Defining expectations: an approach to quantifying trust in modelling

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Abstract: Developing 'trust' in a model involves experience with its predictive capacity in a range of environments, and in particular, the ability to identify circumstances in which we can quantify expectations of performance. In this talk I'll argue that an inability to clearly define our expectations of model performance has led to model evaluation frameworks that are essentially qualitative, and, most importantly, fail to answer the fundamental question of whether or not we have a 'good' model. While this aim might sound subjective, there are a number of ways one might prescribe threshold levels of performance *a priori* – before running a model – that could help define a 'good' model. These include:

1. *Better than another model*. In some subset of regions, variables and metrics we are interested in, a model outperforms another candidate model. While this is the benchmark we are all probably most familiar with, it is potentially a very weak benchmark. It might guarantee incremental improvement of successive model generations, but it does not discount the possibility that both candidate models are very poor.
2. *Fit for a particular application*. An example of this might be the ability to achieve threshold rates of moisture recycling that enable adequate representation of monsoonal phenomena. Once we meet such a threshold, we know that a model is appropriate for its intended use. Ideally, we would have clear benchmarks of this nature for hydrological, ecological, climate and weather applications as a minimum standard. Defining these thresholds meaningfully is in practice extremely difficult, particularly in coupled modelling systems.
3. *Utilisation of information*. This approach defines benchmark levels of performance as a function of the complexity of the model and the amount of information provided to it in its inputs and parameters that is relevant to the quantities it is required to predict. For example, a hydrological or land surface model that is given distributed soil and vegetation information in addition to meteorological forcing should be expected to perform better than one that is not. The same should be true of a non-linear model as opposed to a linear model.

I'll outline an example where this third approach was successfully used to illustrate that a collection of 13 international land surface models were significantly underutilising the available information in their meteorological forcing data about sensible and latent heat fluxes. Despite significant data uncertainties, it was found that an out-of-sample linear regression outperformed all land surface models' prediction of sensible heat flux across 20 flux tower sites globally using four different statistical metrics. While this type of exercise requires a significant volume of process level observational data at the scale of a model's application, this example has opened up a range of difficult questions for the land surface modelling community that are likely shared by other communities were appropriate observational data available or similarly applied. These include:

- What does it mean to say we have "physically-based" model of a natural system when we don't have enough data to construct an empirically-based model? How do we know our conceptual representations have any value in the absence of observations that can directly confirm process representation?
- Is the drive to add more processes (often based on very sparse data sets) leading to intractable modelling systems with relatively poor accuracy?
- Are inappropriate values for the unconstrained parameters (through calibration) actively inhibiting predictive ability at global and regional scales?

These and more are offered as possible discussion material for the session.

Keywords: *Model benchmarking, land surface models*

Space-time monitoring of (sub) soil moisture for agricultural management: a case study

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Abstract: The expected increase in food demand will lead to increased water use in agricultural production in order to improve crop yields, maintain long-season dual-purpose crops and extend areas of perennial pastures. This combined with possible future climate shifts may mean that we will be farming drier and drier soils. One impediment to water-use efficiency and improved crop production is reliable estimates of soil moisture. Accurate estimates of soil moisture can help farmers make better decisions about what, when and how much to sow in their paddocks or when and how much to fertilise pre- and mid-season. The need to monitor soil moisture has lead to the implementation of monitoring networks as part of research projects such as OzNet (Murrumbidgee catchment) or ones developed specifically for growers by DEPI Victoria (Victoria) and FarmLink Research (southern NSW). Although space-time datasets are available the question remains about how transferable the information is to field and farms without probes. Also, remote sensing products available for soil moisture only refer to the top few cm of soil and are provided at a coarse resolution. For management of crops, soil moisture estimates for the entire profile are needed at the spatial resolution of a paddock, the order of 50-1000 m pixels. To tackle this issue we propose the development of a methodology to predict soil moisture for the entire profile at a resolution of 250 m and 7 days using a combination of in-situ measurements and remote sensing products which parameterise components of the soil water balance equation. In this work we present (i) initial modelling results (ii) a soil moisture monitoring network we have established in the Muttama creek catchment, a subcatchment of the Murrumbidgee river.

The basis of our approach is to use the water balance equation

$$S = R + I - ET - DD - RO, \qquad (1)$$

where S is the change in soil moisture, R is precipitation, I is irrigation, ET is evapo-transpiration, DD is deep drainage and RO is runoff. Eqn. 1 is used to estimate the bulk profile soil moisture content and we propose to use geostatistical inversion techniques coupled with in situ measurements of soil moisture to disaggregate the bulk profile predictions into predictions at individual depths. R and ET are estimated by readily available geospatial and remote sensing products, as an example here we use gridded SILO rainfall data (5km, 1 day) and the MODIS 16 ET product (1km, 8 days) to represent DD and RO in Eqn. 1. We have set a total profile water holding capacity of 500mm in the top 1.0 m after which water is lost from the profile. The water balance part of the approach was tested at FarmLink Research sites using daily soil moisture data from 2011 and the median correlation coefficients ranged between 0.4 and 0.7 across all sites and depths.

To understand the relative importance of our model predictions as compared to soil, terrain and weather, a Random Forest was fitted to a suite of variables (slope, aspect, soil order, land use, ET, rainfall, and soil moisture predicted from Eqn. 1). Soil moisture predictions were the 5^{th} most important predictor, ahead of it being slope, aspect, soil order and a dummy monthly variable. This is to be expected as the soil moisture predictions are based on geospatial products with spatial and temporal resolutions coarser than the daily, point soil moisture observations. Therefore local features such as slope and aspect are not represented in the model predictions. Further work needs to consider downscaling the model predictions from Eqn. 1.

The Muttama creek subcatchment encompasses an area of 1025 km^2 and is dominated by cropping and grazing. In January 2014 a network of 26 soil moisture monitoring sites was established which monitor soil moisture at 5 depths to a depth of 1.0 m. It was established as a case study for our research on soil moisture monitoring. In the future we hope to use this more intensively monitored region to test the inversion method and downscaling approaches we intend to use for the P and ET geospatial products.

Keywords: *Soil moisture, Monitoring, Water balance, Remote sensing*

Overcoming the tyranny of climate: capturing the social and economic benefits of great climate research

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Abstract: The inability to predict climate has shaped human history. In Australia, our highly unpredictable climate has shaped where we live, our infrastructure, agriculture, investment and psyche. Australian research is leading to major improvements in the skill of climate forecasting. But we need to ensure that we capture the benefits of this research for the social and economic benefit of Australia.

Are we improving weather forecasts through better initialisation of the land surface state?

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Abstract: The last ten years have seen some significant progress in land surface modelling and data assimilation. There is now a much better appreciation amongst land surface modellers of the nature of model soil moisture and the implications this has for the bias correction of satellite derived surface soil moisture for data assimilation, verification of model soil moisture and the inter-comparison and inter-changeability of model soil moisture.

At the same time, a number of significant satellite systems have been launched to globally monitor surface soil wetness from space. The Advanced Scatterometer (ASCAT) instrument on both the Metop-A (launched 2006) and Metop-B satellites (launched 2012) provides the first remotely sensed operational surface soil wetness product. A third ASCAT instrument will be launched on the Metop-C satellite, thus maintaining the service until at least 2020. The Soil Moisture Ocean Salinity (SMOS, launched 2010) is the first dedicated satellite soil moisture monitoring mission. While the Soil Moisture Active Passive (SMAP) is another dedicated satellite soil moisture mission due to be launched in 2014.

To take advantage of the newly available remotely sensed data, many numerical weather prediction centres have developed new flexible Kalman Filter based land surface data assimilation (DA) systems capable of assimilating a wide variety of remotely sensed measurements such as surface soil moisture, land surface temperature and vegetation properties as well as the traditionally used screen level temperature and humidity observations. The new land DA systems can make more optimal use of the observations by taking into account the expected error variance of the observations and propagate information from the surface measurements into the deeper soil layers.

This talk describes the impact of recent advances in land DA on weather forecasting as well as opportunities to improve land DA systems and land surface models together with a discussion of the utility of land DA for the monitoring and prediction of natural hazards such as bushfires, droughts, heatwaves and floods.

Diagnostic evaluation of land surface models from decision space – the hydrologic genome approach

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Abstract: Land surface models provide a crucial capability for estimating water and energy fluxes in the terrestrial environment. The models employ mathematical formulations together with a set of internal values to provide an estimate of the land surface response to meteorological forcings and changes in the land surface. The major components of a land surface model include model parameters, initial states, input forcing data, and the model structure. These internal components make up the decision space of the model, with each internal setting providing a specific model response/output. An assessment of model decision space is crucial to the identification of model weakness and the ultimate improvement in model forecasts. However, diagnostic evaluation of land surface models is challenging, mainly because of the uncertainties associated with the internal model components and their interactions, which make it difficult to determine the inaccurate parts of the model that need improvement. Until the land surface model decision space is properly characterized, the ability to actually pinpoint the inadequate parts of the model for subsequent adjustment will remain questionable.

In this presentation, a hydrologic genome approach is employed to quantify the uncertainty for internal components of the land surface model, in terms of its soil moisture estimation. The hydrologic genome approach was inspired by biological genome mapping, which has the capability to determine how the structure of the human body functions and the location of genes that battle disease-causing virus and bacteria. The hydro genomic method uses an evolutionary strategy together with a data assimilation framework to generate a genomic-like data set. The evolutionary strategy is able to provide the genomic-like data set to encompass the model decision space, while the data assimilation approach affords a model state updating and temporal monitoring of the changes in model decision space. The resulting genomic data set is a series of model footprints in time, with each footprint comprising an ensemble of optimal internal model settings in decision space. The genomic-like data set was examined using multi-dimensional clustering to map the model decision space, where the land surface model was evaluated on the basis of its temporal stability in decision space.

The hydro genomic approach is demonstrated for the Community Atmosphere Biosphere Land Exchange (CABLE) model for soil moisture estimation in the Yanco area in south-east Australia. Data assimilation was undertaken to assimilate retrieved soil moisture from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) into CABLE. To evaluate the hydro genomic method, open loop and calibration estimates were used. The calibration output was generated by independently calibrating CABLE to the retrieved AMSR-E soil moisture content across the same assimilation time period, whereas the open loop was based on randomly generated values for model parameters, initial states, and input forcing data uncertainty.

The modeling results show that the updated soil moisture is superior to outputs from both the open loop and the calibration. The generated hydro genomic map was found to provide a minimum uncertainty for model components, reducing the original and updated bounds to about 70% and 60% respectively. In terms of soil moisture estimation, the hydro genome map was found to be about 60% as accurate as the updated output based on AMSR-E data, and superior to outputs from both calibration and assimilation when evaluated using in-situ OzNet (www.oznet.org.au/) soil moisture. It is noted that the hydro genomic approach is part of a broader conversation towards the diagnosis and refinement of land surface models for improved water and energy estimates. The key finding is the provision of a model diagnostic framework to better identify model weaknesses and refine land surface models on the basis of their temporal stability in decision space.

Keywords: *Soil moisture, Model weakness, Diagnostic model evaluation, Data assimilation, Evolutionary strategy.*

Verification of numerical models – what are the biggest challenges?

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Forecasts from numerical weather prediction (NWP) have been verified since the 1950s when they first started providing reasonable predictions, and beginning in 1985 modelling centres have exchanged standard scores for forecast fields on selected pressure levels. Operational verification hasn't really kept up with recent improvements in NWP, particularly as models have increased in resolution to <20 km for some global models and 1-2 km (convection-permitting) for mesoscale models. Ensemble prediction is overtaking deterministic NWP as the most important source of numerical guidance, and it too is being run at very high resolution. Coupling of atmospheric models to ocean and land surface models is being brought forward from the seasonal range to shorter ranges. Numerical weather and climate predictions are also being used to drive downstream impact models for emergency management, hydrology, agriculture, energy, and many other applications.

With the improvement in NWP now enabling the prediction of surface weather and its impacts, improved approaches are needed to evaluate these forecasts. This is an active area of research. To measure the performance of high resolution forecasts in a way that is more consistent with how they are used, several new spatial verification approaches have been proposed that consider coherent spatial structures in various ways. As these methods become mature for high resolution deterministic forecasts, they must now be adapted to verify high resolution ensemble predictions. A significant challenge in verifying predictions for extremes is accurately observing them and collecting enough forecast-observation pairs to compute meaningful and robust statistics. In general it is no longer appropriate to ignore observation error; in fact, as models continue to improve, the apparent error in forecasts will become closer and closer to the error in the observations. While it is possible to remove biases in observations when they are known, it is much more difficult to account for random errors in observations which lead to poorer verification scores.

Evaluation of seamless (weather-climate) numerical prediction requires verification approaches that allow for consistent interpretation across time scales. This is tricky because short- and medium- range forecasts tend to be deterministic or ensemble predictions of instantaneous "absolute" weather variables at fine spatial and temporal scales, whereas extended range forecasts are based on coarser resolution ensembles, are typically given as probabilistic predictions of weekly or fortnightly anomalies being in a particular category (e.g., highest tercile), and rely on large hindcast datasets for forecast calibration.

Verification of warnings of impacts associated with extreme weather brings extra challenges. Observations of the impacts may be difficult to obtain for a variety of reasons relating to how they are collected, and by whom, how they are stored and disseminated, and whether they measure something that can be predicted and verified or are only indirectly related to the impact. Communication between the meteorological and various downstream communities is also challenging, with each sector "speaking their own language" and having their own priorities for what makes a forecast useful to them. To enable the benefits of improved NWP and weather forecasting to be translated into improvements in downstream impact forecasts, it is necessary to develop and apply verification metrics that are meaningful to the downstream users.

Although this talk will draw on weather prediction for most of its examples, many of the issues apply to land surface and water prediction as well.

Keywords: *Forecast verification, model evaluation*

Improving hydrological models focusing not on hydrology

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AbstThe problem with describing the whole hydrology of the Earth is very diverse and the uncertainties of the future predictions come from various sources. Whereas new methods for the calculation of soil moisture, evaporation, surface runoff, stream flow and ground water have being developed, the input to the global hydrological cycle of mountain glaciers and ice sheets, in particular of the melted ice from Antarctica, has being taken arbitrary due to the difficulty to estimate the overall mass balance and find triggers of the current downward trends.

Here we are focusing on Antarctica, but the method can be applied to other floating ice tongues as well. One part of the problem comes from the ice sheet models ignoring description of processes that might be crucial for the future stability of the ice sheet. Particularly, we are focusing on is calving of icebergs from the floating parts of the ice sheet, or ice shelves. None of the existing ice sheet models describe the calving process in a comprehensive way. However, only the surface melting that models include so far can have just a minor or indirect influence on the stability of the ice sheet.

The main complication is caused by the large number of processes such as cracks propagation, depth and direction of cracks, penetration of surface melted water into cracks, changing geometry of the basin, tides and basal melting, that may cause calving. In our work we are focusing not on the direct physical influence of each of the above processes, bur on the correlation between calving events and the possible triggers. In other words, we calculate the value showing how each process inputs into a calving at every particular ice shelve. After, by calculating the probability of every event to occur we estimate the combined effect and thus knowing how likely a calving to happened. Thus,we are able to know where calving is more likely to occur and to calculate more precisely the overall loss of the ice from Antarctica. It's a challenge, because not only the calving process at ice tongues has been added to the current models, but neither the growth of the ice tongues, so that the grounding lines are static.

Thus, our work includes three main steps: allowing ice shelves to grow, putting conditions when calving from the ice shelves must occur and constraining the model adding data from satellite images into the calving function. The information about the calving rate can give as a more clear idea about the amount of melted water from Antarctica. Having develop more precise modelling of the ice sheet we can make the current hydrological models be more reliable and will allow us to make better future projections on the global scale.

Keyw *Antarctica, ice shelves, calving rate*

Convection permitting regional climate modelling for short time scale precipitation extremes

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Abstract: Previous work has found that errors in sub-daily precipitation are associated with deficiencies in the cumulus convection parameterization. This suggests studies of short time scale precipitation extremes are best performed using model resolutions that are high enough to remove the need for a convective parameterization (<4km). However, modelling at these resolutions is very computationally expensive particularly given that the domain must be large enough for small scale dynamic structures to develop and that simulations must be long enough to characterize extremes (decades).

Presented here are the results obtained when modelling the climate of the greater Sydney region using the Weather Research and Forecasting (WRF) model at 2km resolution for the period 1990-2009. The model is able to reproduce the 95th percentile of hourly precipitation totals well but tends to overestimate rarer events. This overestimate is much smaller at the daily (and longer) time scale. Examining Intensity-Frequency-Duration curves created by fitting a Generalized Extreme Value distribution to the annual maximum series reveals a similar overestimation of rare events (less than 1 in 2 years) but also demonstrates significant sensitivity to single data points in the time series and hence the uncertainty associated with these rare events.

Using this regional climate model allows investigation of possible future changes in these sub-daily extreme precipitation events. Given the large uncertainty in both the observations and model simulations however, it is very difficult to obtain statistically significant future changes. Nevertheless, estimates of changes in extreme precipitation events spanning a range of accumulation periods (from 1 hour to 1 day) and event frequency (from 1 in 2 years, to 1 in 100 years) have been calculated and are presented here.

Evaluation of the Australian Water Resource Assessment Landscape (AWRA-L) model, WaterDyn and CABLE

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Abstract: Assessing water resources and accounting for their availability and use at a regional and continental scale requires comprehensive and consistent information on water distribution, storage, availability, and use. This information needs to be accurate, up-to-date and take account of local climatic and hydrological conditions. It also needs to be produced in a robust, transparent and repeatable manner. The Australian Water Resource Assessment Modelling System (AWRAMS) provides nationally consistent and robust water balance estimates at a national to regional scale for the past and present using observations where available, and modelling otherwise. The AWRAMS is a new integrated continental hydrological simulation system designed and prototyped by CSIRO and the Bureau through the Water Information Research and Development Alliance (WIRADA) WIRADA initiative completed by June 2016.

The AWRAMS system uses on-ground observations and remotely sensed data sets, combined with hydrological science and computing technology, to estimate water balance fluxes and stores. This includes all major water storages, and the movement of water in and between these, at a ~5 km spatial resolution and daily time step. It is flexible enough to use all available data sources, whether modelling data-rich or data-sparse regions, to provide nationally consistent and robust estimates of water balance terms. The AWRAMS has three modelling components including a landscape water balance (AWRA-L), a groundwater (AWRA-G) and a river balance (AWRA-R).

This paper deals with the AWRA landscape model (AWRA-L) which provides credible estimates of landscape water yield (runoff and baseflow), evapotranspiration, soil moisture, and aquifer recharge across Australia, specifically for retrospective Water Resource Assessment, National Water Account and soil moisture monitoring purposes. AWRA-L is a 0.05° (~5km) gridded soil and groundwater balance model, undergoing continual conceptual and parameter estimation development, towards reducing the uncertainty and error in the water balance estimates. Significant technical improvements in the model performance and conceptual structure have been achieved to date from the initially parameterised AWRA-L v0.5 through to the current AWRA-L v4.5 over the last 7 years. This paper evaluates and compares the hydrologic performance of various versions of AWRA-L model with two similar national water balance models (WaterDyn and CABLE-SLI).

Initial comparison results indicates that streamflow performance has improved with successive versions of AWRA-L, with v4.5 performing better than WaterDyn and CABLE in terms of Nash-Sutcliffe Efficiency and bias across 295 catchments used in calibration and 294 validation catchments. This better performance is not surprising as AWRA-L is currently calibrated to streamflow, whereas CABLE and WaterDyn are not. Secondly AWRA-L is approaching the hydrologic performance of locally calibrated, nearest neighbouring catchment regionalised rainfall-runoff models such as GR4J, highlighting the good performance of the model in ungauged/uncalibrated areas. Comparison against satellite and point based estimates of soil moisture and ET have indicated that AWRA-L model performs relatively well. Variability of performance between various versions of AWRA-L model indicates that calibration to soil moisture and ET could significantly improve the model according to these variables, without degrading performance according to streamflow.

Outputs of the AWRA-L model are currently used each year by the Bureau to populate the water balance terms in the annual National Water Accounts (NWA) and regular water resources assessment products and the Water in Australia (WIA) report. In the near future, the Bureau plans that regularly updated AWRAMS products such as regional water information,, soil moisture (or evapotranspiration) and monthly status report could be provided as a service by the Bureau. The outputs provide valuable information on Australia's water resources for water management practitioners, policy makers and researchers.

Keywords: *Soil moisture monitoring, model evaluation, landsurface water balance*

Spatio-temporal controls on catchment ecohydrology: lessons learnt from eucalypt forests

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Abstract: Evapotranspiration is a major component of the water balance and is spatially variable due to variations in land cover and topography. Among different processes included in evapotranspiration (e.g. transpiration, soil and leaf evaporation, canopy interception) transpiration is the most important component in forested catchments of south-east Australia. The amount of water transpired by trees can be divided into water transpired under stressed and water transpired under non-stressed conditions. While prescribed values of soil moisture are commonly used to define the transition between water-stressed and unstressed conditions, several other variables (e.g. atmospheric humidity, radiation, nutrient availability) can at different times limit vegetation water use, either individually or in combination.

Assessment of physiological response to water stress can be included in hydrological modeling based on a mechanistic framework. A suite of physical models have been used to predict stomatal conductance as a function of water availability in soil and atmosphere and can be included in models of ET such as in the Penman-Monteith equation, depending on the complexity of the hydrological model. Estimation of ET via such models requires extensive data inputs – data that are not readily available in many instances. As an alternative, ET is often simulated more conceptually, as supply-limited, i.e. depending on the soil moisture availability. In reality transpiration is also strongly controlled by atmospheric demand, particularly during demand-limited periods.

Based on empirical data and theory, we revised a supply-limited evapotranspiration function by including atmospheric (VPD) regulation of transpiration during periods when soil moisture is not limiting, using the HBV hydrological model. Surfaces of potential evapotranspiration (ET_p), air temperature and vapour pressure deficit were spatially modeled taking into account the influence of topography on forcing variables. Results showed that aggregated climate variables are superior to the average of point (gauge) measurements for application in lumped hydrological models over a complex terrain. In addition, inclusion of atmospheric-induced limitations to transpiration into the ET sub-model, using only a single extra parameter, made a significant improvement in streamflow simulation.

This study is a coupling of previous process-focused field research on transpiration dynamics of *Eucalyptus* forests, with alternate approaches, to improve modeling of larger-scale catchment water yield. An extension of this study will focus on testing the application of the new ET sub-model for similar catchments.

Keywords: *Evapotranspiration, streamflow, vapour pressure deficit, eucalyptus, water yield*

Evaluation of downscaled soil moisture and vegetation optical depth derived from the Land Parameter Retrieval Model

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Abstract: Space-borne passive microwave radiometers have great potential for observation of land surface parameters such as surface soil moisture and vegetation water content. However, the coarse resolution of the sensors limits the value of the data in hydrology. In this study, a passive microwave soil moisture and vegetation optical depth product is downscaled to ~10 km resolution and then evaluated over the Australian continent, with special attention for the Murrumbidgee and Fitzroy catchments.

First, brightness temperatures from the Advanced Microwave Scanning Radiometer (AMSR-E) are downscaled using the smoothing filter-based modulation technique. In this technique, brightness temperatures from the C-band (~50 km resolution) are adjusted based on data from the Ka-band (~10 km resolution). The downscaled brightness temperatures are then used as inputs in the Land Parameter Retrieval Model (LPRM), which produces downscaled soil moisture and vegetation optical depth products. However, the Ka-band used in the downscaling technique is more sensitive to precipitation, so as a final step a precipitation mask is introduced to improve the quality of the final products. The advantage of this method compared to other downscaling methods is that all data originates from the same sensor and platform.

The downscaled soil moisture and vegetation optical depth products show enhanced detail and have a higher spatial variability compared to the original, coarser resolution. The added value of the precipitation mask is demonstrated by comparing the soil moisture product with time series of in situ soil moisture sensors in the Murrumbidgee catchment. This shows that the precipitation mask removes extraneous values, leading to a slight, but significant increase in the correlation between these datasets.

Visually, the downscaled vegetation optical depth product sharpens the boundaries of changes in vegetation in Australia. This is confirmed by higher spatial correlations between the vegetation optical depth and the MODIS 16-day NDVI product after downscaling. This increase in correlation is significant in areas such as the Fitzroy catchment, where there are a number of distinct patches of sparse and dense vegetation.

The downscaled soil moisture product was evaluated by in situ soil moisture data and an antecedent precipitation index. Both of these methods show that correlations with the downscaled product are similar but slightly worse than correlations with the product at the original resolution. However, irrigation areas in the Murrumbidgee catchment that cannot be distinguished at the original resolution become visible in the downscaled product. On average, these irrigation areas are about 20% wetter after downscaling.

In summary, passive microwave soil moisture and vegetation optical depth products were downscaled using brightness temperatures from the same sensor and platform. Application of a precipitation mask to the downscaled products improved the quality of the products by removing extraneous values. Downscaling improves the performance of LPRM products in areas with strong gradients in vegetation or soil moisture. One important example is that irrigation areas are consistently wetter in the downscaled soil moisture product. These results show that downscaling increases the information content in the soil moisture and vegetation optical depth products, which can benefit hydrological studies at regional scales.

Keywords: *Soil moisture, Downscaling, Passive microwave radiometry, Remote sensing*

Towards dynamic high resolution mapping of cropped areas in Australia

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Abstract: Accurate and timely water accounts need spatially explicit and temporally dynamic estimates of water used by agriculture, seasonal changes and inter-year variations total cropped area and water used per unit of area. A desired but yet nonexistent data product to inform water accounting systems is a high resolution (i.e. tens of meters) map of irrigated crops and area of on-farm water storages which is also updated seasonally. We present preliminary results of a Landsat-based map at 30 meter spatial resolution of summer irrigated crops in the Colleambally irrigation district (NSW).

We used Landsat data from the GA/CSIRO "DataCube" project which made historical Landsat data (from 1987 to 2012) for the entire Australian continent available (GA, 2013). In a first pre-processing step we generated monthly Landsat composites using the medoid (multidimensional median) of cloud-free pixels and filled remaining gaps with linear interpolation. We used training samples from visual interpretation of Landsat data in the summer months where area with irrigated crops and non-cropped areas were identified. Monthly values and rates of change of the Normalised Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI) where used as predictive variables in a Random Forest classification model to map summer irrigated areas for the water-years 2004/05 to 2011/12. All the predictive variables are presented and the algorithm produces a series of ensemble models to predict the resulting variable (crop or non-crop). The algorithm also generates an estimate of the relative merits of each explanatory variable and therefore, a more parsimonious model (i.e. one which produces the best results with the lowest possible number of explanatory variables) can be selected.

The approach produced annual maps of irrigated summer crops for the region which look consistent with visually interpreted spatial patterns. We also used a water detection algorithm for identifying water persistence in each growing season (i.e. the frequency in which water was observed in each pixel) to identify on-farm storages.

Current and future research focuses on expanding this approach to the entire Murray-Darling Basin and using water diversion data, statistics of irrigated areas and production volumes to further validate the results presented.

Keywords: *Remote Sensing, Landsat, Datacube, cropping, on-farm storages, irrigation*

An approach to estimate rainfall at ungauged location by merging the radar and gauge estimates

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Abstract: One of the key challenges in hydrology is the accurate representation of the spatial and temporal distribution of rainfall, especially at ungauged locations. In this research, we ask, "What is the best way of getting accurate estimates of rainfall in a watershed?" Theoretically, we could place enough gauges to eliminate errors in any spatial interpolation, but that would be prohibitively expensive. A better solution is to use radar rainfall estimates from radar reflectivity in conjunction with the existing rain gauge network.

In this study, we propose two new developments to advance this area of research. First, we have proposed a novel approach to estimate rainfall from radar reflectivity and tested whether this approach can provide better estimate compared to traditional power law method. It is a nonparametric Z-R relationship (NPZR) approach based on the conditional probability distribution of the rainfall and reflectivity.

Second, we have developed a combination method to find rainfall at ungauged locations by merging the spatially interpolated gauge rainfall with the NPZR estimates. The merging is done by applying dynamic weights calculated for both of the methods. This weight at any particular pixel for a rainfall event is calculated from the error covariance matrix of historical similar events from nearby gauged locations. The proposed method has been tested by leave-one-out cross validation.

The NPZR method is applied to the data from the densely-gauged Sydney Terrey Hills radar, where it reduces the overall error in the rainfall estimates by 16%, with improvement observed at 90% of the gauges. The combination method shows excellent performance by reducing the estimation error (about 23%) compared to a traditional power law method. The estimates are also improved compared to spatially interpolated point measurements in sparsely gauged areas.

Keywords: Radar rainfall, spatial interpolation, weighted combination

Dissecting PLUMBER: Why are land surface models performing so poorly?

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Abstract: The PALS Land sUrface Model Benchmarking Evaluation pRoject (PLUMBER) (Best et al. submitted) showed a serious across-the-board problem with the performance of 13 international land surface models. PLUMBER found that in key predicted atmospheric fluxes, land surface models are consistently out-performed by relatively simple, out-of-sample empirical models. The problem is especially apparent in sensible heat flux, where *all* land surface models are outperformed by a simple out-of-sample linear regression on incoming shortwave radiation.

Here we briefly describe the PLUMBER results, and then attempt to rule out potential causes of this poor performance. In particular, we investigate: the aggregation methods used in PLUMBER, to rule out that these results are not due to particular sites or metrics used in the experiment; the potential for time-resolution problems, which are potentially important, because land surface models are designed to predict over longer timescales; and the fact that empirical models are not bound by the laws of energy conservation, potentially giving them an advantage in a benchmarking situation.

We find evidence that the performance problems shown in PLUMBER are not due to any of these causes. These results indicate that the problem lies deeper, and we propose a number of further methods of investigation that may provide more insight.

Making the most of the ground based meteorological network using anomaly-based interpolation

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Abstract: High resolution spatially extended values of climate variables play a central role in the assessment of climate trends and extremes, in downscaling of projected future climates and in ecosystem modelling. The ground based meteorological network remains a key resource for deriving these spatially extended climate variables, particularly for the pre-remote sensing era. With the advent of remotely sensed data sources, and the modest decline in ground observing networks, it is attractive to combine both data sources to maximize spatial coverage and accuracy. We report here on the production, and potential applications, of new anomaly-based fine scale spatial interpolations of the key climate variables for ecosystem modelling, at daily and monthly time scale, across the Australian continent. The methods incorporate several innovations that have significantly improved spatial predictive accuracy, as well as providing a platform for the incorporation of additional remotely sensed data.

It is well known that anomaly-based interpolation methods can separately account for the strong dependence on topography of "background field" parameters and the broad atmospheric processes that give rise to the anomalies with respect to the background field. We have enhanced the accuracy, and robustness to source data error, of both. This is done in part by incorporating key physical process aspects of the different climate variables. A key background field parameter is the monthly mean for a specified standard period, which was set as the 30 year period 1976-2005. We have developed new regression procedures to estimate 1976-2005 monthly means for all stations with minimal records over the last century, whether or not they have records in the 1967-2005 period. This has substantially increased the supporting spatial networks. Separate robust correlations for each season take advantage of the strong spatial correlations in monthly temperature and precipitation data. In the case of monthly mean temperature background fields, accuracy has been further enhanced by incorporating process-based coastal effects that have reduced predictive error by around 10%.

A new anomaly structure has been devised for monthly and daily precipitation to take account of the skewness in precipitation data and the large proportion of zero values that present significant challenges to standard interpolation methods. The new structure has been found in particular to accommodate the large spatial gradients in precipitation in the eastern highlands. The anomalies with respect to the various background field parameters for each background field are interpolated by a new extension of the ANUSPLIN package that automates much of the extensive housekeeping required for anomaly-based interpolation. This also includes a new robust method for automatically detecting and removing data errors. Close inspection of the analyses confirms that the data errors are often associated with missing data on preceding days, and in the case of precipitation, non-recognised multi-day accumulations, as well as values systematically recorded for the preceding day.

The methods provide a major advance on the methods reported by Hutchinson *et al*. (2009). Predictive errors of the interpolated monthly temperature fields, in particular, are around 25% less than the errors reported by Jones *et al*. (2009). There are smaller reductions in precipitation errors, reflecting the lower spatial coherence of precipitation fields and the presence of uncorrected errors in test data. The new methods have the potential to improve the automated correction or deletion of such errors. The full set of interpolated grids, called ANUClimate, form a key component of the TERN eMAST facility at http://www.emast.org.au/ and provide key inputs to the National Carbon Accounting System (NCAS) for the Department of Environment.

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Keywords: *Climate grids, climate anomalies, ANUSPLIN, climate data network, error detection*

Driving through floodwaters: what's the point of flood forecasting?

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Abstract: Flood forecasting technologies have come a long way in the past few decades with substantial advances in numerical weather prediction and sophisticated hydrologic and hydraulic models contributing to improvements in accuracy and longer lead times for forecasts. Despite this, in many flood events, there continue to be fatalities and large economic losses due to the behaviour of people who have been caught unprepared or have underestimated the risks associated with the flooding. In some cases inappropriate development has been allowed on floodplains and flood protection infrastructure has mistakenly been believed to fully "flood proof" communities.

This presentation questions whether further improvements to the accuracy of flood forecasting both in Australia and overseas are needed. Instead should the focus be on improving flood education and preparedness? The role of information dissemination is also an important consideration as even a perfect forecast is of no use if not communicated to affected people in a timely and comprehensible way. Are advances in information technology and social media going to ultimately lead to reducing the costs of flooding more than further improvements in forecasts accuracy?

Keywords: *Floods, forecasting, emergency management, human behaviour*

Influence of an optimal stomatal conductance scheme in Australian Community Climate and Earth System Simulator (ACCESSv1.3)

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Abstract: Stomatal conductance (g_s) controls the fluxes of carbon and water between vegetation and the atmosphere and hence plays an important role in the carbon, energy, and water cycles. g_s has traditionally been parameterized using empirical models (Jarvis, 1986) within land surface models. The Community Atmosphere Biosphere Land Exchange (CABLE) model (Wang et al. 2011), the land surface model within the Australian Community Climate and Earth Systems Simulator (ACCESS, see http://www.accessimulator.org.au; Kowalczyk et al. 2013)), parameterizes g_s following Leuning et al. (1995). This scheme, like most traditional models of g_s, does not differentiate between model parameters as a function of plant function types (PFTs), but only in relation to photosynthetic pathway. Recently, a new g_s scheme has been proposed by Medlyn et al. (2011), which is based upon the optimization approach, i.e., that stomata adapt to maximize carbon gain whilst minimizing water loss. The g_s model parameters for this scheme vary per PFT and are derived from observational studies, and hence provide a more physically based approach to parameterize g_s. This scheme was recently implemented with CABLEv2.0.1 and tested globally in offline simulations (De Kauwe et al. 2014). This paper will present preliminary results from simulations with CABLE fully coupled to ACCESS, in atmosphere-only AMIP-style simulations with prescribed sea-surface temperature fields. The paper will focus on the influence of the scheme on both the mean climate and extreme indices.

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Keywords: *ACCESS, CABLE, evapotranspiration, land surface modeling, stomatal conductance*

Hydrological modelling at the catchment scale: Trusty Friend or Devious Foe?

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Abstract: Hydrological modelling – despite its seeming well-defined aim of predicting environmental water flows – is growing to employ a staggering array of models and modelling techniques. It is helpful to view the process of model development and application as a series of decisions, which highlights that the reliability and trustworthiness of the overall modeling chain depends critically on the individual steps. However, making transparent and justifiable choices at each modeling step is far from straightforward.

Even if we limit ourselves to a discussion of model development for catchment-scale streamflow predictions, there are entire schools of thought to choose from – with the historical distinctions between conceptual versus physically based, and lumped versus distributed becoming increasingly grey as broader choices such as black-box models and neural networks, data mining, and others are considered.

As we go from model development to model application, a hydrologist will face further choices, such as those related to parameter estimation – from a priori estimation, to manual calibration, to deterministic optimization to fuller probabilistic uncertainty analyses. As before, each category here is a field of research in its own right, with its own set of orthodoxies and inevitable controversies.

The origins of such a wide gamut of modelling approaches are arguably rooted in the challenging combination of modelling and data analysis tasks facing hydrologists, and environmental modellers in general. Data uncertainty arising from the sparse and imprecise measurements of environmental variables, the nonlinearity and heterogeneity of hydrological systems (both at the surface and in the subsurface), the difficulty in establishing physically realistic constitutive relationships, and other factors are all widely recognized and are continuing to attract major research attention.

Are we as a community making progress? The published literature suggests clear advances, yet, at least sometimes, there is also a sense of slow progress – for example, as evidenced by sessions at major conferences being titled “Why can’t we do better than TOPMODEL?”, and workshops such as the “Hydrological Court of Miracles” where many examples of model failures were exhibited.

One of the difficulties is that, while we are seeing numerous and diverse modelling applications, the studies have tended to use their own sets of models and metrics, and efforts to carry out a meaningful large scale interpretation and attribution of results have been hampered by the myriad of uncontrolled major and minor differences between different models – especially once we get down to the level of actual computing software. And to confound matters further, many current hydrological models do not take advantage of modern numerical techniques, and their trustworthiness is often undermined by major numerical artefacts.

Is there a way of making sense of all this real and perceived “complexity”? Are we in danger of building a Modelling Tower of Babel, where hydrologists speak with each other and their users in a thousand non-transparent technical dialects – or is this an inevitable price of research diversification? Are we any closer to a Grand Unified Theory of hydrological modelling? Should we even be looking for such a theory, or do most modelling contexts demand their own model? Can defensible research-based recommendations be made to model users, and what might some of these recommendations look like? What might be some of the practical challenges and opportunities awaiting the next generation of hydrological model developers and users?

This talk will provide the authors’ perspectives on these and other questions. Examples will be provided, including development, application and integration of inference methods and diagnostics, robust time stepping schemes and flexible hydrological models, with the aim of encouraging a debate and discussion.

Keywords: *Hydrological modelling, model development, transparency, robustness, Bayesian methods, numerical techniques.*

Improvement of soil moisture dataset combining AMSR2 soil moisture products

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Abstract: Soil moisture has been considered as an important variable in hydrological systems affecting the water cycle in the atmosphere, land surface and subsurface. It is considered that microwave remote sensing provides a unique capability for retrieving soil moisture at the global scale and a number of microwave-based soil moisture products have been used in various fields of Earth sciences in the past decades. While microwave can provide near-real time observation (global coverage every 1-3 days for the majority of the sensors), its direct applications have been limited due to the coarse spatial resolution (>100 km^2) and uncertainties resulting from a number of complex factors that affect the radiative transfer model. In this aspect, it is essential to validate the accuracy prior to actual applications and to improve the dataset itself and the retrieval algorithms. As a first step to do this, two remotely sensed soil moisture products from the Advanced Microwave Scanning Radiometer 2 (AMSR2), retrieved by the Japan Aerospace Exploration Agency (JAXA) algorithm and the Land Parameter Retrieval Model (LPRM) are assessed and structural errors noted. The main findings are: 1) The JAXA algorithm generally underestimates the ground soil moisture, whereas LPRM algorithm tends to overestimate soil moisture. 2) Correlation coefficients between AMSR2 products and ground measurements decrease when the mean temperature decreases below approximately 290K. 3) In general the LPRM correlations increase as the surface becomes rougher whilst the JAXA correlations decreases. 4) The performance of JAXA is affected in areas with dense vegetation, particularly for mean EVI greater than 0.30. 5) Distributions of bias and RMSE of LPRM are relatively insensitive to variation of mean ground soil moisture; however JAXA performs better in dry condition. As it is found that the two products are complementary under the various conditions, a combinatorial approach is presented for improving the accuracy of soil moisture dataset. The approach is a linear combination technique which applies a spatio-temporal weighting, calculated based on error statistics of the products, to each product.

Keywords: *AMSR2, JAXA, LPRM, Soil Moisture*

Not Your Average Visualisation Project

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Abst This presentation combines a tale of software development with the opportunities for exploration that seemingly mundane—but well-designed—software can offer. We have created an open-source, python-based, and massively parallel visualisation software system, which we employed to create the imagery for the Australian Carbon and Water Observatory (ACWO; http://carbonwaterobservatory.csiro.au/). ACWO imagery is generated from 26 data variable fields, displayed at national, state, catchment, and natural resource management scales, comprising a collection of millions of images. A sampling of this imagery is presented to demonstrate its illuminative character. The system is sufficiently generic that it can be deployed to the Australian Water Availability Project (AWAP) dataset. We then point out the file-and-data-wrangling facilities, combined with python's formidable numerical mathematics and scientific computing software ecosystem, provide a solid foundation on which big data analytics applications for AWCO and AWAP can be built with aplomb. We conclude with some representative case studies.

"Big Data Analytics" or "Data Science" is currently a hot topic in the commercial sector and the disciplines of computational science and engineering. It is widely agreed that the main obstacles on the road from raw data to understanding are assembling data, implementing quality control, understanding file-naming conventions and data formats, and getting the data into the analysis engine; processes collectively called "data wrangling," "data munging," or "data janitor work." Data munging can occupy 50-80% of the total effort involved in the data mining process[1]. CSIRO's Earth Observation Informatics Transformational Capability Platform provided us with the support to create comprehensive imagery for ACWO[2,3] and the opportunity to amortize the ACWO data-wrangling effort to enable deep analysis of the ACWO data.

The ACWO field variables are organised as two-dimensional arrays of data on a 0.05° x 0.05° latitude-longitude grid that covers the Australian region's landmass. Data files contain one 2D slice per time sample, and the time sampling period is typically one month, spanning the period 1900-present. Thus, for a single variable at the national scale, there are over 1300 data files, corresponding to 1300 images. The ACWO web site's display system shows a mosaic of "thumbnail" images, each of which may be clicked to reveal a full-size, high-resolution image. Thus,visualisation of a single field at the national scale a total of over 67600 images. Generating each image on the fly is prohibitively expensive computationally, and all of the imagery was generated en masse on the CSIRO's burnet multiprocessor cluster. The visualisation system is built on open-source Python tools, notably numpy, matplotlib, and matplotlib-basemap. The parallelization is achieved using the Message Passing Interface Library via mpi4py. Animations are produced from these images using the open-source ffmpeg package. Additionally, the system supports generic geographic masking/subsetting of data; at present, state, catchment, and natural resource management area regionalisations are supported, with the ability to implement and apply user-defined regionalisations. Happily, the ACWO and AWAP file format and file/directory naming conventions coincide, and the system has been tested successfully with AWAP data. Thus, the software infrastructure required to perform the "data janitor" work for ACWO and AWAP is now available in a single open-source code base.

The visualisation system will provide multiscale imagery later this year. Case studies employing information-theoretic techniques will be presented to demonstrate the system's potential to extract new information regarding climate variability and climate change.

Keyw *Carbon and Water Analyses, Big Data Analytics, Climate Variability, Climate Change.*

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Impact of different data assimilation strategies for SMOS observations on flood forecasting accuracy

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Abstract: During the last decade, significant efforts have been directed towards establishing and improving flood forecasting systems for large river basins. Examples include the European Flood Alert System, and the Bureau of Meteorology Flood Warning Systems in Australia. A number of attempts have also been made to increase the accuracy of the forecasted flood volumes from these systems. One attractive way in which this can be achieved is to use remotely sensed surface soil moisture contents to constrain the hydrologic model predictions. Satellite missions such as SMOS can provide very useful information on the wetness conditions of these basins, which in many cases is an important initial condition for discharge generation. Assimilation of these satellite data is thus a logical way to proceed. We will present results from two different assimilation strategies for the Murray-Darling basin in Australia using the Variable Infiltration Capacity (VIC) model. Firstly, the SMOS soil moisture data are assimilated into the hydrologic model at their original spatial resolution. As the spatial resolution of the remote sensing data (25 km) is coarser than the spatial resolution of the model (10 km), a multiscale data assimilation algorithm needs to be implemented. Secondly, the SMOS data are downscaled to the model resolution, prior to their assimilation. In this presentation, the impact of the assimilation of both products on the accuracy of the forecasted flood volumes is assessed.

Keywords: *Data assimilation, water management, flood forecasting, scaling*

A synthesis of a global stomatal conductance database under an optimal stomatal behaviour framework: patterns from leaf to ecosystem

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Abstract: Stomatal conductance (g_s) is a key land surface attribute as it links transpiration, the dominant component of global land evapotranspiration and a key element of the global water cycle, and photosynthesis, the driving force of the global carbon cycle. Despite the pivotal role of g_s in predictions of global water and carbon cycles, a global scale database and an associated globally applicable model of g_s that allow predictions of stomatal behaviour are lacking. We present a unique database of globally distributed g_s obtained in the field for a wide range of plant functional types (PFTs) and biomes. We employed a model of optimal stomatal conductance to assess differences in stomatal behaviour, and estimated the model slope coefficient, g_1, which is directly related to the marginal carbon cost of water, for each dataset. We found that g1 varies considerably among PFTs, with evergreen savanna trees having the largest g_1 (least conservative water use), followed by C_3 grasses and crops, angiosperm trees, gymnosperm trees, and C_4 grasses. Amongst angiosperm trees, species with higher wood density had a higher marginal carbon cost of water, as predicted by the theory underpinning the optimal stomatal model. There was an interactive effect between temperature and moisture availability on g_1: for wet environments, g_1 was largest in high temperature environments, indicated by high mean annual temperature during the period when temperature above 0^oC (T_m), but it did not vary with T_m across dry environments. We examine whether these differences in leaf-scale behaviour are reflected in ecosystem-scale differences in water-use efficiency using eddy flux data set around the world. These findings provide a robust theoretical framework for understanding and predicting the behaviour of stomatal conductance across biomes and across PFTs that can be applied to multi-scale modelling of productivity and ecohydrological processes in a future changing climate in Australia and in the world.

Keywords: *Optimal stomatal behaviour, water-use efficiency*

Observing water availability impacts on vegetation using an enhanced passive microwave remote sensing method

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Abstract: Satellite-based passive microwave observations are sensitive to water amounts on the land surface, including surface soil moisture and vegetation water content. Unlike optical-based observations which are primarily sensitive to canopy greenness, passive microwave observations are available regardless of cloud cover. Its main disadvantage is the relatively coarse spatial resolution that is a consequence of the low energy of the Earth's natural microwave emissions.

The history of satellite-based passive microwave observations goes back to a few decades ago and there are several retrieval algorithms available to derive surface soil moisture and vegetation water content. Unlike other algorithms, the Land Parameter Retrieval Model (LPRM) developed by researchers from VU University Amsterdam in collaboration with NASA can be applied to the passive microwave emissions across all low-frequency microwave bands (<20 GHz) (Owe et al., 2001). The LPRM retrieves surface soil moisture and vegetation optical depth (VOD) simultaneously. VOD is primarily an indicator of total water content contained in all aboveground biomass, including leaves and woody components. It is currently available at 0.25° (~25 km) spatial resolution and it has been demonstrated that this VOD product can capture the biomass changes over various land cover types, including grassland, cropland, savannas and forests at the global and continental scales (Liu et al., 2013).

To observe water availability impacts on vegetation water content at the regional scale, a VOD product with finer spatial resolution is needed. Parinussa et al. (2014) presented an approach to use LPRM and a downscaling method to derive 0.10° (~10 km) surface soil moisture product and demonstrated that the downscaled product is very promising for hydrological applications.

Here the LPRM algorithm and downscaling method is applied to the Advanced Microwave Scanning Radiometer for Earth Observation System (AMSR-E) observations (2002-2011) over Australia to derive downscaled 10-km VOD product which is further compared with currently available 25-km VOD product and optical-sensor based vegetation indices (e.g. enhanced vegetation index (EVI) and normalized difference vegetation index (NDVI)). The analysis includes comparing long-term changes, investigating the influence of ocean circulation indices on vegetation dynamics, and examining the aboveground biomass carbon estimation based on the VOD product. This downscaled VOD product is expected to provide deeper insights into spatiotemporal variations of vegetation water content and biomass over Australia.

Keywords: *Satellite observation, Vegetation water content, Enhanced spatial resolution*

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Alternative configurations of quantile regression for estimating predictive uncertainty in water level forecasts for the upper Severn River: a comparison

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Abstract: Forecasting may reduce but can never fully eliminate uncertainty about the future. Hydrological forecasts will always be subject to many sources of uncertainty, including those originating in the meteorological forecasts used as inputs to hydrological models (e.g. precipitation and temperature), and in the hydrological models themselves (e.g. model structure, model parameters and human influences). Informed decision-making may benefit from estimating the remaining uncertainties.

In the literature, various approaches to estimate predictive uncertainty have been presented. One of those is statistical post-processing. Estimating predictive uncertainty through statistical post-processing techniques comprises an analysis of past, “observed” predictive uncertainty to build a model of future predictive uncertainties. Several hydrologic post-processors have been described in the scientific literature, including the Hydrological Uncertainty Processor, the Bayesian Model Averaging, the Model Conditional Processor, and Quantile Regression. The present research focuses on the latter technique.

The study comprises an intercomparison of different configurations of a statistical post-processor that is used to estimate predictive hydrological uncertainty. It builds on earlier work by Weerts, Winsemius and Verkade (2011; hereafter referred to as WWV2011), who used the quantile regression technique to estimate predictive hydrological uncertainty using a deterministic water level forecast as a predictor. The various configurations are designed to address two issues with the WWV2011 implementation: (i) quantile crossing, which causes non-strictly rising cumulative predictive distributions, and (ii) the use of linear quantile models to describe joint distributions that may not be strictly linear. Thus, four configurations were built: (i) a "classical" quantile regression, (ii) a configuration that implements a non-crossing quantile technique, (iii) a configuration where quantile models are built in normal space after application of the normal quantile transformation (NQT) (similar to the implementation used by WWV2011), and (iv) a configuration that builds quantile model separately on separate domains of the predictor. Using each configuration, four reforecasting series of water levels at 14 stations in the upper Severn River were established. The quality of these four series was intercompared using a set of graphical and numerical verification metrics for a large number of sub-sets of available data, each representative for increasingly higher events.

Verification showed that, unconditionally, in terms of all skills and metrics, forecast quality is positive. However, the analysis also shows that forecast quality and skill decreases with increasing value of the event. Intercomparison showed that reliability and sharpness vary across configurations, but in none of the configurations do these two forecast quality aspects improve simultaneously. Further analysis shows that skills in terms of the brier skill score, mean continuous ranked probability skill score and relative operating characteristic score is very similar across the four configurations.

Keywords: *Uncertainty, hydrological forecasting, Quantile Regression, verification*

Balancing the realities of environmental observations, model uncertainty and model truthfulness

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Abstract: One of the greatest challenges environmental modellers face in this time of climate and ecosystem nonstationarities is how we reconcile limited observations with imperfect models to improve our characterization of physical systems. It is well recognized that observations of physical systems often lack adequate coverage (in time and space) and rarely directly measure the variable we are often most interested in (and certainly not without error). This is compounded by the difficulties in matching observation to models that require a simplified representation of the system processes and often represent measured variables at a different time/space scale.

In light of this, significant effort has been put into the development and refinement of uncertainty frameworks that attempt to probabilistically quantify the relationship between observations and models. However we appear to be at an impasse with how we mathematically describe the complexity of model error. Arguments are made against formal statistical methods for uncertainty analysis that cannot appropriately represent epistemic error, while informal approaches are criticized for their reliance on subjective modeler expertise and their lack of statistical rigor.

For our models to be more truthful we need to identify the patterns in environmental processes that are important to characterize from a systems perspective, and perhaps be less concerned with exactly reproducing time series of observations. This is not a new idea. Several recent studies have demonstrated that by sacrificing/relaxing the desire to produce a perfect fit to observations, by considering novel ways to summarize complex observations, or by incorporating expert knowledge and 'soft' data, we may have models that are more reliable, more 'authentic' (in that they adequately represent environmental physical processes) and better equipped to capture system nonstationarities and extreme conditions. This presentation will aim to discuss how uncommon field observations and expert knowledge can be helpful to improve model trustworthiness and demonstrate how these concepts may be incorporated into uncertainty frameworks.

Keywords: *Model uncertainty, field data, hydrology*

The NARCliM Project: Model Evaluation and Climate Projections for Temperature and Precipitation for South-East Australia

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The objective of NARCliM (NSW / ACT Regional Climate Modelling) Project is to provide regional climate projections for Australia, with a special focus on New South Wales and Australian Capital Territory. The project brings together a diverse set of state and local government departments, and researchers from UNSW Climate Change Research Centre.

Dynamical downscaling of output from General Circulation Models (GCMs) is used to provide 50-km resolution projections for the CORDEX-AustralAsia region, and 10-km projections for South-East Australia. The project improves on previous work in the amount of policy-relevant model output, and in the procedure of climate model selection. The process of selecting driving GCMs has several components. We first assess model performance through a literature review. Second, we rank models by their independence. Finally, we select independent models that adequately sample temperature and precipitation projections in the full model set. The chosen GCMs include MIROC3.2, ECHAM5, CCCMA3.1, and CSIRO-MK3.0. Another set of measures is put in place to select three out of 36 Regional Climate Models (RCMs). These measures include an assessment of model independence, and an evaluation of model skill at reproducing several precipitation events. The three RCMs to perform downscaling are WRF models with different parameterizations of planetary boundary layer, surface layer, cloud microphysics, and radiative exchange. NARCliM model runs span four periods: 1950-2009 (reanalysis), 1990-2009 (present), 2020-2039 (near future), and 2060-2079 (far future). 12 GCM-RCM pairs are used for each period except for the reanalysis, where the three RCMs are used. While each run generates projections for a diverse set of atmospheric and land surface variables, we limit this analysis to temperature and precipitation.

Evaluating the skill of NARCliM models at reproducing current climate is an important step for interpretation of NARCliM projections. For the present and the reanalysis periods, we compute seasonal and annual climatologies of daily mean, minimum, and maximum temperatures, as well as precipitation for each RCM. We perform the same analysis for daily mean temperature and precipitation for driving GCMs. We assess model biases by systematically comparing the results for the present to observations from Australian Water Availability Project (AWAP).

We present preliminary climate projections for the near- and far-future for seasonal and annual climatologies, and changes from present. We compare the RCM and the GCM projections, and speculate on the reasons for the differences between the two.

NARCliM, South-East Australia, Climate Projections, Dynamical Downscaling, Climate Modeling

Challenges of Operational River Forecasters

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Abstract: Skillful and timely streamflow forecasts are critically important to water managers and emergency protection services. To provide these forecasts, hydrologists must predict the behavior of complex coupled human–natural systems using incomplete and uncertain information and imperfect models. Moreover, operational predictions often integrate anecdotal information and unmodeled factors. Forecasting agencies face four key challenges: 1) making the most of available data, 2) making accurate predictions using models, 3) turning hydrometeorological forecasts into effective warnings, and 4) administering an operational service. Each challenge presents a variety of research opportunities, including the development of automated quality-control algorithms for the myriad of data used in operational streamflow forecasts, data assimilation, and ensemble forecasting techniques that allow for forecaster input, methods for using human-generated weather forecasts quantitatively, and quantification of human interference in the hydrologic cycle. Furthermore, much can be done to improve the communication of probabilistic forecasts and to design a forecasting paradigm that effectively combines increasingly sophisticated forecasting technology with subjective forecaster expertise. These areas are described in detail to share a real-world perspective and focus for ongoing research endeavors.

Keywords: *Flooding, Streamflow, Outlooks, Prediction*

Hydrologic Modelling in Non-Stationary Catchments: A Data Assimilation Approach

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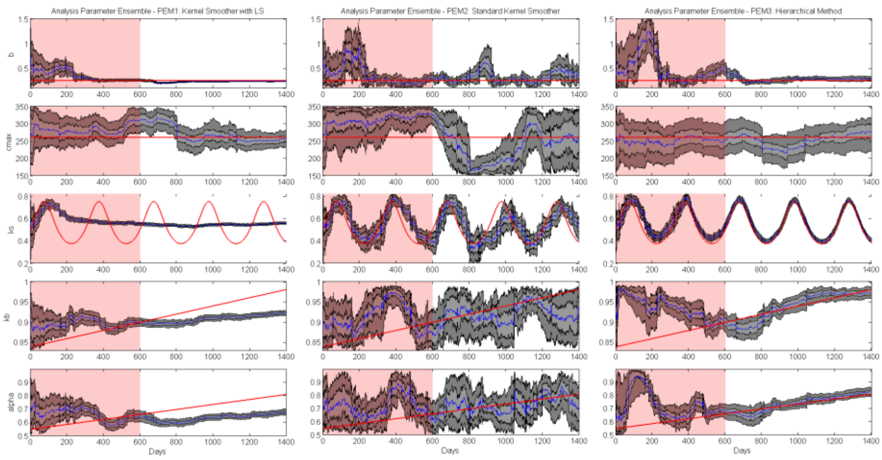
Abstract: Hydrologic modeling is commonly predicated on the assumption that past conditions are representative of future conditions. However, changes to catchment characteristics (eg. Urbanisation), as well as the role of model parameters in pooling together scale effects and other unresolved model processes can easily violate this assumption. These issues raise a number of questions - can a single model and/or set of model parameters adequately represent a catchment's runoff response? Is it possible to design a modelling framework that can adequately represent catchment processes now and in the future? An appreciation of catchment non-stationarity is critical to answering these questions, however this has been given little consideration in the past. Typically a single hydrologic model is adopted, along with a pseudo optimal parameter set which is assumed to be adequate outside the period of calibration/validation.

We present a novel method for dealing with catchment non stationarity that allows model parameterisations to evolve in time through a Data Assimilation framework. Data Assimilation allows model simulations to be dynamically adjusted according to real time observations and the assumed error characteristics of both. The popular Ensemble Kalman Filter (EnKF) along with the Probability Distributed Model (PDM), a lumped conceptual hydrologic model are applied in a synthetic case study. It is shown that careful consideration of the artificial parameter evolution step is critical for non-stationary parameter estimation. Two commonly used artificial parameter evolution techniques, the kernel smoother with location shrinkage and the standard kernel smoother, are considered and found to be problematic when parameters exhibit temporal variability. This is demonstrated in Figure 1a) and 1b), where the time varying structure of PDM parameters is poorly represented.

A new hierarchical EnKF approach is presented which provides an improved prior parameter distribution by updating the parameter evolution process. Figure 1c) shows that the temporal nature of parameters is well represented with this approach, particularly in comparison to estimates from the traditional parameter evolution techniques. This method provides a general framework for establishing dynamically evolving models that will be particularly useful for rapidly changing catchments.



(a) (b) (c)

Figure 1. Estimates of the five PDM parameters over 1400 days using the EnKF and a) Kernel Smoother with Location Shrinkage; b) Standard Kernel Smoother; c) Hierarchical Method. The blue line indicates the ensemble mean whilst the shaded areas indicate the 25th/75th and 5th / 95th percentiles. The red line indicates the true parameter at each time.

Keywords: *Data Assimilation, Ensemble Kalman Filter, Non-stationarity, Parameter estimation*

Towards dynamic continental estimation of irrigated areas and water use

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Abstract: Irrigation agriculture accounts for around 65% of Australia's water consumption and generates 23% of the total value of agricultural production. Despite their importance, the year-to-year geographic distribution and water use of many important irrigated areas remains uncertain. We advance a methodology to map irrigated areas on a year-to-year basis at the regional/continental scale. The region in which the methodology was implemented, the Murray-Darling Basin (MDB) in Australia, possess biophysical characteristics, spatio-temporal climate variability and irrigation practices that makes identification of irrigated areas challenging. The methodology used training samples from Landsat TM/ETM+ reflectance data and monthly time-series of remotely-sensed observations from the MODerate resolution Imaging Spectroradiometer (MODIS). The covariates included in the classification model characterised the monthly dynamics and rates of change of: (i) the vegetation phenology via the recurrent and persistent fractions of photosynthetically active radiation ($fPAR_{rec}$ and $fPAR_{per}$, respectively); (ii) water use via remotely-sensed estimates of actual evapotranspiration (ET_a), precipitation (P) and the difference between ET_a and P. Observed agreement – in terms of the kappa coefficient – for correctly classified pixels in the training sample was 96%. Independent comparisons of yearly irrigated area estimates showed linear relationships with Pearson's correlation coefficients (*r*) generally greater than 0.7 for: (i) reported areas (e.g., Figure 1); (ii) areas with available metered water withdrawals; and (iii) estimates of agricultural yields. The Random Forest model approach and other techniques and data are available to extend this mapping to other areas with complex irrigation practices.

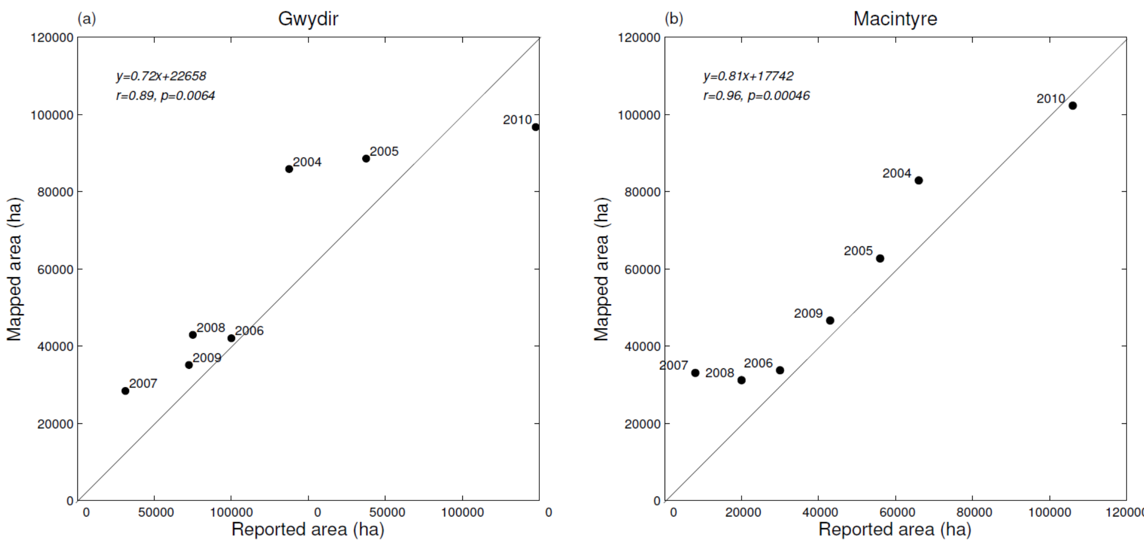

Figure 1. Scatter plots of irrigated areas in the (a) Gwydir and (b) Macintyre valleys reported in the Cotton Yearbook 2011 versus mapped irrigated areas per water-year (where, for example, 2010 corresponds to the water-year 2010/11). The equation represents a one-degree polynomial fit to the data. Also shown are the Pearson's correlation coefficients (*r*) and *p*-values for both datasets.

Keywords: *Irrigation, Image classification, Remote sensing, Random Forest, Mapping*

Towards a hyperresolution land data assimilation system for Australia

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Abstract: In 2011 Wood *et al*. issued an aspirational 'grand challenge' to the global water-carbon-energy modelling community to model terrestrial water balance at ~ 1-km scale globally and ~100-m continentally at (sub-)daily time steps. They argue that efforts towards achieving this *hyperresolution* level of prediction will drive developments in hydrological models and lead to multiple societal benefits, including enhanced capability for droughts and flooding forecasting at unprecedented spatial scales. The demands on computational resources for the task are immense, particularly as the endeavour will utilise the burgeoning of water cycle related satellite products and the many surface observation networks that are increasingly sharing their data via the internet. Storage, assimilation of these data into hydrological models, and the world-wide dissemination of water information products is a formidable challenges for any computing infrastructure.

This paper discusses the potential for hyperresolution modelling of Australia's water and carbon balance. The demands for information products at <1-km resolution are described in the content of water resources and carbon assessments, as they serve as the impetus for the development of a continental land data assimilation system in Australia. We examine the preparedness of the National Computational infrastructure (NCI) to ingest the 'flood' of observations from earth observation and ground-based systems, and to serve as the platform for collaboration between universities and government agencies by providing a common modelling environment for all researchers. Finally we present progress towards the installation of data assimilation software on the NCI, as well as establishment of a satellite soil moisture products collection.

Keywords: *Hyperresolution, land surface modeling, data assimilation, computational infrastructure*

Leveraging Ground and Remotely Sensed Observations for Short-Term Streamflow Forecasting

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Abstract: Methods to improve streamflow forecast using state-parameter-forcing update schemes have been actively researched for many years. However, key technical challenges and practical merits in real applications have not been well communicated. Much of the challenges originate from our limited knowledge of model and observation uncertainties, incomplete representation of the uncertainties due to the model structure, non-linear error propagation and, for some cases, real-time/forecast forcing errors dominating the overall streamflow forecast uncertainties. We present several stochastic data assimilation works applied to catchments with various level of annual rainfall, available monitoring stations and catchment size with an aim to improve the Bureau of Meteorology's continuous short-term flood forecast models. Two-tiered approaches developed for (relatively) well-monitored and data-sparse regions, respectively, are compared and discussions of how errors from various sources add up to the final apparent forecast uncertainty and the nature of the errors that can be corrected by the data assimilation are provided.

Keywords: *Flooding, Remote Sensing, Uncertainty, Data Assimilation*

Hydrologic systems as complex networks: structure, connections, and dynamics

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Abstract: Driven by sheer necessity or pure curiosity and facilitated by advances in technology, hydrology has witnessed an unprecedented growth during the last century. Invention of powerful computers, remote sensors, geographic information systems, and worldwide web and networking tools have enabled collection and sharing of extensive hydrologic data, formulation of sophisticated mathematical techniques, and development of complex hydrologic models.

There is no question that we today possess a far greater ability to represent real hydrologic systems, understand their past and present functions, and project their future trajectories. However, there still remain numerous challenges, not only in developing models to accurately represent hydrologic systems but also in applying them for practical purposes. Among the issues dominating debates and discussions are: (1) models being developed are often far more complex than that may actually be needed; (2) more and more data are collected, without adequate scrutiny of their relevance and significance; and (3) models are often developed for specific situations, and so their extensions to other situations are generally difficult. Although these issues are addressed in many different forms, they all seem to emphasize the need for a generic theory or framework for hydrologic modeling.

A key requirement for developing a generic theory in hydrology is an adequate knowledge of the nature and extent of connections among the different hydrologic system components at various (space and time) scales. This is because, connections are ubiquitous and vital in hydrology. This is abundantly clear from the hydrologic cycle or water cycle itself, as every component in the hydrologic cycle is connected, either directly or indirectly and strongly or weakly, to every other component. Despite our efforts and progress through numerous scientific concepts and mathematical models, our understanding of connections in hydrologic systems remains largely inadequate. The present study proposes that the science of complex networks, a recent development in the field of complex systems science, offers a generic theory for studying all types of connections associated with hydrologic systems.

First, the basic concepts of complex networks and a number of associated measures for identifying network properties are described. Then, the relevance of complex networks for hydrology is explained through several examples, including the hydrologic cycle, rainfall and streamflow monitoring networks, river networks, global climate model outputs and their downscaling, and water distribution systems. Finally, the usefulness of the science of complex networks for studying connections in hydrology is tested through application of several network-based measures (e.g. clustering coefficient, degree centrality, degree distribution) to rainfall and streamflow data. For this purpose, monthly rainfall data monitored over a network of 230 stations in Australia and monthly streamflow data from a network of 639 stations in the United States are analyzed. Different threshold values, which are based on correlations (of rainfall and streamflow), are used in the analysis to obtain and compare some important information about the network properties. The results are discussed in terms of the type and nature of rainfall and streamflow monitoring networks, spatial and temporal connections in rainfall and streamflow, interpolation/extrapolation of rainfall and streamflow data, and catchment classification and regionalization.

The results generally suggest that the above rainfall and streamflow monitoring networks are not random networks, but networks of some other nature. Such results have important implications for rainfall and streamflow modeling theories, model complexities, data collection, and predictability, among others. Efforts to verify, and possibly confirm, the present results are currently underway. The broader implications of the outcomes of the present study for water resources planning and management are also highlighted.

Keywords: *Hydrologic systems, modeling, complex networks, rainfall, streamflow*

The Australian Water Resources Assessment (AWRA) Modelling System Implementation Project: Getting Australia's data and model infrastructure ready for the future

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Abstract: The Australian Water Resources Assessment (AWRA) Modelling System underpins the Bureau of Meteorology water information services that are federally mandated through the Water Act (2007). The AWRA model has been developed for more than six years through the Water Information Research And Development Agreement (WIRADA) collaboration between the Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). While a prototype AWRA Modelling System was developed through WIRADA the AWRA Modelling System has been significantly refactored and enhanced through the Bureau of Meteorology AWRA Modelling System Implementation (AWRAMSI) Project.

The AWRAMSI Project commenced two years ago and initially focused on installing, running, understanding and maintaining the WIRADA prototype. In the past year (particularly the past six months) there has been significant development in the AWRAMSI Project that has led to an AWRA Modelling System that is platform independent, while also being more efficient, functional, and easily maintainable than the WIRADA prototype.

The AWRA Modelling System consists of a landscape (AWRA-L) and river (AWRA-R) model, with both models running at daily resolution and AWRA-L covering the Australian continent at 0.05° (or approximately 5km) spatial resolution and AWRA-R a node-link model applied to regulated rivers. The AWRA-L model is typically run for the period 1 January 1911 to yesterday that corresponds to the availability of the input forcing data, the AWAP (Australian Water Availability Project) meteorological grids of daily rainfall, minimum and maximum air temperature, and solar radiation. The AWRA-R model is typically run for the period 1 January 1970 to 30 June 2013 that corresponds to the availability of observed streamflow (at gauged stations), with AWRA-R using observed streamflow when available and modelled flow otherwise. Both models (AWRA-L and AWRA-R) can be run further back in time by relaxing the reliance on observational data (e.g. by using meteorological climatology or modelling streamflow). To be able to run AWRA-R up to now (like AWRA-L) more efficient methods of extracting and processing the recent streamflow observations need to be developed.

The AWRA Modelling System also contains other components (other than just the models) such as visualisation and benchmarking. The visualisation for AWRA-L allows the plotting of maps or timeseries for any specified region such as Australia, a state, a catchment, a bounding box, or a pixel. The visualization for AWRA-R is yet to be developed but is likely to simply be timeseries for a set of locations. The benchmarking for AWRA-L consists of statistics (NSE, bias, correlation) and plots (timeseries, scatterplots, box and whiskers, and CDF) of the model outputs (catchment aggregated gridded runoff, soil moisture, evapotranspiration (ET) and deep drainage) against in-situ (streamflow, soil moisture probes, flux towers, recharge sites) and remotely sensed soil moisture (AMSR-E and ASCAT) and ET (CMRSET and SLST) products. The benchmarking of AWRA-R is simply against in-situ observations and will soon be developed.

The AWRA Modelling system can be run in three primary modes. These are interactive (that allows simulation, plotting and benchmarking over arbitrary areas and time periods), calibration (using specified observations, statistics, time periods and areas), and scheduled run (automatic updating of model output using live data feeds). The scheduled run readily lends itself to an automatically updated data service and website of the AWRA model inputs and outputs. This will be developed and released to the community (together with the model code) in the next two years.

Keywords: *Water Act, water information services, WIRADA, AWRA, community model*

Interpreting vegetation condition from satellite observations: accounting for the influence of water availability

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Abstract: Vegetation condition is important in landscape dynamics with implications for the state of ecosystems and carbon, energy and water fluxes in the landscape. Understanding the state of vegetation condition through time and space is valuable for assessing the health of ecosystems, informing planning and conservation. Vegetation closely interacts with the water cycle and climate system, both by modulating water, energy and carbon fluxes as well as by being impacted by water availability and climate. Vegetation condition can be expressed using a range of attributes depending on the intended use and the information available. Relevant attributes include; species richness (e.g. species count or genetic diversity), vertical (strata) and lateral (patches, variation) structure, and material stocks (e.g. biomass or carbon) and fluxes (carbon, water, energy). Selecting relevant attributes is dependent on of the question at hand, and which specific ecosystem function or services are being investigated. The quality of selected ecosystem attributes is typically assessed by comparison against benchmark or reference sites. These benchmark sites are selected as "undisturbed" analogue ecosystems, pre-disturbance conditions, natural climax condition based on ecological succession theory or optimal resource use based on ecohydrological principles.

Here we propose an approach to measure vegetation condition using remote sensing and satellite observations. Previous efforts to map vegetation condition using image data exploit regionally derived statistical relationships between field observations and spatial vegetation metrics derived from the imagery. The reliance on field data and moderate to high resolution imagery that is not systematically acquired makes these techniques unsuitable for routine assessments. Our intention is to develop a framework that provides systematic and accurate measures of native vegetation condition with the eventual aim of applying the methodology to a system of national environmental accounts.

Numerous studies, including those that exploit satellite observations, have demonstrate the fundamental relationship between precipitation and a range of vegetation properties including leaf area index, fractional cover, evapotranspiration, and primary productivity. These relationships are curvilinear with thresholds in the response of vegetation to ever increasing precipitation. These relationships have been exploited by recent advances in understanding the interaction of precipitation, vegetative cover, evapotranspiration and runoff. These advances typically build upon the Budyko framework, an established and simple approach for understanding mean annual evapotranspiration (ET) and runoff within large catchments. The framework is useful in predicting fractions of ET and runoff but does not provide insight into how vegetation impacts on these discrete partitions or vice versa. Developing the Budyko framework further, researchers have attempted to account for the impact of vegetation (e.g. Zhang Curves and Budyko-Choudhury-Porporato model) and also to overcome some of the steady state assumptions that restrict the framework to broad spatial and large temporal scales. Many of these advancements also rely on the principles of ecohydrology that dictate an evolutionary drive to optimize the exploitation of available resources.

We propose that the recent revisions to the Budyko framework, developed to understand the impact of vegetation on evapotranspiration and runoff, can also offer an insight into the impact of resource availability and other environmental pressures, on vegetation condition. The ability to examine the relationship between precipitation and vegetative properties using satellite observations and other spatial datasets offer the ability for comparisons and benchmarking across increasing spatial and temporal resolutions. This will enable tends in vegetation conditions to be observed and hopefully measured across space and time with the eventual aim that this information can inform environmental accounts at a national scale.

Keywords: *Vegetation condition, remote sensing*

The potential for improving terrestrial water storage estimates through assimilation of GRACE data into a hydrological model

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Abstract: The lateral and vertical distribution of terrestrial water interacts with Earth's climate system, controlling over water, energy and biogeochemical fluxes，thus having a critical role in characterizing water availability, hydrologic extremes such as drought and flood. Traditional monitoring of terrestrial water change mainly depends on model simulation. Although hydrological models solve the problems in describing water storage change, the lack of systematic global fine-scale hydrological measurements increases the model uncertainty and lowers the simulation accuracy.

Terrestrial water storage (TWS) includes all forms of water stored above and underneath the surface of the earth (e.g. surface water, soil moisture, groundwater, as well as snow and ice). Recently, the combination of remote sensing technology, observation network and hydrological models shows its significant potential in terrestrial hydrology studies. However, ground or satellite based techniques can only provide the measurements of some individual components like surface water and hardly be applied to subsurface water. The problem of the absence of integrated TWS measurements was resolved by the launch of Gravity Recovery and Climate Experiment (GRACE) with unprecedented accuracy for the entire globe. The TWS estimates from GRACE is on the basis of 1 month or 10 days, with a horizontal resolution of about 150 000 km^2. Vertically, GRACE's TWS observations mostly reflect the change in land water storage and ice mass and it integrates changes in groundwater, soil moisture, snow and ice sheets, surface water, and vegetation, after removing the changes in atmospheric and ocean mass.

In this study, a statistical comparison of GRACE and TWS estimates from the World Wide Water Resource Assessment (W3RA) model was conducted to investigate the potential for identifying and diminishing model deficiencies. GRACE TWS estimates agree well with the W3RA model outputs in most of the continents, and the difference indicates the uncertainty of GRACE data and the limitation of the model structure. The discrepancy in Amazon and northwest Australia shows the potential for using GRACE to improve TWS estimates in the area requiring better rainfall estimation. In addition, the model appeared to underestimate the TWS amplitude, which suggests the modeled soil, groundwater and/or surface water systems drain too quickly. Therefore, a model sensitivity study needs to be conducted to investigate the impact of different meteorology forcing datasets (e.g. precipitation, temperature and radiation) on improving the model estimates. Estimates in individual water storage are expected to be improved by the constraints from GRACE TWS estimates in the way of disaggregating GRACE TWS anomalies into individual components.

To isolate individual components from GRACE TWS data, auxiliary information in each component is needed, such as using ground-based measurements or satellite-based retrievals of soil moisture to obtain groundwater storage change. Another approach is to merge GRACE TWS through simulation by a hydrological model via data assimilation. Therefore, the aim of this study is to improve the global TWS estimates through assimilating both GRACE-derived TWS and auxiliary information about individual water storage components into W3RA model. Near surface soil moisture retrievals from Soil Moisture and Ocean Salinity (SMOS) or Advanced Microwave Scanning Radiometer-EOS (AMSR-E) is considered due to the vital role of soil moisture in the estimation of evapotranspiration and runoff.

The improved estimation of TWS by the developed data assimilation system will offer a new perspective on monitoring global water cycle and especially subsurface water storage variation. It will also contribute to drought and flood prediction and management.

Keywords: *GRACE, data assimilation, World Wide Water Resources Assessment (W3RA), total water storage, soil moisture*

Victorian Climate Initiative

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Strategies to ensure the sustainable management of water resources and the provision of secure water supplies for urban and rural water users and the environment are underpinned by assumptions about the current and likely future availability of water resources over a range of time scales (from weeks to decades ahead). The Victorian Climate Initiative (VicCI) was established in 2013 as a three-year program of research to inform the preparation of such strategies for Victoria through improved prediction and understanding of the climate system and its representation by climate models, as well as the linkages between climate and water availability. This strategic knowledge provides the basis for improved projections of future climate and associated water availability in Victoria; in particular, it enhances knowledge of the uncertainties in future projections.

As part of the program first year progress, an attempt was made to develop future streamflow projections using downscaled rainfall calibrated to match catchment-wide observed gridded rainfall on a 5km grid. First a simple statistical model, that uses a linear combination of the current month's precipitation, the previous month's precipitation and the previous 12 months of precipitation to reconstruct the monthly inflow of Melbourne's water catchments, was updated to include the previous 10-years of rainfall as well, and applied across 27 Victorian catchments. The updated model was better able to capture the magnitude of streamflow reductions during the Millennium Drought, and it can be readily applied to provide initial estimates of projected streamflows given projected rainfalls. Secondly, the model has been applied across selected Victorian catchments to generate initial future inflow projections using daily rainfall derived from the analogue-based statistical downscaling of available CMIP5 models. Results from that early attempt to provide streamflow projections suing the latest global climate model based projections will be presented.

In due course, these results will be compared with those from using different downscaling approaches and more sophisticated rainfall – runoff models. In addition, a broader evaluation of some commonly used approaches that provide future climate projections for hydrological modeling (e.g. empirical scaling from global climate models, empirical scaling informed by regional climate models, bias correcting of regional climate model simulations, bias correcting of analogue downscaling) will be performed in order to compare the results with the simple method. The strengths and weaknesses of each method will be assessed, with a view to recommending methods for different applications.

Keywords: *climate, water availability, downscaling, streamflow projections*

CO_2-induced greening reduces streamflow in water-stressed climates in Australia

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Abstract: Global environmental change has implications for the spatial and temporal distribution of water resources, but quantifying its effects remains a challenge. The impact of vegetation responses to increasing atmospheric CO_2 concentration on the hydrological cycle is particularly poorly constrained. CO_2-induced structural and physiological changes in vegetation potentially have consequences for water resources. CO_2 fertilization and associated greening should tend to increase vegetation water consumption by increasing the amount of transpiring leaf area, whereas reduced stomatal conductance should tend to decrease transpiration per unit leaf area – two effects with opposing consequences for streamflow. The CO_2 effect is commonly expected to manifest most strongly in water-limited environments, where moisture is the main limitation on plant growth. However, not all studies show a strong link between aridity and the strength of the CO_2 effect and the magnitude of associated greening and water savings are generally not well constrained across species and ecosystems.

We combine remotely sensed normalized difference vegetation index (NDVI) data and long-term water-balance evapotranspiration (ET) measurements from 190 unregulated, unimpaired river basins across Australia. To analyse whether the effects of rising CO_2 on vegetation and hydrology are detectable at the river basin scale, we calculated CO_2 sensitivity coefficients for NDVI and ET across basins grouped into four aridity categories (wet, sub-humid, semi-arid and arid) with the expectation that the CO_2 effect might vary systematically with aridity. In basins where the CO_2 fertilization effect dominates over the stomatal closure effect, the sensitivity of ET to CO_2 is expected to be positive. Where the stomatal closure effect dominates, the sensitivity of ET to CO_2 is expected to be negative. The sensitivity coefficients could then be used to calculate absolute changes in NDVI and ET due to CO_2 increase.

We show that sub-humid and semi-arid basins are not only 'greening' in response to increased atmospheric CO_2 but also consuming more water (marked by significant positive ET and NDVI CO_2 sensitivities). The CO_2-induced ET increases during this time period amount to 43 mm in sub-humid and 14 mm in semi-arid basins, on average. These translate to 6% and 2% increases, respectively, in mean annual ET during 1982-2010, leading to significant (24–28%) reductions in streamflow (factoring out precipitation effects). In contrast, wet and arid basins show small, non-significant changes in NDVI and reductions in ET and it was thus not possible to determine a CO_2 effect on streamflow in either the wettest or the driest regions on the basis of our measurements. Our results suggest that projected future decreases in precipitation will likely be compounded by increased vegetation water use in sub-humid and semi-arid climates, thus adding to the pressure on water resources in water-stressed regions.

Keywords: *CO_2 effect, evapotranspiration, streamflow, Normalised Difference Vegetation Index*

Australian Water Resources Assessment (AWRA)

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Abstract: Accurate water information (water accounts, water resources assessments, and information on water availability, spatial and temporal water distribution, storage and use) is essential for good and informed water management and water planning. The water information must be accurate, up-to-date and account for local and regional climatic and hydrological conditions. The water information must also be robust, transparent and produced in a repeatable manner. The Australian Water Resources Assessment (AWRA) system has been developed by CSIRO and the Australian Bureau of Meteorology and is used by Bureau (together with other water data) to deliver water accounts and assessments of water resources across continental Australia.

The current AWRA (v4.5) modelling system provides water balance estimates at the national to regional and catchment scale. AWRA consists of sub-components that represent processes between the atmosphere and the landscape (AWRA-L), in gauged rivers (AWRA-R) and in groundwater (AWRA-G). This constitutes a unique example of implementing a coupled landscape, groundwater and regulated river system model at a regional and continental scale and rolled out in high priority regions (National Water Account regions) across Australia. The system uses on-ground observations and remotely sensed data sets, combined with hydrological science and computing technology, to estimate key water fluxes and stores. This includes all major water storages, and the movement of water in and between these, at a 5-km spatial resolution and daily time step. It is flexible enough to use all available data sources, whether modelling data-rich or data-sparse regions, to provide nationally consistent and robust estimates of water balance terms. Outputs from operational versions of the model, such as estimates for soil water storage, streamflow, groundwater recharge and vegetation water use, inform the Bureau of Meteorology's water information products.

The AWRA modelling system will be continually improved and enhanced. Current efforts are focusing on parameterising AWRA-L for regions and across Australia, data-driven system calibration of AWRA-R (together with L and G) in all the key river basins, and establishing an operational AWRA system in the Bureau of Meteorology. Future efforts will build on the above as well as improving the modelling of surface-groundwater interaction and using data assimilation and reanalyses methods to improve modelling of the water fluxes and stores. Over the next decade, improvements in AWRA will come from more and different types of data (from remote sensing and affordable technologies to measure water fluxes), innovations in hydrological science integrating knowledge, models and data, and developments in computing technology. The vision is for the AWRA of tomorrow to take advantage of these developments and be the source of scientifically robust, consistent and agreed information on water accounts, assessments, forecast and prediction.

Keywords: *Water assessments, water accounts, AWRA, regional calibration, landscape modelling, river system modeling*

Challenges in attributing change in Australian natural hazards

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Abstract: Natural hazards such as floods, droughts, wildfires and heatwaves lead to societal impacts such as loss of life, damage to infrastructure, reduced agricultural productivity and ecological degradation. These hazards result from a combination of interacting physical processes that express across a wide range of spatial and temporal scales, and are indicated by climate and weather variables such as rainfall, temperature, pressure and wind. The diverse set of interacting physical processes that can cause changes in the occurrence and/or magnitude of a natural hazard can make the attribution of change to one or several causes extremely challenging. Using recent research on Australian floods as a case study, this presentation describes some of these challenges. Apparent contradictions between alternative datasets and studies are identified, and possible explanations are suggested. Ultimately, we argue that our understanding and modelling capability for how weather and climate processes lead to natural hazards is limited by both data availability and process understanding, and a focused community effort is required to better understand how the magnitude and/or occurrence of natural hazards has changed in the past, and what this augurs for the future.

Validation of SMAP soil moisture products in Australia

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Abstract: Since soil moisture plays a key role in the exchange of water, energy, and carbon at the ground - atmosphere interface, its temporal and spatial distribution is for disciplines, such as hydrology, meteorology, and agriculture. The passive microwave remote sensing technique at L-band (1 – 2 GHz) has been widely acknowledged as the most promising to measure soil moisture at regional and global scales. Consequently, the first space mission dedicated to soil moisture, the Soil Moisture and Ocean Salinity (SMOS) developed under the leadership of the European Space Agency (ESA), carries an L-band (1.4 GHz) radiometer that provides global soil moisture content in the top ~5 cm of soil every 2 - 3 days. However, based on the current level of antenna technology, the spatial resolution of SMOS is limited to approximately 40 km, which is too coarse for hydrological applications. The next Soil Moisture Active and Passive (SMAP) mission, scheduled to be launched by the National Aeronautics and Space Administration (NASA) in January 2015, will employ a combination of L-band (1.4 GHz) radiometer and L-band (1.2 GHz) radar, with the aiming to provide soil moisture data at 9 km spatial resolution. The 36 km resolution radiometer brightness temperature observations from SMAP will be downscaled using 3 km resolution radar backscatter data, with the well-established tau-omega model then used to derive the 9 km resolution soil moisture product. To fully test this new approach, airborne field experiments need to be conducted after the launch of SMAP under diverse land surface conditions, to validate the accuracy of the downscaled brightness temperature data.

Two three-week long intensive airborne field experiments are scheduled for the period immediately following the commissioning of SMAP, being in the Australian autumn (Apr/May 2015) and spring (Sep/Oct 2015) respectively. A total of over 50 hour flight is designed for each experiment across a study area of 71 km by 85 km in the Yanco area of the Murrumbidgee River Catchment. The airborne brightness temperature measurements at 1 km resolution and backscatter measurements at 10 m resolution will be collected coincident with the coverage by SMAP. Meanwhile, ground soil moisture, surface roughness and vegetation sampling will be undertaken in six 3 km by 3 km focus farms within the study area. The brightness temperature measurements will be i) corrected to the 6am SMAP overpass time and normalised to the 40° incidence angle of SMAP; and ii) aggregated to 9 km spatial resolution and compared with SMAP downscaled brightness temperatures. The brightness temperature measurements will also be converted to soil moisture and validated with ground soil moisture measurements before comparing with SMAP soil moisture products.

Keywords: *soil moisture, microwave remote sensing, SMAP*

Coupling gross primary production and transpiration for a consistent estimate of apparent water use efficiency

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Abstract: Water use efficiency (WUE, the amount of transpiration or evapotranspiration per unit gross (GPP) or net CO_2 uptake) is key in all areas of plant production and forest management applications. Therefore, mutually consistent estimates of GPP and transpiration are needed to analysed WUE without introducing any artefacts that might arise by combining independently derived GPP and ET estimates. GPP and transpiration are physiologically linked at ecosystem level by the canopy conductance (G_c). Estimates of G_c can be obtained by scaling stomatal conductance (Kelliher et al. 1995) or inferred from ecosystem level measurements of gas exchange (Baldocchi et al., 2008). To derive large-scale or indeed global estimates of G_c, satellite remote sensing based methods are needed.

In a previous study, we used water vapour flux estimates derived from eddy covariance flux tower measurements at 16 Fluxnet sites world-wide to develop a method to estimate G_c using MODIS reflectance observations (Yebra et al. 2013). We combined those estimates with the Penman-Monteith combination equation to derive transpiration (T). The resulting T estimates compared favourably with flux tower estimates (R^2=0.82, RMSE=29.8 W m^{-2}). Moreover, the method allowed a single parameterisation for all land cover types, which avoids artefacts resulting from land cover classification. In subsequent research (Yebra et al, in preparation) we used the same satellite-derived G_c values within a process-based but simple canopy GPP model to constrain GPP predictions. The developed model uses a 'big-leaf' description of the plant canopy to estimate the mean GPP flux as the lesser of a conductance-limited and radiation-limited GPP rate. The conductance-limited rate was derived assuming that transport of CO_2 from the bulk air to the intercellular leaf space is limited by molecular diffusion through the stomata. The radiation-limited rate was estimated assuming that it is proportional to the absorbed photosynthetically active radiation (PAR), calculated as the product of the fraction of absorbed PAR (fPAR) and PAR flux. The proposed algorithm performs well when evaluated against flux tower GPP (R^2=0.79, RMSE= 1.93 µmol m^2 s^{-1}).

Here we use GPP and T estimates previously derived at the same 16 Fluxnet sites to analyse WUE. Specifically we are interested to check if satellite-derived WUE explains any of the variation in (long-term average) WUE among sites. The benefit of our approach is that it uses mutually consistent estimates of GPP and T to derive plant-level WUE (i.e. GPP/T) without any land cover classification artefacts. To estimate ecosystem level WUE (i.e., GPP/ET), evaporation from the soil and wet canopy would also need to estimated, e.g. by integrating G_c estimates within a water balance model. To estimate net WUE (NEE/ET), respiration would need to be estimated, requiring estimation of ecosystem respiration fluxes. These are the focus of future work.

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Keywords: *Gross primary production, evapotranspiration, water use efficiency, MODIS, remote sensing*