Advanced ParFlow Short Course

October 3-4, 2019

University of Arizona

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Meet your instructors

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MINES
Integrated GroundWater Modeling Center

Tentative Agenda

Day 1 (Thursday October 3rd)

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

Day 2 (Friday October 4th)

8:30 – 9:00	*Coffee and snacks available*
9:00 – 10:00	Recap and special topics from Day 1
10:00 – 12:00	Overland flow formulations and topographic processing
10:30 – 10:45	*Break*
10:00 – 12:00	Overland flow formulations and topographic processing
12:00 – 1:00	*Lunch*
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

JÜLICH
FORSCHUNGSZENTRUM
LTHE
BERKELEY LAB
MINES
universitätbonn
Rheinische Friedrich-Wilhelms-Universität Bonn

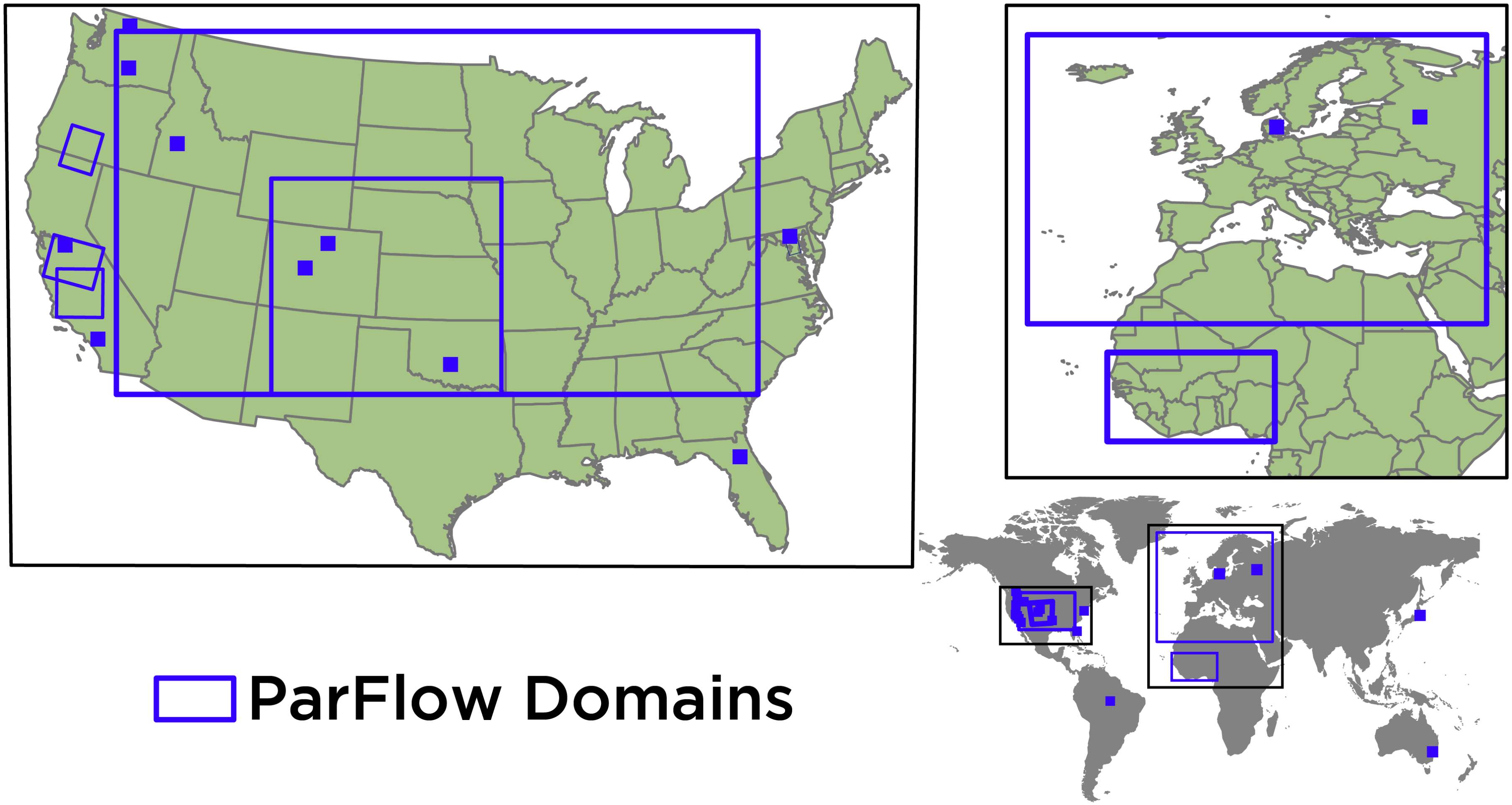
ParFlow has been used in many studies

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

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

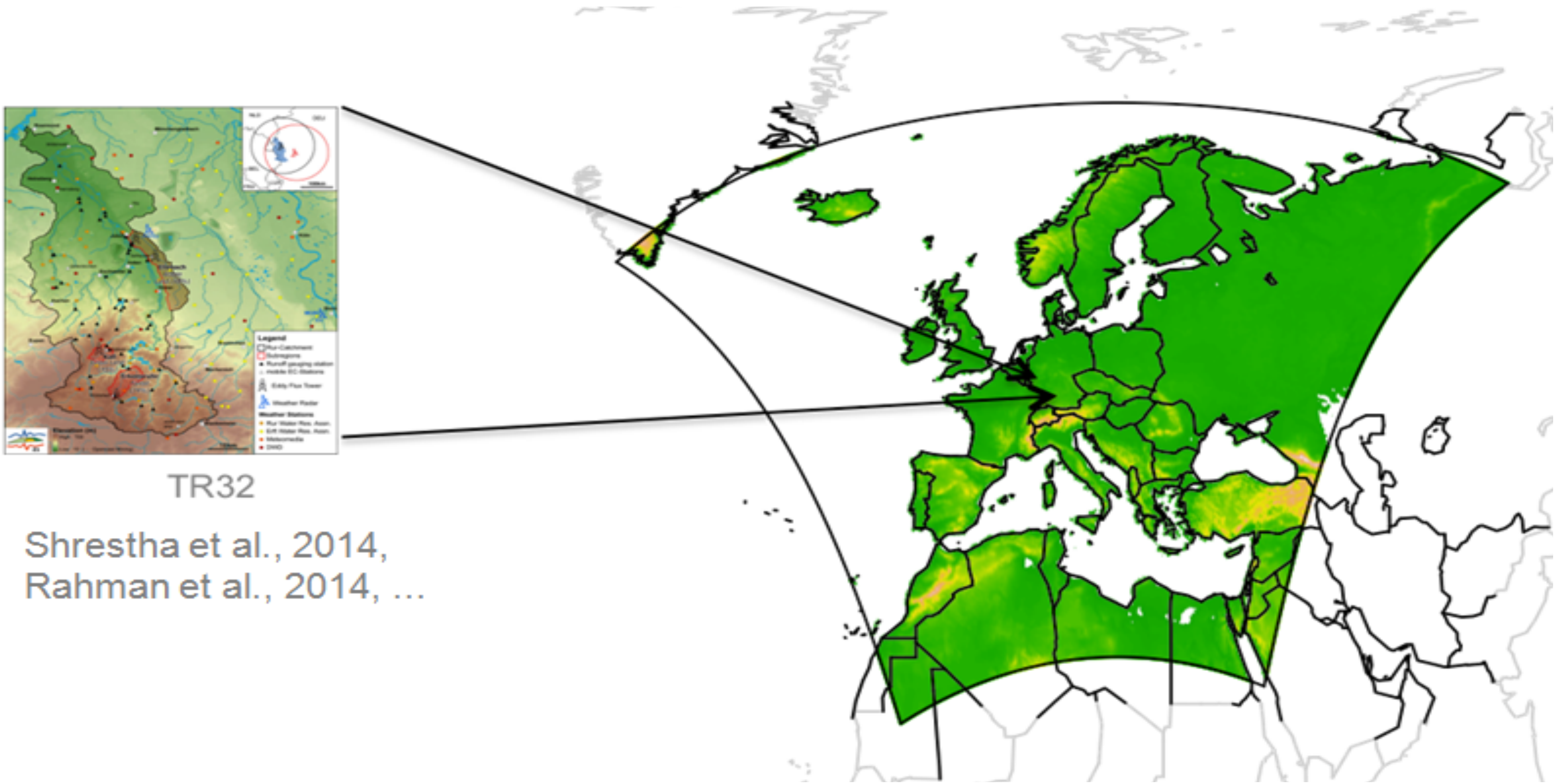
Reference	Coupled Model	Application	Scale	Domain	TB	TFG	VS	Vdz
[9] Bearup et al. (2016)		Hillslope Hydrologic Response; MPB	Hillslope	Idealized			X	
[52] Maxwell et al. (2016)		Residence Time Distributions	Continental	CONUS			X	X
[68] Reyes at al. (2015)	CLM	Surface Heterogeneity, Surface Energy Budget (SEB)	Urban Watershed Ballona 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 subspaces; 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

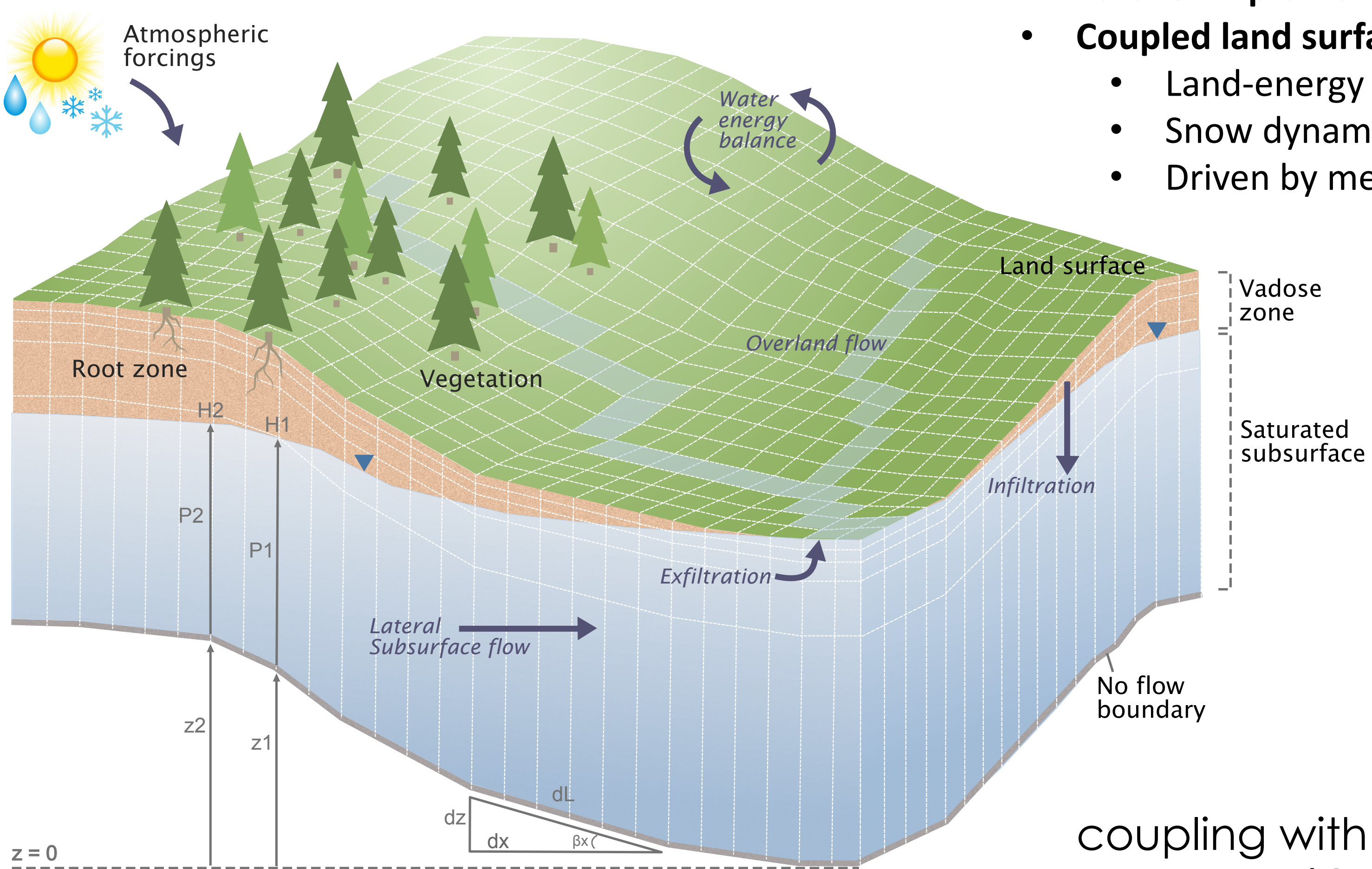
ParFlow has been used to model watersheds around the world at a wide range of scales



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

Maxwell (2013); Kollet and Maxwell (2008); Kollet and Maxwell (2006);Maxwell and Miller (2005); Dai et al. (2003); Jones and Woodward (2001); Ashby and Falgout (1996)

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

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

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

Richards' Equation

Pressure Head (L)

Saturation (-)

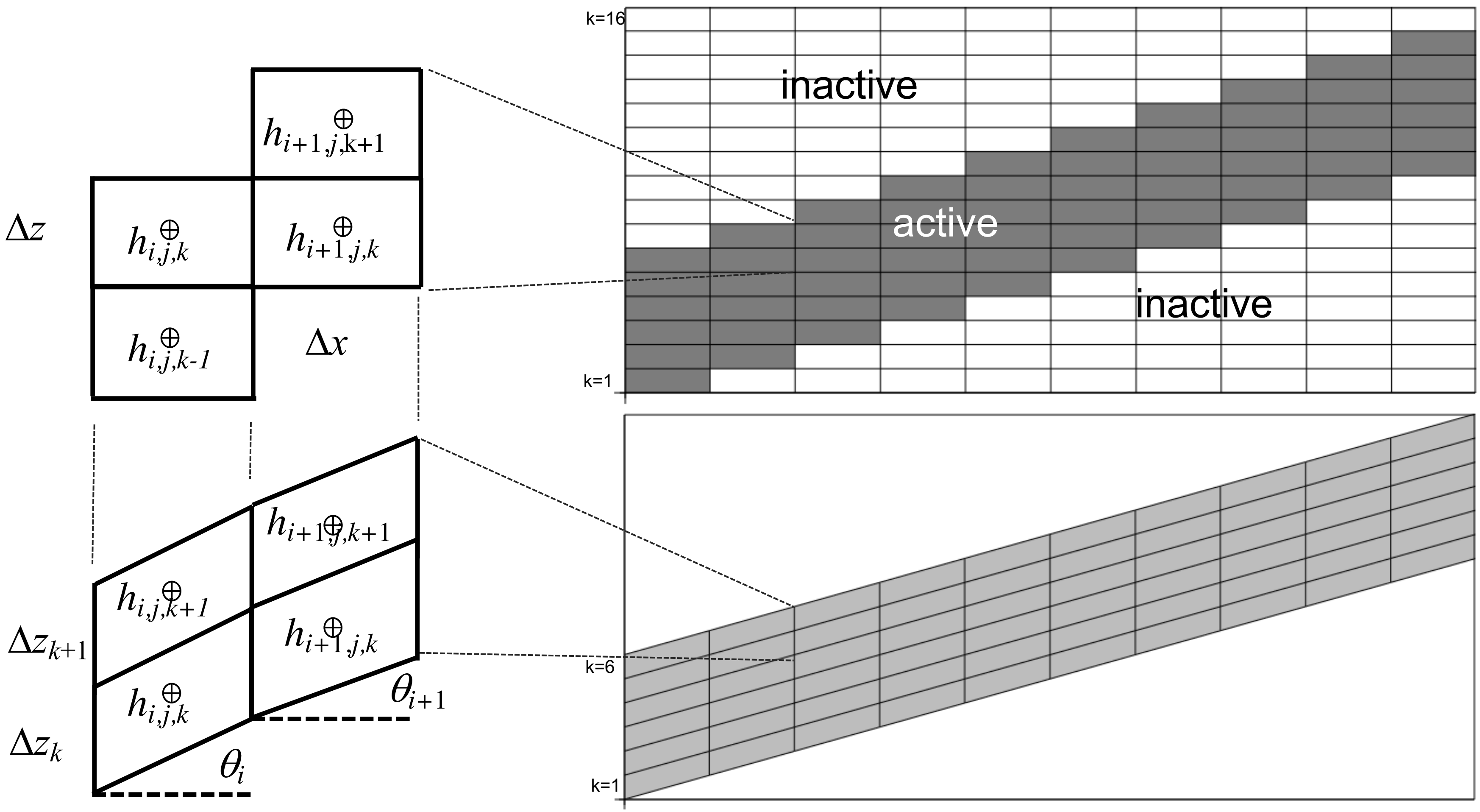
Saturated Hydraulic Conductivity (L/T)

$$\frac{\partial \psi_s}{\partial t} = \nabla \vec{\mathrm{v}} \psi_s + q_r$$

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

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:

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

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

$$= -K_{s,x}(x)k_r(h)\frac{\partial(h)}{\partial x}\cos\theta_x - K_{s,x}(x)k_r(h)\sin\theta_x$$

Diffusive Pressure Term Topographic Term

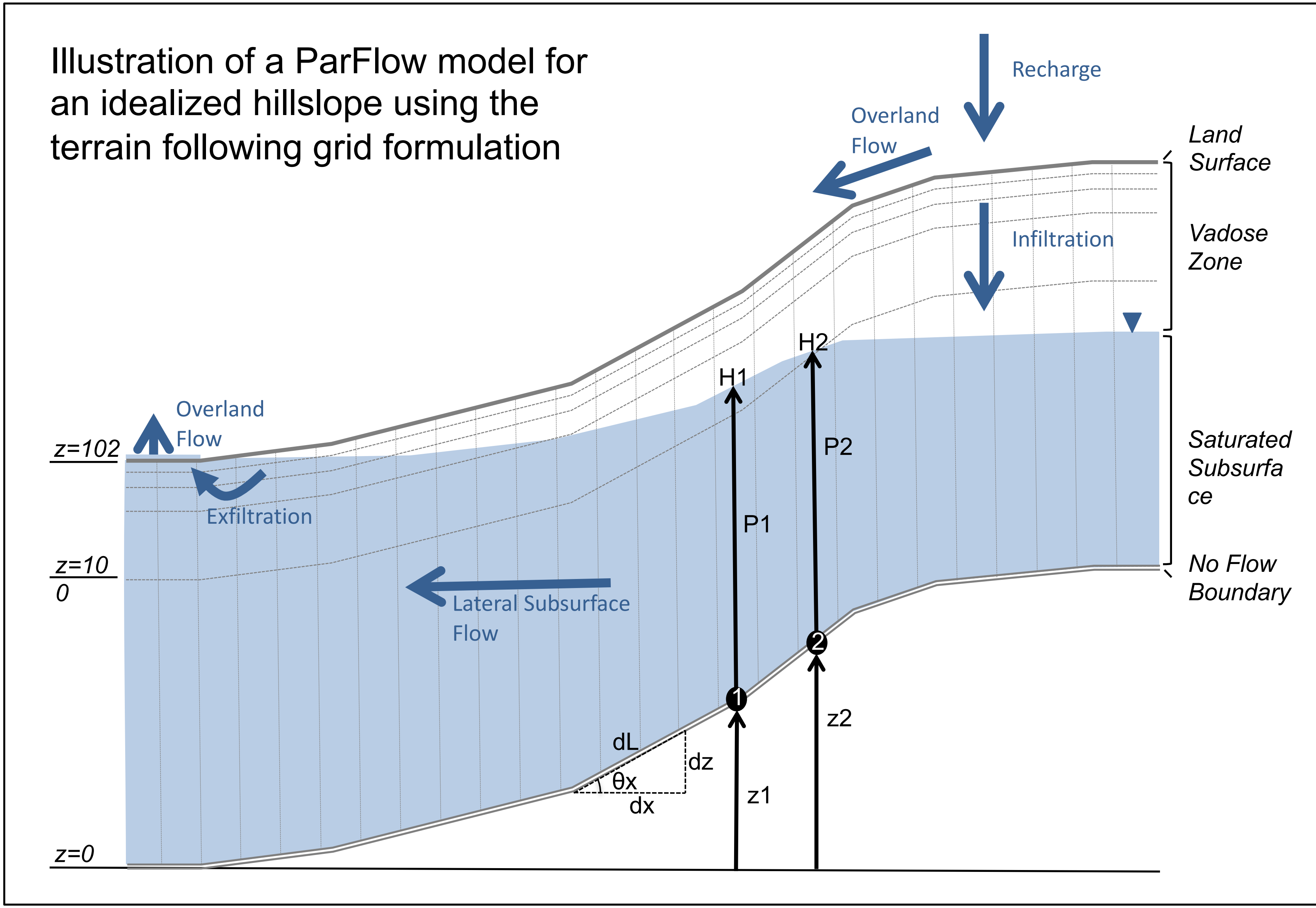


Illustration of a ParFlow model for an idealized hillslope using the terrain following grid formulation
Recharge
Overland Flow
Land Surface
Infiltration
Vadose Zone
H2
H1
Overland Flow
z=102
P2
Saturated Subsurface
Exfiltration
P1
z=100
No Flow Boundary
Lateral Subsurface Flow
2
1
z2
dL
dz
θx
dx
z1
z=0

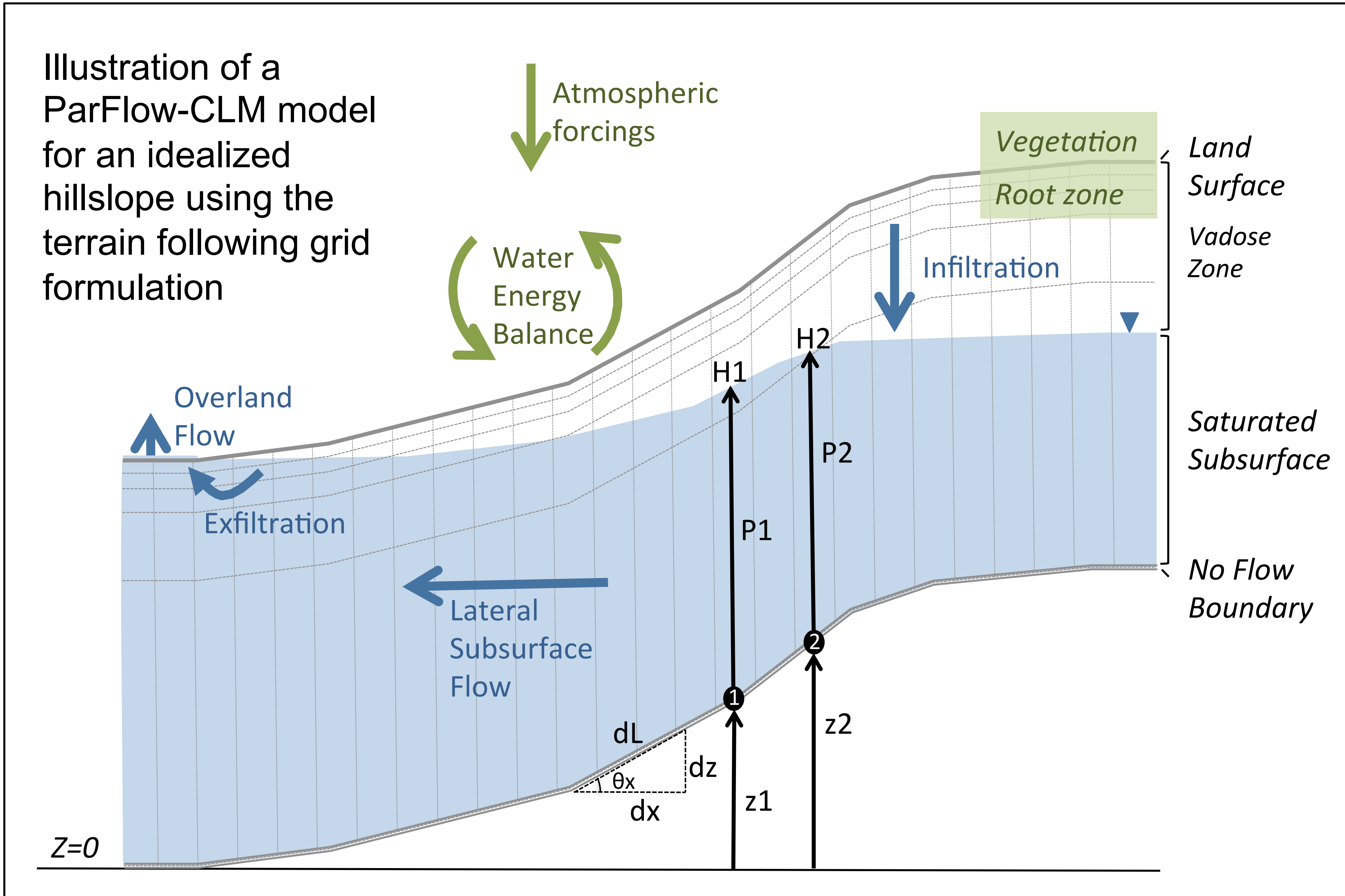
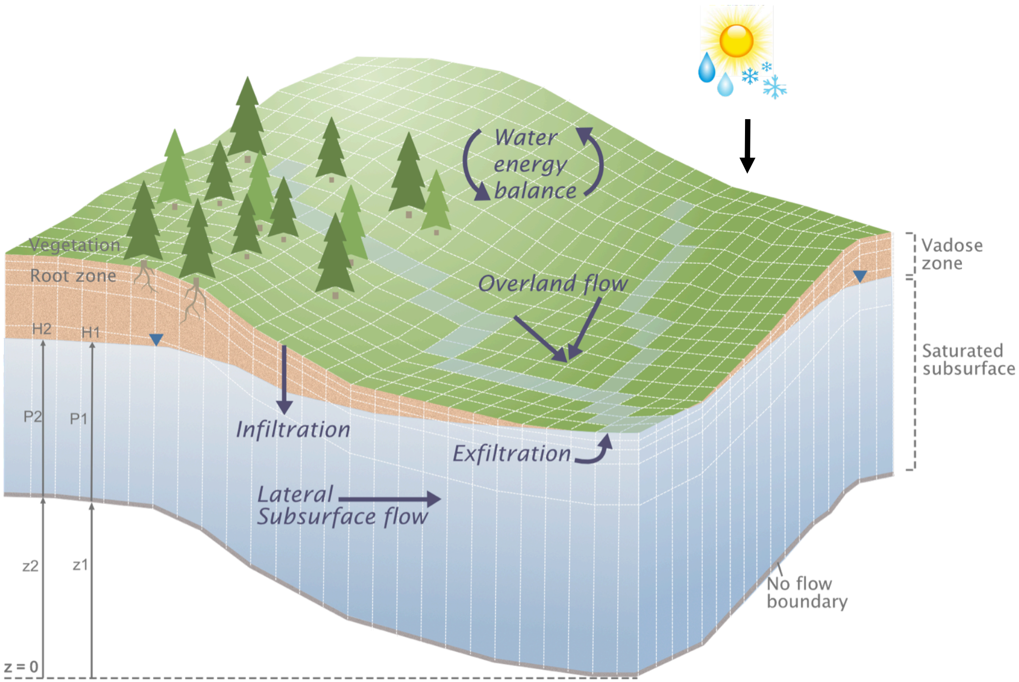


Illustration of a ParFlow-CLM model for an idealized hillslope using the terrain following grid formulation
Atmospheric forcings
Water Energy Balance
Vegetation
Root zone
Land Surface
Vadose Zone
Infiltration
Overland Flow
Exfiltration
H1
H2
P1
P2
Saturated Subsurface
Lateral Subsurface Flow
No Flow Boundary
dL
dz
θx
dx
z1
z2
Z=0

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

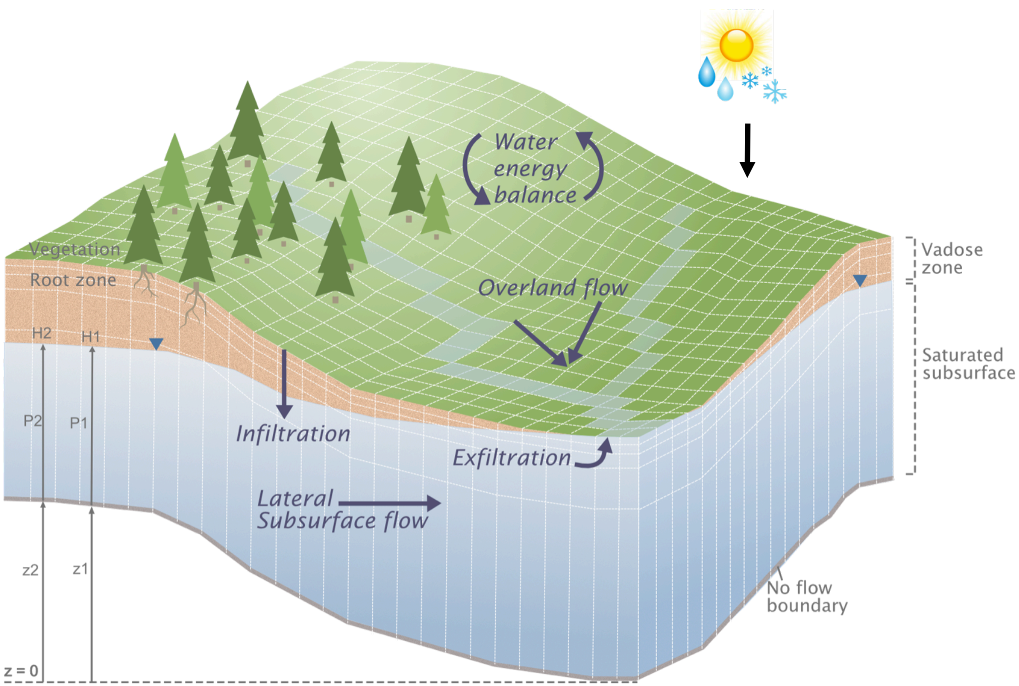
Topography

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
```

Perm/porosity files:

```
myrun.out.perm_x.pfb
myrun.out.porosity.pfb
```

Pressure/Saturation files:

```
myrun.out.press.00001.pfb
myrun.out.satur.00001.pfb
```

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

Mask file:

```
myrun.out.mask.00000.pfb
```

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

Other/diagnostic files:

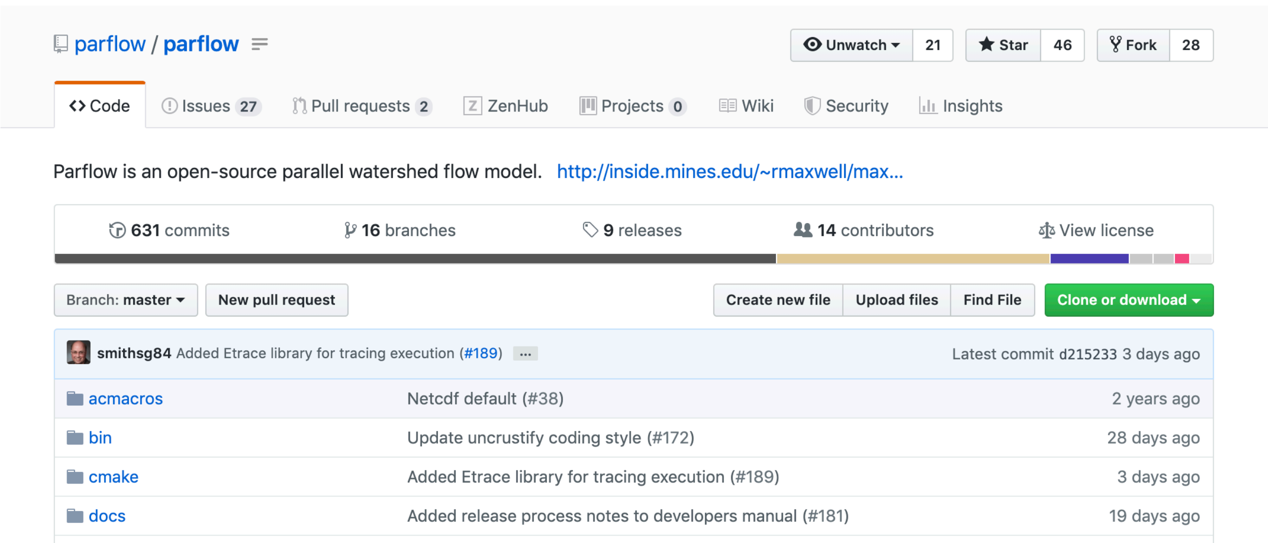
`myrun.pfidb` Parflow database

`myrun.out.pftcl`

`myrun.out.txt` Line output

ParFlow Development

ParFlow is hosted on GitHub

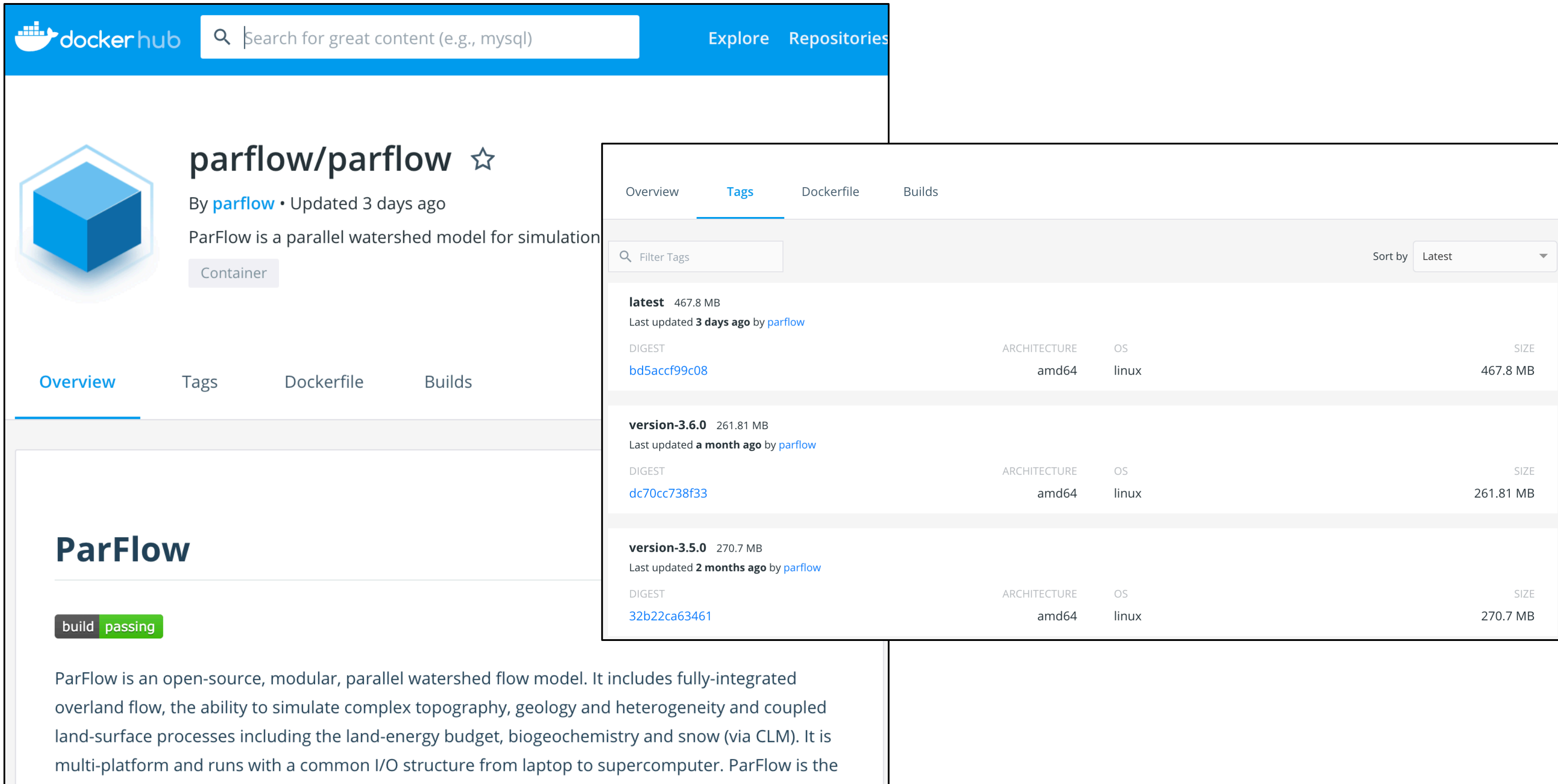


https://github.com/parflow

Git repository used for

- Source code
- Test cases
- Documentation
- Issue tracking

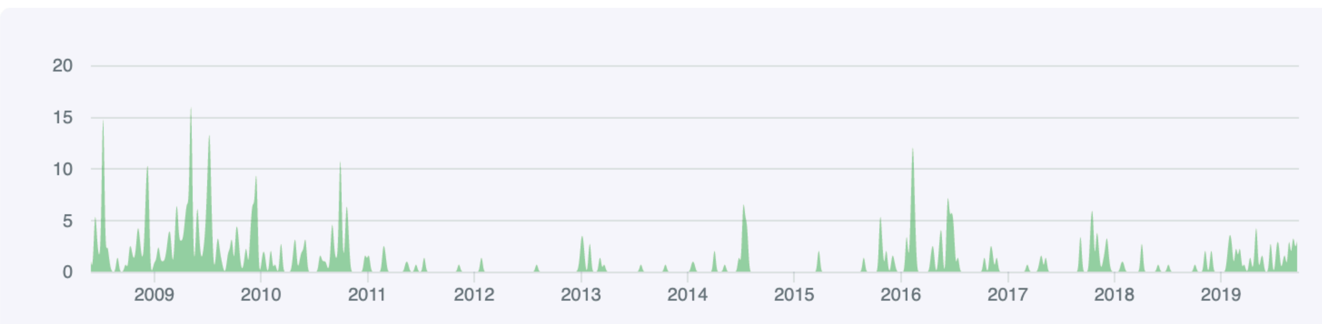
We also auto-build Docker images with tagged releases



https://hub.docker.com/r/parflow/parflow

ParFlow is an active research code with many developers

Timeline of contributions to the master branch



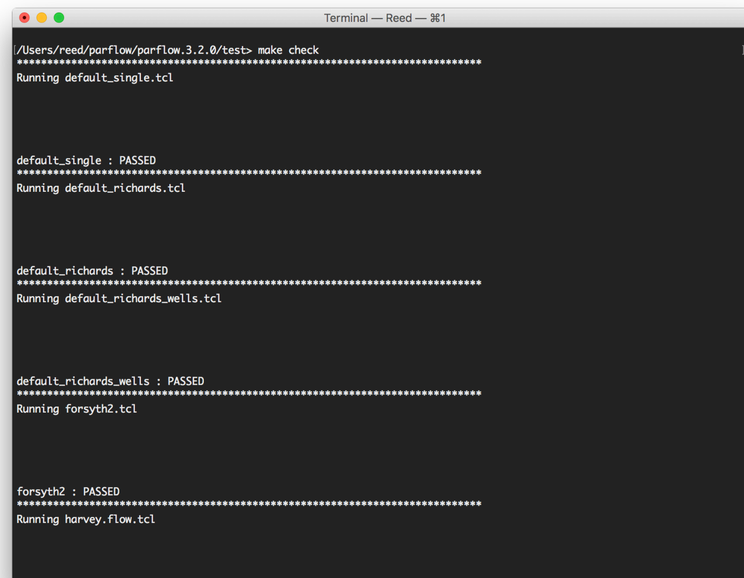
Forks

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

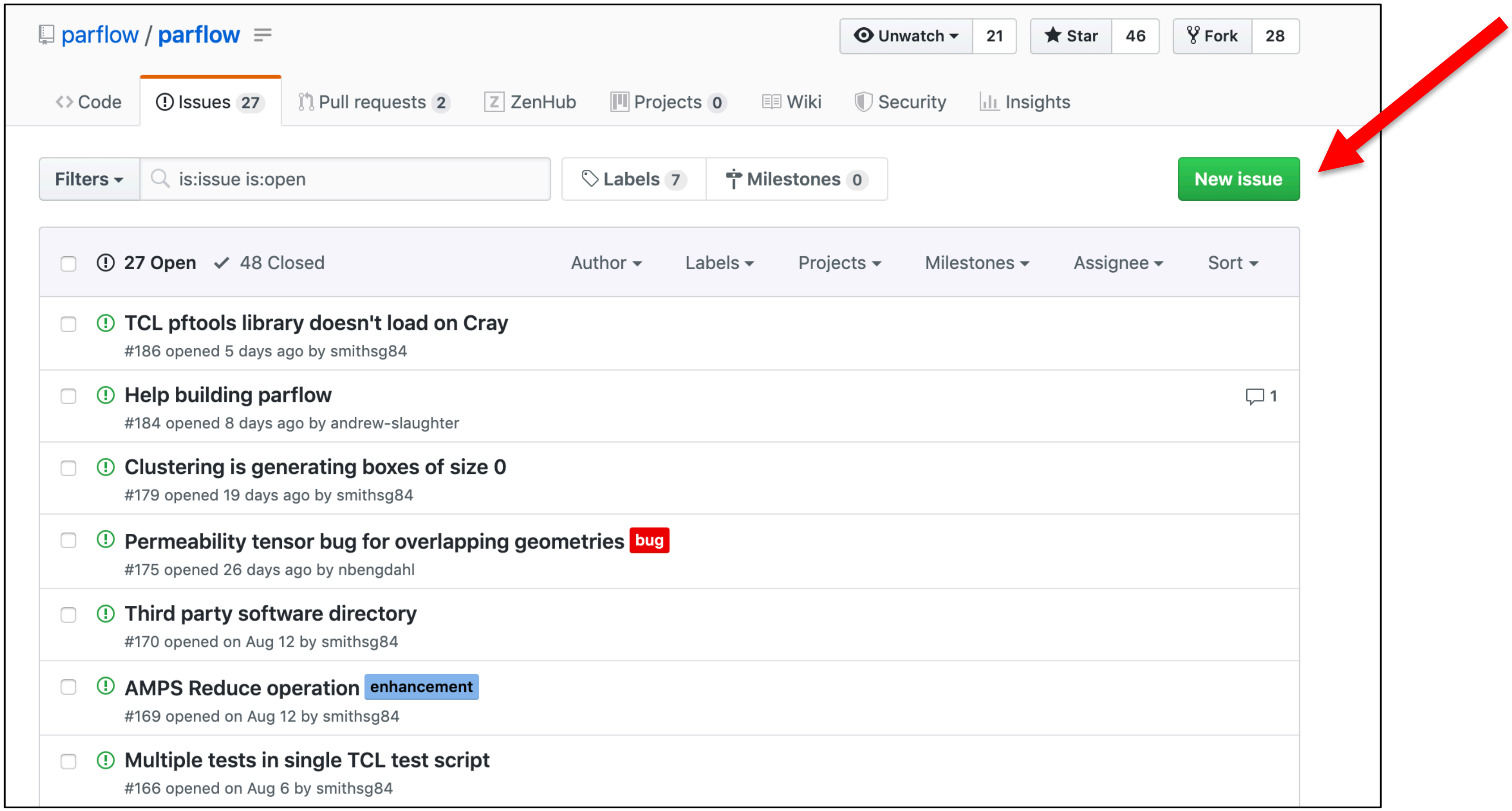
- Suite of test cases testing solvers and code features
- TravisCI integration with GitHub used for continuous integration
- Testing allows check for backward compatibility of new code
- Tests provide examples for new users

Travis CI



Do you have an issue?

Document it on the GitHub issue tracker

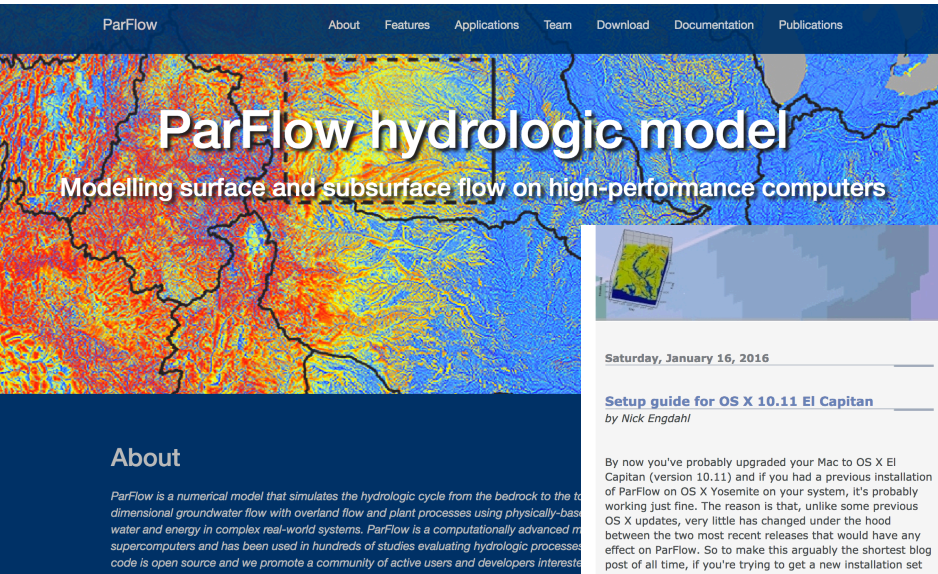


We have an open development community, and you can be a ParFlow developer too!

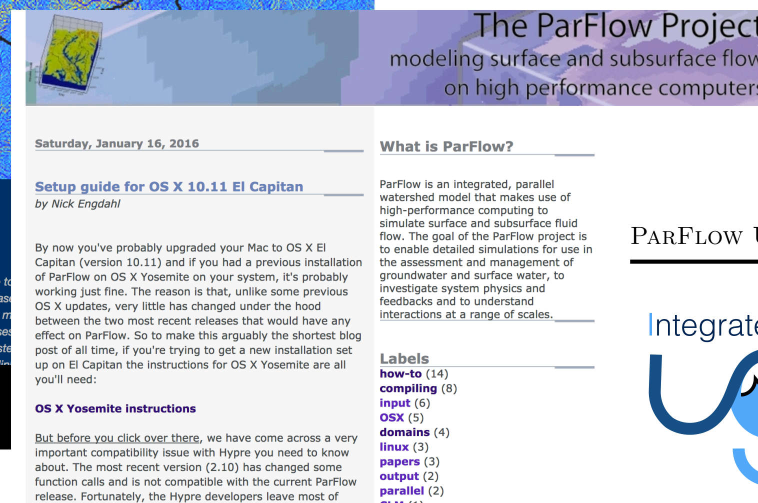
1. Check out our software sustainability plan for all the details https://github.com/parflow/parflow/blob/master/docs/software_plan.md
2. Create your own ParFlow fork and do your development there
3. Document and Test. All new features must:
   - Be documented in the manual
   - Pass the existing tests 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

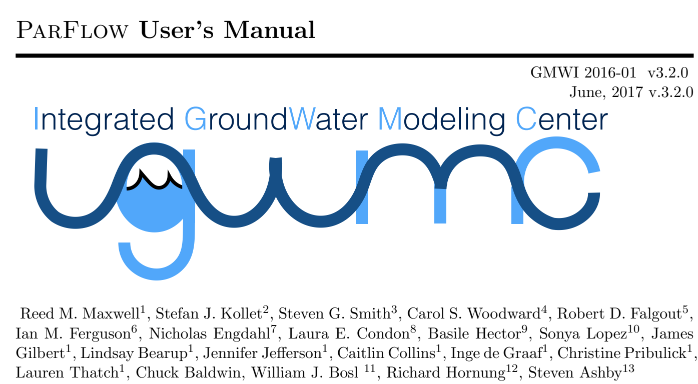
Online Resources



Website



Blog



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/