Overview of NASA’s Earth Observation Systems for Hydrology

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ACWI – SoH Meeting

Present and Future NASA Earth Science Missions

Planned Missions
- SMAP
- GRACE-FO
- ICESat-2
- JPSS
- DESDynl
- OCO-2

Decadal Survey Recommended Missions:
- CLARREO, HyspIRI, ASCENDS,
- SWOT, OCO-CAPE, ACE, LIST,
- PATH, GRACE-III, SGP3, GACM,
- 3D-Winds

Highly relevant to hydrology
Inadequacy of Surface Observations

Issues:
- Spatial coverage of existing stations
- Temporal gaps and delays
- Many governments unwilling to share
- Measurement inconsistencies
- Quality control
- (Un)Representativeness of point obs

Global Telecommunication System meteorological stations. Air temperature, precipitation, solar radiation, wind speed, and humidity only.

River flow observations from the Global Runoff Data Centre. Warmer colors indicate greater latency in the data record.

NASA’s Hydrologic Observations

Figure 1: Snow water equivalent (SWE) based on Terra/MODIS and Aqua/AMSR-E. Future observations will be provided by JPSS-1/VIIRS and DWSS/MIS.

Figure 2: Annual average precipitation from 1998 to 2009 based on TRMM satellite observations. Future observations will be provided by GPM.

Figure 3: Daily soil moisture based on Aqua/AMSR-E. Future observations will be provided by SMAP.

Figure 4: Changes in annual-average terrestrial water storage (the sum of groundwater, soil water, surface water, snow, and ice, as an equivalent height of water in cm) between 2009 and 2010, based on GRACE satellite observations. Future observations will be provided by GRACE-II.

Figure 5: Current lakes and reservoirs monitored by OSTM/Jason-2. Shown are current height variations relative to 10-year average levels. Future observations will be provided by SWOT.
Precipitation

Global Precipitation Measurement (GPM)

The GPM constellation forms the foundation for providing high quality 3-hour merged precipitation estimates around the world. Calibration using the Core Observatory ensures consistency across the different platforms.

GPM Core Observatory
(NASA/JAXA, Launched February 2014)

Instruments:
- DPR (Ku & Ka band)
- GMI (10-183 GHz)
- 65° Inclination, 407 km
- 5 km best footprint
- Sensitivity of 0.2 – 110 mm/hr rain rates and falling snow

Active Joint Projects
(19 International PI's)
Precipitation: Merged Datasets

Global Precipitation Climatology Project (GPCP)
- International community activity in GEWEX, 1979-present
- Fully global merger of microwave, IR, sounding, and gauge data
- Recognized international standard for climate study, with >1500 citations
- Present Version 2 funded as NOAA CDR, Version 3 funded in NASA MEaSUREs

TRMM Multi-satellite Precipitation Analysis (TMPA)
- Pioneered constellation concept
- Pioneered multiple "runs": near- and post-real time
- Has driven wide public use of global satellite precipitation, ~1000 citations

Integrated Multi-satellite Retrievals for GPM (IMERG)
- Unified U.S. algorithm team led by GSFC
- 0.1°x0.1°, 30-min., 60°N-S
- Runs at 4 hours, 8 hours, and 2 months
- Will cover 1998-present

Contact: George Huffman/612

Goddard has a sustained record of pioneering merged satellite datasets

GPM Societal Benefit Areas

Extreme Events and Disasters
- Landslides
- Floods
- Tropical cyclones
- Re-insurance

Water Resources and Agriculture
- Famine Early Warning System
- Water Resource management
- Drought
- Agriculture

Weather, Climate & Land Surface Modeling
- Numerical Weather Prediction
- Land System Modeling
- Climate Modeling

Public Health and Ecology
- Disease tracking
- Food Security
- Animal migration
Soil Moisture Active Passive (SMAP)

**NRC Earth Science Decadal Survey (2007) recommended SMAP as a tier-one mission**

**Primary Science Objectives:**
- Global, high-resolution mapping of soil moisture and its freeze/thaw state to
  - Link terrestrial water, energy, and carbon cycle processes
  - Estimate global water and energy fluxes at the land surface
  - Quantify net carbon flux in boreal landscapes
  - Extend weather and climate forecast skill
  - Develop improved flood and drought prediction capability

**Mission Implementation** (Launch January 29, 2014):

<table>
<thead>
<tr>
<th>Partners</th>
<th>JPL (project &amp; payload management, science, spacecraft, radar, mission operations, science processing)</th>
<th>GSFC (science, radiometer, science processing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk</td>
<td>7120-81 Category 2; 8705.4 Payload Risk Class C</td>
<td></td>
</tr>
<tr>
<td>Launch</td>
<td>Nov. 2014 on Delta II system</td>
<td></td>
</tr>
<tr>
<td>Orbit</td>
<td>Polar Sun-synchronous; 685 km altitude</td>
<td></td>
</tr>
<tr>
<td>Duration</td>
<td>3 years</td>
<td></td>
</tr>
<tr>
<td>Payload</td>
<td>L-band 3-channel SAR (JPL)</td>
<td>L-band polarimetric radiometer (GSFC)</td>
</tr>
<tr>
<td></td>
<td>L-band rotating mesh antenna (JPL)</td>
<td>Shared 6-m rotating mesh antenna (13 to 14.6 rpm)</td>
</tr>
</tbody>
</table>

http://smap.jpl.nasa.gov/
Moderate antecedent soil moisture Applications:

Flood Potential

Moderate-heavy precipitation

Moderate river flooding and numerous reports

Low antecedent soil moisture

Heavy precipitation

Isolated minor flooding

Forecasters at select NWS offices use real-time LIS products to determine antecedent soil moisture prior to an expected precipitation event to determine areal flooding potential. For instance, heavy precipitation falling on dry soil (bottom row) results in only isolated flooding, but moderate precipitation falling on moist soil results in moderate flooding.

Surface Water & Snow
Surface Water Mission Concept (SWOT)
Stream Discharge and Surface Water Height

**Motivation:**
- critical water cycle component
- essential for water resource planning
- stream discharge and water height data are difficult to obtain outside US
- find the missing continental discharge component

**Mission Concepts:**

- **Laser Altimetry Concept**
  - e.g. ICESat (GSFC)
  - Targeted path coincident with river reach

- **Radar Altimetry Concept**
  - e.g. Topex/Poseidon over Amazon R.

- **Interferometer Concept**
  - (JPL)

Source: M. Jasinski/614.3

Routine Lake Level Monitoring (Jason1/2 & ENVISAT)

Contact: Charon Birkett, U. Maryland

http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir
Standard MODIS Snow-Cover Map Products

- Products are available daily at up to 500 m resolution (2000 – present);
- Dataset and algorithms were developed in the Hydrological Sciences and the Cryospheric Sciences Laboratories.

Contacts: Dorothy Hall/615, George Riggs/SSAI/615

MODIS snow-cover maps have been used for:
- Stream-discharge modeling to support drought and flooding decisions;
- Updating land-surface models, including calculating snow-water equivalent in the models;
- Validating model results;
- Monitoring snow-cover changes over time at regional and hemispheric scales;
- Developing climate-quality data records of snow cover.

Terrestrial Water Storage and Ground Water
Gravity Recovery and Climate Experiment (GRACE)

Aqua: MODIS, AMSR-E, etc.

Traditional radiation-based remote sensing technologies cannot sense water below the first few centimeters of the snow-canopy-soil column. GRACE is unique in its ability to monitor water at all levels, down to the deepest aquifer.

GRACE Data Assimilation

GRACE water storage, mm January-December 2003 loop

Model assimilated water storage, mm January-December 2003 loop

Monthly anomalies (deviations from the 2003 mean) of terrestrial water storage (sum of groundwater, soil moisture, snow, and surface water) as an equivalent layer of water. Updated from Zaitchik, Rodell, and Reichle, J. Hydromet., 2008.

From scales useful for water cycle and climate studies... To scales needed for water resources and agricultural applications
Emerging Trends in Global Freshwater Storage

Trends in terrestrial water storage (cm/yr), including groundwater, soil water, lakes, snow, and ice, as observed by GRACE during 2003-13

- Greenland's ice sheet has been thinning at a rate of 142 km3/yr.
- Alaska's glaciers have been melting at 84 km3/yr.
- Drought gave way to flooding in the Missouri River basin in 2011.
- Recent droughts in the southeastern U.S. and Texas.
- Recovery from 2004-05 drought in the Amazon.
- 2010 Chile earthquake and drought in southern Argentina.
- Patagonian glacier melt.
- Russian droughts in 2010 and 2012.
- Groundwater is being depleted across northern India at a rate of about 54 km3/yr due to pumping for irrigation.
- Overexploitation of freshwater resources in the North China Plain.
- Return to normal after wet years in early 2000s.
- The western Antarctic ice sheet has been thinning at a rate of 65 km3/yr.
- Return to normal in the Okavango Delta after drought ended in 2007.
- Drought recovery and flooding.
- Depletion of water resources in the Middle East exacerbated by drought.
- 2010 Chile earthquake and drought in southern Argentina.
- Russian droughts in 2010 and 2012.
- Patagonian glacier melt.
- Return to normal in the Okavango Delta after drought ended in 2007.

GRACE observes changes in water storage caused by natural variability, climate change, and human activities such as groundwater pumping.

Additional Hydrologic Satellites
1/21/2015

ICESat-2 Inland Hydrology

Feasibility of snow depth from ICESat observations over Uinta Mtns, Utah.

Typical Inland Water Height ATL13 Product tested using MABEL 2012 observations over Lake Mead (left) and Chesapeake Bay (right).

ICESat-2 algorithm development from MABEL

Contact: Mike Jasinski/617

Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS Data Products:

- surface temperature
- chlorophyll fluorescence
- vegetation/land-surface cover, conditions, and productivity:
  - net primary productivity, leaf area index, and intercepted photosynthetically active radiation
  - land cover type, with change detection and identification;
  - vegetation indices corrected for atmosphere, soil, and directional effects;
- cloud mask, cirrus cloud cover, cloud properties characterized by cloud phase, optical thickness, droplet size, cloud-top pressure, and temperature;
- aerosol properties
- fire occurrence, temperature, and burn scars;
- total precipitable water
- sea ice cover
- snow cover
- derived evapotranspiration
Evapotranspiration

Satellite Irrigation Management Support (SIMS) Framework

F. Melton/NASA Ames
Land Surface Modeling, Data Integration & Data Assimilation

Land Surface Model Structure

LSMs solve for the interaction of energy, momentum, and mass between the surface and the atmosphere in each model element (grid cell) at each discrete time-step (~15 min)

System of physical equations:
- Surface energy conservation equation
- Surface water conservation equation
- Soil water flow: Richards equation
- Evaporation: Penman-Monteith equation etc.

Input - Output = Storage Change

\[ P + G_{in} - (Q + ET + G_{out}) = \Delta S \]

\[ R_n - G = L_e + H \]
Data Integration Within a Land Data Assimilation System (LDAS)

INTERCOMPARISON and OPTIMAL MERGING of global data fields

Satellite derived meteorological data used as land surface model FORCING

ASSIMILATION of satellite based land surface state fields (snow, soil moisture, surface temp, etc.)

Ground-based observations used to VALIDATE model output

Examples from NASA's GLDAS
http://ldas.gsfc.nasa.gov/

Matt Rodell
NASA GSFC

NASA SPoRT
Mission: Transition unique NASA and NOAA observational and research capabilities to the operational weather community to improve short-term weather forecasts on a regional and local scale.

- Collaboration with numerous WFOs and National Centers across the country
- Activities began in 2002, first products to NWS in 2003
- Funded by NOAA since 2009 through "proving ground" activities
- Proven paradigm for transition of research and experimental data to "operations"

Benefit:
- Demonstrate capability of NASA and NOAA experimental products to weather applications and societal benefit
- Take satellite instruments with climate missions and apply data to solve shorter-term problems

Short-term Prediction Research and Transition (SPoRT) Center

Operational SPoRT LIS

Land Information System (LIS) is used to perform long-term integration of Noah Land model (run in real-time 4 times per day) at high spatial resolution (3 km)

SMOS/SMAP results to WFOs for situational awareness and local modeling
1/21/2015

Applications: Drought Monitor

- Soil moisture from SPoRT LIS has been used by NWS forecasters in Huntsville to refine drought indices on the county scale as part of their participation in the US Drought Monitor.
- Soil moisture and GVF output from LIS could also be applied to situational awareness and forecasts of red flag warnings and potential for fires.

Sub-county scale dry patch shown in SPoRT-LIS (circled; center) used by USDM to expand D1 region into DeKalb County in May 2012.

Water Quality
Highlight: EPA adopts water quality criteria derived using satellite data products

- The remote sensing methodology and results presented in this paper were adopted by EPA in the recent rule for numeric criteria in Florida waters
  [http://water.epa.gov/lawsregs/rulesregs/florida_coastal.cfm](http://water.epa.gov/lawsregs/rulesregs/florida_coastal.cfm)

- Water quality criteria were developed for all of Florida’s coastal waters using the satellite data records

- The methods for developing criteria from the 13-year satellite time-series were vetted by the EPA Science Advisory Board and could be used by other coastal states and states with large inland waters where remote sensing can be used reliably.


Figure 1: Numeric water quality criteria for the coastal water bodies of Florida were proposed by EPA in November 2013 based on this work.

Applications & Training
GRACE Data Assimilation for Drought Monitoring

New process integrates data from GRACE and other satellites to produce timely information on wetness conditions at all levels in the soil column, including groundwater. For current maps and more info, see http://www.drought.unl.edu/MonitoringTools.aspx

GRACE terrestrial water storage anomalies (cm equivalent height of water) for June 2007 (Tellus CSR RL05 scaled).


Surface Soil Moisture Root Zone Soil Moisture Groundwater

Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-present) for 25 June 2007.

Experimental Global Near Real Time Surface Water Extent and Flood Extent Maps

- MODIS Bands 1 and 2 (250m resolution) used for water identification (algorithm by Bob Brakenridge/ Dartmouth Flood Observatory)
- System development and operation – Dan Slayback (SSAI/ GSFC)
- MODIS product MOD44W used to mask for “normal” water extent
- Two and three day composite products available, updated daily
- Work is on-going to improve masking for cloud and terrain shadow, reprocess historical data, improve “normal” water mask, much more.

July 2010 Flooding in Pakistan

Credit: Fritz Pollicelli, NASA/GSFC

http://oas.gsfc.nasa.gov/floodmap/
Applied Remote Sensing Training (ARSET)

http://arset.gsfc.nasa.gov

GOAL: To increase utilization of NASA observational and model data for decision-support through training activities for environmental professionals.

Application Areas: Water resources, disasters, air quality, and land management.

Online courses: Live and recorded, 4-6 weeks in length.

In person training courses: In a computer lab, 2-4 days.

Train the Trainers: Courses and training manuals for organizations interested in conducting their own remote sensing training, beginning in 2015

Accomplishments (2008 – 2014)
- 46 trainings completed
- 2300+ participants worldwide
- 700+ Organizations


Instructors: Brock Blevins, and Amita Mehta

Relevance: Introductory webinar intended for new audiences to NASA Earth Science with a focus on application of EO data for water resources, air quality, agriculture, disaster management and ecoforecasting.

- 111 participants, 96 organizations, 34 countries, 19 states.
- 15 International and National Conservation organizations: WWF, IUCN, WCS, UNOSAT, UNEP-WCMC, UNITAR, Conservation International
- 5 US Federal and State agencies:
  - EPA, BLM, USGS, USDA, Delaware DNR

End-of-Training Survey Results:
- Over 70% had moderate to limited knowledge of remote sensing
- 100% responded that the training met expectations and materials were appropriate
- Over 58% would like to participate in advanced webinars and 37% in person trainings in the future

Participants from 34 countries
Summary & Conclusions

- Due to the incompleteness of ground-based observations, space-based observation of the water cycle is critical.
- Satellite and Earth observations with modeling can now be used to help quantify the entire water cycle.
- NASA's satellite observations provide a wealth of data for science and applications which must be synthesized in a physically meaningful way → 'Land Data Assimilation Systems'
- Impacts on the water cycle will be the most noticeable consequence of climate change.
- There are several new hydrologic satellites with many innovative applications of remotely sensed hydrology data that have national and international value.

Data, Visualization & Educational Materials

http://www.csr.utexas.edu/grace/education/ - GRACE educational materials
http://gracetellus.jpl.nasa.gov/data/gracemonthlymassgridsland/ - GRACE data, images, and animations (scroll down to "The LAND gridded data and browse images are available here")
http://pmm.nasa.gov/GPM/ - Global Precipitation Measurement Mission
http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir - Satellite based monitoring of lake and reservoir levels
http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html - Giovanni Earth science data visualization tool
http://drought.unl.edu – National Drought Mitigation Center
http://grace.jpl.nasa.gov/news/ - Features on groundwater depletion detected by GRACE
http://water.gsfc.nasa.gov - NASA water and remote sensing training