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Variably Saturated Flow Model in ALM

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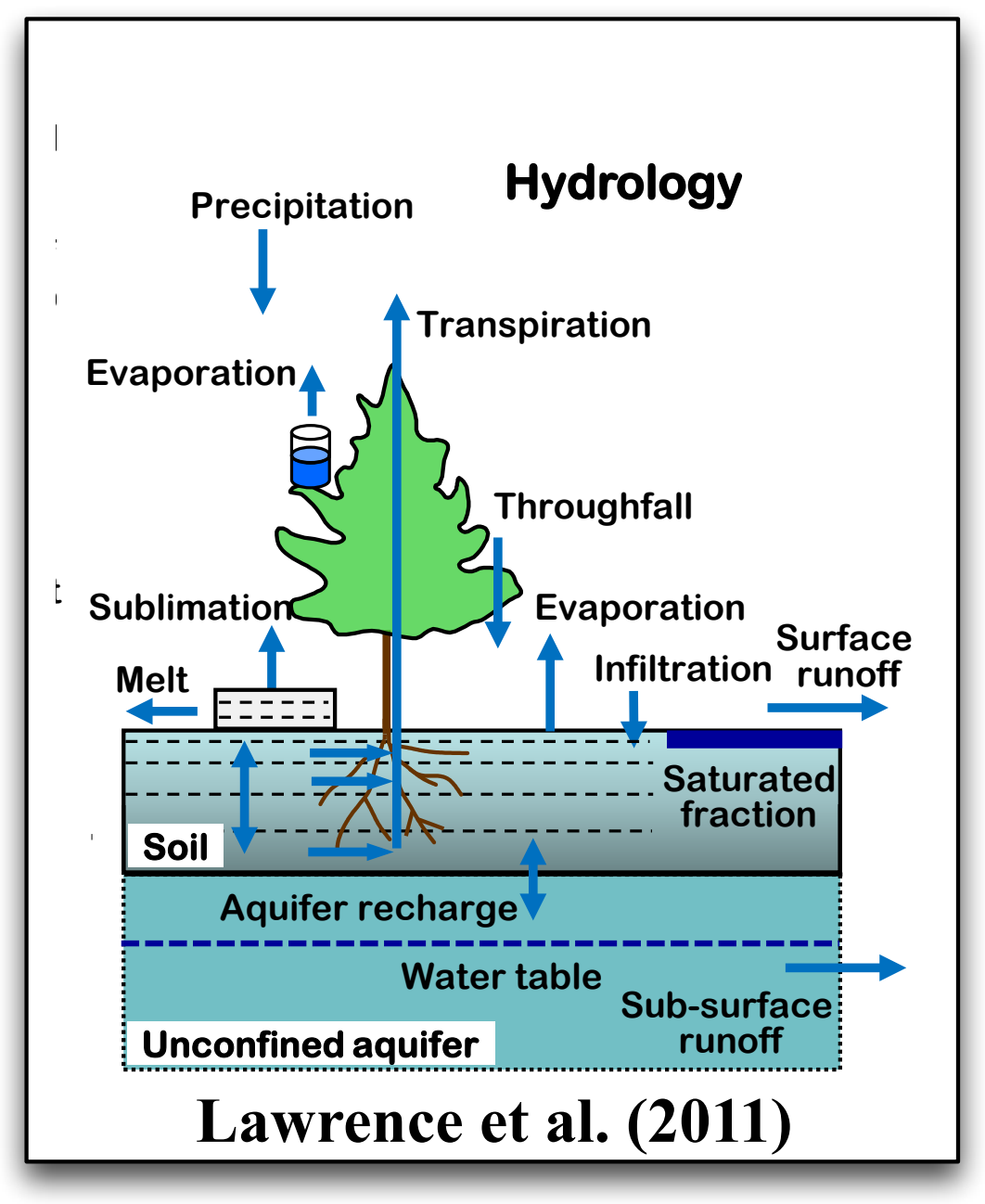
Objective



Lawrence et al. (2011)

- Numerous modeling and observational studies have shown a positive soil moisture – rainfall feedback.
- Groundwater accounts for 30% of freshwater reserves globally and is expected to be impacted in quantity and quality by climate change.
- **A**CME **L**and **M**odel (ALM) version 0 employs a non unified treatment of hydrologic processes in unsaturated and saturated zone:
  - Theata-based Rciahrds equation in unsaturated zone, and
  - Bucket model formulation for unconfined aquifer
- To overcome the above-mentioned shortcoming we developed a **V**ariably **S**aturated **F**low **M**odel (VSFM) that is valid in both saturated and unsaturated zone.
- We use **P**ortable, **E**xtensible **T**oolkit for **Sc**ientific Computation (PETSc) library for solving the discretized equations of VSFM.

Approach

Governing equation:

$$\frac{\partial}{\partial t}(\phi s \rho) = \nabla \cdot (\rho \vec{q}) + Q$$

where ϕ (porosity), s (saturation) and ρ (density) are non-linear function of P (liquid pressure); and Q is a source term.

Darcy flux ($\vec{q}$) is given by

$$\vec{q} = -\frac{k k_r}{\mu} \nabla (P + \rho \vec{g} z)$$

where k is intrinsic permeability, k_r is relative permeability, μ is viscosity of water, $\vec{g}$ is acceleration due to gravity, and z is surface elevation.

In order to close the above system of equations, we choose following constitutive model

- van Genucten [1980] : $s = f(P)$
- Maulem [1976] : $k_r = f(P)$

Discretized equation using FV + Backward Euler:

$$V_i \left(\frac{(\phi s \rho)^t - (\phi s \rho)^{t-\delta t}}{\delta t} \right) - \sum_j (\rho \vec{q})^t_{i,j} \cdot \hat{n}_{i,j} A_{i,j} - Q_i = 0$$

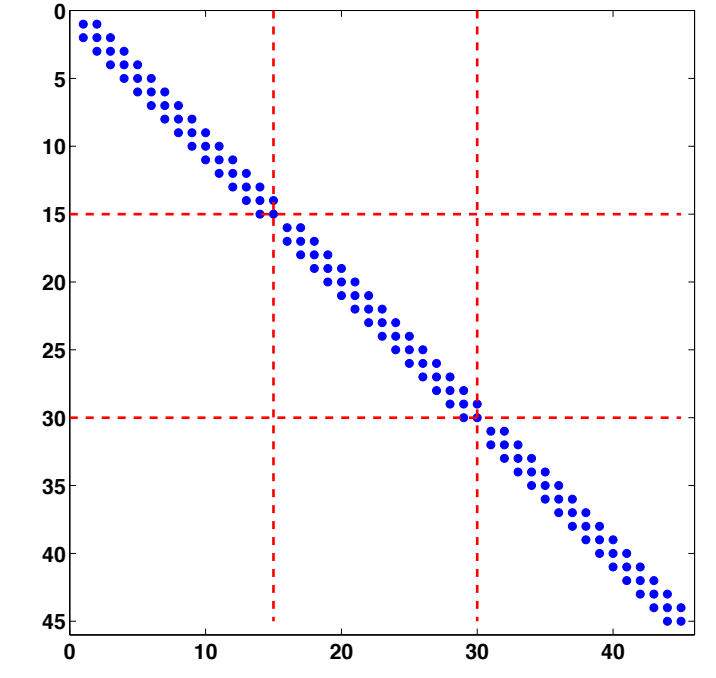
Numerical solution via PETSc:

$$\mathbf{F}(P^t) = 0$$

$$\mathbf{J}(P^t_k) \Delta P^t_k = -\mathbf{F}(P^t_k)$$

F() : `subroutine Residual()`
J() : `subroutine Jacobian()`

Sparsity pattern of **J** for three soil columns with 15 layers



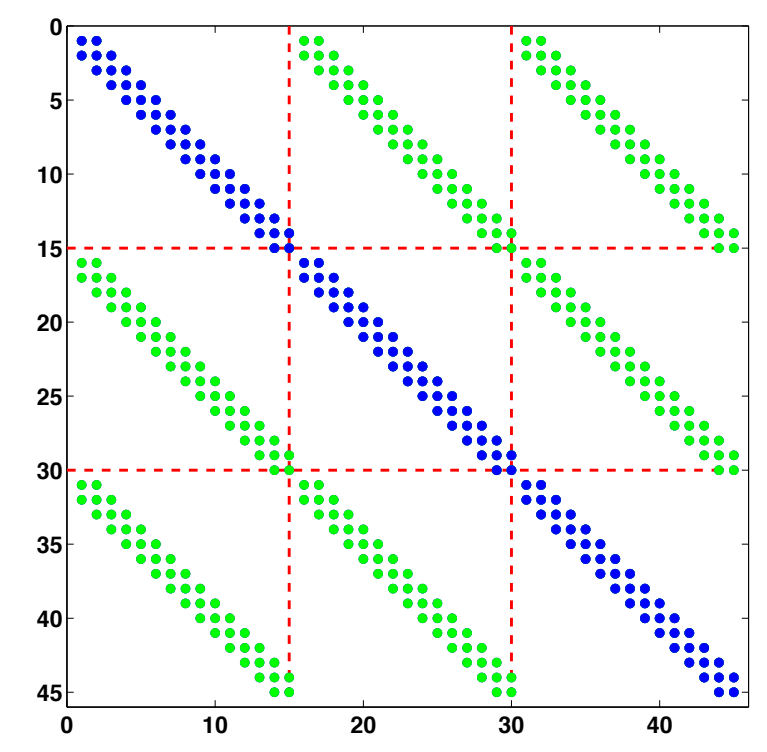
Design Features:

1. Extensible to support a tightly coupled 3D solve independently on each processor.

```
!ALM v0
do j = 1, nlevsoi
  ...
  ...
  ...
enddo
```

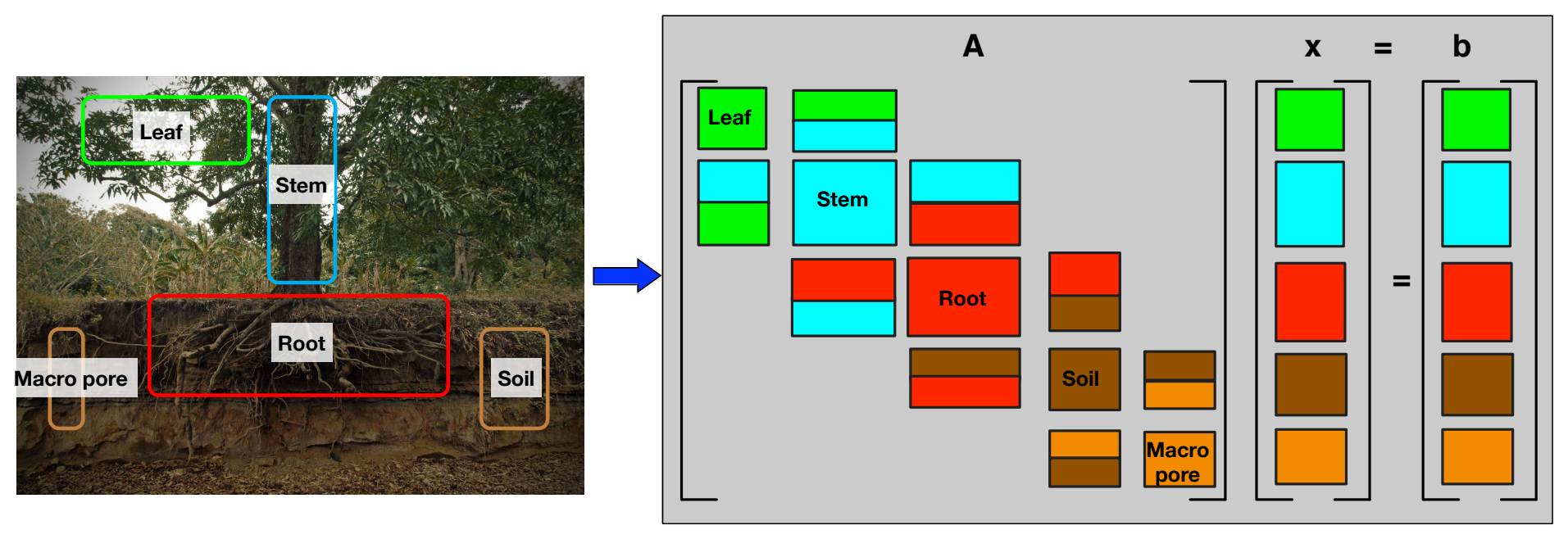
```
!ALM v1
do iconn = 1, cur_conn_set%num_connections
  cell_id_up = cur_conn_set%id_up(iconn)
  cell_id_dn = cur_conn_set%id_dn(iconn)
 ...
enddo
```

Sparsity pattern of **J** for three soil columns with 15 layers for a 3D problem



Design Features:

2. Extensible to support tight coupling of multi-physics problems via PETSc DMComposite.



```
call MatGetLocalSubMatrix(A,1,1,A_leaf)
call MatGetLocalSubMatrix(A,2,2,A_stem)
call MatGetLocalSubMatrix(A,3,3,A_root)
call MatGetLocalSubMatrix(A,4,4,A_mpore)

call MatGetLocalSubMatrix(A,1,2,A_leaf_steam)
call MatGetLocalSubMatrix(A,2,1,A_steam_leaf)
```

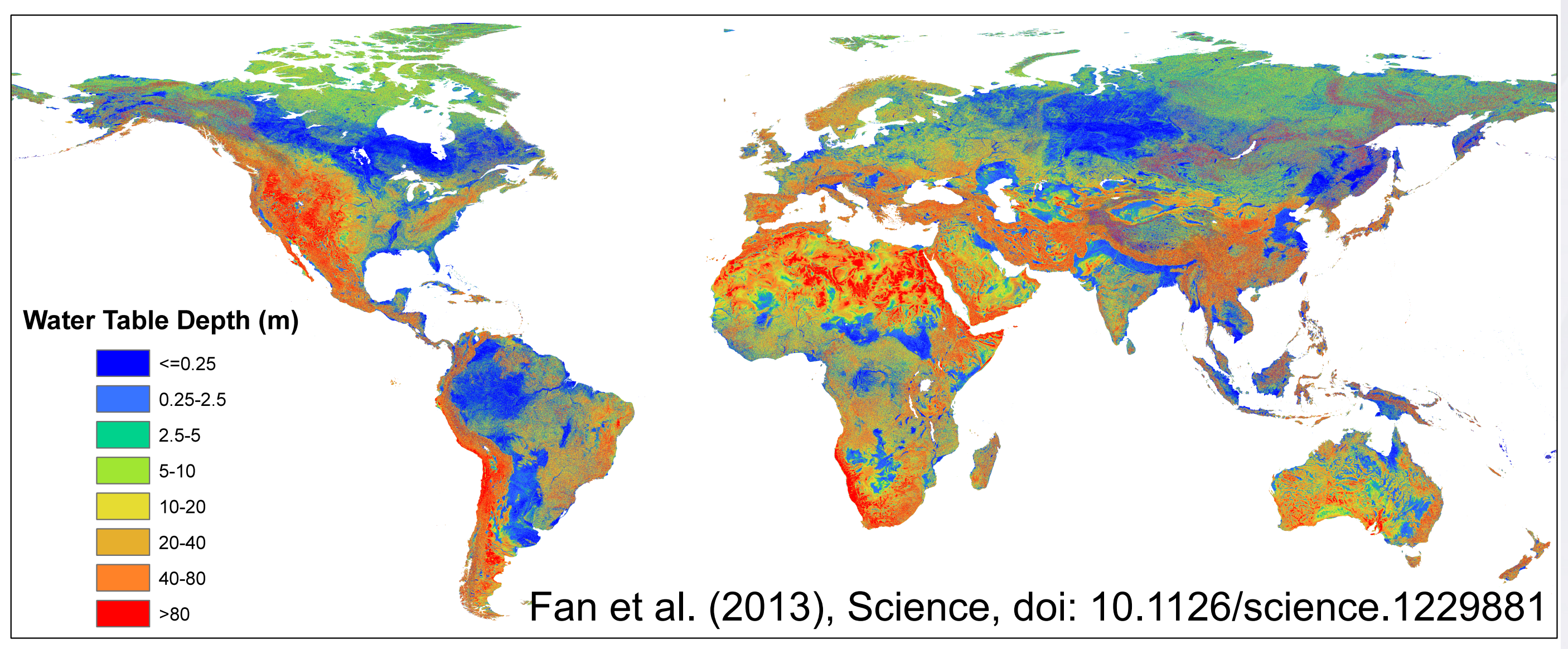
Results

Simulation setup:

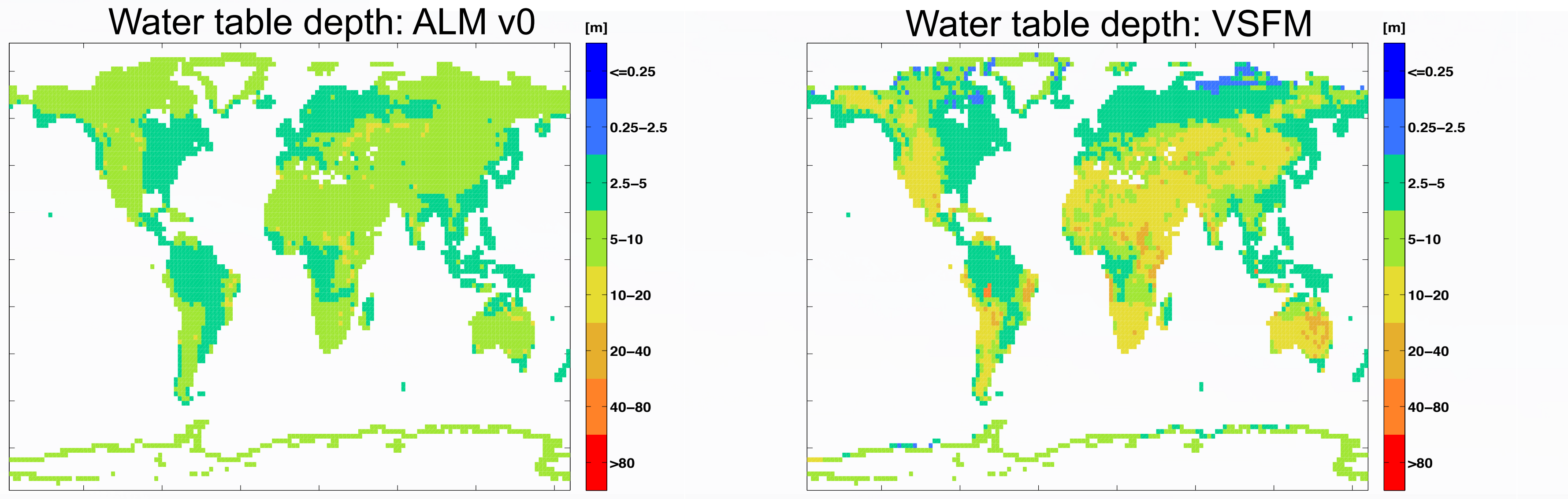
- **COMPSET**: ICRUCLM45
- **Resolution:** f19_g16
- **Forcing data:** 1991-2010
- **Simulation length:** 40-yr

Results shown are average values corresponding to years 21-40.

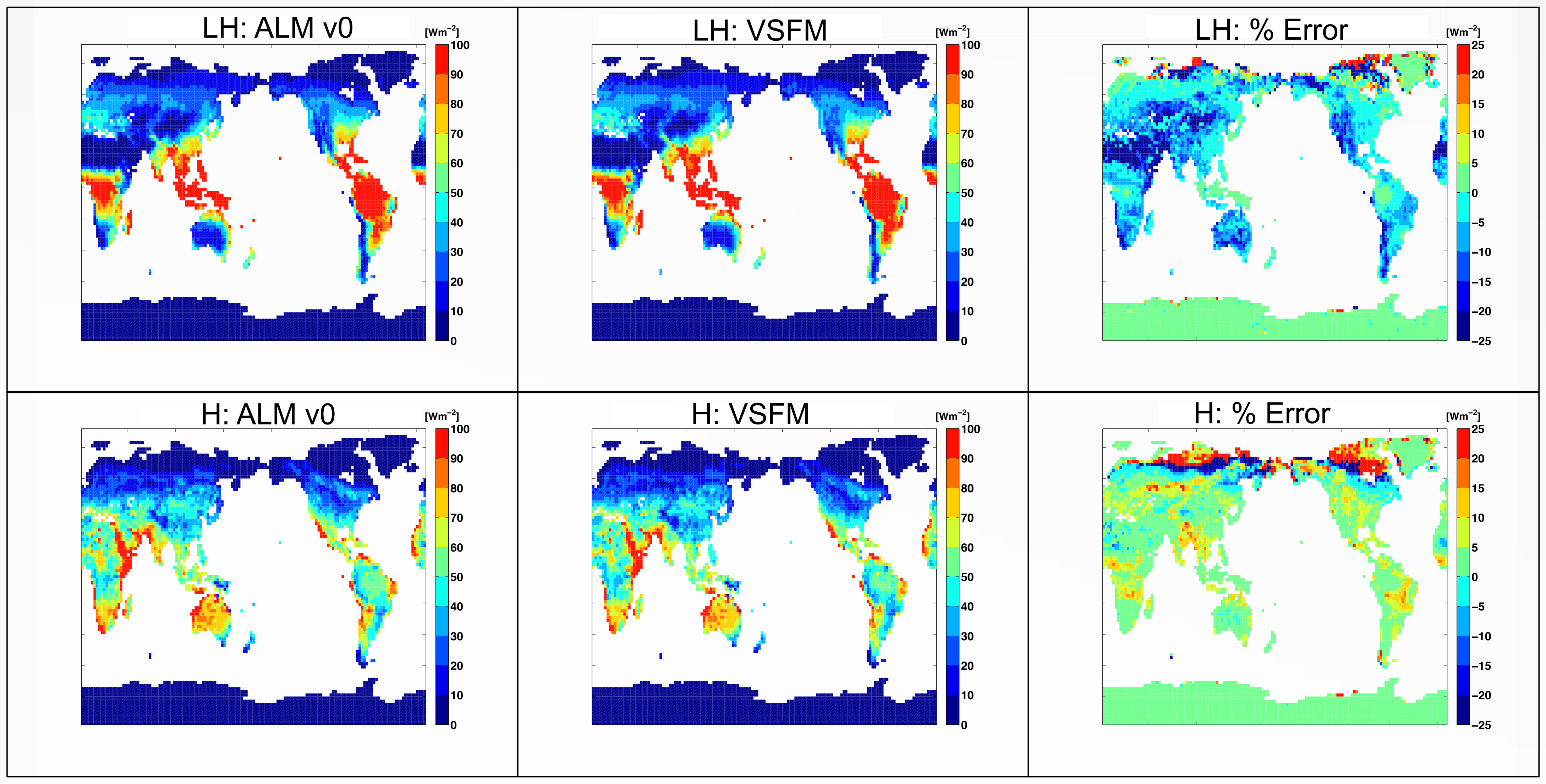
Global Water Table depth dataset



Fan et al. (2013), Science, doi: 10.1126/science.1229881



Water table depth: ALM v0
Water table depth: VSFM



LH: ALM v0
LH: VSFM
LH: % Error
H: ALM v0
H: VSFM
H: % Error

The following performance data is based on 1-yr simulation at f19_g19 for ICRUCLM45

	Throughput	TOT Run	LND Run	ROF Run	ATM Run	CPL Run	CPL COMM
ALM v0	168 [sy/d]	515 [s]	240 [s]	34 [s]	200 [s]	33 [s]	91 [s]
VSFM	87[sy/d]	991 [s]	487 [s]	34 [s]	197 [s]	129 [s]	363 [s]

ACME Accelerated Climate Modeling for Energy

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