Remote Measurement of Environmental Processes: State of the Science and New Directions

Submitted by:

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Introduction

Data from imaging remote sensing instruments have become essential inputs to climate and ecosystem models. Vegetation indices, ratios of red and near-infrared bands, such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) measured from ground, airborne and satellite platforms are used as inputs for many model parameters in Global Circulation Models (GCMs) and Biogeochemical (BGC) models. Current models produce wide disagreement in spatial location, types of ecosystem change, and timing when predicting future responses to climate change. Increased reliability requires understanding of the mechanisms controlling uptake and release of terrestrial carbon and how sink strengths change with climate variability, human interactions and other environmental forcings. It is generally agreed that a number of processes are not accurately parameterized and a long term effort in model development is needed to produce more reliable predictions. Correctly predicting the linkages between the carbon, water, and nitrogen cycles is crucial to monitoring and forecasting changes in the Earth system, to understanding feedbacks to atmospheric concentrations of greenhouse gases, and to estimating primary productivity of the biosphere.

The uncertainty in estimates of carbon storage in North America based on inventory data is thought to be at least 50%, resulting from sparse sampling and problems in extrapolation. Land-use changes from native ecosystems introduced by urbanization, agriculture, logging and other activities produces a landscape that is inconsistent with climate and ecosystems of greatly different functional characteristics. Changes in land-use are further exacerbated by widespread changes in natural disturbance regimes and the introduction of aggressive invasive species that replace native populations. Biomass destruction following logging, wildfire, and land conversion is one of the largest sources of short-term change and variability in patterns of vegetation recovery contributes significantly to the overall uncertainty. Often disturbance events occur at very fine scales of meters to tens of meters. Scaling processes remain poorly understood and small scale heterogeneities and non-linearities may be important in larger scale processes. Improved remote sensing measurements are needed that can map spatial details about land cover and biogeochemical properties at scales between the local, where processes can be explicitly measured on the ground, and the 10-25 kilometer cells of the next generation of land surface models.

New observational capabilities are needed at different spatial scales to reduce model uncertainty, develop constraints and test hypotheses, particularly in land-atmosphere fluxes and predicting future carbon loading. Most instruments that measure fluxes of carbon and water are operated at the field scale, like those used in the Ameriflux network of eddy flux towers. Likewise most ecological monitoring occurs at the local scale and the spatial context is rarely sampled because of a scarcity of sampling instruments at appropriate scales. The NCAR Gulfstream V will provide a new platform a new more capable generation of remote sensing instruments for obtaining measurements of the Earth's surface at the 1-30 m intermediate scales relevant for model testing. Recent advances in materials and optics have allowed the development of smaller, more stable, better calibrated sensors which can measure higher spectral and spatial resolutions. It is feasible to process these much larger datasets in near real-time because of advances in computational and storage capacities. Georeferencing from Global Positioning System (GPS) and Inertial Navigation System (INS), and advanced image processing capabilities will also facilitate model development. These instruments make it possible to obtain accurate quantitative biophysical interpretations based on the spectral absorption and scattering properties of the land surface in spatially geolocated images. In current land-atmosphere models, NDVI or newer vegetation indices (>30 used today) are used to estimate multiple correlated ecosystem properties including LAI, evapotranspiration, photosynthesis, primary productivity and carbon cycling. Clearly more independent measurements are needed to populate models for these properties and this will lead to reducing uncertainties in model predictions. A primary driver for adopting imaging spectroscopy compared to multispectral sensors is the ability to work with data having physical units rather than indices, across the solar spectrum, rather than just the visible and near-infrared region.

There is widespread agreement in the modeling community that additional constraints on land-surface processes are essential for new advances in prognostic capability. Among the most important information that remote sensing observations can contribute to climate change research are detailed spatially explicit distributions of land cover and its spatial variability. This information is essential to understand processes occurring over a wide range of time and space scales. There is an unmet need for new instrument technologies to test and validate models operating at all scales including global and regional climate models, eddy correlation, and ecosystem models. An airborne imaging spectrometer (an imaging instrument that measures many, typically hundreds, of narrow spectral bands across the solar spectrum for each pixel), and LIDAR (Light Detection and Ranging, an active remote sensing technique emitting pulses of light) are two state-of-the-art technologies that if measured simultaneously can estimate both biogeochemical properties and the three-dimensional structure of the land surface.

NASA has operated an imaging spectrometer, the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) since the mid-1980s and has flown several airborne LIDAR instruments, including the Scanning LIDAR Imager of Canopies by Echo Recovery (SLICER) but these instruments do not represent the current state of engineering technology and single instruments cannot meet the needs of the entire research community. A few airborne instruments of varying data quality and availability are flown by commercial vendors. However, fundamental precision and accuracy performance issues undermine the usefulness of these instruments for climate and biogeochemical models and constraints. The climate change research community needs instruments with new measurement capabilities (more than double the precision of AVIRIS) that will be available for frequent or repeat coverage over a wide range of research sites.

The spatial and compositional complexity of most landscapes, makes multispectral remote sensing observations (typically 2-6 bands) inherently under-determined and consequently, produce high errors. Some measures of ecosystem function, like the "red edge" position and shape (which measures chlorophyll content), are better estimators of physiological function than vegetation indices. Such measures significantly reduce the unknowns in radiative transfer solutions and can only be measured using spectroscopy. Therefore an approach that is consistent with the interdisciplinary nature of the problem and which facilitates interpretations based on physical processes and first principles is needed to advance model accuracy. In contrast to multiband sensors, imaging spectrometers that measure the reflected solar spectrum from 350-2510 nm at 5-10 nm bandwidths, can measure and quantify individual spectral features related to pigment composition and content, canopy water content, plant litter and/or wood. These data provide a basis for assessing carbon allocation to different pool fractions and turnover times. Soil chemical and compositional properties of interest for assessing water holding capacity and soil carbon pools, like texture, clay types (montmorillionite, kaolinite, alunite), ferric and ferrous iron, organic matter, surface litter and duff, and others can be measured where there is little or no plant overstory. Atmospheric constituents like water vapor, liquid water and ice clouds, including thin cirrus clouds, can be quantified and mapped. Spectral components of coastal ocean and inland waters, including pigments of different algae, photosynthetic bacteria and coral reef communities, dissolved organic carbon, and suspended sediments can be quantitatively measured. Analytical approaches to data analysis focused on physiologically important biochemical features can achieve better discrimination of ecosystem characteristics than possible from broadband sensors using band ratios and correlative methods. Enhanced detection limits are critical to discrimination of invasive species against a vegetated background.

LIDAR technology is being rapidly adopted because it can produce accurate three-dimensional maps of canopy structure and topography which are used for characterizing spatial variation in forest biomass, canopy height and roughness, and detailed digital elevation maps. Additionally the data provide essential information about fuel load and fuel type for wildfire hazard assessment. Airborne LIDAR systems produce accurately geocoded maps with horizontal resolutions of submeters to meters and height resolutions of a few centimeters.

A Prototype Next Generation Imaging Spectrometer

Imaging spectroscopy is a new field of research (established in the 1990s) using the interactions between matter and electromagnetic radiation expressed in calibrated spectra to measure properties and processes of the Earth's surface. The specific reflectance and emittance spectra of natural surfaces are determined by their chemical bonds and by their structure, permitting the spatial mapping of biogeochemical features. The current generation of imaging spectrometers obtains images in which each pixel is measured by a large number of narrow spectral bands. NASA pioneered the development of this technology and operates the "gold standard" instrument, the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) that all other operating imaging spectrometers are tested against. Although it has been upgraded many times since its fabrication 15 years ago, the current instrument is not at the cutting edge of this technology and its configuration prohibits on-board processing and other advances that would facilitate the science and reduce the time and effort in processing the data. The latest advanced designs use optically fast and compact Offner spectrometer designs with ebeam ruled convex gratings that increase the throughput to more than four times that of AVIRIS. The spectral range of a modern scientific imaging spectrometer would be 350 to 2510 nm at ~5 nm spectral resolution. The mass would be 100 kg or less and occupy a small footprint volume (~0.25m^3). At the flight altitude and velocity of the Gulfstream V, pixel sizes of 5-10 m are possible. Given the flight configuration of the Gulfstream, it would be possible to image the entire continental United States in one year with such an instrument. The adoption of this emerging technology will greatly facilitate detection and quantification of small spectral features, particularly in the reflected shortwave-infrared (SWIR: 1100-2500 nm) where spectral features, both molecular absorptions and scattering, of soil, dry plant litter/wood, and geologic minerals occur. High signal-to-noise imaging spectrometers (double that of AVIRIS) that include SWIR spectral capability to measure the non-green woody and dry plant litter components are required for estimating biomass in low biomass shrublands and semi-arid ecosystems. While LIDAR is recognized to provide the best remote estimates of aboveground biomass in high biomass (forest) ecosystems, imaging spectrometers with SWIR measurements are superior for mapping biomass in low biomass shrublands and woodlands.

A Prototype LIDAR System

Quantification of the structure of the land surface and topography is essential to improving understanding of ecosystem function. Airborne LIDARs can produce precise topographic and surface mapping beyond what is possible with traditional methods. Thousands of light pulses are emitted per second and the travel time to the surface and back to the detector is precisely measured. In older LIDAR technology, an image is created line-by-line by scanning across a swath as the plane moves forward. A newer imaging laser altimeter was developed by NASA Goddard Space Flight Center that simultaneously measures pulses at many different angles, thereby obtaining a image. The airborne Laser Vegetation Imaging Sensor (LVIS) is a large footprint (10-25 m) imaging LIDAR, which would be compatible with the Gulfstream V flight specifications, produces a backscatter profile at a good spatial and vertical scale for mapping mature forests. Emerging technology developments are leading toward pixilated detectors. The airplane position is known using a differential kinematic GPS and the directional orientation of the plane and laser pulse is known using an INS. Sufficient pulses are emitted (~25,000/s) that for a given spatial resolution, some are intercepted and returned throughout the plant canopy while others are returned by the ground surface. Multiple returns (the LIDAR waveform) allows detection and mapping of the full 3-D volume of the surface structure, with a vertical precision of 5-25 cm. The flight altitude of the Gulfstream-V would allow a larger ground swath to be imaged at high spatial resolution. Most ground observing laser transmitters are operated in the near-infrared region (e.g., Nd:YAG diode-pulsed laser at 1064 nm), but a dual frequency LIDAR with a red band at 630-680nm would improve estimates of biomass and decomposition by differentially probing the canopy and contribute to better estimates of low biomass and low stature herbaceous and sparse shrub plant communities. A two-band imaging LIDAR system would produce a unique state-of-the-art measurement capability for NCAR.