Introduction. The overarching vision of this concept is to revolutionize, in situ, wireless atmospheric sensing by developing an ensemble of probes that gather data as they drift passively through the air with no active propulsion or flight. The initial application is improving weather analysis and forecasting by greatly expanding the time and space density of temperature, pressure, wind velocity, and humidity measurements throughout as much of the relevant atmospheric volume as possible. Such data could also provide calibration and validation for space-based remote sensing of tropospheric winds using lidar and carbon dioxide or other trace gases. This capability could extend the commercial potential to applications involving air quality and greenhouse gases initiatives relating to global climate change. The GlobalSense system could have much broader impacts beyond traditional weather forecasting by measuring acoustic, magnetic, chemical, biological, nuclear, or other parameters of interest for surveillance, reconnaissance, and related applications.

The underlying framework for modern-day weather forecasting is numerical weather prediction (NWP). The accuracy of NWP is closely linked to the accuracy as well as the spatial resolution, temporal resolution, and coverage of atmospheric observations assimilated into the NWP models. Even the current and planned combination of in situ and remote sensing platforms leaves observational gaps that are insufficient to meet the requirements of NWP. Current government and commercial weather forecast providers generally have access to the same suite of publicly available (i.e. free) data and use similar NWP modeling systems/algorithms to generate products. Therefore, no single system typically outperforms others by large margins based on forecast accuracy when aggregated over weeks to months, although substantial variability in performance is common for specific cases, locations, and applications.

The key to improving short-range forecasts is to greatly expand coincident measurements of model-dependent variables. The GlobalSense system described here offers a unique approach to fill these data gaps. Improved forecast accuracy has significant social and economic value to many weather-sensitive sectors of the global economy including energy, transportation, agriculture, air quality, and recreation. In fact, a recent study by Lazo et al. (2011) estimated that weather variability impacts more than 3% of the United States (U.S) gross domestic product (~$485 billion in 2008).

System Overview. The GlobalSense system combines three main elements including: (1) an ensemble of disposable, airborne probes, (2) mechanisms to deploy probes and (3) fixed or mobile receiver platforms to gather data from the probes (Fig. 1). The novel probe design exploits component miniaturization as well as integration to minimize complexity, cost, size, mass, terminal velocity (V_t), and power consumption yet still provide measurement accuracy equivalent to or better than currently accepted observing technology. This innovation is based on the trend for ubiquitous sensing (O'Grady et al. 2007) and "smart dust" (Kahn et al. 2000; New York Times 2010a) – extremely large numbers of disposable, low cost electronic devices that measure various parameters and communicate that data to support research and operations for many applications. The original vision for smart dust was to build self-contained, millimeter-scale computing, sensing, and communication platforms to enable integrated, massively distributed, ad hoc networks (Warneke et al. 2001).

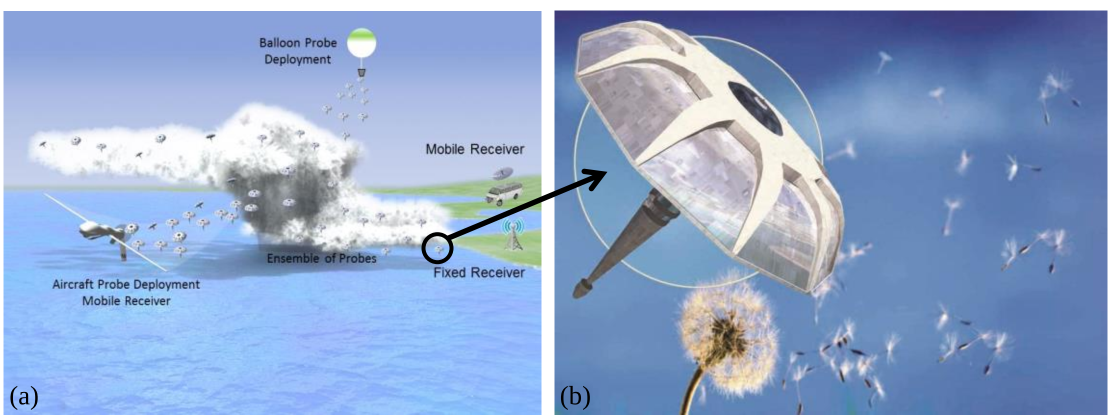

Figure 1. System concept showing main components in panel (a) and expanded probe view in panel (b).

The probes will integrate micro and nanotechnology-based components to achieve the size and mass targets. With mass < 1 gm and an aerodynamic shape based on bio-inspired designs (e.g. dandelion seeds as illustrated in Fig. 1b), probes could remain airborne and make measurements for hours or longer depending on atmospheric conditions (mainly updrafts/downdrafts) and release altitude. For example, with minimal vertical air motion, probes released at an altitude of 3 km above ground would remain airborne almost 3.5 hours given a V_t of 0.25 m/s.

In addition to minimizing V_t, a 1-gm target mass also greatly reduces hazards to people or property (structures, airframes, aircraft engines) as probes settle through atmosphere. The contact hazard for ground-based objects and/or people should be minimal given the target mass and V_t. Probes will be larger than ~¾" hailstones (i.e. 2.0-cm diameter or 1.0-cm radius) but less massive by almost a factor of four. However, the probe target V_t will be smaller than even raindrops so the collision hazard should be negligible. This hazard also depends on the number of probes deployed, deployment location/frequency, and distance they drift before reaching the ground. These factors can be quantified to estimate the probability that probes will strike anything before settling on land or water.

Under certain conditions, winds may accelerate probes to higher speeds (e.g. thunderstorm updrafts) or drifting probes may encounter aircraft traveling at higher speeds. In these instances, the collision hazard may be more significant given that impact energy is proportional to the square of velocity. Previous studies examined this issue based on bird strikes and jet engine ingestion (Manobianco 2005). The probe mass will be substantially lower compared with birds (hundreds of grams to a kilogram or more) that typically pose a strike threat to airframes, windshields, and engines. However, 98% of all bird strikes occur below one kilometer above ground at lower flight speed.

Another potential concern for a fully operational GlobalSense system is the environmental impact caused by the probes settling out of the atmosphere. For the foreseeable future, this issue can be mitigated by designing "biologically inert" probes and minimizing the number of components that could have any negative environmental impacts. Ultimately, probe components would be biodegradable but significant advances in materials science and organic electronics will be needed to achieve these design goals. The probes will not contain materials or components including power sources that pose any significant mechanical, electrical, or environmental hazards.

Probe Components. The probes will require sensors, central processing unit, radio frequency (RF) transmitter, antennas, power source, interface electronics, and packaging. Microsensors will be used to measure ambient air temperature (T), relative humidity (RH), pressure (P), and velocity (V). The proliferation of cell phones, digital cameras, navigation units, and other devices has driven the size and power requirements of micro global positioning system (GPS) chips to the point where they can be leveraged to provide onboard probe velocity and position measurements.

Interface electronics such as resistors, switches, wire bonds, etc. and packaging will be required to connect the main components. The packaging will need to isolate certain components from the effects of turbulence, liquid and frozen water as well as direct solar radiation. A key challenge in miniaturization is energy density and power consumption. Energy density scales with volume and suitable power sources such as small batteries do not often provide high enough peak power output or energy capacity. The key design tradeoff is to minimize component power requirements and effectively manage available power using ultra low-power or sleep modes.

Deployment Mechanisms. In order to observe as much of the relevant atmospheric volume as possible, probes should be deployed at high altitudes using either balloons or aircraft. The deployment strategy depends on a number of factors such as the phenomena of interest, areas to be covered, and probe V_t. The advantage of aircraft deployment is that probes can be targeted to very specific locations and altitudes. However, this option may not always be cost-effective or practical especially if flights are not already being leveraged for operational or research missions. Both manned and unmanned aircraft missions may also be limited in coverage because of routing, flight patterns, and flight path restrictions.

Standard weather balloons are released twice daily by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) at 92 sites around the U.S. The balloons typically carry instrumentation payloads known as rawinsondes that weigh almost 300 gm, collect P, T, RH, and V measurements during ascent, and relay data to ground stations. Rawinsonde stations are separated by hundreds of kilometers but could be supplemented with additional manual or automated balloon launches as well as unmanned aircraft systems (UAS; Elston et al. 2011). Given the proposed probe mass and size, even small UAS could carry a substantial number of probes for research and operational missions (Elston et al. 2011).

NOAA flies operational and research aircraft reconnaissance missions into Atlantic hurricanes and winter storms over the eastern Pacific Ocean. Recent NOAA efforts have also focused on using UAS such as the Global Hawk for hurricane reconnaissance (http://news.nationalgeographic.com /news/2012/09/pictures/120921-hurricane-drones-nasa-usgs-environment-science/). Both manned and unmanned aircraft are equipped with hardware to release small, cylindrical instrument packages known as dropsondes. The dropsonde deployment tubes are large enough to accommodate tens to a hundred or more probes (depending on form factor) that would most likely be encapsulated in a dropsonde cylinder or other rigid packaging to withstand ejection from the aircraft. Given the size and payload capacity of UAS, it may be more effective to design and build an aerodynamic pod on the aircraft exterior to facilitate deployment.

Communication. The probe radio would transmit data packets at a constant power level of 10 mW (10 dB) using an onboard radio in the MHz range at pre-determined intervals. The critical step is to pad the data packets with extra bits before transmission using a signal processing technique called forward error correction (FEC). When combined with code division multiple access, hundreds of probes could transmit on the same frequency without interference.

The FEC communication protocol has been used for years by GPS satellites and cellular telephone networks. It provides gain similar to antennas or amplifiers that increase signal strength, effectively lowering the noise floor so that weaker signals can be detected at greater ranges and decoded with fewer errors. However, the scheme increases the packet size by adding a sequence of bits known as pseudo-random noise or chips so the effective transmission rate after accounting for the additional bits is much lower. The primary limitation is the RF unobstructed line-of-sight which depends on altitude of the transmitter and receiver as well as obstructions such as trees, buildings, and hills. For an aircraft flying at 10 km over open water, the line-of-sight horizon is greater than 400 km. However, a fixed or mobile ground-based receiver would likely have more limited range as most locations do not have clear line-of-sight to the horizon at zero elevation angles. The extended range capability would be most advantageous for airborne receivers such as those carried onboard hurricane reconnaissance aircraft.

Commercialization Potential. There are currently two pathways envisioned for system commercialization. These pathways are positioned at different levels of the value chain in terms of products and services. For path 1, the system would be licensed or sold to users interested in collecting and integrating raw data for specific applications. In this scenario, clients would lease or own and operate the system with reoccurring revenue generated from the purchase of disposable probes. Other system components such as the receiver hardware and software could be leased or sold then operated and maintained by service agreements or internally as part of customer inventory. It would be most cost effective for customers to leverage and/or modify existing infrastructure for deployment and communication hardware.

In path 2, revenue would be generated by selling data from the system or deriving value-added forecast information by integrating data into diagnostic or forecast models to create products that significantly improve accuracy, uncertainty, or other attributes of meteorological information that are important to clients. This pathway for commercialization involves extracting and selling the application-relevant value from the sensor data rather than selling and/or leasing system hardware (including probes). For either path, the fundamental value proposition (VP) is a greatly expanded suite of measurements that can provide substantial benefits to a broad range of applications sensitive to atmospheric conditions.

The market opportunity for licensing or selling the system (path 1) follows the business model of most instrumentation companies (e.g. Vaisala; www.vaisala.com). In the U.S., the primary customers would be civilian (NOAA NWS) and military weather agencies. Although there are a number of weather sensitive sectors (transportation, agriculture, energy), many of the industry and government agencies (e.g. Federal Aviation Administration) rely on and/or collaborate with the NWS to provide both data and products. Most major countries around the world also have government-sponsored agencies that provide similar products and services as the NWS so the market has global potential.

A thorough analysis of the customer value chain is required to estimate market opportunity and size for selling probe data and/or improved forecasts derived from the data (path 2). In 2010, an article appearing in the New York Times claimed "the innovator who manages to aggregate key data about weather patterns…to predict weather and how it affects our grid, stands to make a massive amount of money…[and] potentially upend…the multi-trillion-dollar energy markets" (New York Times 2010b). Studies funded by the National Renewable Energy Laboratory (NREL) suggest potential annual savings in U.S. renewable energy integration costs as large as $1 to $2 billion with improved wind power forecasts (Marquis et al. 2011). Follow-on work at NREL showed that the initial 10-20% improvements provide the greatest relative benefits with diminishing returns as forecast errors approach zero (i.e. perfect forecasts; Lew et al. 2011). With 24% wind energy penetration in the Western Electricity Coordinating Council region covering 14 western U.S. states, Lew et al. (2011) estimated that 20% improvement in wind generation forecasts would reduce costs by about $195M per year. The same improvement translated to the entire U.S. power system would reduce operating costs by about $975M per year (Lew et al. 2011).

These references are generic but imply that improved short-range weather forecasts of wind and temperature for energy management, specifically energy traders, grid operators, and power producers focused on the day-ahead spot markets have significant economic value. A more specific example was recently reported by power producer Xcel Energy (PR Newswire 2011). The utility saved nearly $6M in 2009 using a new forecasting system that integrates detailed observations of atmospheric conditions into a suite of computer models. This analysis revealed that decreasing mean absolute error of Xcel power forecasts by one percentage point results in an annual savings of

$1.8M over three regions (Ahlstrom et al. 2011) in direct proportion to the percent power generated from wind also known as penetration level. Xcel is currently reporting an overall wind penetration level of 12% (Xcel 2013).

The challenge is to quantify forecast improvements that can be derived using probe data without having a prototype system for actual testing. Previous studies demonstrated that integrating simulated probe data into NWP models led to more accurate upper-level wind and surface temperature forecasts for aviation and energy applications (Manobianco 2005; Manobianco et al. 2008). Results from Manobianco (2005; Fig. 4.25i) suggested that the accuracy of low-level wind forecast errors one day in advance can be improved by ~6% using data from a system of probes similar to the one described here. Wind power is proportional to the cube of wind speed in the most rapidly changing part of the power curve (wind speeds between 5-12 m/s) for pitch controlled wind turbines. Therefore, power forecasts would be about 20% more accurate on average given wind forecast improvements in that speed range.

Another portion of the energy sector with weather sensitivity is short term trading used to balance electricity supply (generation) and demand (load) in the U.S. and abroad. For example, power purchased on spot markets (near real time) typically costs more per megawatt hour than day-ahead bids so underestimating load based on weather forecasts could require utilities to incur higher costs to cover generation deficits. These few examples help to illustrate that there are potentially many more clients for path 2 commercialization with enough weather sensitivity who would be willing to pay for even marginal improvements in forecast accuracy. The challenge is to validate these markets and develop a complete business model that accounts for costs to routinely deploy probes, retrieve data, and then leverage those data to create value added products.

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