

# On Using NASA's Ikhana and Global Hawk to Understand Atmosphere-Ocean Interactions

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**Abstract – NASA's newly acquired and recently deployed Global Hawk and Predator B (Ikhana) unmanned aerial systems enable suborbital earth observations over previously unobtainable temporal (>30hrs) and spatial scales (>11,000 nm). These observations, when combined with satellite and ship-based measurements, provide scientists with a unique ability to study the relationship between the long-range transport of natural and anthropogenic compounds (e.g. mineral dust or oxides of nitrogen), their deposition to the remote ocean, and their potential impacts on ocean biogeochemistry. The science rationale for using UAS is discussed, along with the challenges of conducting interdisciplinary science using multiple observation platforms and multiple UAS's. Examples of previous coordination between manned aircraft and surface observations demonstrate the utility of the approach, and a suite of instruments for conducting biogeochemistry investigation using Ikhana and Global Hawk is proposed.**

Keywords: global hawk, ikhانا, airborne science, atmospheric science, aerosols

## 1. Introduction

Contemporary Earth Scientists who focus on observations have a wide array of research platforms and sensors available to them. Platforms such as submersibles, surface-ships and aircraft allow scientists to access remote localities with state-of-the-art instrumentation to conduct detailed, precisely calibrated *in-situ* measurements. The chief limitation to these *in-situ* techniques is the inability to conduct these measurements continuously over the spatial and temporal scales necessary to draw broader conclusions about these phenomena regionally, globally and/or inter-annually.

The advent of satellite-based sensor technologies has enabled Earth Scientists to collect and analyze global data sets at spatial scales of meters to 100's of kilometers and over temporal scales ranging from the diurnal to interannual. Recent reviews of science achievements from sensors aboard NASA's 10-years operational TERRA satellite are beginning to separate multi-year trends from interannual variability (1). To confirm and extend these trends, longer periods of observation are required. These will need to be met by current and future satellite systems such as Aqua, Aura, Glory, and NPOESS.

While satellite sensors can provide global coverage at daily to weekly rates with robust estimates of their precision, careful calibration and validation activities are still required to ensure that satellite data products are comparable to independent observations.

Even using limb-sounding techniques (e.g. TOMS), there are few sensors capable of retrieving vertically resolved information throughout the depth of the troposphere (e.g. Cloud-Aerosol Lidar with Orthogonal Polarization -

CALIOP). Thus some retrievals (e.g. the trace gas CO) require *a-priori* assumptions about their vertical distribution.

Retrievals of surface information (e.g. chlorophyll) often require corrections for atmospheric effects. Correcting for absorbing aerosol, specifically black carbon, brown carbon and mineral dust, is particularly difficult due to their individual and sometimes strong wavelength dependencies, and the fact that they are poorly constrained in current satellite retrievals.

Validation requirements have lead to the development of AERONET, a world-wide network of surface based sun-photometers for calibrating/validating satellite retrievals of atmospheric aerosol and water vapor (2). While highly successful at improving satellite retrievals (3), AERONET has few observations over the remote ocean (4) and lacks vertical resolution.

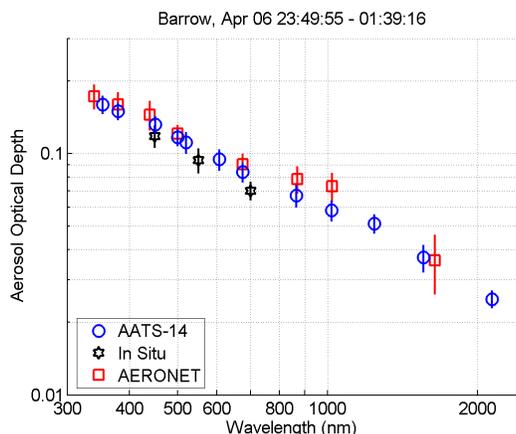
As a result, atmospheric profiling and plume characterization has become an important aspect of NASA's recent airborne science field campaigns (e.g. INTEX-B (5), and ARCTAS (6)). The following paper describes several examples of the use of aircraft to conduct calibration/validation activities in support of NASA's Earth Science goals. We then discuss how the unique capabilities of NASA's unmanned aerial systems (UAS) have some advantages over manned systems when conducting these types of observations, and how these new capabilities can be used to explore ocean-atmosphere interactions.

## 2. Discussion

### *On combining aircraft profiles with surface retrievals*

The chief limitations of the AERONET retrievals are their fixed locations, absence of measurements over the remote ocean, and their lack of vertically resolved information when not paired with micro-pulse lidar measurements of aerosols (MPLNET). During NASA ARCTAS mission, the NASA P-3B was equipped with the AATS-14 instrument used for direct measurements of aerosol optical depth (AOD). The P-3B also carried *in-situ* measurements of aerosol light scattering, absorption and the increase in scattering as a function of relative humidity. In figure 1 the AATS-14 data and integrals of the *in-situ* measurements are compared to retrievals by AERONET. For all of the ARCTAS intercomparison cases the accuracy of the AATS-14 technique is within +/- (3%+0.02) of AERONET AOD (7).

Over the remote ocean, aircraft such as NASA's UAV's may be able to extend the P-3B capabilities, providing larger data sets suitable for statistical analyses. This will enable the study of atmospheric phenomena that vary over large spatial and temporal scales, and provide constraints where vertically resolved measurements are required but AERONET measurements are lacking. And while ship based measurements are also needed, the aircraft enable atmospheric profiling over larger spatial scales during shorter sampling periods.



**Figure 1** – Comparison of AATS-14, in-situ (HiGEAR) and AERONET retrievals of aerosol optical depth at Barrow Alaska during NASA ARCTAS experiment in April, 2008.

### On using multiple aircraft for targeted sampling

In mid April 2008, the NASA DC-8 and P-3B aircraft concluded flight operations in Fairbanks Alaska during Phase-1 of ARCTAS. Near real-time satellite products, regional as well as global climate models operating prognostically, predicted that a large plume of biomass burning aerosol (BB) from Siberia/Kazakhstan was transiting the North Pacific at latitudes north of 45°N while a southern plume of East Asian urban/industrial pollution (AN) was being transported across the Pacific at latitudes south of 45°N. In order to intercept and sample these plumes a coordinated effort was proposed for the April 19<sup>th</sup>, 2008 ferry flight from Fairbanks, AK to Palmdale, CA. The flight included a wingtip-to-wingtip formation flying for instrument intercomparisons within the BB plume. After the intercomparison the DC-8 would use its higher ceiling and airspeed to climb to 8 km and use the NASA Langley Differential Absorption Lidar (DIAL) to map the vertical and meridional distribution of the plumes. The DC-8 would then direct the P-3B into the plumes both before and after a scheduled over flight of NASA's CALIPSO spacecraft carrying the CALIOP lidar. In this fashion, the CALIOP retrieval could be constrained by both an airborne lidar and in-situ measurements of aerosol optical properties, microphysics and chemistry. Figure 2 shows three views of this coordination between suborbital platforms and the CALIOP sensor.

The 532 nm CALIOP measurements of total attenuated backscatter (top panel) appear to capture several features very well. These include the high altitude ice clouds above the Alaskan mountain ranges, marine stratus clouds at 1 km as well as the biomass burning plume. Version 3.01 CALIOP data products (second panel) correctly identify several regions as aerosol plumes including the subtypes “clean marine”, “dust”, “polluted dust” and “smoke”. The retrievals from the DIAL lidar show that intense but thin plumes are missing from the CALIOP retrieval and that even patchy cloud (e.g. near 43.4°N) can prevent adequate spatial characterization of aerosol-laden plumes.

The bottom panel plots the flight tracks for both the NASA DC-8 and the P-3B. Marker size is proportional to total aerosol scattering while marker color indicates the concentration of black carbon in  $\text{ng sm}^{-3}$ . *In-situ* measurements of the spectral

dependency of absorption (absorption Angstrom exponent) confirm that the aerosol plume centered at 55.4°N is definitely smoke from biomass burning. Size distributions reveal that average total aerosol mass from the two aircraft is  $21 \mu\text{g sm}^{-3}$  with a coarse mode component of  $3.3 \mu\text{g sm}^{-3}$ . The fine mode fraction of extinction ( $\text{FF}_{\text{scat}} = \text{submicrometer divided by total extinction}$ ) averages  $0.77 \pm 0.12$  so this plume would typically be considered “fine mode dominated”. Depolarization of light is a characteristic feature of crystalline (e.g. dust) rather than spherical particulate (e.g. seasalt in the marine boundary layer). BB aerosol is known to be slightly depolarizing. Thus, indications of polarizing aerosol detected by CALIOP may account for this plumes classification as “polluted dust”. The AATS-14 measurements of aerosol optical depth in the V-notch during the intercomparison period averaged  $0.25 \pm 0.03$  ( $N=7$ ) at 519 nm. This plume is sufficiently dense that it has partly attenuated the nadir DIAL lidar beam.

For comparison, the anthropogenic plumes sampled independently at various locations by the P3-B and DC-8 indicate a total aerosol mass of  $8.7\text{-}13.7 \mu\text{g sm}^{-3}$  with dust accounting for  $3.7 \pm 1.9 \mu\text{g sm}^{-3}$ . For this case  $\text{FF}_{\text{scat}}$  averages  $0.63 \pm 0.21$  indicating a mixed plume containing Asian pollution and dust.

Though the aerosol subclassification for the Asian plume is accurate, the plume extent may not be adequately retrieved. Daylight retrievals by CALIOP are typically noisier than nighttime retrievals and there appears to be some interference in this retrieval below the patchy high cloud. Careful examination of the attenuated backscatter plot suggests that a region of somewhat higher values does exist in the locality of the plume – perhaps the screening algorithm is too strict? There is a gradient in AOD along the P-3B leg North of 43.4°N that increases from 0.18 to 0.25 with a mean of  $0.21 \pm 0.02$  ( $N=36$ ). The inability of the CALIOP daytime retrieval to identify plumes of this extent and intensity highlights the need for independent calibration/validation by suborbital platforms as well as the need to continue to develop new sensor technologies.

### Global Hawk & Ikhana



**Figure 3** – Global Hawk (left) and Ikhana (right) UAS.

NASA's Dryden Flight Research Center has acquired three developmental-model Northrop Grumman Global Hawk unmanned aircraft from the U.S. Air Force for use in high-altitude, long-duration Earth science missions. These autonomously flown aircraft are the first, sixth and seventh aircraft built under the original Global Hawk Advanced Concept Technology Demonstrator development program sponsored by the Defense Advanced Research Projects Agency.

The ability of the Global Hawk to autonomously fly long distances, remain aloft for extended periods of time and carry large payloads brings a new capability to the science

community for measuring, monitoring and observing remote locations of Earth not feasible or practical with piloted aircraft, most other robotic or remotely operated aircraft or satellites. The aircraft's 11,000-nautical-mile range and 30-hour endurance, together with satellite and line-of-site communication links to the ground control station, allow for eventual worldwide operation. Dedicated satellite communication links provide researchers with direct access to their onboard instrument packages during missions. Researchers have the ability to monitor instrument function from the ground control station and evaluate selected data in real time. Payload capacity is 2,000 lbs with an operating altitude of over 60,000 ft.

A Predator B unmanned aerial system has been acquired by NASA's Dryden Flight Research Center to support Earth science missions and advanced aeronautical technology development. The aircraft, named Ikhana (a Native American Choctaw word meaning intelligence, conscious or aware), will also act as a testbed to develop capabilities and technologies to improve the utility of unmanned aerial systems. NASA obtained the aircraft from the manufacturer, General Atomics Aeronautical Systems, in November 2006. More than 400 pounds of sensors can be carried internally and over 2,000 pounds in external under-wing pods. Ikhana is capable of reaching altitudes above 40,000 feet.

### ***The atmosphere-ocean link***

The low-nutrient, low chlorophyll (oligotrophic) surface waters of the North Pacific subtropical gyre (NPSG) represent one of the largest ecosystems on Earth (8). Similarly the high-nitrate, low chlorophyll waters of the North Pacific subpolar gyre also represent a vast yet largely under sampled ecosystem. The supply of nutrients to marine organisms, their types and their interactions are poorly understood because of the size, remoteness and spatiotemporal complexity of the habitat (9, 10).

The emission, transport and deposition of natural (e.g. SO<sub>x</sub>, mineral dust) and anthropogenic (e.g. CO<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub>) compounds are a significant source of nutrients (11) and/or contaminants to the marine environment.

Doney (12) reports:

*Major observed trends include a shift in the acid-base chemistry of seawater, reduced subsurface oxygen both in nearshore coastal water and in the open ocean, rising coastal nitrogen levels, and widespread increase in mercury and persistent organic pollutants. Most of these perturbations, tied either directly or indirectly to human fossil fuel combustion, fertilizer use, and industrial activity, are projected to grow in coming decades, resulting in increasing negative impacts on ocean biota and marine resources.*

Simulations of pre-industrial rates of nitrogen fixation in the global ocean compared to the difference between future and preindustrial fixation rates suggest a major, anthropogenically induced, response by ocean biology to enhanced atmospheric inputs of Fe and N. Krishnamurthy et al. (13) report that:

*Simulations with increasing Fe and increasing Fe and N inputs raised simulated marine nitrogen fixation, with the majority of the increase in the subtropical North and South Pacific [emphasis added]. Increasing deposition of [soluble iron] along with [anthropogenic*

*nitrogen] could partially explain trend toward increased P limitation at Station ALOHA in the subtropical North Pacific.*

### ***Advanced planning by NASA***

In 2006 NASA published *Earth's Living Ocean: 'The Unseen World'*, an advanced plan for NASA's Ocean Biology and Biogeochemistry Research. One of the four priority science questions identified by the report is, *How do carbon and other elements transition between ocean pools and pass through the Earth System, and how to biogeochemical fluxes impact the ocean and Earth's climate over time?*

Specific strategies for addressing these science questions include:

1. Accurate separation of in-water constituents and correction for the contribution of aerosols,
2. Deployment of active approaches for probing plant physiology and functional composition from polar satellite orbit using laser technologies and,
3. Developing new technologies to obtain ocean particle profiles and aerosol column distributions.

The report recommends that NASA continue "systematic, decadal scale sampling" of the ocean and atmosphere for the "in-situ validation of satellite data products".

### ***On using UAS's to study ocean biogeochemistry***

Operating NASA's long-endurance UAS's over the North Pacific is facilitated by the remoteness of the locality and thus the relative ease of flight operations. The Pacific Missile Range Facility, located on Kauai, controls considerable Air- and Sea-space Northwest of the main Hawaiian Islands and has an established record of collaboration with NASA (14).

The concept for a dual UAV and surface ship based experiment is proposed. The scientific goals of the proposed study are to:

1. Characterize the spatial and temporal evolution of an Asian airmass outbreak over the North Pacific Subtropical Gyre and compare in-situ measurements to retrievals by suborbital and satellite based remote sensors.
2. Characterize the concentrations of gas and aerosol phase nutrients and/or contaminants, and observe the temporal and spatial extents over which they are deposited to the NPSG.
3. Conduct a suite of atmospheric, oceanographic and biological measurements necessary to quantify the type and magnitude of any biological responses to the atmospheric deposition of nutrients and/or contaminants.
4. Compare the type, magnitudes and spatial extent of the deposition event and possible responses by ocean biology to data products from sensors deployed as part of NASA's Ocean Biology and Biogeochemistry program.

A field experiment of this nature will necessitate support from satellite retrievals and weather forecasting as well as global and regional chemical transport models operating prognostically. While not intended to be comprehensive, a sample list of instruments platforms are presented in Table 1. Measurements by a High Spectral Resolution Lidar (HSRL) aboard the Global Hawk could provide data products similar to those discussed, as well as other important quantities such as multiple wavelength measurements of light depolarization by ice and

aerosols (15). Flux radiometers are an important measurement on each platform as differential flux measurements can be used to measure direct radiative forcing by aerosol and cloud (16). Desirable measurements aboard the GH include other lidars profiling the atmosphere for important trace gases such as H<sub>2</sub>O, CO<sub>2</sub>, O<sub>3</sub> and SO<sub>2</sub>.

It is expected that while the Global Hawk is mapping the spatial extent and temporal evolution over ~24+ hour time frame, Ikhana will be launched and then vectored to sample the plume in more detail. These measurements might include trace gas and aerosol quantities for calibrating lidars and remote sensing retrievals, as well as information on aerosol and cloud droplet size distributions. Additional gas phase tracer measurements and fast (<1 min to 1 Hz) measurements of aerosol chemistry would improve the link to ship-based measurements of nutrient and contaminant chemistry.

A surface ship would conduct all the necessary radiation, trace gas, aerosol and nutrient measurements needed to support the UAS's and calibration/validation of available satellite data products. This should include studies of microbial ecology and information about the type and abundance of primary producers, as these are quantities NASA hopes to derive from the next generation of satellite sensors.

Sampling over 1-2 months between January and May would capture the most intense period of trans-Pacific transport. Staging operations over a 1-3 year time frame would increase the probability of observing an event with sufficient intensity to create a biological response by organisms found in the NPSG.

### 3. Conclusions

In this article we have highlighted the need to conduct suborbital measurements in support of the calibration and validation of current and future space-based remote sensors. Suborbital platforms including multiple aircraft and surface-based observations were presented and highlight the challenges and utility of this approach to satellite sensor calibration and validation. NASA's newly deployed unmanned aerosol systems provide an opportunity to conduct these types of investigations over large spatial and temporal scales than manned aircraft. A field campaign was proposed that focused on using two UAS's and a surface ship to observe and characterize the effects of atmospheric deposition of Asian pollution and dust on the North Pacific Subtropical Gyre. An investigation of this type would address key unknowns in ocean-atmosphere interactions and biogeochemical cycling and support research activities in NASA's new Ocean Biology and Biogeochemistry research program.

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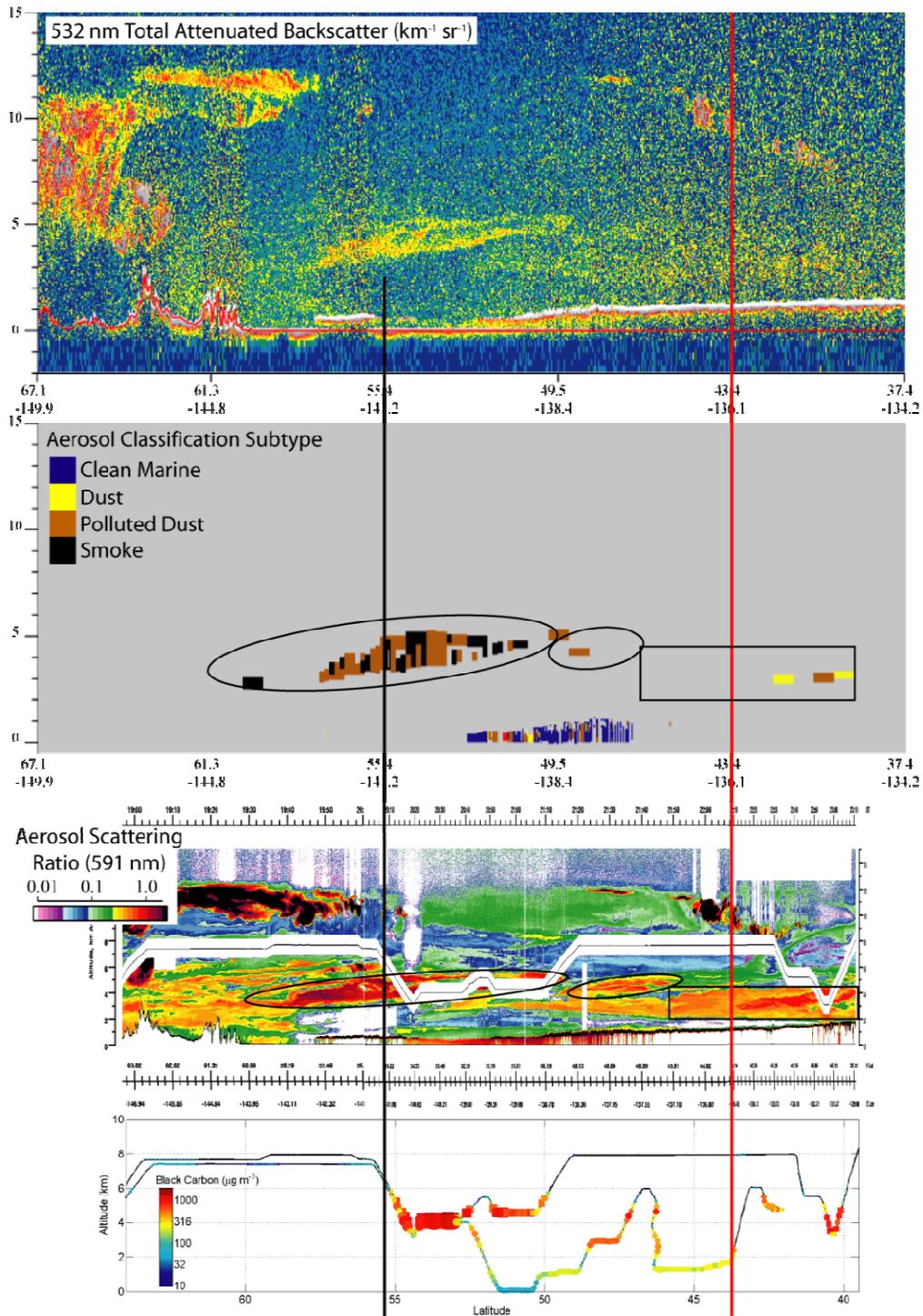
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**Table 1** –Example payloads for NASA’s two UAS’s and a surface ship in order to carry out biogeochemical characterization of atmospheric deposition of nutrients and contaminants to the North Pacific Subtropical Gyre.

Global Hawk		Ikhana		Ship
Priority 1	Priority 2	Priority 1	Priority 2	
HSRL Lidar	Trace Gas Lidar (H <sub>2</sub> O, CO <sub>2</sub> , SO <sub>2</sub> )	Trace Gases (CO <sub>2</sub> , CO, O <sub>3</sub> )	Trace Gases (DMS, SO <sub>2</sub> , HNO <sub>3</sub> )	Trace Gas Chemistry
Flux Radiometers		Aerosol Optics	Submicrometer Aerosol Chemistry	Aerosol Microphysics
		Aerosol Size (0.02-20.0 μm)	Supermicrometer Aerosol Chemistry	Aerosol Optics
		Cloud Droplet Number, Size		Aerosol Chemistry
		Flux Radiometers		Flux Radiometers
				Seawater Chemistry (N, P, Al, Fe, Hg)
				Nutrient Chemistry (C,N,P,Fe)
				Microbial Ecology Primary Productivity



**Figure 2** – (top row) April 19<sup>th</sup>, 2008 retrieval of aerosol backscatter by the CALIPSO spacecraft along the West Coast of North America from Alaska to California. (second row) Aerosol classification subtype from the V3.01 CALIOP data product. (third row) NASA Langley DIAL plot of aerosol scattering ratio measured from onboard the NASA DC-8. (bottom) NASA DC-8 (square) and P-3B (circle) in-situ measurements of aerosol scattering (marker size) and black carbon concentrations (marker color – log scale) along the aircraft flight tracks. From 56°N to 52°N the two aircraft performed a wingtip-to-wingtip intercomparison while sampling an intense biomass burning plume generated in Kazakhstan and Siberia. South of 52°N the DC-8 lidar data was used to direct the P-3B into an intense plume of Asian Pollution and Dust transported across the North Pacific.