Maldives AUAV Campaign (MAC)

Observing Aerosol-Cloud-Radiation-Climate Interactions Simultaneously from Three Stacked Autonomous Unmanned Aerial Vehicles (AUAVs)

Report of the Field Campaign Held from March 05 to March 31 2006 at the Island of Hanimaadhoo, Maldives.

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The National Science Foundation (J. Fein)
The National Oceanic and Atmospheric Administration (C. Koblinsky)
The National Aeronautics and Space Administration (H. Maring & C. Yuhas)
Ministry of Environment, The Government of Maldives (Deputy Minister, Dr. A. Majeed)

Hanimaadhoo Airport

Hanimaadhoo Island

I. ***Overall Summary:***

From March 6 to March 31 2006, we probed the polluted atmosphere over the N. Indian Ocean with light weight Unmanned Aerial Vehicles (or UAVs) fully equipped with instruments. This UAV campaign launched from the Maldives laid a solid foundation for the use of UAVs to study how human beings are polluting the atmosphere and their impact on climate, including global warming.

Particles in the pollution enter the clouds from below; producing more cloud drops; the clouds in turn reflect more sunlight back to space. In addition the particles suppress rainfall. The particles also directly scatter and absorb sunlight, thus shielding the surface from sunlight. These and other interactions between particles in pollution, clouds and reflected solar radiation are one of the fundamental challenges in the global warming problem, which we need to resolve before we can reliably answer questions such as: How large is the global warming going to be in the future?

It is this particles-cloud-solar radiation interaction which we were observing with UAVs. It requires one aircraft below the cloud to observe the nature and number of particles entering the cloud and the amount of sunlight penetrating through the cloud and the particles; one inside the cloud to document how the clouds are responding to the particles; and one above the clouds to measure the sunlight reflected by clouds and the particles that are exported out of the clouds. We need all three aircraft in stacked formation measuring simultaneously over the same cloud system… we need the 3 aircraft observing the same cloud within a fraction of a minute of each other, in view of the fast time life times of most clouds.

During the four weeks in March 2006 at Maldives, we proved that light weight UAVs are uniquely suited to conduct such an experiment. MAC logged over 120 flight hours that included 55 takeoffs and 18 science mission. The science missions collected data on pollution and dust transported from S. Asia, Arabian and SW Asian deserts and their impacts on global dimming at the sea surface, the energy absorbed in the atmosphere and cloud properties. We made direct measurements of the role of black carbon in the solar heating of the atmosphere. Hundreds of polluted and dusty shallow cumulus clouds were penetrated with the in-cloud aircraft. The above cloud and below cloud UAVs were stacked within ten seconds of the in-cloud UAV with minimal pitch such that reliable solar radiation measurements could be made. The UAVs were flown not only in stacked formation but also in tandem (wing tip to wing tip with 1 km apart) formation to validate the reliability and repeatability of the airborne sensors.

Measurements were made within the boundary layer in the vicinity of the Maldives Climate Observatory at Hanimaadhoo (MCO_H), an ABC_Super observatory. MCO_H instruments that were nearly identical to the airborne instruments were used to validate the UAV data. Real time data and in-cloud video transfer from the UAV to the ground station greatly enhanced the quality of data collection by allowing us to control the altitude of cloud penetration. Specific details of the flights and mission objectives that we were able to accomplish as well as a listing of what we could not accomplish are described in the next section.

SPONSORS

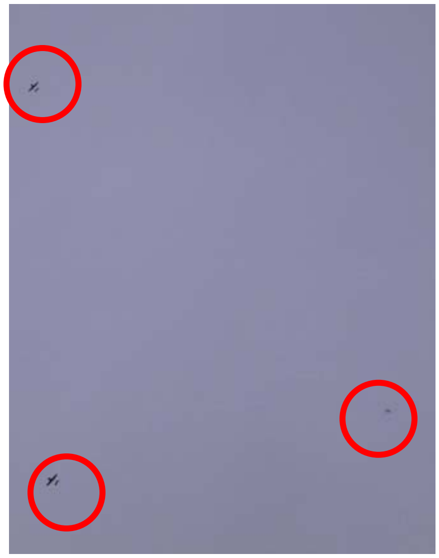
In spite of operating in a hot-humid climate in a remote part of the world and that too in a commercial airport, the mission ended with a loss of only one UAV among the 6 UAVs that were in operation. The loss of the one UAV was due to an improper battery, a freak error that is never bound to happen again. All in all MAC demonstrated the ability of light weight UAVs to conduct complex science missions and collect unique data sets on a problem of great importance to climate change and global warming.

It is my hope that many scientists will scrutinize the conduct of this campaign and the data we collected to learn about the MAC campaign and improve upon it. Based on MAC's success, it is possible that in about five years from now, hundreds of such light weight UAVs will be documenting how human beings are polluting the planet and hopefully provide an early warning system for potential environmental disasters in the future. The following translated MAC from a mere dream and vision into a reality (see the attached participants list):

Mr. Hung Nguyen, the mission manager who directed the flight missions and helped me with the overall conduct of the campaign; The scientists in my lab, Drs. Greg Roberts, Muvva Ramana and Craig Corrigan who designed and developed the instruments; Dr. Greg Roberts who integrated the instruments with the UAVs; the ground support and flight crew of The Advanced Ceramics Research for the Manta UAV, the 3-UAV stacker software and for operating the UAVs and ensuring the safe data collection at Hanimadhoo; the Scripps Institution of Oceanography and UCSD's engineering facilities that built some of the instruments and data integration packages; and Droplet Measurement Technologies who built the cloud physics instruments The advisory committee consisting of Drs. Jay Fein, Dave Fahey, Joachim Kuettner, Hal Maring and Cheryl Yuhas provided expert guidance of MAC; NASA-Dryden provided advice on safe conduct of flights in the field; Dr Jay Fein nurtured the UAV work in my lab for nearly 3 years; to Dr. Chet Koblinsky for providing the start up funding for MAC and funding the ABC observatory at Hanimaadhoo; and to Hal Maring& Cheryl Yuhas for a fast response to fund MAC.

Finally grateful thanks are to the National Science Foundation, the National Oceanic and Atmospheric Administration and NASA for supporting this campaign and for guiding it; and to Scripps Institution of Oceanography and the Vetlesen foundation for generously supporting my lab for the last 15 years. We are deeply indebted to the Govt of Maldives for its unprecedented cooperation and help without which MAC would have remained just a dream.

Take Off at Hanimaadhoo Airport



3 UAVs stacked

Instrument Payload

MAC_5 About to Enter Trade Cu

MAC TEAM

II. Specific Details of the Campaign:

1. **Flight Hours:** Flight hours totaled 126.8 hrs. There were a total 55 takeoffs, 54 safe landings and one crashed into the water close to the island of Hanimaadhoo within a few kilometers of the airport. The flight hours include about 6 hours of test flights to get the UAVs ready for the science missions. It normally took about 30 minutes to launch all 3 UAVs and about 15 minutes to get them all lined up with the tracker software at their respective altitudes and another 10 minutes to track each other. While the aerosol measurements start as soon take off, useable radiation measurements and black carbon measurements are taken only when they reach level flights on the tracker. It takes about 20 minutes to land all UAVs. Thus out of a typical flight duration of 3.5 hours, we obtained only about 2 to 2.5 hours of radiation, black carbon data. With respect to clouds, we were able to sample clouds on about 75% of the flight days. The details of number of hours of data collection are being worked out, but my initial guess is we have about 75 to 90 hours of data (i.e. about 25 to 30 hours for each UAV) that can be used for analysis.

   Shortfall: The number of hours is about 50% of what we expected. This is largely because of two major factors: The campaign started three weeks late, March 6th instead of Feb 15th; and the in-cloud aircraft had an endurance of only 3.5 hours as opposed to the 6 to 7 hours requested in our specs. Had each of the 18 missions flown 6 hours instead of 3.5 hours, we would have obtained about 75% of the expected hours in spite of starting late.

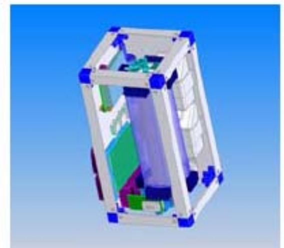
   Cause of the Crashlanding: NASA-Dryden has written a report on this incident. In addition ACR has provided a detailed report. These will be forwarded as soon as the chief scientist receives them. Basically, the cause is that ACR had only one set of 4 batteries, where as it requires between 2 to 4 sets of 4 batteries. As per ACR, this mistake was due to miscommunication between the engineering dept and flight crew.

   Overall Damages and Losses: We took 6 UAVs with instruments for all six including additional back ups for data integration systems. Except for the loss of one UAV with in-cloud instruments, we have all other UAVs and instruments in good working condition.

   Flying Outside the Safe Gliding Range of UAVs: Many missions were flown outside the safe gliding range of the UAVs (typically about 2 nm for the bottom UAV and 5 nm for the top UAV flying at 10000 ft). The farthest we flew were about 7 nm and recovered safely. However, the range was still in communication range of the radio and antenna. We did not undertake longer flights using iridium as originally intended for three reasons: First there was no compelling science reason for doing so. We encountered the desired pollution and clouds within the above range. Second, because of the late start of the mission, we did not have adequate time to devote for test flights with the iridium system. Lastly, the loss of one aircraft on day one of the mission, made us a bit conservative and reluctant to take risks, unless the science absolutely demanded it.

Condensation Particle Counter
Weight: 0.87 kg
Dimensions: 250 x 120 x 70 mm
Measure: # /cc for D > 10 nm

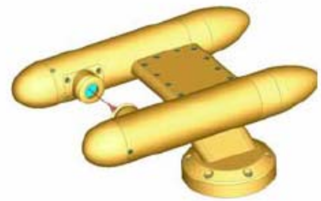
Optical Particle Counter
Weight: 0.30 kg
Dimensions: 96 x 60 x 34 mm
Measure: size distr. 0.3 - 3 um



Cloud Condensation Nuclei Counter
Weight: 3 kg
Dimensions: ca. 100 x 100 x 200 mm
Measure: # /cc for supersat. > 0.2%

Aethalometer
Weight: 0.8 kg
Dimensions: 140 x 110 x 75 mm
Measure: absorbing aerosol

Aerosol Inlet
Weight: 0.037 kg
Dimensions: 10 Ø x 200 mm
Designed to minimize bias to aerosol size distribution



Cloud Droplet Probe
Weight: 1.42 kg
Dimensions: 216 x 115 x 100 mm
Measure: drop size distr. 0.7 - 70 µm
NOTE: electronics in fuselage

Pyranometer
Weight: 0.2 kg
Dimensions: 80 Ø x 100 mm
Measure: Irradiance 305 – 2800 nm

PAR radiometer
Weight: 0.03 kg
Dimensions: 24 Ø x 25 mm
Measure: Irradiance 400 – 700 nm

Spectral Radiometer
Weight: NA
Dimensions: 150 x 90 x 15 mm
Measure: 350 - 1150 nm 256 channels

AUAV instruments for above, in and below cloud platforms

2. **Science Missions:** There were a total of 18 science missions. Specific details of these missions will be provided in a Table in the near future. About half of the missions were 3-UAV stacked flights. The below cloud UAV normally flew at about 1500 to 1800 ft; the in-cloud UAV at about 2200 to 3000 ft; and the above cloud UAV between 5000 to 10000 ft(mostly at 10000 ft).

   It took about a week of flights before the starter software could be made to meet our stringent requirements of level flights and tracking each other within 20 seconds and 20 meters of each other. The other half were distributed between two UAV stacked flights and vertical profiling flights and Tandem flights. This (having just 50% of the 18 missions on3-UAV stacker) did not limit us from achieving our science objectives because the first week of flights showed that the Hanimaadhoo observatory measurements were nearly identical to the aerosol properties measured at the cloud base (1700 feet).

Short fall: We requested 16 science missions in our Missions document and we accomplished 18. However we wanted 4 to 6 hours for each mission and most of our missions lasted only 2 to 4 hours due to endurance limitation and due to working within the flight window times given to us by the air traffic. We were operating from a commercial airport with about 2 take offs and two landings, typically during the day.

3. **What Did We Accomplish?**

a) The successful demonstration of the 3-UAV stacked flights, in which the fully instrumented UAVs flew over each other (at altitudes ranging from 1500 ft for the bottom UAV to 10000 ft for the top UAV) within 20 meters of each other(horizontally) and within 20 seconds of each other maintaining level flights with a pitch less than 2 degrees most of the time, was a major step forward. The data we collected also has given us a clear indication that new insights into aerosol-cloud-radiation interactions can be achieved with such 3-UAV stacked flights.

b) That we conducted MAC in a remote tropical environment with harsh weather and living conditions demonstrates that UAV operations have matured sufficiently to perform difficult science tasks.

c) That we conducted the operations in a commercial aircraft, gives us an indication about the safety of UAV operations. However, in this regard, we need
Help in developing emergency procedures and formalized code of conduct for interactions between ground support crew, flight crew and the scientists.

d) With respect to science accomplishments, it will take us about 3 months to assess this reliably, but, some preliminary observations are offered here. But frequency distributions of the observed aerosol concentrations, cloudy sky albedos and cloud droplet concentration reveals that we have adequately sampled the atmosphere, i.e. we have sampled albedos from 0.04 (clear sky) to 0.5 (overcast or sidewise illumination by 3-D clouds) ; aerosol number concentrations from 200 #/cc to 3000 #/cc; droplet concentration ranging from 100 to 500 #/cc with 1% in the 1000 #/cc. We have also sampled about 400 or more trade cu clouds. We have made repeatable observations of solar absorption between 1.5 km to 3 km; 0.5 to 1.5 km and made collocated observations of aerosols, BC and cloud albedos and drop concentration.

I personally feel confident that we will be able to make definitive conclusions about the amount of solar energy absorbed in cloudy atmospheres.

With respect to aerosol-cloud-radiation interactions, our measurements should be adequate to link aerosol concentrations with CCN and to cloud droplet concentration. However, this will amount to confirming or providing additional data on INDOEX findings of Ramanathan et al (JGR,2001). The 3-UAV formation was intended to go beyond that by linking all these to cloudy sky albedos. Here the verdict is uncertain due to an important practical constraint. Let us consider the variations of CN (aerosol concentration) and BC (black carbon) from Feb 15th to March 31st as shown from observations of MCO_H (Figs 1 and 2).

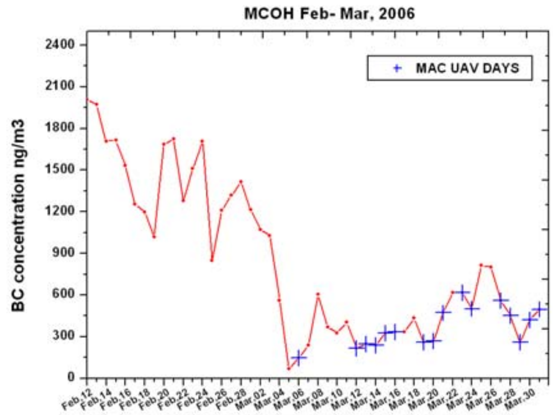


Fig 1: Black carbon concentration measured at Hanimaadhoo at the ABC observatory from Feb 10 to March 31, 2006

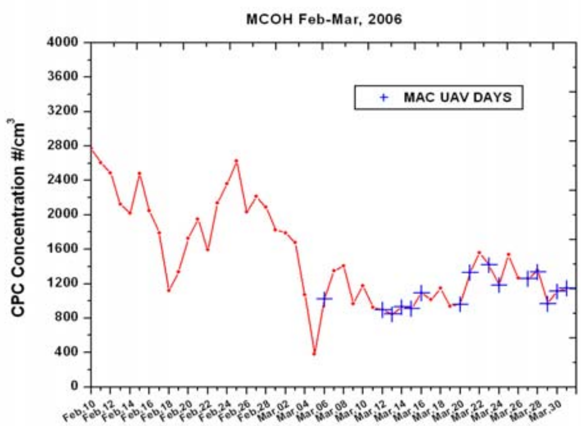


Fig 2: Total Aerosol concentration measured at Hanimaadhoo at the ABC observatory from Feb 10 to March 31, 2006.

From Feb 15 (proposed starting date of MAC) to March 5th (actual start date), the aerosol concentration dropped by a factor of 2 and BC concentration also dropped by a factor Of two to three. It is this large variation we were going to exploit to capture the dependence of aerosols-cloud-cloud albedo. Because of the late start (due to the mishaps in getting the export permit and the proper batteries for the UAVs), we lost the dynamic range of a factor of 3 in aerosol-Pollution variations. However, we still captured some variations and further data analysis will tell us soon.

Any Potential surprises: From March 23 onwards there was a major dust + BC mixed airmass that dominated the skies from March 23rd to March 31st. It was concentrated between 5000 ft and 7500 ft. Even the surface data (Figs 1 and 2) show a modest bump in total CN and BC. We flew several sorties between 3000 ft and 10000 ft to document the BC peaks and the corresponding absorption. Such mixture of BC and dust has enormous interest and we may have some unique insights into if solar absorption is enhanced in such condition. Again a problem that requires stacked multi-UAV observations.

List of Participants

<u>Scripps Institution of Oceanography</u>

Unmanned Aerial Vehicle Team: C. Corrigan, F. Li, H. Nguyen, M. V. Ramana, V. Ramanathan and G. Roberts

Maldives Climate Observatory at Hanimaadhoo Team: C. Corrigan, D. Kim, D. Lubin, M.V. Ramana, V. Ramanathan and P. Siva

Data Analysis Team: F. Li and A. Zhu

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MALDIVES CLIMATE OBSERVATORY AT HANIMADHOO
AN ABC SUPER SITE SPONSORED BY UNEP