Hydrological extremes and feedbacks in the changing water cycle (HydEF)
INCEPTION REPORT
March 2011

Scope of report
This document records key information related to start-up of the HydEF project: project management, changes to the proposed programme, start-up activity, and list of project contacts.

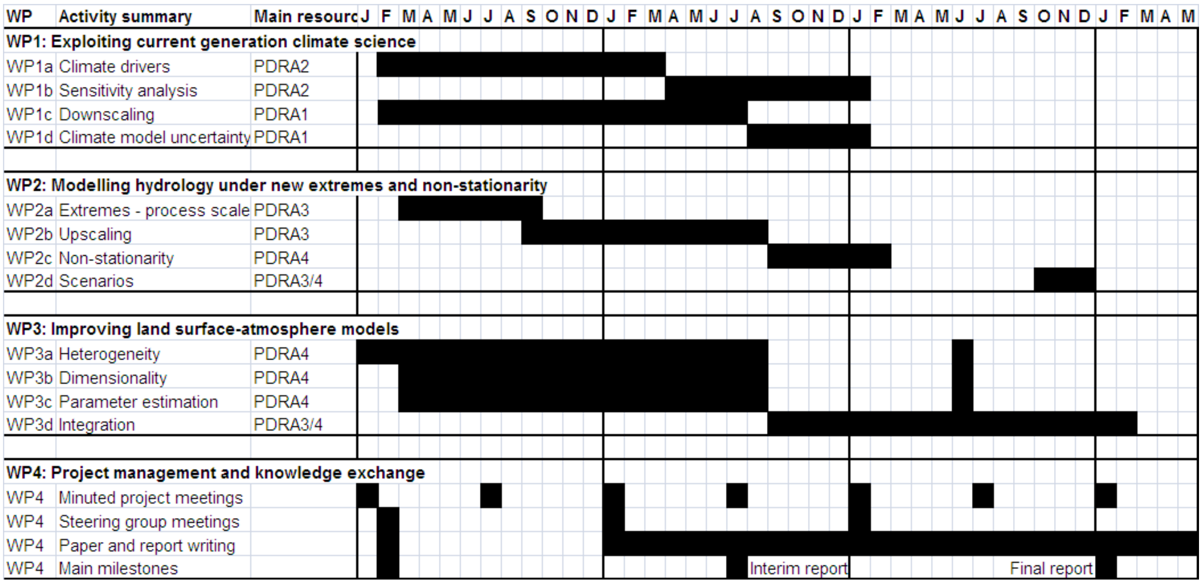
Project background and aims
The project is funded under NERC's Changing Water Cycle programme, and formally runs from 1st Sept 2010 to 31st January 2014. Four research institutions are funded under the project: Imperial College London, University of Reading, University College London, British Geological Survey. Details of awards are on the programme website (see list of websites in App A).

The project aims to:
1. Exploit current generation climate science and statistical methods to improve and enhance projections of potential change in hydrologically-relevant metrics over a time-scale of 10 to 60 years, in particular extremes of heavy precipitation and drought.
2. Build on the analysis of historical data to improve scientific understanding and develop innovative methods for the modelling of extremes and non-stationarity in the hydrological response to climate variability.
3. Improve the representation of hydrological processes in land surface models, in particular, the enhanced modelling of unsaturated zone and groundwater processes on land-atmosphere feedbacks.

Project programme and staffing
The planned programme below has been modified from the originally proposed programme to allow for actual start dates of research staff. There are three significant changes:

1. PDRA1 (Chiara Ambrosino, UCL) has started eight months earlier than originally programmed. This is partly in response to a NERC request that the project should start as soon as possible, and partly in response to staff availability. Although this has benefits in terms of allowing more parallel work with PDRA2 (Reading), it also means less PDRA resources for supporting WP2 and WP3 with climate data at the later stages of the project. To manage this, the UCL and Imperial staff on WP1, Dr Chandler and Dr Onof, will provide the required support at that stage.
2. PDRA3 (BGS) has not been appointed at time of writing this report (recruitment is underway). It has been assumed in the programme below that the appointment will be made in April 2011, with an adjustment to the original programme. However, BGS have significant additional staff time on the project so WP2 is progressing with minimal delay.
3. PDRA4 (Nataliya Bulygina, Imperial) was appointed as programmed in January 2011, however is working half-time on the project until 30th September 2011 due to unavoidable over-lap with an EPSRC-funded project. From 1st October she is scheduled to work full-time on HydEF until 31st May 2014, five months longer than originally programmed. This has not affected early progress because an independently funded researcher (Christina Bakopoulou) has joined the project.

Since the proposal there have been two changes to Co-Is. David Brayshaw (Reading), who was a named researcher on the proposal, is now a Co-I, having been awarded an independent NERC Fellowship. Howard Wheater (Imperial & University of Saskatchewan) remains a Co-I, but will not be involved day-to-day due to his recent move to Canada. Christian Onof (Imperial), who was not named on the proposal, is now a Co-I, taking up the day-to-day role of Prof Wheater. These Co-I changes have been approved by NERC.



Data management

The project will:

1. Use existing freely-available data
2. Purchase a limited amount of data (soil maps from NSRI is the envisaged requirement)
3. Maintain a meta-database (data and models)
4. Store model files for any published/key model results
5. Have a 'data manager'(Imperial, Nataliya Bulygina)
6. Maintain a project website (address in App A), hosted on the Imperial College site, with suitable links and holding all key outputs and meta-data base.
7. Consult with CWC Science Management about additional requirements/protocols for data management.

And the project will not:

1. Do significant field work (except in associated BGS projects)
2. Store model outputs
3. Maintain a central database with all project data

Steering group

The role of the steering group is to steer the research at a high level with respect to stakeholder research needs; facilitate integration with other R&D programmes; to assist with dissemination and uptake of research; and scientific and stakeholder review of project reports. The Group presently consists of:

Sir Brian Hoskins (Grantham/Walker Institutes), Doug Clarke (CEH Wallingford & Met Office representative for JULES development, Glenn Watts (Environment Agency of England and Wales), Mike Keil (OFWAT), Mike Jones (Thames Water), Mike Packman (Southern Water), Rob Sage (Veolia Water), Graham Leeks (CEH and CWC Science Management Team leader). The Steering group will meet at least once per year, and members will be invited to project meetings as and when appropriate. Steering group contacts are listed in App A.

Summary of progress since start-up

PDRAs have been appointed by Imperial, Reading and UCL. Imperial has also appointed a project student and an independently funded student to work on WP3. All researchers and project staff are listed in App A.

A project kick-off meeting was held at Imperial on 19th November 2010. A Steering Group meeting was held at Imperial on 14th February 2011. Imperial hosted the first CWC Science Management meeting on 23rd February 2011. Cross-WP meetings have been held between Reading/UCL, Imperial/UCL, Imperial/Reading and Imperial/BGS. A project meeting is scheduled for 5-6 May 2011 combined with a field visit to the Eden case study sites. Case studies have been discussed and a specification drafted (App B).

A brief summary of initial work is:

WP1: Preliminary analysis to identify potential relationships between large-scale climate and local-scale precipitation is underway at Reading. The Reading and UCL teams have so far held two joint meetings to share expertise and discuss how most effectively to work together. The UCL team have also met with the Imperial team to discuss the requirements for the weather generator in WP1. Data to support the development of this generator have been obtained, and a literature review is under way. At least one and possibly two Masters students at Reading will be involved in the project, working on alongside Co-Is and the PDRA to complement the main research by exploring further climate drivers on local scale precipitation and the identification of 'hydrologically interesting weather'. The Reading PDRA has started by looking at the relationship between mean sea level pressure and monthly precipitation and river flows at sites across the UK. This is currently being extended to other climate descriptors and in addition, rainfall extremes are being related to the position of the jet stream over the Atlantic.

WP2: An initial assessment of the areas for study has ben undertaken. Preliminary data gathering has been undertaken for the Jurassic Limestones in the upper part of the Thames Basin. This has helped the development of understanding of the main groundwater issues in the Cotswolds. Prior knowledge has been used for other areas, i.e. Colne, Pang/Lambourn and the Eden Valley.WP3: Connections have been made with CEH researchers working with JULES and a number of meetings attended. A literature review has been conducted on land surface modelling (App C). Initial analysis of sensitivity of JULES outputs to representation of heterogeneity, and strategy for developing this. It is intended that JULES version 2.2 will be used throughout the research.

Appendix A: project contacts and websites

NERC's CWC programme: http://www.nerc.ac.uk/research/programmes/cwc/facts.asp
HYDEF site:
http://www3.imperial.ac.uk/ewre/research/currentresearch/hydrology/changingwatercycles

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Appendix B: Case study specification

This appendix outlines the rationale for selecting case studies; and specifies case study areas at three scales: catchment (~10000km2), subcatchment (~100-1000km2) and grid and sub-gridscale (~0.01-1km2). The available data sets and existing models are listed.

Rationale

The project is committed to using two contrasting catchments in the UK: the Thames catchment in southern England (from its headwaters to Teddington, area 9950 km2) and the Eden catchment in north-east England (to the Sheepmount gauge downstream of Carlisle, area 2300 km2). (The Isle of Wight is the tied studentship case study and is not considered in this note). The Thames and Eden catchments include a variety of geological, hydrogeological and hydrological environments to ensure transferability of the research outputs. The Thames and Eden catchments are also appropriate because of the data and models available, and relevant parallel and previous research. In the Thames, the Marlborough and Berkshire Downs and South West Chilterns (MaBSWeC) Chalk aquifer has been extensively modelled for Thames Water by BGS, and instrumented and modelled under NERC's LOCAR and FREE programmes. The Eden is a Defra-EA funded Demonstration Test Catchment (DTC), and has also been instrumented under NERC's CHASM programme, and is a test catchment under EPSRC's Flood Risk Management Research Consortium. BGS has carried out hydrogeological studies in the Eden in collaboration with the Environment Agency and United Utilities.

The Thames and Eden case studies therefore provide a strong foundation for the project. However, the initial proposal was non-committal about which areas within these catchments would be focussed upon to develop process knowledge. Hence one of the first tasks of the project is to identify appropriate sub-areas.

The selection of these areas is governed by:

1. The project has no resources for field work so existing data sets must be used. This includes including adequate data on the meteorology, and surface and subsurface hydrology, soils, geology, land cover, etc.
2. The aim of looking at scale effects and heterogeneity in estimating hydrological extremes and land-atmosphere fluxes. This means that plot-scale studies (e.g. using a grid scale of 1x1m over an area of 10000m2), with suitable supporting data and including challenging heterogeneity, need to be included.
3. The central role of JULES, and the need to employ JULES at the basin scale, probably using a grid scale of 1km2. This calls for subcatchments which can be used to test and develop JULES and its coupling with groundwater models.
4. The central role of groundwater in the proposal: at least some of the case study areas need to have significant potential for groundwater role in land-atmosphere feedbacks; and significant issues with groundwater extremes including flooding and borehole draw-down.
5. The proposal is to build on existing modelling capability: in particular using the existing BGS groundwater models. The case study areas, at plot to basin scale, need to tie in with existing groundwater models.
6. The need for existing multi-scale data points to use of data sets developed under previous programmes such as LOCAR and CHASM.
7. Ideally the project should tie in with the Defra-EA Demonstration Test Catchment (DTC) programme in the Eden.
8. The climate modelling work package does not impose tight restrictions on choice of study area, except for the need for reasonable rain gauge and weather station data.

THAMES CASE STUDY

1. Catchment scale

Objectives: to test sensitivity of basin-scale /GCM grid fluxes to improved water cycle models; to test new models of extremes with respect to basin-scale water resources; to identify hydrologically-relevant basin-scale climate variables and develop improved climate modelling methods.

Area: Thames River to Teddington (9950 km2).

Existing catchment-scale models:
Groundwater: Thames Water/BGS MaBSWeC model.
Geology: BGS GSI3D
Land surface models: JULES v2.2
CMIP3, HiGEM and CMIP5 and other GCMs/RCMs

Available catchment-scale data sets:
EA flow gauge network (~50 stations, including daily data from 1883 at Teddington).
Met Office - MIDAS Land Surface Stations data (daily data from 1853).
NCEP climate forecast system reanalysis (1979-2010) and ERA 40/Interim
HOST maps (CEH)
NSRI soil maps: soil hydraulic data sets (for purchase from NSRI)
Land cover LCM2000 (CEH)
Geology maps (BGS)
Gridded rainfall and PE data (access to be discussed with Met Office).

2. Subcatchment scale

Objectives: to use for development of integrated JULES-groundwater models; to develop up-scaling and nested modelling procedures; to investigate non-stationarity and uncertainty; to develop intermediate scale climate models.

Areas: Lambourn to Welford (area 176km2) Is it Welford or Shaw?
Kennet to Theale (1033km2)
Colne to Denham (743 km2)
Cotswold Jurassics and Oxford gravels. Thames to Sutton Courtenay (3414 km^2).

Various other gauges will be used by Reading in the Thames basin, namely the Enborne at Brimpton and the Dun at Hungerford. In addition, a further nine catchments around Great Britain will be considered as part of the Reading work being representative of different geologies and climate regimes and with limited abstractions These catchments are: Avon at Delnashaugh, Coquet at Morwick, Dyfi at Dyfi Bridge, Ellen at Bullgill, Ewe at Poolewe, Falloch at Glen Falloch, Great Stour at Horton, Harpers Brook at Old Mill Bridge and the Tiddy at Tideford.

Existing models:
Groundwater: Thames Water/BGS MaBSWeC model
Subsurface: Imperial/BGS 1&2D unsaturated zone hill-slope models
Hydrology: Reading/Imperial INCA models from the LOCAR programme
Rainfall: Imperial's GLM model of the Kennet

Available data sets:
NSRI, MIDAS, geology, land cover and climate data (as for Thames)
NERC's LOCAR data sets: large database including weather stations, lysimeters, boreholes, flow gauges, HYDRA site (see http://www.nerc-wallingford.ac.uk/locar/catch_pl.htm)

3. Grid and sub-grid scale

Objective: to investigate effects of heterogeneity on JULES fluxes; to test small-scale effects of a including a more realistic boundary condition in JULES; to condition JULES parameters and explore uncertainty; to investigate responses of groundwater levels and borehole draw-down to extremes; to develop process knowledge under extremes to incorporate into catchment models.

Areas:
Frilsham-Grimsbury Wood-Trumpletts farm area;
Warren Farm recharge site
Borehole array at Westbrook Farm;
Boxford wetland sites;
Thames/BGS borehole sites

Available data sets:
NERC's LOCAR data sets: including weather stations, lysimeters, boreholes, flow gauges, HYDRA site (see http://www.nerc-wallingford.ac.uk/locar/catch_pl.htm)

EDEN CASE STUDY

Specification of the Eden case study will be subject to further discussions with the Eden DTC partners and site visits.

1. **Catchment scale**

Objectives: To extend the Thames case study research to the Permo-Triassic Sandstone, upland soils and vegetation, and the wetter climate of the Eden.

Area: The Eden River to Sheepmount (2300 km2).

Existing catchment-scale models:
Land surface models: JULES v2.2
CMIP3, HiGEM and CMIP5 and other GCMs/RCMs

Available catchment-scale data sets:
EA flow gauge network (~12 stations).
NERC's CHASM gauge network (11 stream gauges, 20 rain gauges and 4 automatic weather stations)
Met Office - MIDAS Land Surface Stations data (daily data).
NCEP climate forecast system reanalysis (1979-2010) and ERA 40/Interim
HOST maps (CEH)
NSRI soil maps: soil hydraulic data sets (for purchase from NSRI)
Land cover LCM2000 (CEH)
Geology maps (BGS)
Gridded rainfall and PE data (access to be discussed with Met Office).

2. **Subcatchment scale**

Objectives: To extend the Thames case study research to the Permo-Triassic Sandstone, upland soils and vegetation, and the wetter climate of the Eden.

Areas:

Caldew to Cummersdale (249 km2)
Eden to Temple Sowerby (616km2)
Various other gauges will be used by Reading.

Existing models:
PDM model to Temple Sowerby (Reading)
A number of preliminary groundwater models have been developed for the area.

Available data sets:
NSRI, MIDAS, geology, land cover and climate data (as for Eden)

3. Grid and sub-grid scale

Objective:
Objectives: To extend the Thames case study research to the Permo-Triassic Sandstone, upland soils and vegetation, and the wetter climate of the Eden.

Areas:
A selected DTC site: Pew Beck (Caldew), Dacre (Eamont), Lyvennet (Eden)

Available data sets:
DTC hydrometry and soils data, BGS boreholes

Appendix C: summary review of LSMs

Commonly, Land Surface Models (LSMs) are used by Global Climate Models (GCMs) to derive their boundary conditions. This requires modelling of the following balances by LSMs:

- The surface energy balance that includes
  - Sensible heat,
  - Latent heat,
  - Soil heat flux,
  - And chemical energy (photosynthesis);
- The surface water balance that includes
  - Evapotranspiration (ET),
  - Runoff,
  - And storage;
- And the carbon balance.

Over the last four decades LSMs underwent through a variety of structural changes resulting in three model generations [*Pitman*, 2003]. The **first generation** models are often called ''Manabe bucket models''[*Manabe*, 1969] (Figure 1), and have the following distinctive features:

- Globally constant soil depth and soil properties,
- No heat conduction into the soil,
- Water content limited rate of ET,
- And saturation excess runoff generation.

The Project for Intercomparison of Landsurface Parameterisation Schemes (PILPS) [*Henderson-Sellers et al.*, 1995] has shown that the first generation models are inadequate for diurnal to multi-annual scale surface hydrology representation.
A decade later, the **second generation** models were developed [*Deardorff*, 1978; *Dickinson*, 1983] (Figure 2), so that the models got the following distinctive characteristics

- Several soil layers (two or more) with location specific properties,
- Modelling of vegetation impacts on energy, water budgets, and momentum transfer,
- Soil type specific Richards' equation based subsurface water transfer,
- And saturation/infiltration excess surface runoff generation.

These models outperformed the first generation LSMs [*Henderson-Sellers et al.*, 1995], and improved modelling of surface-atmosphere interactions on the time scale of days [*Beljaars et al.*, 1996], and improved European soil temperature prediction [*Viterbo et al.*, 1999].
Carbon balance modelling and improved representation of vegetation conductance (to calculate ET) constitute the main advances in the **third generation** LSMs [*Collatz et al.*, 1991; *Sellers et al.*, 1992] (Figure 3).
There were a number of projects comparing different LSMs. For example, GWSP/EU-WATCH model inter-comparison project [http://www.eu-watch.org/nl/25222736-Global_Modelling.html] applied 10 surface exchange schemes of various complexities to large catchments around the world, using the same driving data. The results show that there is a significant difference in inter-model simulated annual ET and runoff (±40-100%). This is attributed to differences in the considered LSMs model structures (parameter uncertainty was not included in the study).
As a part of **Changing Water Cycle** research programme, a third generation British Land Surface Model **JULES** [*Cox et al.*, 1999] will be considered, and the following current model limitations will be targeted:

- Simple grid spatial heterogeneity treatment;
- 1-dimensional (compare to 3-dimensional) vertical water movement;

- o Lack of in-between soil columns interactions;
- o Parameterisation via pedo-transfer functions (no uncertainty quantified);
- o No coupling with groundwater.

JULES recognises different land cover type over a grid cell, but does not account for soil moisture (states) differences for the land use types (tile type C on Figure 4). There are LSMs that treat land cover spatial **heterogeneity** explicitly without soil state averaging, and assigning soil states for each land cover type over a grid (tile types D and E on Figure 4): dynamic tiles –NSIPP [*Koster et al.*, 2000], static tiles - CLM4 [*Oleson et al.*, 2008], Mosaic [*Koster and Suarez*, 1992], SECHIBA [*de Rosnay and Polcher*, 1998]. Another issues related to representation of naturally **heterogeneous** properties and states in JULES include treating grid scale soil moisture and soil properties in horizontal and vertical (in each soil layer) directions as being homogeneous. This was tackled in other models by introducing probability distributed soil moisture [*Moore*, 2007], topographically dependent water table [*Beven and Kirkby*, 1979] using probability distributions for soil saturated hydraulic conductivity [*Gusev and Nasonova*, 2003], and its adjustments with depth [*Koster et al.*, 2000; *Oleson et al.*, 2008; *Yang and Niu*, 2003].
Some other LSMs represent **interactions** between grids via channel routing of surface flow [*Decharme and Douville*, 2006], holistic catchment- based modelling [*Koster et al.*, 2000], and sub-grid interactions in lower soil layers[*de Rosnay and Polcher*, 1998].
Pedo-transfer functions that relate available soil characteristics (sand, silt, clay contents, etc) to soil hydraulic properties are widely used in current LSMs [*Cox et al.*, 1999; *Koster and Suarez*, 1992; *Oleson et al.*, 2008; *Yang and Niu*, 2003]. Commonly, just a single value derived in this way is used for model **parameterisation**, without accounting for uncertainty in the pedo-tarnsfer relationships.
JULES in its current state does not include groundwater, groundwater interaction with unsaturated zone, and saturated zone grid inter-connectivity. Some models add an additional layer to represent a coupled **groundwater** [*Oleson et al.*, 2008], or make soil column depth time-variable [*Gusev and Nasonova*, 2003].
To conclude, structures of the state-of-the-art Land Surface Models approximate large scale physical processes using point-scale laws, and rely on various system simplifications. The effects of such assumptions are not known, and the corresponding prediction uncertainty is not properly evaluated.

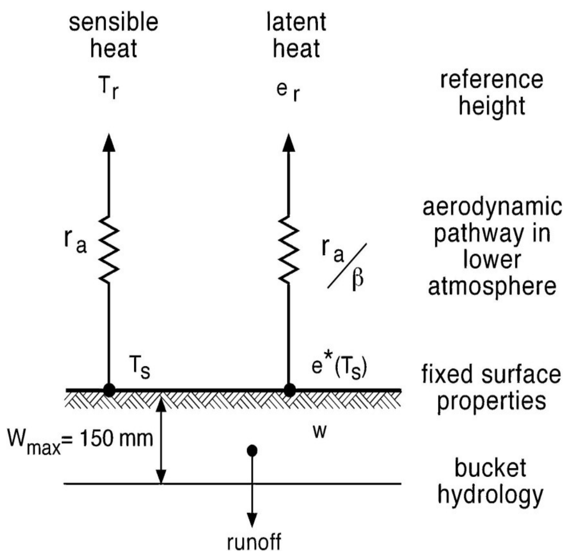

Figure 1: A first generation Land Surface Model (Source: Pitman, 2003).

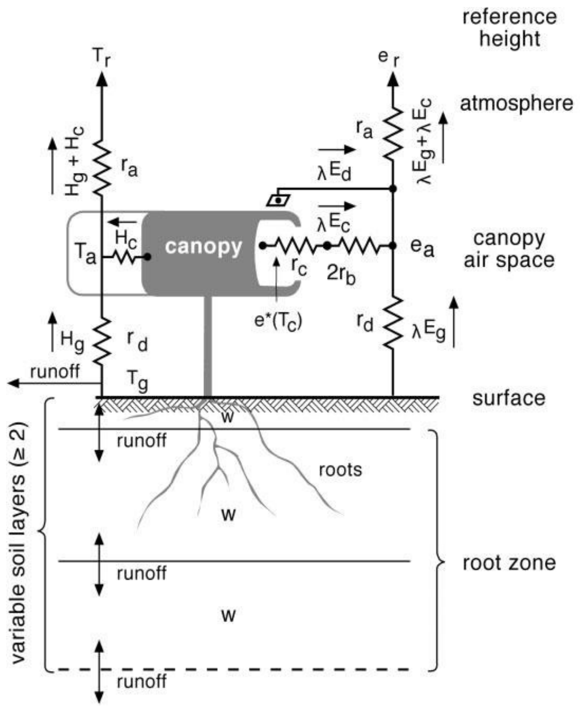

Figure 2: A second generation Land Surface Model (Source: Pitman, 2003).

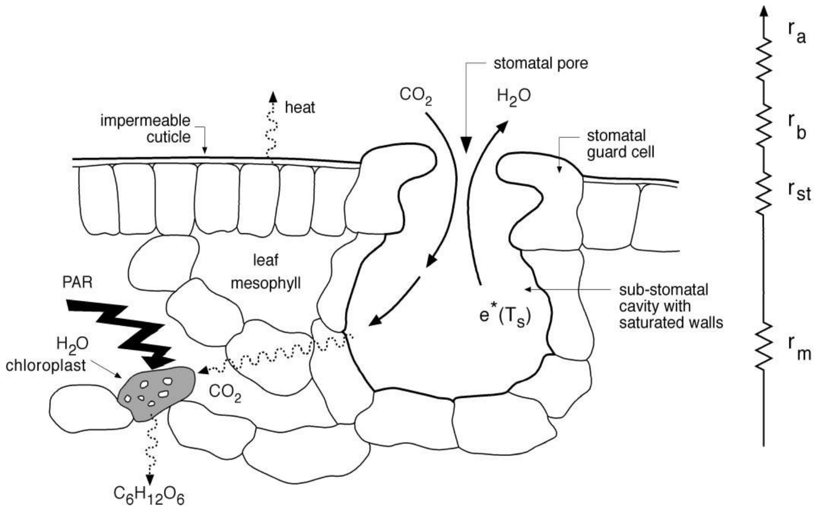

Figure 3: A third generation Land Surface Model (Pitman, 2003).

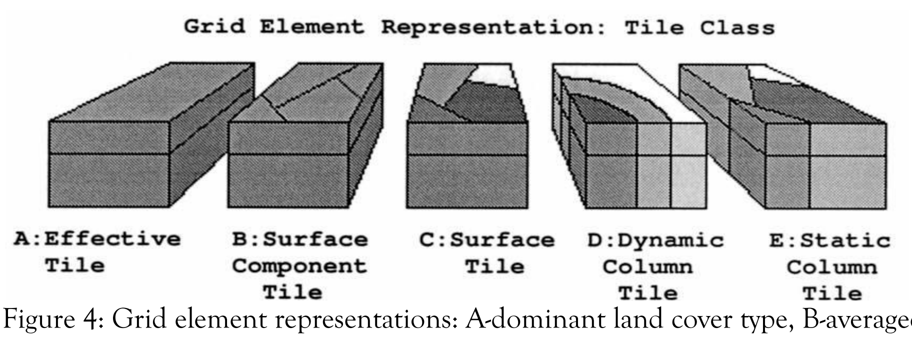

Figure 4: Grid element representations: A-dominant land cover type, B-averaged land cover properties, C-distinct land cover & a single subsurface state (for each soil layer), D and E – distinct land cover & corresponding distinct subsurface states (Source: Boone, 2004).

REFERENCES

Beljaars, A., et al. (1996), The anomalous rainfall over the United States during July 1993: Sensitivity to land surface parameterization and soil moisture, *Monthly Weather Review*, *124*(3), 362-383.

Beven, K., and M. Kirkby (1979), A physically-based variable contributing area model of basin hydrology, *hydrol. SCI. bull.*, *24*, 43-69.

Collatz, G., et al. (1991), Physiological and environmental-regulation of stomatal conductance, photosynthesis and transpiration - a model that includes a laminar boundary-layer, *Agricultural and forest meteorology*, *54*(2-4), 107-136.

Cox, P. M., et al. (1999), The impact of new land surface physics on the GCM simulation of climate and climate sensitivity, *Clim. Dyn.*, *15*(3), 183-203.

de Rosnay, P., and J. Polcher (1998), Modelling root water uptake in a complex land surface scheme coupled to a GCM, *Hydrology and earth system sciences*, *2*(2-3), 239-255.

Deardorff, J. (1978), Efficient prediction of ground surface-temperature and moisture, with inclusion of a layer of vegetation, *Journal of geophysical research*, *83*(NC4), 1889-1903.

Decharme, B., and H. Douville (2006), Introduction of a sub-grid hydrology in the ISBA land surface model, *Clim. Dyn.*, *26*(1), 65-78.

Dickinson, R. (1983), Land surface processes and climate surface albedos and energy-balance, *Advances in geophysics*, *25*, 305-353.

Gusev, Y. M., and O. N. Nasonova (2003), The simulation of heat and water exchange in the boreal spruce forest by the land-surface model SWAP, *J. Hydrol.*, *280*(1-4), 162-191.

Henderson-Sellers, A., et al. (1995), The project for intercomparison of land-surface parameterization schemes (pilps) - phase-2 and phase-3, *Bulletin of the American Meteorological Society*, *76*(4), 489-503.

Koster, R., and M. Suarez (1992), Modeling the land surface boundary in climate models as a composite of independent vegetation stands, *Journal of geophysical research*, *97*(D3), 2697-2715.

Koster, R., et al. (2000), A catchment-based approach to modeling land surface processes in a general circulation model 1. Model structure, *Journal of geophysical research*, *105*(D20), 24809-24822.

Manabe, S. (1969), Climate and the ocean circulation: 1, the atmospheric circulation and the hydrology of the Earth's surface, *Monthly Weather Review*, *97*, 739-805.

Moore, R. J. (2007), The PDM rainfall-runoff model, *Hydrology and earth system sciences*, *11*(1), 483-499.

Oleson, K. W., et al. (2008), Improvements to the Community Land Model and their impact on the hydrological cycle, *J. Geophys. Res.-Biogeosci.*, *113*(G1), 26.

Pitman, A. (2003), The evolution of, and revolution in, land surface schemes designed for climate models, *International journal of climatology*, *23*(5), 479-510.

Sellers, P., et al. (1992), Canopy reflectance, photosynthesis, and transpiration .3. A reanalysis using improved leaf models and a new canopy integration scheme, *Remote sensing of environment*, *42*(3), 187-216.

Viterbo, P., et al. (1999), The representation of soil moisture freezing and its impact on the stable boundary layer, *Quarterly journal of the Royal Meteorological Society*, *125*(559), 2401-2426.

Yang, Z. L., and G. Y. Niu (2003), The versatile integrator of surface and atmosphere processes - Part 1. Model description, *Glob. Planet. Change*, *38*(1-2), 175-189.