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# MITIGATING THE EFFECTS OF SEVERE FIRES, FLOODS AND HEATWAVES THROUGH THE IMPROVEMENTS OF LAND DRYNESS MEASURES AND FORECASTS

## Annual project report 2015-2016


**Imtiaz Dharssi and Vinod Kumar**
Bureau of Meteorology
Bushfire and Natural Hazards CRC


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Cover: Assessing the landscape.

Photo: Bushfire and Natural Hazards CRC

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# EXECUTIVE SUMMARY

The Australian people, businesses and environment are all vulnerable to wildfires, floods and other natural hazards. Deloitte Access Economics (2016) estimate the 2015 total economic cost of natural disasters in Australia exceeded $9 billion. Some examples of recent extreme events are the 2015 West Australia Esperance bushfire, the 2015 South Australia Pinery bushfire, the 2009 Victoria Black Saturday bushfires, the Millennium drought spanning from 1998 to 2009 and the summer 2010/2011 floods in Eastern Australia. A recent United Kingdom Meteorological Office report concludes that investment in weather services provides around a tenfold return (Gray 2015).

Accurate soil moisture information is critical for the management and warning of fires, floods and landslips and this project addresses fundamental limitations in our ability to prepare for these events. Fire ignition, intensity and spread rate are strongly influenced by soil moisture content. Knowledge of soil moisture is essential for the accurate prediction of wildfire incidence and the occurrence of large destructive fires corresponds to very large soil moisture deficit values. Soil moisture also strongly influences temperatures and heatwave development by controlling the partitioning of net surface radiation into sensible, latent and ground heat fluxes. Rainfall forecasts are crucial for many applications and many studies suggest that soil moisture can significantly influence rainfall.

Currently soil moisture, for fire danger prediction, is estimated using very crude models developed in the 1960s that oversimplify the calculation of evapotranspiration and runoff leading to significant errors. These crude models do not take into account different vegetation properties, soil types, terrain and many other factors. They are poor drivers of the models used by fire agencies, and the Bureau of Meteorology to predict dangerous fire conditions as the science is outdated and has been verified as not effective (Dharssi and Vinodkumar 2015).

Soil moisture can have very high spatial variability due to the very high spatial variability of vegetation properties, soil textures, orography and rainfall. Therefore, it is highly desirable to analyse soil moisture at the highest possible spatial resolution. Many applications, such as fire danger warnings, agriculture and weather forecasting, require soil moisture information at a spatial resolution of 5 km or better. A state of the art, high resolution soil moisture information system is under development with daily updating and a spatial resolution of 5 km. The system provides information on 4 soil layers. The top layer is 10 cm thick and the total thickness of the soil column is 3 m. Verification against ground based soil moisture observations and a case study show that this prototype system is significantly more skillful than the over-simplified models currently used operationally. This new system will significantly improve Australia's ability to manage multiple hazard types and create a more resilient community.

# END USER STATEMENT

## Andrew Sturgess, Manager Predictive Services Unit, Queensland Fire and Emergency Services

Australian fire agencies have used the current fire danger rating system and the associated soil dryness indices for around 50 years. This has resulted in a level of comfort and familiarity with the values and what they mean for fire management. Predictive services is a rapidly growing field within fire and emergency management. Some of the challenges include overcoming the resistance to change that 50 years' experience working with KBDI and SDI has provided, and keeping up to date with the volume and rate of technological change. As I understand it this project is to be trialled in the near future. This will provide an opportunity for fire agencies to become familiar with this work. It will be an important element in the future development of the research moving to operations, should it prove useful during this trial period. Soil moisture is not measured consistently across the country and this gap provides another opportunity for the project. Improving our understanding of soil moisture, and especially how it drives extreme weather events, is an integral part in building resilient communities for contemporary fire and emergency services.

## Paul Fox-Hughes, Severe Weather Section, Hobart, Bureau of Meteorology

This project has made some very substantial progress in the last year. Comparisons of the JULES numerical model soil moisture system with observations and with the traditional measures used in Australia have highlighted the improvements that can be made using modern techniques. A recently completed case study of the State Mine Fire in NSW in 2013 further demonstrates the potential for improvement. The project is sufficiently advanced that consideration is being given to presenting its outputs as prototype, pre-operational products for user consideration, a really useful step towards operational implementation of the new system as a cornerstone of the Australian fire danger and fire weather warning system. In addition, the project team are investigating how the JULES output might be incorporated into a trial of the new National Fire Danger Rating System. I look forward to the Land Dryness Improvement project delivering a very significant advance in the way soil moisture is represented in Australian weather and emergency management models, with a concomitant increase in our capacity to warn the community.

## Mark Chladil, Fire Management Planning Officer, Tasmania Fire Service

The results so far are both encouraging and tantalising. Fire Danger forecasting and operational fire behaviour prediction are limited by the relatively crude soil moisture modelling we commonly use. The availability of the advanced fine scale multi-layer soil moisture information arising from this project will be a boon to Fire Behaviour Analysts everywhere in Australia even though the richer data will be a challenge for us to understand, exploit and communicate.

## Adam Leavesley, ACT Parks and Conservation Service Fire Unit

This project is making excellent progress towards improving the operational capacity to predict bushfire risk at greatly reduced spatial resolution and with greater accuracy than present systems. The improvement in spatial resolution of soil dryness from 25 km to 5 km should allow agencies to more accurately determine risk and make better decisions about the distribution of resources. The possibility of a further reduction to 1km is even more exciting because it opens up the possibility that the information could be incorporated into tactical decision-making such as determining where and when the landscape is in condition for agencies to achieve planned burning objectives. A very attractive feature of the work is that the scope is continental and I expect will feed into a wide array of emergency management uses.

# INTRODUCTION

Accurate soil moisture information is essential for the accurate forecasting of natural hazard events such as fires, floods, droughts and heatwaves. The strong coupling between soil moisture and rainfall means that extreme surface conditions can persist for long periods. Therefore, soil moisture is important both for short term prediction from a few hours to a few days and longer range weekly and monthly forecasting. Studies such as Dutta et al. (2013)and Gellie et al. (2010) show that fire ignition, intensity and spread rate are very sensitive to soil moisture conditions. Both surface and root zone soil moisture are important.

Operational fire danger indices currently use soil moisture estimates calculated using very simplistic models developed in the 1960s. In Australia, the Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968) developed by the US Forest Service, and the related Soil Dryness Index (MSDI; Mount, 1972) developed by Forestry Tasmania are used to estimate soil moisture deficit. Dharssi and Vinodkumar 2015 have shown, by verification against ground based soil moisture observations, that both KBDI and MSDI have limited skill and contain large errors. In particular, KBDI has a significant wet bias due to an over-simplified parameterisation of evaporation that is too strongly linked to annual rainfall.

The best way to improve the analysis of soil moisture for operational fire warnings is through the development of a high resolution system that uses a physically based land surface model, observation based rainfall and temperature analyses and the ability to use satellite derived observations of soil moisture and land surface temperature. A prototype, high resolution soil moisture information system has been developed with a spatial resolution of 5 km and daily updating. The high resolution is required since soil moisture can have a very high spatial variability. Famiglietti et al. (1999, 2008) show using ground based observations that soil moisture can change significantly even over short distances of a few 10s of meters.

The new soil moisture analysis system provides information on 4 soil layers, with a 10 cm thick surface layer and a soil column of 3 m thickness to represent the root-zone. Therefore, the system can predict surface soil moisture which is more closely related to dead fuel moisture content and root-zone soil moisture that provides information on live fuel moisture content. KBDI and MSDI are much less useful since the assumed depth of soil is ambiguous.

A case study and verification against ground based soil moisture observations shows that this prototype system is significantly better than the over-simplified KBDI and MSDI models currently used operationally. This new soil moisture analysis system will significantly improve Australia’s ability to predict and manage multiple types of natural hazards and create a more resilient community. It is imperative to the Australian community that the best available science and technology is used effectively and incorporated into warnings systems.

# PROJECT BACKGROUND

## Importance of this Research

The outputs of this project will significantly improve Australia's ability to plan for and predict many natural hazard events and in particular bush fires. This project addresses fundamental limitations in the current operational soil moisture accounting systems. This project is developing a state of the art soil moisture analysis system that makes use of many different sources of observations. This research uses physically based land surface models, remotely sensed satellite measurements and ground based observations for the monitoring and prediction of soil moisture. Verification against ground based soil moisture observations shows that this new system is significantly more accurate. The new information will be calibrated with the old operational scheme so that it can be used within existing fire and flood forecasting prediction systems.

## Research Methodology

1. Production of a **historical dataset of the KBDI and MSDI at 5 km horizontal resolution** using analyses of rainfall and maximum temperature. This new gridded dataset of MSDI and KBDI can be compared with the much used, lower 25 km resolution, Finkele-Mills dataset (Finkele et al. 2006) and will be a valuable resource for researchers working on fire climatologies, ecological and flooding studies across Australia.
2. The **development of a high resolution soil moisture system** based around the JULES land surface model (Best et al. 2011). The JULES based Australian Soil Moisture Information (JASMIN) system can include data from many sources; such as surface observations of rainfall, temperature, dew-point temperature, wind speed, surface pressure as well as satellite derived measurements of rainfall, surface soil moisture, downward surface shortwave radiation, skin temperature, leaf area index and tree heights. The JASMIN system analyses soil moisture on four soil layers over the top 3 meters of soil, the surface layer has a thickness of 10 cm. The system takes into account the effect of different vegetation types, root depth, stomatal resistance and spatially varying soil texture. The analysis system has a one hour time-step with daily updating. JASMIN soil moisture analyses are available from 2010 to the present day.
3. **Verification of soil moisture information** from KBDI, MSDI, JASMIN, Numerical Weather Prediction (NWP) models and remotely sensed measures against ground based soil moisture observations.
4. **Calibration** of JASMIN and NWP analyses of soil moisture so that they can be incorporated into operational models for fire danger prediction. The calibration preserves the existing biases in the operational models that forecasters have become accustomed to.
5. Investigate the **relationship between soil moisture and litter fuel** moisture content.

## Potential Outcomes

The benefits of this project will be:

- ✓ More accurate, higher horizontal and vertical resolution and more detailed analyses and forecasts of soil moisture, and hence an expectation of more accurate predictions of fire danger and fire behaviour, rainfall forecasting, flood forecasting and heatwave prediction.

- ✓ Benefits extend from landscape management and fuel reduction burns to the highest intensity wildfires.

- ✓ Accurate long-term datasets of soil moisture to support a wide range of other research for natural hazard monitoring and prediction.

# HIGH RESOLUTION JULES BASED AUSTRALIAN SOIL MOISTURE INFORMATION (JASMIN) SYSTEM

Soil moisture can vary greatly over short distances such as a few 10s of meters (e.g. Famiglietti et al. 1999). Therefore, it is highly desirable to analyse soil moisture at the highest possible spatial resolution. The high resolution JULES based Australian Soil Moisture Information (JASMIN) system is run with daily updating at a spatial resolution of 5 km. JULES is configured with 4 soil layers. The top layer is 10 cm thick and the total thickness of the soil column is 3 m. JULES requires meteorological input data to drive the land surface. JULES provides analyses of soil moisture, soil temperature, evaporation, latent and sensible heat fluxes as well as other surface variables.

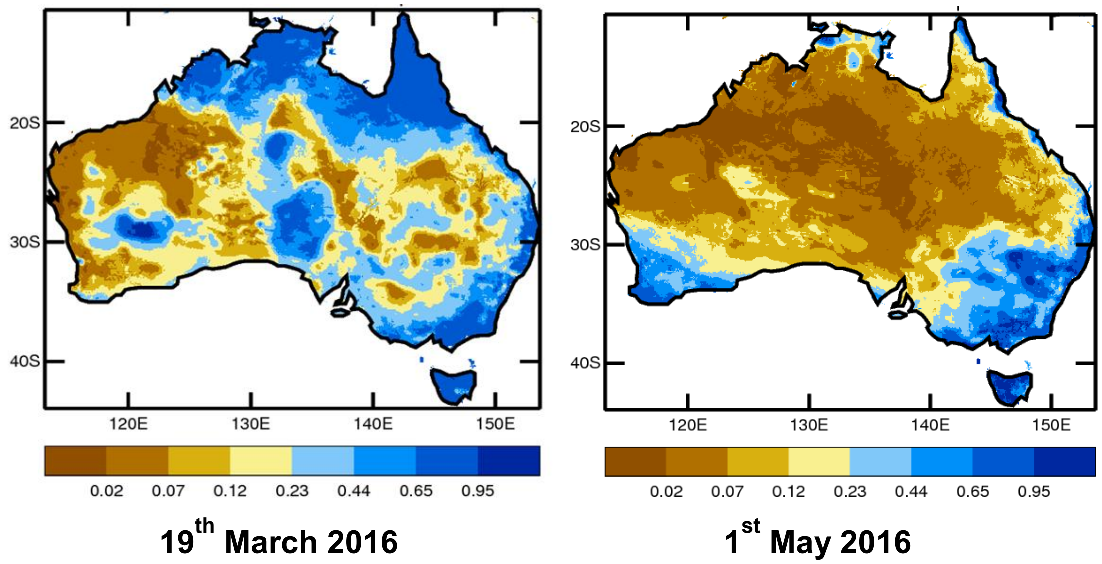


FIGURE 1: EXAMPLE ANALYSES, AT A SPATIAL RESOLUTION OF 5 KM, FROM THE JASMIN SYSTEM OF THE SURFACE SOIL MOISTURE.

## Physically based land surface model

JULES is used by the Bureau of Meteorology and other international weather centres for NWP and is also used for climate prediction. JULES can include many different land surface processes such as the hydrological cycle, surface energy balance, carbon cycle and dynamic vegetation (this project uses static landcover). JULES models the partitioning of rainfall into canopy interception, through fall, runoff and infiltration. The JULES soil hydrology is based on a finite difference approximation of the Richards' equation and Darcy's law. The van Genuchten (1980) equations are used to define the relationship between soil moisture and soil hydraulic conductivity. Transpiration by plants extracts soil water directly from the soil layers via the plant roots while bare soil evaporation extracts soil water from the top soil layer only. The ability of plants to access water from each soil layer is determined by the root density distribution and soil moisture availability. The soil moisture availability is a function of soil moisture and soil texture. A sophisticated photosynthesis model is used to calculate the bulk stomatal resistance. The photosynthesis model includes the effects of incident solar radiation, vegetation type, leaf area index (LAI), surface air temperature and humidity deficit. JULES includes 5 plant functional types (PFTs; broadleaf trees, needle-leaf trees, C3 (temperate) grass, C4 (tropical) grass and shrubs).

JULES simulates 4 non-vegetation types (urban, inland open water, bare soil and land ice). To model the sub-grid scale heterogeneity of land cover types, JULES uses surface tiles.

JULES uses ancillary input data which are static or only have a seasonal variation. JULES uses static information about land cover types, vegetation heights, soil texture, soil albedo, soil hydraulic and thermal properties. JULES uses seasonally varying information on LAI. The soil albedo and vegetation information is derived from remotely sensed satellite measurements. The ancillary data (particularly the soil hydraulic properties) can have a significant impact on the soil moisture analyses (Dharssi et al. 2009).

## Verification against soil moisture observations

Unfortunately, there are few in-situ observation of soil moisture. However, these few observations are very useful for the validation of soil moisture analysis systems and land surface models. Vaz et al. (2013) have evaluated the accuracy of eight different types of electromagnetic soil moisture sensors. They find sensor accuracies of about 0.02 $m^3/m^3$ when using soil specific calibration functions. The observations also require quality control to filter out gross errors.

**COSMOZ**

A cosmic-ray probe measures the number of fast neutrons near the soil surface and measured intensities reflect variations in soil water. CosmOz is a network of cosmic ray soil moisture probes installed at a number of locations around Australia (Hawdon et al. 2014). The effective sensing depth depends strongly on soil moisture itself, decreasing non-linearly with increasing soil moisture and ranges from about 70 cm to 10 cm. One advantage over traditional point measurement sensors is that cosmic-ray probes have a horizontal footprint of about 660 m in diameter at sea level. This study uses level 4 processed data which are seven hour moving averages that have been quality controlled. Only observations from calibrated CosmOz sites are used in this study. Figure 2 shows the location of the CosmOz observing stations.

## Conclusions and Future Work

The JASMIN system uses a physically based land surface model that is already used by the Bureau of Meteorology's NWP systems. The JASMIN system is flexible and can provide soil moisture information on four clearly defined soil layers over a soil depth of 3 meters. For fire danger prediction, both the surface and root-zone soil moisture are important. Root-zone soil moisture is strongly correlated to the live fuel moisture content that influences fire propagation while surface soil moisture is more strongly correlated with the dead fuel moisture content which is important for fire ignition (dead fuels have a much faster time scale and are usually drier). In contrast, the KBDI and MSDI outputs are ambiguous since the assumed depth of soil is not clearly defined. The JASMIN system currently has a resolution of 5 km. Downscaling methods will be used to provide soil moisture information at 1 km resolution. Future work will develop increases to the horizontal and vertical resolution of the JASMIN system.

Verification using ground based soil moisture observations shows that KBDI has a significant wet bias and that both KBDI and MSDI have limited skill (Dharssi and Vinodkumar 2015). The JASMIN system can provide fire agencies with the most accurately available high resolution analyses of soil moisture. Figures 3 and 4 show that the JASMIN system agrees much more closely with observed soil moisture than KBDI or MSDI. The JASMIN system has a much higher temporal correlation with the soil moisture observations and the lowest root mean square difference (RMSD) to the observations. Figures 5 and 6 show results from a case study of the Blue Mountains State Mine Fire that started on the 16th of October 2013. Figure 5 shows that KBDI indicated wet soils at the fire location and was ineffective for the prediction of fire danger. Figure 6 shows volumetric soil moisture analyses from the JASMIN system. The JASMIN surface layer is very dry and the level 4 soil layer also indicates dry conditions near the point of fire ignition. Therefore, for this case, the JASMIN system would have provided much more useful guidance than KBDI.

JASMIN soil moisture analyses for the period 2010 to present day are available to all researchers. Case studies of past fire events will be used for the subjective evaluation of the JASMIN soil moisture analyses. Calibration of JASMIN soil moisture analyses will be performed so that they can be incorporated into operational models for fire danger prediction. The calibration preserves the existing biases in the operational models that forecasters and post-processing systems are accustomed to. Discussions are underway with the AFAC advisory board on the use of JASMIN system outputs in the new National Fire Danger Ratings System (NFDRS).

The JASMIN system is closely related to the Bureau of Meteorology's NWP systems meaning that improvements to the science and resolution of the NWP systems can directly feed through to improvements to the JASMIN system.

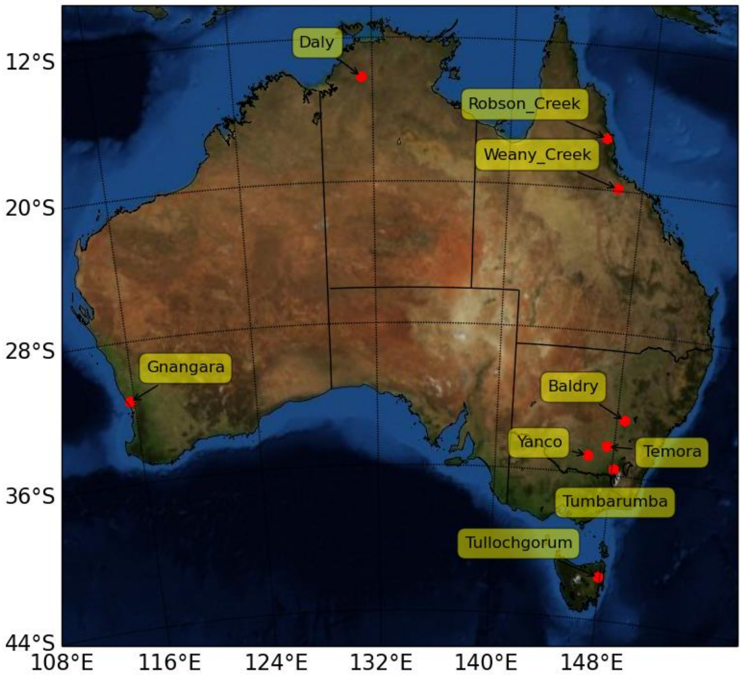


FIGURE 2: THE COSMOZ SOIL MOISTURE MONITORING NETWORK.

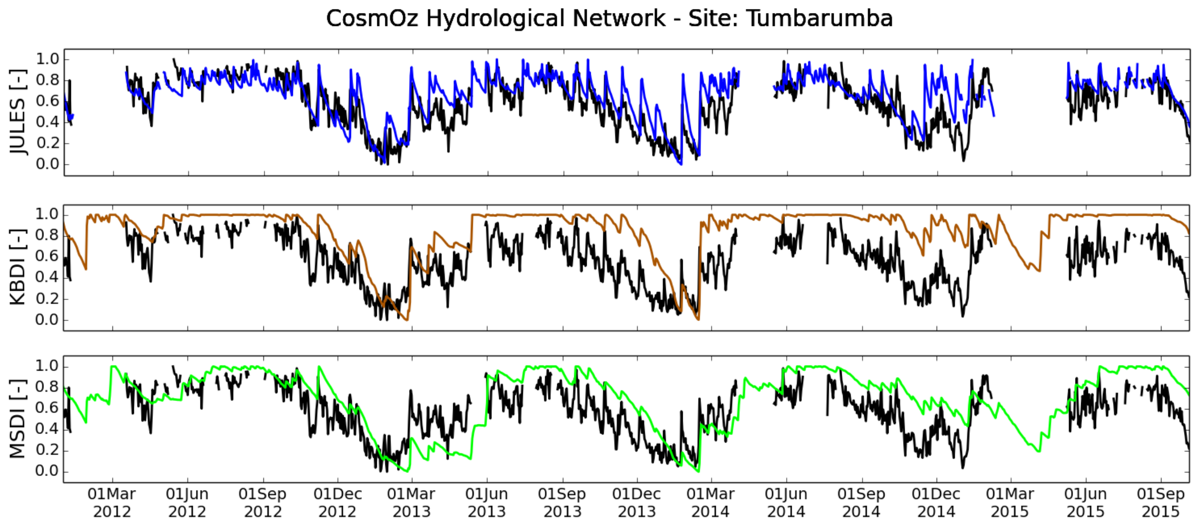


FIGURE 3: SOIL MOISTURE TIME SERIES COMPARING OBSERVATIONS FROM THE COSMOZ TUMBARUMBA SITE WITH ANALYSES FROM JASMIN (TOP PANEL), KBDI (MIDDLE PANEL) AND MSDI (BOTTOM PANEL).

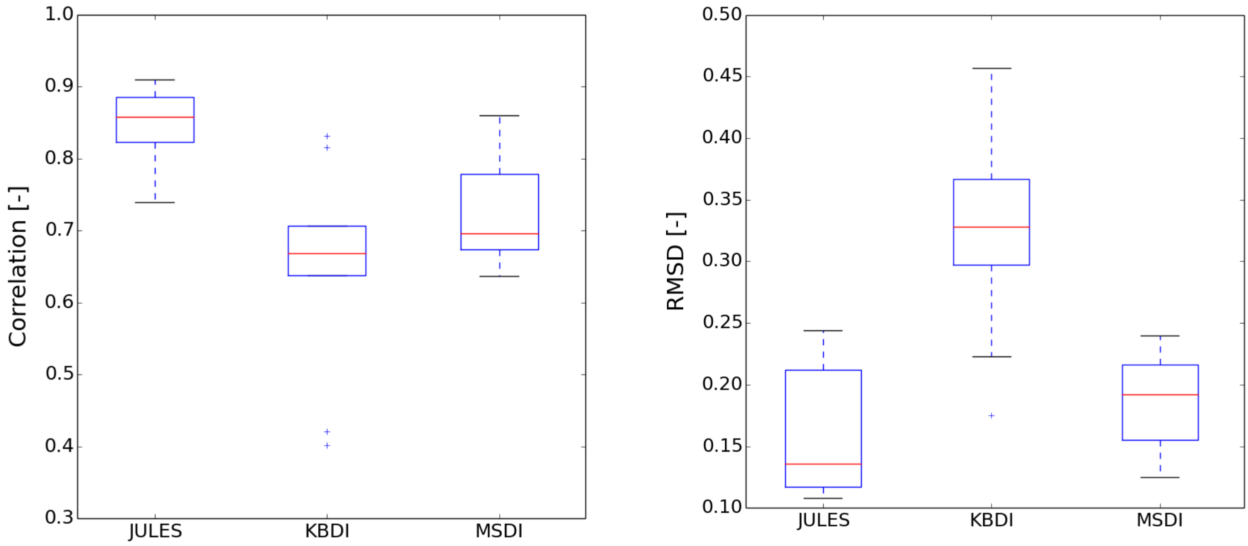


FIGURE 4: BOX PLOTS SHOWING THE TEMPORAL CORRELATION AND ROOT MEAN SQUARE DIFFERENCE (RMSD) BETWEEN COSMOZ SOIL MOISTURE OBSERVATIONS AND ANALYSES FROM JASMIN (JULES), KBDI AND MSDI. THE JASMIN SYSTEM HAS MUCH GREATER SKILL THAN KBDI AND MSDI.

## Case Study: Blue Mountains State Mine Fire

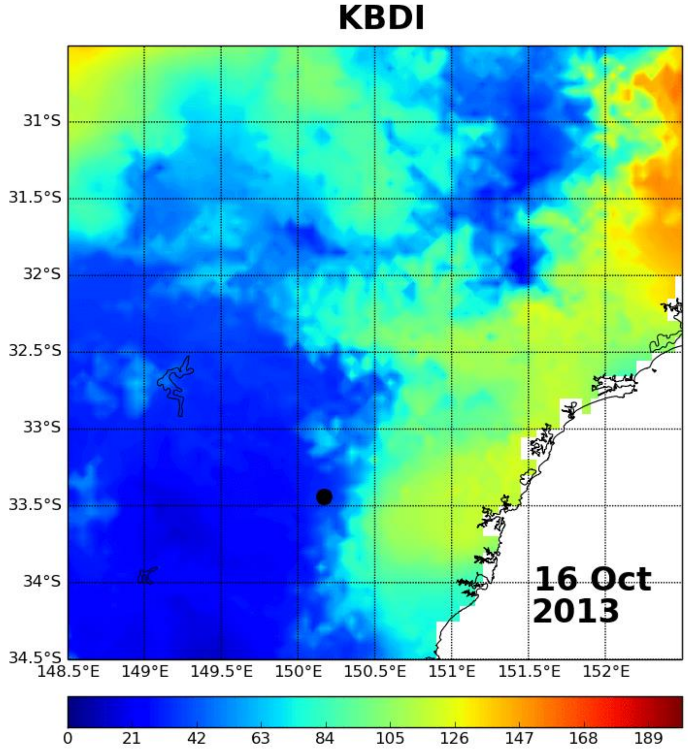


FIGURE 5: PLOT OF KBDI SOIL DRYNESS FOR THE 16TH OF OCTOBER 2013. THE BLACK DOT SHOWS THE LOCATION OF THE FIRE. LOW KBDI VALUES INDICATE WET SOILS. IN THIS CASE, KBDI IS INEFFECTIVE FOR PREDICTION OF FIRE DANGER.

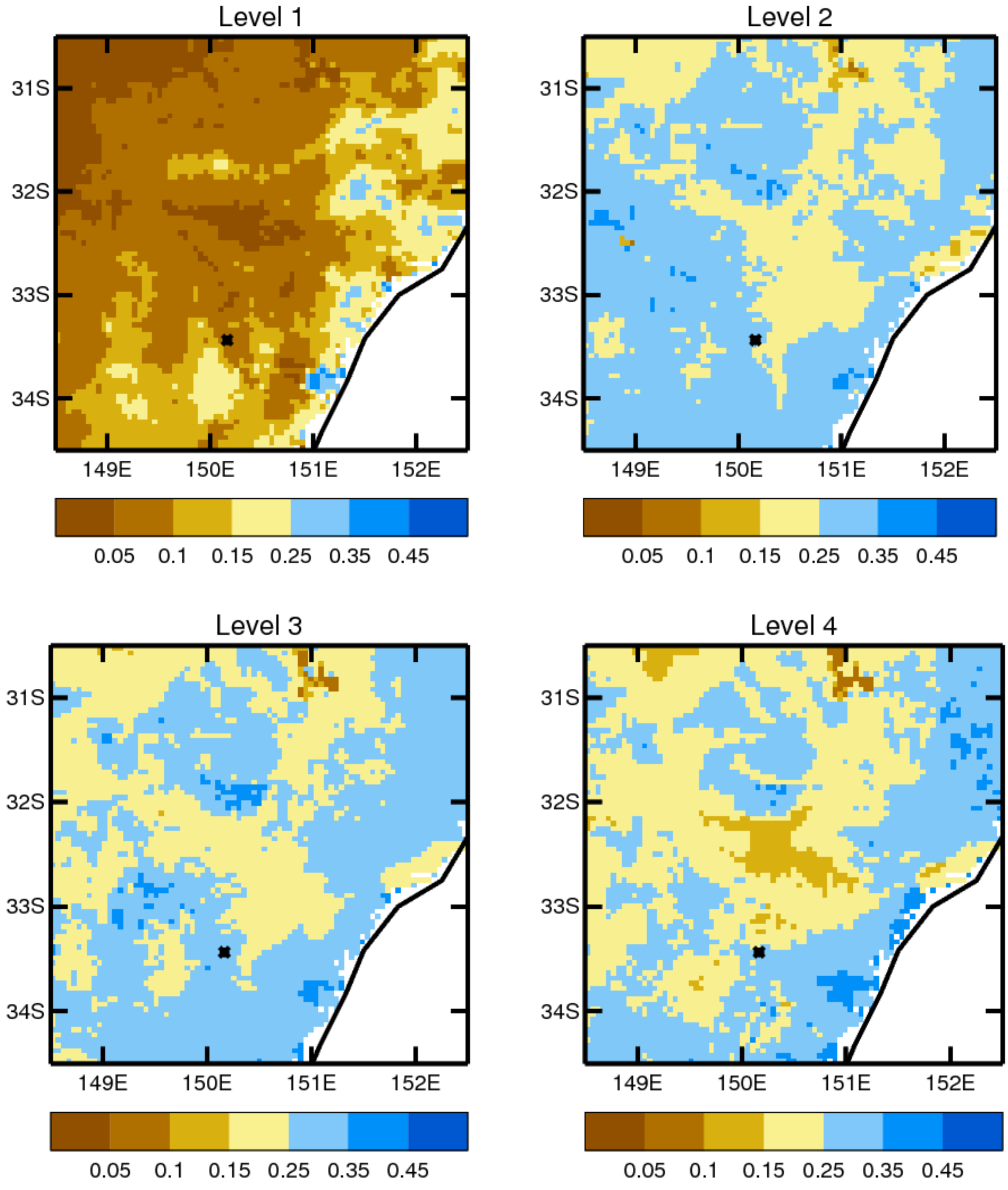


FIGURE 6: VOLUMETRIC SOIL MOISTURE ANALYSES FROM THE JASMIN SYSTEM FOR THE 16TH OCT 2013. THE SURFACE LAYER IS VERY DRY. THE LEVEL 4 SOIL LAYER (100 CM TO 300 CM) ALSO HAS VERY DRY REGIONS NEAR THE POINT OF IGNITION (33.436S, 150.166E), MARKED BY A THE BLACK CROSS.

# EVALUATION OF DAILY SOIL MOISTURE DEFICIT USED IN THE OPERATIONAL AUSTRALIAN FOREST FIRE DANGER RATING SYSTEM

The fuel availability estimates in the McArthur Forest Fire Danger Index used in Australia for issuing operational fire warnings is based on soil moisture deficit, calculated as either the Keetch–Byram Drought Index (KBDI, see figure 7) or Mount's Soil Dryness Index (MSDI, see figure 8). These indices are designed to estimate soil moisture depletion in the soil layer. Daily values of the two simple indices are calculated over Australia at 0.05° resolution from 1974 onwards. A detailed verification of these two indices against ground based soil moisture measurements from the CosmOz, OzNet and OzFlux networks is performed. The verification results show that both KBDI and MSDI have relatively low skill in estimating shallow layer (~ 0–30 cm) soil moisture. The modest sensitivity of both KBDI and MSDI to weather changes indicate that they are not an accurate measure for estimating moisture in the duff layer (see figures 9 and 10).

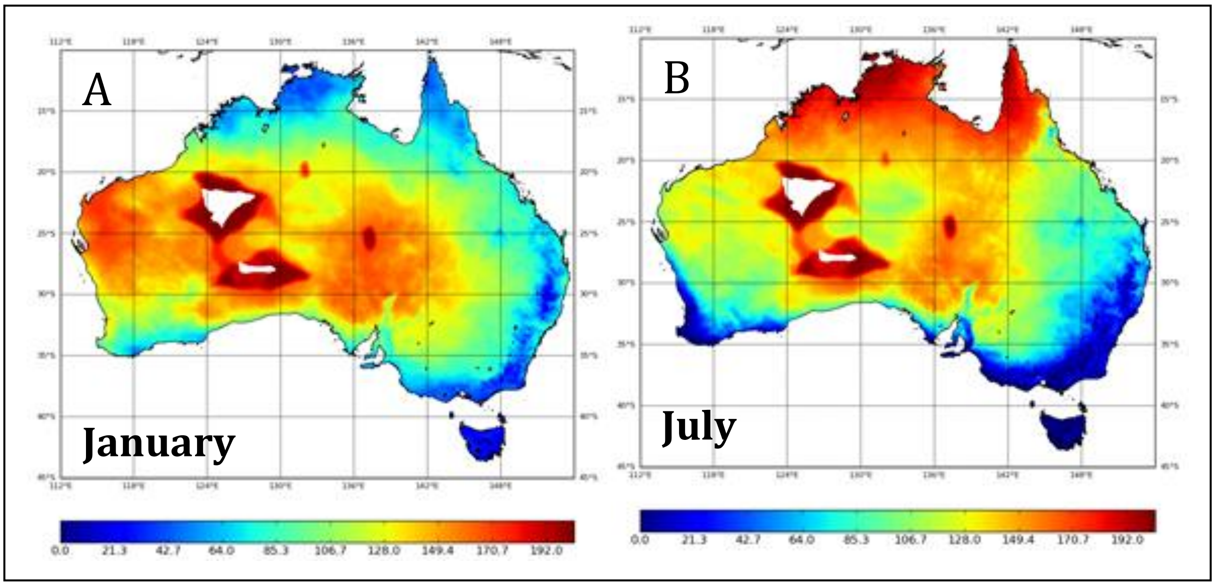


FIGURE 7: MEAN MONTHLY KBDI VALUES FOR (A) JANUARY, AND (B) JULY. THE MEAN IS CALCULATED USING A 40 YEAR DATA FROM 1974 – 2014.

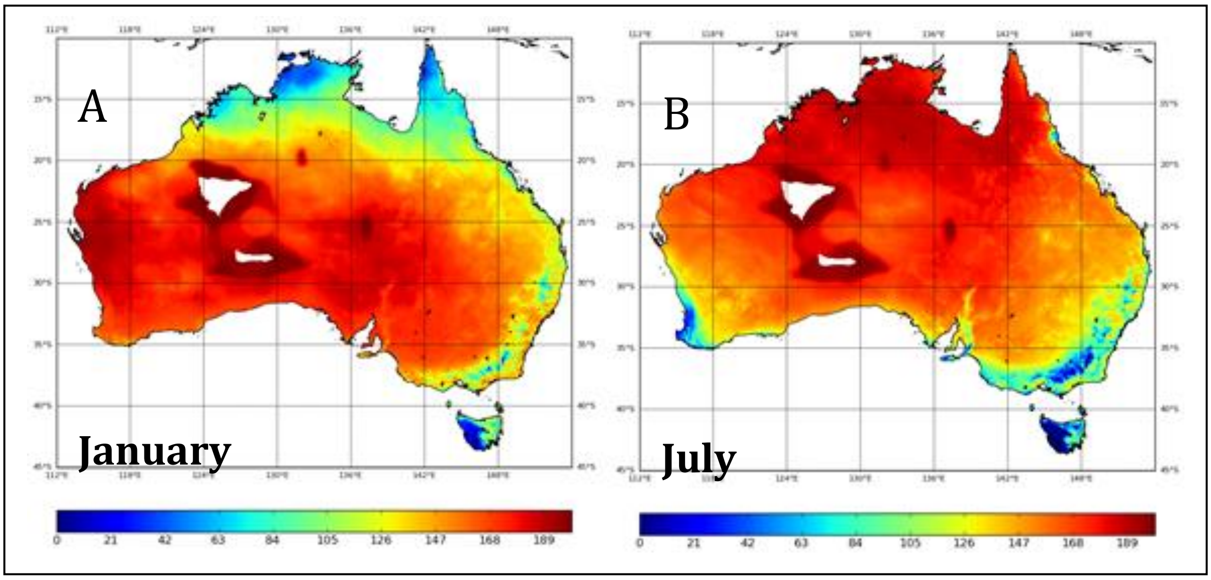


FIGURE 8: AS FIGURE 7, BUT FOR MSDI.

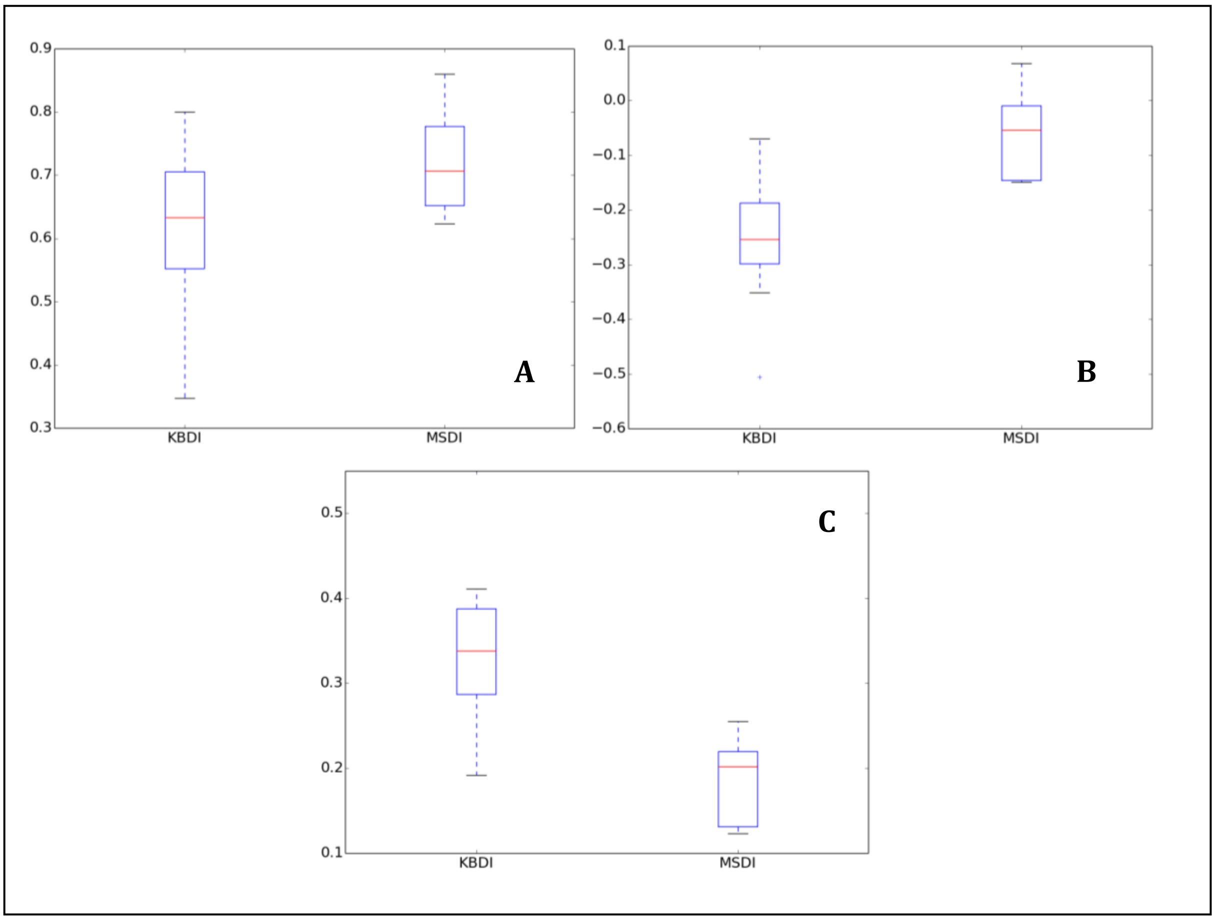


FIGURE 9: BOX AND WHISKER PLOTS DEPICTING (A) CORRELATION, (B) BIAS, AND (C) RMSD OF KBDI AND MSDI AGAINST COSMOZ SURFACE OBSERVATIONS.

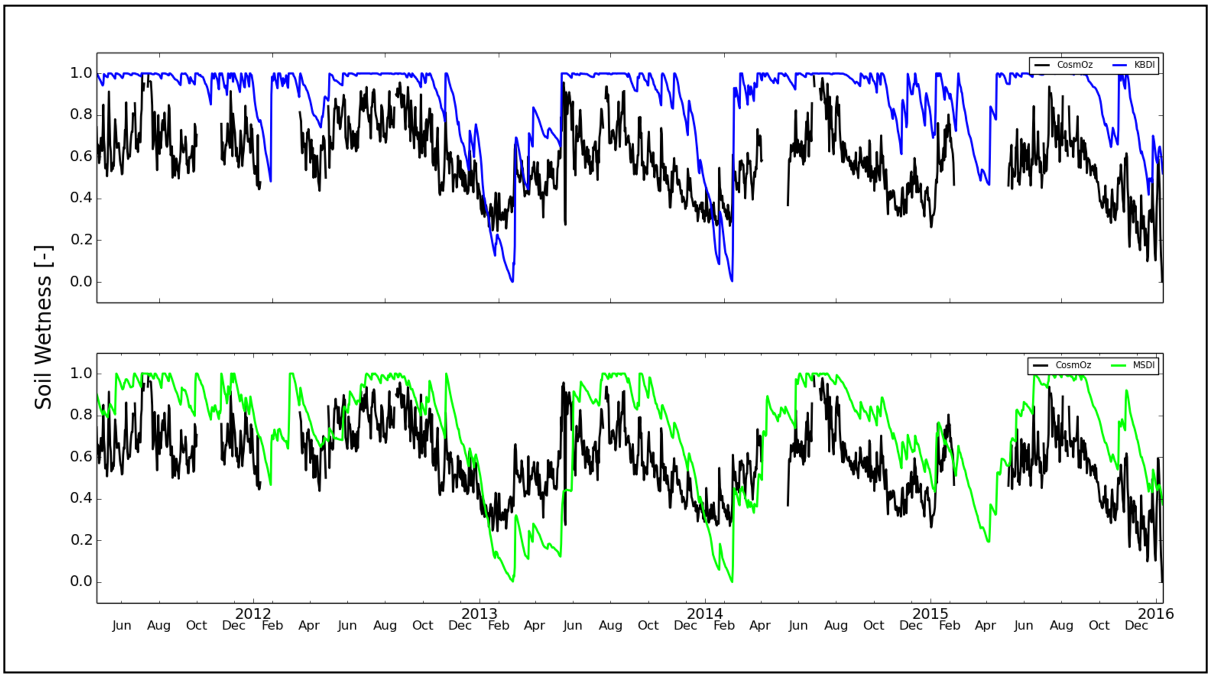


FIGURE 10: TIME SERIES OF SOIL WETNESS AT TUMBARUMBA FROM KBDI (BLUE LINE, TOP PANEL) AND MSDI (GREEN LINE, BOTTOM PANEL). COSMOZ IN-SITU OBSERVATIONS ARE IN BLACK.

# DOWNSCALING OF SOIL MOISTURE: A SHORT REVIEW

This high spatial variability of soil moisture is driven by parameters such as vegetation, soil type, topography, and meteorology. Microwave soil moisture sensors on board various satellites are either passive (use naturally emitted radiation), or active (emit and receive own signal). Current passive sensors have a coarse resolution of about 40km. An inverse relationship exists between wavelength and antenna size imposing a technological constraint to increasing the spatial resolution. Consequently, passive microwave remote sensing techniques cannot meet the spatial resolution requirement of many applications. Active sensors can provide a much higher spatial resolution of up-to 500 m. However, active data are more strongly affected by local roughness and topography making the accurate retrieval of soil moisture more difficult. Land surface temperature (LST) has a strong relationship to soil moisture and can be remotely sensed at a resolution of about 1km. Future work will investigate the use of LST and active microwave derived soil moisture to downscale the 5 km soil moisture analyses from the JASMIN system to a spatial resolution of about 1 km.

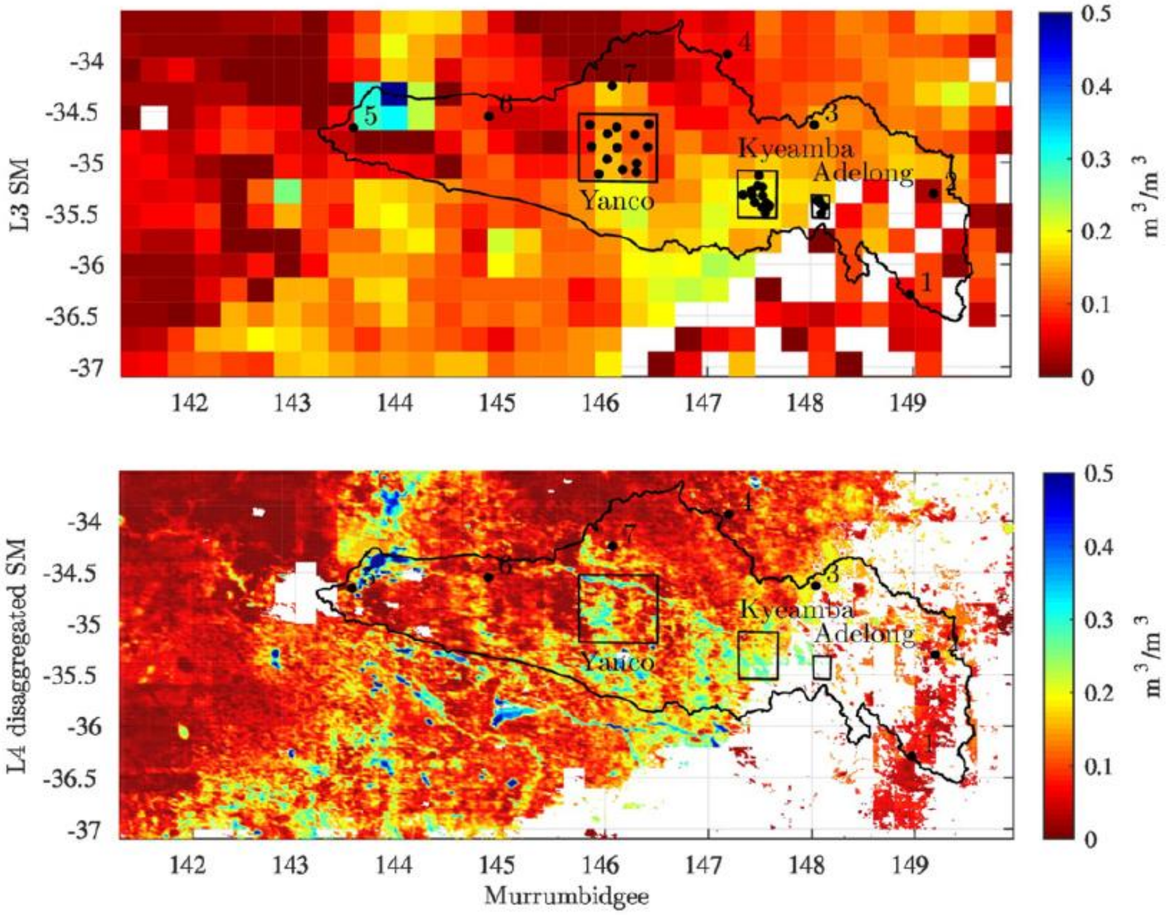


FIGURE 11: SOIL MOISTURE DOWNSCALING EXAMPLE. UPPER PANEL SHOWS REMOTELY SENSED COARSE RESOLUTION SOIL MOISTURE FROM THE SOIL MOISTURE OCEAN SALINITY (SMOS) MISSION. THE LOWER PANEL SHOWS SMOS SOIL MOISTURE DOWNSCALED USING REMOTELY SENSED LST. FROM:

B. Molero, et al, SMOS disaggregated soil moisture product at 1 km resolution: Processor overview and first validation results, Remote Sensing of Environment, Volume 180, July 2016, Pages 361-376, ISSN 0034-4257, http://dx.doi.org/10.1016/j.rse.2016.02.045.

# PUBLICATIONS LIST

Dharssi, I. and Vinodkumar 2015: Inter-Comparison of Land Surface Model Soil Moisture Data with Traditional Soil Dryness Indices. 21st International Congress on Modelling and Simulation, Gold Coast, Australia. http://www.mssanz.org.au/modsim2015/A4/dharssi.pdf

Dharssi, I. and Vinodkumar 2016: A prototype high resolution soil moisture analysis system for Australia. Technical Report.

Vinodkumar and I. Dharssi 2016: Evaluation of daily soil moisture deficit used in Australian forest fire danger rating system. Technical Report.

Vinodkumar and I. Dharssi 2016: Downscaling of soil dryness estimates: A short review. Technical Report.

Kumar, V. and I. Dharssi, 2015: Sources of soil dryness measures and forecasts for fire danger rating. Bureau Research Report No. 009.

Vinod Kumar 2016: Can NWP soil moisture improve the fire warnings? Australian Meteorological and Oceanographic Society National Conference, Melbourne, 2016.

Vinodkumar and I. Dharssi, 2015. More accurate fire danger warnings through the use of NWP systems. In Coupled Modelling and Prediction: from weather to climate - abstracts of the ninth CAWCR Workshop 19 October - 22 October 2015, Melbourne, Australia. CAWCR Technical Report No. 080. http://www.cawcr.gov.au/static/technical-reports/CTR_080.pdf

# CURRENT TEAM MEMBERS

| | |
|---|---|
| Imtiaz Dharssi<br>Scientist<br>Bureau of Meteorology | David Taylor<br>End User<br>Parks Tasmania |
| Vinod Kumar<br>Scientist<br>Bureau of Meteorology | Claire Yeo<br>Scientist<br>Bureau of Meteorology |
| Alex Holmes<br>PhD Student<br>Monash University | Jeff Walker<br>Scientist<br>University of Monash |
| John Bally<br>Lead End User<br>Bureau of Meteorology | Jeff Kepert<br>Scientist<br>Centre for Australian Weather and Climate Research |
| Andrew Sturgess<br>End User<br>Queensland Fire and Emergency Services | Peter Steinle<br>Scientist<br>Centre for Australian Weather and Climate Research |
| Adam Leavesley<br>End User<br>ACT Parks | Adam Smith<br>Scientist<br>Bureau of Meteorology |
| Paul Fox-Hughes<br>End User<br>Bureau of Meteorology | Ian Grant<br>Scientist<br>Bureau of Meteorology |
| Mark Chladil<br>End User<br>Tasmania Fire Service | Jackson Parker<br>End User<br>Department of Fire and Emergency Services, Western Australia |
| Rob Sandford<br>End User<br>Country Fire Service, South Australia | |

# REFERENCES

Best, M.J., Pryor, M., Clark, D.B., Rooney, G.G., Essery, R.L.H., M´enard, C.B., Edwards, J.M., Hendry, M.A., Porson, A., Gedney, N., Mercado, L.M., Sitch, S., Blyth, E., Boucher, O., Cox, P.M., Grimmond, C.S.B. and Harding, R.J. 2011: The Joint UK Land Environment Simulator (JULES), model description - Part 1: Energy and water fluxes. Geoscientific Model Development, 4(3) 677–699. doi:10.5194/gmd-4-677-2011. http://www.geosci-model-dev.net/4/677/2011/

Deloitte Access Economics 2016: The economic cost of the social impact of natural disasters. Australian Business Roundtable for Disaster Resilience and Safer Communities. http://australianbusinessroundtable.com.au/our-papers/social-costs-report

Dharssi, I. and Vinodkumar 2015: Inter-Comparison of Land Surface Model Soil Moisture Data with Traditional Soil Dryness Indices. 21st International Congress on Modelling and Simulation, Gold Coast, Australia. http://www.mssanz.org.au/modsim2015/A4/dharssi.pdf

Dharssi, I., Vidale, P., Verhoef, A., Macpherson, B., Jones, C. and Best, M. 2009: New soil physical properties implemented in the Unified Model at PS18. Meteorology Research and Development Technical Report 528, Met. Office, Exeter, UK. http://tinyurl.com/UKMOreport528-pdf

Dutta, R., J. Aryal, A. Das, and J. B. Kirkpatrick, 2013: Deep cognitive imaging systems enable estimation of continental-scale fire incidence from climate data. Scientific reports, 3.

Famiglietti, J., Devereaux, J., Laymon, C., Tsegaye, T., Houser, P., Jackson, T., Graham, S., Rodell, M. and Van Oevelen, P. 1999: Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997(SGP 97) Hydrology Experiment. Water Resources Research, **35**(6) 1839–1851.

Famiglietti, J., Ryu, D., Berg, A., Rodell, M. and Jackson, T. 2008: Field observations of soil moisture variability across scales. Water Resources Research, **44**(1) W01423.

Finkele, K., G. A. Mills, G. Beard, and D. A. Jones, 2006a: National gridded drought factors and comparison of two soil moisture deficit formulations used in prediction of Forest Fire Danger Index in Australia. Australian Meteorological Magazine, 55, 183–197.

— 2006b: National gridded drought factors and comparison of two soil moisture deficit formulations used in prediction of Forest Fire Danger Index in Australia. BMRC research report 119, Bureau of Meteorology, Melbourne, Australia.

Gellie, N., K. Gibos, and K. Johnson, 2010: Relationship between Severe Landscape Dryness and Large Destructive Fires in Victoria. VI International Conference on Forest Fire Research, Coimbra, Portugal. http://www.academia.edu/6303942/Relationship_between_Severe_Landscape_Dryness_and_Large_Destructive_Fires_in_Victoria

Gray, M. 2015: Public Weather Service Value for Money Review. Public Weather Service Customer Group Secretariat, UK Meteorological Office, Exeter, UK. http://www.metoffice.gov.uk/media/pdf/c/a/PWS_Value_for_Money_Review_-_March_20151.pdf

Hawdon, A., D. McJannet, and J. Wallace, 2014: Calibration and correction procedures for cosmic-ray neutron soil moisture probes located across Australia. Water Resources Research, 50, 5029–5043.

Keetch, J. J. and G. M. Byram, 1968: A drought index for forest fire control. Research Paper SE-38, USDA Forest Service: Asheville, NC, USA.

McArthur, A. G., 1967: Fire behaviour in eucalypt forests. Leaflet 107, Department of National Development Forestry and Timber Bureau: Canberra, Australia.

Mount, A., 1972: The derivation and testing of a soil dryness index using run-off data. Technical report, Tasmanian Forestry Commission, Hobart, Tasmania.

van Genuchten, M. 1980: A closed-form equation for predicting the hydraulic conductivity of
unsaturated soils. Soil Sci. Soc. Am. J, 44(5) 892–898.

Vaz, C.M., Jones, S., Meding, M. and Tuller, M. 2013: Evaluation of standard calibration functions for eight electromagnetic soil moisture sensors. Vadose Zone Journal, 12(2).