Cloud Aerosol Radiative Forcing Dynamics EXperiment (CARDEX)

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Proposed Period and Location of Campaign:

Location:	Maldives, over the N Indian Ocean and Arabian Sea
Experiment Period:	31/01/2012 – 22/03/2012
Flight Operations Period:	14/02/2012 – 13/02/2012
Target Systems:	Trade Cu clouds; Anthropogenic (India; SE Asia) and biogenic (Sea Salt; dust) aerosol

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Modified June 13, 2011

1. Project Summary

Boundary layer clouds (Strat-CU and Trade-CU) are the dominant atmospheric regulators of the climate - by reflecting solar radiation back to space and by aiding the air-sea-free troposphere exchange of water vapor. On a very fundamental level, we can think of how the dynamics, physics and chemistry interact to create, maintain and destroy these cloud systems.

The last two decades have witnessed significant progress in our understanding the individual processes occurring in these boundary layer cloud systems, thanks to field experiments such as: ASTEX; INDOEX; DYCOMS; RICO; and VOCALS. Such studies have provided a sound experimental background to explain individual relationships between cloud process such as dynamics and entrainment, and aerosol-cloud interaction, however, as we utilize these datasets in our research under NSF grant ATM07-21142: Cloud, Climate Feedbacks due to Extra-Tropical Clouds Systems, we realize that these otherwise valuable aerosol and dynamics measurements do have limitation, since they were not made simultaneously. This is the motivation for this supplemental proposal.

NSF has supported development of lightweight unmanned aerial vehicles (UAVs) (Ramanathan et al., 2007) and suits of advanced instrumentation (Corrigan et al., 2008; Ramana et al., 2007; Roberts et al., 2008) for measuring aerosol, cloud physics, and radiation physics. More recently, NOAA has furthered this development by funding measurement capability of the dynamics and water vapor fluxes. Thus, by using a combination of UAV, satellite and surface measurements, the Scripps team has the capability to make simultaneous measurements to explore the linkages between dynamics, aerosol chemistry, optical cloud properties, and cloud albedos –the overarching motivation behind this proposal.

This proposed experiment will support ATM07-21142 in the following areas:

• (Of the two objectives) Objective #2: The role of aerosols and large scale dynamics in regulating cloud albedo; and

• (Of the 4 approaches) Approach A: Creating an integrated observational data set of aerosol-cloud-dynamics-radiative forcing, however with CARDEX these data elements will be measured simultaneously.

Pending airspace availability and governmental approvals and permissions we propose a 4-week campaign in the Maldives.

We request permission to re-budget 575K from existing grant funds of ATM07-21142, and also request a supplemental fund of 175K.

2. Project Description

2.1 Scientific Overview and Research Questions

This proposal aims is to investigate on a fundamental level the dynamical, physical and chemical parameters which create, maintain and destroy boundary layer clouds. This will be achieved by the simultaneous measurement of relevant properties by a combination of UAV and ground based measurements during a month long campaign. This campaign is motivated by the following key question:

Are Polluted Clouds brighter than pristine clouds?

To be addressed during these proposed measurements through a series of sub-questions:

Q1) What is the linkage between cloud water content, water vapor fluxes and entrainment/inversion strength?
Q2) How is cloud droplet size distribution affected by entrainment?
Q3) What is the relationship between cloud droplet size distribution and albedo?
Q4) What is the relative importance of the burning off of clouds due to solar absorption by BC (the semi-direct effect) and nucleation of more cloud drops (due BC and other manmade aerosols)

Investigation of these questions can be split into three components:

Water Budget: Constraint of the 1D cloud layer water budget by measurement of surface water vapor flux, cloud-top entrainment rate, water vapor in the boundary layer, cloud liquid water content and drizzle rates.

Aerosol –Cloud –Radiative Forcing Link: Simultaneous measurement of cloud droplet distribution and the cloud albedo by flying the aircraft in a vertically stacked formation, vertical profiles of aerosol physical properties and bulk chemical properties will also be obtained.

Integrated Analyses: The integration of data collected under the Water Budget and Aerosol-Cloud-Radiative forcing link components; designed to lead to new insights into the research questions above.

2.2 Background and Motivation

The boundary layer clouds (Strat-CU and Trade-CU) are the dominant atmospheric regulators of the climate, first by reflecting solar radiation back to space (Strat CU is the major contributor; while Trade CU also has a role) and by aiding the air-sea-free troposphere exchange of water vapor (Strat CU and Trade-CU). They exhibit a large negative net cloud radiative forcing (CRF) due to a much greater shortwave to longwave radiative forcing ratio than that of higher level clouds (Hartmann et al., 1992; Ramanathan et al., 1989). Yet even after decades of observations and modeling attempts, the cloud, aerosol and radiative interactions have not been satisfactorily reconciled and future climate change forcing estimations remain highly uncertain (e.g. Bony and Dufresne, 2005; Clement et al., 2009; O'Hirok and Gautier, 2003; Ramanathan and Vogelmann, 1997 and references therin). At present the effect of climate change on even the sign of low-level cloud feedback is unknown (Forster, 2007). Clearly, it is imperative that further more research is undertaken to parameterize the processes which affect the formation and duration of these clouds, made all the more urgent by geo-engineering proposals designed to increase planetary albedo through the maintenance of boundary layer clouds (Salter et al., 2008).
On a fundamental level, Strat-CU and Trade-CU cloud systems can be thought of as being created, maintained and destroyed by interactions between atmospheric dynamics, aerosol chemistry and cloud physics:

Atmospheric Dynamics: Turbulent flux of moisture from the sea surface provides the moisture to sustain the cloud against desiccation by precipitation (drizzle) and by entrainment of air from the drier free-troposphere above. In essence, we can think of the cloud thickness and total liquid water content as being determined by the dynamics, to zeroth order. Clearly then, both these have to be measured simultaneously (i.e, for the same cloud system).

Aerosol Chemistry: Given the vertical velocity and the condensed moisture in the cloudy layer, the number and size of the drops are determined by the number of CCN. The aerosol physics and chemistry determine the CCN. CCN and Aerosol chemistry will be measured at the surface. One other quantity is vital in determining the drop number and size and that is the vertical velocity distribution, which has to be determined at the cloud base as part of the dynamics.

Cloud Physics: The cloud thickness, and the size and number of cloud drops determine the albedo of clouds, to zeroth degree. The morphology (shape of clouds is important for Trade CU) is less of an issue for the Strat-CU, which is horizontally extended. Clearly cloud albedos, both broad band and visible spectrum values, have to be measured simultaneously. One other physical process that may be important is the heating of the boundary layer by absorbing aerosols (black carbon and dust). Cloud-scale modeling with INDOEX data (Ackerman et al., 2000), suggests that the black carbon heating may be sufficiently large (Ramanathan, 2001) to speed up the late afternoon burning off of low clouds. So, the black carbon concentration must be determined as well as its contribution to cloud heating.

Several major field experiments (e.g. ASTEX; INDOEX; DYCOMS; RICO; and VOCALS), have provided a sound experimental background to explain the individual relationships between cloud process such as dynamics and entrainment, and aerosol-cloud interactions; a brief overview of these studies is given below (summarized in Table 1):

DYCOMS-I (Lenschow et al., 1988) looked at the properties of the subtropical marine stratocumulus clouds off the coast of California, as well as the budgets of some trace species (ozone, sulfur and nitrogen compounds and radionuclides), and techniques for measuring entrainment rates. The follow-up study **DYCOMS-II** (Stevens et al., 2003) , also studied the stratocumulus clouds of the Northeast Pacific, with a focus on entrainment and drizzle and their interactions and effects on cloud break-up. Flights were mainly performed at night to eliminate the effects of shortwave radiative forcing with a focus on the longwave cooling processes which drive the in-cloud turbulence and entrainment.

ASTEX (the Atlantic Stratocumulus Experiment) conducted over the northeast Atlantic Ocean in 1992 focused on the dynamics of the transition from stratocumulus to cumulus clouds in the subtropics (Albrecht et al., 1995).

The 1999 **INDOEX** addressed the role of atmospheric aerosols, studying their forcing and feedbacks on the climate system. While primarily focusing on the transport and direct (cooling) radiative effects of sulfate aerosol, the Indian Ocean site for this experiment was chosen for its wide variety of both natural and anthropogenic aerosol species, and its potential for studying cloud-aerosol interactions as well. Hence regional forcing from direct, indirect, and semi-direct aerosol could be derived, and black carbon was identified as a major contributor to surface and atmospheric forcing (Ramanathan, 2001).

The **RICO** (Rain in Shallow Cumulus over the Ocean) study isolated shallow cumulus convection in an area in the Caribbean in 2004-2005, and particularly focused on initiation and effects of precipitation in these clouds (Rauber et al., 2007).

A very recent campaign was the 2008 **VOCALS** study (e.g. Rahn and Garreaud, 2010; Ramanathan et al., 2007) which intended to study chemical and physical couplings between ocean, land and atmosphere, and aerosol-cloud-precipitation interactions in the Southeast Pacific. Although part of the original experimental design, to the best of our knowledge, radiative fluxes were not measured during this campaign. A main aim of this experiment was also to understand the dynamics and chemistry specific to the geographical focus area off the coast of South America.

Table 1: *Overview of major boundary layer cloud experiments*

EXPERIMENT	DATE	LOCATION	PRIMARY OBJECTIVE
Dynamics and Chemistry of the Marine Stratocumulus (DYCOMS-I)	Jul-Aug 1985	Pacific, off the coast of California	Study properties, formation and dissipation of stratocumulus, and budget of trace species in pristine, well-mixed and horizontally homogeneous boundary layer.
First ISCCP Regional Experiment (FIRE)	Jun-Jul 1987	Pacific, off the coast of California	Study physical processes in and radiative processes of stratocumulus clouds.
The Atlantic Stratocumulus Transition Experiment (ASTEX)	Jun 1992	Atlantic, off the coast of North Africa	Study the transition from stratocumulus to trade cumulus.
Indian Ocean Experiment (INDOEX) 1999	Feb-March 1999	The Maldives, Indian Ocea	Study natural and anthropogenic climate forcing by aerosols and feedbacks on regional and global climate
Dynamics and Chemistry of the Marine Stratocumulus (DYCOMS-II)	Jul 2001	Pacific, off the coast of California	Study the physics and dynamics of marine stratocumulus, specifically focusing on entrainment and drizzle
Rain In shallow Cumulus over the Ocean (RICO)	Nov- Jan 2005	Atlantic, off Caribbean islands	Study the initiation and effects of precipitation in marine cumulus.
VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experient (VOCALS-Rex)	Oct - Nov 2008	Pacific, off the coast of South America	Study chemical and physical couplings between ocean, land and atmosphere, and aersosol-cloud-precipitation interactions in the South-East Pacific

Our review of these experiments concludes that these studies have provided a sound experimental background to explain the individual relationships between cloud process such as dynamics and entrainment, and aerosol-cloud interactions, but that none them simultaneously (for the same cloud system) measured the dynamics (air-sea fluxes of vapor and momentum), the aerosol chemistry, aerosol optics, cloud albedos, air-sea surface fluxes, and entrainment of vapor between free troposphere and cloudy boundary layer. Thus leaving the stage set for us to explore the missing link in the aerosol-cloud indirect effects.

In our opinion, except for the very special case of ship tracks, *Q1* has not been answered experimentally (by in-situ data). One major issue is: The cloud-indirect effect theory (Twomey, 1974) requires the cloud liquid water content to be the same for polluted and pristine clouds. This assumption has been questioned by Twohy et al (2005). On a macro scale, Feng and Ramanathan (2010) examined the hemispheric asymmetries in low cloud optical depth and found them to be remarkably similar whereas the three dimensional aerosol, cloud chemistry, and physics model developed by them (with prescribed cloud water content and cloud cover) suggested the northern hemisphere clouds should have much larger optical depths and thus be brighter (Figure 1).

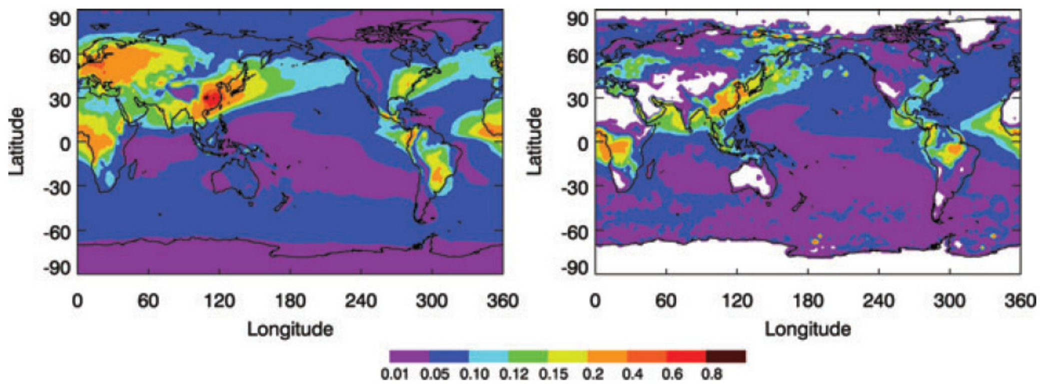


Figure 1: *Annual mean fine-mode aerosol optical depth at 550nm. Left-hand panel: the SIO model; right-hand panel: MODIS.*

Q1 investigates the relationship between the dynamics of the cloud layer and the distributions of water vapor within the cloud. Boundary layer clouds are typically capped by a warmer and drier free tropospheric inversion within a subsiding synoptic regime. Buoyancy-driven turbulence is generated primarily by cloud-top longwave radiative cooling coupled with latent heat supply from surface fluxes, and redistribution due to evaporation and condensation processes within the cloud. Turbulence at the top of the cloud acts to entrain drier, warmer air from a shallow layer (typically <100m) above. Recently it has been noted that absorbing aerosol present above the cloud layer aerosol appears to strengthen the capping inversion thereby enhancing cloud thickness and/or liquid water content (Johnson et al., 2004; Wilcox, 2010). Thus, by obtaining cloud thickness and water content information, and the water vapor budget (surface replenishment and entrainment loss) under different inversion strengths (not necessarily induced by BC heating aloft) we will be able to directly assess these assertions.

One of the outstanding problems in cloud processes is the link between entrainment processes and cloud microphysical structures – as warm, dry air is entrained into the saturated cloud tops below, cloud droplets will naturally begin to evaporate. By measuring this evolution within the same cloud system, some insight may be gained into *Q2*.

Q3 aims to target the relationships between perturbations of the cloud microphysical properties and albedo, parameters not easily measured, but desired for studies of the indirect effect on clouds. By utilizing the ability of UAVs to fly in close stacked formation, with precision accuracy, it is be possible to measure the albedo of the cloud from above and the microphysical characteristics of the cloud aerosol directly below.

Using the suite of UAV aerosol and radiation instruments, Q4 specifically seeks to investigate the effects of black carbon on the cloud lifetime – enhancement due to increased CCN availability, or suggested destruction due to heating of the cloud layer by black carbon increasing the rate of afternoon cloud burn-off (Ackerman et al., 2000; Ramanathan, 2001).

2.3 Experimental Description

2.3.1 Proposed Components

In this campaign, we are proposing to use small (65lbs takeoff weight) UAVs and ground based systems to make the necessary measurements. Each flight mission will be carefully planned to consist of up to two simultaneously flying UAVs fitted with one of four scientific payloads. As shown in Table 2, surface and airborne data will be integrated with relevant satellite data retrievals to fulfill the scientific objectives identified from the research questions above. Each component is described in more detail below:

Constraint of the 1D cloud layer water budget
For a vertical 1D representation of a boundary layer cloud (assuming horizontal homogeneity and atmospheric stationarity for a given averaging period) the net water (q_T) budget the cloudy layer extending from z=0 (the surface) to the inversion top (ZT)

$$[<dq_T /dt>]ZT = <wq_v>_0 - <wq_v>_{ZT} - P \qquad (1)$$

where the symbol < > indicates time average (typically the duration used for flux estimates) and [} denotes vertical average. The sum of the columnar liquid (LWC) and vapor water content (q_v) is the total water content, q_T, is modified by the addition of surface water vapor fluxes ($<w'q_s'>$) and removal of water vapor at the top of the cloud layer $<w'q_e'>$ (both measured and averaged during the interval t) and by precipitation, P, during the averaging period. Each term on the rhs of Eq 1is represented during the experiment: q_v by an insitu RTD/RH probe installed on each UAVs; LWC using a combination of UAV mounted liquid water probe (LWP) and a ground based microwave radiometer; supplied surface moisture, $<w'q_s'>$ and $<w'q_e'>$ from UAV measurements of water vapor flux profiles throughout the boundary layer; water removed from the column due to precipitation, *P*, will be measured by a laser disdrometer. By measurement of the water vapor concentration 'jump' across the boundary layer capping inversion (in addition to the vertical flux profiles), the entrainment rate will also be calculated using the equations of Lilly (1968) and Stevens et al (2003). Additionally, a water vapor flux system (sonic anemometer and infra-red gas analyzer) will be installed on a 30ft surface tower.

Measurements of cloud droplet distribution, cloud albedo, physical and chemical aerosol properties
Cloud droplet spectra (1<Dp<50µm) will be measured in-situ by a UAV equipped with a cloud droplet probe. For simultaneous albedo measurements, a second aircraft can be located directly above the first using differential GPS technology and visible (400 – 700nm) and broadband (0.3-2.8 µm) radiation fluxes measured using upward and downward facing radiometers. The radiation payload also contains an optical particle counter (OPC, 0.03<Dp<0.3 µm), a condensation particle counter (CPC, Dp>0.01µm) and a three channel aethalometer (370, 520, and 880nm absorption bands). An aerosol filter system for the bulk measurement of aerosol is being developed currently and will be added to the aerosol/radiation payload.
Supporting ground measurements will consist of a handheld sun photometer (Microtops) to measure aerosol optical depth (AOD), Broadband (285–2800nm), visible (400–700nm) and longwave (3.5–50 µm) radiometers. A ground based filter system will also be installed to capture aerosol for analysis for organic and elemental carbon (OC/EC), inorganic ions, organic tracers, metals, and dust components.

Integration of airborne, ground and satellite datasets

Table 2 indicates how the objectives identified from the research questions can be met using data from measurements from sections A and B above. Satellite measurements of parameters related to this study offer not only verification of our data, but also a mechanism by which to scale our relatively local-scale observations to more regional scales, but are limited in temporal and spatial resolution (most of the satellites provide a maximum of 2 overpasses per day). We intend to utilize radiative flux data from the CERES instrument; cloud droplet effective radius, aerosol optical thickness and cloud optical depth from the MODIS instrument; column liquid water path (LWP) can be obtained from the AQUA platform; and the CLOUDSAT radar can be used to highlight any regions of drizzle and, provided the cloud layers are >250m in thickness, provide information on cloud vertical extent. Further information on the cloud tops and broad aerosol types can be obtained from the CALIPSO satellite.

In addition to the tasks above, we seek to compare our data with external sources, such as the recently released NASA Goddard dataset: Satellite-based Surface Turbulent Fluxes (GSSTF) Data Set for Global Water and Energy Cycle Research Version 2b (GSSTF2b).

2.3.2 Location and Timing

To adequately complete the CARDEX objectives we have sought to identify a period when we expect the meteorology in the region to be largely consistent, yet interspersed with enough BC pollution events at <4km in altitude to allow investigation of black carbon effects on cloud burn-off and boundary layer heating, and also to provide sufficient variability in the measured parameters to detect such effects. In the Maldives, the dry monsoon (often called the Northeast monsoon) is typically active from November to April, when the wind comes from the northeast (with an increasing consistency from January) and brings air from the Asian continent out over the Indian Ocean. As a result, the region becomes charged with black carbon and other anthropogenic pollutants. This is in contrast with the wet monsoon (June- September) where warm, moist air travels from the south west towards the Indian subcontinent and is generally less polluted; hence CARDEX is best performed within the dry season.

Focusing on the dry monsoon period from January, back trajectory and surface station data (from the Maldives Climate Observatory, MCOH) display a consistent pattern of easterly winds in February sourced from near the Indo-Gangetic region, transitioning annually to more easterly sources between the end of March and May (Figure 2). MCOH data also indicate an increase in single-scattering albedo (a measure of particle reflectiveness and hence composition) from the beginning of March, indicative of a declining fraction of BC in the aerosol mass. Columnar measurements of the AOD show a range of 0.2-0.7 between 2005-2009 and the associated Angstrom exponent (essentially the dependence of AOD on wavelength) suggests smaller particles dominate the aerosol column until mid April. Vertical aerosol extinction profiles obtained from the grid 9.0N-4.0N, 70.50E-75.5E (Maldivian region) show a clear increase in aerosol content in the 0.5km region from January to April, with a smaller and broader increase from 1-4km (Figure 3).

There is a balance to be met in CARDEX timing between the desired source region of the Indo-Gangetic plains and increasing pollution from this region during the dry monsoon, and the timing of the meteorological and source region changes associated with the monsoon transition beginning at the end of March. Based on the information discussed above, we will request airspace access from the Maldivian authorities for the period **February 15th - March 15th 2011** to conduct CARDEX. This may also allow collaboration with the DYNAMO and GVAX campaigns occurring concurrently in the Indo-Gangetic and Southern Indian Ocean regions respectively.

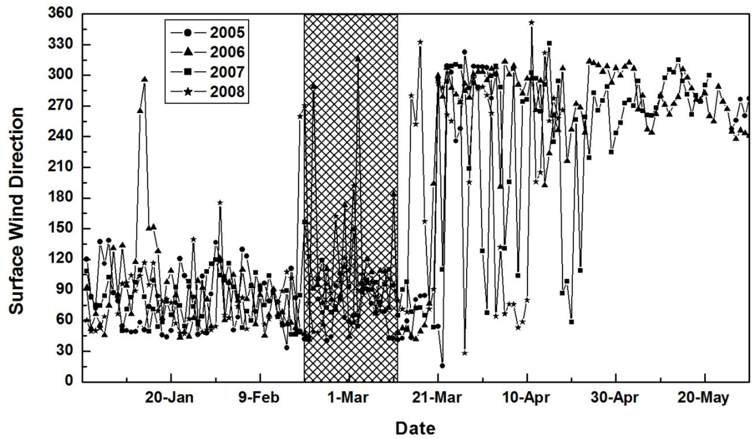


Figure 2: *Day to day variation of surface wind direction at Maldives Climate Observatory – Hanimaadhoo during October 2004 to July 2008.*

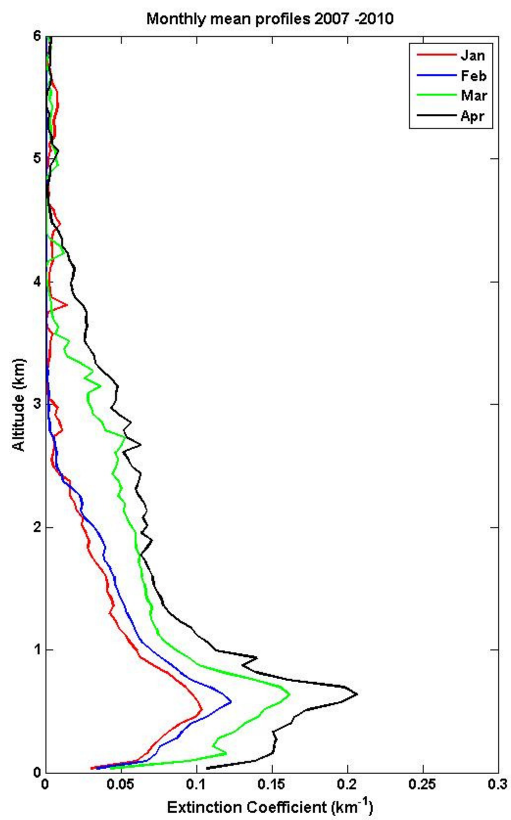


Figure 3: *Monthly mean vertical extinction profiles measured by CALIPSO over the grid 9.0N-4.0N, 70.50E-75.5E (Maldives region) during dry season of 2007- 2010.*

2.3.3 Flight Planning and Patterns

Day-to-day flight planning will follow the successful procedures used in past UAV missions, notably the MAC (2006) and CAPMEX (2008). In general, selection of target objectives and development of a flight plan prior to each mission will rely on forecast simulations, analysis of near-real-time satellite data and satellite and ground based remote sensing data, weather model output, back trajectory analysis, inputs from the UAV science team, and reviews of progress in meeting mission objectives. An experimental schematic showing the approximate flight setup is shown in Figure 4.

From the matched list of objectives and measurements in Table 2, each flight mission requires two payloads to be flown either simultaneously, or within a short duration of each other. The typical aerosol-radiation payload flight pattern includes vertical profiling from the surface up to 2-3 km altitude to profile aerosol, and then either in-cloud for Objectives 1 & 2 or above-cloud (Objective 5). Flux flight paths also profile the boundary layer and, conduct multiple horizontal flux averaging legs at altitudes form the surface to above the entrainment layer, and for the greatest permissible horizontal distance (depending on airspace and time constraints) to record the vertical flux divergence profile. The cloud microphysics UAV will be flown during each mission and will generally profile the cloud layer for the duration of the mission. For Objective 5 the flight of the cloud microphysics UAV will be closely coordinated with the aerosol radiation payload in stacked formation. Where possible, all flights will be co-located with the surface measurement station, and additional UAV flybys will be performed during takeoff and landing to compare/calibrate the UAV measurements against surface data.

Figure 5a gives an approximation of the UAV work area for which permission will be requested from the relevant Maldivian authorities. Two zones are selected: Zone A is a near-shore zone for use in inclement weather; Zone B is the larger, operational zone which provides the space required to properly fulfill the objectives. We anticipate that the flights in Zone B will slowly increase in horizontal distance as the experiment progresses and the flight operational procedures specific to Hanimaadhoo become well rehearsed. For example, the pyranometers require level flights of >5km to achieve thermal equilibrium in the sensor. More stable results will be achieved by increasing the run length, balanced against the number of runs required and the available flight time. Similarly, in order to adequately sample low frequency turbulent eddies, the run length must be increased with altitude; for this purpose, we anticipate a small number of flights will complete flux runs of close to 100kms, but typically a series of shorter runs, flown in a racetrack pattern will be conducted at several altitudes, as shown by the example in Figure 5b.

2.3.4 UAV Description

Small UAVs, such as the BAE Systems *Manta*, have been previously launched and recovered from remote field camps. The proposed campaign thus will use a proven UAV platform and models of instruments that have been successfully operated in previous deployments.

BAE's *Manta* UAV offers an economic, compact, durable and aerodynamic platform with extended flight endurance. Currently, the *Manta* is capable of carrying a 5 kg payload (not including fuel) during a 5-hour flight. The Manta aircraft are equipped with differential GPS (DGPS) capability and perform automated takeoff and landing when commanded. The DGPS gives the aircraft the ability to control its flight path to within less than 1 meter. A rolling takeoff requires about 200 meters of smooth, flat surface and another 200 meters of unobstructed space for climb out. Landing requires an unobstructed approach of 400 meters and a 200 meter rollout. Iridium satellite communication will be used for beyond-the horizon missions. The aircraft has a service ceiling of 16,000 feet and can climb to 10,000 feet in under 15 minutes. With only slight modifications, it can carry both internal and external instrumentation and sensors. These UAVs are ideally suited for the scientific goals of CARDEX because they are the only platform which will permit the required close coordination in time and space. Precision stacked formation of 2-3 aircraft has been proven during the MAC campaign in March 2006 and the Cheju ABC plume Asian Monsoon Experiment (CAPMEX) in August-September 2008. Currently, SIO have three operational aircraft.

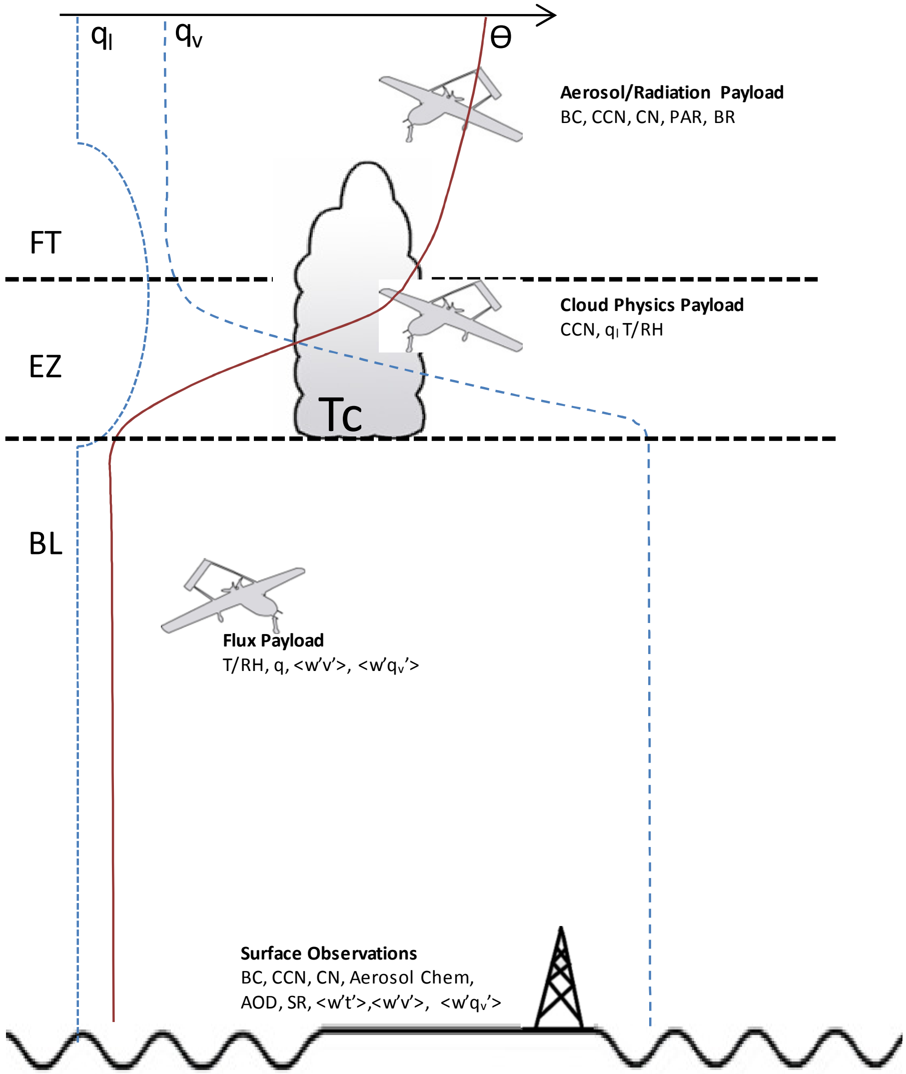
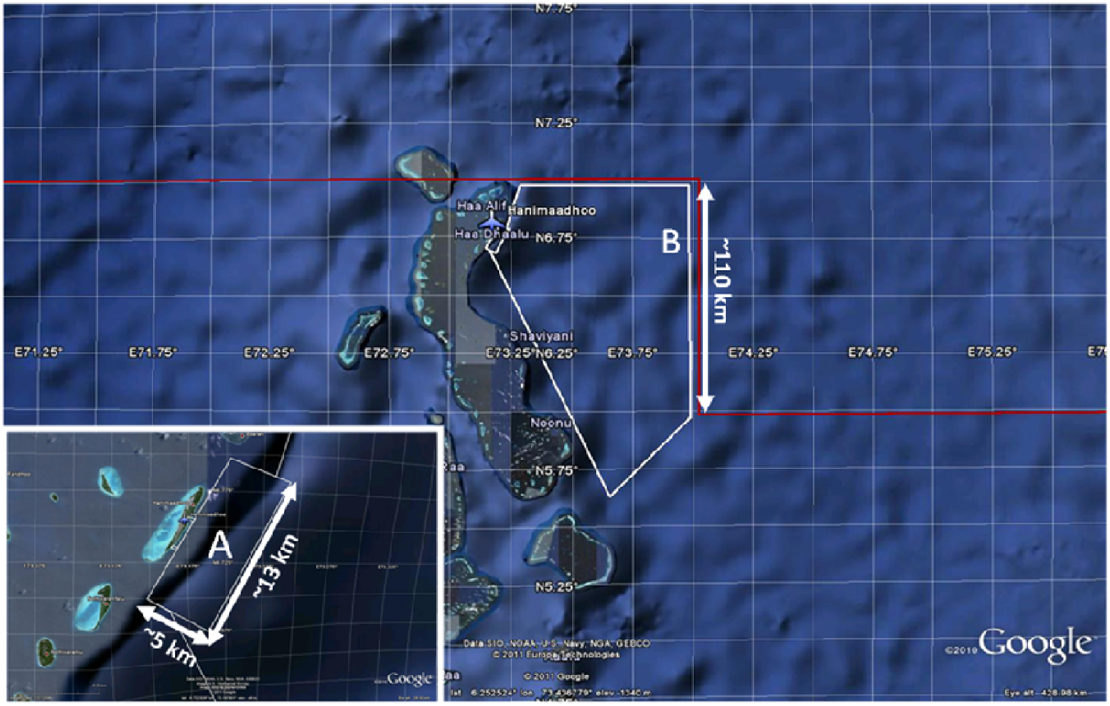
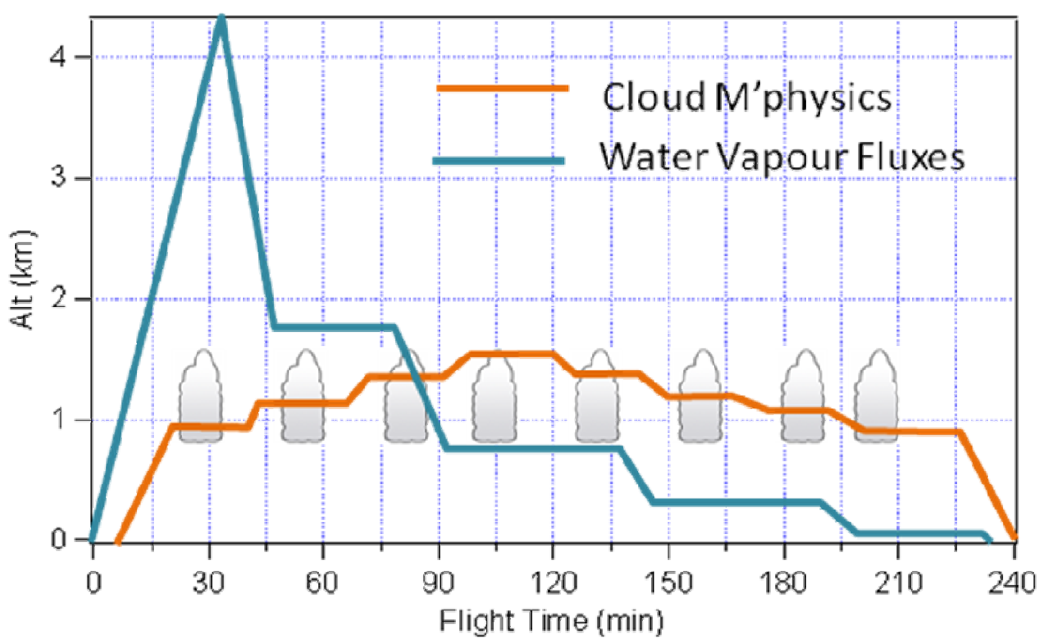


Figure 4: *Schematic of the proposed measurement approach showing all three aircraft (a maximum of two aircraft will fly simultaneously) and their approximate locations. Idealized traces of potential temperature (θ), and water in liquid (q_l) and vapor (l_v) forms for a trade cumulus (Tc) cloud are shown. FT, EZ & BL are Free Troposphere, Entrainment Zone and Boundary Layer respectively. Black carbon (BC), Cloud Condensation Nuclei (CCN), Condensation nuclei (CN), Photosynthetically Active Radiation (PAR), and Broad band radiation (BBR) are measured by the upper aircraft, flown in synchronized formation with the in-cloud microphysics platform which measures Cloud Droplet Spectra (CDS)and liquid water content. Surface measurements include Aerosol Optical Depth (AOD), sensible heat and momentum fluxes (<w't'> and <w'v'> respectively) and liquid water path (measured by a microwave radiometer).*



(a)



(b)

Figure 5:(a) Anticipated work area for the UAVs showing the near-shore zone (A, inset) for use during inclement weather. **(b)** Example flight profile for Objectives 3 & 4.

Table 2: *The combination of Airborne, ground and satellite measurements required to fulfill scientific objectives.*

		Airborne Measurements												Ground measurements												Satellite measurements						
Payload:		*All*		*Aerosol/Radiation*						*Flux*		*Cloud M'phys*																				
Objectives	Number of UAVs	θ	q_v	Aerosol chemistry	BBR (285-2800nm)	PAR (400-700nm)	CN (Dp>0.01µm)	Aerosol size distributi	BC	Turbulence Paramete	$<w'q_v'>$	Cloud Droplet Spectr:	q_l	BC	CCN	CN	Aerosol Chemistry	Drizzle rate	AOD	LWP	LWR (3.5-50µm)	PAR (400-700nm)	BBR (285-2800nm)	Turbulence paramete	$<w'q_v'>$	CL'DSAT/ CALIPSO: Cloud thickness	MODIS: Cloud optical depth	MODIS: Cloud drop effective	AQUA: Liquid Water Path	MODIS: Aerosol optical	CALIPSO: Aerosol type	CERES: Radiative fluxes
1) Linking aerosol chemistry and cloud microphysics (number and size)	2	✓	✓	✓								✓	✓	✓	✓	✓	✓		✓	✓										✓	✓	
2) Linking CCN and cloud droplet size distribution	2	✓	✓				✓	✓	✓			✓	✓	✓	✓	✓			✓	✓								✓				
3) Linking surface fluxes, cloud depth and cloud liquid water content	2	✓	✓							✓	✓	✓	✓					✓	✓	✓	✓			✓	✓	✓	✓		✓			
4) Linking entrainment fluxes, cloud liquid water content and effective radii	2	✓	✓							✓	✓	✓	✓							✓				✓	✓			✓	✓			
5) Linking cloud depth, cloud drop number, effective radii and cloud albedo	2	✓	✓		✓	✓	✓	✓	✓			✓	✓								✓	✓	✓		✓	✓	✓	✓	✓			✓

2.3.5 Payload Description

New Capability: Water Vapor Fluxes

The water vapor flux system consists of a turbulent gust probe, an inertial navigation sensor and a fast response humidity sensor all logging data at 100Hz (Fig. 8). Thus the system captures sufficient information about the atmospheric turbulence, the motion of the aircraft, and water vapor fluctuations to derive the Reynolds decomposed vertical wind and water vapor fluctuations (*w'* and *q'* respectively), enabling computation of the time-averaged eddy covariance flux <w'q'>. Two test flights were conducted on May 27th 2010 at the Nasa Dryden lakebed test facility located within Edwards Air Force Base, California. One flight was in the morning and one in the afternoon for 2.5 hrs and 1.5 hrs in duration respectively. The lake bed offers excellent test flight facilities due to the large, smooth nature of its surface, allowing landing and take-off in all directions. For comparison with a well established measurement technique, colleagues at NOAA installed eddy covariance water vapor flux measurement instrumentation system on a 30ft mast close to the test location.

Both flights followed a similar racetrack pattern (Fig. 6), at up to four altitudes ranging from 1km to 1.6km above mean sea level (Fig. 6, inset), with horizontal legs of <8.5 km – the maximum leg length possible in the UAS work area at the facility. Two to three patterns were conducted at each altitude. Strengthening southwesterly winds during the day led to the reduction in the duration of the second flight due to safety concerns.

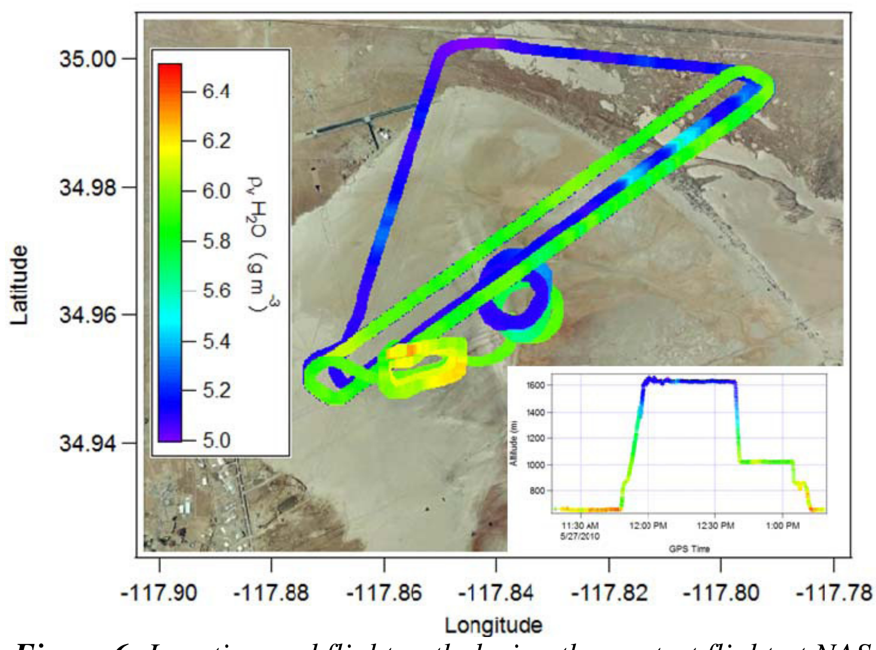


Figure 6: *Location and flight path during the pm test flight at NASA Dryden, 27th May 2010.*

The flight and flux systems performed well on the 27th, enabling the successful collection of high-frequency data in both the morning and the afternoon flights. It is important to note the experiment was not conducted at ideal altitudes for tower comparisons because low flying is a risk worth taking only when we know desirable data will be collected. Therefore we do not expect λE to agree directly with the surface tower measurements but to offer a linearly diverging trend with altitude. In fact, the calculated 5 minute fluxes for the along wind legs at each altitude show not so much a linear trend, but are centered around a zero flux (within the standard error of these measurements). This is in agreement with the surface tower system, which measured an emission flux of ~1 W $m^{-2}s^{-1}$, using both 15minute and 30 minute averaging periods (Figure 7a). Turbulent power spectra for the vertical wind component, *w*, are also observed to adhere to the theoretical -2/3 slope (expected for fS(f) plots) and also demonstrate close agreement with the surface measurement site within the frequency range 0.5-5Hz.

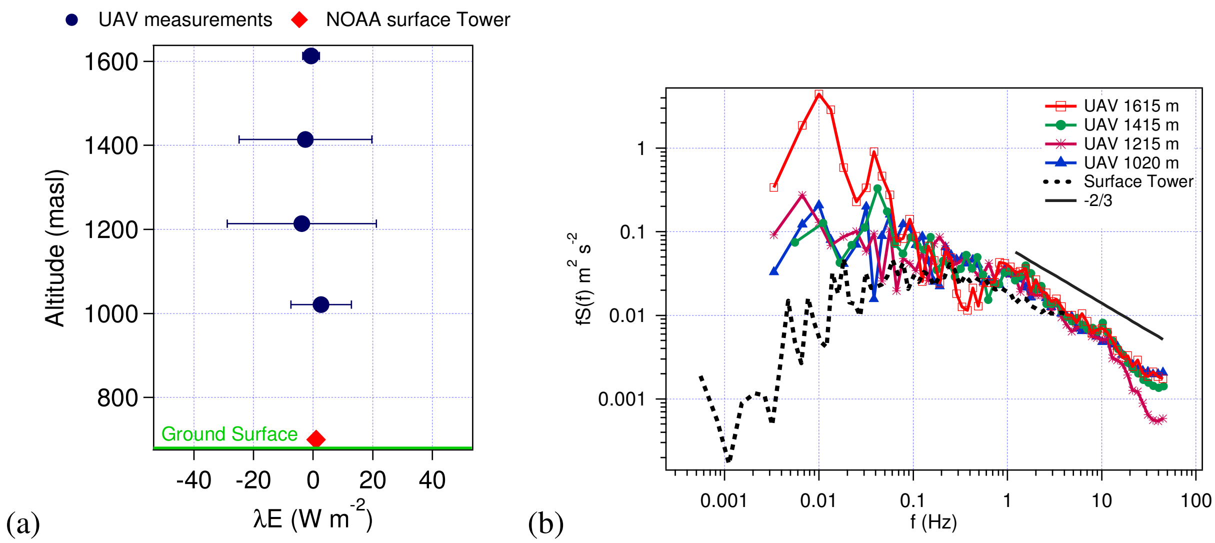


Figure 7: *(a) Water vapor fluxes at four measurement altitudes derived from along-wind legs using a 300 second averaging window.(b) Power spectra of vertical wind measurements used in the computation of flux data, showing theoretical -2/3 line within the inertial sub-range. 15 minute surface tower measurement data is shown in both graphs for comparison.*

From these measurements, the minimum resolvable vertical wind velocity was calculated to be 0.17m/s – similar to estimates of manned aircraft systems (e.g. Garmen et al., Kalogiros and Wang) – but still leaving room for improvement. Due to the shortened afternoon flight, gust probe calibration maneuvers were not performed; these along with improved system grounding/wiring and the possible integration of DGPS with the inertial sensor unit should reduce system error considerably.

The agreement between the surface tower and the UAV data is encouraging, but Dryden's situation in the Mojave Desert naturally does not lend itself for proper validation of water vapor flux data. Following the successful test of the systems here we intend to undertake an additional marine test in Autumn 2011, prior to the proposed campaign.

Pre-Existing Capabilities: Aerosol/Radiation and Cloud Microphysics

Experiments by our group, such as the Maldives UAV campaign (March 2006), the California Air Pollution Campaign at Edwards AFB/NASA-Dryden (April-October 2008), the Beijing Olympics Campaign from *Cheju*, S. Korea (August-September 2008), and the Vandenberg AFB experiment (November 2008), have demonstrated the specific use of UAVs for aerosol-cloud-radiation-climate studies.
Figure 7 shows the various instruments developed during the MAC campaign available for use on the UAV. Developed aerosol and radiation flux instruments are modified for inclusion into

the aircraft from commercially available versions, and as such have shorter lifetimes than their commercial counterparts due to the extra strain incurred by flight conditions. To minimize the risks to data collection from this campaign a complete set of UAV aerosol/radiation instruments are required (the current sets are nearing the end of their lives) and a spare water vapor flux measurement system (there is no duplicate at present), as well as two spare data loggers (a crucial hub to the aerosol/radiation instruments and the CDP/LWC probes) and aerosol inlets (easily bent on improper landings), it is critical to have a replacement cloud droplet probe on hand because it is crucial to every mission (Table 2) and currently only one exists in the C^4 instrument pool.

The payload (about 3-4 kg per aircraft) includes instruments and data systems developed for lightweight UAVs. Each miniaturized instrument is described below:

Condensation Particle Counter (CPC)**:** The CPC measures total aerosol concentrations between 0 and 10^5 cm^{-3} in the diameter range (0.01μm < D < 1.0μm). The CPC serves as a reference for comparison with other aerosol measurements, and as an indicator for clean versus polluted regimes. The Model 3007 is TSI's smallest CPC and has been integrated into the fuselage of the UAV.

Optical Particle Counter (OPC): The OPC measures ambient aerosol size distributions between 0.3 and 3 μm diameter. Since aerosols cover a wide range of sizes, it is fundamental to have an understanding of the size distribution. The MetOne OPC has been repackaged and integrated into the fuselage.

Aethalometer (AETH): Light absorbed by aerosol particles reduces the amount of sunlight reaching the earth's surface while simultaneously heating the surrounding air. The miniaturized aethalometer measures the absorption of the aerosol by depositing the particles onto a fibrous filter and observing the change in light transmission and can detect concentrations >50 ng/m^3 with an averaging time of 30 min; longer averaging times can be used for greater sensitivity. The instrument is typically calibrated to give results in concentration of black carbon per volume of air, comparing favorably with filter measurements ob BC (Corrigan *et al.,* 2006), and the raw absorption data can also be used to estimate the absorption coefficient for in-situ aerosols by using empirical corrections (Bond et al., 2004).

Broadband Radiometer (Pyranometer): The pyranometer accurately measures the solar radiation, defined as the downward direct and diffuse radiation received on a horizontal surface for a broad spectral range. Downward solar irradiance is the forcing function for surface climate processes and is measured by an upward-facing horizontal pyranometer. Conversely, a downward-facing pyranometer measures the amount of downward solar irradiance reflected back towards space by clouds, or aerosols, or the earth's surface. The ratio of upward and downward solar irradiance yields the albedo. During MAC, the Kipp & Zonen made CM 21 pyranometers ware used to measure downward and reflected solar radiation in the spectral range of 0.3-2.8 μm. We have reduced the pyranometer mounting structures and added an amplified circuit and temperature probe.

Narrowband Radiometer (Photosynthetic Active Radiation, PAR): The solar radiation for plant growth occurs in the spectral band from 0.4-0.7 μm wavelengths and is called Photo-synthetically Active Radiation (PAR). This region is important because aerosols contribute 70-

80% of the atmospheric absorption in the visible region (Ramana et al., 2007), and this region avoids any near-infrared water vapor absorption.

Aerosol Filter system: This system is currently under development, but is a relatively simple device which utilizes a spare port on the existing UAV aerosol inlet system to actively collect a minimum of 6 lpm of aerosol onto a 25mm quartz fiber filter, triggered at a programmable altitude. Currently attempts are being made to increase the flow rate to increase filter loading to enable analysis to be made other than the currently obtainable OC/BC ratio (based on an estimated atmospheric loading of 0.2 – 2.0µg/m3).

2.3.6 Calibration and Validation of Instruments

Calibration and validation of the miniaturized aerosol, cloud and radiometric instruments ensures their scientific integrity. The Aerosol-Radiation-Cloud instruments have been well characterized in previous UAV experiments (Corrigan et al., 2008; Ramana et al., 2007; Ramanathan et al., 2007; Roberts et al., 2008). All instruments will be calibrated and validated before launch. During the campaign, the complete instrument package will be compared with ground based instruments to validate performance. In addition, occasional flights past the surface measurement site at low altitude will provide the opportunity to compare in-situ measurements of the UAV instruments with ground based data.

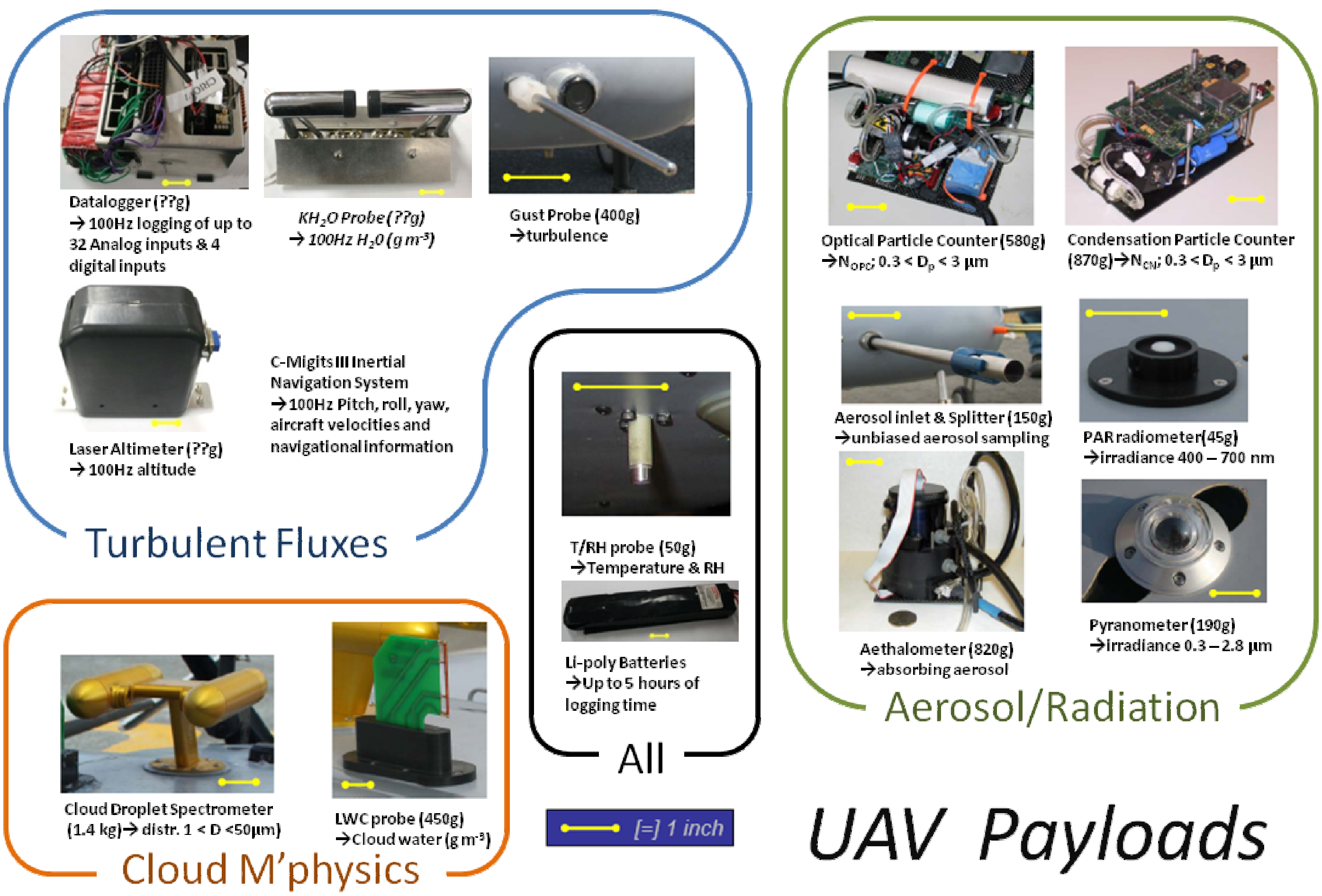


Figure 8: *Diagram showing major instrument components of each payloads, and the batteries and Temperature/Relative Humidity sensor common to all payloads.*

2.3.7 Surface Measurements

The MCOH observatory is well equipped with meteorological, radiation and aerosol characterization instruments (Table 3) and their use is paramount to the success of this project for two reasons 1) they allow comparison of the UAV instruments with well-characterized, stable instruments; and 2) they are required to fulfill the objectives (Table 2). In the first instance we envisage, UAV instruments pyranometers, PAR sensors, CPC and OPC, temperature and RH sensors will be checked against their MCOH counterparts (CM 21 Pyranometer, Narrowband radiometer, CPC 3022A, CCN counter, AWS, respectively) to confirm reliability. Low-altitude flybys will be performed during the campaign phase for further verification. This is essential for pickup of instrumental drift and faults anticipated to occur when flying such delicate instruments in aircraft. Secondly, although we anticipate some differences between the surface measured aerosol properties and those at altitude (depending on meteorology encountered), the characterization by the suite of instruments available at MCOH is much greater than those squeezed into the 5kg payload limit of the UAVs. All available aerosol characterization data will likely be useful particularly for objectives 1 and 2, where links between aerosol chemistry and cloud microphysics and CCN and cloud droplet size, are explored. As well as for calibrations, the comprehensive radiation measurements at MCOH will be of particular benefit to Objective 5.

A number of additional instruments will be required; we require the liquid water path of the boundary layer and the use of a microwave radiometer is being sought to make such measurements. Surface turbulent flux instrumentation would be desirable, SIO shall temporarily install a Gill sonic anemometer (for wind components u,v, and w, and sensible heat flux, H) and if possible source a fast response water vapor probe.

We will request that the campaign can occur in Feb-March 2012 and will liaise with the MCOH operators to assist where possible to ensure all required instruments are operating smoothly and to select suitable locations for the instruments we hope to setup.

2.3.8 Scientific Impacts

The research conducted under this proposal is of great societal interest. It will generate new integrated data sets of water budget, cloud microphysical, and radiative forcing properties. These enhanced observations, with improved spatial and temporal coverage will be critical for furthering our understanding or cloud feedback systems, and are of particular current relevance regarding the uncertainties surrounding marine low cloud geo-engineering proposals.

The data collected are certain to provide a major reference in the decades ahead for our understanding of boundary layer cloud's response to climate change. In addition, using the strength of UAVs to simultaneously measure multiple components of the same cloud system, whilst only perturbing the cloud to a minor degree, further demonstrates and develops the scientific ability to utilize these platforms to deliver new insights into urgent atmospheric issues.

Table 3: *Instrument list and status at the Maldives Climate Observatory.*

	Instrument type & Manufacturer	Parameter	Operating
	Radiation Measurements:		
1	CM 21 Pyranometer (0.3-2.8 µm) **Kipp & Zonen**	Diffuse solar radiation	Yes
2	CM 22 Pyranometer (0.2-3.6 µm) **Kipp & Zonen**	Diffuse solar radiation	Yes
3	CM 21 Pyranometer (0.3-2.8 µm) **Kipp & Zonen**	Global solar radiation	Yes
4	CH1 Pyrheliometer (0.2 - 4.0 µm) **Kipp & Zonen**	Direct solar radiation	Yes
5	Pyrheliometer with Quartz window, Pyrheliometer with Calcium Florid window, **Eppley**	Direct solar radiation	Yes
6	CG4 Pyrgeometer (4.5 – 42.0 µm), **Kipp & Zonen**	Net radiation in the far IR	Yes
7	2AP-GD Sun tracker with sun sensor, pointing and shading ball assembly, **Kipp & Zonen**	Sun tracking	Yes
8	Narrowband radiometer GUV-2511 (0.305, 0.313, 0.32, 0.34, 0.38, 0.395, 0.4-0.7 µm) **Bio-Spherical Instruments**	Global PAR	Yes
9	Hand-held Spectroradiometer **Analytical Spectral Devise Inc.**	Irradiance Spectrum	NO
	Aerosol Optical Depth (AOD), O_3 column, water Vapor		
10	Microtops II Sunphotometer (AOD at 380, 440, 500, 675, 870, 1020 nm; PWV at 940 nm) **Solar Light Co.**	Aerosol spectral optical depth	Yes
11	CIMEL Sunphotometer (AOD at 340, 380, 440, 500,670, 870, 1020 nm; PWV at 940 nm) **AERONET**	Aerosol spectral optical depth, Columnar Precipitable water vapor	Yes[1]
12	Microtops II Ozonometer (305, 312, 320nm), **Solar Light Co.**	Columnar Ozone Precipitable water vapor	Yes
13	Micro pulse LIDAR at 523 nm, **Science and Engineering Services Inc.**	Aerosol Vertical Profiles	NO
	Meteorology		
14	**AWS, R. M. Young Company instruments**	Meteorological Parameters	Yes

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4. Biographical Sketches

V. RAMANATHAN

(a) Professional Preparation:

Annamalai University, India	Engineering	B.E., 1965
Indian Institution of Science,	Engineering	M.Sc., 1970
State University of New York at Stony Brook	Planetary Atmosphere	Ph.D., 1974

(b) Appointments:

Research Positions:

1990- date: Victor C. Alderson Professor of Applied Ocean Sciences, and Professor of Climate and Atmospheric Sciences, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
1991-date: Director, Center for Clouds, Chemistry and Climate, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
1996-date: Director, Center for Atmospheric Sciences, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
1998: First K.R., Ramanathan Visiting Professor, Physical Research Laboratory, India
2004-date: Distinguished Professor of Atmospheric and Climate Sciences, Scripps Institution of Oceanography, University of California, San Diego

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OTHER POSITIONS:

1992-date: Board of Directors, Tata Energy Research Institute, Arlington, Virginia
1993: Chief Scientist, Central Equatorial Pacific Experiment (CEPEX)
1996-2002: Co-Chief Scientist, Indian Ocean Experiment (INDOEX)
1996-2002: Chair, International Steering Committee, (INDOEX)
1999-date: Science Editorial Board, NASA Earth Observatory
2002-date: Co-Chief Scientist, The Atmospheric Brown Cloud Project (ABC)
2002-date: Member, Geophysical Institute Review Panel for Atmospheric Sciences
2005-date: Member, Advisory Board, World Clean Air Congress
2005-date: Member, NCAR, Earth Observing Laboratory External Advisory Committee
2005-date: Chairman, ABC project
2006-date: Chair, United States Climate Change Science Program (CCSP)

(c)PUBLICATIONS:

Related to the proposed project

Flanner, M.G., C.S. Zender, P.G. Hess, N.M. Mahowald, T.H. Painter, V. Ramanathan, and P.J. Rasch: Springtime warming and reduced snow cover from carbonaceous particles. *Atmos. Chem. Phys.,* 9, 2481-2497, 2009.

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Other Significant publications:

Ramanathan, V. and Y. Feng: Air pollution, greenhouse gases and climate change: global and regional perspectives, *Atmospheric Environment,* 43*,* 37-50, 2009.

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Kim, D., and V. Ramanathan: Solar radiation budget and radiative forcing due to aerosols and clouds. *J. Geophys. Res*., 113, D02203, doi:10.1029/2007JD008434, 2008.

(d) Synergistic Activities: Committee Memberships:

Member, Committee for the 2008 Trieste Science Prize, 2008-date

Chair, Committee on Strategic Advice on the US Climate Change Science Program, National Academy of Sciences, 2006-date

Member, Environment and Sustainability Steering Committee, University of California San Diego, 2006-date

International Advisory Board, International Union of Air Pollution Prevention and Environmental Protection Associations (IUAPPA), 2005-date

Member, Ocean Research Awards Committee, American Meteorological Society, 2005-date

Member, Awards Oversight Committee, American Meteorological Society, 2005-date

Member, Advisory Board, World Clean Air Congress, 2005-date

Steering Committee Chair, National Aerosol-Climate Interactions Program, 2002-date

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(a). Professional Preparation

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2007-2009	*Postdoctoral Researcher,* Formation, emission and fates of inorganic agricultural particles, Centre for Ecology and Hydrology (CEH, Edinburgh) and The University of Manchester.
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2001-2003	*Consultant*, Enviros Consulting Limited
2000-2001	*Contaminated Land Analyst*, ESW Scientific, Edinburgh
1999	*Laboratory Assistant*, Environmental Geochemistry Laboratory, The University of Edinburgh

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E.2. Graduate and Postdoctoral Advisors

Graduate advisor: Greg Cowie (University of Edinburgh, UK)
Postdoctoral sponsor: Eiko Nemitz (CEH, Edinburgh) and Hugh Coe (The Univeristy of Manchester)

E.3. Thesis Advisor and Postgraduate-Scholar Sponsor

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University of Sai Gon, Viet Nam Graduated from Pharmacy School Pharmacy, 1975
National University, San Diego Business Administration BBA, 1985
National University, San Diego Business Administration & Finance Mgt. MBA, 1987
UC Management Institute, UC Irvine Management Certificate,1999

(b) Appointments

1985-1988	Instructional Services Supervisor, San Diego Community College District
1988-1991	Management Services Officer, Graduate School of International Relations and Pacific Study, University of California, San Diego
1991-1992	Management Services Officer and Assistant Director, Administration Scripps Institution of Oceanography, University of California, San Diego
1992-2001	Assistant Director, Center for Clouds, Chemistry and Climate Scripps Institution of Oceanography, University of California, San Diego
2001-	Associate Director, Center for Atmospheric Science

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1992	Executive Secretary, Science Team, the Central Equatorial Pacific Experiment (CEPEX)
1995-2001	Executive Secretary, the International Steering Committee, the Indian Ocean Experiment (INDOEX)
2002-	Executive Secretary, the Science Team, Project Atmospheric Brown Clouds (ABC). Program Manager, ABC Surface Observatories.
2004	Program Manager, the ABC Post Monsoon Experiment
2006	Mission Director, the Maldives Autonomous-UAV Campaign (MAC)
2008	Mission Director, the California AUAV Air Pollution Profiling Study (CAPPS)
2008	Mission Director, CAPMEX (UAV campaign in S.Korea)
2008	Mission Director, PACTEST (UAV campaign at Vandenberg air force base, CA)

(c)PUBLICATIONS

Related to the proposed project

Ramanathan, V., F. Li., M.V. Ramana, P.S. Praveen, D. Kim, C.E. Corrigan, H. Nguyen, et al.: Atmospheric brown clouds: Hemispherical and regional variations in long range transport, absorption, and radiative forcing, J. Geophys. Res., 112, D22S21, doi:10.1029/2006JD008124, 2007.

Ramanathan, V., G. Roberts, C. Corrigan, M. Ramana, and H. Nguyen: Maldives AUAV Campaign (MAC): Observing Aerosol-Cloud-Radiation Interactions Simultaneously from Three Stacked Autonomous Unmanned Aerial Vehicles (AUAVs), http://www-abc-asia.ucsd.edu/MAC/MAC_proposal_FINAL_2005July05.pdf, 2005b.

Ramanathan, V., G. Roberts, H. Nguyen, M. Ramana, C. Corrigan, M. Patterson, and T. Mulligan: First Observations with a New Observing System of Stacked Multiple UAVs for observing effects of air pollution on Clouds and Climate Forcing, in NASA Earth Science Technology Conference, http://www-abc-asia.ucsd.edu/MAC/RamanathanESTAbstract2006.pdf, College Park, University of Maryland, 2006a.

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(d) Synergistic Activities:

Committee Memberships:

Member, Executive Steering Committee of Civilian Applications of UAS in US (CAUAS)

(e) Collaborators and other Affiliations: N/A

(d) Synergetic Activities: N/A

(e) Collaborators & Other Affiliations

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Thesis Advisor and Postgraduate-Scholar Sponsor: N/A