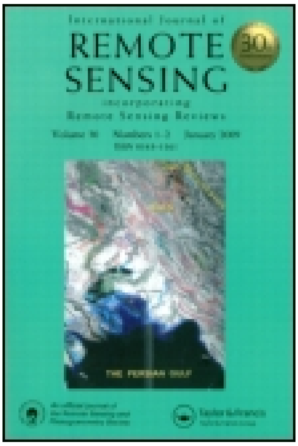

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

Satellite-based observations of hydrological processes

Qiuhong Tang [a] , Michael Durand [b] , Dennis P. Lettenmaier [a] & Yang Hong [c]

[a] Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA

[b] Byrd Polar Research Center, The Ohio State University, Columbus, OH, USA

[c] School of Civil Engineering and Environmental Sciences, University of Oklahoma, Norman, OK, USA

Available online: 04 Aug 2010

To cite this article: Qiuhong Tang, Michael Durand, Dennis P. Lettenmaier & Yang Hong (2010): Satellite-based observations of hydrological processes, International Journal of Remote Sensing, 31:14, 3661-3667

To link to this article: http://dx.doi.org/10.1080/01431161.2010.483496

International Journal of Remote Sensing
Vol. 31, No. 14, 20 July 2010, 3661–3667

Taylor & Francis
Taylor & Francis Group

Preface

Satellite-based observations of hydrological processes

QIUHONG TANG*†, MICHAEL DURAND‡, DENNIS P. LETTENMAIER† and YANG HONG§

†Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA
‡Byrd Polar Research Center, The Ohio State University, Columbus, OH, USA
§School of Civil Engineering and Environmental Sciences, University of Oklahoma, Norman, OK, USA

This special issue of the *International Journal of Remote Sensing* is based on papers presented in a special session at the American Geophysical Union (AGU) 2008 Fall Meeting in San Francisco. The session consisted of 85 contributions from the research, operational and user communities that addressed various applications of remote sensing observations in the development, improvement, validation and use of hydrological models. Of the papers presented, 15 were eventually selected for publication. They cover a range of applications of remote sensing in hydrological study and have been loosely assembled into three categories, focusing on (a) hydrological state variables, (b) moisture fluxes and (c) water storage and surface water budget.

1. Hydrological state variables

In contrast to point-based observations, most remote sensing techniques provide spatially continuous observations of hydrological state variables and parameters such as soil moisture, snow cover and land cover characteristics. Surface soil moisture plays an important role in the partitioning of precipitation between surface run-off and infiltration (Liang *et al*. 1994) and in the partitioning of available energy at the ground surface into sensible and latent heat exchanges with the atmosphere (Anderson *et al.* 2007). Despite its importance, *in situ* measurements of soil moisture are essentially limited to points, and are available at only at a few locations globally (Robock *et al.* 2000). Remote sensing measurements at microwave wavelengths are sensitive to dielectric soil properties and thus moisture content, and can provide near-global coverage. However, remotely sensed soil moisture is spatially coarse, provides information about only the top few centimetres of the soil column (depending on the wavelength of the sensor), and is most effective (again, depending on wavelength) in areas of low to moderate vegetation coverage (Margulis *et al.* 2002). Thus, development and evaluation of satellite soil moisture retrieval algorithms remains an area of active research interest. Champagne *et al*. (2010) evaluate three passive microwave derived soil moisture datasets over multiple growing seasons using ground-based soil moisture monitoring networks in agricultural sites in Canada. They find that there was high variability in the accuracy of soil moisture estimation related to different retrieval algorithms and suggest that consistency is needed in these remotely sensed soil moisture datasets if they are to be integrated in long term studies for yield estimation or data assimilation. Du *et al*. (2010) develop a soil moisture retrieval

*Corresponding author. Email: qiuhong@hydro.washington.edu.

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2010 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431161.2010.483496

algorithm for the Chinese Environment and Disaster Monitoring Satellites (HJ constellation) which are scheduled to be launched in 2010–2012 and include four satellites with S-band synthetic aperture radar (SAR) and four satellites with optical sensors.

Snow cover can be characterized by visible (VIS) and infrared (IR) sensors (Simpson *et al.* 1998, Hall *et al.* 2002, Painter *et al.* 2009), although characterization is complicated by cloud cover due to the similarities between snow and cloud VIS/IR signatures. Snow water equivalent (SWE) can be estimated with passive microwave sensors, which are sensitive to the water equivalent of dry snowpacks as well as its microphysical properties under almost all weather conditions. Clifford (2010) reviews the history, challenges, and future development of SWE estimates from passive microwave instruments. Clifford finds that relative to an independent model-based reanalysis dataset, there is less confidence in SWE estimates derived from passive microwave measurements than in snow cover estimates derived from VIS/IR measurements. Nonetheless, Akyurek *et al.* (2010) develop a blended all-weather snow product that utilizes both VIS/IR (Moderate Resolution Imaging Spectroradiometer (MODIS)) and passive microwave (Advanced Microwave Scanning Radiometer-Earth (AMSR-E)) data. The blended snow product is evaluated in the mountains of Eastern Turkey, and shows improvement in snow cover extent mapping relative to using either MODIS or AMSR-E products. Tang and Lettenmaier (2010) evaluate the MODIS/Terra daily snow cover 500-m resolution product (MOD10A1) through comparisons with *in situ* snow observations over the western USA. They find that the misclassified fractions of MOD10A1 are generally lower at high elevations than at low elevations, and are greatest during the ablation period and at the beginning of the snow accumulation period. The MOD10A1 data are used to update the snow cover status in the variable infiltration capacity (VIC) hydrology model applied to the Feather River Basin, California over the 2000–2008 period of MODIS observations. Their results show that assimilation of MODIS data reduces the error of two-week lead-time streamflow forecasts in the snow melt season, but has little effect during the snow accumulation season.

2. Moisture fluxes

In general, remote sensors cannot directly measure water fluxes. However, remote sensors can observe state variables such as land cover, land surface reflectance, land surface temperature, vegetation properties and cloud characteristics. Moisture fluxes can then be inferred based on relationships between the state variables and fluxes. The main moisture fluxes at the land–atmosphere surface are precipitation and evapotranspiration. Precipitation can be inferred from cloud top conditions using VIS/IR satellite imagery (e.g. Arkin and Meisner 1987), from microwave signals because microwave radiation interacts strongly with precipitation particles (Simpson *et al.* 1988, Prabhakara *et al.* 2000), or from a combination of VIS/IR and microwave estimates (Kuligowski 2002, Hong *et al.* 2004). Remotely sensed precipitation increasingly has shown promise as an input to hydrological models, which in turn can produce other moisture fluxes (evapotranspiration and streamflow). Yilmaz *et al.* (2010) provide an initial evaluation of a global flood monitoring system that utilizes precipitation estimates from the (Tropical Rainfall Measuring Mission (TRMM)) Multi-satellite Precipitation Analysis (Huffman *et al.* 2007). The global flood monitoring system was able to simulate the onset of flood events produced by heavy precipitation and detected 38% of global floods although it suffered from region-dependent bias.

Evapotranspiration (equivalent to latent heat flux) is commonly inferred as a residual in the surface energy balance. Factors that affect the surface energy balance include climatic parameters (energy availability, humidity gradient away from the leaf surface, and wind speed), environmental conditions (water availability and soil characteristics) and vegetation characteristics (leaf area index, vegetation height, and stomatal resistance). Land surface state variables such as vegetation properties, surface temperature, surface albedo, emissivity, reflectance and land cover are observable by remote sensing and can be related directly to the factors that affect surface energy balance. A number of algorithms have been developed for mapping evapotranspiration using these variables (e.g. Bastiaanssen *et al.* 1998, Su 2002, Tang *et al.* 2009). Yang *et al*. (2010) evaluate the Surface Energy Balance System (SEBS) model using MODIS land products. In comparison with eddy covariance flux tower observations, their results show the relative error of remote sensing evapotranspiration is less than 20% over agricultural sites in the North China Plain. Khan *et al*. (2010) implement the SEBS model using MODIS land products and meteorological data from the Oklahoma Mesonet. The remotely sensed evapotranspiration estimates show agreement with surface observations with daily bias less than 15% and seasonal bias less than 8%. Ferguson *et al*. (2010) explore the impact of alternate input datasets (meteorological, radiation and vegetation) on evapotranspiration estimates derived using the Mu *et al*. (2007) Penman–Monteith based algorithm. They identify the most important sources of uncertainty as (a) choice of vegetation parameterization; (b) surface temperature estimate, and (c) the source of net radiation data. French and Inamdar (2010) find that remotely sensed thermal infrared emissivity is related to fractional vegetative cover but is largely independent of plant greenness. They suggest that incorporating emissivity data into an energy balance modelling scheme would improve evapotranspiration estimation. Chang *et al*. (2010) map surface sensible and latent heat fluxes using MODIS data and airborne thermal infrared data over the Chiayi Plain in Taiwan. They evaluate estimates of surface heat fluxes from both airborne and space-borne imagery in comparison with an eddy covariance and two Bowen ratio flux tower sites. Their results show that over 90% of net radiation at their vegetated sites is converted to latent heat flux, but only half of net radiation is converted to latent heat flux over urban surfaces.

3. Water storage and surface water budget

Terrestrial water storage, which is the water stored on and below the land surface, is a fundamental component of the water cycle, yet it is poorly observed globally (Alsdorf *et al.* 2003, Tang *et al.* 2010). The GRACE (Gravity Recovery and Climate Experiment) has the capability to monitor monthly changes of terrestrial water storage (Tapley *et al.* 2004, Lettenmaier and Famiglietti 2006) at large scales (Swenson *et al.* 2003). Krogh *et al*. (2010) compare terrestrial water storage variations from global isotropic and regionally constrained GRACE mascons (i.e. mass concentration parameters) and hydrological models over Southern Africa. Their results suggest that the use of regional constraints yields more detail than using the isotropic constraints.

Although GRACE can measure the variation of terrestrial water storage, it cannot partition total storage variations into components such water storage in lakes, reservoirs, and wetlands, snowpacks and soil moisture. Radar altimeters have been used to measure the dynamics of fresh water levels and to infer the variations in water storage of the water components (Birkett 1995, Alsdorf *et al.* 2007). Given the size of the altimetric footprints (between 1 and 10 km), most altimetric studies have focused on surface water targets with surface area larger than 300 km^2 (e.g. Birkett 1995). Zhang *et al*. (2010) explore the application of satellite radar altimetry for the monitoring of small inland water bodies using a water-detection algorithm, which is based on the fact that the radar waveform returned from water is different from that returned from land. They find that water elevations from their algorithm show improvement over water elevations processed using standard radar altimetry techniques when compared with *in situ* measurements.

A critical limitation of the current altimetry missions for inland water applications is that the instruments are nadir looking with 200- to 300-km spacing between orbital tracks. Thus, the current instruments can only observe a small fraction of the Earth's largest lakes, reservoirs, wetlands and rivers, and cannot simultaneously monitor water elevation and inundated area. The planned Surface Water and Ocean Topography (SWOT) mission is a swath mapping radar interferometer that will provide simultaneous measurements of water elevation and inundated area for inland water bodies (Alsdorf *et al.* 2007). Lee *et al*. (2010) evaluate the anticipated SWOT storage change accuracy for the lakes in the Peace-Athabasca Delta, Northern Alaska and Western Siberia. They conclude that the accuracy of the anticipated SWOT storage change products is primarily controlled by lake size and is sensitive to lake shapes, but is insensitive to orbital inclination and to repeat period.

The above papers concentrate on different constituent variables in the land surface water balance. The terrestrial water balance can be written as:

$$\Delta S = P - E - R \tag{1}$$

where ΔS is the terrestrial water storage change over time, P is precipitation, E is evapotranspiration, and R is run-off. Most of the constituent variables (ΔS, P and E) are now observable at varying spatial and temporal resolutions and accuracies via remote sensing. Gao *et al*. (2010) attempt to close the surface water budget using satellite-based ΔS, P and E products and observed R over major US river basins. Among the nine satellite-based estimates they use, precipitation has the largest uncertainties. The inferred run-off (as a residual of satellite-based ΔS, P and E) is generally overestimated, due both to excessive P and underestimation of combined E and ΔS from remote sensing. This suggests that current retrievals from remote sensing are not yet able to provide consistent observations of the land surface water budget.

4. Future directions

Satellite remote sensing is providing hydrological data needed for the characterization of the hydrological cycle with unprecedented spatial coverage. The papers of this special issue address a range of advances that have recently been made in our understanding of the Earth's hydrosphere through the use of satellite measurements. Hydrologists increasingly are using these remote sensing data for hydrological applications. Most of these applications have had an objective of evaluating remote sensing retrieval algorithms and/or the use of remote sensing in modelling large-scale hydrological processes. A few applications attempt to use remote sensing data for operational water management and basic hydrological research. Nonetheless, there remain gaps in the use of remote sensing among the hydrological research, operations and user communities. There has been considerable recent progress in producing high-level hydrological products rather than low-level or raw remotely sensed data, which make remote sensing data more accessible to a broader cross-section of the hydrological community. Nonetheless, hydrological remote sensing products have often been evaluated in isolated areas under rather disparate conditions using different sensors and retrieval methods. They are often provided with varying spatiotemporal resolutions and accuracies, and usually are not hydrologically consistent (e.g. with respect to their ability to close the water balance). A challenge to the hydrological remote sensing community is therefore to improve the observation accuracy of remote sensing products (recognizing that, in many cases, this will require new and perhaps dedicated sensors) and to become more user-oriented. The hydrology community needs to play a more active role in the evaluation of high-level remote sensing products at large spatial scales and long time scales; such evaluations are usually not performed by the remote sensing community. At the same time, the hydrology community should develop innovative ways to use the current generation of remote sensing products, notwithstanding their limitations, to augment traditional models and methods. Finally, the hydrology community should take the opportunity to transition the most useful remotely sensed products to the applied hydrology community.

References

AKYUREK, Z., HALL, D.K., RIGGS, G.A. and SENSOY, A., 2010, Evaluating the utility of the ANSA blended snow cover product in the mountains of eastern Turkey. *International Journal of Remote Sensing*, **31**, pp. 3727–3744.

ALSDORF, D., LETTENMAIER, D.P. and VÖRÖSMARTY, C., 2003, The need for global, satellite-based observations of terrestrial surface waters. *Eos, Transactions American Geophysical Union*, **84**, doi:10.1029/2003EO290001.

ALSDORF, D.E., RODRIGUEZ, E. and LETTENMAIER, D.P., 2007, Measuring surface water from space. *Reviews of Geophysics*, **45**, RG2002, doi: 10.1029/2006RG000197.

ANDERSON, M.C., NORMAN, J.M., MECIKALSKI, J.R., OTKIN, J.A. and KUSTAS, W.P., 2007, A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *Journal of Geophysical Research*, **112**, D10117, doi:10.1029/2006JD007506.

ARKIN, P.A. and MEISNER, B.N., 1987, The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982–84. *Monthly Weather Review*, **115**, pp. 51–74.

BASTIAANSSEN, W.G.M., MENENTI, M., FEDDES, R.A. and HOLTSLANG, A.A., 1998, A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology*, **212–213**, pp. 198–212.

BIRKETT, C.M. 1995, The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. *Journal of Geophysical Research-Oceans*, **100**, pp. 179–204.

CHAMPAGNE, C., BERG, A., BELANGER, J., MCNAIRN, H. and DE JEU, R., 2010, Evaluation of soil moisture derived from passive microwave remote sensing over agricultural sites in Canada using ground-based soil moisture monitoring networks. *International Journal of Remote Sensing*, **31**, pp. 3669–3690.

CHANG, T.-Y., LIOU, Y.-A., LIN, C.-Y., LIU, S.-C. and WANG, Y.-C., 2010, Evaluation of surface heat fluxes in Chiayi plain of Taiwan by remotely sensed data. *International Journal of Remote Sensing*, **31**, pp. 3885–3898.

CLIFFORD, D., 2010, Global estimates of snow water equivalent from passive microwave instruments: history, challenges and future developments. *International Journal of Remote Sensing*, **31**, pp. 3707–3726.

Du, J., Shi, J. and Sun, R., 2010, The development of HJ SAR soil moisture retrieval algorithm. *International Journal of Remote Sensing*, **31**, pp. 3691–3705.

Ferguson, C.R., Sheffield, J., Wood, E.F. and Gao, H., 2010, Quantifying uncertainty in a remote sensing-based estimate of evapotranspiration over continental USA. *International Journal of Remote Sensing*, **31**, pp. 3821–3865.

French, A.N. and Inamdar, A., 2010, Land cover characterization for hydrological modelling using thermal infrared emissivities. *International Journal of Remote Sensing*, **31**, pp. 3867–3883.

Gao, H., Tang, Q., Ferguson, C.R., Wood, E.F. and Lettenmaier, D.P., 2010, Estimating the water budget of major US river basins via remote sensing. *International Journal of Remote Sensing*, **31**, pp. 3955–3978.

Hall, D.K., Riggs, G.A, Salomonson, V.V., Di Girolamo, N.E. and Bayr, K.J., 2002, MODIS snow-cover products. *Remote Sensing of Environment*, **83**, pp. 88–89.

Huffman, G.J. Adler, R.F., Bolvin, D.T., Gu, G., Nelkin, E.J., Bowman, K.P., Hong, Y., Stocker, E.F. and Wolff, D.B., 2007, The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, **8**, pp. 38–55.

Hong, Y., Hsu, K.L., Sorooshian, S. and Gao, X. 2004, Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. *Journal of Applied Meteorology*, **43**, pp. 1834–1852.

Khan, S.I., Hong, Y., Vieux, B. and Liu, W., 2010, Development and evaluation of an actual evapotranspiration estimation algorithm using satellite remote sensing and meteorological observational network in Oklahoma. *International Journal of Remote Sensing*, **31**, pp. 3799–3819.

Krogh, P.E., Andersen, O.B., Michailovsky, C.I.B., Bauer-Gottwein, P., Rowlands, D.D., Luthcke, S.B. and Chinn, D.S., 2010, Evaluating terrestrial water storage variations from regionally constrained GRACE mascon data and hydrological models over Southern Africa – preliminary results. *International Journal of Remote Sensing*, **31**, pp. 3899–3912.

Kuligowski, R.J., 2002, A self-calibrating real-time GOES rainfall algorithm for short-term rainfall estimates. *Journal of Hydrometeorology*, **3**, pp. 112–130.

Lee, H., Durand, M., Jung, H.C., Alsdorf, D., Shum, C.K. and Sheng, Y., 2010, Characterization of surface water storage changes in Arctic lakes using simulated SWOT measurements. *International Journal of Remote Sensing*, **31**, pp. 3931–3953.

Lettenmaier, D.P. and Famiglietti, J.S., 2006, Hydrology – water from on high. *Nature*, **444**, pp. 562–563.

Liang, X., Lettenmaier, D.P., Wood, E.F. and Burges, S.J., 1994, A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research*, **99**, pp. 14415–14428.

Margulis, S.A, McLaughlin, D., Entekhabi, D. and Dunne, S., 2002, Land data assimilation and estimation of soil moisture using measurements from the Southern Great Plains 1997 Field Experiment. *Water Resources Research*, **38**, doi:10.1029/2001WR001114.

Mu, Q., Heinsch, F.A., Zhao, M. and Running, S.W., 2007, Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sensing of Environment*, **111**, pp. 519–536.

Painter, T.H., Rittger, K., McKenzie, C., Slaughter, P., Davis, R.E. and Dozier, J., 2009, Retrieval of subpixel snow covered area, grain size, and albedo from MODIS. *Remote Sensing of Environment*, **113**, pp. 868–879.

Prabhakara, C., Iacovazzi Jr, R., Wienman, J.A. and Dalu, G., 2000, A TRMM microwave radiometer rain rate estimation method with convective stratiform discrimination. *Journal of the Meteorological Society of Japan*, **78**, pp. 241–258.

Robock, A., Vinnikov, K.Y., Srinivasan, G., Entin, J.K., Hollinger, S.E., Speranskaya, N.A., Liu, S. and Namkhai, A., 2000, The global soil moisture data bank. *Bulletin of the American Meteorological Society*, **81**, pp. 1281–1299.

Simpson, J., Adler, R.F. and North, G.R. 1988, A proposed Tropical Rainfall Measuring Mission (TRMM) satellite. *Bulletin of the American Meteorological Society*, **69**, pp. 278–295.

Simpson, J.J., Stitt, J.R. and Sienko, M. 1998, Improved estimates of the areal extent of snow cover from AVHRR data. *Journal of Hydrology*, **204**, pp. 1–23.

Su, Z., 2002, The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. *Hydrology and Earth System Sciences*, **6**, pp. 85–99.

Swenson, S., Wahr, J. and Milly, P.C.D., 2003, Estimated accuracies of regional water storage variations inferred from the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, **39**, doi:10.1029/2002WR001808.

Tang, Q. and Lettenmaier, D.P., 2010, Use of satellite snow-cover data for streamflow prediction in the Feather River basin, California. *International Journal of Remote Sensing*, **31**, pp. 3745–3762.

Tang, Q., Peterson, S., Cuenca, R.H., Hagimoto, Y. and Lettenmaier, D.P., 2009, Satellite-based near-real-time estimation of irrigated crop water consumption. *Journal of Geophysical Research*, **114**, D05114, doi: 10.1029/2008JD010854.

Tang, Q., Gao, H., Yeh, P., Oki, T., Su, F. and Lettenmaier, D.P., 2010, Dynamics of terrestrial water storage change from satellite and surface observations and modeling. *Journal of Hydrometeorology*, **11**, pp. 156–170.

Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F. and Watkins, M., 2004, GRACE measurements of mass variability in the Earth system. *Science*, **305**, pp. 503–505.

Yang, D., Chen, H. and Lei, H., 2010, Estimation of evapotranspiration using a remote sensing model over agricultural land in the North China Plain. *International Journal of Remote Sensing*, **31**, pp. 3783–3798.

Yilmaz, K.K., Adler, R.F., Tian, Y., Hong, Y. and Pierce, H.F., 2010, Evaluation of a satellite-based global flood monitoring system. *International Journal of Remote Sensing*, **31**, pp. 3763–3782.

Zhang, M., Lee, H., Shum, C.K., Alsdorf, D., Schwartz, F., Tseng, K.-H., Yi, Y., Kuo, C.-Y., Tseng, H.-Z., Braun, A., Calmant, S., Filizola, N. and Seyler, F., 2010, Application of retracked satellite altimetry for inland hydrologic studies. *International Journal of Remote Sensing*, **31**, pp. 3913–3929.