The Role of Satellite Observation in Australian Water Resources Monitoring

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Abstract - Where dense on-ground water resources monitoring networks do not exist, satellite observation can play a key role. The Australian water resources assessment system (AWRA) couples hydrological models and combines these with on-ground and satellite observations. Some satellite observations are currently being used in the operational system but there is potential for much greater use. Opportunities include improved precipitation and model parameter estimation, data assimilation, model evaluation and model-data synthesis. Operational challenges include the reliability of satellite missions and data services, and the computational overheads associated with data assimilation. For successful use of satellite observations, detailed information on observational error and the relationship between remotely-sensed and model variables is critical.

Keywords: water resources, monitoring, data assimilation, Australia, climate

1. INTRODUCTION

Water resource monitoring systems can provide valuable information in support of water management. The recent severe drought in Australia exposed a lack of water resources information and led to the development of such a monitoring system. New water laws in 2007 delegated a legislative mandate and resources to the Bureau of Meteorology (BoM) to develop a range of up-to-date water information services, including an annual national water account, scheduled water resources assessments that interpret current and future water availability, and forecasts of water availability for days to decades (http://www.bom.gov.au/water/).

To achieve this, BoM and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 2008 initiated development of the Australian water resources assessment system (AWRA). The system couples landscape models with models describing surface water and groundwater dynamics and water use. The purpose of AWRA is to provide up-to-date, accurate and relevant information about the history, present state and future trajectory of the water balance, with sufficient detail to inform water resources management. Necessary innovations include the explicit description of water redistribution and water use from river and groundwater systems, achieving greater spatial detail (particularly in key features such as irrigated areas and wetlands), and improving accuracy as assessed against hydrometric observations, as well as assimilating those observations. Because the on-ground climate and water monitoring network is very sparse across most of Australia, satellite observations may play a key role.

Here, we introduce AWRA system design and describe the way in which satellite observations are used. In addition, we assess opportunities and challenges to achieve greater use of satellite observations. Further technical details on AWRA and the use of satellite observations can be found elsewhere (Van Dijk and Renzullo, 2011;Van Dijk, 2010;Van Dijk and Warren, 2010).

2. SYSTEM DESIGN

AWRA has conceptually been designed as a modular system with four components (Figure 1): (1) a grid-based, one-dimensional landscape hydrological model; (2) a model describing the river and floodplain water balance and routing; (3) groundwater system models for regions where groundwater dynamics are not well described by the grid-based model; and (4) a water use model that uses metering and gridded satellite ET estimates to spatially infer lateral inflow derived from the river and groundwater systems.

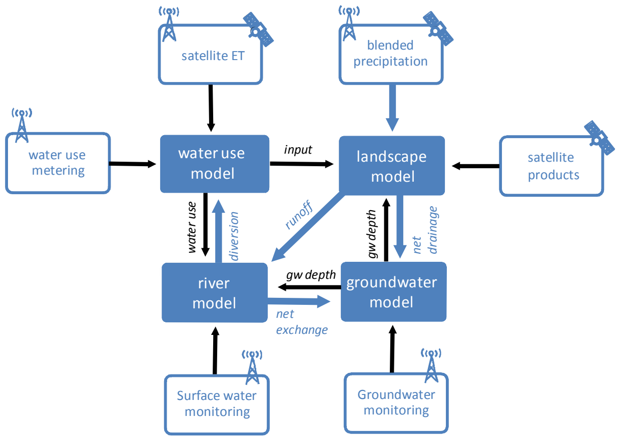

Figure 1. Illustration of the conceptual structure of the AWRA system and the role of satellite and on-ground observations (from Van Dijk and Renzullo, 2011).

The landscape model (AWRA-L; Van Dijk, 2010) offers the most immediate and numerous opportunities to integrate satellite observations. This component may be described as a hybrid between a simplified 'tiled' land surface model and a lumped catchment model. Grid resolution, domain and the number of sub-grid land cover classes are not prescribed but defined by the model inputs. The version currently implemented uses Australia-wide forcing data at 0.05° resolution and considers two land cover classes (deep- and shallow-rooted vegetation). The model evolves on a daily time step and for each cover class simulates the water balance of a top soil, shallow soil and deep soil compartment as well as vegetation dynamics; whereas groundwater and surface water dynamics are estimated at grid resolution.

The system is operational and used in the preparation of experimental water accounts and assessments. Up-to-date water balance estimates are publicly available for research purposes (http://csiro.connect.au/water/). An example output is shown in Figure 2.

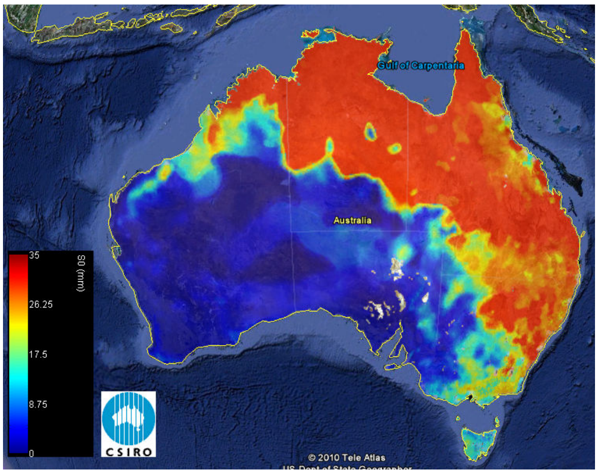

Figure 2. Example AWRA output (top soil moisture content for 6 January 2010, visualised in GoogleEarth)

3. UTILITY OF SATELLITE OBSERVATIONS

Satellite observations relevant to water resources include atmospheric variables (in particular precipitation but also cloud cover); land cover properties (such as surface albedo, vegetation density and water status); snow; soil moisture and soil hydraulic properties; surface water extent and total water storage dynamics. These variables can be derived from multi-spectral measurements of reflectance, thermal and microwave emissions, radar backscatter, altimetry, and gravity measurements. The observations or derived products can be used for interpretative purposes (e.g., mapping, evaluation) as well as quantitative uses (as model input or in data assimilation). Uses can also be distinguished as relating to (1) dynamic forcing; (2) a priori parameter estimation; (3) model evaluation and development; and (4) data assimilation, including both non-sequential techniques (such as parameter calibration) and sequential techniques (i.e., state updating). A related use is the synthesis of satellite (and other) observations and model estimates in analysis for research or routine assessments.

4. CURRENT USE OF SATELLITE OBSERVATIONS

4.1. Operational uses

The AWRA system currently uses daily rainfall and temperature fields derived from interpolated of station data alone (Jones et al., 2009). Satellite observations are however used in the operational production of incoming shortwave radiation, by combining solar reflective measurements from imagers aboard the Japanese GMS and MTSAT-1R geostationary satellites with station-level radiation measurements (Weymouth and Le Marshall, 2001). Grid cell fractions of deep- and shallow-rooted vegetation are estimated from persistent and recurrent greenness fractions based on AVHRR NDVI observations (Donohue et al., 2009). MODIS albedo and vegetation products were used to derive parameters describing the interrelationships between LAI, fraction canopy cover and albedo, whilst a photosynthetic capacity index was calculated from the enhanced vegetation index (EVI) (Huete et al., 2002) and used to parameterise surface conductance. Finally, ENVISAT ASAR GM radar (Pathe et al., 2009) observations were used to derive parameters describing the relationship between top soil moisture content and soil albedo. Canopy dynamics are explicitly simulated by the model and satellite vegetation climatology is not used operationally.

AWRA currently does not operationally assimilate satellite observations. However in research and reporting, a multiple-lines-of-evidence approach is used that relies on qualitative or formal comparison and combination of model estimates and satellite products. An example is the combination of AWRA soil and surface water storage estimates with GRACE total water storage estimates to infer trends in groundwater storage (Figure 3).

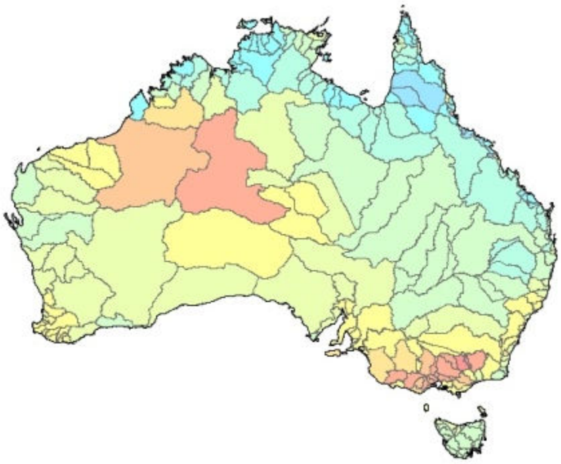

Figure 3. Deep moisture and groundwater storage trends for Australian river basins between 2002 and 2009. Trends are –34 (red) to +17 (blue) mm/year.

4.2. Experimental uses

An important aspect of AWRA development has been the generation of better quality precipitation fields, in terms of spatial and temporal resolution as well as in accuracy. In several regions the density of stations is very low and consequently interpolation uncertainty large. The global Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA 3B42; Huffman et al., 2007) extends back to 1998. Only a subset of the Australian station network is used for bias correction in the product and therefore opportunities exist to improve the synthesis product. Alternative statistical approaches to blending station data and satellite rainfall products have been explored (Renzullo et al., in prep.) and a prototype system that blends station observations with the satellite product is currently being tested.

Satellite observations have proven very useful to evaluate model performance and identify structural deficiencies. AWRA simulations have been assessed against satellite-derived estimates of top soil moisture content, surface and vegetation properties (fraction cover, FPAR, EVI), total terrestrial water storage, and ET estimates (Van Dijk and Warren, 2010). Top soil moisture derived from ENVISAT/ASAR GM showed spatial patterns that corresponded well with independent satellite product error estimates (Pathe et al., 2009; Doubkova et al., submitted.). AVHRR- and MODIS-derived estimates of FPAR, canopy cover fraction and greenness were reproduced well for seasonal vegetation that responds dynamically to water availability, while temperature driven phenology and small variations in canopy properties for evergreen forests were not reproduced (Figure 4).

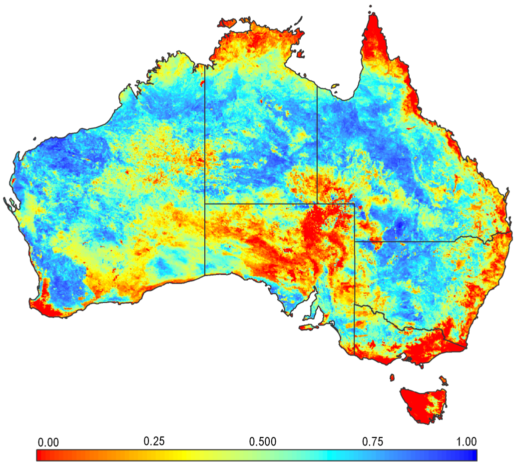

Figure 4. Coefficient of correlation (*R*) between MODIS-derived fraction vegetation cover (Guerschman et al., 2009a) and AWRA model estimates.

AWRA simulated total terrestrial water storages have also been evaluated against GRACE-derived terrestrial water storage estimates (Van Dijk et al., submitted). This showed good agreement in the dynamic range and patterns and emphasised the utility of satellite gravity observations to identify errors in forcing and the model description of soil and groundwater dynamics, even if currently only at coarse scale. Evaluation against AMSR-E and TRMM derived soil moisture products along with radar based estimates and in situ observations has helped to assess optimal soil moisture blending methods (Liu et al., 2010); and comparison against a MODIS reflectance-based scaling ET product (Guerschman et al., 2009b) has allowed the mapping of areas where lateral inflows of river or groundwater occur. Some data assimilation experiments have also been done to guide implementation in future.

5. NEW OPPORTUNITIES AND CHALLENGES

5.1. Forcing

There are opportunities to use alternative or additional satellite precipitation products and rainfall radar observations in blending. These data sources may facilitate the generation of informative estimates of sub-daily rainfall distribution, which is known to have an important influence on hydrological processes. There are also challenges to be addressed. In particular, caution needs to be taken when relying on satellite observations as a critical system input of data if continuity is not assured, or the quality relies on research missions. Another challenge is the need to understand the error in gauge records as well as satellite products, and the temporal and spatial scaling between the two.

5.2. Model parameter estimation

There are many opportunities for greater use of satellite observations to derive spatially continuous fields of soil and vegetation parameters (see Van Dijk and Renzullo, 2011, for examples). There are also some challenges in the inference of vegetation and soil parameter fields from satellite observations. All biophysical properties (e.g. LAI, albedo, biomass) inferred from remote sensing are subject to uncertainties in the parameters and assumptions of the retrieval model (e.g. Glenn et al., 2008). In addition, there can be conceptual differences between variables that appear superficially similar between remote sensing products and models. Examples include the difference between FPAR and fraction canopy cover, between optical depth and biomass, and between remotely-sensed surface soil properties and desired integrated soil properties.

5.3. Model evaluation

Where systematic differences are observed and can be attributed to model error, this can subsequently lead to improvements in model structure or parameterization. Model inter-comparison experiments tend to be confounded by the inability to ascribe observed performance differences to forcing, parameters and model structure, and satellite observations can be more helpful in this context. However, there is an equivalent challenge in using satellite retrieved data in the uncertainty introduced by the retrieval model. Even so, a distinct additional advantage of satellite observations over field observations is that model and observations can be compared at the same spatial scale, and in some cases satellite estimates have achieved an accuracy and uncertainty that is on par with field observations, e.g. the measurement of ET using flux towers.

5.4. Data assimilation

The operational uses and published experiments of data assimilation emphasise that the greatest benefit can be expected where the model does not simulate processes well and observations are of sufficient accuracy and relevance to improve the analysis; that is, 'good data can fix a bad model'. Whether data assimilation is successful and useful depends on a number of factors.

[1] The effectiveness of data assimilation hinges on the degree to which the target variables are influenced by the processes and improved by assimilation. For example, because of low importance of snow in Australia's water resources, AWRA-L does not simulate snow hydrological processes, nor would assimilation of snow observations improve water balance estimates except perhaps for a small fraction of the continent. Experiments with a precursor of AWRA-L indicated that microwave and TIR observations only impart useful information under certain conditions: microwave emissions are informative for top soil wetness in sparsely vegetated areas, whereas TIR can constrain root-zone water content over vegetated areas (Barrett and Renzullo, 2009).

[2] The complexity of the observation model required to assimilate the observations. From a theoretical point of view, 'raw' observations (that is, radiances, brightness temperatures, backscatter) rather than derived products should ideally be assimilated. However, hydrological models typically require considerable extensions to produce forward estimates of these variables, with associated complexity, model structural errors and parameter uncertainties. This approach can also increase computational requirements and affect system robustness, for example where observations in several bands or polarisations simultaneously need to be assimilated. Assimilation of derived hydrological products can be more straightforward but tends to introduce errors through the poor specification of observational errors required for assimilation. A promising approach would be to use the product retrieval models to generate spatially and temporally explicit uncertainty bounds.

[3] The assimilation of satellite observations obtained at scales coarser than the model resolution poses a methodological

challenge. Given the current system resolution (0.05°) this is particularly the case for GRACE and passive microwave observations. Progress towards the development of operational methods to assimilate coarse data has been made, but challenges remain, including accurate specification of the footprint, and in the case of microwave observations, the development of methods to account for the non-linearity in scaling and the variable influence of surface water on the soil moisture retrieval.

[4] In operational applications the computational overheads that parameter optimisation and state updating can introduce pose a challenge. In particular, multi-dimensional parameter optimisation can require a very large number of iterations, and ensemble filtering approaches are computationally intensive (see Van Dijk and Renzullo, 2011 for an example).

6. SUMMARY AND CONCLUSIONS

The AWRA system was introduced. The current operational and non-operational uses of satellite observations in AWRA were presented, and new opportunities and challenges to increase the use of satellite observations were discussed. Opportunities for greater use of satellite observations were identified as well as challenges that need to be overcome to achieve operational uses. We summarise these as follows:

- Opportunities exist to develop and use more accurate and higher spatial and temporal resolution precipitation products, but precipitation scaling and the operational reliability of these products need to be considered.

- Many opportunities exist for greater use of remote sensing products to provide a priori model parameter estimates related to vegetation and soil. This requires good understanding of conceptual differences between satellite products and their model equivalents.

- Model evaluation against satellite observations provides unique spatial information on model output uncertainty, can help guide further improvement, and is a logical precursor to the development of model-data assimilation techniques. This does require a good quantitative understanding of errors in satellite retrievals, however.

- The utility of satellite observations through data assimilation depends on dominant hydrological processes. Hydrological models are not always well equipped to assimilate 'raw' satellite observations. Assimilation of derived hydrological variables may be more attractive but requires correct and detailed specification of retrieval error. Methods are also required to deal with the coarse resolution of passive microwave and gravity observations. The computational implications of data assimilation techniques needs to be carefully considered in operational implementation.

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ACKNOWLEDGEMENTS

This work is part of the water information research and development alliance between the Bureau of Meteorology and CSIRO's Water for a Healthy Country Flagship.