadership for the GEWEX Cloud System Study (GCSS), improving GCM parameterizations for cloud-topped boundary layers, and his close connections to the NCAR CCSM effort. His field coordinating activities include ASTEX, DYCOMS, and EPIC. Bretherton will coordinate the modeling activities in the proposed work, including the model assessments PreVOCA and VOCA model assessments.

Research Scientist II Matthew Wyant has 15 years of experience in LES modeling and in the analysis of datasets from multiple sources including climate model output, reanalysis. Wyant will conduct the pre-REx modeling work, and will serve as LES mentor for the second student. Graduate student Rhea George is about to enter her 2nd year of study and will focus initially upon existing SEP datasets and then upon observational data from the C-130 following REx.

Existing computers within the Department of Atmospheric Sciences will be used for the bulk of the data processing. Data archival for the raw C-130 observational data, and for the integrated datasets proposed here, will be coordinated with NCAR EOL and the VOCALS-PIs.

5. Research plan by years

Year 1:
- Wood and the VOCALS-PIs finalize the experimental strategy for REx
- Wyant, Wood and Bretherton complete the Pre-VOCA sub-project
- Wyant begins prognostic aerosol parameterization work for LES
- Wood, Bretherton and George participate in REx.

Year 2:
- Start analysis of C-130 observational datasets (Wood, George)
- Wood organizes post-REx analysis workshop, in conjunction with VOCALS Modeling Workshop. Initial observational “golden days” are determined for focused study by VOCALS PIs. Details of Integrated Datasets (IDs) are finalized and production starts.
- First observational cases are prepared for initialization/evaluation of LES simulations and are written up for publication. Coordination with GCSS. Graduate student, under supervision of Wyant and Bretherton, conduct LES simulations are conducted to study aerosol-cloud-precipitation feedbacks using REx Lagrangian missions
- Wood and VOCALS-PIs prepare and submit manuscript on REx for submission to BAMS
- C-130, other observational datasets, and participating model simulations are prepared for the VOCA assessment.

Year 3:
- Multi-flight Lagrangian studies are completed and written up for publication.
- Wyant writes up VOCA assessment results for publication
- IDs are released for use by the broader scientific community
- Graduate student writes up LES Lagrangian simulations for publication