Quantifying land-atmospheric interactions by satellite remote sensing

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Motivation
Approaches
Achievements

Future Work
Research agenda
Potential collaborations
Hongbo Su’s academic research falls into three different areas (I, II & III):

- **Quantifying the land-atmospheric interactions (evapotranspiration) at large scales**
  Terrestrial Evapotranspiration from Landsat/TM and MODIS

- **Quantitative Remote Sensing and Image Processing**
  Land surface temperature; multi-sensor image merging; scaling

- **Land Surface Modeling Framework**
  Enabling Land Surface Modeling with the two-way interactions with sensor webs
The above 3 areas are closely related, benefit each other inherently. Contributed to 31 journal papers indexed by Web of Science (ISI). Citation reaches 210 times in 11/2010 according to the statistical report from the ResearcherID Company.

- Total Articles in Publication List: 31
- Articles With Citation Data: 31
- Sum of the Times Cited: 210
- Average Citations per Article: 6.77
- h-index: 8
- Last Updated: 11/03/2010 14:37 GMT
Academic Research & Activities (Area I)

Relationship between the three areas

Land Surface Parameters from Satellite

Land Surface Meteorology, In Situ Measurements

Remote Sensing Models for Hydrological Vars

Data Assimilation

Land Surface Models for Hydrological Vars

Integrated Estimation of Hydrologic Cycle

Validation

Model Improvement
What is Evapotranspiration?

Evapotranspiration (ET) is the combination of water that is evaporated from the surface and transpired by plants as a part of their metabolic processes.
Importance of Evapotranspiration Study?

- Water Balance
  \[ P = ET + Q - \frac{dS}{dt} \]

- Surface Energy Balance
  \[ R_n = H + LE + G \]

- Carbon assimilation & ET process are closely related at stomatal level

Potential Applications:

- Draught and flood monitoring and prediction, water resource management
- Weather prediction and climate change detection
- Crop yield estimation, optimal irrigation planning
Quantifying the land-atmospheric interactions
Terrestrial Evapotranspiration from Ground

Bowen Ratio System

Eddy Correlation System

Limitation of the ground measurements:
Spatial scale is about tens or hundreds of meters, dependent on the land surface. Instruments can’t be deployed in remote area.

Advantage: High Accuracy (10-15%)
Quantifying land-atmospheric interactions

Challenges:
Larger scale Global Circulation Model (GCM), regional numerical weather prediction models and Agricultural applications require a globally or regionally distributed ET product to improve the global study and their prediction accuracy.

However, ground (point) based ET measurement can’t meet the challenges because of:

• Limited spatial representativity
• Highly cost to maintain a field network

Opportunity:
Make use of the abundant satellite data observed from Space

Terra Aqua
• Quantifying the land-atmospheric interactions

Advantages of using remote sensing data:

• Capture the spatial heterogeneity of the land surface characteristics; (1km)
• Global coverage;
• Data Routinely available once employed in its orbit; (2 passes/Day)
• Relative low cost, compared to ground based observation;
• Abundant basic data products (Landcover, Aldebo, LAI, VI, LST/EM, SW_d)

Disadvantages:

Visible and thermal bands (finer spatial resolution) are different with microwave band (radar).

MODIS is the name of a satellite sensor: the Moderate Resolution Imaging Spectroradiometer

Data availability is affected by weather condition. Only available at clear days.
Our Approach:
- Based primarily on the Surface Energy Balance System (SEBS) Model
- Shorter time scale (Instantaneous), finer spatial (1km) resolution
Daytime Heat Flux

- Shortwave Radiation
- Longwave Radiation (Surface) (Atmosphere)
- Evapotranspiration
- Soil Heat Flux
- Artificial Heat Discharge
Energy Balance:

\[ R_n = G_0 + H + LE \]

Estimation using:
- incoming \( R_{swd} \)
- downward \( R_{lwd} \)
- surface infrared temperature
- emissivity
- albedo

Radative balance, conveniently estimated by remote sensing

Heat balance, often used in Hydrology and Meteorology

\[ G_0 = R_n \cdot (f_c \cdot \Gamma_c + (1 - f_c) \cdot \Gamma_s) \]

Parameterized using fractional vegetation cover

Quantifying land-atmospheric interactions by satellite remote sensing
Use Similarity Theory for the Atmospheric Surface Layer to Solve the Turbulent Heat Fluxes

\[
\begin{align*}
  u &= \frac{u_\ast}{k} \left[ \ln \left( \frac{z - d_0}{z_{0m}} \right) - \Psi_m \left( \frac{z - d_0}{L} \right) + \Psi_m \left( \frac{z_{0m}}{L} \right) \right] \\
  L &= -\frac{\rho C_p u_\ast^3 \theta_v}{kgH} \\
  H &= k u_\ast \rho C_p (\theta_0 - \theta_a) \left[ \ln \left( \frac{z - d_0}{z_{0h}} \right) - \Psi_h \left( \frac{z - d_0}{L} \right) + \Psi_h \left( \frac{z_{0h}}{L} \right) \right]^{-1}
\end{align*}
\]

Wind, air temperature, humidity
(aerodynamic roughness, thermal dynamic roughness)

\[
\left[ z_{0m}, d_0, z_{0h} \right] \rightarrow \left[ T_a, u, q \right] ?
\]
Academic Research & Activities (Area I)

- Retrieval of Hydrological Variables
  Terrestrial Evapotranspiration from Satellite: Validation
  The field campaign of Soil Moisture Atmospheric Coupling Experiment (SMACEX 02) was Conducted in Iowa from June 19 through July 9 in 2002.

- Watershed consists predominantly of corn and soybean fields ~ 45% each
- 12 towers measuring heat fluxes
- In situ measurements include surface meteorology, radiation, heat flux.
Academic Research & Activities (Area I)

- Retrieval of Hydrological Variables
  Terrestrial Evapotranspiration from Satellite: Validation

Landcover Classification of Walnut Creek and the locations of tower sites in 30m resolution

Soil Moisture Atmospheric Coupling Experiment (SMACEX 02)
Regional ET estimates from SEBS using Landsat, MODIS, GOES and NLDAS derived data. Darker shades represent the soybean field sites, with lighter shades the corn.
Retrieval of Hydrological Variables

Terrestrial Evapotranspiration from Satellite: Validation


Circles: corn sites
Triangles: soybean fields
Solid symbols: sensible heat
Open symbols: latent heat flux
X-error bars: the range of tower observations
Y-error bars: standard deviation of satellite based estimates across the region
MODIS based ET estimation in OK in summer of 2002
MODIS+GOES+LDAS

Extent of the region: 900*500 km  Dark area: No data available (Cloud)
Resolution: 1km and daily instantaneous at 11:00am
Quantitative Remote Sensing and Image Processing

Land Surface Temperature (LST)

To measure the LST remotely, thermal emissivity is a required parameter:

\[ \text{Radiative Flux: } E = \varepsilon \sigma T^4 \]

\[ T \sim \pm 1K \iff \varepsilon \sim \pm 0.01 \]

Due to multi-reflection, effective emissivity is often larger than the surface emissivity, dependent on the topography, or surface roughness.

**Monte Carlo Method** was used for the first time to compute the effective thermal emissivity, which improves the accuracy of the LST retrieval from remote sensing.

Quantitative Remote Sensing and Image Processing
Vegetation Fraction

Computer Graphics was successfully applied to study the directional vegetation fraction (DVF) by solving a Geometrical Optical Model.

We proposed a method to estimate the vegetation fraction based on the Multi-angle (Off-nadir) observations from the satellites.

A trous wavelet transform (AWT) and empirical mode decomposition (EMD) are two distinct methods used for analyzing nonlinear and nonstationary signals. A combination of AWT and EMD is proposed as an improved method for fusing remote sensing images.

Quantitative Remote Sensing and Image Processing
Spatial scaling behavior of surface shortwave downward radiation

In situ measurements from Oklahoma Mesonet, and Baseline Surface Radiation Network (BSRN), MODIS based downward solar radiation were used.
Findings: the RMS difference and the MSD inside the coarser grid are highly dependent on its size by a fitted log–linear equations. This provides a possible approach to downscale the surface SWD radiation statistically and to link radiation data sets derived from satellites at different spatial resolutions.

• **Land Surface Modeling Framework**
  Enabling Land Surface Modeling with the two-way interactions with sensor webs

Environmental Sensors are deployed everywhere (underground, ground, water, air, space, etc).

The sensors are connected to each other and form a web. The sensors are becoming smarter. They can adjust the properties (moving locations/orbit, changing observation frequency/accuracy) of themselves. Provide data on-demand.

There is a gap between LSMs and & the emerging of sensor webs.
Land Surface Modeling Framework

Enabling Land Surface Modeling with the two-way interactions with sensor webs

Study is supported by Advanced Information Technology System Program, NASA since 2006.

Base on Land Information System. Enable the two-way interaction between LIS and a virtual sensor web, to minimize the overall uncertainty in the model predictions.
Background info:

The relationship between the components is shown here. SPS: Sensor planning Service.

SCS: Sensor Collection Service

Sensor Web Framework Integration

Top Level Diagram
Implementation Details (top down)

- REST-ful Web Services: Java Servlet-based frontend connected to a backend message-oriented middleware (MOM).

  * MOM: key to the integration, provides messaging substrate and subscribe/publish model support

  Our choice: ActiveMQ from Apache.org, a Java Message Service (JMS)-based, open-source middleware which supports loosely coupled, asynchronous communications.

-- Other middleware implementations we surveyed:

  ** IBM Websphere Message Broker ($$$$)

  ** Open Sensor Web Architecture (OSWA, Chu & Buyya, 2006)

  ** Mires (Souto et al, 2004)

  ** NaradaBrokering (Fox & Pallickara, 2005)

  ** xmlBlaster (http://www.xmlblaster.org/)
Land Surface Modeling Framework
High performance computing
Sensor Web Budget/Cost Experiment

There are 4 sets of soil moisture in each Scenario

- **Control**: “virtual land truth” of 1st layer SM from CLM
- **OBS**: by adding random noise into the 1st layer soil moisture from the “virtual land truth”
- **Openloop**: Noah (operational model from NCEP) run
- **Assimilated**: OBS was assimilated to Noah

OBS is daily at 12H UTC in this example, all others inputs are 3 hrly

Unit: volumetric, m³/m³
Noise level: ~N(0,0.02)
Sensor Web Budget/Cost Experiment

A Scenario Analysis targeting the future SMAP mission.

The relationship between the frequency of observations and the reliability of the model predictions.

\[
y = -0.0067 \ln(x) + 0.0834
\]

\[R^2 = 0.9844\]
A real Sensor Web to measure SNOW Depth

Temperature and humidity, net radiation, soil moisture measurements (at 3 depths: 5cm, 20cm, and 50 cm), Wind speed and direction, Total Precipitation.
A real Sensor Web to measure SNOW Depth

Radio Modem:
900 MHz operating frequency
Power output: 1 mW - 1 Watt (0 - 30 dBm), software selectable
Outdoor/RF line-of-sight range: up to 40 miles (64 km)
RF data rate: 9.6 or 115.2 Kbps
Interface data rate: Up to 230.4 Kbps
• Land Surface Modeling Framework

Recent Findings

GDAS based study

Input Data to generate global land “truth”, is from either GDAS (Global Data Assimilation System) or derived from Satellite Observations.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Description</th>
<th>Source</th>
<th>Spatial Resolution</th>
<th>Temporal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDAS</td>
<td>The Global Data Assimilation System (GDAS)</td>
<td>NCEP</td>
<td>about 0.7 degree</td>
<td>3-hourly</td>
</tr>
<tr>
<td>UMD Land/Sea Mask</td>
<td>Contains the LDAS unified land/sea mask</td>
<td></td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>UMD Vegetation classification map</td>
<td>Lists the frequency with which all of the vegetation types occurs</td>
<td>UMD</td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>Soil color</td>
<td>Estimated available water content from the FAO soil map of the world, global soil profile databases, and pedo-transfer functions.</td>
<td></td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>Soil clay fraction</td>
<td></td>
<td>NOAA</td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>Soil sand Fraction</td>
<td></td>
<td></td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>LIS Elevation</td>
<td>LIS uses elevation data based on GTOPO30</td>
<td>USGS</td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>Quarterly Albedo climatology</td>
<td>Surface Albedo fraction (snow-free)</td>
<td></td>
<td>1km~25km</td>
<td>quarterly</td>
</tr>
<tr>
<td>Monthly greenness fraction</td>
<td>Green vegetation fraction</td>
<td>Noah 2.6</td>
<td>1km~25km</td>
<td>monthly</td>
</tr>
<tr>
<td>Maximum snow Albedo</td>
<td>Seasonally snow covered lands in the Northern Hemisphere.</td>
<td></td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>Bottom temperature without elevation correction</td>
<td>Serves as the annually fixed, soil-temperature bottom-boundary condition</td>
<td>Noah 2.6</td>
<td>1km~25km</td>
<td>-</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
<td>Boston Univ</td>
<td>1km~25km</td>
<td>monthly</td>
</tr>
<tr>
<td>SAI</td>
<td>Stem Area Index</td>
<td></td>
<td>1km~25km</td>
<td>monthly</td>
</tr>
</tbody>
</table>

Table I: Input Data for LIS4.2
(Meteorological forcing is shown in green and parameter data is in orange.)
• Land Surface Modeling Framework
  Recent Findings

GDAS based: yearly mean Latent Heat Flux in 2005
Example of Output Data generated from LIS: yearly mean Soil Moisture (1st layer) in 2005
• Land Surface Modeling Framework
  Recent Findings (3 hourly, 25km, May 4-5, 2004)
Land Surface Modeling Framework
Recent Findings (3 hourly, 25km, May 4-5, 2004)
Relationship between the three areas

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Future Agenda

• **Research agenda**
  
  My future research interests will be focused on studying the Planet Earth by the observations from space. More specifically, it includes *quantitative remote sensing* and its application in *surface hydrology and land-atmospheric interactions*.

My research interests include:

• **Study the terrestrial hydrologic dynamics by **assimilating space observations** into land surface models**

• **Drought monitoring and prediction**, to improve water resources management using space technology

• **Interactions between the land surface and lower atmosphere and their impacts on water balance and climate change (coupling between LSMs and Climate Model)**

• **Spatial analysis and scaling issue** in hydrology

External funding is expected to be obtained from NASA, NSF and NOAA.
Future Agenda

Collaboration within the College of Engineering:

- Engage the **sensor web technology** into the environmental monitoring, such as water quality, air quality monitoring and assessment
- Integration of **remote sensing observations and GIS** into the environmental modeling to build the decision support tools
- Modeling of **water cycling for semi-arid coast area at large scale (1km resolution)** (1st step, physical process, then couple with chemical and ecological processes)

Collaboration with the HPCC

- Developing **new data assimilation and data fusion techniques**
- Building a **high resolution land surface modeling system for southern Texas**
To understand and solve the scientific questions and environmental challenges, interdisciplinary collaboration with external partners is also needed. Partnership has been made with:

In US
Prof. Eric Wood, Princeton University
Prof. Paul Houser, George Mason University
Prof. Ignacio Rodriguez-Iturbe, Princeton University
Prof. Rachel Pinker, Department of Meteorology, University of Maryland

Outside of US
Prof. Bob Su, International Institute for Geo-Information Science and Earth Observation (ITC), the Netherlands
Prof. Zhaoliang Li, University of Louis Pasteur, Strasbourg, France
Prof. Renhua Zhang, Chinese Academy of Science, China
Prof. Matthew McCabe, University of New South Wales, Australia
Thanks for your attention!

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