Western Pacific Autonomous UAV Campaign
Aerosol-Dust-Cloud Interactions and Climate Effects

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# WPAC Organization

## Goals and Objectives

### Introduction
- Stability of the Global Albedo
- Role of Dust-Soot-Cloud Interaction
- Regional Impact on Pacific and North American Climate
- CIFEX: The Long Range Transport of Dust and Aerosols across the Pacific Ocean
- The Maldives AUAV Campaign

### The Proposed WPAC for April - May 2009
- Executive Summary
- Scientific Strategy
- Temporal Sampling and UAV Endurance
- UAV Selection
- Description of Available Miniaturized Instruments
  - Cloud-aerosol physics
  - Radiation
  - Data Integration Package
  - Calibration and Validation of Instruments
- Proposed New Instruments
  - New Photonics Systems
  - MEMS Systems
  - Chemical Sensors including Nano-sensors
- Mission Logistics
  - Western Pacific Base of Operations in Korea
  - Eastern Pacific Base of Operations in Alaska or West Coast of US
  - ARM Mobile Facility (AMF) Deployment in China
  - Complementary Sites in China
- The WPAC Studies, from In-Situ to Regional and Global Scales
  - MACR with an updated code for dust-soot interactions
  - Global Aerosol-Dust-Cloud Interactions Model (GADCIM)
  - A-Train Satellites: Regional-Scale Forcing
  - Coupled Ocean-Atmosphere Model Simulations
  - International Collaboration with East Asian Scientists
  - Interagency Collaboration

### Appendix - UAV Program Milestones

### Reference
WPAC Science and Project Team

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D. Kim, Modeling and Analysis
F. Li, A-Train Coordination
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M.V. Ramana, Instrumentation
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M. Sailor, UCSD-Chemistry, Nanosensors
A. Zhu, Regional Modeling

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Chief Scientist, ABC Gosan Supersite

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UAV Operations (Candidates)
- Advance Ceramics Research
- UCSD Engineering Department
- Aerosonde
- Swift Engineering

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J. Kuettner, UCAR
R. Curry, NASA-Dryden
W. Wiscombe, DOE-ARM Chief Scientist

The ACR’s Manta UAVs at Hanimaadhoo Airport, Hanimaadhoo Island in the Maldives, during the Maldives Autonomous UAV Campaign (MAC) in March 2006 (V. Ramanathan, PI). In the foreground is the aerosol-cloud aircraft. The other two are the radiation-aerosol aircraft.
A six-week campaign is being proposed for April-May 2009 using 9 lightweight UAVs capable of 12 hour endurance to collect sophisticated sets of data on the long range transport of dust, soot and other particles, VOCs, ozone and CO across the Pacific Ocean from west to east. It will also collect data on how these pollutants are modifying clouds and solar radiative forcing.

Six UAVs will be launched from Jeju, Korea to intercept the plume over the western Pacific Ocean and 3 more will be launched from the eastern Pacific close to US coast, but the flight will be controlled remotely from WPAC operation center in Korea. The mission profile will include groups of 3 UAVs each, stacked vertically from 500m to about 5km, sampling upstream and downstream of the dust plume to address fundamental science issues related to how dust and soot interact with the atmosphere-ocean system.

The campaign will bring together the latest development in instrument technology including MEMS and nano technologies with state-of-the-art UAV technologies in avionic, navigation and communication systems. WPAC will help establish the viability of UAVs as a global observing system for observing and monitoring the complex ways by which human activities and natural phenomenon are altering the planet.

Specifically, WPAC aims to achieve a range of scientific and technological objectives, including

**Scientific**
- Evaluate the long-range atmospheric transport of soot and dust across the Pacific Ocean.
- Measure directly the solar heating rates due to dust and soot aerosols and polluted clouds.
- Understand the role of dust-soot-cloud interactions in the regulation of the Pacific albedo.
- Integrate UAV measurements with A-Train cloud-aerosol data and estimate the magnitude of the dust-soot-cloud interactions in both the dimming and albedo over the Pacific Ocean.

**Technical**
- Deploy and validate miniaturized instruments for advanced and state-of-art measurements.
- Validate A-Train data over one of the most complex regimes, the dusty, sooty and cloudy atmosphere.

**Technological**
- Develop and demonstrate the capability of lightweight and longrange UAVs for advanced atmospheric and climate research.
- Develop and test the operational procedures for deployment of multiple UAVs.
- Test the real-time interplay between data and flight navigation.
- Develop nano-sensors for chemical measurements of reactive species such as VOCs.
- Integrate miniaturized photonics and MEMS measurement systems into UAVs.
Stability of the Global Albedo

The presence of clouds enhances the albedo of a cloud-free Earth by about a factor of two, from 15% to 30%. The atmospheric circulation determines the location and extent of clouds and their water content. Aerosol chemistry and microphysics determine the size and number distribution of cloud drops and ice crystals. All of these parameters including the aerosol concentration and composition undergo significant temporal (minutes to years) and spatial (meters to planetary scales) variations. Yet it is remarkable that our general circulation climate models are able to explain the observed temperature variations during the last century solely through variations in greenhouse gases, volcanoes and solar constant. This implies that the planetary albedo has not changed during the last 100 years by more than ±0.2% (out of 30%). Is the albedo of the planet really this stable, in spite of the large regional, seasonal and interannual variability of clouds and aerosols?

On a more practical level, the link between aerosols and cloud albedo produces the so-called indirect effect of anthropogenic aerosols. Many models and some field observations including the Indian Ocean Experiment (INDOEX) and Aerosol Characterization Experiments (ACE)-II have shown that an increase in anthropogenic aerosols can nucleate more cloud drops (see Figure 1) and enhance the cloud albedo thus lead to a cooling effect. The Intergovernmental Panel on Climate Change (IPCC)-2001 report shows that this cooling effect may be large enough to offset from 50% to 100% of the radiative heating due to the build-up in greenhouse gases. This indirect effect, the regulation of cloud albedo by anthropogenic aerosols, has been recognized the largest source of uncertainty in understanding the human impact on the global climate.

Role of the Dust-Soot-Cloud Interaction

We have witnessed major progress in our understanding of the aerosol-cloud interactions, thanks to major field programs (ACE, INDOEX), new satellite instruments [the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multiangle Imaging SpectroRadiometer (MISR)], and regional to global aerosol assimilation models (Collins et al., 2001; Carmichael et al., 1991; Chin et al., 2002). The observations have clearly revealed (Figure 1) a strong link between aerosol concentrations and cloud drop concentration. One fundamental unresolved issue is the role of dust soot-cloud interactions. Major dust regimes are the tropical Atlantic Ocean (Saharan dust plumes), the tropical Indian Ocean (Arabian, Central Asian and Indian deserts) and the extra-tropical Pacific Ocean (dust from East Asia). Of interest to the present study is the Pacific region where dust mixes with soot from East Asia (Figure 2). We have recently estimated the direct radiative forcing from the dust-soot mixture; clearly, from Figure 3, it has a major impact on surface dimming, atmospheric solar heating and forcing at the top of the atmosphere (TOA).

The impact of the dust-soot mixture on the Pacific Ocean cloud systems is of importance to this
study. Globally, clouds have a net radiative forcing of -15 to -20 Wm\(^{-2}\) (Ramanathan et al., 1989; Ramanathan and Inamdar, 2006). The main contribution to this forcing arises from the extra-tropical oceanic cloud systems over the Pacific, the Atlantic and the Indian Ocean, where the cloud forcing is on the order of 50-75 Wm\(^{-2}\) (Figure 4). The major contributor to the large cloud forcing is the marine stratocumulus and stratus systems that are persistent over the extra tropical oceans. How does the soot mixture alter the microphysics, the albedo and the solar absorption of these cloud systems, i.e., the indirect effect? During the last few years, several studies have suggested that the dust and soot have significant influence on the radiative forcing of Pacific oceanic cloud systems (Huang et al., 2006; Sassen, 2002). This is virtually an unexplored area. Another major question is the role of large amount of soot and VOCs in enhancing cloud drop absorption. We have reasons to speculate that this effect could be very large based on laboratory studies we published recently (Figure 5). Of major concern are the Pacific and the Atlantic cloud systems, which are polluted by man-made aerosols from East Asia and North America, respectively.
Regional Impact on the Pacific and North American Climate

Our focus is on the Pacific Ocean, largely because of its potential importance to the North American climate. We have recently shown that more than 75% of the black carbon over the west coast of North America was the result of transport across the Pacific from East Asia and other regions (Hadley et al., 2006) during springtime and possibly other seasons as well. We have also shown the dust-soot mixture has a large impact on TOA and surface radiative forcing and atmospheric solar heating rates. However, we do not know the magnitude of the impact on clouds through the indirect effect, a potentially important mechanism for regulating cloud forcing. The potential impact of these soot-dust modified forcing terms on the regional circulation and climate is one major motivating factor for this proposed study.

CIFEX: The Long Range Transport of Dust and Aerosols across the Pacific Ocean

There have been very few campaigns to examine how particles transported across the Pacific Ocean influence clouds and radiative forcing in the region. In April 2004, the Cloud Indirect Effects Experiment (CIFEX) (Ramanathan, 2003; http://bornetto.ucsd.edu/cifex/KingAir_request_SIOUCSD.pdf) followed the Intercontinental Transport and Chemical Transformation (ITCT) campaign, undertook a pilot examination with airborne aerosol and cloud instruments onboard the University of Wyoming’s KingAir aircraft. The collected data provided unique insights into the role of long-range transport of aerosols across the Pacific Ocean (Roberts et al., 2006; Hadley et al., 2006; Wilcox et al., 2006). First, Hadley et al., 2006 demonstrated that aerosols from long-range transport were the dominant source of black carbon and other fine particles above 2 km over the west coast of North America during spring time (Figure 6). Second, the size distribution of these particles had markedly different characteristics when compared with marine sources or North American sources (Figure 7). Lastly, the particles provided efficient source of CCN (Roberts et al., 2006) and nucleated cloud drops that in turn reduced the drop radii (Figure 8) and enhanced the cloudy sky albedo (Wilcox et al., 2006).

The UAV fleet at Hanimaadhoo Airport, the Maldives during the MAC campaign in March 2006.

Figure 6: CFORS fraction of Asian BC to total BC as a function of altitude at 130°W (Hadley et al., 2006).
The CIFEX and ITCT findings and results (Figures 6 to 8), together with the MAC campaign results, provide the foundation for launching the WPAC campaign.

Figure 7: Flight patterns during the CIFEX campaign (left panel), and dependence of particle size distribution on air mass (right panel a-f). The size distributions of Asian air mass are distinctively different from North American or marine particles (Roberts et al., 2006).

Figure 8: (a) cloud drop number concentration (Nd) and (b) cloud drop effective radius (reff) from aircraft FSSP measurements. Both are shown as a function of cloud liquid water path (LWP) for clean and polluted clouds. Number of 0.25° grid cells is 113, comprising 17,748 1 s FSSP samples (CIFEX data; Wilcox et al., 2006).
The Maldives Autonomous UAV Campaign


Most of the instruments (details to follow) were purchased commercially and were stripped or altered to reduce weight and power requirements (see Roberts et al., 2005). First field test with instrumented payload began in 2003 over California desert areas and culminated in the Maldives Autonomous UAV Campaign (MAC) in March 2006. In the first 3 years, the program was funded by NSF and the Vetlesen Foundation while the MAC campaign was jointly funded by NSF, NOAA and NASA.

Aerosol-Radiation-Cloud Sampling with Stacked UAVs

During March 6-31, 2006, the polluted atmosphere over the Arabian Seawas probed by flights of lightweight UAVs laden with instruments (Figure 9). The MAC campaign (Ramanathan et al., 2005) was the first demonstration of sampling aerosol-cloud-radiation interactions with 3 UAVs flying in stacked formation. This campaign has laid a solid foundation for the development of UAVs as an advanced platform for atmospheric research. Descriptions of the campaign and first results from MAC have been reported in Ramanathan et al., 2006a-b and Roberts et al., 2006.

In MAC, we observed the particles-cloud-solar radiation interactions using one aircraft flying below the clouds to observe the nature and number of particles entering the clouds and the amount of sunlight penetrating through the clouds and the particles; one flying through the clouds to document how clouds were responding to the particles; and one above the clouds to measure sunlight reflected by clouds and the particles that are exported out of the clouds. All 3 aircraft must fly in perfectly stacked formation measuring simultaneously over the same cloud system within a fraction of a minute of each other, in view of the fast lifetime of most clouds.

MAC has proved that lightweight UAVs are uniquely suited to conduct rigorous field experiments. The MAC fleet logged 18 science missions that consisted of 55 takeoffs covering over 120 flight hours, collected data on a full range of issues including the transport of pollution and dust from South Asia, Arabian and southwestern Asia deserts and its impacts on global dimming at sea surface, the level of solar energy absorbed in the atmosphere and cloud properties. Direct measurements were made of the role of black carbon in the solar heating of the atmosphere. The in-cloud aircraft penetrated hundreds of polluted, dusty and shallow cumulus clouds. The above-cloud and below-cloud aircraft flew in stacked formation within ten seconds of the in-cloud aircraft; their flight was controlled with minimal pitch and roll to enable reliable solar radiation measurements. The UAVs were flown not only in stacked formation but also in tandem, wing tip to wing tip with 1km separation, to validate the reliability of the airborne sensors and repeatability of the measurements.

Measurements were made within the boundary layer in the vicinity of the Maldives Climate Observatory at Hanimaadhoo.
(MCO-H), a super observatory of the Project Atmospheric Brown Cloud (ABC) (Figure 10). MCO-H instruments, nearly identical to the airborne instruments, were used to validate the UAV data. Real-time data and in-cloud video transmitted to the ground station greatly enhanced the quality of data collection by allowing the flight director to control the altitude of cloud penetration. Sample data collected from the 3 UAVs are shown in Figure 11 for vertical aerosol distribution; Figure 12 reveals the quality of radiometric data collected by comparing solar fluxes from two UAVs flying in tandem at 3km altitude; and Figure 13 shows the frequency distribution of cloud particle effective radius averaged over all flights. In spite of operating in the tropical hot and humid climate in a remote part of the world, the mission encountered a loss of only one UAV from a MAC fleet of 6. The single loss was caused by improper installation of aircraft batteries, resulting in a premature power cutoff to onboard flight control—an error that has been corrected permanently by more stringent preflight check and verification procedures. All in all, MAC demonstrated the utility of lightweight UAVs as viable platform to conduct complex climate science experiments to collect unique datasets on a problem of great importance to climate change and global warming. This WPAC proposal is built upon our UAV experience and the success of MAC.

\[ r_e = \frac{\int n(r) r^3 \, dr}{\int n(r) r^2 \, dr} \]
The Proposed WPAC for April-May 2009

Executive Summary

We propose a six-week campaign during April and May of 2009, which is well within the peak of the dust season (Figure 14) while the long-range transport is also efficient (Figure 15). We are interested in understanding the fundamental issue of dust-soot-cloud interactions that occur both close to the source of pollution and dust to conduct process studies (over the Yellow Sea) and far from the source of pollution (over the Eastern Pacific) to evaluate the global implications. Accordingly, we have chosen two sites for UAV operations: W. Pacific site on Jeju Island, Korea which will be the WPAC base of operations, and an auxiliary site in eastern Pacific in Alaska (the Aleutians) or in northern California.

Figure 14: Monthly/latitudinal (30°N-50°N) mean AVHRR AOD (630nm) averaged from 1981 to 2001 over the Pacific Ocean. Red box represents the peak season of dust events.

Figure 15 shows (top panel) the locations of the ABC observatories in China, Korea and Japan as well as the base of UAV operations. The top panel (Figure 15) shows the mean AOD for April 2001. The bottom two panels show model simulations of dust and black carbon (courtesy of G. Carmichael) for April 2004. It is clear that the dust and ABCs will be mixed together. The mixing will have already taken place when dust from Taklamakan and Mongolia advects past China onto the Yellow Sea. The scientific questions that we aim to address with WPAC are:

1. How are dust and soot vertically distributed? in separate and distinct layers or mixed uniformly?
2. Are the aerosol size distributions distinctly different between dust-soot mixtures compared with soot outside dust layers?
3. How does the dust-soot mixture alter the solar radiation budget: i.e., albedo, heating rates and surface solar fluxes?
4. How does the dust-soot mixture alter the single scattering albedo?
5. How does dust-ABC mixture alter cloud microphysical properties, compared with clouds with just ABCs? This is the so-called aerosol indirect effect.

From Jeju, WPAC flights will be configured similar to those conducted in MAC. We will fly the UAVs in
stacked formation with one below cloud level; one within the clouds and one above the clouds. One important advance feature over MAC is that we will fly 3 UAVs within the dust plume and 3 more ahead of the dust plume. Observation from the two sets of 3-UAVs will enable us to understand how dusts modify the background atmosphere which is mainly polluted with East Asian ABCs. Figure 16 summarizes the flight configuration.

Scientific Strategy

We are interested in understanding the fundamental issues of how the advancing dust modifies the atmosphere and the climate forcing terms at the surface and the TOA. The required observations could be most rigorously and unambiguously done if we sample the atmosphere within the advancing dust plume and just ahead of it. The dust travels in the westerly direction. We propose to sample the dusty atmosphere at about 10 km to 25 km both ahead of and behind the dust front, or the leading edge of the plume as shown in Figure 16.

Flight Missions

We have planned the following missions for WPAC:

A. 6 flights for dust-pollution interaction. This is basically the primary WPAC mission as shown in Fig 16. This would require 6 UAVs flying in West Pacific and 3 UAVs from East Pacific or the US West Coast.

B. 4 flights for pollution chemistry (i.e., ABC) measurements to document ozone, total aerosol, black carbon, VOCs and cloud microphysics. The flight features 2 UAV with one outside clouds and one inside cloud.

C. 4 flights to document solar absorption in polluted atmosphere and sea surface albedo and albedo at 3 km altitude.

D. 4 flights dedicated to cloudy sky albedo and solar absorption
and hyper spectral solar irradiance at the surface and at cloud top for model validation and potential impact of pollution on marine photosynthesis.

UAV Selection

We have considered several UAVs including the Aerosonde Mark IV, the ACR Manta-B, the Swift Engineering KillerBee 3 and the Insitu SeaScan, as shown in Table 1 and Figure 17.

Also in prime consideration is the long endurance (>36 hours) and lightweight UAV designed by UCSD (J. Kosmatka of UCSD Engineering Department) under an NSF MRI grant.

General characters of the UAVs under consideration are the following:
- Empty Weight: 15-20 kg
- Pusher-type, with propeller in the rear. No electric engines.
- Speed capable of 70 knots
- Payload Bay volume is at least 5000cc
- Unit cost and ease of operations are not being considered at this time.

Table 1: Candidates of UAVs. Performance data subject to actual field verification and flight test. Also, see evaluation of the UCSDs UAV below.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Aerosonde</th>
<th>ACR</th>
<th>Swift Engineering</th>
<th>Insitu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Mark IV</td>
<td>Manta-B</td>
<td>KB-3</td>
<td>SeaScan</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>15</td>
<td>17</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>Altitude (Kft)</td>
<td>20</td>
<td>16</td>
<td>20</td>
<td>16</td>
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<tr>
<td>Payload (kg)</td>
<td>5</td>
<td>5</td>
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<td>5</td>
</tr>
<tr>
<td>Duration (hr)</td>
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<td>5</td>
<td>5</td>
<td>3</td>
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<tr>
<td>Speed (knot)</td>
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<td>70</td>
<td>90</td>
<td>70</td>
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<td>Generator</td>
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<td>90W</td>
<td>80W</td>
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<tr>
<td>Landing</td>
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<td>Wheels</td>
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<td>Hook + Wire</td>
</tr>
<tr>
<td>Take-off</td>
<td>Car top</td>
<td>Wheels/launcher</td>
<td>Car top/launcher</td>
<td>Launcher</td>
</tr>
<tr>
<td>Payload Bay (cm)</td>
<td>20×15×15</td>
<td>33×33×13</td>
<td>12×30×30</td>
<td>tube 28L×16D</td>
</tr>
<tr>
<td>Payload V (cm³)</td>
<td>4500</td>
<td>14157</td>
<td>10800</td>
<td>5626</td>
</tr>
<tr>
<td>Possibility of 12 hr duration + 5 kg payload</td>
<td>May not be possible</td>
<td>Under testing with new engine using heavy fuel</td>
<td>Possibly with the bigger KB-4 (drawing only)</td>
<td>May not be possible</td>
</tr>
<tr>
<td>Stacked Flight</td>
<td>Required new software</td>
<td>Yes</td>
<td>Requires new software</td>
<td>Requires new software</td>
</tr>
</tbody>
</table>

General Assessments

UCSD UAV
This UAV is under development through an NSF-MRI grant to SIO and UCSD (Kosmatka and Ramanathan are PIs). A number of flight tests controlled by a human RC pilot on the ground have been completed. It is now being prepared for a 10-12 hour flight endurance with 5 kg payload. Technical issues to be solved prior WPAC selection include a larger fuel tank for longer duration, integration of navigation software, over-the-horizon communication and development of stacker software.

Aerosonde
- Must be the Mark-IV version with smaller Piccolo box to increase the payload volume currently at 4500 cm³, this is still the smallest volume of the 4 UAVs.
- With 5 kg payload, fuel capacity is 1 kg, duration is 3.5 hrs. Increase duration to 10-12 hrs seems difficult, may require new and enlarged fuselage to increase fuel capacity.
- Belly skid landing is detrimental to bottom pyranometer.
- Stacked flight is possible but requires new software development.

ACR Manta B
- Take-off and landing with conventional wheels, provides ample ground clearance. Recently, ACR added launcher capability for take-off.
- Does not have generator, thus useful payload for instruments is reduced by batteries.
- Long duration will be feasible only with new engine using heavy fuel, currently in final development and testing.
- Proven stacked flight capability during the MAC (March 2006) (Figure 17).

Swift Engineering KB-4
- Existing KB-3 (9ft wingspan) will be insufficient for the payload and duration requirement for WPAC; KB-4 (11ft wingspan) will be needed; but currently exists only in drawings.
Wheel-landing has been demonstrated, but with possible penalty in endurance due to added weight and aerodynamic drag.
- Stacked flight possible but requires new software development.
- The least matured system of the 4 UAVs in consideration.

**Insitu SeaScan**
- Actual payload volume is small due to intrusion of wing roots.
- Increasing duration to 10-12 hours would, probably, require a new and longer fuselage to increase fuel capacity.
- Launcher and Wire Recovery apparatus are massive.
- Stacked flight possible but requires new software development.

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**Summary of UAV Selection**

Currently, October 2006, there is no UAV of the 30 kg empty-weight class capable of 10-12 hr duration while carrying 5 kg payload and flying in stacked formation. *Manta B* looks to be promising if the new engine program is successful. We will be better able to assess the readiness of the UCSD-UAV for the WPAC after the 12 hour flights (with 5 kg payload) planned during the next 2 months. We intend to make our final choice within 3 months of proposal approval.

**Description of Available Miniaturized Instruments**

The UAV payload, which has been successfully flown on dozens of test flights and 45 scientific flights accumulating more than 120 research hours in MAC campaign, has proven to be robust and reliable. Our payload (about 3-4 kg per aircraft; Table 2 and Figure 9) includes instruments and data systems developed for lightweight UAVs. Each instrument payload will be thoroughly tested and validity of scientific results quantified before and during the experiment. Each UAV instrument is described below.

**Cloud-aerosol physics**

*Condensation Particle Counter (CPC)*: The CPC measures total aerosol concentrations \( N_{\text{CN}} \) between 0 and \( 10^5 \) cm\(^{-3} \) in the diameter range \( (0.01 \ \mu\text{m} < D < 1.0 \ \mu\text{m}) \). 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 AUA V. To reduce weight and volume by over half of the commercial version, the CPC engine, electronics, filters, and pumps have been repackaged into a lightweight enclosure with the sample line attached to the aerosol inlet.

*Cloud Condensation Nuclei Counter (CCN)*: Measurements of CCN are fundamental to provide the link between cloud microphysics and aerosols. The instrument PI has developed a cylindrical continuous-flow thermal gradient diffusion chamber to measure particles that activate between 0.1% and 2% supersaturation (Roberts and Nenes, 2005). The miniature version for UAV weighs less than 1.5 kg and autonomously measures CCN concentrations at 1 Hz at a single supersaturation between 0.2% and 2%.
Cloud Droplet Probe (CDP): DMT, Inc. has designed a miniature forward-scattering spectrometer probe (FSSP) based on a light scattering measurement when a particle passes through a laser beam and will provide in-situ measurements of droplet size distributions for non-precipitating clouds. The CDP measures particle concentrations (up to $10^4$ cm$^{-3}$) for diameters between 1 and 50 µm. The CDP will be externally mounted on the fuselage such that the probe measures outside the influence of the aircraft to avoid biasing the droplet size distribution. Anti-ice heaters have already been installed in the in-cloud in the case of freezing conditions.

Liquid Water Content Probe (LWC): The sensor’s temperature is maintained via a digitally-controlled current pulse. The more liquid water present, the greater the current required to maintain the fixed 125°C temperature on the coil. Liquid water content is then determined as a function of current through the device and the true air speed.

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 particle 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 aethalometer measures the absorption of the aerosol by depositing the particles onto a fibrous filter and observing the change in light transmission. The instrument is typically calibrated to give results in concentration of black carbon per volume of air, but the raw filter absorption data can be used to estimate the absorption coefficient for in-situ aerosols by using empirical corrections (Bond et al., 1999). The aethalometer requires several minutes to generate a data point and this period is dependent upon the concentration of absorbing material in the atmosphere.

Visible Region (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 50-60% of aerosol forcing occurs in the visible spectrum, and this region avoids any near-infrared water vapor absorption. During MAC, the Li-Cor Li-190 quantum (or PAR) sensors were used to measure downward and reflected solar radiation in the visible spectral range (0.4-0.7 µm). We have built an amplified circuit inside the PAR sensor and they were flown successfully during MAC.

Data Integration Package

Data Acquisition System (DAQ): An integrated data acquisition system connects to the instruments via an interface that supplies power and distributes the data signals to the computer. A single-board computer samples 16 channels of analog-to-digital (A/D), reads/controls up to six instruments via standard serial communication, and stores the data to a compact flash card. Several integrated circuits are embedded into the interface to increase its functionality as the central data system, including a GPS for time stamping and spatial coordination.

Calibration and Validation of Instruments

Calibration and validation of the miniaturized aerosol, cloud and radiometric instruments ensures their scientific integrity. These instruments have been well characterized in previous UAV experiments (see MAC Campaign). Their performance will be verified again during a rehearsal mission in March 2007 and further validation will be performed in conjunction with NOAA ground-based observations during the ARCUS experiment (proposal for the International Polar Year Program). Occasional flights within the boundary layer near the observatory will provide the opportunity to compare...
in-situ measurements of the UAV instruments with ground based data.

Table 2: UAV instrumentation and payload configuration for aerosol, cloud, and radiation experiments.

(a) Instrument used for MAC campaign

<table>
<thead>
<tr>
<th>Instrument</th>
<th>ID</th>
<th>Weight (kg)</th>
<th>Power (W)</th>
<th>Data acquisition</th>
</tr>
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<tbody>
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<td>Condensation Particle Counter</td>
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<td>2.3</td>
<td>RS-232</td>
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<td>Optical Particle Counter</td>
<td>OPC</td>
<td>0.27</td>
<td>5.4</td>
<td>RS-232</td>
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<td>AETH</td>
<td>0.85</td>
<td>5</td>
<td>A/D</td>
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<tr>
<td>Pyranometer</td>
<td>PYR</td>
<td>0.17</td>
<td>&lt; 0.2</td>
<td>A/D</td>
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<tr>
<td>Photosynthetic Active Radiation</td>
<td>PAR</td>
<td>0.29</td>
<td>&lt; 0.2</td>
<td>A/D</td>
</tr>
<tr>
<td>Cloud Droplet Probe</td>
<td>CDP</td>
<td>1.42</td>
<td>14</td>
<td>RS-232</td>
</tr>
<tr>
<td>Liquid Water Content Probe</td>
<td>LWC</td>
<td>0.6</td>
<td>10</td>
<td>A/D</td>
</tr>
<tr>
<td>Video camera &amp; transmitter</td>
<td>VID</td>
<td>1</td>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>Temperature / relative humidity</td>
<td>TRH</td>
<td>0.05</td>
<td>&lt; 0.1</td>
<td>A/D</td>
</tr>
<tr>
<td>Data acquisition system</td>
<td>DAQ</td>
<td>0.65</td>
<td>10</td>
<td>--</td>
</tr>
<tr>
<td>Aerosol inlet</td>
<td>AI</td>
<td>0.21</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

(b) New instrument planning for WPAC Campaign

<table>
<thead>
<tr>
<th>Instrument</th>
<th>ID</th>
<th>Weight (kg)</th>
<th>Power (W)</th>
<th>Data acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Condensation Nucleus Counter</td>
<td>CCN</td>
<td>1.5</td>
<td>25</td>
<td>RS-232</td>
</tr>
<tr>
<td>Multi Angle Absorption Photometer</td>
<td>MAAP</td>
<td>1.0</td>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>Spectroradiometer</td>
<td>--</td>
<td>0.4–0.9</td>
<td>1</td>
<td>--</td>
</tr>
<tr>
<td>Hyperspectral Sensor</td>
<td>HSI</td>
<td>0.9</td>
<td>5</td>
<td>--</td>
</tr>
<tr>
<td>MEMS based Auto Leveling Platform</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Ozone Monitor</td>
<td>O3</td>
<td>0.45</td>
<td>5</td>
<td>--</td>
</tr>
<tr>
<td>Nanocrystal VOC sensor</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>0.2</td>
<td>3</td>
<td>--</td>
</tr>
</tbody>
</table>

WPAC will also push the miniaturized instrument technology to a more advanced level. Especially, we plan to deploy the following systems.

New Photonics Systems

Spectroradiometer: The atmospheric heating rate due to shortwave radiation (K/day) can be observed directly by measuring the shortwave flux divergence as a function of altitude and time. Furthermore, a spectral measurement of the flux divergence will allow unambiguous identification of the contribution to the heating rate from various types of aerosol. We will measure the flux divergence using a pair of miniaturized spectro-radiometers, one for downwelling hemispheric flux, a second for upwelling hemispheric flux, both fitted with cosine collectors. The spectrometers proposed for future UAV deployment will be purchased either from Stellar Net, Inc or from Ocean Optics Inc. (Figure 18).

Hyperspectral Imaging: Hyperspectral imaging (HSI) systems are becoming of increasing interest, especially for detection of chemical and biological species for probing the optical properties of aerosols in the atmosphere. Hyperspectral sensors scan many channels (visible: 0.4-1.0 µm; NIR: 0.9-1.7 µm) simultaneously and provide detailed information about object spatial and spectral patterns. Absorption and emission bands of given substances often occur within very narrow bandwidths. They allow high-resolution, hyperspectral sensors to distinguish the properties of the substances to a finer degree than an
ordinary broadband sensor. Many objects and substances have spectral characteristics that are unique and a unique. These spectral signatures allow that object or substance to be identified through various spectral analyses. Once the fingerprints are detected, then assessing them to differentiate various natural and manmade substances from one another is possible. The HSI proposed for future UAV deployment will be purchased either from Headwall Photonics Inc, whose instruments were flown on other airborne platforms (Figure 19).

**Multi Angle Absorption Photometer (MAAP):** This instrument will be explored as a possible upgrade of the aethalometer instrument described above. By incorporating additional optical measurements, the MAAP is able to correct for scattering interferences that complicate the AETH measurements. The MAAP has already been partially miniaturized for UAV applications. The instrument only operates at one wavelength (520 nm). Estimated weight is 1.0 kg and power consumption is 12 Watt.

**MEMS Systems**

**MEMS-based Auto Leveling Platform:** The irradiance on a surface depends on its orientation relative to the radiant beam according to Lambert’s cosine law. Hence, proper leveling of the sensor surface is required in order to accurately measure the global radiation. The accuracy of the upward looking radiation instruments is severely affected by the non-horizontal orientation of the instruments due to aircraft pitch and roll. Hence, the receiving element for measuring the global irradiance has to be mounted on stabilization platform in order to compensate for the pitch and roll of the aircraft motion. The stabilization platform will keep the radiometers level to the earth’s surface based on an electronic inertial navigation signals. These navigation signal sensors will be onboard the aircraft and may incorporate the MEMS (Micro-electromechanical Machine Systems) technology. Auto leveling platforms will also be used in the Hyperspectral imaging sensor for image stabilization in cameras.

**Chemical Sensors including Nano-sensors**

**Ozone Monitor (O3):** Ozone monitor will measure the concentration of ozone gas which results from industry and transportation activity. A 2B Technologies ozone monitor will be further miniaturized to fit within the payload requirements by reducing packaging and replacing the pump with a smaller unit. This instrument measures the amount of absorption that occurs when 253 nm wavelength ultraviolet light passes through the ambient air. The significant species present in the atmosphere that absorbs at this wavelength is ozone. Data has a two second resolution. Estimated weight is 0.45 kg and power consumption is 5 Watt.

**Carbon Monoxide (CO):** Ambient concentrations of carbon monoxide gas will be monitored using either an optical cell (sensitive, but bulky) or an electrochemical sensor (light, inexpensive, but less sensitive). This technology is still being evaluated and any final choice will include considerations for size, weight, and power consumption. Estimated weight is 0.2 kg and power consumption is 3 Watt.

**Nanocrystal VOC sensors:** Nanosensors and MEMS (Micro-electrical-mechanical systems) sensors are perfectly suited for UAV applications. Nanosensors made of porous silicon photonic crystals (to produce a Bragg film) will allow quasi real time detection of volatile organic compounds (VOCs) in the ppm-ppb concentration range. As seen in Figure 20, photonic crystals can be prepared to change color in the presence of a broad class of chemical agents, and are thus uniquely suited as low-power chemical sensors on remote platforms.

As VOC material deposits in the pores of the crystal (an equilibrium process dependent upon atmospheric concentration), the crystal’s color change will be measured by a photodetector. Some prototype devices have already been tested by Dr. Sailor’s group at UCSD (Sailor and Link, 2005; Pacholski et al., 2005 and Dorvee et al., 2005) and are already small enough for UAV applications (See Figure 21). A final version of the instrument will be significantly smaller and more robustly packaged.

Further development will improve sensitivity and stability with the final goal of constructing a final lightweight UAV-class instrument. The tasks for achieving a deployable
the perspective of climate study and air quality. It is known that dusts originate from the arid regions of northwestern China and Mongolia and are then transported eastward under the predominant westerly in these East Asian mid-latitudes. Severe outbreaks of dust storms can result in a significant impact on the Earth's radiation budget due to the strong scattering effect of dusts resulting in atmospheric circulation changes. This is a real concern, in particular when the desertification trend in those source regions is taken into consideration.

The western side of Jeju is considered an ideal location to monitor the continental outflows from the Asian continent and to estimate air/sea exchanges of trace gases and aerosols because there are no local industrial sources (Chen et al., 1997). The Gosan supersite (33°17′32″ N, 126°09′42″ E, 56 m above mean sea level) is located on the western tip of Jeju, and ~100 km south of the Korean peninsula, ~250 km west of Kyushu, Japan, and ~500 km east-northeast of Shanghai, China. The Gosan site is far enough apart from major land masses (China, Korea Peninsular, and Japan) to be representative of the relatively remote marine environment (Figure 22). Lacking of industrial activities on this island also ensures limited local anthropogenic emissions.

There have been ongoing efforts to determine the microphysical and optical properties of Asian dust/aerosol such as ACE-Asia and Asian Atmospheric Particle Environmental Changes (APEX) over the East Asian seawaters, using various ground and airborne measurements of optical and chemical components in Gosan. The most recent intensive field experiment in Jeju was the ABC/EAREX05 (East Asia Regional Experiment) conducted in March-April of 2005 which provided good scientific opportunities to understand the natural/anthropogenic and continental/marine characteristics in regional aerosol and cloud chemistry. During the proposed WPAC, an intensive field campaign led by the Korean ABC

Figure 21: Simple prototype to demonstrate the application of Si photonic crystals to measuring VOCs. A final instrument would be significantly smaller and more robustly packaged. Ref: M. Sailor, UCSD Chemistry.

### Table 3: Instrumentation at ABC Gosan Observatory operated by SNU and Yonsei University

<table>
<thead>
<tr>
<th>Instrument Manager</th>
<th>Manufacture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky radiometer (POM02) SNU (Sohn)</td>
<td>Net radiation in SW and LW, Kipp and Zonen CNR 1</td>
</tr>
<tr>
<td>Net Radiometer SNU (Sohn)</td>
<td>Kipp and Zonen CM 21</td>
</tr>
<tr>
<td>Pyranometer (global) SNU (Sohn)</td>
<td>Kipp and Zonen CH 1</td>
</tr>
<tr>
<td>Pyrheliometer (direct) SNU (Sohn)</td>
<td>Kipp and Zonen 2AP-GD</td>
</tr>
<tr>
<td>Sun Tracker-2AP SNU (Sohn)</td>
<td>Kipp and Zonen CM 22</td>
</tr>
<tr>
<td>Sun photometer SNU (Yoon)</td>
<td>Cimel 318-2C</td>
</tr>
<tr>
<td>Micro Pulse Lidar SNU (Yoon)</td>
<td></td>
</tr>
<tr>
<td>MFR-7 Yonsei University (J. Kim)</td>
<td></td>
</tr>
</tbody>
</table>

**Mission Logistics**

**WPAC Base of Operations in Korea**

After careful consideration, the Korean Airlines training facility on Jeju Island of Korea has been selected as the base of operations for WPAC. Co-PI, Prof. SC. Yoon will be the primary coordinator in Korea.

**Ground-based Observations at the Project ABC Gosan Supersite**

The Gosan observatory on Jeju Island is one of the supersites of Project ABC (V. Ramanathan, Science Team chair). Northeast Asia including northeastern China, Korea, and Japan is the region where Asian dust (or yellow sand) is frequently observed during springtime. This fact has attracted much attention from
Team will be mounted at the Gosan observatory with radiation and aerosol instruments including balloon-sonde for vertical distribution of particles.

**Primary site for UAV launching in Korea, the WPAC Western Pacific Base of Operations**

Prof. SC. Yoon proposed Jung-Sok Airport, the training school for Korean Airlines pilots located in the southern part of Jeju Island (Figure 22) to be the operations center for WPAC. The Jung-Sok Airport is a large and modern facility with a 2300 m x 45 m runway. The airport operation is controlled by the Department of Transportation and the Jeju Special Self-Governing Provincial Government to which Prof. Yoon is applying for permission on behalf of WPAC.

Flying over the Yellow Sea, however, will require clearance from appropriate agencies in the Korean government and military. At appropriate time, Prof. Yoon will coordinate with key personnel from C4/SIO to make presentations at government agencies to facilitate the permission process. The Yellow Sea air space is also under China air traffic control authority. NSF International Representative at the US Embassy in Beijing has been briefed on WPAC and is keenly interested to help to coordinate with the Chinese government. Similarly, the US Embassy in Seoul, Korea will be contacted in due time.

**Alternative site in Korea**

*Baengnyeong-do*, a Korean Meteorological Administration (KMA) weather station, located in the northern part of S. Korea (37°58’N, 124°39’E, 145.53m; an island northwest of Incheon International Airport. The leading concern with this location is that it is very close to North Korea (Figure 24).
- Facilities: AWS (Automatic Weather System), radiosonde station (from 2000), radar (C-band) station, PM10 (from March 2003) and lidar (from December 2004) for Asian dust measurements.
- Natural airport of sand beach: length 2km, width 200m at ebb tide. The sand beach is strong enough to be used as runway. The airport was used during the Korean War.

**WPAC Eastern Pacific Base of Operations in Alaska or California**

A plume of dust and pollution during April will generally move from Asia in an arc across the northern Pacific Ocean to North America as seen in Figure 15. The main sampling site at Gosan will be the first to observe the plume,
and a second UAV sampling site will be chosen to capture the plume either mid journey or when it reaches North America. This approach will allow the observation of changes in the plumes chemistry and physical parameters after crossing the Ocean. These possible sites: Adak, Alaska and Trinidad, California (white circles) are shown in Figure 15.

Halfway through its journey, much of the Asian plume passes over Adak, which is located midway in the Aleutian Island chain. Operating from this location would provide some operational challenges, primarily with weather and logistics, but the site has a strong likelihood of capturing large portions of the plume. While at Trinidad, California, the plume would be more diluted and will be at high altitudes once it reaches North America. Trinidad is of specific interest since it hosts an NOAA/ABC climate monitoring station that would provide ground-based data. Flight restrictions may be a concern at this location due to the proximity of a commercial airport. Other locations along the West coast of the US, in time, should also be investigated.

**ARM Mobile Facility (AMF) Deployment in China**

The Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) will be deployed by DOE in China in early 2008, as part of the approved proposal Application of the ARM Mobile Facility (AMF) to Study the Aerosol Indirect Effects in China, PI: Zhanqing Li. AMF will deploy aerosol, radiation and cloud measurements (Table 4) with the collaboration of China in terms of human resource and logistic assistance.

**Table 4: AMF Aerosol-Cloud-Radiation Instruments**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Instruments</th>
<th>Additional details</th>
</tr>
</thead>
</table>
| **Aerosol** | - Integrating Nephelometer (TSI 3563, 3 wavelength)  
- Particle/Soot Absorption Photometer (PSAP; Radiance Research, 3-wavelength)  
- Condensation Nuclei Counter (CN; TSI 3010)  
- Multiple-Supersaturation Cloud Nuclei and Condensation Nuclei Counter (CCN; DMT) | Two Nephelometers (one will be operated at low RH and the other at RH scanned from 40-90%) |
| **Cloud** | - W-band (95 GHz) ARM Cloud Radar (WACR)  
- Microwave Radiometer (MWR)  
- Micropulse Lidar (MPL)  
- Total Sky Imager | WACR measures cloud boundary (up to 15 km)  
MWR: column-integrated amounts of water vapor and liquid water  
MPL: the altitude of clouds overhead  
Broadband shortwave (solar), longwave (infrared), and ultra violet irradiances  
AERI measures the absolute infrared spectral radiance (3-19.2 µm and 3-25 µm: Wm⁻²str⁻¹cm⁻²) |
| **Radiation** | - Broadband instruments (Pyranometer, Pyrgeometer, and Pyrheliometer)  
- The atmospheric emitted radiance interferometer (AERI) | |

**Complementary Sites in China**

It is important to characterize the dust before it mixes with pollution in China and just before it exits China into the W Pacific Ocean. We are considering several different Chinese candidate sites for dust observations and have begun detailed discussions with four potential host institutions: the Chinese Academy of Sciences, Lanzhou University, Peking University, and the Chinese Meteorological Administration.

**IAP/CAS (Institution of Atmospheric Physics, Chinese Academy of Sciences):** Xianghe site was recommended by IAP/CAS, which has a long history for the field campaigns, such as EAST-AIRE led by Dr. Zhanqing Li etc. Xianghe is also one of the permanent AERONET sites in China since 2001. Xianghe site has almost all the instruments to support the field campaign. According to Dr. Hongbin Chen’s introduction, who is the deputy director of IAP/CAS, they may also provide the tethered balloon observation during WPAC, which is very efficient to get the vertical profiles over the observatory. Xianghe site is southeast of Beijing, downstream of the pollutants emitted from the city, so its aerosol sampling during dust events would represent mixtures of mineral dust and industrial aerosols.

**Lanzhou University:** The Semi-Arid Climate and Environment Observatory is located on the new campus of Lanzhou University. This observatory includes the surface radiation monitoring system (pyranometer, pyrgeometer, pyrheliometer), the eddy covariance system (sonic anemometer, infrared gas analyzer etc.), soil heat and water content monitoring system.
(water content reflectometer, soil temperature profile, heat flux sensor and so on), gradient monitoring system (wind, T, RH), aerosol and ozone monitoring system (multi-filter radiometer, APS, backscattering Lidar, TSI nephelometer, CIMEL sun-photometer), the ambient air quality monitoring system (air analyzer), surface heat flux monitoring system (large aperture scintillometer). Lanzhou University is one of the CEOP sites and has been set to be one of the new AERONET site in China (green star in Figure 23). Although the campus is downstream of Lanzhou city, the dean of the college mentioned they can make measurements near the dust source region if they get funding to support the field campaign.

**Peking University**: There are three permanent dust observatories operated by the Department of Atmospheric Sciences, Peking University. All these sites have been located in the remote rural regions for about two years, which are Duolun (Inner Mongolia), Yulin (Shaanxi Province), and Zhangye (Gansu Province) (Figure 24). Currently, the instruments on the sites include general meteorological measurement, turbulence, radiation, soil observation, and dust sampling. Other aerosol instruments such as nephelometer, sunphotometer and aethalometer which can be installed on one of the sites during WPAC. There is also a small Lidar that could be used to determine the base of the dust layer (Purple stars in Figure 23).

**CMA (China Meteorological Administration)**: CMA had built a dust monitoring network since 2001. Currently, there are 24 sites in the desert and semi-arid regions in Northern China, locating at the Taklamakan Desert, Gobi Desert, Loess Plateau, Northern Plain, and Northeast Plain. Some of these sites was jointly supported by CMA and Korea and equipped with sun-photometer, nephelometer, aerosol concentration sampling, and Lidar (Figure 25).

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**The WPAC Studies, from In-situ to Regional and Global Scales**

**Our primary interests are two fold:**
- To estimate the dust-soot-cloud forcing on the scale of the Pacific Ocean; both the direct and the indirect forcing of dust-ABC mixtures.
- To use this forcing as input in coupled ocean-atmosphere models and estimate the impact on regional climate and rainfall. The regions of focus for climate impact studies are East Asia and the Pacific Ocean and North America. We are interested in both the local effects on East Asia as well as the rest of the world through teleconnection.

We have to integrate the field observations with ground based data, satellite data, regional transport models and global scale aerosol-cloud-chemistry-radiation interaction models. We have developed such an ambitious integration scheme over the last 10 years beginning with the INDOEX field campaign (See Ramanathan et al., 2001) and now continuing with ABC. The approach has been adopted for WPAC as follows (Figure 26).

The multi-platform WPAC data will be integrated with models (STEM2K, GADCIM, MACR) and satellite data (A-Train and GMS) to produce the direct and indirect aerosol forcings for the entire Pacific Ocean; the forcing will be subsequently employed in the NCAR coupled ocean-atmosphere system model to evaluate the impact on the hydrological cycle (e.g.,

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Figure 24: Surrounding environment of the dust observatories of Peking University.

Figure 25: Map of CMA dust monitoring stations (blue dot: the first step station; red dot: China-Korea collaboration station)

WPAC Page 20
As a first step towards this goal, we will employ cloud and aerosol data from A-T rain, particularly Aura, CloudSat, and CALIPSO. For the calculation of dust and other aerosol radiative forcing, we will use the state-of-the-art Monte Carlo Aerosol-Cloud-Radiation (MACR) model developed by our group over the last 10 years (e.g., Podgorny et al., 1998; Satheesh et al., 1999; Vogelmann et al., 2000; Ramanathan et al., 2001a). We (Zhu et al., 2006) have now improved MCR by adding a capability to treat the dust effects on shortwave and longwave radiation.

The MACR model can treat not only the individual aerosol component but also the mixture of different aerosol species. The measurements near dust source regions (e.g., Taklamakan and/or Gobi desert) can provide the optical properties for pure dust, and those over the Yellow Sea provide the properties for dust-soot mixtures. The difference in the radiative forcing between the Gobi Desert and the Yellow Sea represents the contribution of anthropogenic aerosols. For example, the optical properties of pure dust originated from East Asian desert regions can be represented by the single scattering albedo (SSA) measured in Dunhuang (AERONET site), which has an SSA at 550 nm of ~0.96. But when the dust particles interact with the soot aerosol, the SSA sharply decreases as shown by the value measured downstream at Anmyon (AERONET site in central Korea) (Figure 27a). The variances of the optical properties from pure mineral dust to dust-soot mixtures result in large differences in aerosol radiative forcing and the change of atmospheric heating rate (Figure 27b).
the global distribution of aerosols (Liu and Penner, 2002; Feng et al., 2004; Rotman et al., 2004; Liu et al., 2005; Feng and Penner, 2006). Figure 28 shows the schematic of the global model. The aerosol types considered include sulfate, mineral dust, sea salt, black and organic carbons, nitrate, and ammonium aerosols. Each of aerosol types is transported in multiple size bins, going through processes of emissions, gaseous and aqueous chemistry, heterogeneous chemistry, transport, and deposition. The global model has a spatial resolution of $2^\circ$ by $2.5^\circ$ in the horizontal, with 26 layers in the vertical from the surface to 0.1 hPa.

Figure 28: Schematic of the global aerosol and chemistry transport model, Scripps/IMPACT.

For the present study, the transport model is driven by the ECMWF 40-year reanalysis (ERA-40) meteorological fields, which are available at a 6-hour time interval and are interpolated to a 1-hour model time interval.

The resulted aerosol composition and concentration are then used to calculate the cloud droplet concentration and then cloud optical depth. We have developed a parameterization method to relate the cloud droplet number concentration (CDNC) to the concentration of sea salt and sulfate mixture based on the Köler theory and the Twomey’s solution. The calculation of CDNC depends on the aerosol number concentration, chemical composition, and updraft velocity distribution in clouds (Feng and Ramanathan, 2006). Figure 29 shows the increase in cloud drops as a function of aerosol number concentration predicted by the model compared with the derived INDOEX composite scheme (Ramanathan et al., 2001).

Besides sea salt and sulfate, mineral dust particles can undergo modifications that change their chemical and optical properties, and act as CCN, thereby affecting the cloud formation. Dust particles coated with hygroscopic sulfate have been collected in various locations. This coating has been attributed to in-cloud processing (Levin et al., 1996) and to aqueous phase chemistry occurring in the source regions (Falkovich et al., 2001). Additionally, formation of nitrates in mineral dust as a result of heterogeneous chemistry has been suggested from a number of laboratory experiments (Pakkanen, 1996; Zhuang et al., 1999; Galy-Lacaux et al., 2001) and ambient measurement (Laskin et al., 2005). Different from sulfate that mostly exists in the size range smaller than 1 µm, a large fraction of nitrate is found in the coarse mode from field campaigns (e.g., ACE-Asia). By replacing insoluble carbonate calcium in dust with soluble nitrate calcium under the typical atmosphere conditions, nitrate on small particles has an enhancing effect on cloud droplet formation similar to sulfate aerosol; on the other hand, large dust particles that were not activated could become efficient CCN with nitrate, possibly leading to the opposing effect. These effects associated with dust-nitrate activation to cloud drops have not been investigated in field campaigns or examined in the global model studies yet. It also has been suggested that dust aerosols may have an important impact on the formation of ice clouds through contact nucleation (Lohmann, 2001; Sakai et al., 2004).

One of the major scientific questions we are addressing with WPAC is to estimate the indirect radiative forcing by dust aerosol mixed with anthropogenic pollutants through altering cloud microphysical properties. Our fully interactive aerosol model is capable of predicting the concentration of sulfate-nitrate-dust mixture in both fine and coarse mode, varying as a function of space and time. Figure 30 shows the model predicted (a) geographic distribution and (b) vertical structure of the fine mineral dust aerosol mass (diameter < 1.25 µm), over the Pacific ocean for April 2001. Especially, our aerosol model is more accurate than previous models for treatment of nitrate and ammonium in aerosol, because it considers mass transport...
The partitioning of nitrate between gas and aerosol phases and the size distribution of nitrate aerosol has an important impact on dust indirect effect. Based on the calculated aerosol distribution, we can parameterize cloud droplet concentration for dust aerosol mixture similarly as for sea salt and sulfate mixture. Together with the ERA-40 cloud liquid water content constrained by the satellite microwave measurements (SSM/I), cloud optical properties can be calculated. Figure 31 shows the model calculated cloud effective radius over the oceans at 813 hPa. Finally, we can estimate the indirect radiative forcing of dust aerosol by coupling with the MACR model. During WPAC, the integrated model for aerosol-cloud interactions will be validated thoroughly from the predicted aerosol concentrations to the estimated aerosol indirect forcing. It will significantly improve our understanding of the role of aerosol-cloud interactions in the regulation of planetary albedo.

**A-Train Satellite: Regional Scale Forcing**

The afternoon or *A-Train* satellite constellation consists of six satellites flying in formation around the globe (Aqua, CloudSat, CALIPSO, PARASOL and OCO). Each satellite within the *A-Train* has unique measurement capabilities that greatly complement each other. For the first time, near simultaneous measurements of aerosols, clouds, temperature, relative humidity, and radiative fluxes (the change of radiation in a layer) will be obtained over globe during all seasons. This ensemble of observations will allow us to understand how large scale aerosol and cloud properties change in response to changing environmental conditions. It will further allow us to determine how changing cloud and aerosols distributions influence our climate with greater clarity than possible before. For much of its life, the *A-Train* will be maintained in orbit within 15 minutes of the leading and trailing spacecraft while traveling at over 15,000 miles per hour. CloudSat and CALIPSO will be controlled to an even finer requirement, within 15 seconds of each other, so that both instrument suites will view the same cloud area at nearly the same moment. This capability is crucial for studying clouds, which have lifetimes often less than 15 minutes.

Aqua provides CERES dataset including longwave and shortwave radiation fluxes at TOA with cloud-sky categories; and MODIS datasets with (1) aerosol products with aerosol optical depth (AOD) for small-mode or/and large-mode aerosols, aerosol effective radius, angstrom exponent, and asymmetry factor; and (2) cloud products with
cloud optical depth, cloud fraction, cloud effective radius, water path, cloud top pressure, cloud top temperature, cloud phase index, and spectral cloud forcing. CloudSat will give cloud geometrical profile, cloud classification, cloud liquid water content, cloud ice water content, and cloud optical depth. CALIOP is a two-wavelength polarization-sensitive lidar that provides high-resolution vertical profiles of aerosols and clouds. Joint with a three-channel Imaging Infrared Radiometer (IIR), CALIOP/IIR creates datasets for retrievals of cirrus cloud emissivity and particle size. PARASOL provides a wide-field imaging radiometer/polarimeter. Aerosol output includes AOD, single scattering albedo, small and large mode effective radius, refractive index of fine mode, refractive index of coarse mode, cloud coverage, cloud middle pressure, and cloud thermodynamic phase. Aura will give information in study of atmospheric chemistry, focusing on the horizontal (10 km resolution) and vertical (1 km resolution) distribution of key atmospheric pollutants and greenhouse gases (O$_3$, H$_2$O, CH$_4$, N$_2$O, NO$_2$, HNO$_3$, N$_2$O$_5$, CFC11, CFC12, ClONO$_2$, and aerosols) and how these distributions evolve and change with time.

As an example of our technique, we recently used MISR, CERES data along with surface sites (AERONET, BSRN, GEBA and ABC) to generate aerosol and cloud radiative forcing (Figure 33).
errors in simulated cloud fraction by models could translate into large errors in the estimated aerosol radiative forcing. It also can change sign with changes in the vertical distribution of aerosols (Podgorny et al., 2001).

International Collaboration with East Asian Scientists

We have had detailed discussions with scientists in China and Korea about WPAC and have received enthusiastic support for collaboration. We intend to initiate innovative partnerships for providing unique airborne observations of the yellow sand dust and its impact on society. The collaboration will be in the form of setting up ground observations, balloon borne observations and support for UAV operations and joint data analyses and publications. We have initiated discussions with the following groups:

South Korea:
• Prof. S. C. Yoon, Seoul National University

China (Proposed):
• Prof. Hongbin Chen, Institute of Atmospheric Physics, Chinese Academy of Sciences
• Prof. J. Huang, Lanzhou University
• Profs J. Mao, H. Zhang and C. Li, Peking University

Interagency Collaboration

• NSF: International Office, US Embassy in Beijing, for coordination with China.
• NOAA: ABC Observatories in NorthAmerica and East Asia.
• DOE: ARM Mobile Facility to be deployed in China (PI: Z. Li, University of Maryland).
• NASA: A-Train satellite data in real time.
• Industry: Joint collaboration for developing miniaturized instruments and long range UAVs.

Historical Moment. The SIO Team and the ACR Flight Team achieved First Stacked Flight of two autonomous and fully instrumented UAVs over Yuma, Arizona on August 18, 2005 (Top panel). The Science Team (from left, M. Ramana, V. Ramanathan, Chief Scientist, C. Corrigan, G. Roberts and H. Nguyen) standing behind the two UAVs (the radiation aircraft, left, and the cloud physics aircraft with red wingtips) after the historical flight.

The Science Team and Flight Team with R. Curry of NASA-Dryden standing behind five UAVs at the successful conclusion on March 31, 2006 of the MAC campaign in Hanimaadhoo, the Maldives.


