

Advanced ParFlow Short Course

October 3-4, 2019
University of Arizona

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U.S. DEPARTMENT OF
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CUAHSI
Universities Allied for Water Research

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IDEAS
productivity

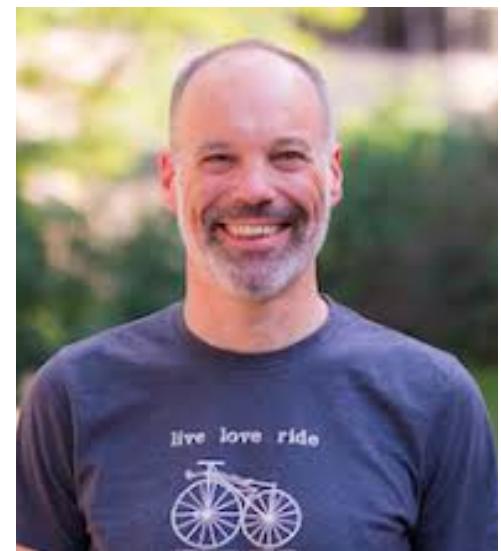
Meet your instructors



Laura Condon
University of
Arizona



Nick Engdahl
Washington
State University



Reed Maxwell
Colorado School
of Mines



Tentative Agenda

Day 1 (Thursday October 3rd)

8:30 – 9:00	<i>Coffee and snacks available</i>
9:00 – 9:30	Introductions
9:30 – 9:45	CUAHSI introduction
9:45 – 10:15	ParFlow overview and setup
<i>10:15 – 10:30</i>	<i>Break</i>
10:30 – 12:30	Building the subsurface
<i>12:30 – 1:30</i>	<i>Lunch</i>
1:30 – 2:30	Building the subsurface
<i>2:30 – 2:45</i>	<i>Break</i>
2:45 – 5:00	Solvers and Scaling
<i>5:00 - 6:30</i>	<i>Break</i>
6:30	<i>Dinner at Reilly Craft Pizza and Drink (101 East Pennington Street)</i>

Day 2 (Friday October 4th)

8:30 – 9:00	<i>Coffee and snacks available</i>
9:00 – 10:00	Recap and special topics from Day 1
10:00 – 12:00	Overland flow formulations and topographic processing
<i>10:30 – 10:45</i>	<i>Break</i>
10:00 – 12:00	Overland flow formulations and topographic processing
<i>12:00 – 1:00</i>	<i>Lunch</i>
1:00 – 2:30	ParFlow CLM
2:30 – 3:00	Wrap up

Introductions

1. Who are you and where are you from?
2. What is your experience with ParFlow so far?
3. What would you like to do with ParFlow and/or what are your goals for this class?
4. What are the most confusing/painful parts of working with ParFlow for you?



CUAHSI

universities allied for water research

www.cuahsi.org

ParFlow-CLM Overview

ParFlow has a long development history

- *Ashby and Falgout 1996*, parallel multigrid saturated flow
- *Jones and Woodward 2001*, parallel Richards' equation flow
- *Maxwell and Miller 2005*, CLM coupling
- *Kollet and Maxwell 2006*, parallel overland flow
- *Maxwell 2013*, Terrain following grid

ParFlow is a community code, developed by several groups

- Started at Lawrence Livermore National Laboratory (LLNL)
- Center of development moved to Colorado School of Mines (CSM) in 2009
- Now active development from groups in F-Z Jülich, UniBonn, CSM, LLNL, LBL, LTHE, UA and WSU



ParFlow has been used in many studies

Table 1.1- 1.6 in the ParFlow manual lists most of the published studies to date and some details about them

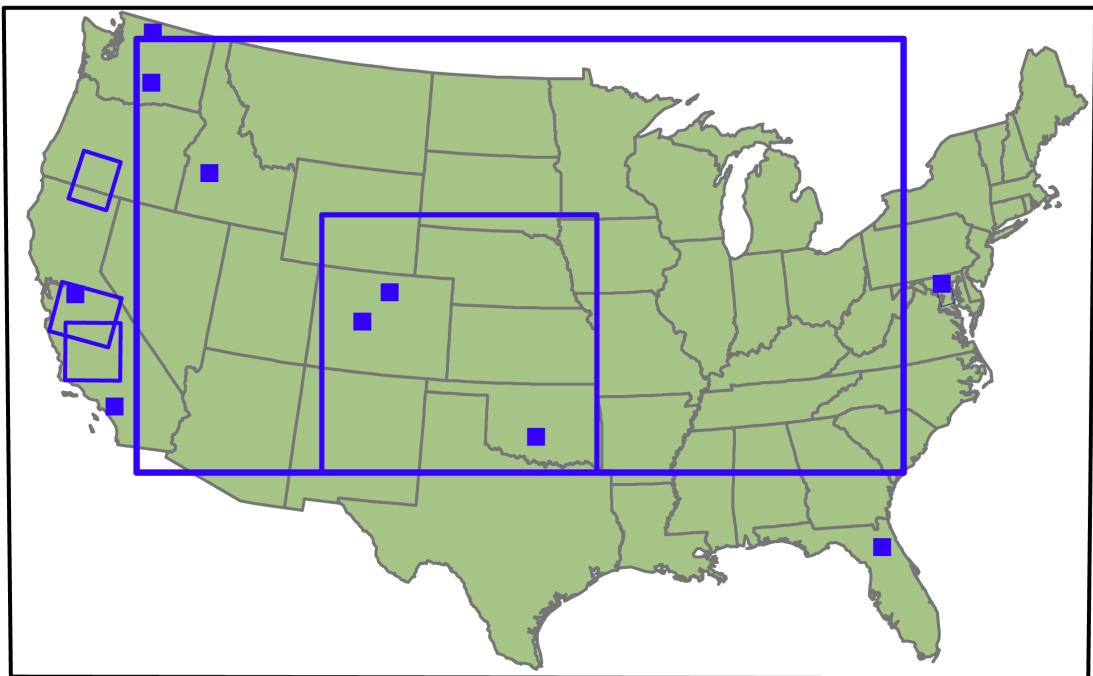
1.2. PUBLISHED STUDIES THAT HAVE USED PARFLOW

3

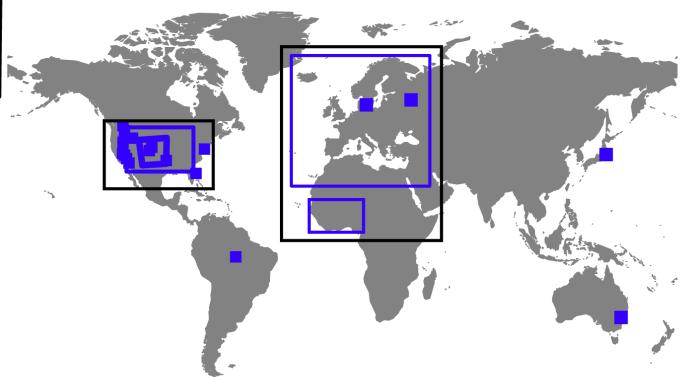
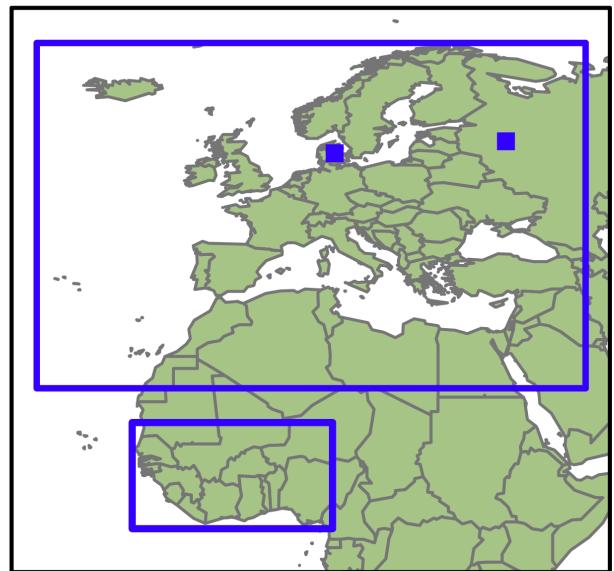
Table 1.1: List of PARFLOW references with application and process details.

Reference	Coupled Model	Application	Scale	Domain	TB	TFG	VS	Vdz
[9] Bearup et al. (2016)		Hillslope Hydrologic Response; MPB	Hillslope	Idealized			X	
[52] Maxwell et al. (2016)		Residence Time Distributions	Continental	CONUS			X	X
[68] Reyes et al. (2015)	CLM	Surface Heterogeneity, Surface Energy Budget (SEB)	Urban Watershed Bal-lona Creek Watershed, CA		X	X	X	
[17] Condon and Maxwell (2015)		Subsurface Heterogeneity (groundwater fluxes and topography)	Continental	CONUS			X	X
[33] Jefferson et al. (2015)	CLM	Active sub-spaces; Dimension reduction; Energy fluxes	Hillslope	Idealized				
[32] Jefferson and Maxwell (2015)	CLM	Sensitivity Analysis (evap-	Column	Idealized				

ParFlow has been applied at many sites worldwide



ParFlow Domains

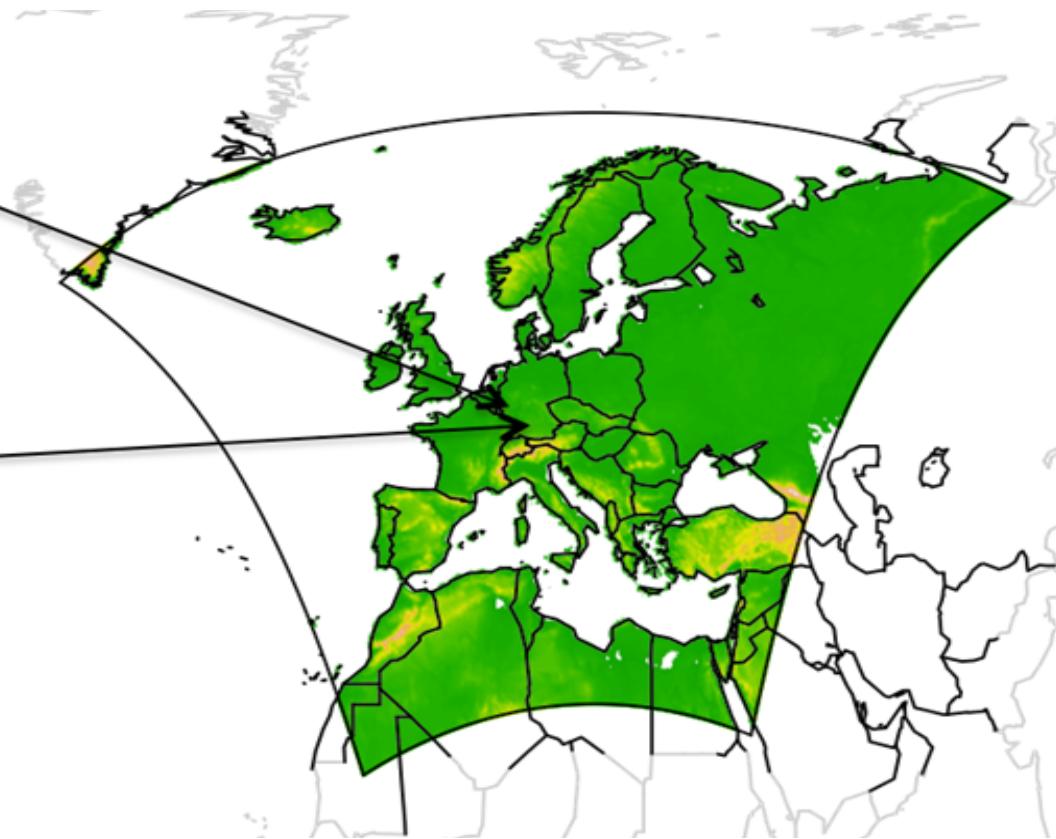


ParFlow has been used to model watersheds around the world at a wide range of scales



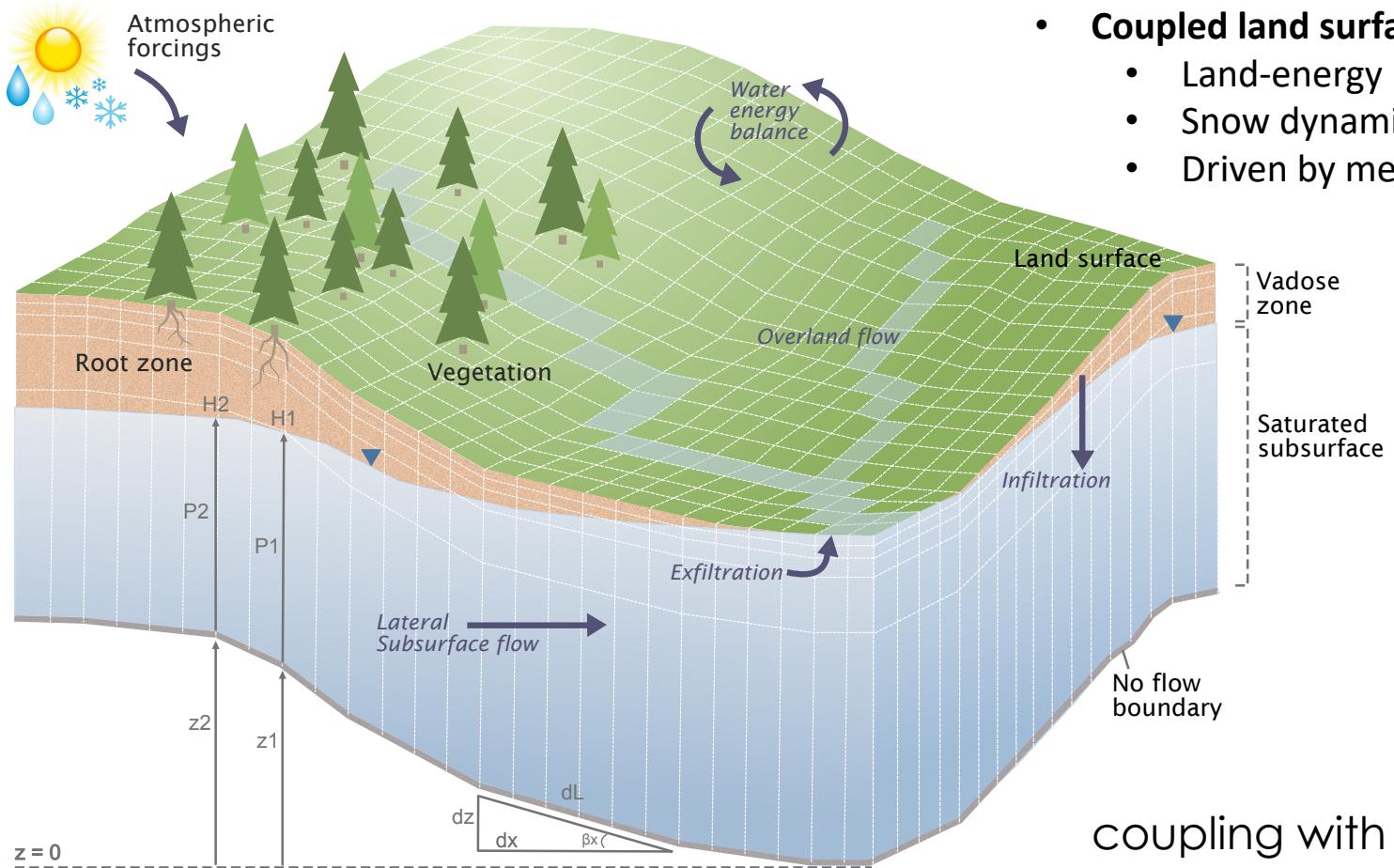
TR32

Shrestha et al., 2014,
Rahman et al., 2014, ...



Including Big Thompson (CO), Chesapeake (MD), CONUS, CORDEX, East Inlet (CO), East River (CO), Klamath (OR), Little Washita (OK), Rur (Germany), San Joaquin (CA), Sante Fe (FL), Skjern (Denmark), Wüstebach (Germany)

ParFlow-CLM



- Variably saturated groundwater flow
- Fully integrated surface water
- **Parallel implementation**
- **Coupled land surface processes**
 - Land-energy balance
 - Snow dynamics
 - Driven by meteorology

coupling with land surface processes (CLM) allows for simulation of interactions and connections

ParFlow Equations: Steady Flow

$$\nabla \cdot \mathbf{q} = q_s$$
$$\mathbf{q} = -k(x) \nabla (\psi_p - z)$$

}

Groundwater flow
and Darcy's Law

Pressure Head (L)

Saturated
Hydraulic
Conductivity (L/T)

ParFlow Equations: Richards' and Overland Flow

$$S_s S_w \frac{\partial \psi_p}{\partial t} + \phi \frac{\partial S_w(\psi_p)}{\partial t} = \nabla \cdot q + q_s$$

$$q = -k(x)k_r(\psi_p) \nabla(\psi_p - z)$$

$$\frac{\partial \psi_s}{\partial t} = \nabla \cdot \bar{v} \psi_s + q_r$$

$$v_x = -\frac{\sqrt{S_{f,x}}}{n} \psi_s^{2/3}$$

Richards'
Equation

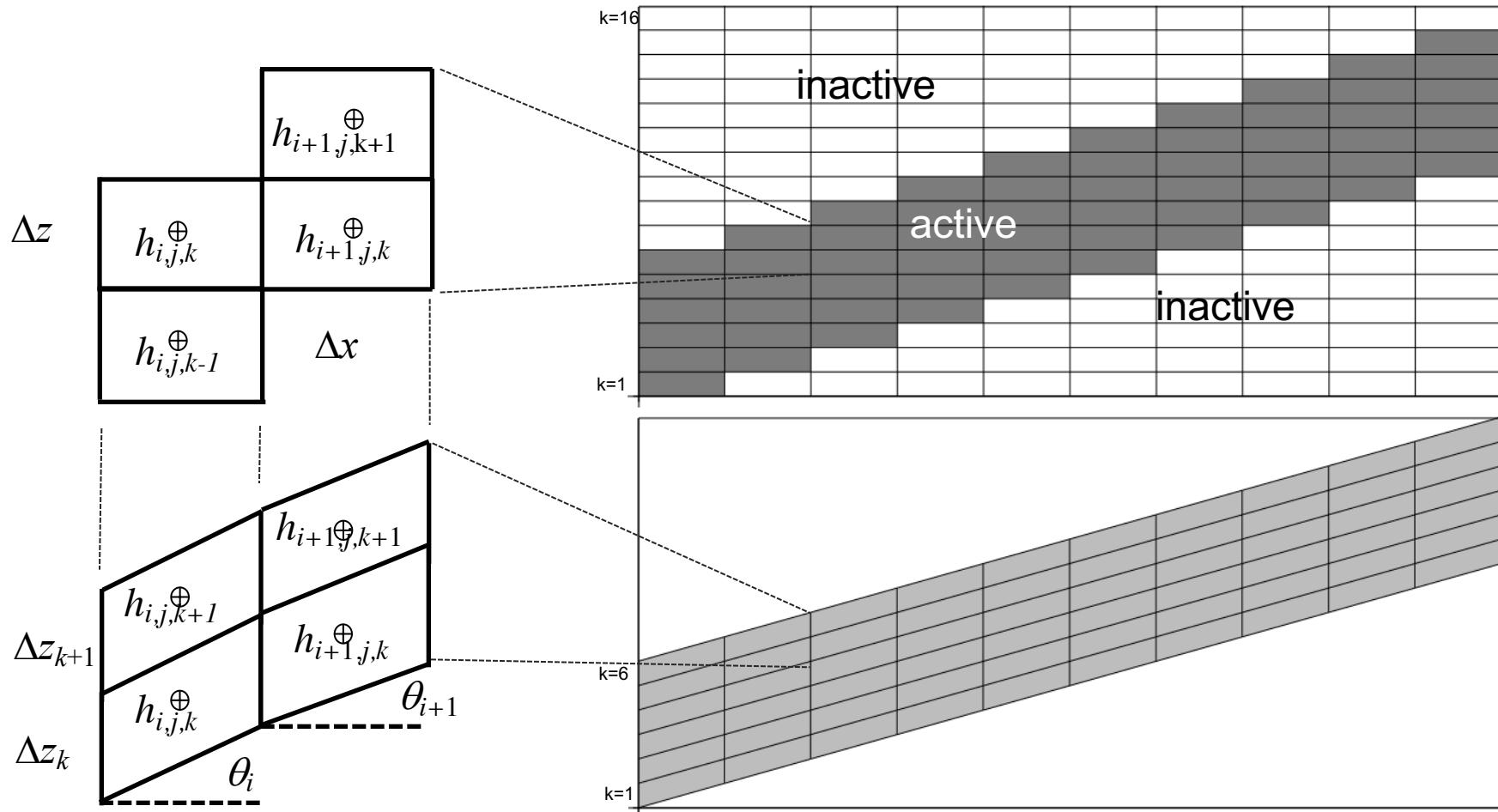
Pressure Head (L)

Saturation (-)

Saturated
Hydraulic
Conductivity (L/T)

Kinematic Wave
Equation

ParFlow Gridding



Terrain Following Grid EQ

Modified Darcy's Law:

$$\mathbf{q} = -\mathbf{K}_s(\mathbf{x})k_r(h)[\nabla(h + z) \cos \theta_x + \sin \theta_x]$$

Slopes and fluxes:

$$\theta_x = \tan^{-1}(S_{0,x}) \text{ and } \theta_y = \tan^{-1}(S_{0,y})$$

$$\begin{aligned} q_x &= -K_{s,x}(\mathbf{x})k_r(h) \left[\frac{\partial(h)}{\partial x} \cos \theta_x + \sin \theta_x \right] \\ &= -K_{s,x}(\mathbf{x})k_r(h) \frac{\partial(h)}{\partial x} \cos \theta_x - K_{s,x}(\mathbf{x})k_r(h) \sin \theta_x \end{aligned}$$

Diffusive Pressure Term

Topographic Term

Illustration of a ParFlow model for an idealized hillslope using the terrain following grid formulation

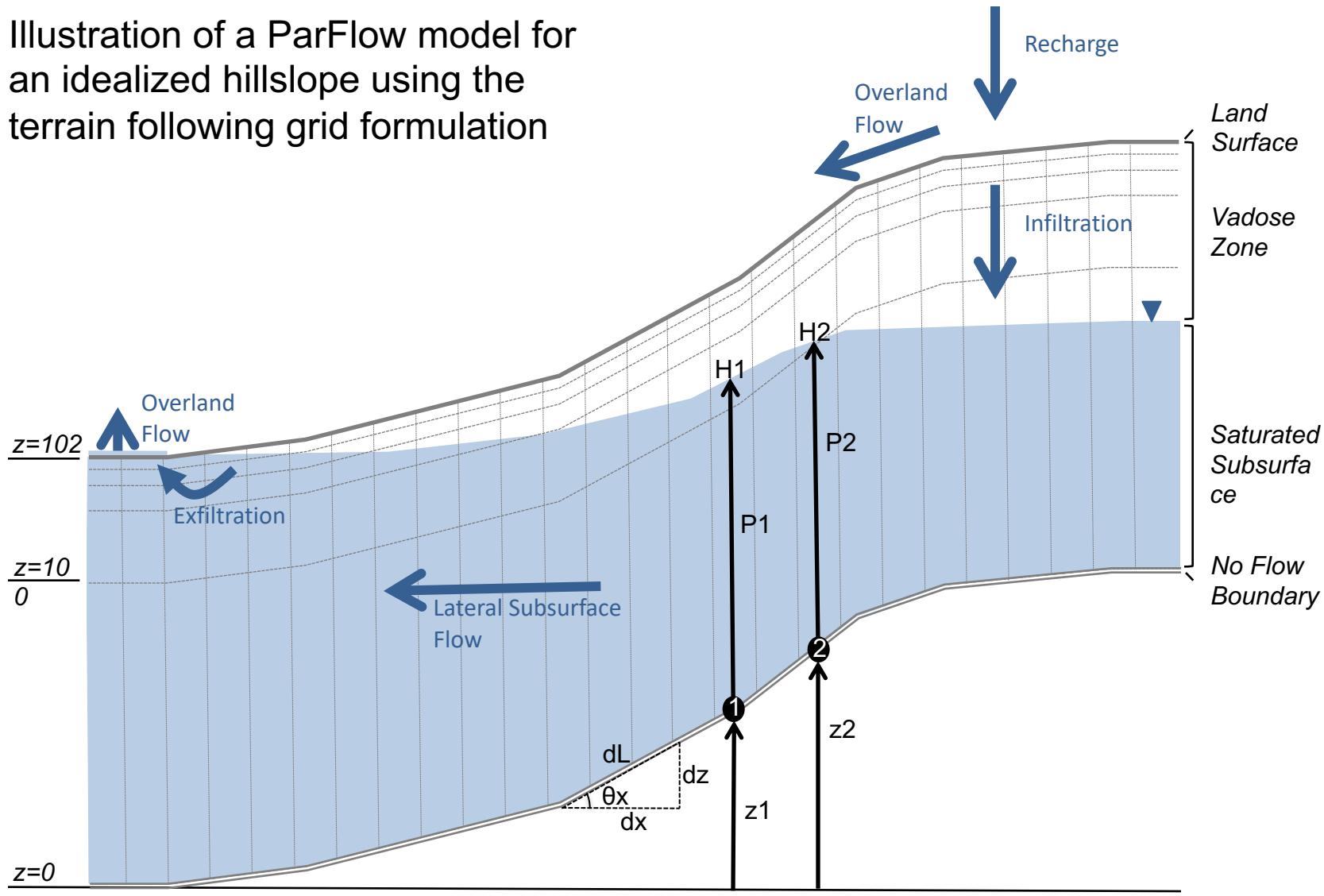
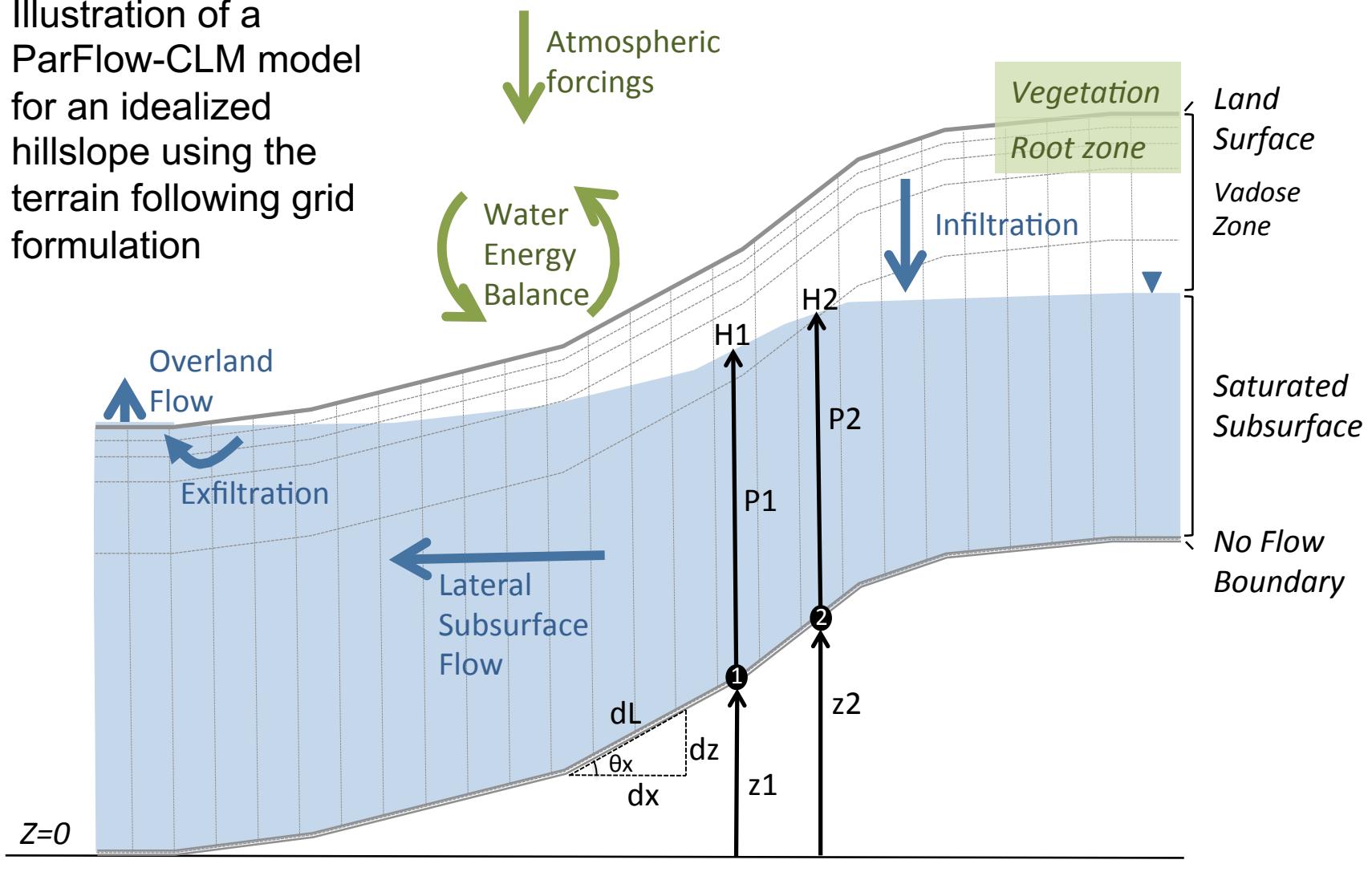


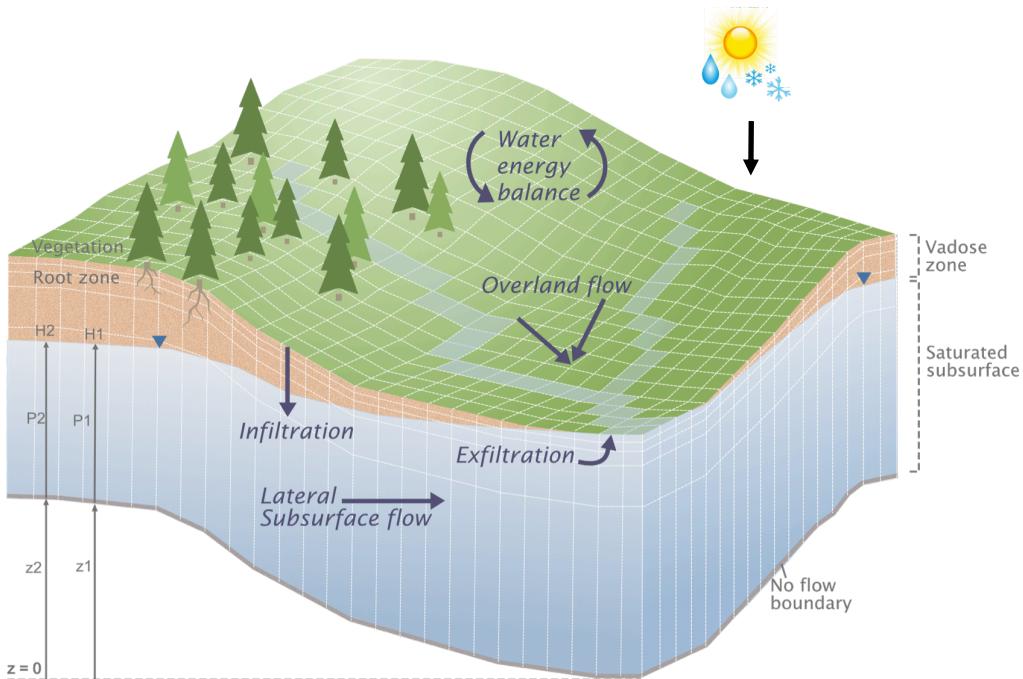
Illustration of a ParFlow-CLM model for an idealized hillslope using the terrain following grid formulation



Workflow Outline For Watershed Applications:

1. Evaluate available model inputs
2. Determine your domain configuration
3. Process topography and test with parking lot simulations
4. Setup the subsurface
5. Initialize the model (i.e. spinup)
6. Additional setup for PF-CLM

Model Requirements



ParFlow

1. Gridded Inputs

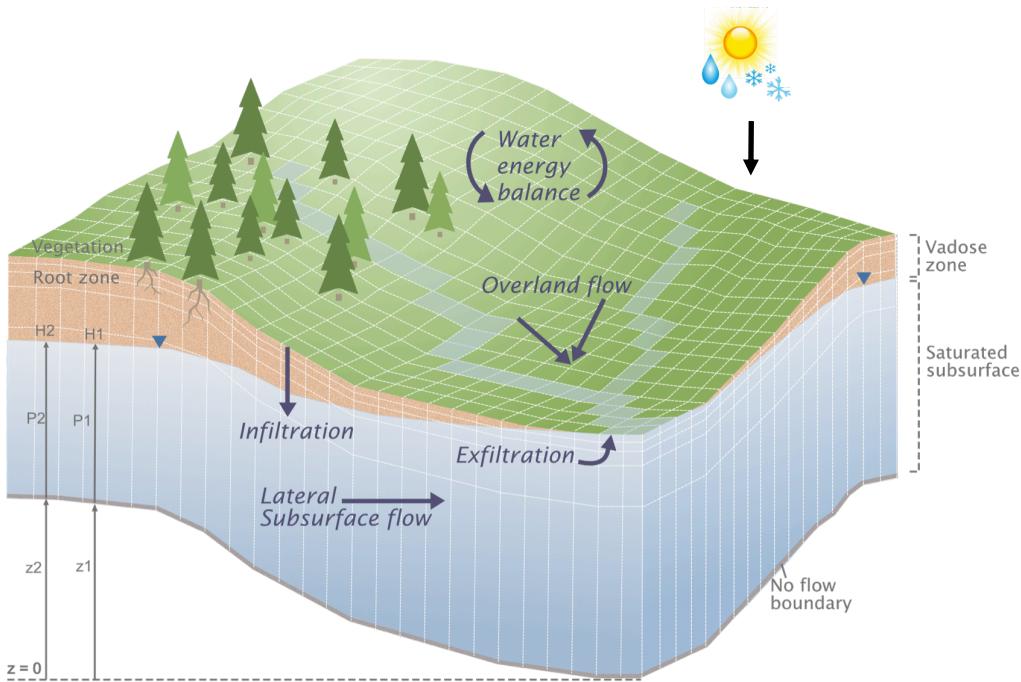
Topography

Subsurface Properties

2. Boundary Conditions

3. Initial Conditions

Model Requirements



ParFlow

1. Gridded Inputs

Topography

Subsurface Properties

2. Boundary Conditions

3. Initial Conditions

CLM

- Land cover types (`drv.vegm.dat`)
- Vegetation parameters (`drv_vegp.dat`)
- Driver script (`drv_clmin.dat`)
- Meteorological forcing file(s), 1D or 3D

Input Scripts

- TCL/TK scripting language
- All parameters input as keys using pfset command
- Keys used to build a database that ParFlow uses
- ParFlow executed by pfrun command
- Since input file is a script may be run like a program

Best practices for building an input file:

- Start from an existing script:
 - Look at the annotated input scripts in the manual (Section 3.6)
 - Look at the test problems that come with ParFlow (See list in section 3.5)
- Get the details on every input key from the manual (Section 6)

Running ParFlow (file structure)

- Project name is the base for all output
- Most output is *project.out.var.time.ext*

For a project called ‘myrun’

Log files:

myrun.out.log

myrun.out.kinsol.log

Pressure/Saturation files:

myrun.out.press.00001.pfb

myrun.out.satur.00001.pfb

Mask file:

myrun.out.mask.00000.pfb

The mask is a file of zero’s and ones,
0=inactive cell, 1=active cell

Perm/porosity files:

myrun.out.perm_x.pfb

myrun.out.porosity.pfb

Output time step, 00000 is initial,
integer values depending on output
times

Other/diagnostic files:

myrun.pfidb

Parflow database

myrun.out.pftcl

myrun.out.txt Line output

ParFlow Development

ParFlow is hosted on GitHub



[parflow / parflow](https://github.com/parflow/parflow)

Code Issues 27 Pull requests 2 ZenHub Projects 0 Wiki Security Insights

Parflow is an open-source parallel watershed flow model. <http://inside.mines.edu/~rmaxwell/max...>

631 commits 16 branches 9 releases 14 contributors View license

Branch: master New pull request Create new file Upload files Find File Clone or download

Author	Commit Message	Date
smithsg84	Added Etrace library for tracing execution (#189) ...	Latest commit d215233 3 days ago
aclmacros	Netcdf default (#38)	2 years ago
bin	Update uncrustify coding style (#172)	28 days ago
cmake	Added Etrace library for tracing execution (#189)	3 days ago
docs	Added release process notes to developers manual (#181)	19 days ago

<https://github.com/parflow>

Git repository used for

- Source code
- Test cases
- Documentation
- Issue tracking

We also auto-build Docker images with tagged releases

The screenshot shows the Docker Hub interface for the `parflow/parflow` repository. The repository has 1 star and was updated 3 days ago by the owner `parflow`. The description states: "ParFlow is a parallel watershed model for simulation". The repository type is listed as "Container".

The main navigation tabs are `Overview`, `Tags`, `Dockerfile`, and `Builds`. The `Tags` tab is currently selected, displaying three tags:

Tag	Digest	Architecture	OS	Size
<code>latest</code>	<code>bd5accf99c08</code>	amd64	linux	467.8 MB
<code>version-3.6.0</code>	<code>dc70cc738f33</code>	amd64	linux	261.81 MB
<code>version-3.5.0</code>	<code>32b22ca63461</code>	amd64	linux	270.7 MB

The `version-3.6.0` tag was last updated a month ago. The `version-3.5.0` tag was last updated two months ago.

The `Overview` section contains a summary of ParFlow: "ParFlow is an open-source, modular, parallel watershed flow model. It includes fully-integrated overland flow, the ability to simulate complex topography, geology and heterogeneity and coupled land-surface processes including the land-energy budget, biogeochemistry and snow (via CLM). It is multi-platform and runs with a common I/O structure from laptop to supercomputer. ParFlow is the". Below this summary, there is a status indicator showing "build passing".

A prominent orange bar at the bottom of the screenshot contains the URL: <https://hub.docker.com/r/parflow/parflow>.

ParFlow is an active research code with many developers

Timeline of contributions to the master branch

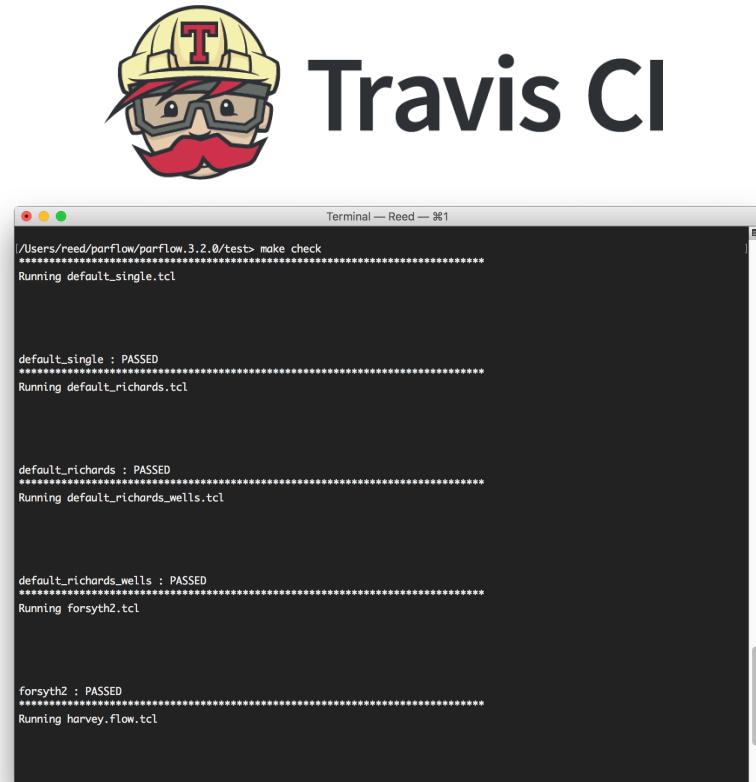


Forks

	parflow / parflow
	arezaii / parflow
	basileh / parflow
	cswoodward / parflow
	cvoter / parflow
	DeltaresProjects / HYD_SIM-parflow
	ecoon / parflow
	ElangoThevar / parflow
	elappala / parflow
	geouke / parflow
	hasencios / parflow
	hokkanen / parflow
	hydroframe / ParFlow_PerfTeam
	ian-bertolacci / parflow
	jbeisman / parflow
	jkeune / parflow
	khm293 / parflow
	kkyong77 / parflow
	KoenigKrote / parflow
	ksingha55 / parflow
	lecondon / parflow
	lpoorthuis / parflow
	mstiegl / parflow
	nbengdahl / parflow
	reedmaxwell / parflow
	tpops / parflow
	valerieige / parflow
	vibraphone / parflow
	xy124 / parflow

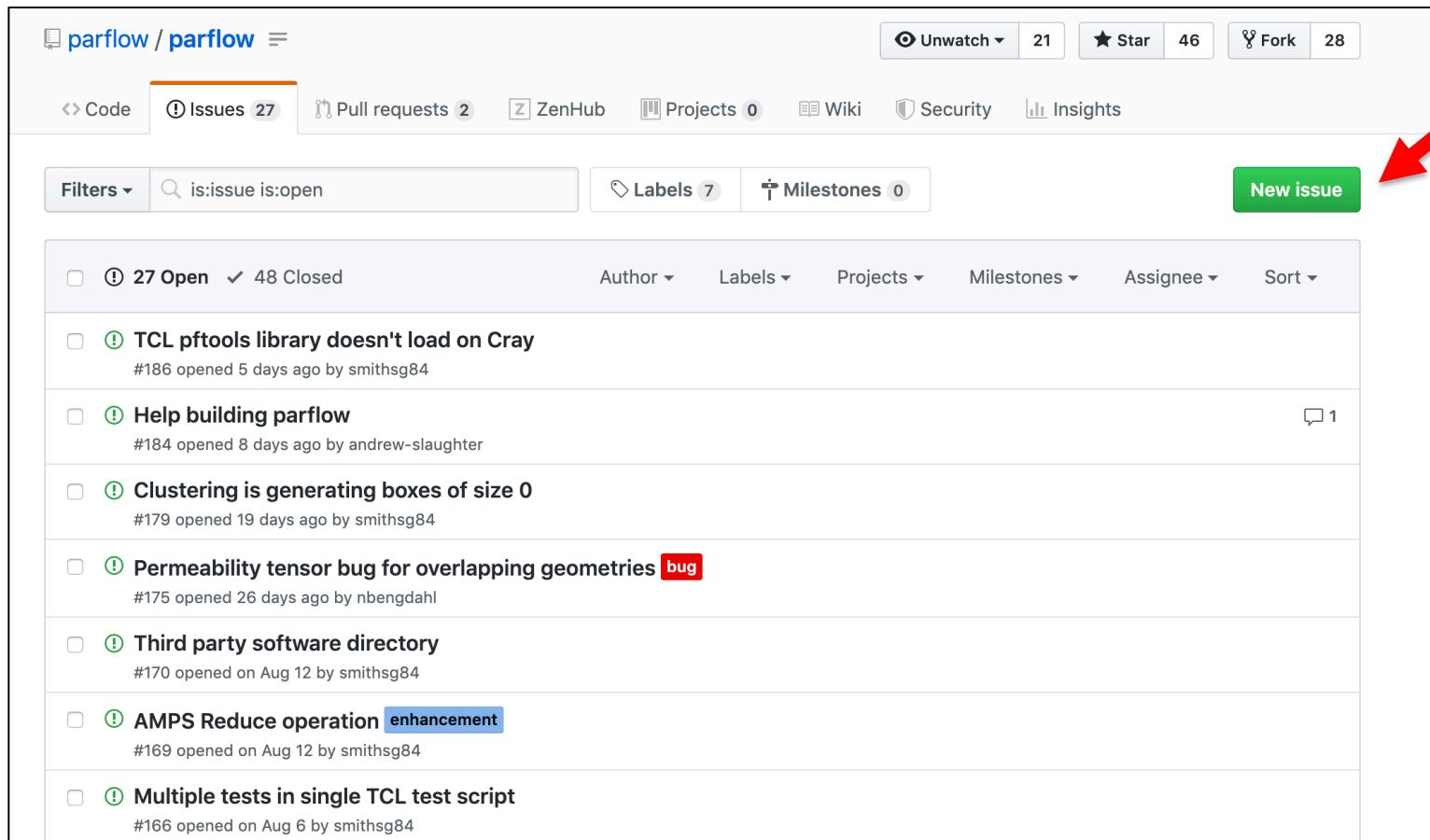
Automated test cases provide code verification mechanism

- Suite of test cases testing solvers and code features
- TravisCI integration with GitHub used for continuous integration
- Testing allows check for backward compatibility of new code
- Tests provide examples for new users



Do you have an issue?

Document it on the GitHub issue tracker



A screenshot of the GitHub Issues page for the repository "parflow / parflow". The page shows 27 open issues. A red arrow points to the green "New issue" button in the top right corner of the issue list.

The GitHub interface includes a header with "Unwatch 21", "Star 46", "Fork 28", and navigation links for Code, Issues (27), Pull requests (2), ZenHub, Projects (0), Wiki, Security, and Insights. Below the header are filters for "is:issue is:open", "Labels 7", and "Milestones 0".

The issue list displays the following items:

- ① **TCL pftools library doesn't load on Cray** #186 opened 5 days ago by smithsg84
- ① **Help building parflow** #184 opened 8 days ago by andrew-slaughter
- ① **Clustering is generating boxes of size 0** #179 opened 19 days ago by smithsg84
- ① **Permeability tensor bug for overlapping geometries** bug #175 opened 26 days ago by nbengdahl
- ① **Third party software directory** #170 opened on Aug 12 by smithsg84
- ① **AMPS Reduce operation** enhancement #169 opened on Aug 12 by smithsg84
- ① **Multiple tests in single TCL test script** #166 opened on Aug 6 by smithsg84

We have an open development community, and you can be a ParFlow developer too!

1. Check out our software sustainability plan for all the details https://github.com/parflow/parflow/blob/master/docs/software_plan.md
2. Create your own ParFlow fork and do your development there
3. Document and Test. All new features must:
 - Be documented in the manual
 - Pass the existing tests suite
 - Include additional tests as needed
4. Submit a pull request. Pull requests are reviewed by the lead maintainers for
 - Correctness
 - Consistency with coding style
 - Verify test for new feature was added
 - Regression tests pass

Other resources for help

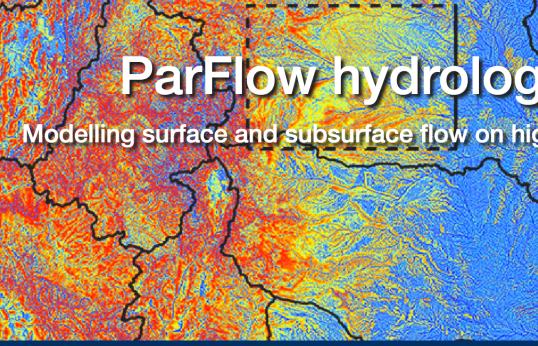
Online Resources

ParFlow

About Features Applications Team Download Documentation Publications

ParFlow hydrologic model

Modelling surface and subsurface flow on high-performance computers



Saturday, January 16, 2016

[Setup guide for OS X 10.11 El Capitan](#)
by Nick Engdahl

By now you've probably upgraded your Mac to OS X El Capitan (version 10.11) and if you had a previous installation of ParFlow on OS X Yosemite on your system, it's probably working just fine. The reason is that, unlike some previous OS X updates, very little has changed under the hood between the two most recent releases that would have any effect on ParFlow. So to make this arguably the shortest blog post of all time, if you're trying to get a new installation set up on El Capitan the instructions for OS X Yosemite are all you'll need:

[OS X Yosemite instructions](#)

But before you click over there, we have come across a very important compatibility issue with Hypre you need to know about. The most recent version (2.10) has changed some function calls and is not compatible with the current ParFlow release. Fortunately, the Hypre developers leave most of the code open source and we promote a community of active users and developers interested in contributing to the project. Details about the model, source code, publications and more can be found at the [GitHub repository](#).

About

ParFlow is a numerical model that simulates the hydrologic cycle from the bedrock to the top of the atmosphere. It solves for three-dimensional groundwater flow with overland flow and plant processes using physically-based models. ParFlow uses high-performance computing to simulate water and energy in complex real-world systems. ParFlow is a computationally advanced model that has been used in hundreds of studies evaluating hydrologic processes. The code is open source and we promote a community of active users and developers interested in contributing to the project.

Website

Blog

The ParFlow Project

modeling surface and subsurface flow on high performance computers

PARFLOW User's Manual

GMWI 2016-01 v3.2.0
June, 2017 v.3.2.0

Integrated GroundWater Modeling Center



Reed M. Maxwell¹, Stefan J. Kollet², Steven G. Smith³, Carol S. Woodward⁴, Robert D. Falgout⁵, Ian M. Ferguson⁶, Nicholas Engdahl⁷, Laura E. Condon⁸, Basile Hector⁹, Sonya Lopez¹⁰, James Gilbert¹, Lindsay Bearup¹, Jennifer Jefferson¹, Caitlin Collins¹, Inge de Graaf¹, Christine Pribulick¹, Lauren Hatch¹, Chuck Baldwin, William J. Bosl¹¹, Richard Hornung¹², Steven Ashby¹³

Manual

Links for getting the code, getting more information and getting help

ParFlow web page:

www.parflow.org

Github

<https://github.com/parflow/parflow>

ParFlow Blog

<http://parflow.blogspot.com/>

ParFlow User's list

parflow-users@mailman.mines.edu

Lets get started!

Software check:

- 1. ParFlow** - <https://github.com/parflow/parflow> * Needs to be the latest version of ParFlow
- 2. ParaView** - <https://www.paraview.org/download/>
- 3. Visit** - <https://wci.llnl.gov/simulation/computer-codes/visit/downloads>
- 4. R or Rstudio:** <https://www.r-project.org/>