DRAFT White Paper

CentNet: The Next Generation Surface Flux System

20 Mar 2013
Introduction

The mission of the National Center for Atmospheric Research’s Earth Observing Laboratory (NCAR/EOL) is “to develop and deploy observing facilities and provide data services needed to advance scientific understanding of the Earth system”. To accomplish this mission, EOL maintains a suite of observational facilities and deploys them at the locations and times required for NSF-selected projects. EOL constantly strives to ensure that our facilities match the observational needs of the NSF research community.

Climate, air quality, atmospheric composition, surface hydrology, and ecology processes are directly affected by the Earth’s surface. Complexity of this surface exists at multiple spatial scales, which complicates the understanding of these processes. Flows over complex terrain or within the roughness sublayers of vegetative or urban canopies have obvious physical inhomogeneities. Fragmentation in landscapes introduce gradients of roughness, albedo and soil moisture that can complicate seemingly simple situations. To make scientific progress when these features are present requires measuring and modeling gradients in state variables and their concomitant fluxes at unprecedented spatial scales.

EOL proposes to address this challenge by constructing a new surface network facility, taking advantage of innovations in sensor technology and wireless network communication. This network will consist of order 100 self-contained flux systems to be deployed over a broad range of spatial scales (1m--100km) in support of a wide variety of biogeophysical field studies. At its core, CentNet would feature direct research-quality measurements of all components of the surface energy and water budgets and key elements of the carbon budget. For example, the 3-component wind vector would be measured at frequencies that span those of turbulence production, allowing the calculation of the momentum flux. Other measurements include the fluxes of carbon dioxide, water, heat, and visible/infrared radiation. With the addition of a modest set of other sensors, CentNet will support research in many disciplines concerned with atmosphere-surface interactions.

1. Science Need

Traditionally, the interpretation of measured mass, energy, particle, and momentum fluxes relied on the simplifying assumptions that the flow is stationary, planar-homogeneous, lacking any subsidence, and is at sufficiently high Reynolds number so that molecular effects can be ignored. These idealized assumptions had a number of practical benefits in field experiments. They allowed micrometeorological methods to be conducted at a single location, they simplified the linkages between measured fluxes in the atmosphere and emission or uptake rates from the land surface, and they ensured that the flow field transporting mass, energy, particulate matter, and momentum to follow many of the niceties of the so-called Monin-Obukhov similarity theory. However, these assumptions are too restrictive in many geophysical flows. Carbon dioxide transport within a forest canopy, shallow nocturnal drainage flows, and near-surface water flow over even slightly complex terrain, are all processes associated with large changes in concentrations and fluxes over small distances.
The consensus of a workshop that EOL convened in 2008 on “adaptive sensor arrays” was that a large network of ground-based sensors would facilitate research in the biogeosciences, hydrology, and urban meteorology, in addition to the mesoscale meteorological research traditionally supported by tower networks. Measurements that were listed as essential included turbulent fluxes and radiation. The workshop participants’ research interests included understanding turbulent flow over complex terrain, predicting convective initialization, characterizing the exchange of trace gases within a vegetative canopy, understanding above and subsurface water pathways, and the effect of the planetary boundary layer on pollution transport in an urban environment.

Since 2008, numerous one-on-one discussions have been held at professional meetings, culminating with a Discussion Forum in 2010, scheduled during joint American Meteorological Society Symposia on Boundary Layers and Turbulence, Agricultural and Forest Meteorology, and Urban Environment. All have endorsed the concept of a large network and provided valuable guidance on needed capabilities.

The need for large quantities of turbulence sensors is confirmed by the increasing number that has been requested of the EOL Integrated Surface Flux System (ISFS), shown on right. Clearly, although some projects were satisfied by small numbers of turbulence sensors, many required large numbers and the trend is for these numbers to increase.

**Microscale Meteorology:** Most of the world's land surface is heterogeneous, invalidating models and parameterizations. The least understood part of the boundary layer is common heterogeneity on scales of hundreds of meters to several kilometers. Such heterogeneity modulates the surface fluxes, induces local circulations and also induces propagating motions. A data network over a domain of a few kilometers with adequate spatial coverage would provide the first opportunity to study these important influences on surface conditions. These scales of motions are the least understood part of the boundary layer. They impact a host of applied issues such as frost, dispersion of contaminants, CO₂ exchange with the surface, fog formation and so forth.

**Mesoscale Meteorology:** One recommendation in the National Research Council report on *A Nationwide Network of Networks* is: “The national network architecture should be sufficiently flexible and open to accommodate auxiliary research-motivated observations and educational needs, often for limited periods in limited regions”. Key observations for mesoscale meteorology are identified as “soil moisture and temperature, wind profiles and divergence fields, water vapor distribution, and gauge/radar coverage of precipitation”. Meteorological stations are needed that measure surface properties and quantities related atmospheric dynamics. Observations are needed on spatial scales from 10m—2000km, depending on the phenomena of interest.

**Climate Research:** The US Global Climate Research Program’s strategic plan (2011) states: “Continued investments in current networks are essential for … achieving the necessary understanding of the Earth system and global change. These networks measure the Earth’s radiation budget, temperature, concentration of greenhouse gases, leaf area index, land cover, albedo,
precipitation, winds, and sea level.” “In addition, there are a number of measurements for which there are significant geographic or temporal gaps, such as ground-based snow cover measurements, especially in mountainous areas, and terrestrial observations of ice caps, ice sheets, glaciers, and permafrost.” Observations of atmosphere-biosphere interactions in remote locations are a high priority for climate research.

In addition, the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS, 2005) notes that “iLEAPS research activities should ideally include…enhanced observation periods”, that “the catchment as a well-defined landscape element may in many cases be a suitable study unit”, and that “combining experimental studies with observations and modeling at a wide range of temporal and spatial scales” is ideal. At NCAR, the BEACHON program has been making observations of biogenic chemicals and aerosols over a coniferous forest in a confined valley. An extensive campaign is planned at that site to study advection of CO$_2$ within the canopy using the box budget method. This requires a dense spatial array of CO$_2$ flux observations with multiple vertical levels within and just above the top of the canopy. CentNet must have sensors distributed in three -- not just two -- dimensions to address this requirement.

**Hydrology:** One limitation of hydrological research is knowledge of water forcing at the ground surface. Warm climate precipitation from convective systems is not evenly distributed over landscapes. Variations of soil types, vegetation, and topography on small scales affect both the amount of runoff and the rate of soil wetting. In cold climates, snowpack water amounts are affected not only by spatial variations of the original precipitation, but also by snowdrift, ablation, melting, and sublimation. All of these processes again vary with surface properties at small spatial scales.

**Urban meteorology:** The structure of the Planetary Boundary Layer in urban areas is still poorly understood, although that understanding is essential to predicting the transport of aerosols and other pollutants. In order to make progress in understanding PBL structure and dynamics, increasingly sophisticated field studies are needed to understand the complexities of this flow situation. According to Baklanov et al. (2008) “The existing measurements have limitations which arise due to inescapable constraints on field programmes in cities, including… Sufficient number of sensors to be deployed within the city area as well as at a number of reference rural sites so that influences due to the city can be differentiated from the daily and diurnal changes under various prevailing meteorological situations.” A network to address urban meteorological research needs must be flexible, use methods that require minimal assumptions, and should include observations of scalar quantities such as aerosols.

**Wind Energy:** To obtain optimal use of wind turbines and to quantify the local and regional impacts of wind energy, more knowledge is needed of the flow field in the lower boundary layer. CentNet can contribute in several ways.

- Although CentNet will not include towers capable of measurements at typical hub heights (or higher), CentNet will collect critical data on winds and turbulence in the surface layer and in the bottom portion of typical multi-MW turbine rotor disks. These surface measurements are critical for providing boundary conditions for the models that estimate flow at turbine rotor heights.
Further, the flow models often used in wind energy applications still have large errors that often are due to their treatment of the surface. A recent European Energy Research Alliance (EERA) “Workshop on Wind Conditions” showed failures of many models to simulate flow over the single Askervein hill (Walmsley and Taylor, 1996). Data from the Askervein study were limited by the number of observations in a recirculation region downstream of the crest of the hill.

Also, there is recent interest in studying the effect of turbine wakes on productivity of agricultural systems; it is thought that the enhanced turbulent mixing from turbines will modify surface exchanges of heat, moisture, momentum, and CO2. Given the heterogeneity of the surfaces of wind farms, a broad network such as CentNet is required to collect data to confirm or deny such impacts (Rajewski et al., 2013).

Finally, numerical models of the impacts of large wind farms (e.g. Fitch et al., 2012, among others) have been proposed but lack validation, which would require measurements over a large 10km x 10km (or larger) region.

To address these issues and others, detailed measurements such as those provided by CentNet, in conjunction with other measurements within the turbine rotor disk regions, were advocated in the recent Department of Energy Complex Flow workshop [http://www1.eere.energy.gov/wind/news_detail.html?news_id=18197](http://www1.eere.energy.gov/wind/news_detail.html?news_id=18197)

Fire Meteorology: Coupled atmosphere and fire behavior models, such as WRF-FIRE and MesoNH-ForeFire, have been developed to simulate the interactions between wildland fires and the atmosphere and support decisions in wildfire management. These models, however, have not been adequately validated by observations due largely to the lack of observational data at the required spatial and temporal scale. Most existing observations have been focused on capturing the variations of atmospheric conditions associated with fire fronts. The high spatial resolution and high frequency measurements availability from CentNet would allow better characterization of the ambient atmospheric conditions (wind, humidity, stability, etc.) in the burn area that is usually in complex terrains. The network would also enable capturing the modification of fire to the lower atmospheric mean (fire-induced convergence/divergence, vortices, strong updrafts etc.) and turbulence properties (heat and moisture fluxes, radiative flux, and turbulence kinetic energy, etc.). In addition, CentNet could also be used to help describe CO2 flux and smoke from wildland fires.

2. Observation Scenarios

We intend to respond to these science needs by producing a facility capable of flux observations at 100 locations, that we call CentNet. Similar to EOL’s current Integrated Surface Flux System (ISFS), CentNet could be deployed both intensively and extensively. Although we anticipate that each request for this facility will have unique needs, two common ‘use cases’ are:

1. A set of 20, 30m towers instrumented with 5 levels of turbulence sensors.
2. A set of 100 surface flux stations with 10m masts.

Case 1 deployments would be intensive studies at one site to measure 3-D fields of mean and turbulent wind, temperature, humidity, and CO2. Higher towers could be used in forest canopies, in which the 3-D variation of CO2 and radiation also would be of interest.
Case 2 deployments would be used to study regional variations of the atmosphere and its interactions with the Earth’s surface. It would be necessary to measure standard meteorological variables, all components of the surface energy balance (including turbulence fluxes and radiation), and other quantities to characterize the surface. For some quantities (e.g. soil properties) it would be desirable to have multiple subplots per station to obtain representative sampling. A subset of stations could measure atmospheric composition, subject to the availability of suitable instrumentation.

In both cases, CentNet, like ISFS, would use direct measurement methods to enable use in the largest number of flow situations. For example, turbulent fluxes would be measured using the eddy-covariance method, which does not assume spatial homogeneity or even that the dominant flux is vertical. Soil heat flux would use heat flux plates buried close to the surface, along with soil temperature and heat capacity sensors to determine the heat storage term needed to correct the measured subsurface flux to a surface value.

Two proposed experiment designs that could use CentNet. BEFIRST (left) would study CO\textsubscript{2} advection within a sparse forest canopy using the box budget method with several clusters of multiple-level CO\textsubscript{2} flux towers. EERA’s two-hill experiment (right) would employ an extensive array of multiple-level towers to produce a flow map over complex terrain (Jørgensen, 2011). This map would be used as a validation data set for wind turbine siting models.

We note that Aubinet et al. (2010) tried and failed to use reasonably large quantities of sensors to improve the measurement of CO\textsubscript{2} fluxes over forests. They recognize that “one of the most likely causes of the observed differences was that the spatial resolution of the [CO2] network was insufficient to take account of small-scale field heterogeneities.” They acknowledge that a more dense network might help, but caution that this could be expensive and may never be dense enough. CentNet would provide an opportunity to revisit this question, especially if combined with other EOL tools, such as TRAM (Oncley et al., 2009).

Another feature of having 100 systems is that the facility could be split among 2 or more projects. Many of the science questions mentioned above would benefit from long-term measurements. For example, NEE observations must be made over an entire year. Splitting the facility would allow, say, 50 systems to be allocated to a long-term study while the other 50 systems could support other users.

3. Sensors
The required priorities for any sensor used by CentNet are research data quality, low power consumption, and low maintenance. CentNet would use commercial off-the-shelf sensors whenever they meet these criteria. When necessary, EOL often can modify or develop new sensors to satisfy these needs.

Every CentNet sensor is 'intelligent' in minimizing power consumption, maximizing the value of data stream in active and quiescent periods, and self-diagnosing. Each sensor has a microprocessor that retains sensor-specific calibration coefficients and reports both raw and calibrated data, along with an ID number unique to the data system. The coefficients are updated every time the sensor is tested in the EOL calibration laboratory. The microprocessor also provides any control signals to the sensor, including those needed to clean the sensor, and can monitor operating parameters, such as power consumption. We also are evaluating the possibility of adding altitude sensors to each anemometer. This would avoid having to manually survey their orientation, which can be difficult and time consuming. The use of intelligent sensors allows “plug-and-play” capability for sensor installation or replacement.

The core CentNet measurements and sensors are:

- **Wind:** 2-D sonic anemometers, rather than propeller-vanes, will be used to measure wind speed and direction since they resolve winds as small as 10 cm/sec (or less) and, with heating, operate in freezing conditions.

- **Temperature/Relative Humidity:** EOL has created an accurate T/RH sensor based on a commercial solid-state module in a mechanically-aspirated housing with a low-power fan.

- **Pressure:** We are exploring the use of commercial digital barometers using ‘nano-resolution’ that would enable a wide range of research into the role of near-surface pressure fluctuations and high-accuracy local pressure gradients.

- **Precipitation:** In all but extremely heavy rain, tipping bucket rain gauges work well and would be used for CentNet. For cold conditions, we are working with participants in the WMO/CIMO Solid Precipitation Intercomparison Experiment (SPICE) to determine the optimum sensor combination for reliable measurement of frozen precipitation and snowpack with easily-deployed sensors, including testing of a new commercial ribbon sensor that measures the integrated dielectric constant of the snowpack.

- **Turbulence and atmosphere/surface exchange fluxes:** 3-D sonic anemometers still appear to be the best approach for measurements of momentum and sensible heat fluxes and have seen recent improvements by manufacturers.

- **Water vapor/Carbon dioxide fluxes:** Fast-response open-path infrared-absorption sensors appear to be the best option for measuring water vapor fluxes (in combination with sonic anemometers) and have the added benefit of measuring carbon dioxide fluxes as well. A new commercial sensor is now available with less than half the power consumption of earlier
sensors. EOL is currently testing this sensor to determine if its calibration is stable enough for measurement of spatial gradients of CO₂.

- **Radiation:** CentNet will measure all 4 broadband components of radiative forcing of the Earth’s surface (incoming/outgoing longwave and shortwave). We are testing commercial integrated sensors, that would be easier to deploy and less expensive than ISFS’s individual high quality pyranometers and pyrgeometers, to determine if their accuracy can be made adequate for research purposes. We have patented a low-power cleaning/deicing system to improve the data quality from these sensors.

- **Soil heat flux:** We have optimized a suite of 4 sensors (moisture, temperature profile, heat flux, and thermal properties) to measure the heat entering the top 5cm of soil. This suite has redundancy, minimal corrections, and can be deployed in a wide range of soil types.

- **Leaf wetness:** CentNet will use commercial sensors to detect moisture from dew or precipitation.

- **Video camera:** ISFS has used video cameras to document changes in surface characteristics (e.g. snow cover), propagation of winds events on surface vegetation, and other events.

Other sensors we are actively considering include:

- **Air Composition:** Commercial ozone and 4-size-range aerosol sensors are available that use 4W each.

- **Surface temperature:** Several commercial infrared sensors are available to derive a ‘skin temperature’ of the Earth’s surface for a small view angle. (A large-area measurement can be derived from the outgoing longwave radiation measurement, mentioned above.) Infrared cameras also are commercially available that produce a surface temperature image.

- **PAR:** Photosynthetically-active radiation is a key parameter driving models of photosynthesis, and hence, physiological regulation of mass that enters or diffuses out of plant stomata. EOL has constructed PAR sensors that would be inexpensive to replicate.

- **NDVI:** Normalized differential vegetative index sensors are radiometers with filters that produce data similar to those from satellites. NDVI is often used in model parameterizations of vegetative surfaces.

- **Lightning:** New Mexico Institute of Mining and Technology has offered FRONT (see Section 6) the use of a portable lightning detector network that can create 3-D images of cloud-to-cloud strokes, which are needed by cloud microphysicists. CentNet would offer timing, power, and data transmission infrastructure to host this network.

- **Sap flow:** These sensors are compatible with deployment inside a sensor network and are both easy to build and commercially available. EOL likely would partner with an ecology group to ensure that appropriate probes are used and that required supporting observations are taken.
• User-supplied: CentNet will inherit ISFS’s capability to support a wide variety of user-supplied sensors and ingest their data for direct archival with the CentNet data set.

EOL’s aspirated T/RH sensor (left) and suite of soil heating sensors (right), including an EOL-designed 4-prong soil temperature profile sensor.

4. Infrastructure

With 100 stations, CentNet is being designed to minimize the staff time required for deployment, operation, and data handling. RF communications will be utilized as much as possible to reduce cabling (reducing set-up time, failure modes, and weight). Each station will have two-way communication via the Internet for real-time data display and control. The data system will run EOL’s NIDAS software that time-tags and archives every sample to enable users to have the largest choice of data analysis methods. This system also has the ability to cycle power on any sensor, e.g. one that is not reporting. Work is ongoing to develop automatic cleaning systems to minimize field maintenance of sensors. We also are designing new tower infrastructure to be lightweight, easily deployed, and have a minimal footprint.

Calibration: EOL has an extensive calibration laboratory with primary standards for atmospheric pressure (dead-weight piston gauge), temperature and humidity. We have a wind tunnel with a 0.9m diameter by 1.5m long test section for wind speeds up to 30 m/s, two oil-filled temperature baths for temperature calibrations to 3mK accuracy, and a temperature/humidity chamber. Automated procedures will be created to load calibration coefficients into microprocessors embedded within CentNet sensors to enable each to output digital data in physical units.

Data handling: CentNet will use the NCAR In-Situ Data Acquisition Software (NIDAS) running on a low-power Linux computer (DSM). This is already in use by ISFS and EOL’s research aircraft. DSMs can be connected to the internet by a variety of methods (cellular data modem, WiFi, etc.) for real-time data transfer and system control. Early CentNet development focused on
utilizing low-power wireless network technology to send data from spatially-distributed sensors to the DSM along with an accurate time stamp to synchronize the several data streams. We now use commercial radio modules that also support ‘packet-hopping’ to extend the distance that the sensors can be deployed from the DSM (otherwise <100m). Since several sensors are commonly used together, e.g. suites of complementary radiation or soil sensors, we have combined these radios with ‘mote’ boxes that ingest data from 1—5 sensors.

**Towers:** For Use Case 1, CentNet will use climbable triangular towers. ISFS has utilized these at heights of up to 45m. These can be deployed in a wide variety of locations using several anchoring methods and do not permanently disturb the land. Deployment time is about a day and EOL has created boom mounts that are easy to use for sensor deployment and access.

For Use Case 2, CentNet needs a rapidly-deployable mast. EOL has successfully used a custom tripod-based 10m mast with internal guying for over 30 years; however it was not designed to support heavy sensors near the top and takes more than an hour to set up. We are now evaluating the use of hydraulic ‘pump-up’ masts that would reduce mechanical stresses on the structure while retaining deployment flexibility.

In both cases, construction details are being engineered whenever possible to reduce deployment time. For example, quick-release fasteners would be used throughout. Also, we are determining how to use tower elements for multiple purposes to minimize the number of structures.

**Power:** ISFS stations have used solar, wind, fuel cell, and thermoelectric power systems when AC power was not available. Of these, solar remains the easiest to use in most situations and thus will be primarily used for CentNet. Quite small (0.06m$^2$) panels have worked well to power the mote boxes and their sensors, even in winter.

5. Data Products

**Standard Products:** Since CentNet is based on EOL’s NIDAS software, it would produce data in internationally-accepted formats. We expect that NetCDF will be the primary format for data distribution of both the recorded time series and statistics derived from them. Like other EOL datasets, CentNet data can be made available to users world-wide through the Community Data Portal.

**Display Tools:** ISFS presently uses a variety of data display tools that will be augmented as needed for CentNet. Plots of statistics and spectra are distributed via the WWW in near real-time. An internet-based display of the time series from every sensor also is available for real-time data monitoring. Tools such as pop-up displays or automatic e-mails will be developed to bring the data quality flags mentioned below to the attention of CentNet staff. Data analysis tools for both real-time and post-project data will be provided based on the publicly-available R software package.
Example of the real-time time series display of all variables from all sensors (left) and zoomed in on a few variables (right) from a 5-level flux tower for NCAR’s BEACHON program. Current values are plotted in yellow, light blue traces show past values, red lines show off-scale values, and sensors not reporting are flagged with ‘RIP’.

**Data Quality:** CentNet will take several approaches to ensure that the data delivered to the investigator is of research quality. All of these approaches will be implemented in real-time so that problems can be fixed soon after they develop.

- Sensors will be selected to be as robust as possible. As we know from 30 years of experience with field data, there still will be unavoidable problems stemming from a wide variety of sources.
- Archival of all samples by each sensor, which gives the greatest chance of being able to identify and correct bad data.
- Internal monitoring of operating parameters by the sensors themselves. For example, CentNet will use commercial sonic anemometers and H₂O/CO₂ analyzers that monitor their acoustic and optical signal levels and flag data that are out of range. EOL’s TRH sensor will monitor current used by its fan and flag times when sensor aspiration is insufficient.
- Redundant and/or complementary sensors will be compared whenever possible. We expect to deploy independent wind, temperature, and humidity sensors for the meteorology and energy balance packages. We have found that ‘leaf wetness’ sensors give valuable information as to whether water (e.g. dew) is on sensors (such as radiometers) that might impact their measurements.
• Application of automated criteria to flag data that are not physically reasonable. Several software packages such as TK2, EdiRE, and ECPack are in operational use by the CarboEurope program (Mauder et al., 2008) and have criteria that will be considered.

• Application of network analysis algorithms, possibly based on neural networks. EOL would seek an external collaborator to investigate the merit of this type of tool, realizing that many deployments are expected to be in unusual settings where spatial gradients could be high.

• Human examination of time series, statistics, spectra, etc. Even with automation using the above steps, our experience is that manual overview (both real-time and post-project) of the data is always necessary to ensure the best data quality, especially in research deployments. The CentNet Operations budget includes a new Associate Scientist position primarily for this task.

After these steps, CentNet data will be provided with flags to indicate EOL’s confidence in the quality of the data.

6. Connections to Other Facilities

ISFS (Integrated Surface Flux System): CentNet will be the next generation of ISFS. Indeed, ISFS standard radiation and soil sensors have already been upgraded to operate using CentNet’s wireless sensor networking and were deployed for the PCAPS experiment. ISFS’s present capabilities to deploy sensors with unique requirements (high power, special data processing, control, etc.) would still be available at a limited number of sites.

ACCORD: The Atmospheric Chemistry Center for Observational Research and Data program within NCAR/ACD will utilize air chemistry instrumentation more closely with EOL facilities. ACCORD would maintain replicate instrumentation suites for use in CentNet deployments. ACD and EOL would work together to integrate these suites into CentNet. For example, ACD is actively working on a version of their PTRMS that is portable (briefcase-size), able to operate from solar power (10W), and could be replicated (10 systems).

COSMOS (Cosmic-Ray Soil Moisture Observing System): This system has been developed by Arizona State University under NSF support that has resulted in 123 sensors now deployed world-wide to measure area-averaged water content in soils, vegetation, and other pools. CentNet would be able to provide infrastructure support to deploy these sensors at our stations, with data transmitted to ASU for processing and distribution through their existing network.

NEON (National Ecological Observatory Network): CentNet staff have had numerous discussions with NEON during the development of both facilities. The primary topics have been experience with specific instruments, data acquisition system hardware and software, sensor calibration facilities, and infrastructure. Because the NEON deployment is for 30 years and CentNet deployments are typically for a few months, the solutions for many issues have been different. For example, NEON sites are primarily line-powered, whereas CentNet sites would be solar-powered, which greatly affects the choice of sensors. However, we have endeavored to use compatible approaches whenever possible. One example is NEON’s adoption of EOL’s NIDAS data acquisition software.

FRONT (Front Range Observational Network Testbed): EOL and Colorado State University are integrating research radars in Northeast Colorado to create a facility to address both short and long-term research questions. It would greatly enhance the utility of this facility to have a surface network
to provide surface meteorology as well as surface fluxes. For example, precipitation estimates by the polarimetric radars could be combined with surface measurements of evapotranspiration and soil moisture as input to hydrological models. Two possible approaches would involve CentNet:

- A number of CentNet stations could be replicated for exclusive, continuous, use by FRONT. This approach would leverage CentNet’s infrastructure. For example, sensors from FRONT could be rotated through the CentNet calibration facilities. This would add to the cost of FRONT.
- A subset of CentNet stations could be deployed at semi-permanent FRONT locations when not deployed elsewhere. This is the approach being used by EOL’s SPOL radar for FRONT. In either case, funding would have to be identified for operation of these stations.

**University collaborations:**
EOL has sought university partners in the development of CentNet and will continue to collaborate on the testing and development of new measurement technologies, to ensure that university observations needs are being met. Two past collaborations are:

- Center for Embedded Network Sensing: Shared experience with wireless sensor networks that defined various issues (power conservation, data packet hopping, time tagging data).
- University of Colorado, Department of Ecology: Collaborated on a study (NSF/Ecology 0528793) to deploy sensor networks within a forest canopy to understand CO$_2$ sources and sinks.

**7. Timeline**

EOL has incrementally been converting ISFS into a CentNet prototype. The 7 stations deployed for the 2010/2011 PCAPS field experiment utilized the CentNet data system. All of the soil and radiation sensors were converted to smart, wireless operation. In 2011, development effort has focused on sensor evaluation and infrastructure design with the goal of completing prototype station construction in 2012. At that point, construction of the entire network will be possible.

**Milestones:**

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<th>Year</th>
<th>Event</th>
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<td>2004</td>
<td>CME04 experiment uses wireless soil sensors.</td>
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<tr>
<td>2006</td>
<td>ISFS first uses NIDAS during TREX experiment.</td>
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<td>2008</td>
<td><em>Adaptive Sensor Array Workshop</em> held in Boulder to define network needs.</td>
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<td>2009</td>
<td>Outdoor testing of CentNet wireless networking at Boulder Foothills Laboratory.</td>
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<td>2009</td>
<td>New ISFS TRH sensor deployed for ASP Colloquium.</td>
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<td>2010</td>
<td><em>Discussion Forum</em> at AMS Boundary Layers and Turbulence Symposium to get user input.</td>
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<tr>
<td>2010-2011</td>
<td>ISFS uses CentNet wireless sensor arrays during PCAPS experiment.</td>
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<tr>
<td>2012</td>
<td><em>CentNet Engineering Review</em> held in Boulder to review implementation methods.</td>
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<tr>
<td>2013</td>
<td><em>CentNet Science Review</em> held in Boulder to review design.</td>
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**Work Plan:**

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<th>Year</th>
<th>Task</th>
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<td>2011-2012</td>
<td>Evaluate candidate sensor performance</td>
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<td>2012</td>
<td>Complete selection of initial CentNet sensors.</td>
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<td>2012</td>
<td>Construct CentNet prototype stations.</td>
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2012 | Submit proposal for CentNet construction.
2013 | Build CentNet.
2014 | First CentNet deployment.

8. Budget

To date, CentNet development has not had a specific cost target. We put the highest priority on scientific needs and technical requirements and may select more expensive sensors to provide a truly unique capability to the research community. In some cases, we may choose components to reduce maintenance requirements and thus the number of staff required for operation.

CentNet development will be completed largely with EOL resources. Thus, new funds are needed only for construction, along with an increment for operation and maintenance. The majority of CentNet costs are associated with the sensors. EOL is actively working to identify and/or develop lower-cost options whenever possible. The estimated costs below assume that all stations have the meteorology and energy balance sensors and half of the network (50 stations) also include sensors for atmospheric composition and vegetation monitoring.

**Construction:** Station non-labor: $6.4M; Infrastructure non-labor: $0.2M; Labor: $0.2M
**Total Construction:** $6.8 M (FY13,FY14)
**Incremental O&M** (mostly labor): $0.4 M/year (starting FY14)

References:


Jørgensen, H. et al., 2011: “Design of experimental activities”, EERA Workshop on Wind Conditions, Porto, Portugal, [http://indico.conferences.dtu.dk/materialDisplay.py?contribId=48&sessionId=10&materialId=slides&confId=70](http://indico.conferences.dtu.dk/materialDisplay.py?contribId=48&sessionId=10&materialId=slides&confId=70)


**CentNet Steering Committee:**

- Larry Mahrt, Northwest Research Associates
- Julie Lundquist, University of Colorado
- Gabriel Katul, Duke University
- Sharon Zhong, Michigan State University
- Ken Davis, Pennsylvania State University
- Jielun Sun, NCAR/MMM
- David Gochis, NCAR/RAL
- Edward Patton, NCAR/MMM

**List of Acronyms:**

AMS – American Meteorological Society
ASA – Adaptive Sensor Array
BEACHON – Biosphere-atmosphere Exchange of Aerosols within Cloud, Carbon and Hydrologic cycles, including Organics & Nitrogen
BEFIRST - BEACHON-Manitou Experimental Forest Integrated Regional Study
CIMO – Commission for Instruments and Methods of Observation
CME04 – Carbon in the Mountains Experiment, 2004
CSU – Colorado State University
DSM – Data System Module
EERA – European Energy Research Alliance
EOL – Earth Observing Laboratory
FRONT – Front Range Observational Network Testbed
FY – Fiscal Year (October 1 – September 30)
IGBP – International Geosphere-Biosphere Programme
iLEAPS – Integrated Land Ecosystem-Atmosphere Process Study
ISFS – Integrated Surface Flux Facility
MMM – Mesoscale and Microscale Meteorology
NCAR – National Center for Atmospheric Research
NDVI – Normalized Differential Vegetation Index
NEON - National Ecological Observatory Network
NIDAS – NCAR In-Situ Data Acquisition Software
NSF – National Science Foundation
PAR – Photosynthetically-Active Radiation
PBL – Planetary Boundary Layer
PCAPS – Persistent Cold Air Pool Study
RAL – Research Applications Laboratory
RF – Radio Frequency
SPICE - Solid Precipitation Intercomparison Experiment
SPOL – S-band Polarized radar
TREX – Terrain-induced Rotors Experiment
TRH – Temperature and Relative Humidity sensor
UCAR – University Corporation for Atmospheric Research
USGCRP – United States Global Change Research Program
WMO – World Meteorological Organization