Core Modelling Team

Pathways to better land modelling systems

Martyn Clark

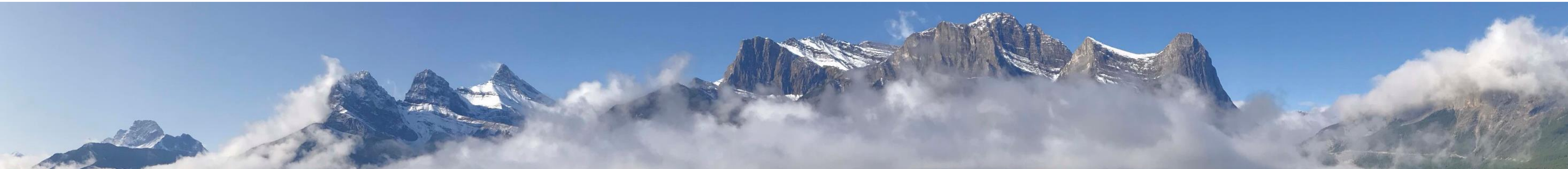
Land Surface Modelling Summit, Oxford, 13 September 2022

Subtitles

Why are land models so terrible?

– or –

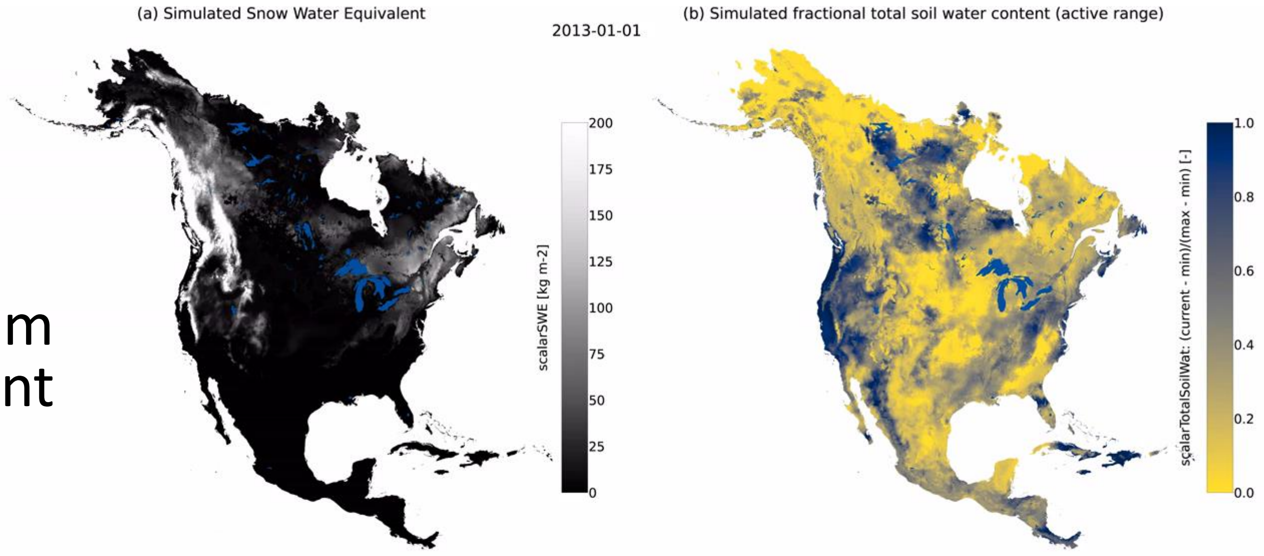
How can we explain the PLUMBER results?



What we do

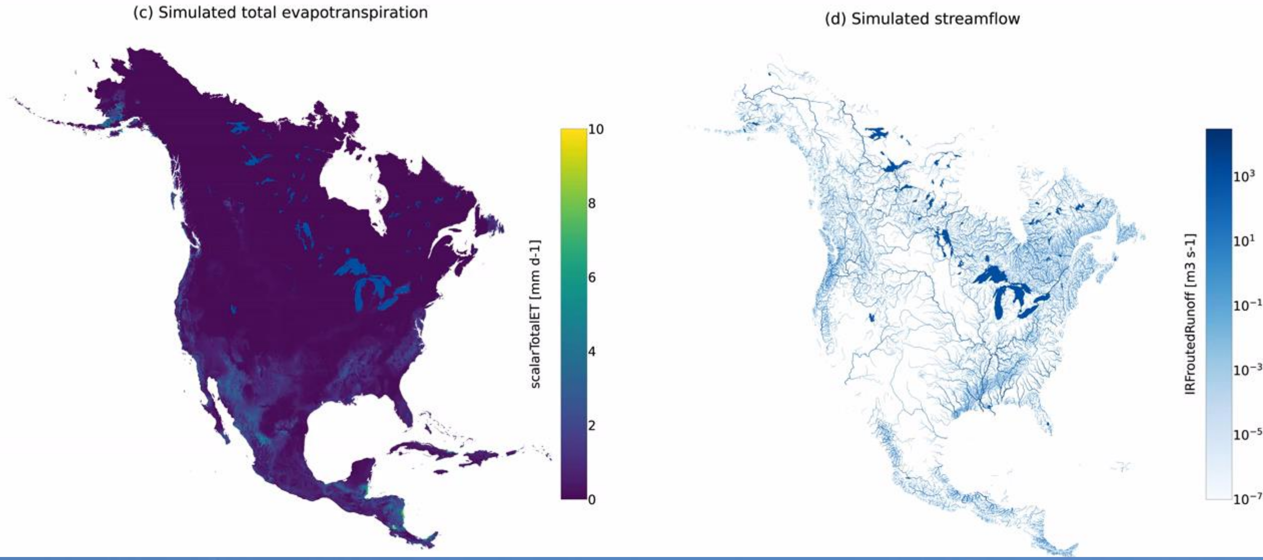
- Research goal:
  - ❑ Develop ***numerically robust*** terrestrial system models that faithfully represent the dominant physical processes across continental domains

- Research foci:
  - ❑ Flexible model design
  - ❑ Robust numerical solutions
  - ❑ Agile parallelization strategies
  - ❑ Improved process representations

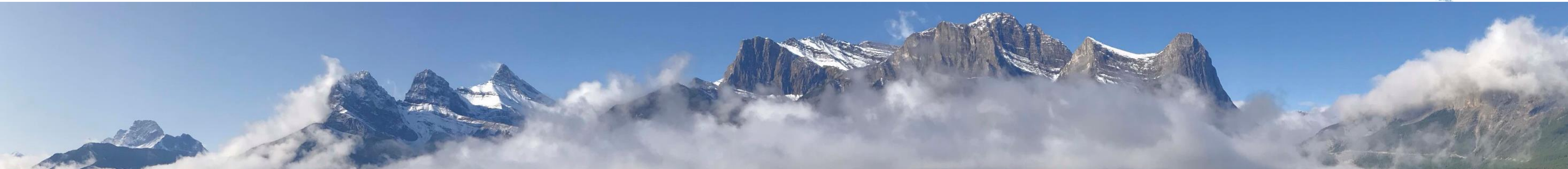

(a) Simulated Snow Water Equivalent

(b) Simulated fractional total soil water content (active range)

2013-01-01


(c) Simulated total evapotranspiration

(d) Simulated streamflow



Problems with hydrological models

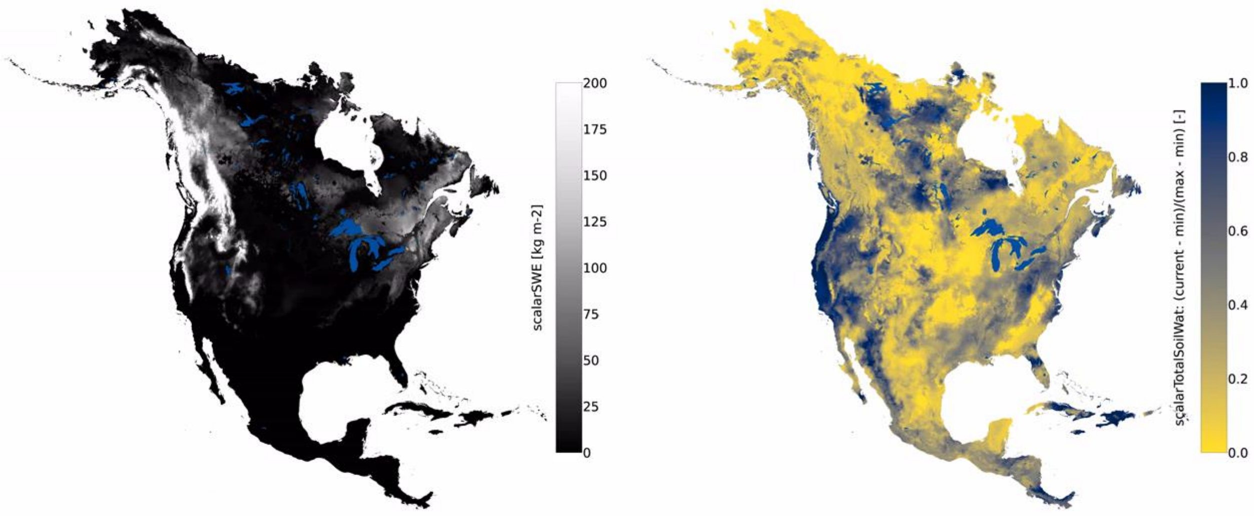
- Cumbersome and non-reproducible model workflows
- Unwieldy model structures
- Poor numerical implementation
- Statistically-oriented parameter estimation methods
- Weak model evaluation methods and weak theoretical underpinnings

Common model requirements…

Computational hydrology experiments such as this require:

- Domain discretization (basins and rivers)
- Meteorological data
- Land use data
- Processing of all inputs into the setting files each model requires
- Code to run, calibrate models
- Code to analyze and visualize outputs
- Experiment outcomes (should) lead to new scientific insights and/or management decisions

- 517315 model elements (median 33 km^2)
- 40 years of hourly sims
- ~13 TB of input and output data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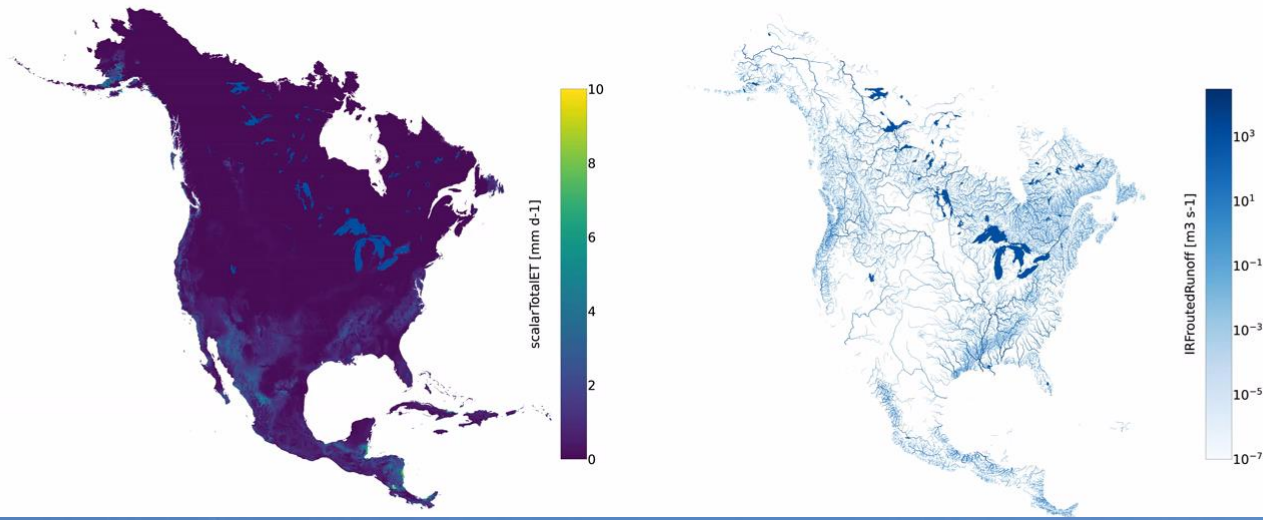
2013-01-01


(c) Simulated total evapotranspiration

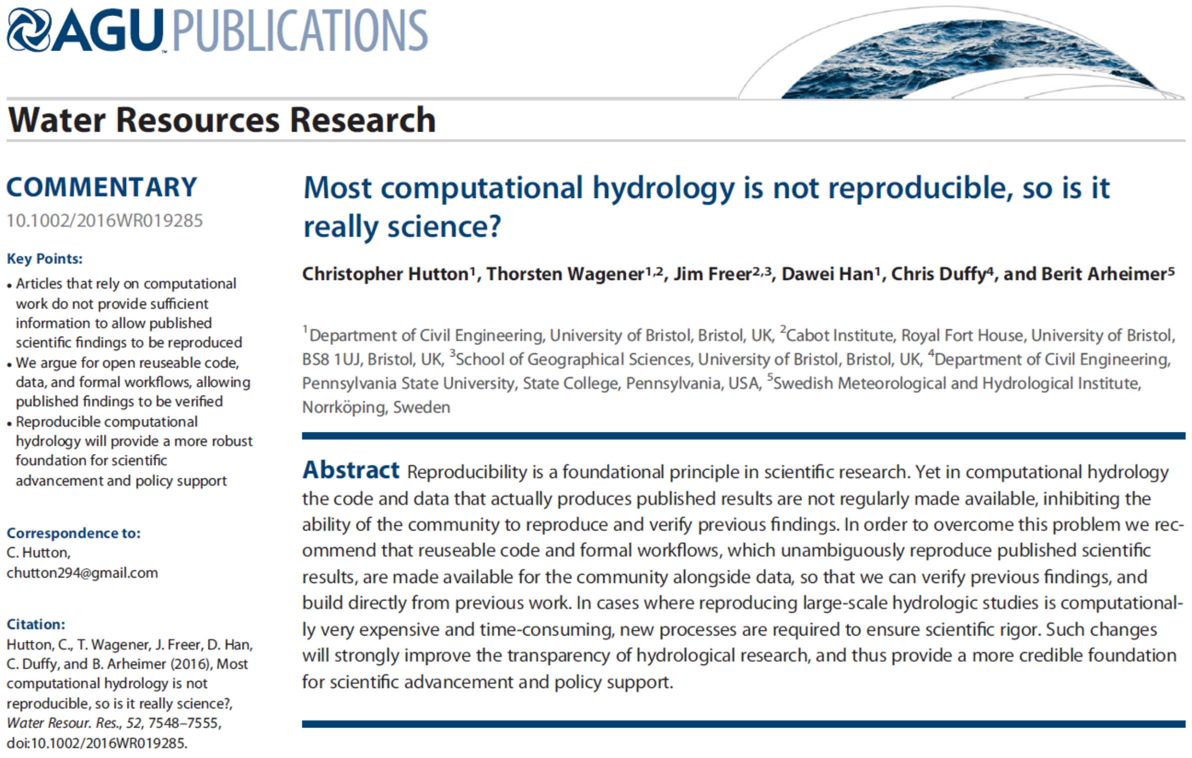
(d) Simulated streamflow

…but we are all configuring our models in different ways

While models have similar data requirements, they are configured in an individualistic and ad-hoc way

We need reproducible and sharable workflows

- ☐ Good scientific practice
- ☐ Easier to keep track of work for reporting and paper reviews; easier to collaborate
- ☐ Potentially large efficiency gains



AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2016WR019285

Key Points:

- Articles that rely on computational work do not provide sufficient information to allow published scientific findings to be reproduced
- We argue for open reuseable code, data, and formal workflows, allowing published findings to be verified
- Reproducible computational hydrology will provide a more robust foundation for scientific advancement and policy support

Correspondence to:
C. Hutton,
chutton294@gmail.com

Citation:
Hutton, C., T. Wagener, J. Freer, D. Han, C. Duffy, and B. Arheimer (2016), Most computational hydrology is not reproducible, so is it really science?, *Water Resour. Res., 52*, 7548–7555, doi:10.1002/2016WR019285.

Most computational hydrology is not reproducible, so is it really science?

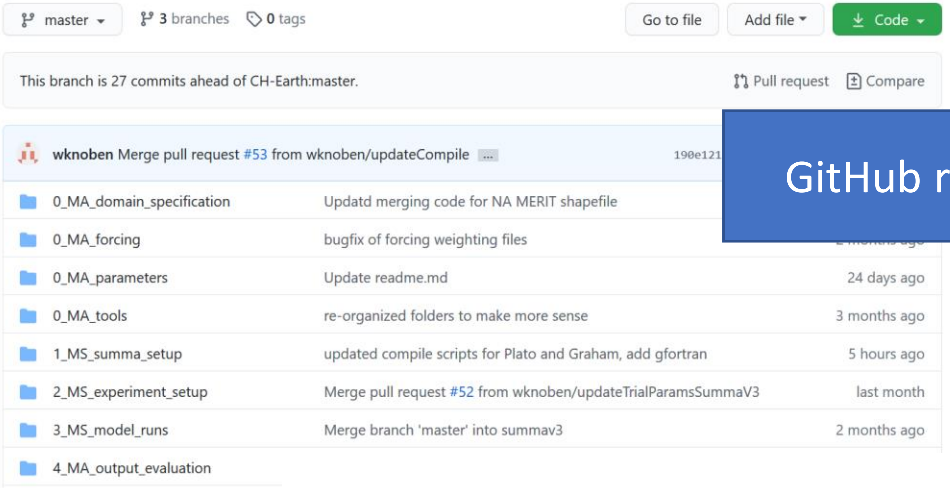
Christopher Hutton[1], Thorsten Wagener[1,2], Jim Freer[2,3], Dawei Han[1], Chris Duffy[4], and Berit Arheimer[5]

[1]Department of Civil Engineering, University of Bristol, Bristol, UK, [2]Cabot Institute, Royal Fort House, University of Bristol, BS8 1UJ, Bristol, UK, [3]School of Geographical Sciences, University of Bristol, Bristol, UK, [4]Department of Civil Engineering, Pennsylvania State University, State College, Pennsylvania, USA, [5]Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

Abstract Reproducibility is a foundational principle in scientific research. Yet in computational hydrology the code and data that actually produces published results are not regularly made available, inhibiting the ability of the community to reproduce and verify previous findings. In order to overcome this problem we recommend that reuseable code and formal workflows, which unambiguously reproduce published scientific results, are made available for the community alongside data, so that we can verify previous findings, and build directly from previous work. In cases where reproducing large-scale hydrologic studies is computationally very expensive and time-consuming, new processes are required to ensure scientific rigor. Such changes will strongly improve the transparency of hydrological research, and thus provide a more credible foundation for scientific advancement and policy support.

Developing model-agnostic workflows

- Goal: Improve the efficiency of continental-domain model implementation tasks
- Easier to collaborate; easier to keep track of work for reporting and paper reviews
- Increase transparency, reproducibility, and code re-use
- Advance ***community hydrological modelling***, rather than a *community hydrological model*

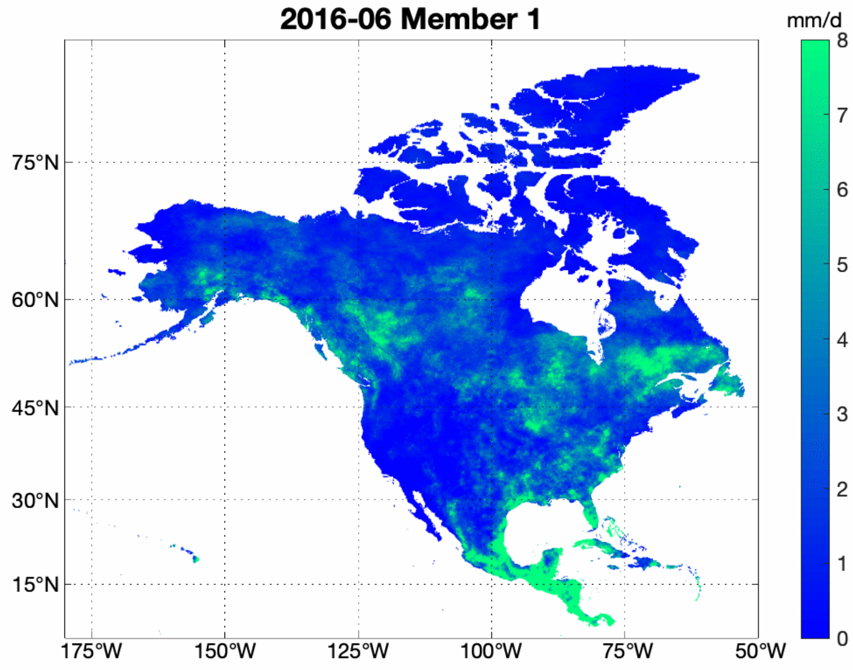


This branch is 27 commits ahead of CH-Earth:master.

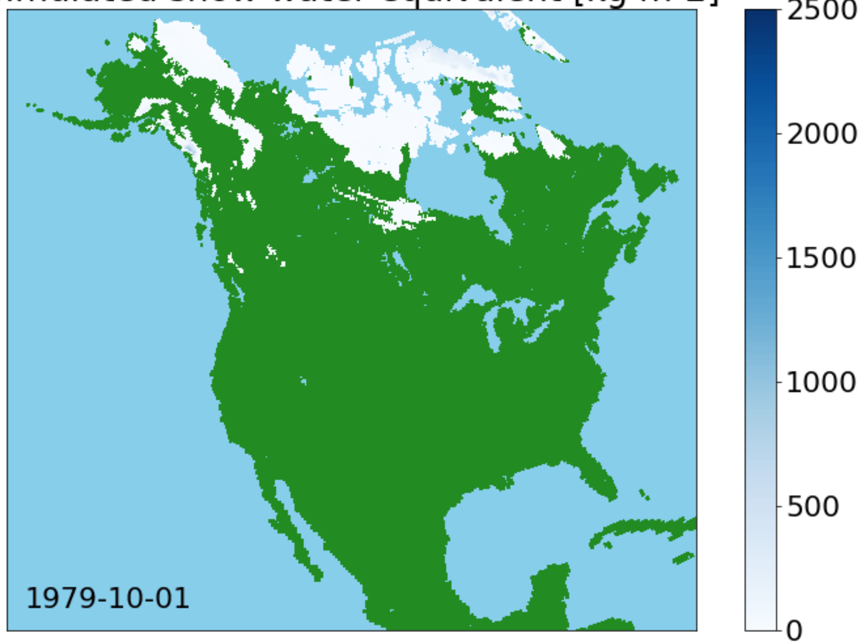
wknoben Merge pull request #53 from wknoben/updateCompile … 190e121

0_MA_domain_specification	Updatd merging code for NA MERIT shapefile	
0_MA_forcing	bugfix of forcing weighting files	
0_MA_parameters	Update readme.md	24 days ago
0_MA_tools	re-organized folders to make more sense	3 months ago
1_MS_summa_setup	updated compile scripts for Plato and Graham, add gfortran	5 hours ago
2_MS_experiment_setup	Merge pull request #52 from wknoben/updateTrialParamsSummaV3	last month
3_MS_model_runs	Merge branch 'master' into summav3	2 months ago
4_MA_output_evaluation		

GitHub repository



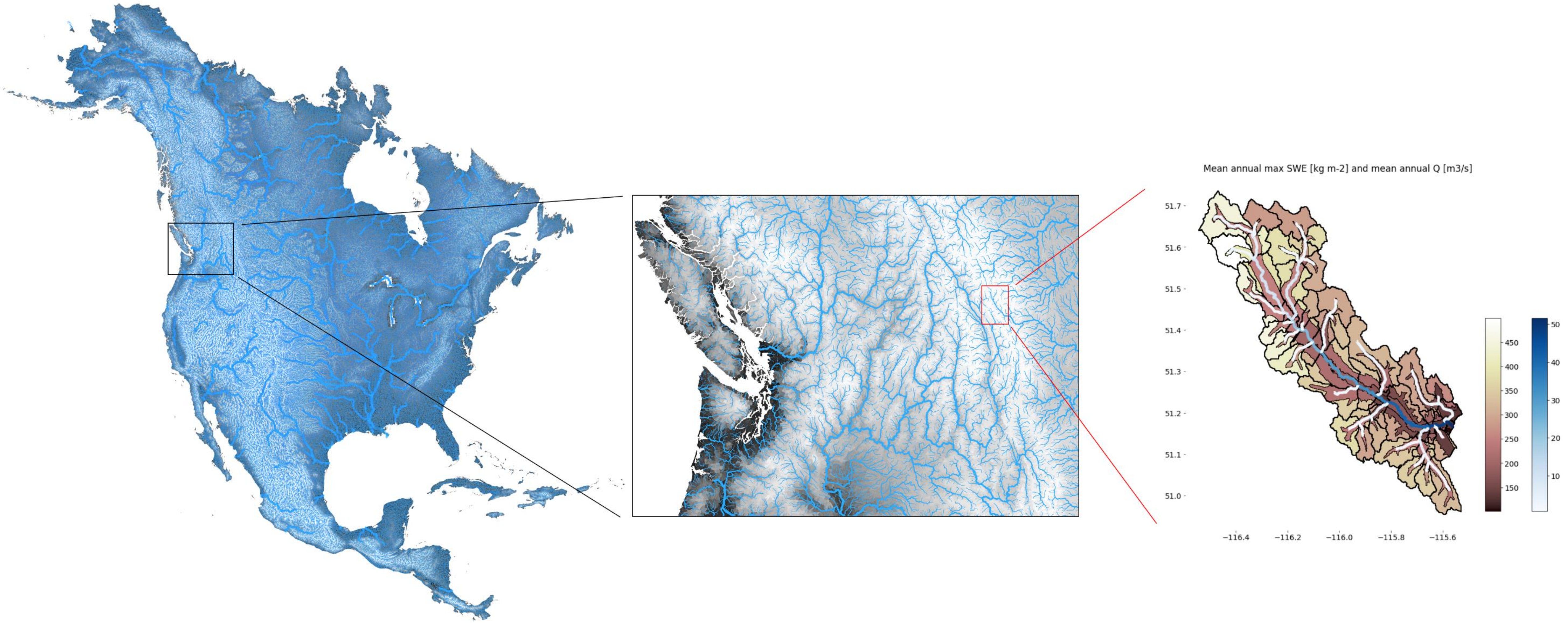
Simulated snow water equivalent [kg m-2]



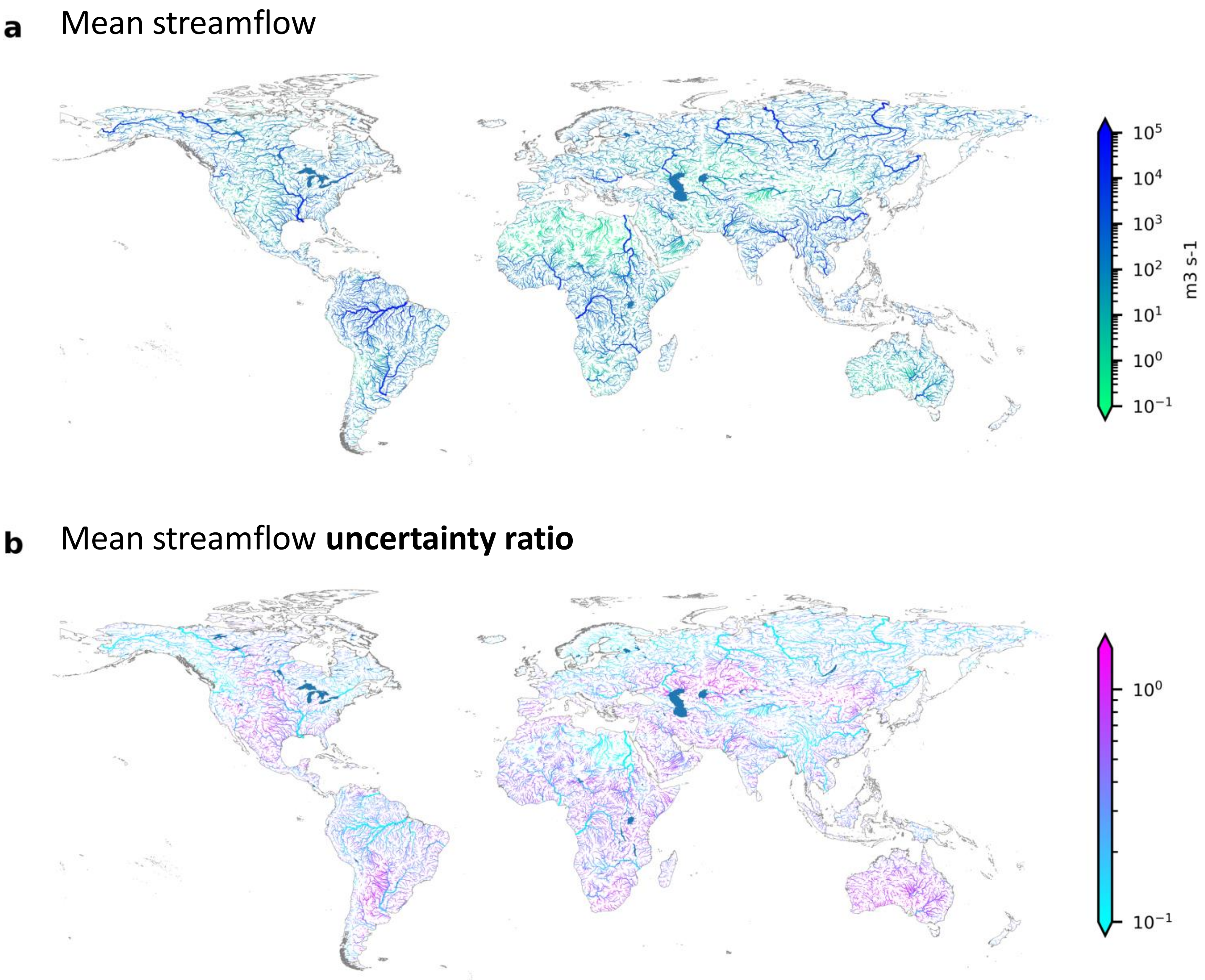
Streamflow and lake level

Map tiles by Stamen Design, CC BY 3.0 — Map data (C) OpenStreetMap contributors

Fully reproducible modeling at all scales.. from catchments



… to the globe

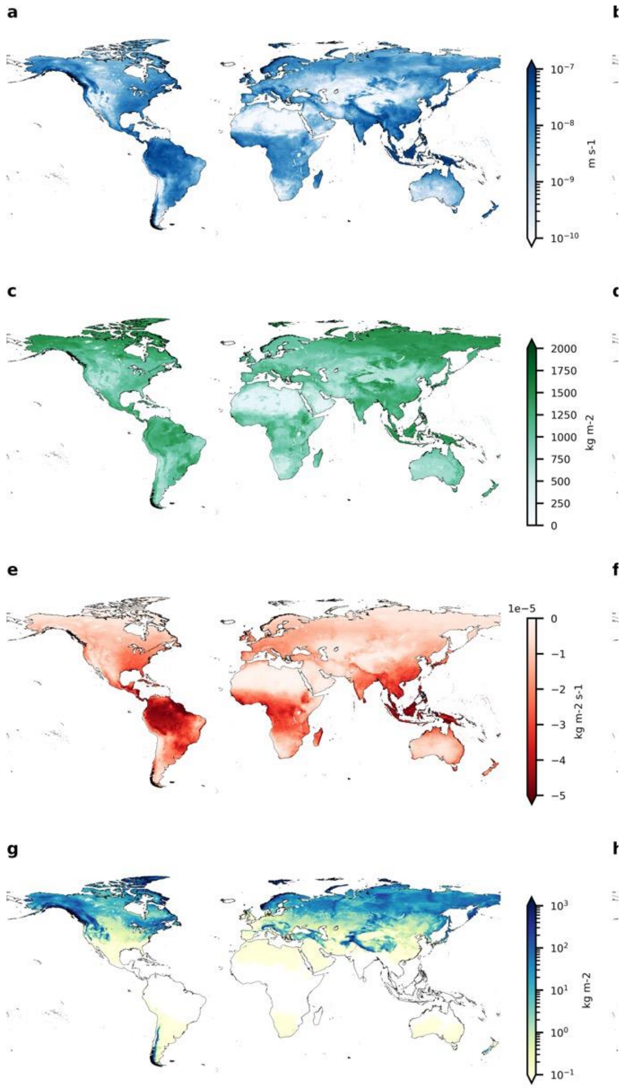


Runoff

Total
soil water

ET

SWE



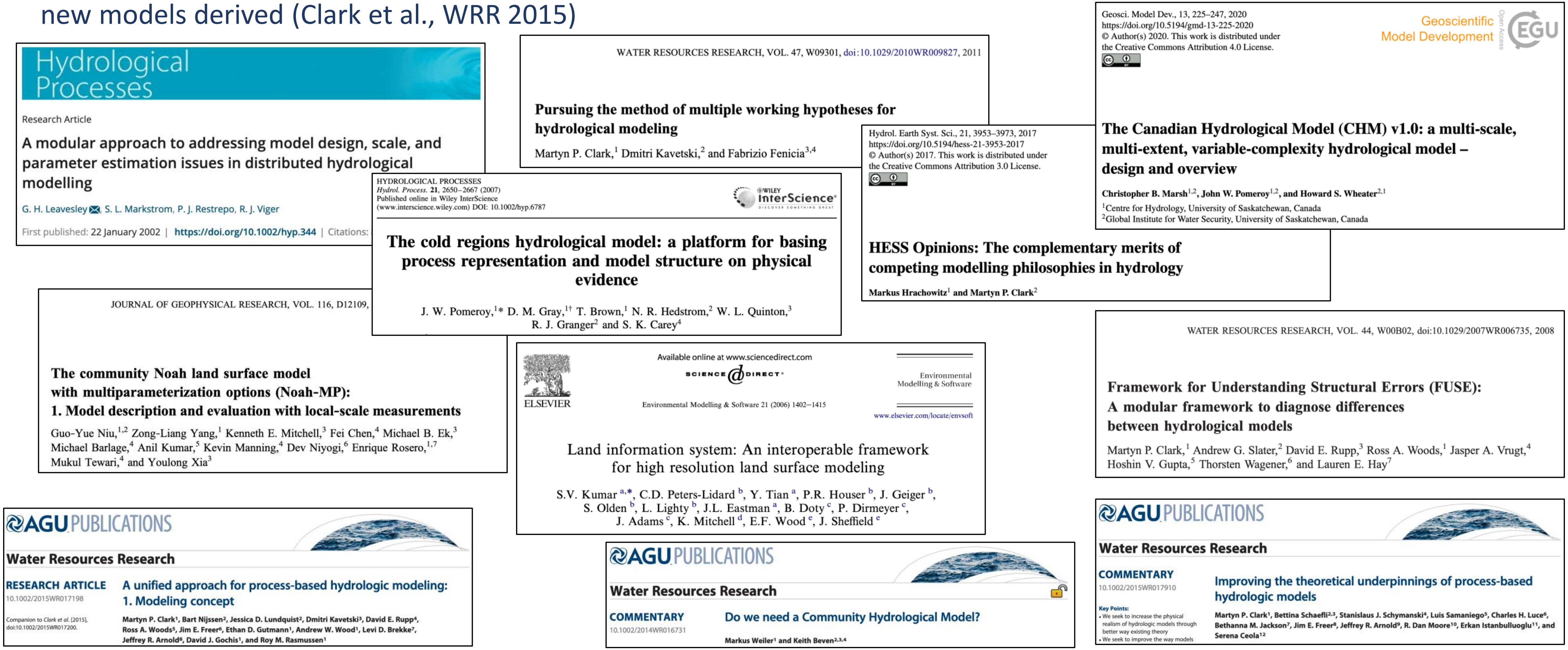
Problems with hydrological models

- Cumbersome and non-reproducible model workflows
- Unwieldy model structures
- Poor numerical implementation
- Statistically-oriented parameter estimation methods
- Weak model evaluation methods

Unifying model physics

- **The problem**: There is a glut of hydrological models (Clark et al., WRR 2011) – in many cases there are more models in use than there are algorithms to populate them (same algorithms across multiple models)

- **The challenge:** How can we define a general master modeling template from which existing models can be constructed and new models derived (Clark et al., WRR 2015)



Hydrological Processes

Research Article

A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling

G. H. Leavesley, S. L. Markstrom, P. J. Restrepo, R. J. Viger

First published: 22 January 2002 | https://doi.org/10.1002/hyp.344 | Citations:

WATER RESOURCES RESEARCH, VOL. 47, W09301, doi:10.1029/2010WR009827, 2011

Pursuing the method of multiple working hypotheses for hydrological modeling

Martyn P. Clark,[1] Dmitri Kavetski,[2] and Fabrizio Fenicia[3,4]

Geosci. Model Dev., 13, 225–247, 2020
https://doi.org/10.5194/gmd-13-225-2020
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Geoscientific Model Development
Open Access
EGU

The Canadian Hydrological Model (CHM) v1.0: a multi-scale, multi-extent, variable-complexity hydrological model – design and overview

Christopher B. Marsh[1,2], John W. Pomeroy[1,2], and Howard S. Wheater[2,1]
[1]Centre for Hydrology, University of Saskatchewan, Canada
[2]Global Institute for Water Security, University of Saskatchewan, Canada

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Hydrol. Earth Syst. Sci., 21, 3953–3973, 2017
https://doi.org/10.5194/hess-21-3953-2017
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HESS Opinions: The complementary merits of competing modelling philosophies in hydrology

Markus Hrachowitz[1] and Martyn P. Clark[2]

HYDROLOGICAL PROCESSES
Hydrol. Process. 21, 2650–2667 (2007)
Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/hyp.6787

WILEY InterScience

The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence

J. W. Pomeroy,[1]* D. M. Gray,[1†] T. Brown,[1] N. R. Hedstrom,[2] W. L. Quinton,[3] R. J. Granger[2] and S. K. Carey[4]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D12109,

The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements

Guo-Yue Niu,[1,2] Zong-Liang Yang,[1] Kenneth E. Mitchell,[3] Fei Chen,[4] Michael B. Ek,[3] Michael Barlage,[4] Anil Kumar,[5] Kevin Manning,[4] Dev Niyogi,[6] Enrique Rosero,[1,7] Mukul Tewari,[4] and Youlong Xia[3]

Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Environmental Modelling & Software 21 (2006) 1402–1415
Environmental Modelling & Software
www.elsevier.com/locate/envsoft

Land information system: An interoperable framework for high resolution land surface modeling

S.V. Kumar[a,*], C.D. Peters-Lidard[b], Y. Tian[a], P.R. Houser[b], J. Geiger[b], S. Olden[b], L. Lighty[b], J.L. Eastman[a], B. Doty[c], P. Dirmeyer[c], J. Adams[c], K. Mitchell[d], E.F. Wood[e], J. Sheffield[e]

WATER RESOURCES RESEARCH, VOL. 44, W00B02, doi:10.1029/2007WR006735, 2008

Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models

Martyn P. Clark,[1] Andrew G. Slater,[2] David E. Rupp,[3] Ross A. Woods,[1] Jasper A. Vrugt,[4] Hoshin V. Gupta,[5] Thorsten Wagener,[6] and Lauren E. Hay[7]

AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE
10.1002/2015WR017198

Companion to *Clark et al.* [2015], doi:10.1002/2015WR017200.

A unified approach for process-based hydrologic modeling: 1. Modeling concept

Martyn P. Clark[1], Bart Nijssen[2], Jessica D. Lundquist[2], Dmitri Kavetski[3], David E. Rupp[4], Ross A. Woods[5], Jim E. Freer[6], Ethan D. Gutmann[1], Andrew W. Wood[1], Levi D. Brekke[7], Jeffrey R. Arnold[8], David J. Gochis[1], and Roy M. Rasmussen[1]

AGU PUBLICATIONS

Water Resources Research

COMMENTARY
10.1002/2014WR016731

Do we need a Community Hydrological Model?

Markus Weiler[1] and Keith Beven[2,3,4]

AGU PUBLICATIONS

Water Resources Research

COMMENTARY
10.1002/2015WR017910

Key Points:
- We seek to increase the physical realism of hydrologic models through better way existing theory
- We seek to improve the way models

Improving the theoretical underpinnings of process-based hydrologic models

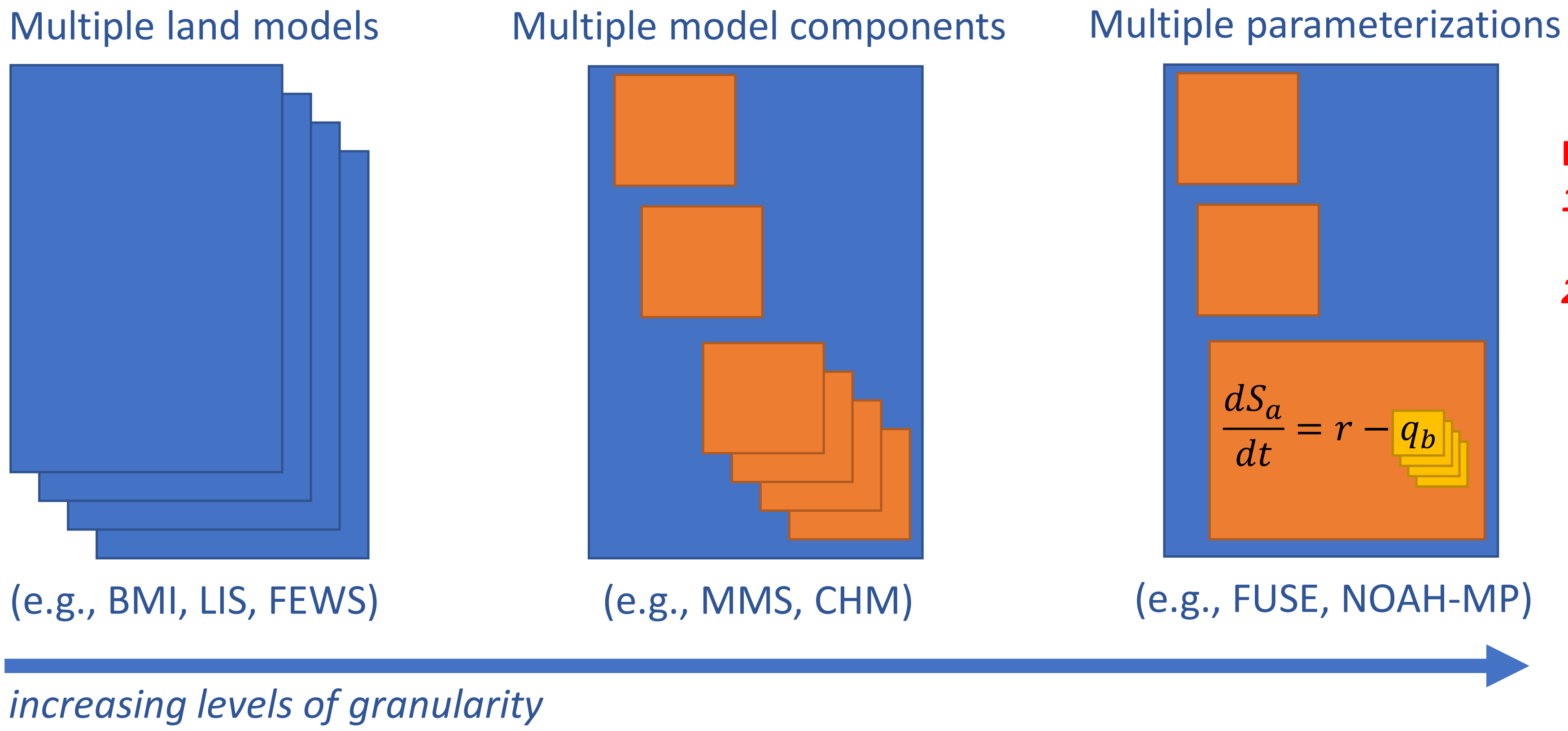
Martyn P. Clark[1], Bettina Schaefli[2,3], Stanislaus J. Schymanski[4], Luis Samaniego[5], Charles H. Luce[6], Bethanna M. Jackson[7], Jim E. Freer[8], Jeffrey R. Arnold[9], R. Dan Moore[10], Erkan Istanbulluoglu[11], and Serena Ceola[12]

Unifying model physics

- **The problem**: There is a glut of hydrological models (Clark et al., WRR 2011) – in many cases there are more models in use than there are algorithms to populate them (same algorithms across multiple models)

- **The challenge:** How can we define a general "master modeling template" (general design principles) from which existing models can be constructed and new models derived (Clark et al., WRR 2015)

- **The challenge:** How can we unify model building blocks across multiple levels of granularity



Multiple land models | Multiple model components | Multiple parameterizations

$$\frac{dS_a}{dt} = r - q_b$$

(e.g., BMI, LIS, FEWS) | (e.g., MMS, CHM) | (e.g., FUSE, NOAH-MP)

increasing levels of granularity

How do you thread the needle between:

1. ***Multiple models*** *that work together in the same framework; and*
2. ***Multiple parameterizations*** *that work together in a plug-and-play environment*

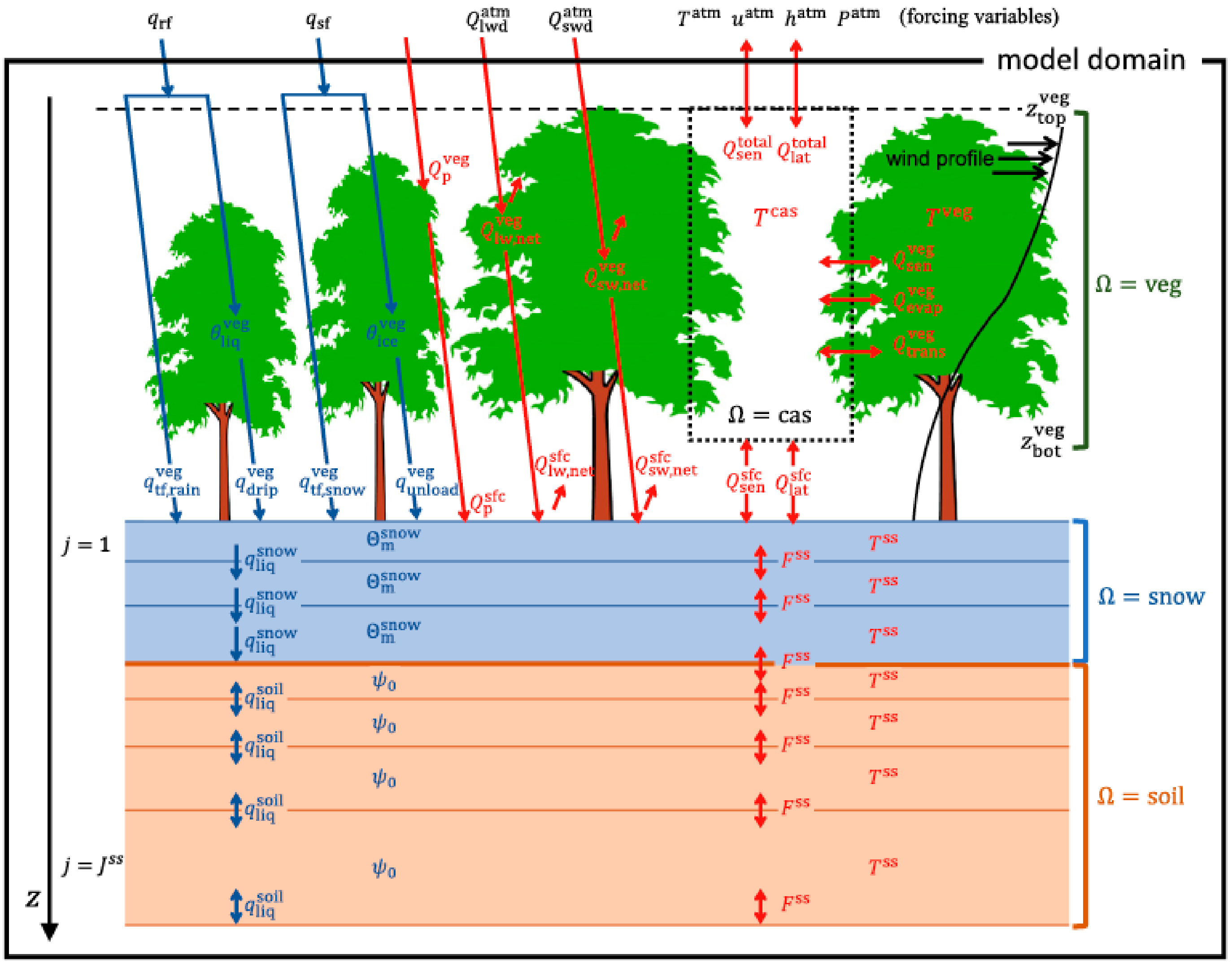
Unifying model physics

- **A general problem formulation**:
  - Sub-domains
    $\Omega = \text{cas}$ (canopy air space)
    $\Omega = \text{veg}$ (vegetation canopy)
    $\Omega = \text{snow}$ (snow)
    $\Omega = \text{soil}$ (soil)
  - State equations

$$\frac{\partial H^{\Omega}}{\partial t} = -\frac{\partial F^{\Omega}}{\partial z} + \mathcal{F}^{\Omega}_{\text{sink}}, \quad \Omega = cas, veg, snow, soil$$

$$\frac{\partial \Theta^{\Omega}_{m}}{\partial t} = -\frac{\partial q^{\Omega}_{\text{ice}}}{\partial z} - \frac{\partial q^{\Omega}_{\text{liq}}}{\partial z} + \mathcal{M}^{\Omega}_{\text{sink}}, \quad \Omega = veg, snow, soil$$

- **The state-space formulation means that different modeling approaches can be incorporated at multiple levels of granularity**
  - Use different coupled equations for a model sub-domain
  - Use a different conservation equation for a given state variable (e.g., canopy interception)
  - Use a different flux parameterization within a given conservation equation (e.g., canopy drainage)
  - Use a different numerical method to solve model equations
- **Enables systematic scrutiny of modeling alternatives (model hypotheses) in support of evidence-based decision-making**



Clark et al. (JHM 2021)

Unifying spatial configurations

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Global Water Futures

➢ Hierarchical spatial organization

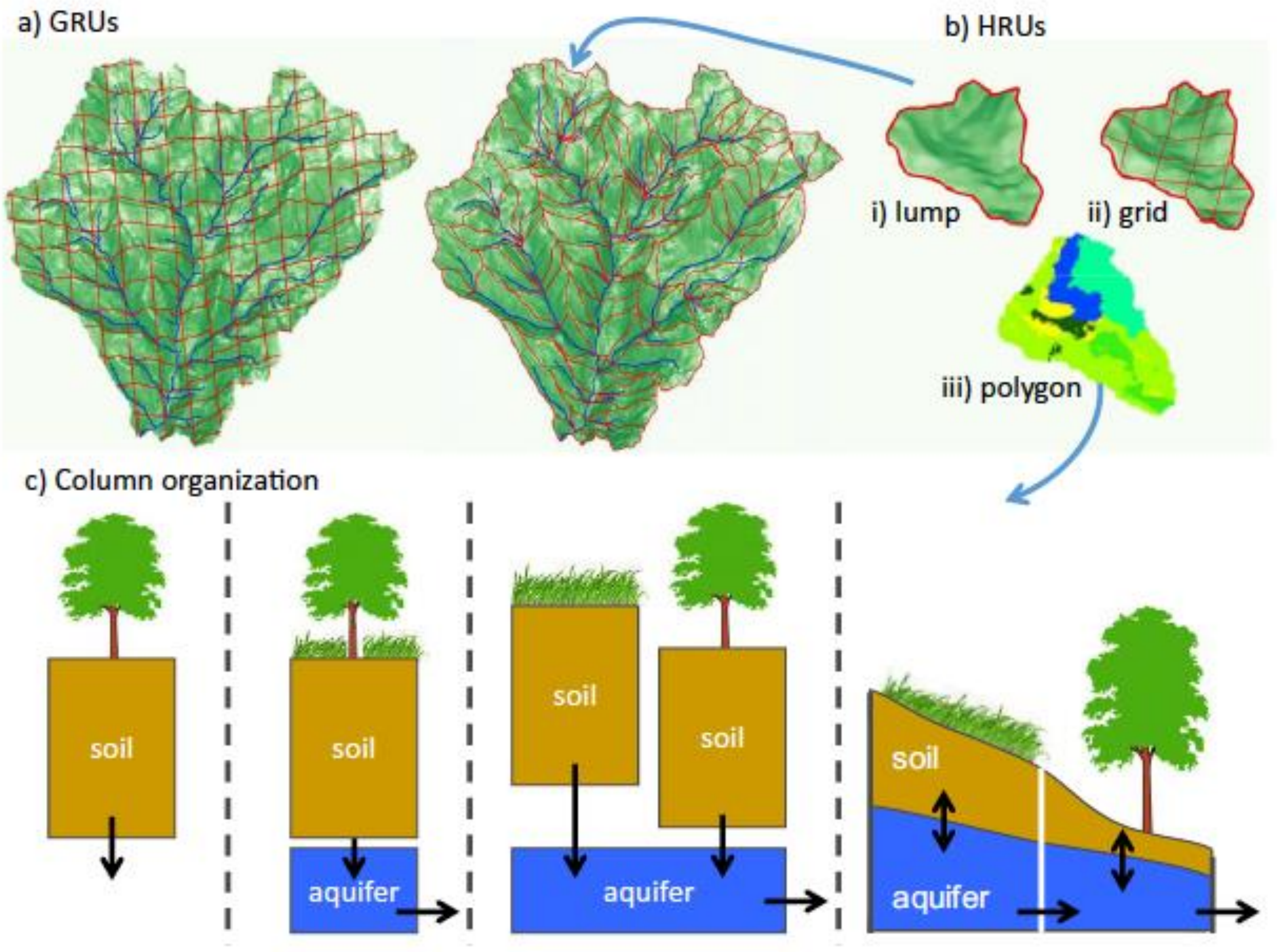
- ❑ Used in RHESSys, CLM, SUMMA, etc.
- ❑ Can reproduce the spatial organization/discretization used in many existing models

➢ GRUs (Grouped Response Units):

- ❑ Grid, sub-basin, etc.
- ❑ GRUs can be any size or shape (but must be spatially contiguous)

➢ HRUs (Hydrological Response Units):

- ❑ Fine mesh, elevation bands, vegetation types, or (more generally) hydrologically similar areas of the landscape
- ❑ HRUs can be any size or shape (need not be spatially contiguous)
- ❑ HRUs can be hydrologically connected



Clark et al. (WRR 2015)

Problems with hydrological models

- Cumbersome and non-reproducible model workflows
- Unwieldy model structures
- Poor numerical implementation
- Statistically-oriented parameter estimation methods
- Weak model evaluation methods

Numerical solution methods

- **Operator splitting:** It can be very difficult to solve equations simultaneously; most models follow a solution sequence
- **Iterative solution procedure:** Many fluxes are a non-linear function of the model states; iterative methods can be used to estimate the state at the end of the time step
- **Numerical error monitoring and adaptive sub-stepping:** Dynamically adjust the length of the model time step to improve efficiency and reduce temporal truncation errors

Consider the example from Woldegiorgis et al. (2022)

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - Q_d - Q_i \tag{11}$$

$$Q_d = k_d S \tag{12}$$

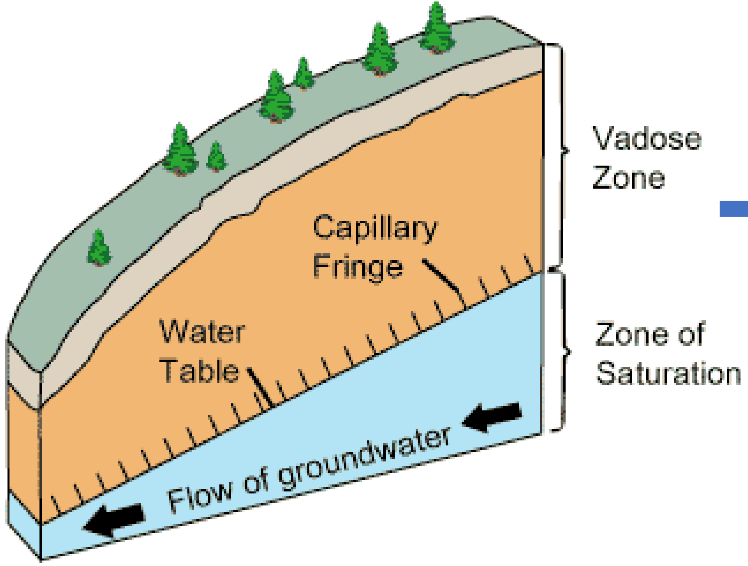
$$Q_i = k_i S \tag{13}$$

where P is precipitation, Q_d is vertical drainage, Q_i is interflow, and k_d and k_i are time constants.

Now consider $P = 0$ and $k_d = k_i = 0.5$. Given $S(t) = 1$, computing fluxes successively means that $Q_d = 0.5$ and $Q_i = 0.25$

What is actually done in practice?

- A very simple land model…

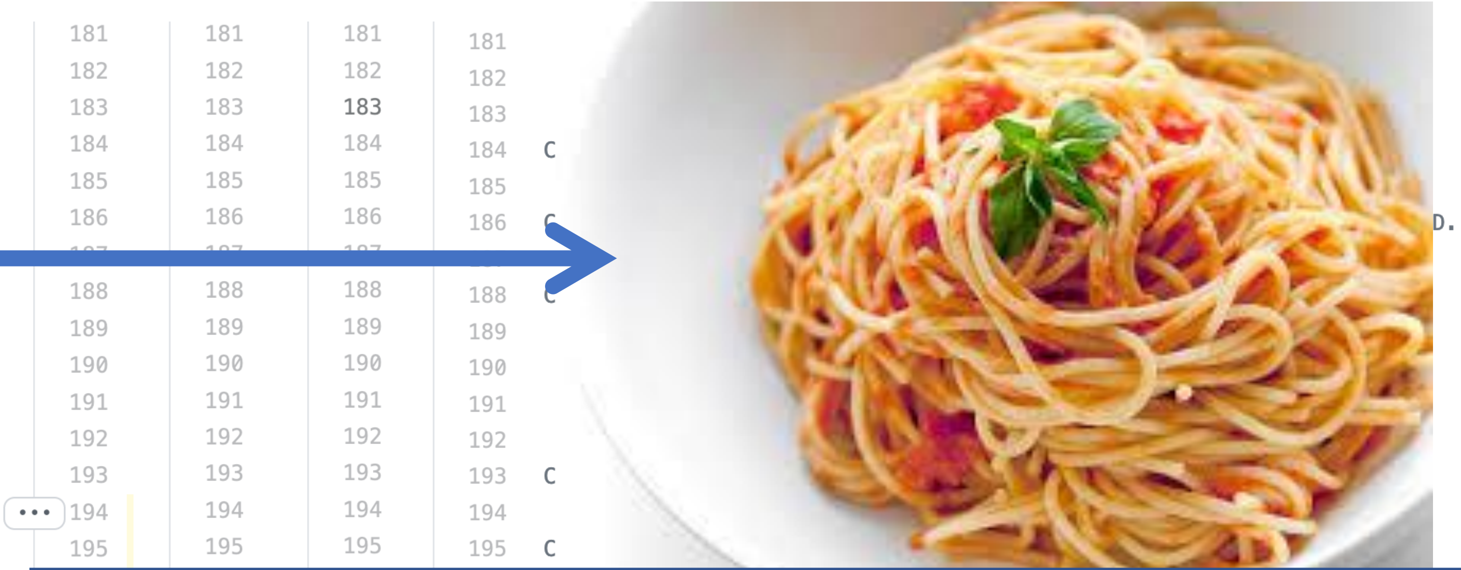


- Conservation equations that can be solved elegantly (at least in principle)

$$\frac{dS_1}{dt} = p - q_{sx} - e - q_{12}$$

$$\frac{dS_2}{dt} = q_{12} - q_b$$

The model used for operational streamflow forecasting in the USA



Key problems:

- The state updates are sprinkled through the source code like confetti at a wedding… the physical representations are intertwined with the numerical solution.
- The numerical solution is difficult to understand (some basic form of operator-splitting). The time step is not even defined explicitly.
- The numerical solution (time evolution of model states = the state updates) does not take advantage of decades of progress in applied mathematics. We can (and should) do better.

What is actually done in practice?

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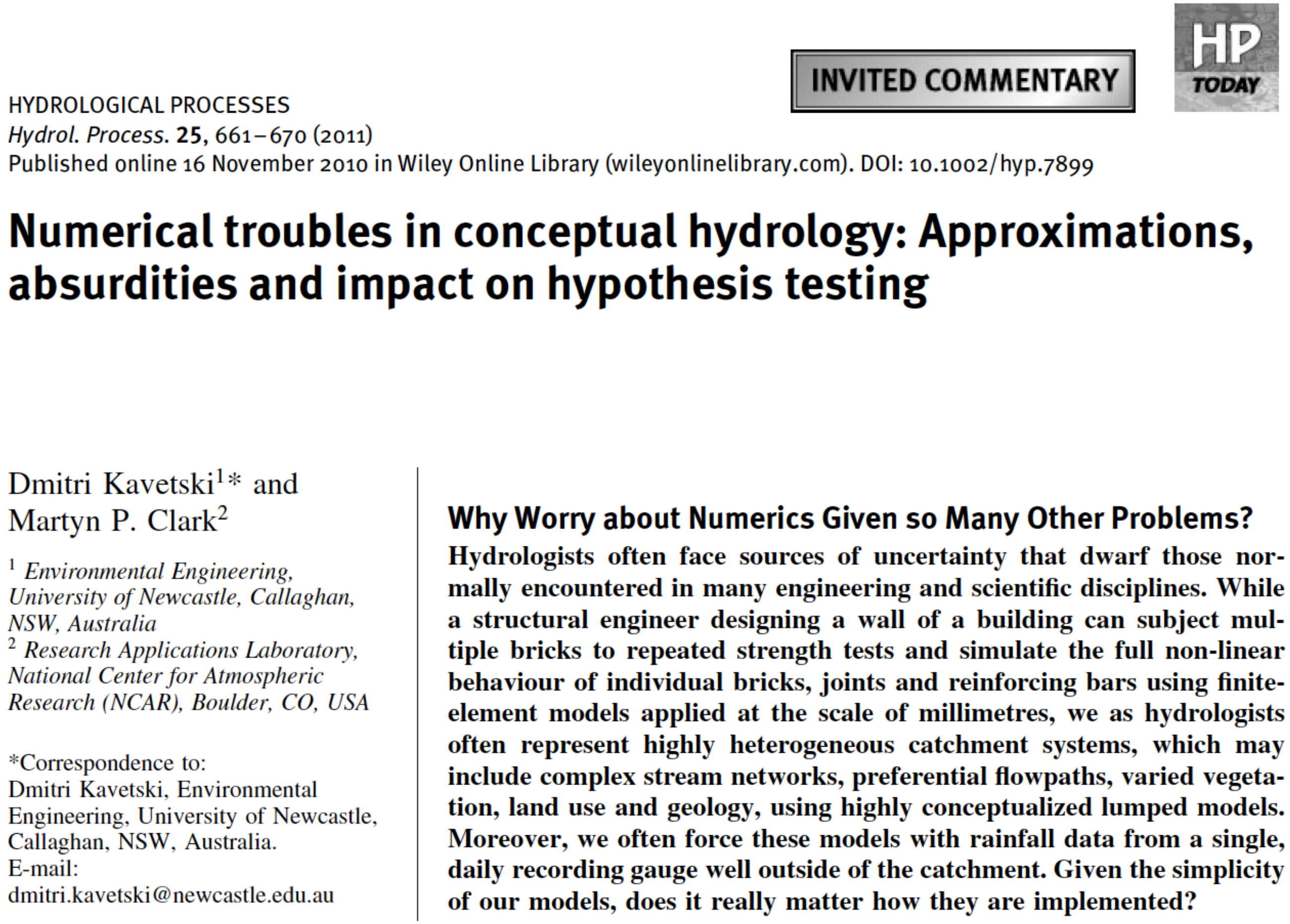

INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **25**, 661–670 (2011)
Published online 16 November 2010 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/hyp.7899

Numerical troubles in conceptual hydrology: Approximations, absurdities and impact on hypothesis testing

Dmitri Kavetski[1]* and
Martyn P. Clark[2]

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[2] *Research Applications Laboratory, National Center for Atmospheric Research (NCAR), Boulder, CO, USA*

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Dmitri Kavetski, Environmental Engineering, University of Newcastle, Callaghan, NSW, Australia.
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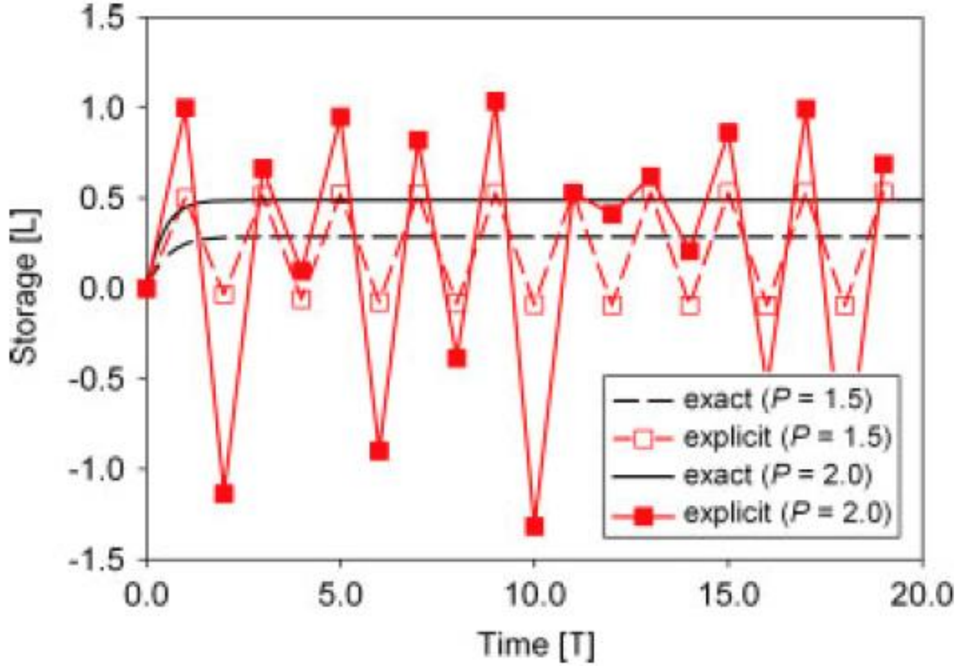
Why Worry about Numerics Given so Many Other Problems?

Hydrologists often face sources of uncertainty that dwarf those normally encountered in many engineering and scientific disciplines. While a structural engineer designing a wall of a building can subject multiple bricks to repeated strength tests and simulate the full non-linear behaviour of individual bricks, joints and reinforcing bars using finite-element models applied at the scale of millimetres, we as hydrologists often represent highly heterogeneous catchment systems, which may include complex stream networks, preferential flowpaths, varied vegetation, land use and geology, using highly conceptualized lumped models. Moreover, we often force these models with rainfall data from a single, daily recording gauge well outside of the catchment. Given the simplicity of our models, does it really matter how they are implemented?

Surprisingly common model implementation…

```
Srz = Srz_ini ! initialize store
DO i = 1, n   ! loop over time steps
  ! calculate outflow using parameters
  outflow(i) = b * exp(k * Srz)
  ! update storage
  Srz = Srz + inflow(i) — outflow(i)
END DO
```



A cleaner and more robust way to construct models…

- The model state equations can be written as

$$\frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \mathbf{g}\left(\mathbf{S}, t\right)$$

- The exact solution of the average flux over the interval t^n (start of the time step) to t^{n+1} (end of the time step) is

$$\overline{\mathbf{g}}^{n \to n+1} = \frac{1}{\Delta t} \int_{t^n}^{t^{n+1}} \left(\mathbf{g}(\mathbf{S}, \varsigma), \varsigma\right) \mathbf{d}\varsigma$$

  - *The exact solution is computationally expensive, so approximations to the exact solution are used*
  - *The approximation controls the stability, accuracy, smoothness, and efficiency of the solution*

- Given an estimate of the average flux, the model state variables can be updated as

$$\mathbf{S}\left(t^{n+1}\right) = \mathbf{S}\left(t^{n}\right) + \Delta t \overline{\mathbf{g}}^{n \to n+1}$$

- Note the separation of the physics from the numerical solution – hydrologists can “worry” about $\mathbf{g}(\cdot)$ and numerical analysts can “worry” about how to obtain $\mathbf{S}$.

Build complex models "from the inside out"

➢ A general problem formulation:

- ❑ Sub-domains
  - $\Omega = \mathrm{cas}$ (canopy air space)
  - $\Omega = \mathrm{veg}$ (vegetation canopy)
  - $\Omega = \mathrm{snow}$ (snow)
  - $\Omega = \mathrm{soil}$ (soil)
- ❑ State equations

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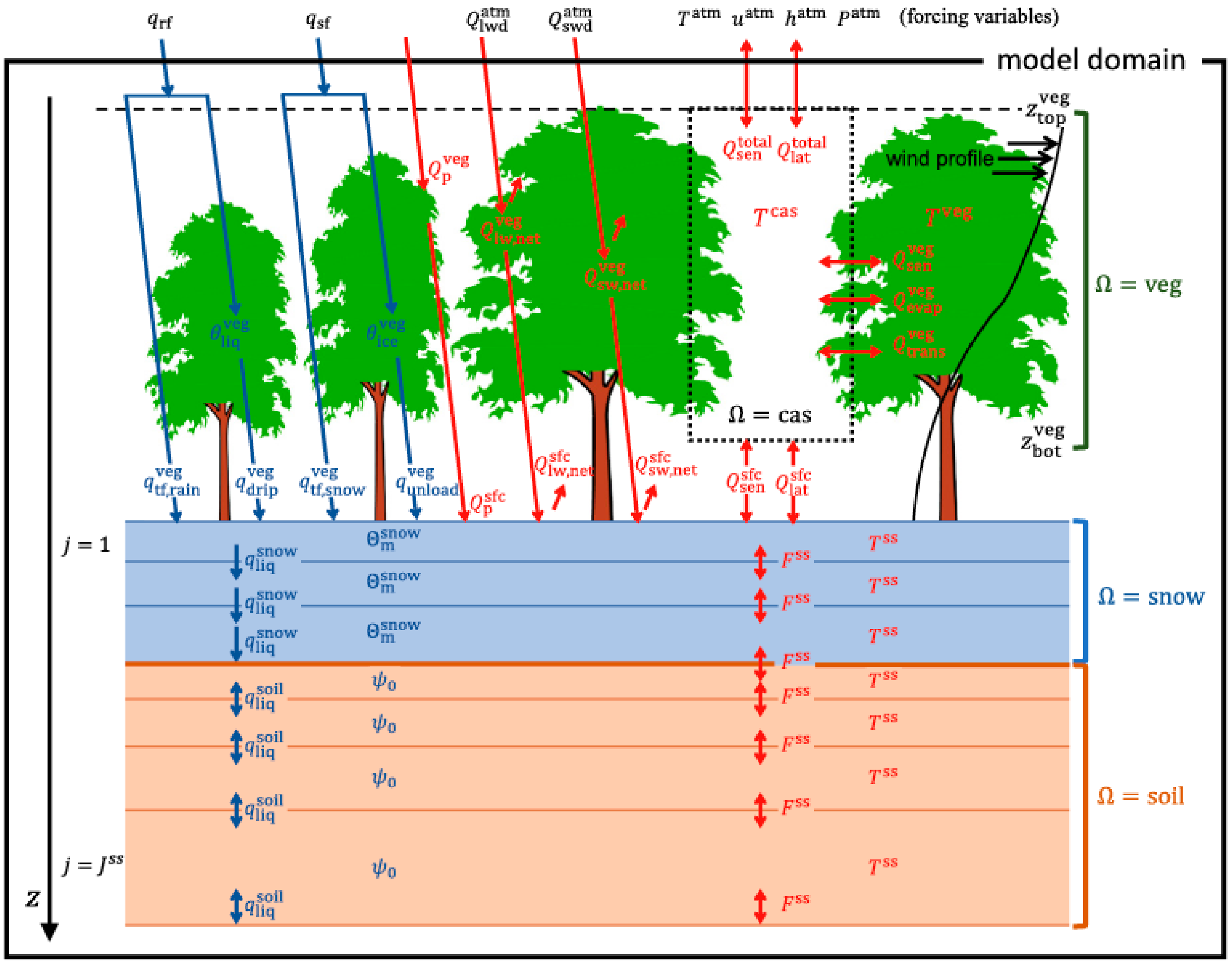
➢ Separate the parameterization of physical processes from their numerical solution

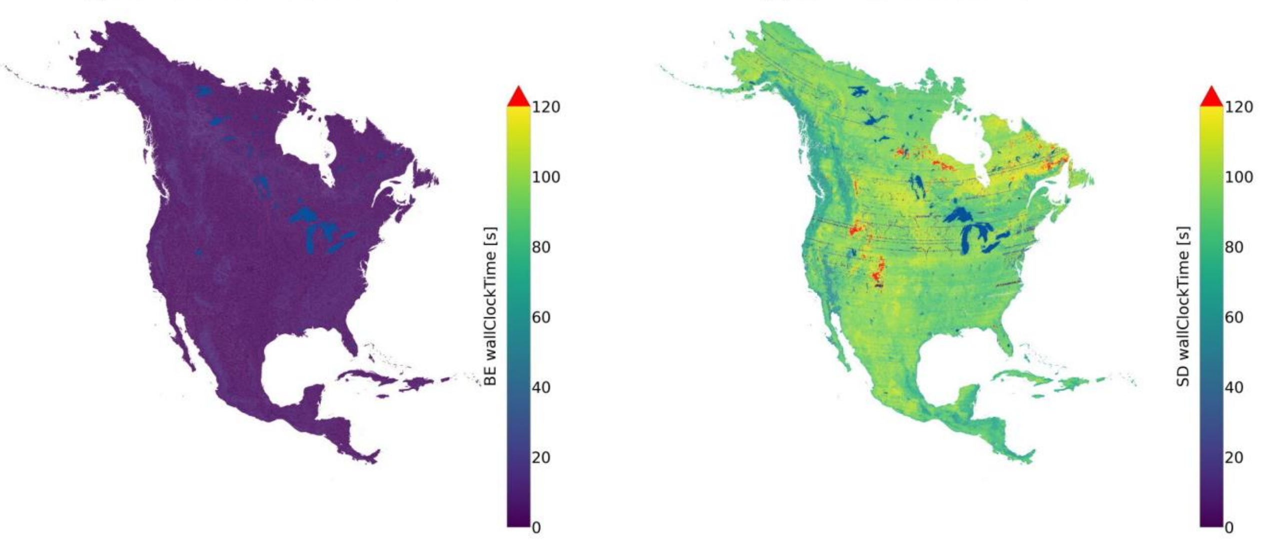
- ❑ Given a model state vector, calculate the fluxes and the derivatives of the fluxes with respect to the relevant state variables
- ❑ Enables experimenting with alternative numerical solution methods (e.g., 3rd party solvers, new numerical solutions)



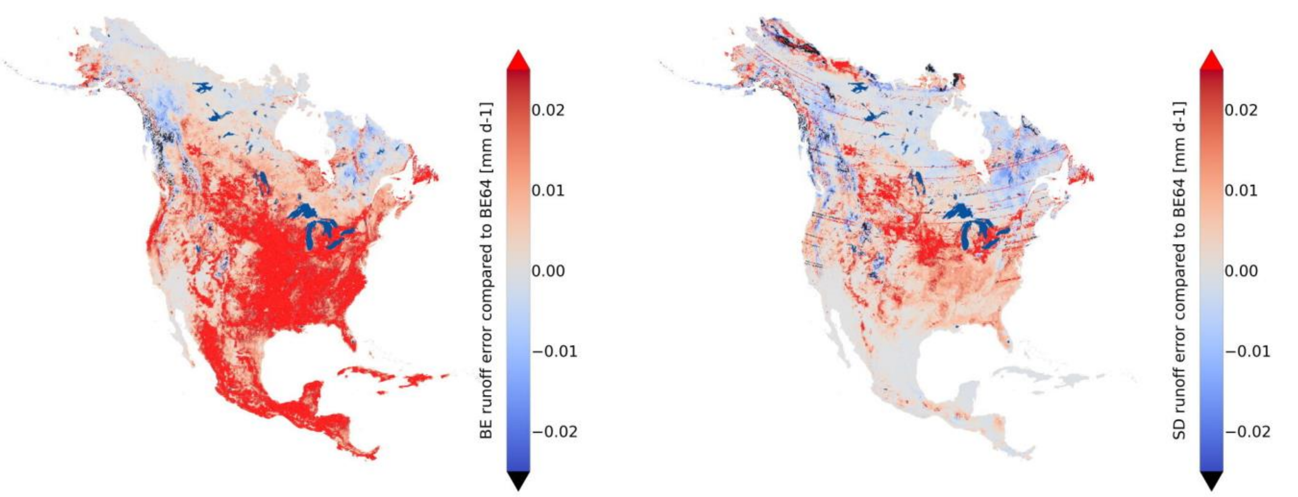
Clark et al. (JHM 2021)

Robust numerical solutions

- **Separate the physical representations from their numerical solution**
  - ❑ Use of industry-standard solvers (SUNDIALS)
  - ❑ Take advantage of decades of progress in numerical analysis
- **The common numerical solution strategies in land models are quite different than the industry standard**
  - ❑ Land models typically use Backward Euler, taking a step as large as possible (typically the entire length of the data window) – can require many iterations and can have large error
  - ❑ SUNDIALS uses variable-order variable-stepsize methods, taking steps that are as large as possible while respecting error tolerances
- **Solving all equations simultaneously is a blunt instrument**
  - ❑ Different processes "act" on different time scales
  - ❑ Need controlled operator splitting methods that take advantage of the unique aspects of the problem (link to model design)
- **The use of more advanced numerical solvers means computational hot spots change over time**
  - ❑ In "standard" parallelization methods the spatial decomposition is constant in time
  - ❑ Need more agile parallelization methods to address the temporal variability in computational hot spots


(a) Backward Euler wall clock time

(b) SUNDIALS wall clock time


(c) Backward Euler runoff error

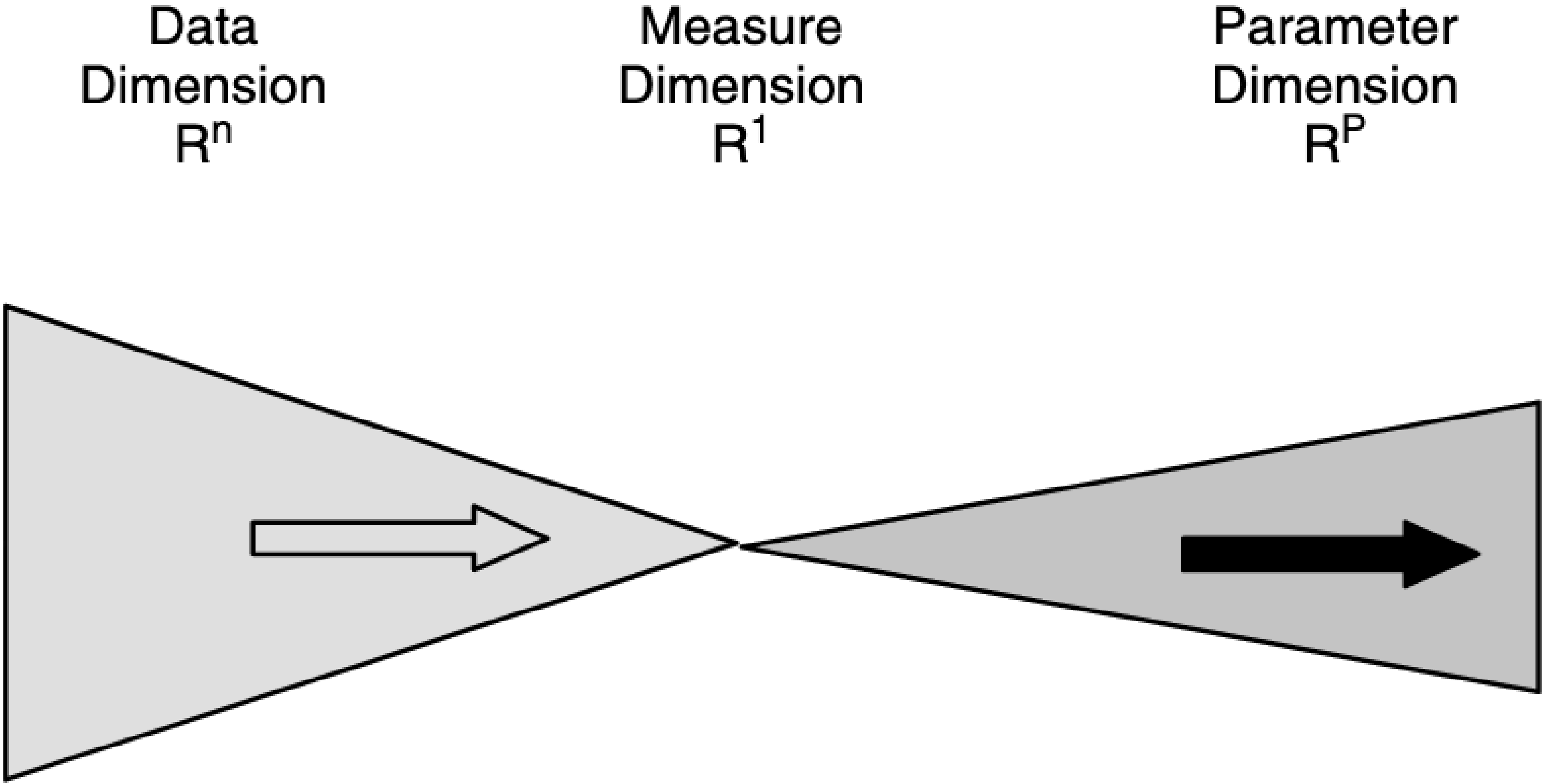
(d) SUNDIALS runoff error

Spiteri et al. (WRR in prep)

Problems with hydrological models

- Cumbersome and non-reproducible model workflows
- Unwieldy model structures
- Poor numerical implementation
- Statistically-oriented parameter estimation methods
- Weak model evaluation methods

The classical approach to model evaluation



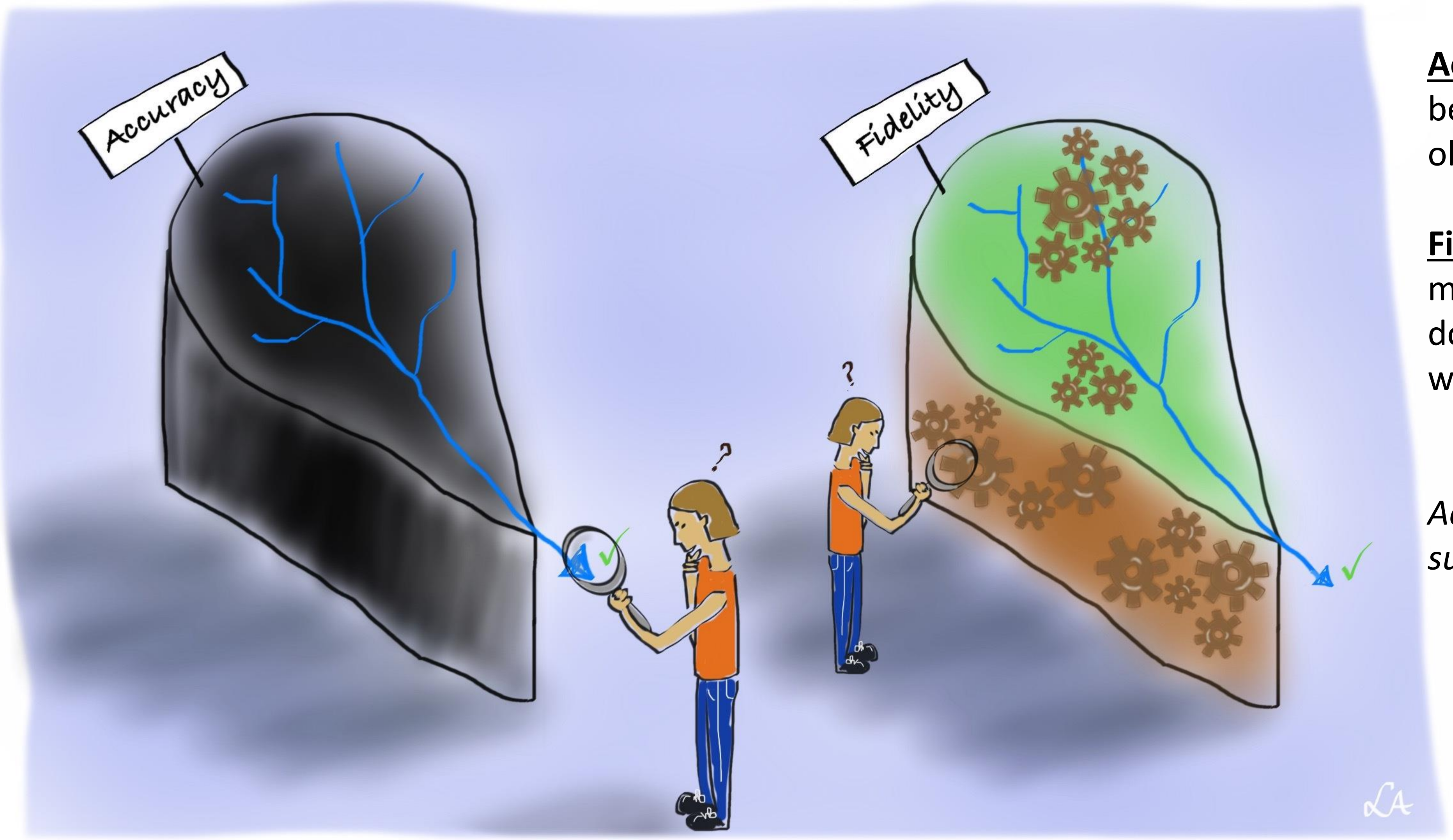
Data Dimension R^n

Measure Dimension R^1

Parameter Dimension R^P

Gupta et al., HP 2008

The quest for “fidelious” models



Accuracy describes discrepancies between model simulations and observations

Fidelity describes the extent a model faithfully represents the dominant processes in the region where it is applied.

Accuracy is a necessary (yet not sufficient) condition for fidelity.

Just for fun: https://uofs-comphyd.github.io/blog/fidelious

@ArnalLouise

Problems with hydrological models

- Cumbersome and non-reproducible model workflows
- Unwieldy model structures
- Poor numerical implementation
- Statistically-oriented parameter estimation methods
- Weak model evaluation methods and weak theoretical underpinnings

Laugh tests for land models

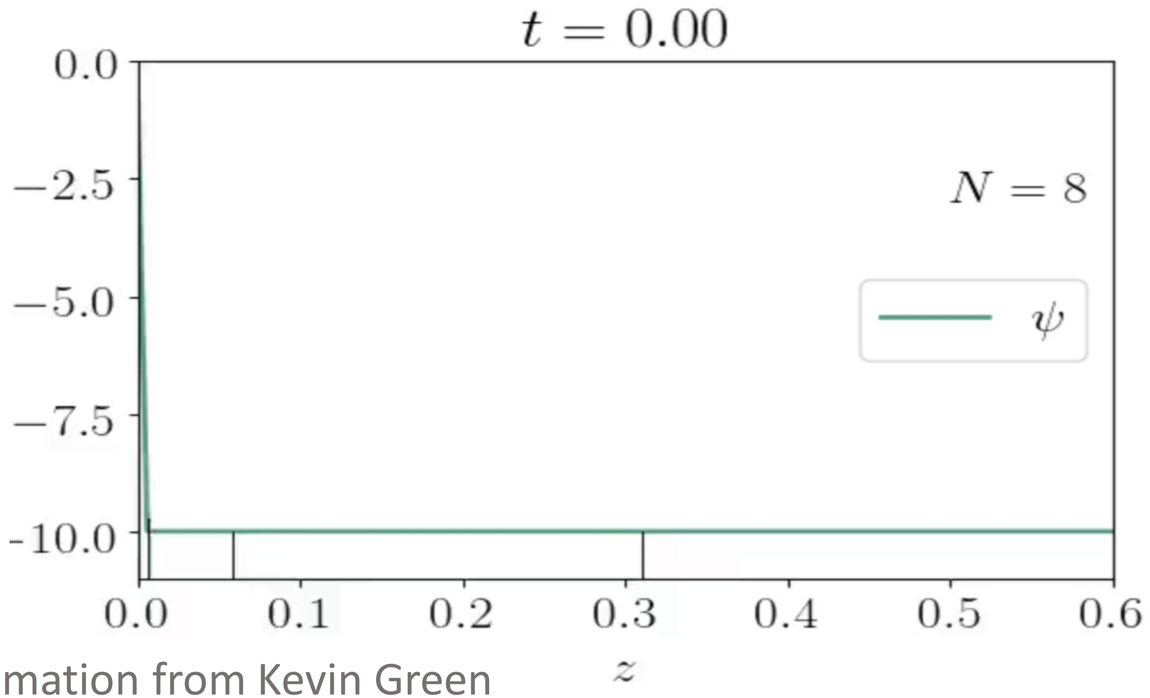
Laugh tests

- Also known as *synthetic test cases* or *functional unit tests*
- Evaluate the implementation of the model equations, including impacts of numerical approximations
- Considered “laugh tests” because they provide the most rudimentary test of model capabilities
- If a model fails a laugh test, then it is difficult to seriously consider the use of the model for its intended applications

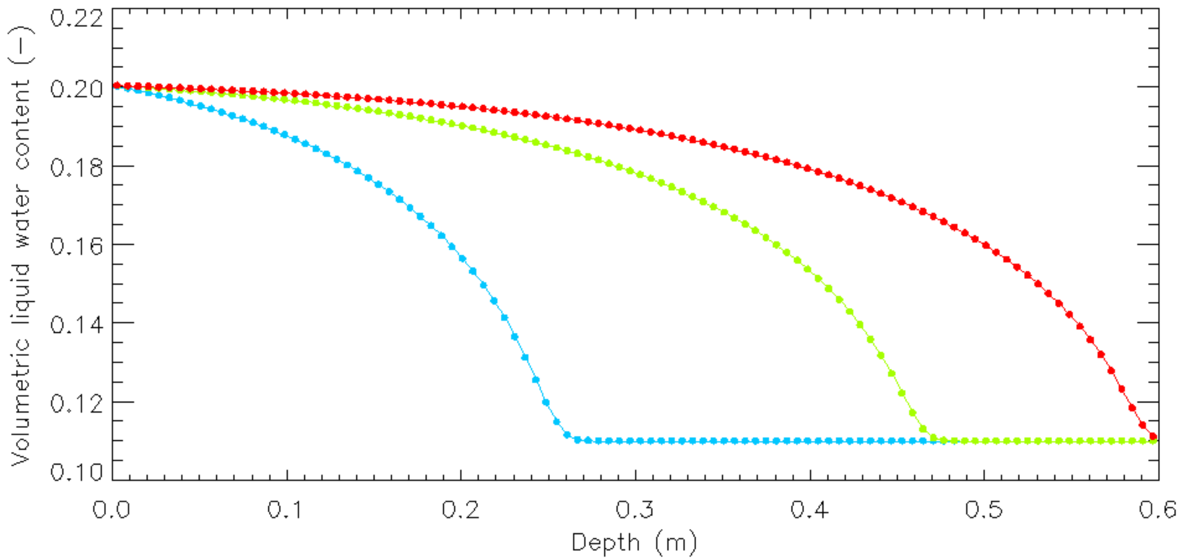
Laugh test: Infiltration into dry soil

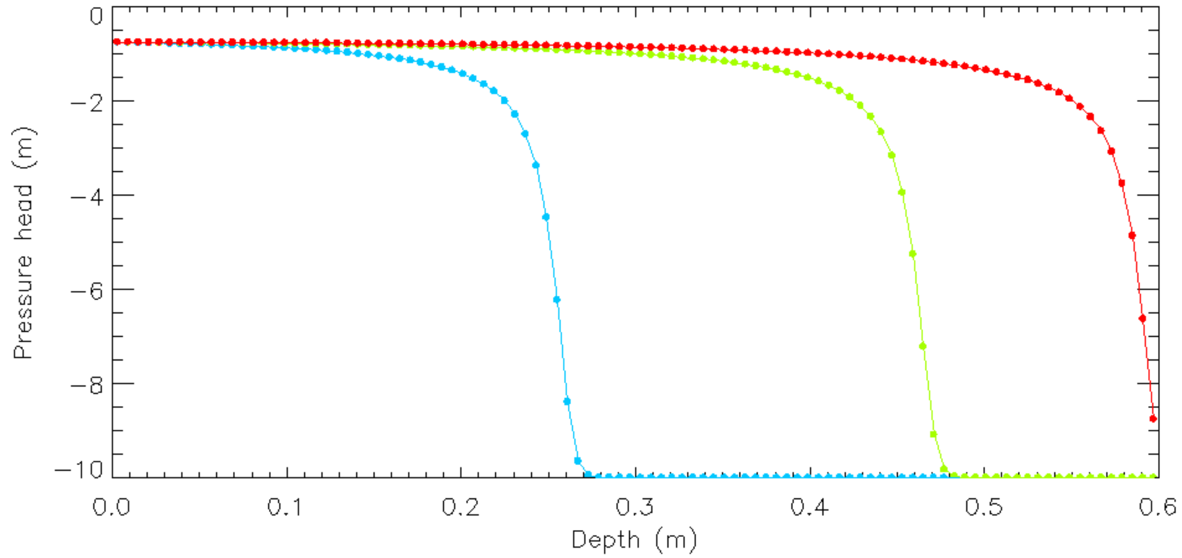
Core Modelling Team

- Mixed form of Richards equation (Celia et al., 1990)
- Blue/green/red = SUMMA outputs at different times
- SUMMA simulations match expected volumetric water content (top; compare Fig. 1 in Kavetski et al, 2002)
- SUMMA simulations match expected pressure profiles (bottom; compare Fig. 1 in Kavetski et al, 2001)



Animation from Kevin Green





Laugh test: Steady-state flux in a layered soil profile

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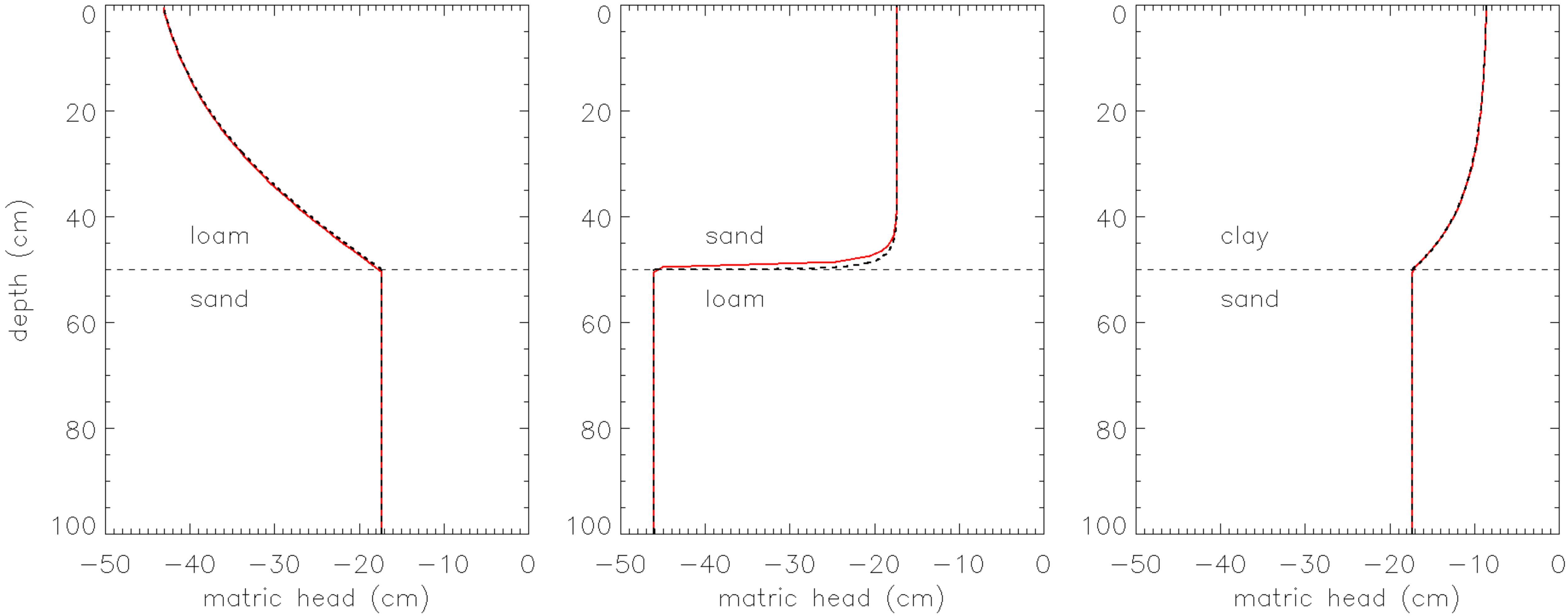
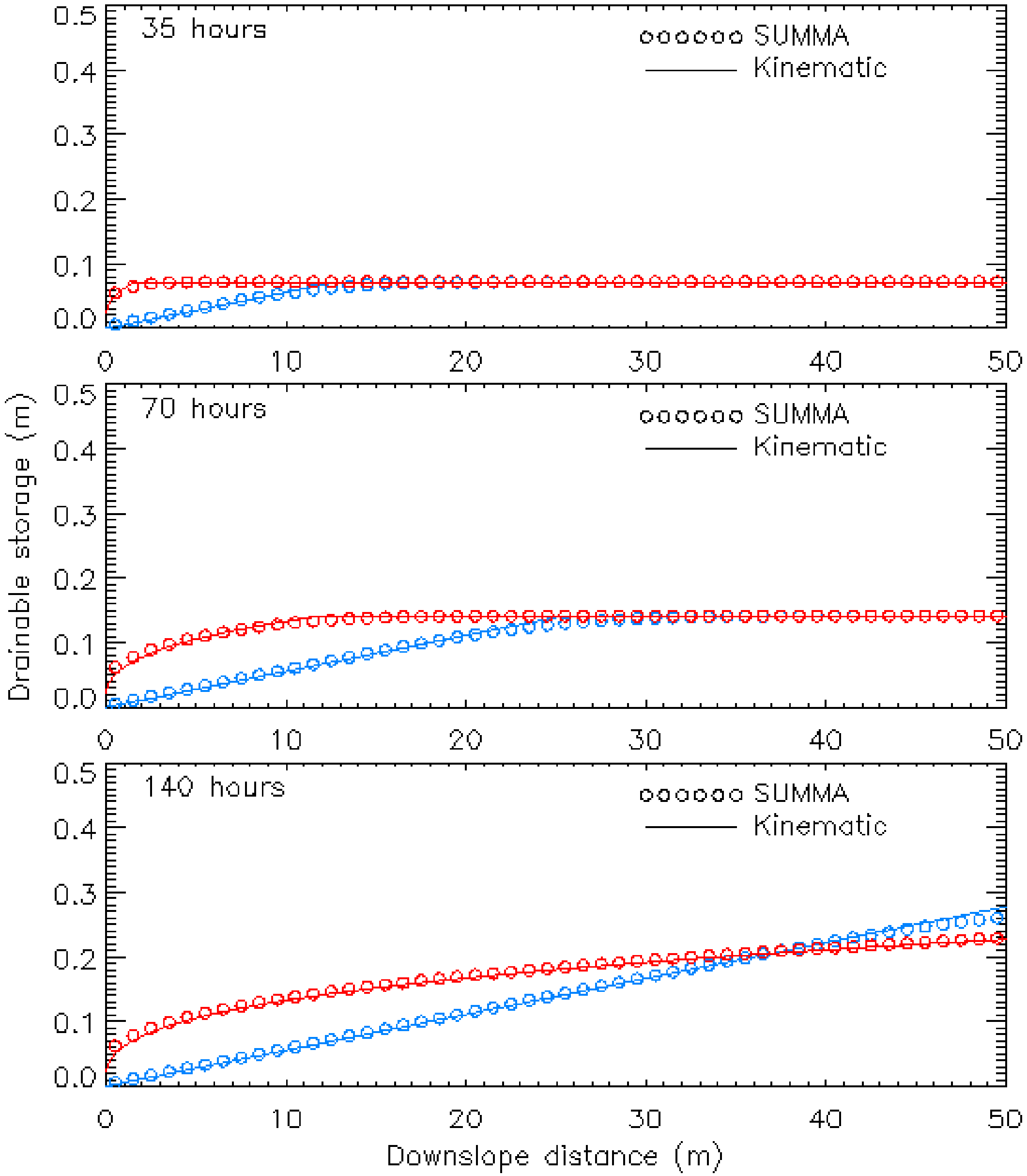


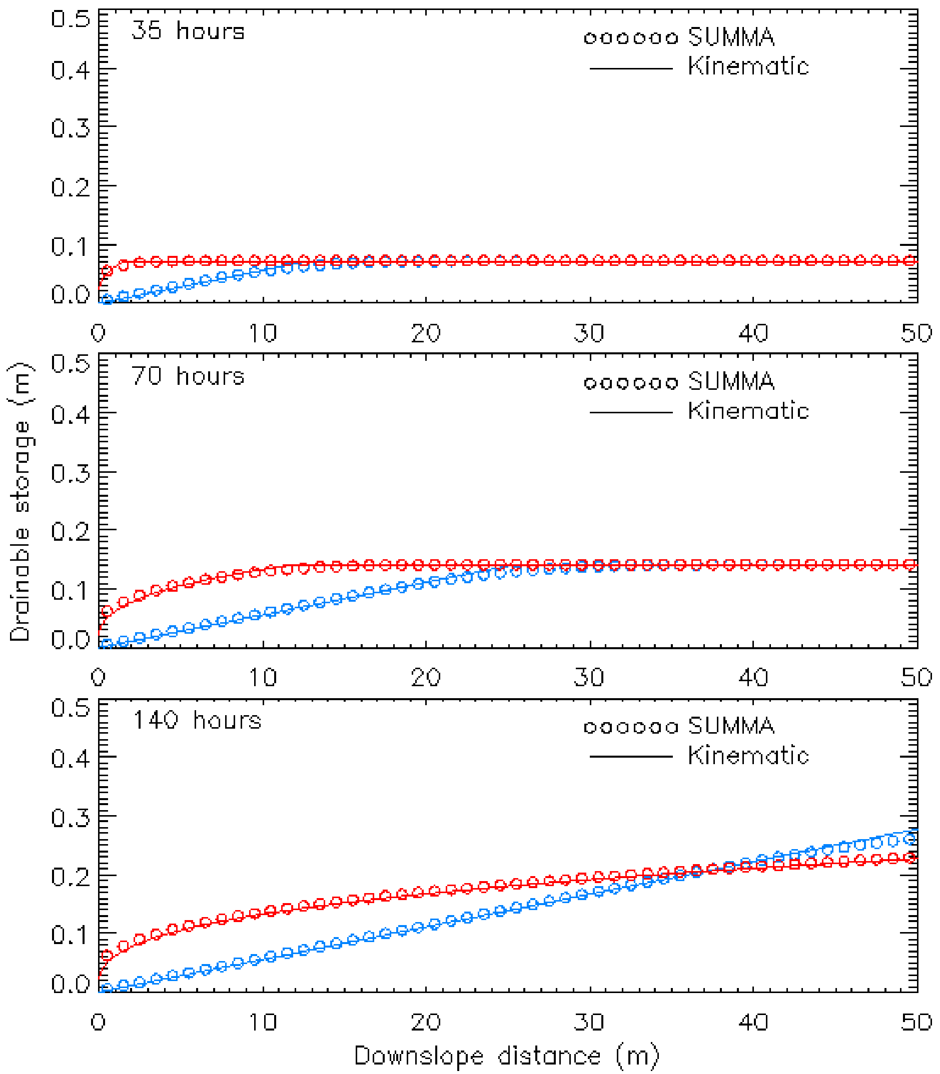
- Analytical solution of pressure head profile in layered soil (eq. 14 in Vanderborght et al, 2005)
- SUMMA simulations (red) closely resemble analytical solution (black)

Laugh test: Lateral flow on a hillslope

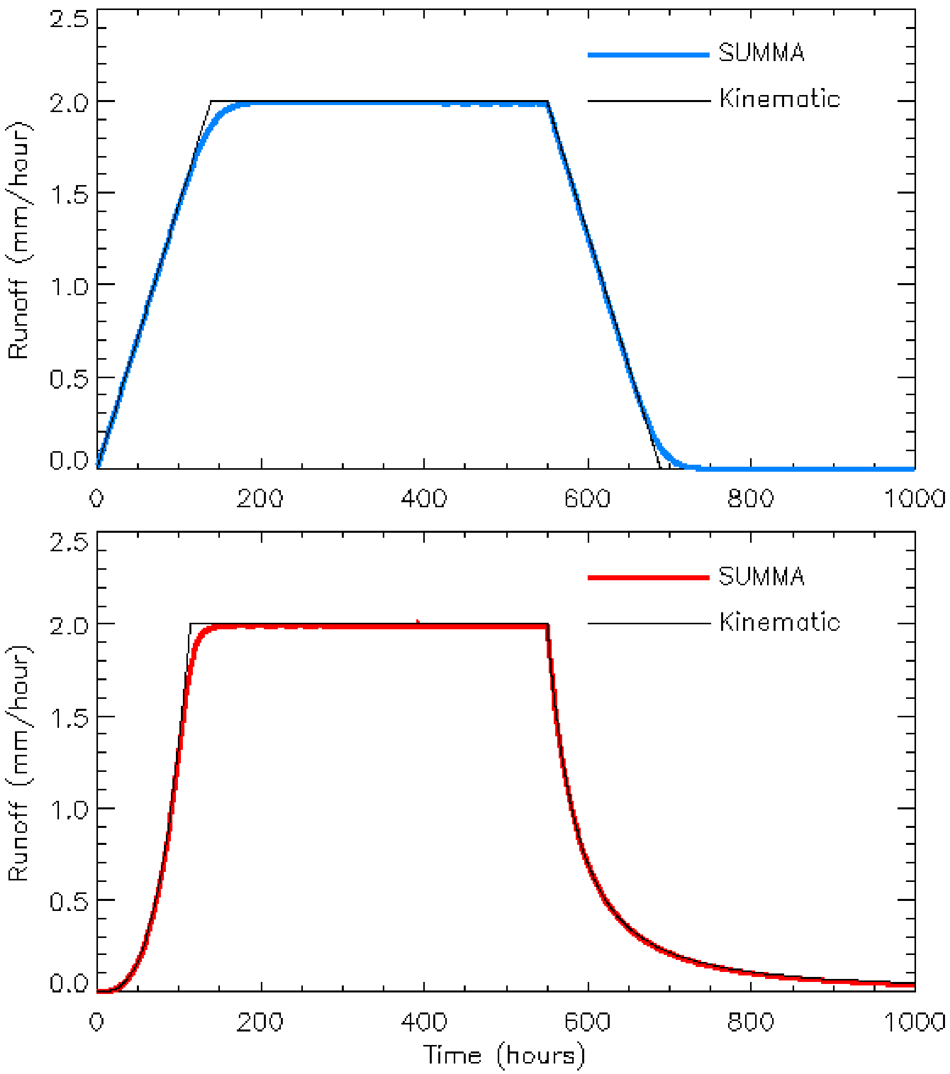


- Flow through uniform soil for a plane with constant slope (Wigmosta & Lettenmaier, 1999)
- Blue: linear transmissivity function
  Red: power law transmissivity (n=3)

Laugh test: Lateral flow on a hillslope



SUMMA closely resembles analytical solution for storage

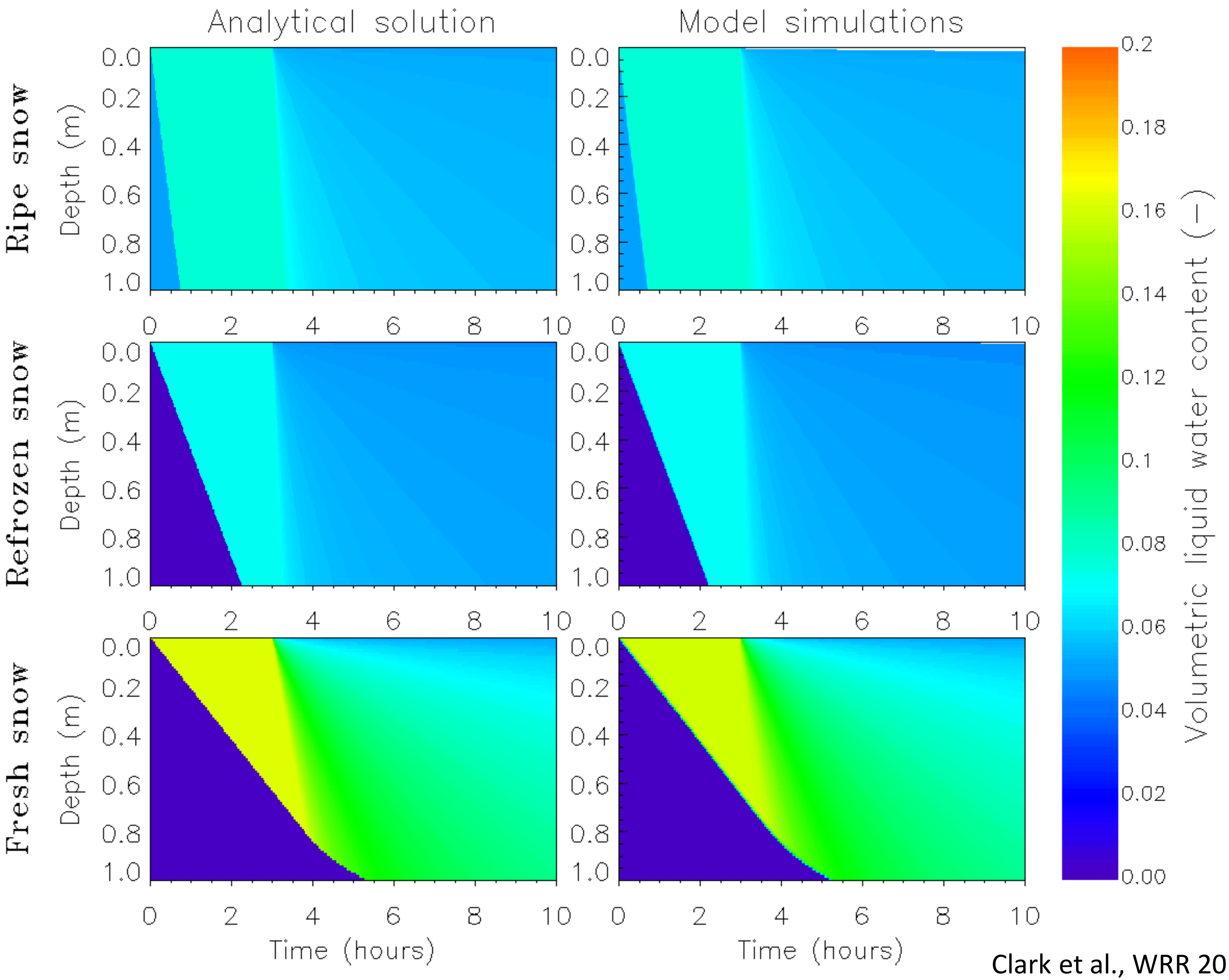


SUMMA closely resembles analytical solution for runoff

Laugh test: Water movement through snow

Core Modelling Team

- Originally based on numerical experiments from Colbeck (1976): *Rainfall for duration of three hours on a one-meter snowpack; different snowpack initial conditions*
- Analytical solutions completed to provide estimates of volumetric liquid water content at every point in space and time
- Useful to evaluate coupled hydrological and thermodynamic processes in snow
- Close correspondence between numerical and analytical solutions.



Clark et al., WRR 2017

Laugh test: Water movement through snow

Global Water Futures

Core Modelling Team

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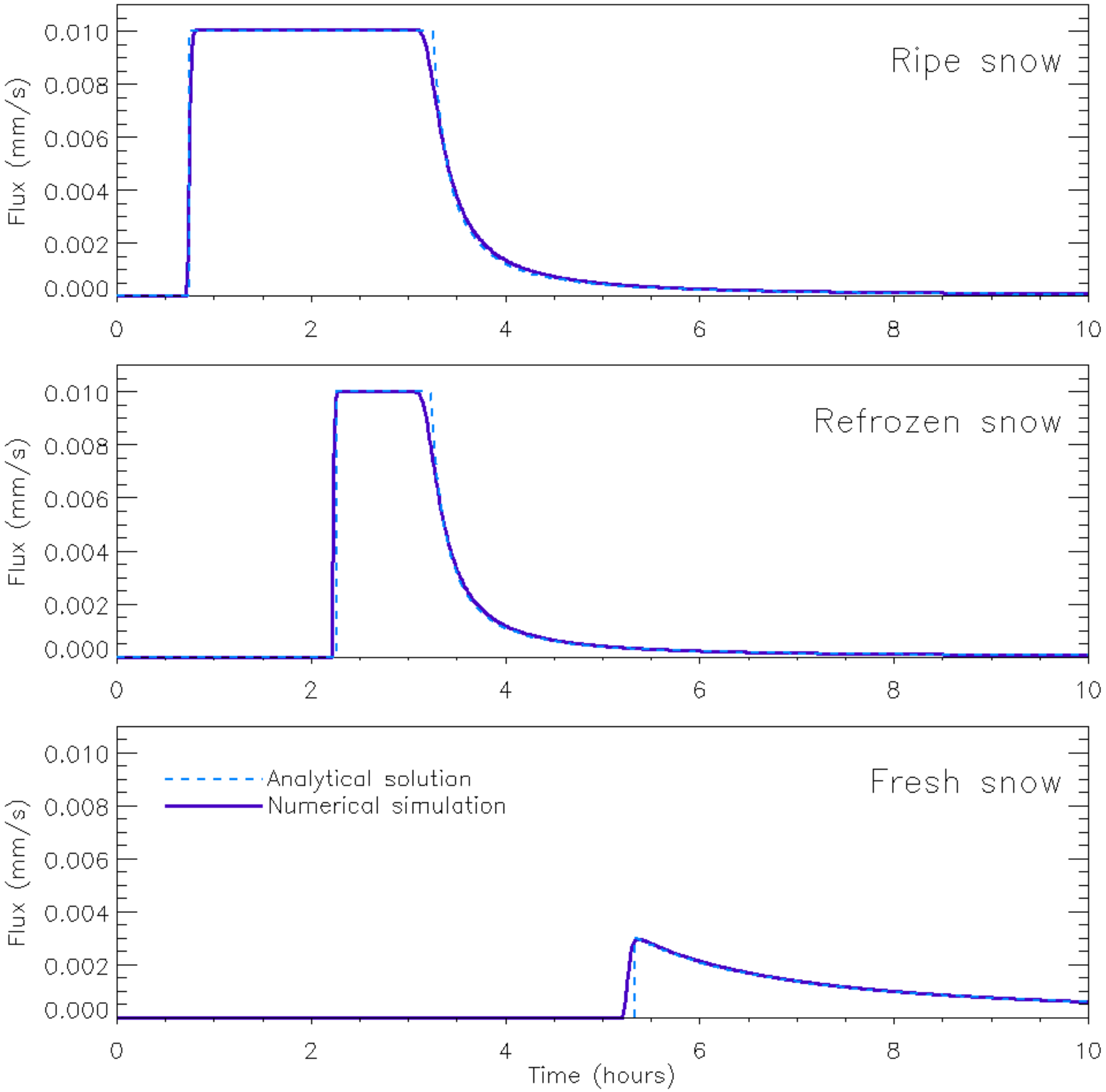


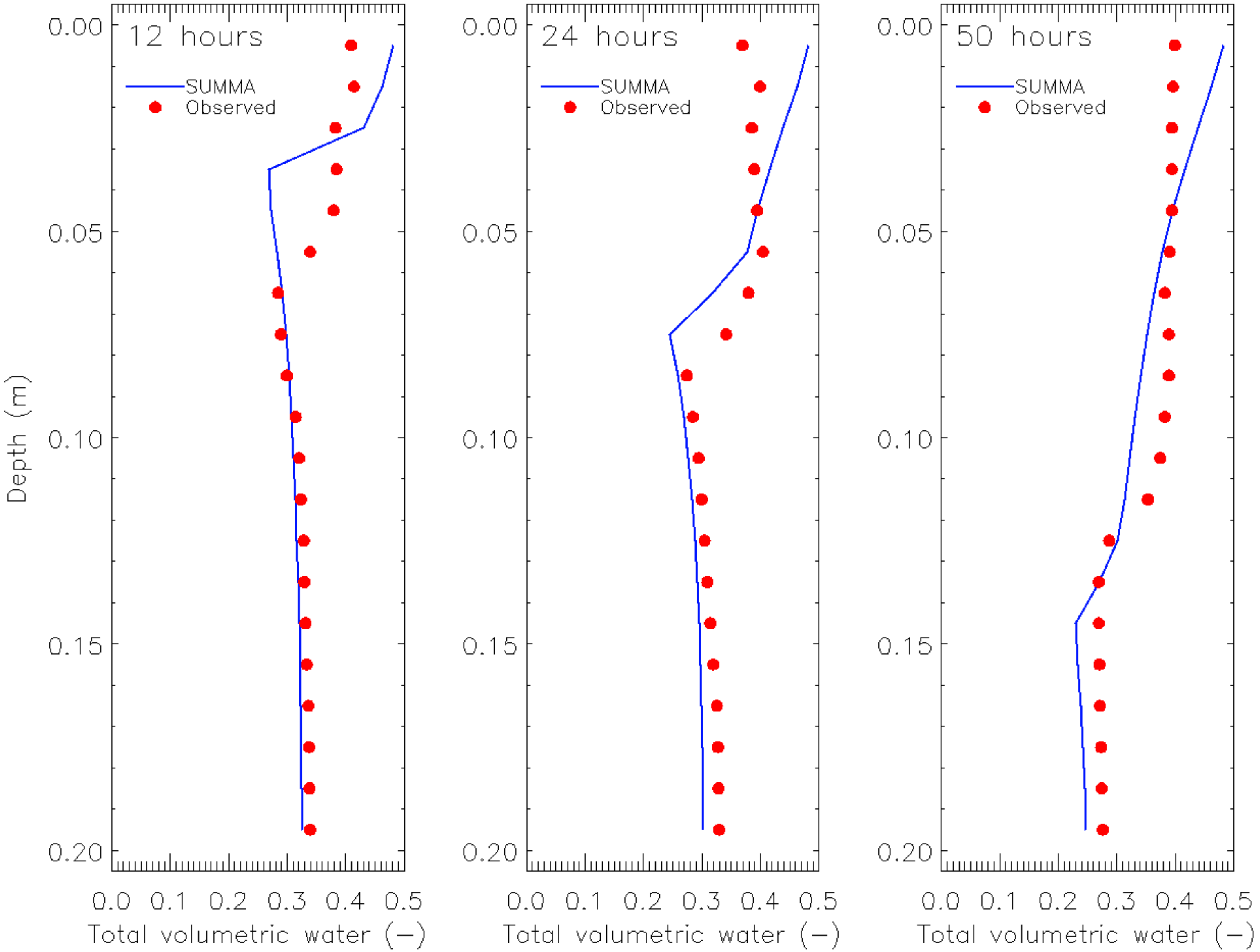
Clark et al., WRR 2017

Laugh test: Cryosuction

Core Modelling Team

Global Water Futures

- Laboratory observations of cryosuction: soil columns with vertically constant initial water content were subjected to cooling from above for different time periods (Mizoguchi, 1990)
- Cryosuction: Freezing sets up negative pressure gradients and causes migration of water to the freezing front
- SUMMA simulations show the general effect of cryosuction processes
- As with other models, SUMMA deviates somewhat from observations (here we only expect to mimic the cryosuction behaviour)

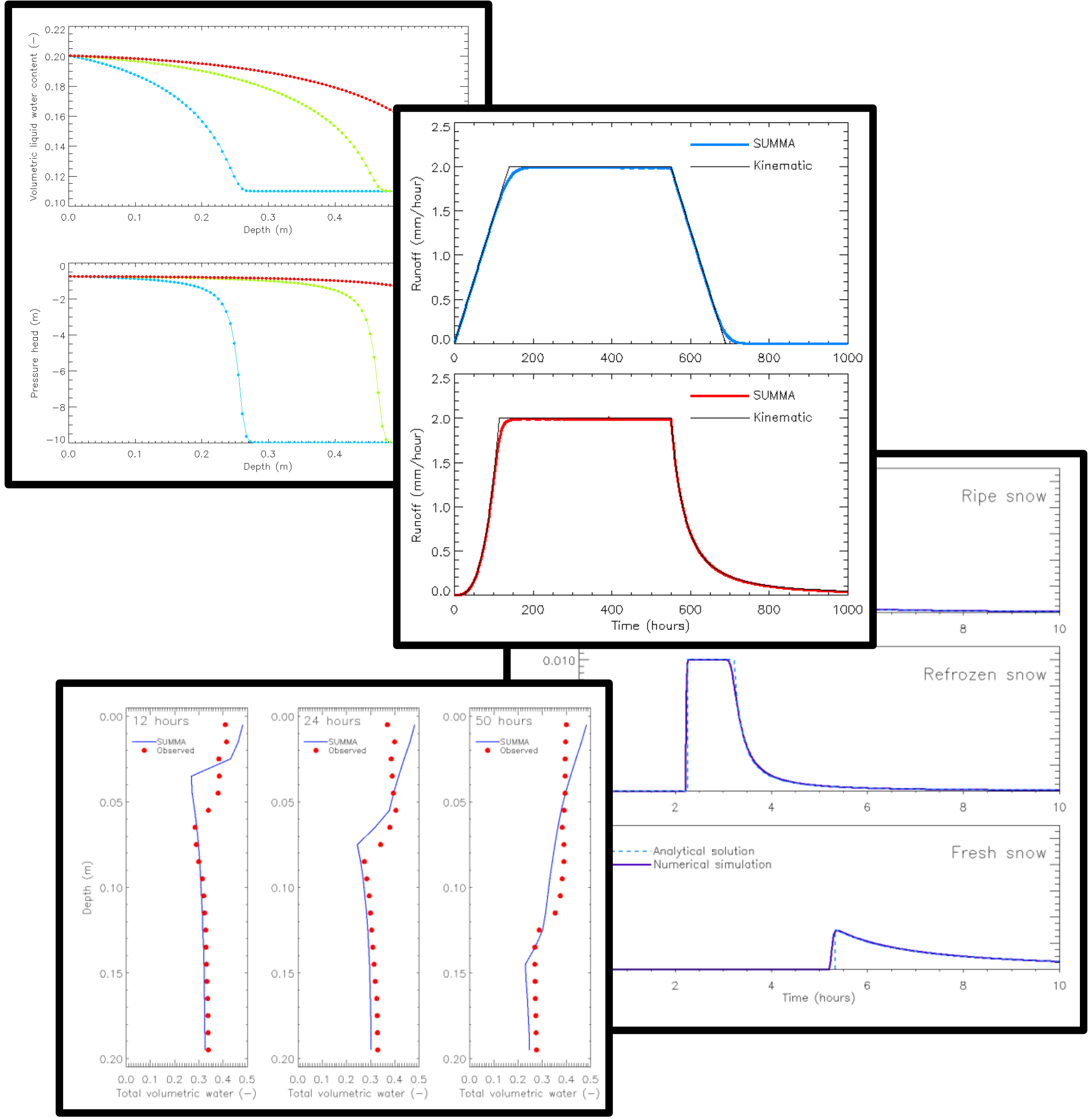


Laugh tests: Summary

- Three different laugh tests (functional unit tests):
  - ☐ *Compare to simulations from other papers*
  - ☐ *Compare to analytical solutions*
  - ☐ *Compare to lab experiments*

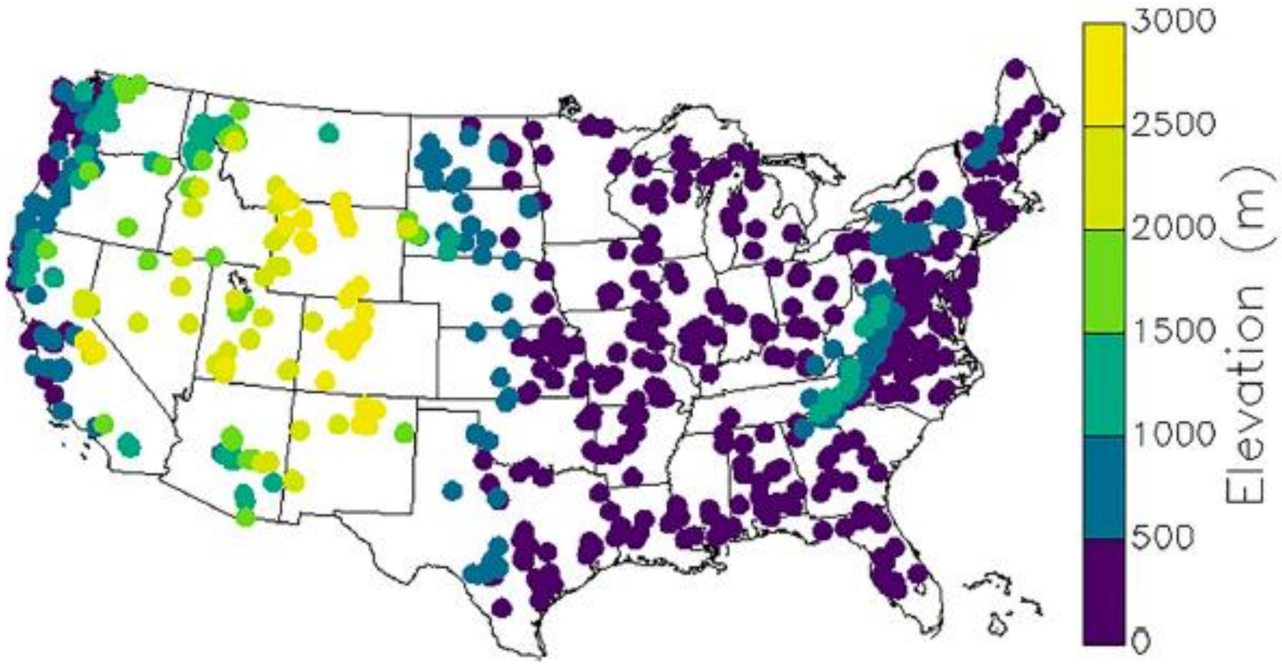
- Synthetic test cases (functional unit tests are considered “laugh tests” because they provide the most rudimentary test of model capabilities.
  - ☐ *If a model fails a laugh test, then it is difficult to seriously consider the use of the model for its intended applications*

- Laugh tests evaluate the implementation of the model equations, including impacts of numerical approximations



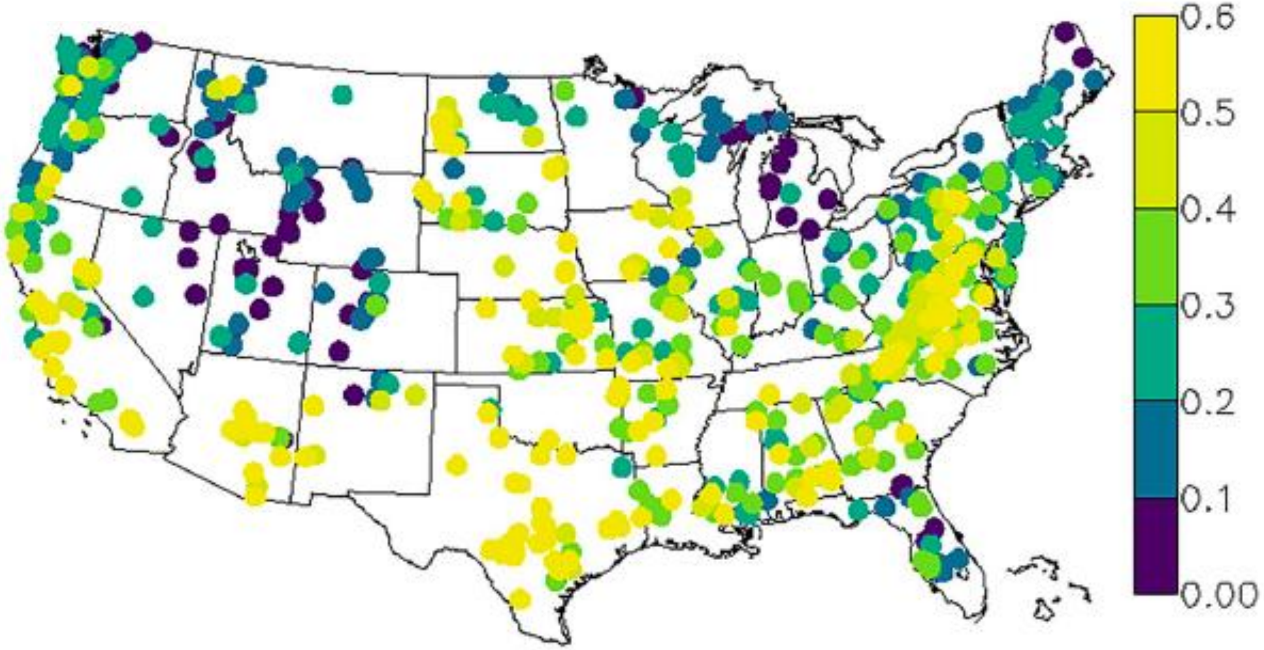
Sampling uncertainty in performance metrics

- Large sample analysis of CAMELS catchments
  - ❑ VIC simulations from Mizukami et al. (HESS 2019)
  - ❑ VIC calibrated using DDS by maximizing the $\widehat{NSE}$ and $\widehat{KGE}$ performance metrics (separate calibrations for each basin)
- Quantify the influence of individual data points
  - ❑ Rank values of squared errors for all time steps
  - ❑ Calculate influence of *k* largest errors on the sum of squared errors
- Quantify uncertainties in the $\widehat{NSE}$ and $\widehat{KGE}$ metrics
  - ❑ Non-overlapping block sampling
  - ❑ Jackknife estimates of standard error
  - ❑ Bootstrap estimates of standard error and tolerance intervals
- Quantify the standard error in the bootstrap tolerance intervals
  - ❑ Jackknife-after-bootstrap

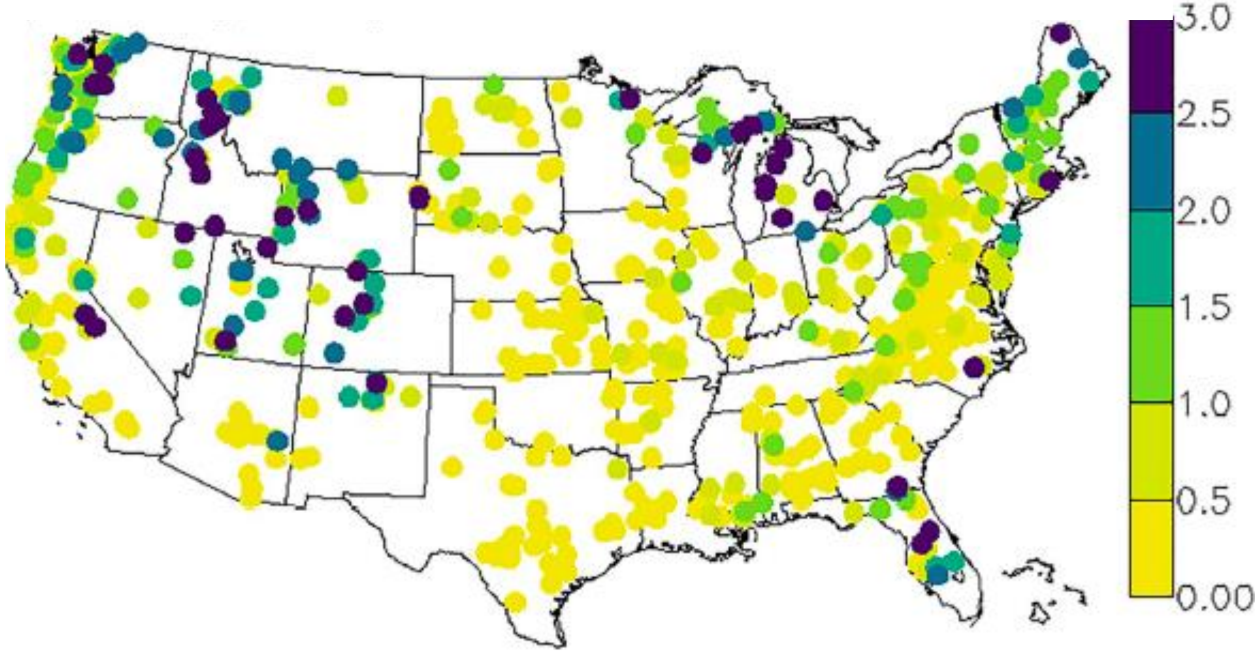


Location and mean elevation of catchments in the CAMELS dataset

Contribution of a subset of days to the $\widehat{MSE}$ estimate



Fraction of the $\widehat{MSE}$ estimate contributed by 10 days with the highest error



Percentage of days that contribute 50% of the $\widehat{MSE}$ estimate

Jackknife and bootstrap estimates of sampling uncertainty

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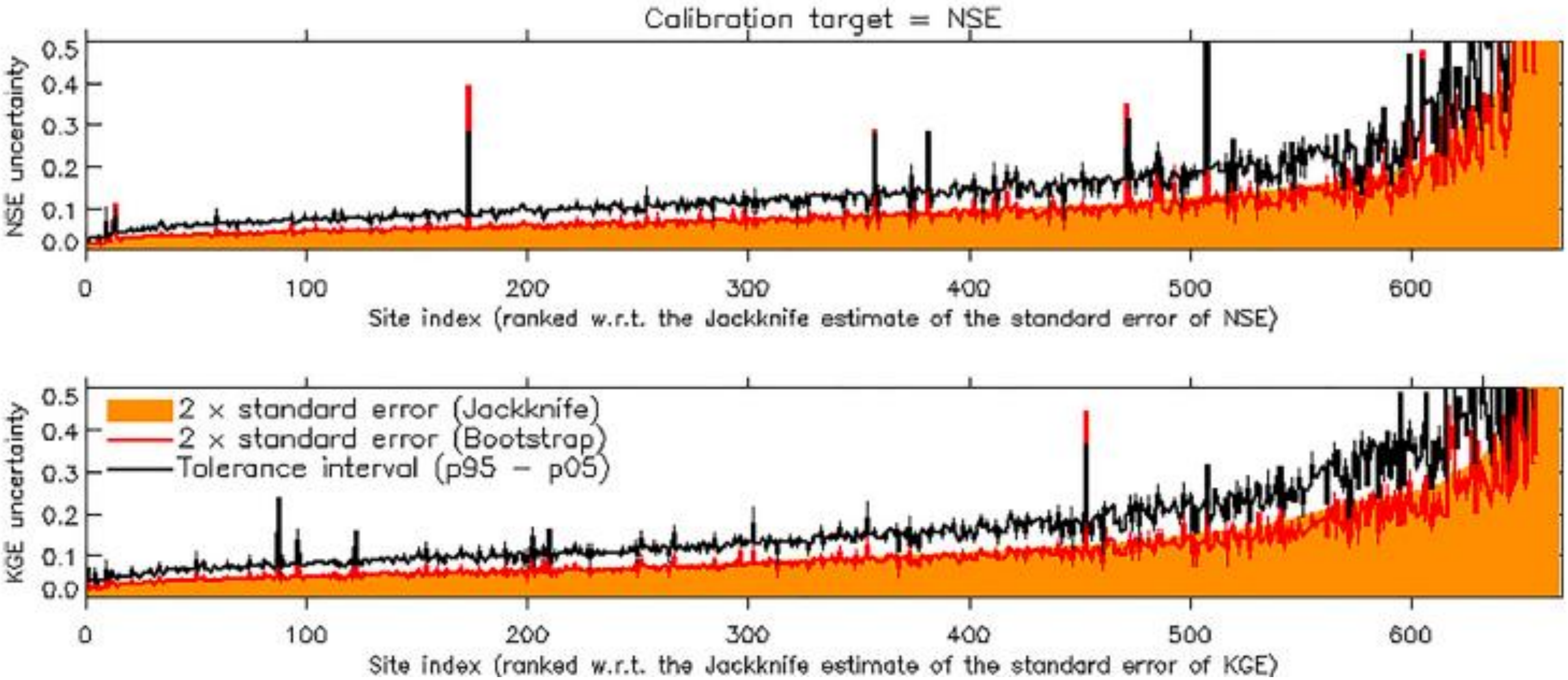
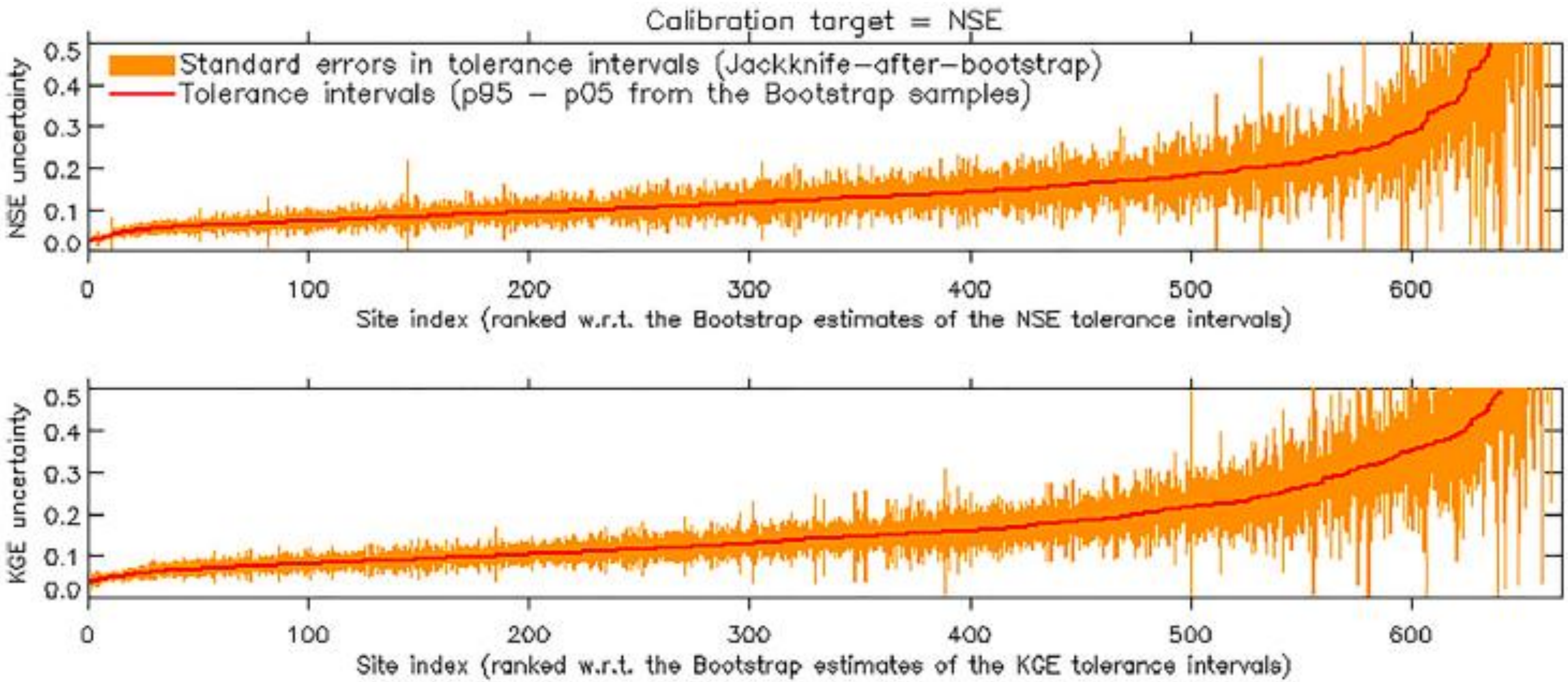


Standard error in bootstrap tolerance intervals



Weak theory

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Water Resources Research

COMMENTARY

10.1002/2015WR017910

Key Points:
- We seek to increase the physical realism of hydrologic models through better way existing theory
- We seek to improve the way models are used to integrate and evaluate different process explanations
- We define a set of key issues to address that will help narrow the gap between theory and models

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Improving the theoretical underpinnings of process-based hydrologic models

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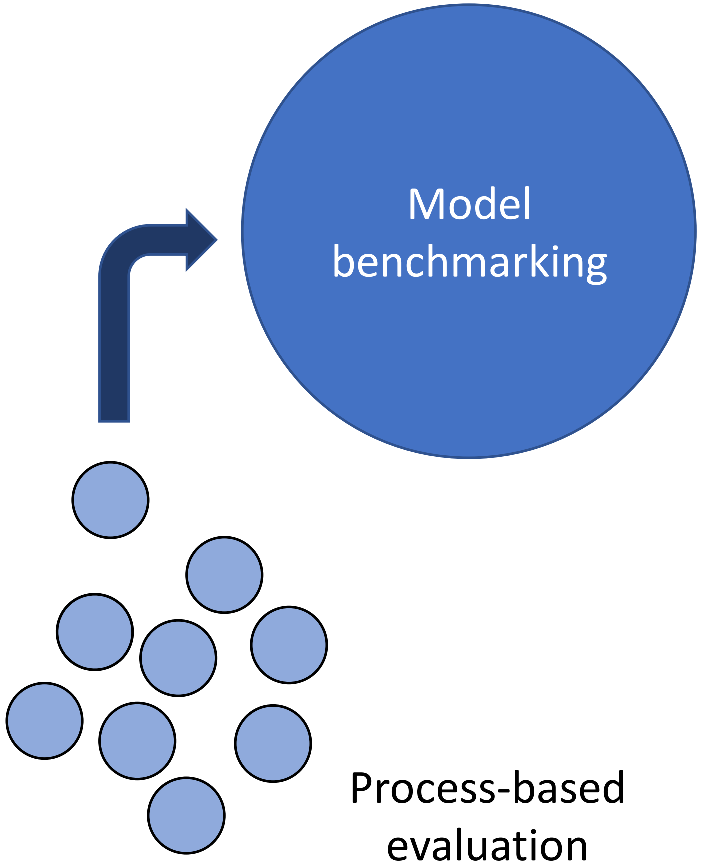
Abstract In this Commentary, we argue that it is possible to improve the physical realism of hydrologic models by making better use of existing hydrologic theory. We address the following questions: (1) what are some key elements of current hydrologic theory; (2) how can those elements best be incorporated where they may be missing in current models; and (3) how can we evaluate competing hydrologic theories across scales and locations? We propose that hydrologic science would benefit from a model-based community synthesis effort to reframe, integrate, and evaluate different explanations of hydrologic behavior, and provide a controlled avenue to find where understanding falls short.

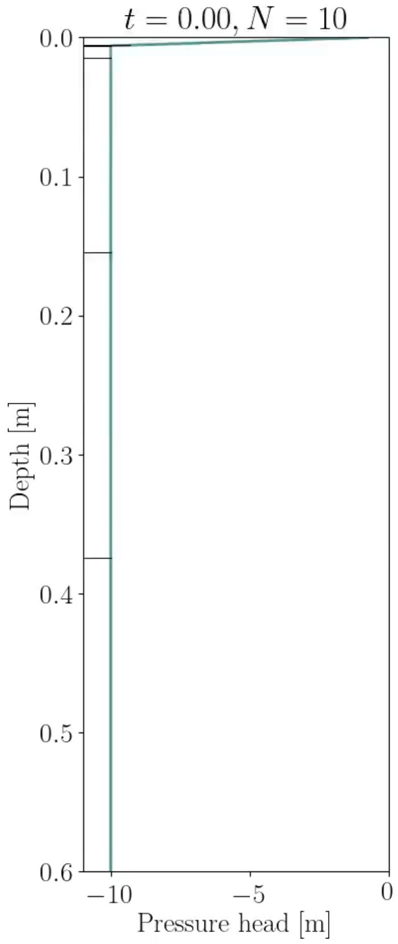


Model benchmarking

Process-based evaluation

Summary and outlook

- Working to develop ***numerically robust*** terrestrial system models that faithfully represent the dominant physical processes across continental domains
    - Flexible model design
    - Robust numerical solutions
    - Agile parallelization strategies
- Model agnostic philosophy
    - Interested in a ***terrestrial systems modelling community of practice*** in order to more effectively share code and concepts across different model development groups (nextGen NWM)
    - To achieve numerically robust continental-domain models, there is a need for us to come together and think more about the interconnections between model design, numerical solvers, and parallelization strategies across multiple model structures



Questions?