"Emerging Topics in Biogeochemical Cycles (ETBC): Cheju ABC Plume-Monsoon Experiment [CAPMEX] during the summer Olympics of 2008"

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Co-PIs of the International field campaign: V Ramanathan and S C Yoon

Dates of Proposed Campaign: June to September, 2008

Site Where Field Campaign Conducted: Cheju Island, Korea.

B. Project Summary

The proposed campaign will improve our understanding of how atmospheric brown clouds (ABCs) influences the reduction of photo synthetically active radiation (PAR) and broad band solar radiation reaching the western pacific ocean, off of E Asia. In addition, it will document the long range transport of black carbon; the impact of ABCs on clouds; the role of biogenic and anthropogenic aerosols on CCN; and attempt measurements of volatile organic compounds (VOCs) using nano sensors. It will also make first time observations of how East Asian black carbon mixed with dust and other pollutants increases the solar heating of the low level atmosphere over the ocean; and first time measurements of solar radiation fluxes using MEMS based gyro-stabilized platforms. These are all important components of the bio-geo chemical cycles of the region. A parallel major thrust of CAPMEX is that it will bring the latest development in instrument technology including MEMS and nanotechnology and usher in an era of autonomous (through UAVs) observations of air pollution and its impact on regional environment and climate, thus opening the door for Robotic observations. In addition, the timing of the campaign takes advantage of the reduction in emissions from Beijing during 2008 Olympics. The proposed campaign will observe pollution levels before, during and after the so-called "great shutdown" (of Beijing pollution) by integrating ground-level and high-elevation UAS measurements with NASA-satellite observations, documenting the effects particularly downwind from E.Asia.

Intellectual Merit: The research consists of two components:

I. Aerosol and Cloud forcing and aerosol-cloud parameterization: We will estimate the vertical distribution of atmospheric radiative heating (or cooling) and surface dimming due to aerosols; same for cloud radiative forcing; provide input for anthropogenic and possibly biogenic CCN for both low and high clouds on regional scales; develop a regional model with explicit parameterizations for interactions between aerosols, clouds, chemistry and synoptic scale dynamic. The research consists of three parts: **A**. creating an integrated observational data set of aerosol-cloud-dynamics-radiative forcing. This will include UAV data, surface observatories in China, Japan and Korea (thru collaborations with E Asian scientists) and satellite data from COSMIC, CALIPSO and CLOUDSAT. **B**. estimating the 3-D structure of the radiative forcing of clouds and aerosols; **C**. developing an aerosol-cloud-chemical-transport-radiation model that accounts for the observed field and forcing.

II. New Technologies: The campaign will bring together the latest development in instrument technology including MEMS, nano technologies and advanced photonics with state-of-the-art UAV technologies in avionic, navigation and communication systems. Specifically, the proposed campaign aims to achieve a range of technological objectives, including (a) Develop nano-sensors for chemical measurements of reactive species such as VOCs, (b) Integrate miniaturized MEMS based photonic instruments into UAVs, (c) Develop a wireless based data acquisition system using Bluetooth and WiFi radios, (d) Test the real-time interplay between data and flight navigation, and (e) Deploy and validate miniaturized instruments for sophisticated and state-of-art measurements for advanced atmospheric and climate research.

Broader Impact: The research conducted under this proposal is of great societal interest. It will generate new integrated 3-D data sets on aerosol and cloud forcing over the Pacific Ocean. Since it will be observationally based, it will be of great use for validating GCM treatment of aerosol and cloud impacts on climate. The forcing estimates and climate impact studies will be used in national and international assessments of human impact on climate. The collaborations with E.Asian scientists will be of great value for obtaining reliable data for the Asian region. Lastly, the students and post docs involved in the project will have a unique opportunity to get exposed to a challenging new avenue of research and participate in international collaborations. Lastly and most importantly, it will set the stage for future evolution of robotics (unmanned) observations of the atmosphere.

D. Project Description

D.1. Prior Research Findings

a) **Productivity, education, training, outreach and broader impact**: 39 journal papers; 70 conference presentations; 6 PhD students (3 women); 6 post doctoral fellows (one woman); Two training courses organized in Maldives and in Bangkok for over 25 students (40% women) and researchers in Asia, Europe and US(partly funded by NSF). Lectures widely to undergraduate students in campuses, rotary clubs, business and community leaders and policy makers on issues related to air pollution and climate change. The scientific findings on global dimming by aerosols, unique 3-UAV platforms, and findings on the impact of climate change on Indian Rice production were widely covered in news media in the US, Europe and India, and in educational TV by Discovery channel, NOVA, National geographic.

b) **Collection and Creation of worldwide data on aerosols and climate forcing**: Participated and organized 7 field campaigns (**MINOS** organized by Germany; **CIFEX** by NSF; **APMEX** by NOAA; **EAREX** organized by Korea/Japan; **Nepal** Campaign by NOAA; **CRYSTAL** Face by NASA and **MAC** by NSF, NOAA and NASA). NSF funds were leveraged to analyze the data collected from the Mediterranean, East Pacific, S Asia, Indian Ocean and west Pacific. All of these data are now in public domain (publications: P8; P10; P13; P16; P25 listed at the end).

c) **Clarifying and Reducing Uncertainties in IPCC AR4 Studies:** We developed a Global Monte Carlo Aerosol-Radiation model (MACR) for aerosol radiative forcing and provided one global aerosol direct forcing estimates that was constrained by observations, and showed that global wide dimming by aerosols is three 5 to 10 times larger than the aerosol forcing at the top-of-the atmosphere. We developed an assimilation technique for injecting ground and aircraft data with satellite data. These estimates were used in the new IPCC-AR4 report. (P6)

d) **Creative partnership with industry to develop instruments and UAV platforms:**

Developed miniaturized aerosol-radiation-cloud instruments for Light weight UAVs: 4 CPC for total CN concentration; 4 OPC for size distribution of CN; 2 aerosols absorption photometers, 8 pyranometers; 6 narrowband radiometers; 4 cloud physics instruments; an innovative data logger for integrating all of these instruments. These instruments were successfully test flown and the data were validated with ground based measurements.

Developed a new Stacked 3-UAV platform in collaboration with Advanced Ceramics Research Co. For the first time 3 UAVs were flown synchronously and stacked vertically to directly measure radiative heating rates and link these with pollution.

e) Interdisciplinary study with agro-economists on brown clouds and agriculture: In an interdisciplinary study that is unique, an Agro-Economic model was linked with NCAR parallel climate model simulations of the climate impact of brown clouds and greenhouse gases. This paper was mentioned in highlights by Nature, PNAS, New scientist, etc (P1).

UAV Research: Major Instrument & Platform Development:

NSF Award # 0542531, Title: Maldives AUAV Campaign (MAC): Observing Aerosol-Cloud-Radiation Interactions Simultaneously from Three Stacked Autonomous Unmanned Aerial Vehicles (AUAVs), Project Period: 11/1/2005-10/31/2007:

The MAC campaign took place from March 6 to March 31 2006 over the Northern Indian Ocean off the coast of Hanimaadhoo, Maldives. The unique aspect of MAC was to fly3 UAVs stacked vertically to directly measure radiative heating profiles within the atmosphere and relate these to aerosol, cloud and water vapor distribution. Six unmanned aircraft were outfitted with instruments to measure aerosol, solar radiation, meteorological, and cloud properties. The UAVs flew GPS guided tracks and maintained stacked formations so that cloud systems could be

simultaneously viewed from above, below, and within clouds. The science mission collected data on ABCs 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 dust shallow cumulus clouds were penetrated. The two UAVs were stacked within ten seconds of the in-cloud UAV which enabled the simultaneous measurements of upwelling and down welling fluxes at the same time.

Papers published

Ramanathan, V., M.V. Ramana, G. Roberts, D. Kim, C.E. Corrigan, C. Chung, and D. Winker. Warming trends in Asia amplified by brown cloud solar absorption, *Nature*, 448 (7153): 575-U5, 2007.

Ramana, M. V., V. Ramanathan, D. Kim, G. Roberts, and C.E. Corrigan. Albedo, Atmospheric solar absorption, and atmospheric heating rate measurements with light weight autonomous stacked UAVs, *Q. J. R. Meteorol. Soc.*, 133, 1913-1931, 2007

Corrigan, C.E., G. Roberts, M.V. Ramana, D. Kim and V. Ramanathan. Vertical profiles of aerosol physical and optical properties over the Northern Indian Ocean. *Atmos. Chem. Phys.*, 8, 737-747, 2008.

GC Roberts, MV Ramana, C Corrigan, D Kim, V Ramanathan. Simultaneous observations of aerosol-cloud-albedo interactions with three stacked unmanned aerial vehicles. *Proc. Natl. Acad. Sci.*, 2008 (in press)

NSF Award # 0201946: "Aerosol Radiative Forcing and Climate Response: A Regional Focus" $3,110,850.00 04/01/02-03/31/07

I. Aerosol Direct Forcing:

a. Global aerosol radiative forcing: We have developed a global version of the Monte Carlo Aerosol-Cloud-Radiation (MACR) model on the T42 resolution scale (roughly 2.7°×2.7°). It involved a) using observed global ozone, precipitable water, and surface albedo, b) accounting for the effect of the surface orography, c) using observed cloud information from ISCCP or CERES; d) aerosol data from MODIS, AERONET, and GOCART. We generated the global aerosol forcing climatology on a monthly scale (P2, P6, and P14).

b. S Asian Forcing: *NEPAL Campaign (collaboration with ICIMOD, Nepal).* The first direct observations of aerosol radiative forcing over the foothills of Himalayas in Nepal were carried in winter 2003 by installing aerosol-radiometric instruments. The study showed that the aerosols in the brown haze heat the lower atmosphere as much as 1.0K/day within the first two kilometers and led to a large reduction in the solar radiation at the surface (see P11, P4, P15).

II. Aerosol Indirect Forcing:

Long range transport of E. Asian Aerosols in the Pacific: CIFEX Campaign (P5; P18; P21). The Cloud Indirect Effects Experiment, which took place off the coast of Northern California during April 2004 (funded by NSF), combined aircraft and surface measurements with satellite observations and model results in order to determine the effect of aerosols on cloud radiative properties. This field campaign was conducted in collaboration with the University of Wyoming, NASA Goddard, and NCAR and has resulted in the publication of several papers. The major findings of these papers showed that: 1.) There is significant transport of Asian black carbon and other aerosol during the spring over N America (see P5 and P19), 2.) Both locally generated and

long range transport of aerosols affects cloud drop size and number concentration (see P18 and P19), and 3.) Enhancement of pollution in clouds increases the albedo of the clouds measured by satellite (see P28) and therefore the shortwave forcing.

III. Regional Impacts of Aerosol Forcing: (P1; P14): We conducted an ensemble of coupled ocean-atmosphere simulations from 1930 to 2000 in order to understand the role of Atmospheric Brown Clouds (ABCs) over S. Asia in the observed climate trends. The simulations adopt the aerosol radiative forcing from the Indian Ocean Experiment observations and also account for global increases in greenhouse gases and sulfate aerosols. The simulated decreases in surface solar radiation, changes in surface and atmospheric temperatures over land and sea and decreases in monsoon rainfall are similar to the observed trends.

IV. ABC Surface Observatories (NOAA funding for sites with NSF funds used for analysis) (P22): A string of observatories that collect core aerosol and radiation measurements have been deployed. We showed (P3; P11) how the monsoon flow plays a dominant role in modulating the aerosol chemical speciation and radiative forcing (P22-27).

Papers published supported fully or in part by the NSF fund:

P1. Auffhammer, M., V. Ramanathan, and Jeffrey R. Vincent, Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India, PNAS, 10.1073/pnas.0609584104, 2006.

P2. Chung, C. E., and V. Ramanathan, Weakening of N. Indian SST gradients and the monsoon rainfall in India and the Sahel, J. Clim., 19: 2036-2045, 2006.

P3. Corrigan, C.E, V. Ramanathan, et al., Impact of monsoon transition on the physical and optical properties of aerosols, J. Geophys. Res., 111, D18208, doi:10.1029/2005JD006370, 2006.

P4. Di Girolamo, L.,…,V. Ramanathan, Analysis of Multi-angle Imaging SpectroRadiometer Aerosol Optical Depths Over Greater India During Winter 2001-2004, Geophys, Res. Let., 31, L23115, doi:10.1029/2004GL021273, 2004.

P5. Hadley, O. L., V. Ramanathan, ..., Trans-Pacific transport of black carbon and fine aerosols (D<2.5 mm) into North America, J. Geophys. Res., 112, D05309, doi:10.1029/2006JD007632, 2007.

P6. Kim, D., and V. Ramanathan, Solar radiation budget and radiative forcing due to aerosols and clouds, J.Geophysics. Res., 113, D02203, doi:10.1029/2007JD008434.

P7. Lelieveld, J., ..., V. Ramanathan, et al., Global Air Pollution crossroads over the Mediterranean, Science, 298, 794-799, 2003.

P8. Markowicz, K. M., …, and V. Ramanathan, Absorbing Mediterranean Aerosols Lead to a Large Reduction in Solar Radiation at the Surface, Geophys. Res. Lett., 29(20), 1968, doi:10.1029/2002GL015767, 2002.

P9. Mikhailov, E. F., ...,V. Ramanathan, ..., Optical properties of soot-water drop agglomerates: An experimental study, J. Geophys. Res., 111, D07209, doi:10.1029/2005JD006389, 2006.

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P11. Ramana, M. V., and V. Ramanathan, Abrupt transition from natural to anthropogenic aerosol radiative forcing: observations at the ABC-Maldives Climate observatory, J. Geophys. Res., 111, D20207, doi:10.1029/2006JD007063, 2006.

P12. Ramanathan, V., and P.J. Crutzen, New Directions: Atmospheric Brown Clouds, Atmos. Environ., 37, 4033-4035, 2003.

P13. Ramanathan, V., and M. V. Ramana, Atmospheric Brown Clouds: Long Range Transport and Climate Impacts. EM, December 2003, 28-33, 2003.

P14. Ramanathan, V., C. Chung et al., Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, PNAS, 10.1073/pnas.0500656102, 2005.

P15. Ramanathan, V., and M. V. Ramana, Persistent, widespread and strongly absorbing haze over the Himalayan foothills and the Indo-Gangetic Plains, PAGEOPH, Vol. 162, 1609-1626, 2005.

P16. Ramanathan, V., Global Warming, Bulletin of the American Academy, spring, 2006.

P17. Ramanathan, V., et al., Hemispherical and regional variations in long range transport, absorption and radiative forcing, J. Geophys. Res., Submitted for Publication, 2006.

P18. Roberts, G., O. Lariviere, G. Mauger, and V. Ramanathan, Physicochemical transition of aerosols and its effect on cloud condensation nuclei over the Eastern Pacific Ocean: A case study, American Meteorological Society, 2005.
P19. Roberts, G.C., G. Mauger, O. Hadley, and V. Ramanathan, North American and Asian aerosols over the Eastern Pacific Ocean and their role in regulating cloud condensation nuclei, J. Geophys. Res., 111, Art. No. D13205, 2006.
P20. Tanre, D., Y. Kaufman, T. Nakajima, and V. Ramanathan, Preface to Special Section on Global Aerosol System. J. Geophys. Res., 110, doi.10.1029/2004JD005724, 2005.
P21. Wilcox, E., G. Roberts, and V. Ramanathan, Influence of aerosols on the shortwave cloud radiative forcing from North Pacific oceanic clouds: Results from the Cloud Indirect Forcing Experiment (CIFEX), Geophys Res Lett, 33, doi: 10.1029/2006GL027150, 2006.
P22. Ramanathan, V., F.Li., M.V. Ramana, P.S. Praveen, D.Kim, C.E. Corrigan, H. Nguyen et al., Atmosphric brown clouds: Hemispherical and regional variations in long range transport, absorption, and radiative forcing, J. Geophys. Res., 112, D22S21, doi:10.1029/2006JD008124, 2007
P23. Ramanathan, V. and G. Carmichael, Global and regional climate changes due to black carbon, Nature Geosciences, 1, 221-227, 2008.
P24. Lau, K.-M, V. Ramanathan,G.-X. Wu, Z. Li,S.C. Tsay, C. Hsu, R. Sikka, B. Holben, et al., The Joint-Aerosol-Monsoon Experiment(JAMEX), Bull.Amer.Meteor. Soc.,89, 1-15, 2008.
P25. Adhikary, B.,…,V. Ramanathan et al., Characterization of the seasonal cycle of South Asian Aerosols: a regional scale modelling analysis, J. Geophys. Res., 112, D22S22,doi:10.1029/2006JD008143, 2007
P26. Zhu, A., V. Ramanathan, F. Li, and D. Kim, Dust plumes over the Pacific, Indian, and Atlantic oceans: Climatology and radiative impact. *J. Geophys. Res., 112, D16208, doi:10.1029/2007JD008427, 2007*
P27. *Stone, E.A., …,V. Ramanathan, Understanding the origin of black carbon in the atmospheric brown cloud over the Indian Ocean. J. Geophys. Res., 112, D22S23, doi:10.1029/2006JD008118, 2007.*

D.2. Proposed Project:

D.2.1 Scientific Goals:

China has emerged this year (middle of 2007 to now) as the top emitter of Carbon Dioxide. At about 26 million tons per year of SO_2 emissions and 1.5 million tons of black carbon emissions (as of 2005) it is already the top emitter of air pollutants and particles that dominate atmospheric brown clouds (ABCs). For comparison, USA is the second largest emitter of CO_2 (was the top emitter until 2007) and the second largest emitter of SO_2 at 12.8 million tons per year (as of 2005). Thus the impact of E Asia on the Pacific Ocean and N America is a major issue for climate change studies.

The wide spread pollution over the northern Pacific Ocean makes it one of the largest pollution-affected oceanic regions of the world. This transport is sufficiently fast that several studies have reported that transport across the Pacific from Asia to North America contributes significantly to atmospheric loading of black carbon (Van Curen, et al., 2005; Hadley, et al., 2007), mercury (Friedli, et al., 2004), carbon monoxide and ozone (de Gouw, et al., 2004; Jaffe, et al., 2005). During the last few years, several studies have suggested that the dust and soot aerosols could have significant influences on the surface solar radiative forcing of the Pacific Ocean. Yet this is virtually an unexplored area. Another major question is the role of a large amount of soot and VOCs in enhancing cloud drop absorption.

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 is transported across the Pacific from East Asia and other regions (Hadley, et al., 2007) during spring time, and possibly other seasons as well. There has been selected field studies of the aerosol issue in China (ACE-Asia in 2001 and EAREX in 2005) but none of these studies have characterized the aerosol-cloud interactions (the indirect effect) nor have they made direct measurements of the soot radiative heating. The radiative heating by soot

is emerging as a major contributor to the glacier retreat of the Himalaya-Tibetan glaciers; while the surface cooling from the aerosol-indirect forcing is being suggested as one source for the long term surface cooling trend in southern part of China and the shift of the East Asian monsoon system. Lastly, due to fast long range transport, ABCs from China have implications for N America, particularly the west coast of USA.

For these reasons, we are proposing a field campaign with light weight unmanned aircraft from Cheju Island in S Korea, which is directly down-wind of eastern China. During a period of 4 months from June to September of 2008, this island witnesses air mass from most parts of eastern China as well as from Mongolia and Siberia; ranging from southern parts of east China (Shangai; Hong kong etc) in June to northern parts in September. This is a remarkable window into long range (about 1000 km) transport of ABCs from the most industrialized parts of China. CAPMEX will also establish an atmospheric base line to judge future changes as this great nation embarks on its rapid development. Another unique aspect of the campaign is that it has a good chance to assess the impacts of air pollution regulations in Beijing in preparation of the summer-2008 Olympics.

The specific scientific focus of the campaign will be to collect direct measurements of:

- Dimming of the western Pacific Ocean caused by ABCs;
- Vertical distribution of aerosol number density and black carbon concentration;
- volatile organics;
- Ozone concentration;
- direct measurements of absorption optical depths of ABCs;
- Direct measurements of aerosol solar heating at visible and broad band wave lengths;
- Cloud microphysics;
- Direct measurements of Aerosol-cloud interactions and its effect on the surface dimming;
- During the 4 month long campaign we will be seeing air masses from several major cities including Beijing, Shanghai and others.
- We intend to examine if air masses from Beijing are less polluted compared with other mega city air masses in China. This issue arises because, in a well publicized effort, China has taken efforts to reduce ABC emissions in and around Beijing area as part of the summer Olympics preparation.

To this end, we will observe the evolution of the physicochemical properties of aerosols in both the boundary layer and upper troposphere. The first issue is the vertical profiles (from surface to about 15 km) of radiatively important aerosols such as dust, black carbon, organics and sulfates and their impact on surface dimming and atmospheric absorption over the western North American region. Second, black carbon in cloud drops or ice crystals can enhance solar absorption (Chylek and Hallet, 1992; Michailov, et al., 2006) and potentially lead to a dimming over the Pacific Ocean. Fundamental measurements we need to make are the albedo, identification of the major type of absorbing aerosol in cloud droplets, and the absorption and single scattering albedo of polluted clouds. Such measurements, if they can be made with sufficient absolute accuracy, will lay the foundation for resolving the outstanding anomalous absorption issue. The northern Pacific Ocean is the ideal region to examine this question due to abundance of soot, dust and other aerosols in the most cloudy regions of the planet.

In addition, the California Energy Commission (CEC) has funded a project to routinely profile black carbon concentration, aerosol concentration, CO and ozone in the atmosphere using light-weight UASs over a period of one year, starting from April 2008. Flights are occurring every two to four weeks with additional intensive periods to catch pollution events of interest. The vertical

profiles are measured from the surface to 12,000 feet above sea level at the NASA Dryden facility at Edwards Air Force Base north of Los Angeles. This location allows for sampling pollution from both central and southern California as well as long-range transport from Asia and Mexico. By integrating the vertical profile measurements over California with the measurements in *Cheju* Island, we intend to get additional insights into long range transport of CO, Ozone and aerosols.

The links between CAPMEX and the objectives of the bio-geo chemical cycles program of NSF and the environmental technology program of the engineering division of NSF are described below.

D.2.2. Bio-geo Chemical Cycles:

Thus far, we are not aware of any field experiment that has examined the effect of ABCs on Biogeochemical fluxes and cycles. The proposed campaign helps to address the following issues: a) By measuring the dimming effect of ABCs on the western Pacific Ocean (off of E Asia) from wave lengths from 200 nm extending into the PAR region, we are providing the data sets to examine if the ABC dimming is influencing marine productivity over coastal oceans which are not nutrient limited; b) By making direct observations of black carbon and linking with transport and ABCs we are providing insights into an important component of the bio-geo chemical cycles; c) By providing first time data on aerosol-cloud interactions, we are addressing a major objective of this program as described in IGBP; d) By developing capability to measure velocities at 20 Hertz and using nano technology to measure fluxes of biogenic volatile organic compounds (VOCs) and oxidants, we are advancing our measurement capability to measure sea surface fluxes of dimethyl sulfides and other organics.

In addition, the proposed campaign provides the detailed aerosols data sets, which allows the investigation of couplings between the ocean microbiota, marine biogenic sulfur emissions and the atmospheric aerosols at regional scales relevant for potential climate regulation. As far as we know, the only previous work based on global satellite data to investigate the coupling between ocean microbiota and atmospheric aerosols is that of Cropp et al. (2005). The current data provides an unprecedented opportunity for the scientific community to investigate these biogenic coupling between the ocean and atmosphere.

D.2.3. Environmental Technology development:

The measurements will employ following cutting edge engineering and technology:

a) MEMS technology for mounting radiometers with micro gimbals to measure for the first time radiation fluxes with balanced platforms. This will enable us to determine the dimming at the sea surface and reduction of PAR fluxes to the ocean by ABCs. b) New sensors with inertial navigation to determine vertical velocities at 20 Hertz; this capability is critical for measuring bio-geo chemical fluxes from the ocean. c) Nano-technology to measure volatile organics. This work constitutes collaboration with Professor Sailor's Lab (a major research group in nano sensors) in the Department of Chemistry and Biochemistry at UCSD. The construction and deployment of chemical sensors based on porous silicon photonic crystals will be integrated with UAVs for real-time exposure assessment. The essential part of this exploratory project is to construct a sensor to detect a VOCs and oxidants as two separate classes; d) Photonics technology: For the first time we will deploy miniaturized high spectral resolution spectrometers to determine fluxes and heating rates at very high spectral resolution; in addition, we will deploy miniaturized lidar to determine ABC thickness and cloud morphology.

D.2.4. Uniqueness of the *Cheju* Island for CAPMEX

The Gosan observatory on *Cheju* Island is one of the supersites of Project ABC (V. Ramanathan, Science Team chair). The western side of *Cheju* 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, 56m above mean sea level) is located on the western tip of *Cheju*, 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 1a). Lacking of industrial activities on this island also ensures limited local anthropogenic emissions.

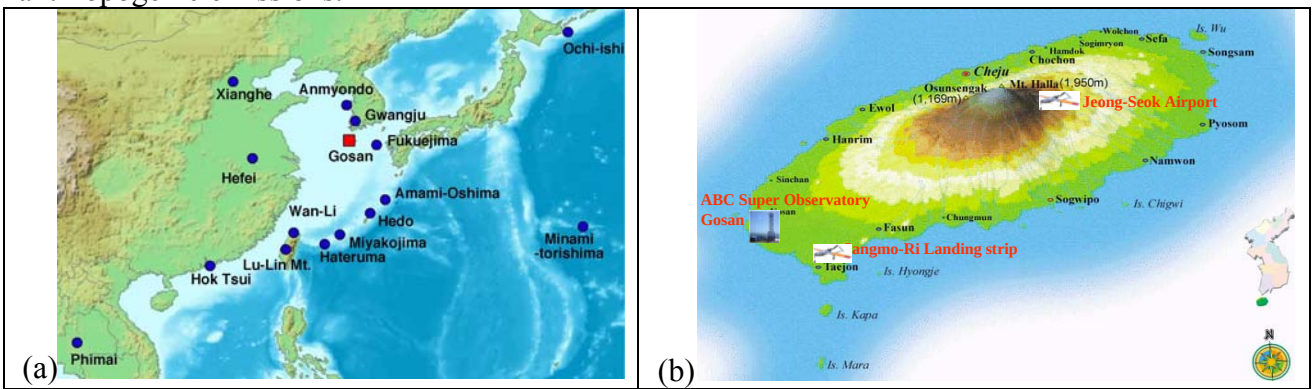


Figure 1: (a) The red mark indicates the location of *Cheju* island where Project ABC Gosan observatory is located. (b) *Cheju* island showing the two possible UAV launching sites; (i) Jeong-Seok Airport and (ii) Sangmo-Ri Landing strip.

D.2.5. Primary site for UAV launching in Korea:

Jeong-Seok Airport, the training school for Korean Airlines (KAL) pilots located in the eastern part of *Cheju* Island (Figure 1b), tentatively has been identified as the operations center for CAPMEX. The Jeong-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 Cheju Special Self- Governing Provincial Government. Prof. SC. Yoon, Seoul National University, Korea, Co-PI of this experiment, has obtained necessary permissions on behalf of CAPMEX. Also, operational permission for an alternate site, Sangmo-ri on the southwestern tip of Cheju, is being requested from the Korean government.

D.2.6. Justification for Timing and Location of CAPMEX

Observations off the Coast of *Cheju* Island in June-Sept offer the greatest potential for collecting data at various levels of pollution (pollution levels before, during and after the unprecedented shutdown of emissions in China/Beijing). These variations will allow us to document the modulation of ABCs by the East Asian Monsoonal flow. Also, this location provides exceptional conditions for observing high cloud cover under both clean and polluted conditions depending upon regional flow pattern. Figure 2 shows the regional distribution of monthly mean aerosol optical depths derived from MODIS for June-Sept averaged over 2001-2006, and reveals the presence of widespread pollution haze layer downwind of E. Asia. Figure 3 shows the monthly mean and seasonal mean variation of aerosol optical depth (AOD) at Gosan obtained using AERONET Cimel sunphotometer averaged over 2001-2006. Figure 3 also presents the angstrom

exponent alongside the AOD data and shows that smaller particles exist during July-Sept even as the over all AOD diminishes.

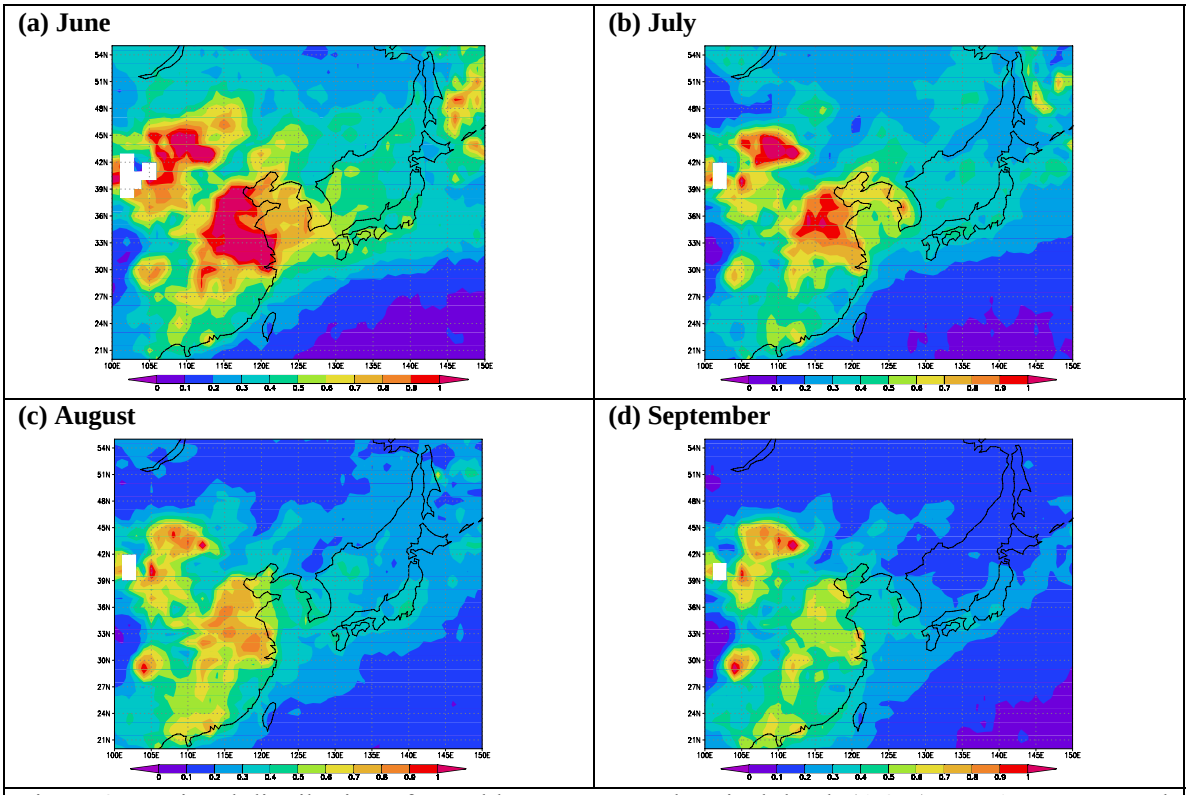


Figure 2: Regional distribution of monthly mean aerosol optical depth (AOD) at 550nm, averaged over 2001 and 2006. The data were obtained from MODIS instrument onboard NASA's satellite.

This increase in the angstrom exponent along with decrease in AOD suggests that natural dust is diminishing while the fraction of anthropogenic pollution is increasing. Figure 4 shows the seven day wind back trajectories at Gosan during June and Sept 2006 at different altitudes. In June, the air mass originates from eastern China and Mongolia. July and August show a stronger influence from the South and Oceanic sources. September once again brings a more northerly regional flow. These figures suggest that both pristine and polluted air should be observed during the June-Sept time frame. By taking advantage of these meteorological patterns and unprecedented emission gradients associated with the Olympic Games, the linkage between aerosols, cloud absorption, surface dimming and atmospheric heating can be explored.

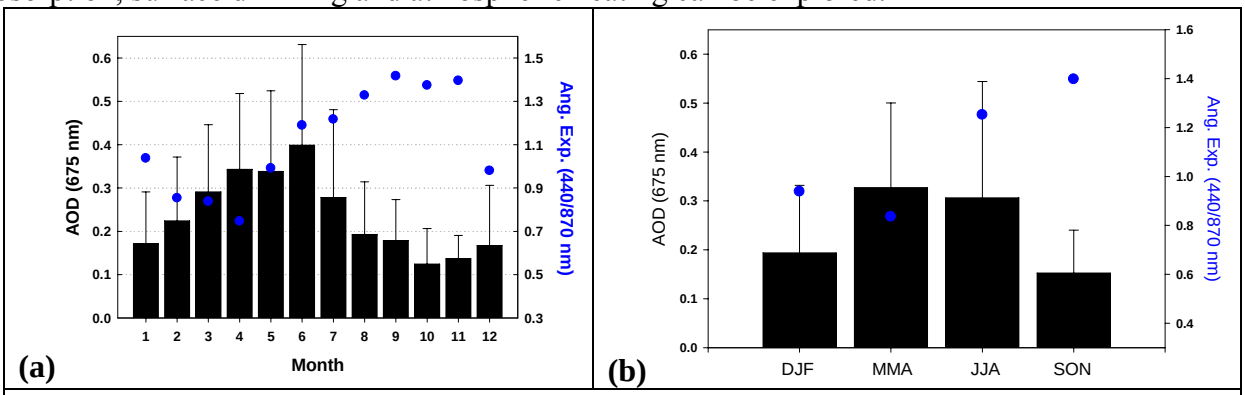


Figure 3: (a) Monthly mean, and (b) seasonal mean aerosol optical depth (AOD) at 675 and Angstrom exponent averaged from 2001-2006. The data were obtained from AERONET.

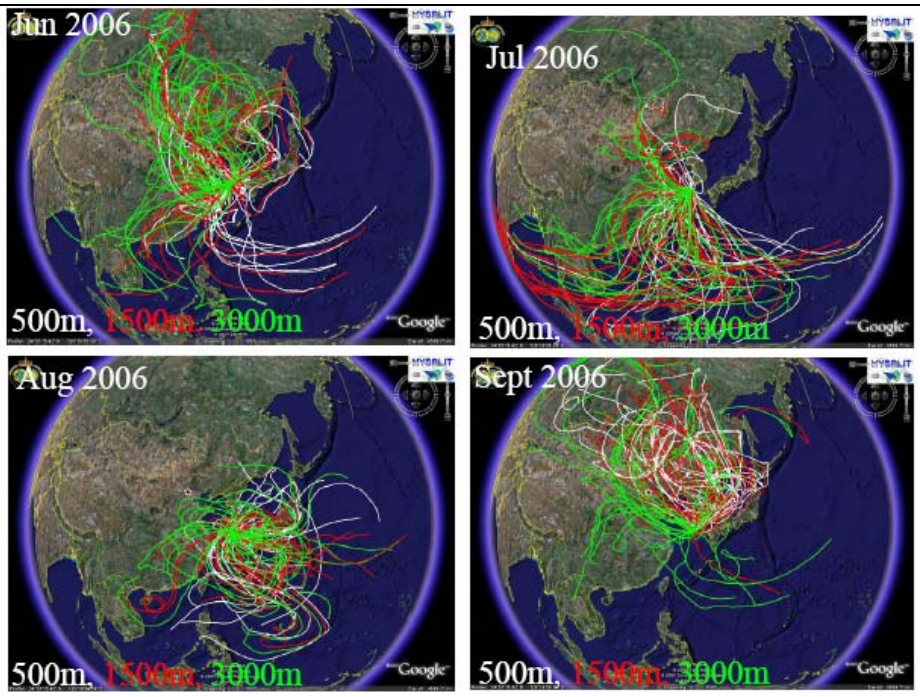


Figure 4: Seven day wind back trajectories at Gosan during June and Sept 2006 at 500m, 1500m and 3000m altitudes.

D.2.7. CAPMEX schedule and posible flight missions

To sample efficiently over the 4-month project, data flights will be scheduled for 10 conscutive days in each month (June-September). Each day will involve 1 or 2 flights of 4-5 hrs duration. Most of the instruments were the same as in the successful MAC campaign of 2006(see section 2.2.8). The new instruments are 1) Grating spectroradiometer and altimetric Lidar; 2) MEMS based auto leveling platform, 3) Nano crystal Volatile organics; 4) Biogeochemical fluxes (water vapor and Vertical velocities) and 5) gaseous measurements (see section 2.2.9).

The possible science missions will consist of primary missions involving one platform, and stacked missions with 2 platforms. The primary missions will perform "Aerosol-Radiation" and "Cloud' measurements. "Aerosol-Radiation" platform will fly first when there are no clouds. In the event of clouds, measurements of cloud microphysics will be performed first, followed by "Aerosol-Radiation' measurements. In stacked missions, "Aerosol-Radiation" and "Cloud' platforms will fly in stacked formation and Gosan ABC observatory measurements will be used as a proxy for below cloud measurements. In addition, UAV flyby's will be performed during takeoff and landing to compare the UAV measurements with surface measurements.

D.2.8. Description of Available Miniaturized Instruments:

The UAV group within the Center for Clouds, Climate, and Chemistry (C4) at the Scripps Institution of Oceanography has developed several instrument payloads for the UAVs under the Global Albedo and MAC projects. A complete suite of miniaturized instruments were developed, flight tested on UAVs and validated to demonstrate that the instruments meet the accuracy required for understanding aerosol-cloud-climate interactions (Ramanathan et al., 2007, Ramana et al., 2007, Corrigan et al., 2008, Roberts et al., 2008). Figure 5 shows the various instruments developed during the MAC as part of this proposal. Our payload (about 3-4 kg per aircraft) includes instruments and data systems developed for lightweight UAVs. Each UAV instrument

is described below. The instruments were calibrated on the ground as well as airborne by two independent methods: a) Flybys over ground observatories; b) wing-tip-to-wing tip flying of 2 UAVs with identical instruments. Each miniaturized instrument is described below:

Figure 5: Miniaturized AUAV instruments for aerosol, radiometric and cloud microphysics platforms.

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 AUAV.

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 miniaturized 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).

Cloud Droplet Probe (CDP): Droplet Measurement Technology Inc. has designed a miniature forward-scattering spectrometer probe 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 ºC temperature on the coil. Liquid water content is then determined as a function of current through the device and the true air speed.

Broadband Radiometer (Pyranometer): The pyranometer accurately measures the global solar radiation, defined as the downward direct and diffuse solar radiation received on a horizontal surface for a broad spectral range. Downward solar irradiance is the forcing function for 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 50-60% of aerosol forcing occurs in the visible spectrum, and this region avoids any near-infrared water vapor absorption.

D.2.9. Proposed New Instruments:

CAMPEX will also push the miniaturized instrument technology to a more advanced level. These new instruments include advanced photonics, MEMS, Nano sensors, gas phase instruments and CO2 and water vapor fluxes. Each new instrument payload will be thoroughly tested and validated prior to being deployed in the filed.

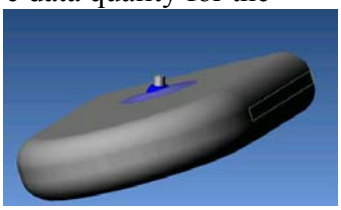
Photonics instruments

Spectroradiometer (200-1100 nm): The atmospheric heating rate due to shortwave radiation 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 spectroradiometers, one for down welling hemispheric flux, a second for upwelling hemispheric flux, both fitted with cosine collectors. The spectroradiometers proposed for CAPMEX deployment will be purchased from Stellar Net, Inc Laboratories. These spectroradiometers sensors scan many channels (200-1100 nm at 1nm) simultaneously and provide detailed information on spectral columnar absorption and spectral albedo measurements. Estimated weight is 0.7 kg and power consumption is 1 Watt.

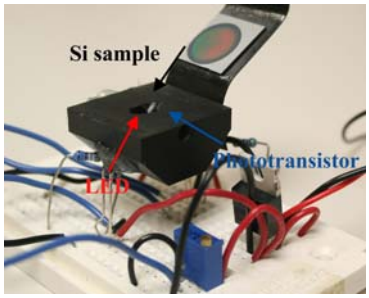
Laser Altimeter: The recently emerged technique of airborne altimetric LiDAR (Light Detection and Ranging) determines the distance to the Earth's surface by measuring the time-of-flight of a short flash of infrared laser radiation. The round trip travel times of the laser pulses from the aircraft to the ground are measured with a precise interval timer and the time intervals are converted into range

measurements knowing the velocity of light. The TruePulse-200 from Lasertech will be used to during the CAPMEX for altimeter measurements. The TruPulse-200 is integrated with tilt sensor which provides accurate height measurements, even from the steepest angles. Its accuracy is ±30cm in height measurements and ±0.25deg in inclination angle measurements. The weight of the instrument is 220gms (12cm x 5cm x 9cm) and has measurement range of 1.5 km. Both the standard serial port and Bluetooth wireless option allow for easy transfer of data once it's been collected. This instrument is currently being evaluated to measure cloud and atmospheric properties, as well as to measure sea-ice thickness and ice-sheet topography. The primary goal is to measure vertical structure of cloud and aerosol measurements to determine the radiative forcing and vertically resolved atmospheric heating rate due to cloud and aerosol.

MEMS: *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. To improve data quality for the CAPMEX missions, the sensor element for measuring the incoming solar radiation will be mounted on a 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 using an electronic orientation sensor in the onboard navigation system or from an independent MEMS (Micro-Electromechanical Machine Systems) technology device. The onboard navigation system contained within the auto pilot hardware is able to resolve the pitch and roll of the aircraft at a resolution of 0.2deg at 20Hz. This signal or an independent electronic gyroscope will be used to control fast acting mechanical actuators that will return a 5cmx10cm platform to level 20 times a second. The figures shown illustrate the design concept showing the PAR radiometer held by a gimble on the top fuselage surface of the UAV. The radiometer is held level during the pitch and roll that the aircraft undergoes during missions. Development and testing of this device is currently ongoing, in collaboration with Latitude engineering company.



Nano Technology: *Nanocrystal VOC sensors*: Nano sensors 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. The 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 (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 us (Sailor and Link, 2005; Pacholski et al., 2005 and Dorvee et al., 2005) and are already small enough for UAV applications (See the figure). A final version of the instrument will be significantly smaller and more robustly packaged.



Biogeochemical fluxes

Water vapor fluctuations: A KH 20 Krypton Hygrometer (Campbell Scientific) is used to measure fluctuations of absolute water vapor pressure around the mean value. The measurements

are based upon the absorption of water vapor at 123.58 nm band emitted by a low-pressure Krypton glow tube. Since this instrument is subject to scaling of the source tube window (caused by the disassociation of atmospheric constituents by UV photons), it cannot be used as an absolute sensor for the humidity. Therefore, a slow response humidity sensor will serve as reference for the KH 20 measurements.

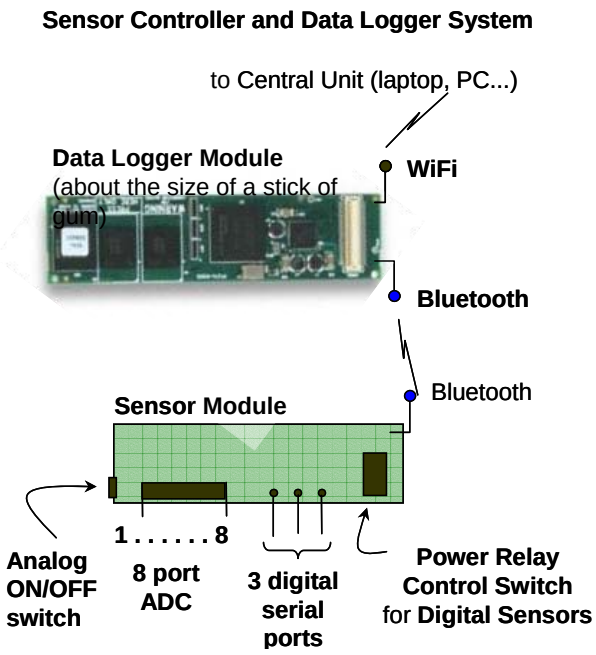
Gust Probe with Inertial Navigation System: A 5-hole gust probe is used to measure the three-dimensional wind relative to the aircraft. Two vertical aligned pressure ports are used to derive the angle of attack, while two horizontally aligned pressure ports are used to measure the angle of sideslip. In order to derive the three-dimensional wind field with respect to the earth, the aircraft attitude and motion has to be known. A CMIGITS III by Systron Donner will be used to derive the three attitude angles (roll, pitch and yaw) with accuracy better than 0.1°, and the aircraft velocity better than 0.1 m s^{-1}. The data is available at a sampling rate of up to 100Hz. The motion pack integrates an Inertial Navigation System with a GPS, thereby combining the advantages of each subsystem.

Gaseous instruments:

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.

Wireless based Data Acquisition system: This device will be developed using Bluetooth radios and industry-standard WiFi radios, in collaboration with the wireless sensor networking company called *Erallo* Technologies. The long term objective of this Wireless Data Logger program is to develop a flexible data logger platform with wireless capabilities to enable UAV researchers to modify experiment configurations easily and deliver data in usable forms efficiently without any complex programming. The Bluetooth connectivity will be used to communicate between the Data Logger unit and the Sensor Module. The proposed wireless sensor and data logger platform system will have two-way commands and controls. This feature will enable researchers to monitor their experiments in real-time, and if



required, modify the parameters in real-time by issuing commands or changing configurations from the ground. These configurations and commands will then be wirelessly uploaded onto the UAV sensor system. As a technology demonstrator and proof of concept, *Erallo* will provide a prototype system that can be integrated and deployed in the CAPMEX. The power and connectivity requirements will complement the existing UAV design. The proposed platform will use low power, MEMS-based electronics so that power requirements will not exceed 500 milliamps.

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 (MAC Campaign; Ramanathan et al., 2007, Corrigan et al., 2008, Ramana et al., 2007, Roberts et al., 2008). Any new miniaturized instruments not utilized in previously published experiments will be tested and evaluated thoroughly in the laboratory and during the California AUAV Air pollution profiling study (CAPPS) missions.

D.2.10. UAV description: Manta

Advance Ceramic Research'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. For CAPMEX, modifications to UAV have been considered that will enable fully automated launch, flight and recovery. The Manta aircraft are equipped with differential GPS capability and perform automated takeoff and landing when commanded. The differential GPS 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. The UAVs are ideally suited for the scientific goals of CAPMEX because they are the only platform which will permit the required close coordination in time and space.

D.2.11 Ground-based Observations at the Project ABC Gosan Supersite

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 *Cheju* 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 CAPMEX, an intensive field campaign led by the Korean ABC Team will be mounted at the Gosan observatory on *Cheju* Island with aerosol, gaseous, radiation and cloud microphysics instruments including Lidar and balloon-sonde for vertical distribution of particles. In addition to the above list of instruments, cloud condensation nuclei (CCN), Nanocrystal VOC sensor will be installed during the CAPMEX period at Gosan observatory. An Intensive Surface measurements campaign will start from May 1, 2008 until the end of September, 2008. This site

will have all of the air borne UAV instruments making measurements for validation of the UAV instruments.

D.2.12. Integration of CAPMEX Measurements into Models:
Models will play an integral role in the design, execution, and interpretation of CAPMEX. The modeling group at the University of Iowa has developed an operational regional- to intercontinental-scale forecasting and analysis system to assist in atmospheric field experiments. The system consists of 3 major components: 1) detailed mesoscale meteorological model with on-line air mass and emission tracers; 2) detailed 3-dimensional photochemical calculations using CTMs; and 3) enhanced emission products that intimately link emitted amounts and activities to the transport and chemistry analysis. This system was successfully applied in the design and execution of the NASA TRACE-P, NSF ACE-Asia, the NOAA ITCT-2K2, NASA/NOAA/NSF INTEX and ICARTT, and several ABC-related intensive field experiments (Carmichael et al., 2003; Tang et al., 2004; Seinfeld et al., 2004). In these previous experiments they demonstrated that these models can be used effectively in the execution and analysis of field experiments. The University of Iowa group has authored or co-authored over 30 papers related to these recent field experiments.

Broader Impacts of the proposed activity:

a. Interagency Collaboration and international collaboration with East Asian Scientists
The proposed activity integrates observations and model created by NSF, NOAA, NASA and DOE and thus the integrated data sets generated by this activity will benefit a large community of researchers funded by these agencies. We have had detailed discussions with scientists in China and Korea about CAMPEX and have received enthusiastic support for collaboration: China: Dr. Hongbin Chen, Vice president, Inst of Atmospheric Physics, the Chinese Academy of Sciences; Prof. J. Huang, Dean of Earth Sciences, Lanzhou University and Profs. J. Mao, H. Zhang and C. Li, Peking University; S Korea: Profs. Soon-Chang Yoon (Co-PI), K.R. Kim, B.J. Shon, Seoul National University; Prof. C.H. Kang, Cheju National University; Prof. M.K. Kim, Kongju National University; Korea Aerospace University, and Korean Airlines, Japan: Prof Hatakeyama, ABC Okinawa site. US students and post docs involved in this project also has the unique opportunity to interact with an international community of researchers, and access data collected in China and west Pacific.

b. Education and Training: The PI has a long and demonstrated track record of educating and training young researchers in the US and this will continue. He will continue entraining students and post docs in under represented groups; continue and expand the international ABC training school program with NSF and UNEP help. The PI and his group have submitted proposals to continue the UAV program, and this program will bring in tremendous innovation in instrumentation, data gathering, and UAV platforms. Students (graduate and under graduate) will play a large role in these activities. Finally we will also work closely with the Scripps' famous Stephen Birch aquarium to develop educational materials for the public at large (over 200000 per year). We have developed an exhibit of the UAV and brown clouds during fall of 2007 in Stephen Birch aquarium.

c. Research Impact: The data and findings generated from the project, since they deal with the major uncertainty in climate change predictions and furthermore will assess the impact of E Asian emissions on regional climate, will be of major importance to national and international assessments (e.g., IPCC) of climate change.

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