A vision for an ultra-high resolution integrated water cycle observation and prediction system

Paul R. Houser, George Mason University

Outline
1. Global Water Cycle
2. Water Cycle Observations & Mission
3. Hyper Resolution Land Modeling
4. Advanced Integration (Data Assimilation)
The Water and Energy Cycle

Role of the Water & Energy Cycle in the Climate System:

- Water exists in all three phases in the climate system; its phase transitions regulate global and regional energy balances.
- Water vapor in the atmosphere is the principal greenhouse gas; clouds represent both positive and negative feedbacks in climate system response.
- Water is the ultimate solvent which mediates the biogeochemical and element cycles.
- Water directly impacts and constraint human society and its well-being.

The Energy and Water Cycle is tightly intertwined:

- Solar radiation drives and feedbacks with the water cycle.
- Energy is transferred through water movement and phase change.
Multi-model ensemble mean change from IPCC GCMs

Change in \((P-E)\) for 2100 minus 2000
“Dry regions get drier, wet regions get wetter”

Δ\((P-E)\) mm/day

Held and Soden (2006)
“Thermodynamic” component

Paul R. Houser
Vecchi and Soden (2007)
Land precipitation is changing significantly over broad areas. Smoothed annual anomalies for precipitation (%) over land from 1900 to 2005; other regions are dominated by variability.

**Observed change in precipitation over land**

1901–2010

1951–2010

Trend (mm/year/decade)
The fact is, we don’t know how much water is stored in North America’s lakes, reservoirs, streams, groundwater systems or snow packs which is fundamental knowledge needed to manage any resource.

Our knowledge of Earth’s water environment at the surface and shallow subsurface remains appallingly insufficient.

Our nation’s hydroclimate modeling assets are simply not up to the task of addressing our most pressing societal issues of food, energy, water, and national security. We are behind where we need to be. (Famiglietti 2012)
The importance of Water

IPCC 100 year projected change in freshwater

- Streamflow decreases such that present water demand could not be satisfied after 2020, and loss of salmon habitat
- Groundwater recharge decreases by more than 70% by the 2050s
- Electricity production potential at existing hydropower stations decreases by more than 25% by the 2070s
- Increased pathogen load due to more heavy precipitation events in areas without good water supply and sanitation infrastructure
- Thickness of small island freshwater lens declines from 25 to 10 m due to 0.1 m sea level rise by 2040-2080
- Increased pollution
- Flooded area for annual peak discharge in Bangladesh increases by at least 25% with a global temperature increase of 2°C

Figure 3.8. Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions.
Background map: Ensemble mean change of annual runoff, in percent, between present (1981 to 2000) and 2081 to 2100 for the SRES A1B emissions scenario (after Nohara et al., 2006).
Linking Science to Consequences

End-to-end coordination enabling understanding and prediction of the Earth system:

*Research driven by the needs of society*

To deliver social, economic and environmental benefit to stakeholders through sustainable and appropriate use of water by directing towards improved integrated water system management

Use the adequate tool for the job...
Water Cycle Questions

What are the causes of water cycle variations?

Are variations in the global and regional water cycle predictable?

How are water and nutrient cycles linked?
# State of the Water and Energy Cycle

<table>
<thead>
<tr>
<th>Variable ↓</th>
<th>Sphere →</th>
<th>Ocean</th>
<th>Terrestrial</th>
<th>Atmosphere</th>
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<tr>
<td>Internal or State Variable</td>
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<td>upper ocean currents (I/S)</td>
<td>topography/elevation (I/S) land cover (I/S)</td>
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<td>soil moisture/wetness (I/S)</td>
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<td>incoming LW radiation (I/S)</td>
<td>surface soil moisture (I/S) surface soil temperature (I/S)</td>
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<td>PAR radiation</td>
<td>surface topography (I/S)</td>
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<td>surface winds (I)</td>
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<td>surface air temperature (I/S)</td>
<td>CO₂ &amp; other greenhouse gases, ozone &amp; chemistry, aerosols (I/S)</td>
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<td>albedo (I/S)</td>
<td>snow/ice cover (I/S)</td>
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<td>air-sea CO₂ flux (I)</td>
<td>evapotranspiration (I/S)</td>
<td>SW and LW surface radiation budget (I/S)</td>
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<td>organic &amp; inorganic effluents (I/S)</td>
<td>land use (I/S)</td>
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<td>biomass and standing stock (I/S)</td>
<td>deforestation (I/S)</td>
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<td>biodiversity (I)</td>
<td>land degradation (I/S)</td>
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<td>human impacts-fishing (I)</td>
<td>sediment transport (I/S)</td>
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<td>air-land CO₂ flux (I)</td>
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**Water & Energy Balance**

\[
\frac{d\langle Q \rangle}{dt} = \langle E \rangle - \langle P \rangle
\]

\[
R = P - E \pm \Delta G
\]

\[
P_0 = E_0 - D_0 + D_t = E_0 - R
\]

\[
P_t = E_t + D_0 - D_t = E_t + R
\]

\[
\frac{\partial S}{\partial t} = -\nabla H \cdot \mathbf{\hat{R}}_o - (E - P)
\]

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What does an 1/8 degree grid cell look like in real life?
Water Cycle Prediction Components

- **Observation**: Quantify long-term water cycle trends & variability; progress toward a coordinated water cycle observation system; extract knowledge and understanding from diverse observations.

- **Modeling**: *Diagnose* state-of-the-art “operational” Earth system models; conduct sensitivity and predictability experiments; infuse process-scale understanding to predict water cycle extremes, enhance prediction through observational constraints; explore limits of water cycle predictability.

- **Solutions**: Enhance operational decision support tools; Engage in public and research community education; link to other earth system components.
**Water Cycle Remote Sensing**

Types of Microwave Sensors:
1. Microwave radiometers: Emission
2. Non-imaging RADARs
   - Altimeters – measure elevation
   - Scatterometers –microwave backscatter
3. Imaging RADARs
   - Synthetic Aperture Radars – map variations in microwave backscatter

The “A-Train”
- AMSR-E radiometer (6-89 GHz)
- AMSU-A (15 channels 15-90 GHz)
- HSB profiler (150, 183 GHz)
- CloudSat Radar (94-GHz)

The “W-Train”?
- TRMM TMI radiometer (10.7-85.5 GHz)
- GPM (active/passive)
- TRMM-PR (radar at 13.6 and 35 GHz)
- Aquarius/SMAP (1.413GHz A/P)
- SMOS (1.4GHz radiometer)
Global Water and Energy Cycle: Observation Strategy

Future: Water Cycle Mission
Observation of water molecules through the atmosphere and land surface using an active/passive hyper spectral microwave instrument.

Primary missing global observations: Precipitation, Soil Moisture, Snow

Need a strategy to compare and integrate and make sense of existing observations

<table>
<thead>
<tr>
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<th>Temporal Res.</th>
<th>Frequency</th>
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</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>50km</td>
<td>Monthly</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>1km</td>
<td>Daily</td>
<td>1.4 GHz</td>
</tr>
<tr>
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<tr>
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<td>5km</td>
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<td>10-90 GHz</td>
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<tr>
<td>Snow</td>
<td>100m</td>
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<tr>
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</tr>
<tr>
<td>ET</td>
<td>10km</td>
<td>Daily</td>
<td>1-90 GHz</td>
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</tbody>
</table>
Water Cycle Mission:

Microwave radiation is modified strongly by the dipole of water molecules

- Through the earth’s surface and in the atmosphere
- Dependent on the microwave radiation source and frequency and on the water phase and concentration.
- Soil moisture, rainfall, snowfall, snow cover, water vapor, total precipitable water, soil freeze-thaw, ocean salinity, vegetation water-content, surface inundation, streamflow

There is the potential of developing a water cycle mission:

- High-resolution, active-passive, multi-frequency microwave mission
- Make simultaneous observations of almost every critical water-cycle process, and bring water-cycle science to a more compelling level.
- This mission could be built around a single, elegant, highly-integrated large aperture (10's of meters in size) multi-frequency active/passive microwave antenna
- Could be deployed in a geostationary orbit, or as part of a polar orbiting constellation

If we want to achieve this goal, we will need to take decisive, calculated steps:

- Focused experimental ground, air, and space based instruments (i.e. TRMM, GPM, HYDROS, AQUARIUS).
- Development of robust microwave radiative-transfer algorithms to derive the desired quantities.
- Develop mission concept options in the near-term.

Non-microwave water cycle observations involving visible and infrared derived snow cover, surface temperature, and cloud top temperature, as well as lidar or radar altimetry derived river and lake levels would further increase the relevance of a potential “water cycle” mission.
## Water Cycle Mission: Options?

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</table>
**Challenge:** progress from single-variable water-cycle instruments to multivariable integrated instruments.

**Vision:** dedicated high-resolution water-cycle microwave-based satellite mission may be possible based on large-aperture antenna technology that can harvest the synergy that would be afforded by simultaneous multichannel active and passive microwave measurements.

**Demonstration:** A partial demonstration of these ideas can be realized with existing microwave satellite observations to support advanced multivariate retrieval methods that can exploit the totality of the microwave spectral information.

**Impact:** Simultaneous multichannel active and passive microwave retrieval would allow improved-accuracy retrievals that are not possible with isolated measurements.
Today:
Large space-based Observatories

Single sensor retrievals
Spatial/temporal inconsistency
Parameter-driven requirements

Tomorrow:
Integrated environmental information system

- Coordination for distributed monitoring, processing, and decision making
- Easy deployment of technology and scalability
- Multiple sensor retrievals
- Spatial/temporal consistency
- Integrated cross-sensor calibration
- System-driven requirements
- Reconfigurable ground and space information systems
Climate models’ grid-box representation of Earth’s processes...

Each grid-box can only represent the “average” conditions of its area.

However, controlling processes of the water cycle (e.g. precipitation) vary over much smaller areas.

How can climate models effectively represent the controlling processes of the global water cycle?

“Conventional” approach: make the model grid-boxes smaller (increase resolution)
  • Slow progress: may take ~50 years to be computationally feasible

Breakthrough approach: Simulate a sample of the small-scale physics and dynamics using high resolution process-resolving models within each climate model grid-box
  • “Short-cut” the conventional approach (~10 years to implement)
Terrestrial hydrologic cycle: many coupled processes

Weather generating processes

Biogeochemical cycles (N, C)

Water resources
Yet it is usually simulated with disconnected models

Groundwater/Vadose Model

Runoff

Surface Water Model

Land Surface Model

Atmospheric Model

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Surface energy fluxes

Hydrology and rivers

CLM4 - First (zero) generation land component of ESM

Carbon cycle

Ice sheets

Climate change

Disturbance

Establishment

Urbanization

Vegetation dynamics

Land use

Deforestation

Reforestation

Competition

Growth
Future of Hyper-Resolution Land Modeling

Future Land Modeling Grand Challenges:

- **Surface-Subsurface dynamics**: Stream-Groundwater interaction, river networks, etc..
- **Land-Atmosphere interactions**: Small scale lateral feedbacks
- **Water quality**: Nutrient transport, CO2, and pollution
- **Human Impacts**: Anthropogenic abstractions, urban, storage, diversions, land change.
- **Computational considerations**: Land Data Assimilation, Observations, etc.
- **Observations & Data**: How to use the observations to constrain, calibrate and learn

Goal:

Progress toward a fully process-scale resolving model of land surface hydrology, atmospheric dynamics, and cloud processes over the global domain.

Integrate all obviously interdependent land-atmosphere processes into a common ultra-resolution (100’s of meters) framework for Earth system modeling, through fusion of traditional land surface hydrology modules with boundary-layer turbulence and cloud process modules.

*Wood et al., 2011*
Vegetation: DeFries et al., University of Maryland
- Can be modified by 1km Max Fractional Vegetation, Zeng & Dickinson
- Seasonal cycle specified by NESDIS green vegetation product

Data Availability: Real-time and short-term retrospective
- "Modern" forcing available from 1996 - uses the same modern forcing and resolution as is used in the real-time LDAS

<table>
<thead>
<tr>
<th>LDAS Forcing Product</th>
<th>Time Res.</th>
<th>Space Res.</th>
<th>Archive</th>
<th>Real-Time</th>
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<tr>
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<td>40km</td>
<td>June 1996</td>
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<td>Eta 3hr Forecast</td>
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<td>40km</td>
<td>June 1999</td>
<td>5hr</td>
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<td>Eta 6hr Forecast</td>
<td>6hr</td>
<td>40km</td>
<td>June 1996</td>
<td>5hr</td>
</tr>
<tr>
<td>NESDIS GOES SW dwn</td>
<td>1hr</td>
<td>1/2 degree</td>
<td>June 1999</td>
<td>2hr</td>
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<td>Pinker GOES SW dwn</td>
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<td>Jan 1996</td>
<td>2hr</td>
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<td>Stage-4 Gage-Radar Ppt</td>
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<td>4km</td>
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<td>18hr</td>
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<td>CPC Gage Only Precip</td>
<td>24hr</td>
<td>1/4 degree</td>
<td>July 1997</td>
<td>12,24hr</td>
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</tbody>
</table>

Other Data: GOES-Temps, Snow, Streamflow, SSMI Products
Quality of land surface model (LSM) output is closely tied to the quality of the meteorological forcing data used to drive the model.

Temperature, pressure, humidity and longwave radiation adjusted for terrain height using standard lapse rate and holding relative humidity constant.

Corrections of up to 6K, 120mb, 40W/m², 2 g/kg.
Merged Downward Shortwave Radiation (W/m²) 00Z 4/29/02

Combine

GOES undefined at low sun angles over eastern seaboard, so EDAS used in merged product as filler over this region.

GOES shortwave radiation is zenith angle corrected, used in place of ETA data when possible.
### North American LDAS: Precipitation

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<th>Data</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<td>NCEP Stage II Doppler radar / RFC gauge</td>
<td>Hourly, 4km</td>
<td>Errors in radar magnitude</td>
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<td></td>
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<td>Holes in coverage</td>
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<td>Sparse coverage over Canada, Mexico</td>
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<tr>
<td></td>
<td></td>
<td>0.25 Degree Resolution</td>
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<tr>
<td>CPC daily rain gauge data</td>
<td>Accurate</td>
<td>Coarse temporal resolution</td>
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<td></td>
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<td>Sparse coverage over Canada, Mexico</td>
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<td>0.25 Degree Resolution</td>
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<tr>
<td>CPC Reprocessed daily rain gauge data</td>
<td>Most accurate (additional stations and qc checks)</td>
<td>Coarse temporal resolution</td>
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<td>Light coverage over Canada, Mexico</td>
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<td>0.25 Degree Resolution</td>
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<td>Only through 1998</td>
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</table>

### Doppler Radar Precipitation

**NCEP Stage II Precipitation (mm), May 1998**

### Interpolated Gage Precipitation

**CPC Daily Gage Precipitation (mm), May 1998**

### Merged LDAS Precipitation

**CPC Reprocessed Daily Gage Precipitation (mm), May 1998**

- Use ETA model, Stage II and CPC data to form best available product—a temporally disaggregated hourly CPC gage value
Global Hyper-resolution Terrestrial Forcing (HTF)

- **PROPOSE**: a global, hourly, 500-m Hyper-resolution Terrestrial Forcing (HTF) land surface weather boundary condition dataset (air temperature/humidity, wind, LW/SW radiation, pressure, precip), starting in 2010.

- **APPROACH**: Globally downscaled numerical weather forecast analysis first guess, integrated with satellite observed precipitation, radiation and temperature.

- Temporal and spatial downscaling will be performed using a combination of physically-based downscaling techniques (temperature/humidity lapse rate corrections, radiation slope corrections, land use, etc.) and validated with high-resolution weather observation networks.

- **5-year hyper-resolution (hourly, 500-m) terrestrial forcing dataset:**
  - 135 million km² (excluding Greenland and Antarctica) = 540 million pixels
  - Dataset approaching 1-pb (uncompressed).
HTF Datasets

• Near-Real Time Atmospheric Analysis:
  – NASA GEOS-5: Real Time Met Analysis, 5/16 x ¼-deg (5-km by 2016).
  – NOAA Global Forecast System (GFS): 27-km (July 2010), and T1534 (13km) in 2014.

• Precipitation Products: (now GPM)
  – TRMM Multi-satellite Precipitation Analysis (TMPA): 3-hr, 0.25-deg, 60S-60N.
  – Hydro-Estimator: ½-hr, 0.045-deg, 60S-60N:
  – PERSIANN: ¼ degree – 4km, ½-hr, 60S-60N:
  – CMORPH: ½-hr, 8-km, 60S-60N:
  – GSMaP: ½-hr, 0.1-deg, 60S-60N:

• Radiation Products:
  – SRB Surface Radiation Budget (SRB): global 1-deg, 3-hr, surface LW and SW:
  – UMD (R. Pinker): 3-hr, ½ deg, surface incident longwave and shortwave:

• Elevation Products:
  – SRTM: 30 to 90-m:
  – Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010): 250-m global:
  – ASTER Global Digital Elevation Model Version 2 (GDEM V2): 30-m global:

• Land Use Products:
  – MODIS Land Cover: Yearly 500-m global:
  – MODIS Vegetation Indices 16-Day Global 250-m:

• Satellite Air Temperature: Global 4-km 60N-60S, ½-hr IR temperatures from geostationary.

• High-resolution weather networks: DOE-ARM sites and the Oklahoma mesonet.
Physical Downscaling

- **Spatial Interpolation** to the 500-m hourly grid (conservation interpolation).
- **Temporal Interpolation**: (linear except for SW zenith angle interpolation).

**Physical corrections:**
- **Topography corrections** to temperature, humidity, longwave radiation.
- **Land use and land cover Temperature Corrections** – generally temperatures are cooler near water or forests, and hotter near cities and bare ground.
- **Precipitation Corrections**: elevation and orography (PRISIM), NDVI disaggregation
- **Terrain Adjustments**: slope-aspect correction to shortwave radiation, wind corrections.
- **Roughness correction**: wind field correction based on land cover information and topographic data.
- **Adjust variance**: include missing small-scale variance with available high-resolution data from research networks or mesonets.

**Observation corrections:**
- **Integrate high-resolution observations when available**
  - Geostationary radiation & temperature, satellite precipitation, etc..

**Quality Control and Uncertainty Evaluation**
- **Theory, realism or sanity checks; Buddy checks; Background checks; Bias determination and correction; Observation withholding**

**Other downscaling ideas?**
Data Assimilation merges observations & model predictions to provide a superior state estimate.

\[ \frac{\partial x}{\partial t} = \text{dynamics} + \text{physics} + \Delta x \]

Land State or storage observations (temperature, snow, moisture) are integrated with models.

Data Assimilation Methods: Numerical tools to combine disparate information.

1. Direct Insertion, Updating, or Dynamic Initialization:
2. Newtonian Nudging:
3. Optimal or Statistical Interpolation:
4. Kalman Filtering: EKF & EnKF
5. Variational Approaches - Adjoint:

- Model errors result from:
- Initialization error.
- Errors in atmospheric forcing data.
- Errors in LSM physics (model not perfect).
- Errors in representation (sub-grid processes).
- Errors in parameters (soil and vegetation).

Model Prediction

Data Assimilation Model
Optimally merges 3D array of observations with previous predictions

Real Time Data Collection

Observations have error and are irregular in time and space

Irregular 3D Data Flow in Real Time

Quality Control

Interpolation in time and space

Model Prediction

Insertion of Data into the Model

Model Integration
Soil Moisture Assimilation: *Walnut Gulch (Monsoon 90)*

Model

Model with 4DDA

Observation

Tombstone, AZ

40m resolution

Houser et al., 1998
Data Assimilation merges observations & model predictions to provide a superior state estimate. Remotely-sensed hydrologic state or storage observations (temperature, snow, soil moisture) are integrated into a hydrologic model to improve prediction, produce research-quality data sets, and to enhance understanding.

**Soil Moisture Assimilation**

**Snow Cover Assimilation**

**Theory Development**

\[ \frac{\partial x}{\partial t} = \text{dynamics} + \text{physics} + \Delta x \]

**Observation Assimilation with Bias Correction**

**No Assimilation**

**Snow Water Assimilation**

**SSMI Snow Observation**

**Insertion of Data into the Model**

**Model Integration**

**EKF**

**EnKF**

update x and P

integrates state estimate \( x \) and error covariance \( P \)

update ensemble members \( x \)

integrates ensemble of states and compute sample covariance \( P \)
Data Assimilation Algorithm Development:
- Land models are highly nonlinear -> push for *model independent assimilation algorithms*.
- *Radiance Assimilation* – use forward models in the assimilation to assimilate brightness temperatures directly.
- *Link calibration and assimilation* in a logical and mutually beneficial way.
- Understand the potential of data *assimilation downscaling*

Land Modeling:
- Better *correlation* of land model states with observations
- Advanced processes: *River runoff/routing, vegetation and carbon dynamics, groundwater interaction*
- Parallel development of land model and their *adjoints*

Assimilate new types of data:
- Hyper-Spectral Active Passive Forward Model(s) for multi-variate water cycle retrieval
- Streamflow, Vegetation dynamics, and Groundwater/total water storage (Gravity)
- Boundary layer structures/evapotranspiration
- OSSE's for optimizing future system planning

Coupled feedbacks:
- Understand the impact of land assimilation feedbacks on coupled system predictions.
Land Information System

Co-PIs: P. Houser, C. Peters-Lidard

2005 NASA SOY co-winner!!

Summary: LIS is a high performance set of land surface modeling (LSM) assimilation tools.

Applications: Weather and climate model initialization and coupled modeling, Flood and water resources, precision agriculture, Mobility …

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200 Node “LIS” Cluster
Optimized I/O, GDS Servers

http://lis.gsfc.nasa.gov
LIS: Enabling Process-Resolving Earth System Models

LIS uses interoperability standards:

- The Earth System Modeling Framework (ESMF)
- Assistance for Land Modeling Activities (ALMA)
- GrADS Data Server (GDS)
- Open-source Project for a Network Data Access Protocol (OPeNDAP)

Enables LIS integration with other components:

- Weather Research and Forecasting (WRF) model
- Goddard Cumulus Ensemble (GCE) model
- etc.

LIS Impact Example: Coupling LIS to a Weather Model

Observed Rainfall

12-Hours Ahead Atmospheric Mod Forecasts

With LIS

Without LIS

Paul R. Hou
Objective: A 1/4 degree (and other) global land modeling and assimilation system that uses all relevant observed forcing, storages, and validation. Expand the current N. American LDAS to the globe. 1km global resolution goal

Consistent Global Intercomparison

Observed Forcing

Land Data Assimilation

Insertion of Data into the Model

Model Integration

Obs 4DDA Model

Improved products, predictions, understanding

Mean Downward Shortwave Flux (W/m²), 11 November 2002

Mean Root Zone Water Content (%), 31 May 2001

Soil Moisture (May 2001)

U.MD AVHRR-Veg Cover

Mean Surface Temperature (K), 11 November 2002

Tsurface

Total Precipitation (mm), 11 November 2002

Merged Ppt Forcing

Mean Snow Water Equivalent (mm), 11 November 2002

Snow WE
Coupled Model Forecast: 1988 Midwestern U.S. Drought

(JJA precipitation anomalies, in mm/day)

Observations

Predicted: AMIP

Predicted: LDAS

Predicted: Scaled LDAS

Koster et al., 2004
Summary of Selected LDAS Projects

Global  GSWP (Dirmeyer)
MENA  A-LDAS (Bolton)
U.S.  NLDAS (NOAA/NASA)
Global  GLDAS (Rodell)
S. America  SALDAS (Degoncalves)
Europe  ELDAS (Van Den Hurk)
West Africa  AMMA/African LDAS
Japan  CALDAS (Koike)
Korea  KLDAS (Byun)
Canada  CALDAS (Belair)
Australia  Australian LDAS
France  French LDAS (Boone)
U.S.  HRLDAS (Chen)
U.S.  Ameriflux DAS (Oak Ridge)
U.S.  EO-LDAS (ESA)
China  CN-LDAS (Xin)
Vision: A near-real time “patched” Global LDAS

Action: Overlay high-res regional LDAS model forcing and output over baseline low-res GLDAS model for best local information

Advantage: Share land-hydrology data/forcing globally in a Hydrologic “GTS” framework

Issues: Global consistency studies
Linking to Water Resource Applications

- Collaborating with other agencies, e.g., the U.S. Bureau of Reclamation, to integrate the use of LDAS products in water resource management issues.
- Developing retrospective studies and working to maintain land surface model simulations in both near real-time and forecast settings to be used by water resource managers and policy/decision makers.
- Evaluation of LDAS in ongoing case investigations to monitor and forecast extreme flooding and drought events.
- Produce successful demonstration of these applications-based studies and begin applying to other countries facing water resource-related issues.

Harrah, WA. Station Compared to LDAS: 1998 Downward Shortwave Radiation

\[ r = 0.94 \]

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A vision for the future: 

**Ultra-high resolution integrated water cycle observation and prediction system**

- Integration of
  - Hyper-spectral microwave water cycle sensors or smart sensor webs (in-situ, airborne, and space-based)
  - Ultra-High resolution high-performance prediction systems (Global-scale, locally relevant)
  - Advanced data assimilation and calibration systems
  - Decision support tools (planning, management, operations)

Can we link these advanced tools to reduce uncertainties in end-uses?