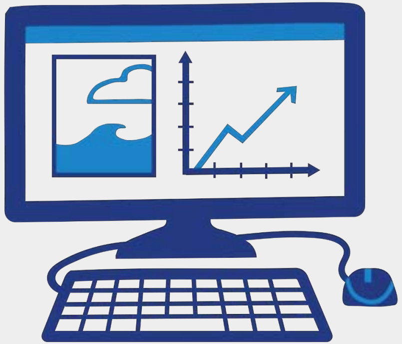

Land model development for climate and ESM applications

Elena Shevliakova and land team

Q1: Concerning GFDL's core strength of building and improving models of the weather, oceans, and climate for societal benefits, how can GFDL leverage advances in science and computational capabilities to improve its key models? What are the strengths, gaps, and new frontiers?

NOAA
GEOPHYSICAL FLUID DYNAMICS LABORATORY

5-YEAR REVIEW
JANUARY 28-30, 2025

Land in ESMs: Motivation & Challenges

NOAA and DOC Strategic Objectives:

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  - Land hydroclimate hazards such as flooding, hydrological and ecological droughts, and fire have a limited representation in climate models
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  - Additional ecosystem responses to warming not yet fully included in climate models, e.g. wetlands, permafrost thaw, and wildfires would further increase concentrations of GHG gases in the atmosphere and change climate
  - Coupling between hydrology, biogeochemical cycles, and unmanaged and managed ecosystem processes is complex
  - Very few quantitative mechanistic theories to capture ecological processes needed to characterize climate-land BGC interactions and feedbacks

LM4 modeling system

- Time step ≤ 30 min
- Implicitly coupled

Three configurations:

LM4.0 -> CM4.0 and SPEAR
LM4.1 -> ESM4.1
LM4.2 -> new developments

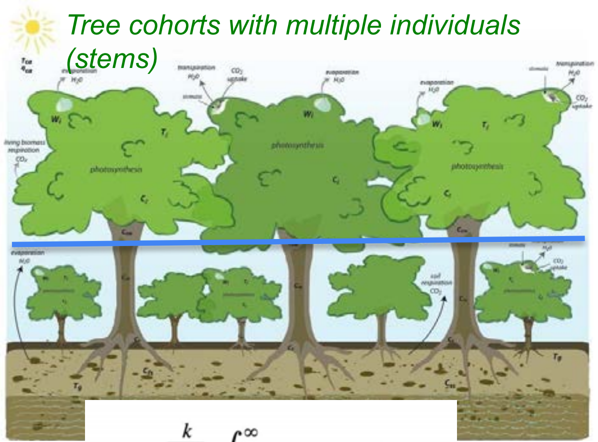
Belowground processes:

- Soil and bedrock layers
- Variably-saturated hydraulics
- Thermal diffusion with freeze-thaw
- Sub-surface runoff
- Groundwater table, including perched over permafrost
- N cycle/microbes
- CH_4 /microbes

Aboveground and lake/river processes:

- Canopy/soil evapotranspiration
- Multi-layer snow
- River runoff
- Lake, including ice/snow, parameterized circulation
- Plant hydraulics
- Dynamic vegetation
- Fire
- Plant phenology
- Land use, irrigation, and urban
- River and reservoirs
- Plant N cycle
- Dust emissions
- River BGC and H_2O quality (LM3->LM4)

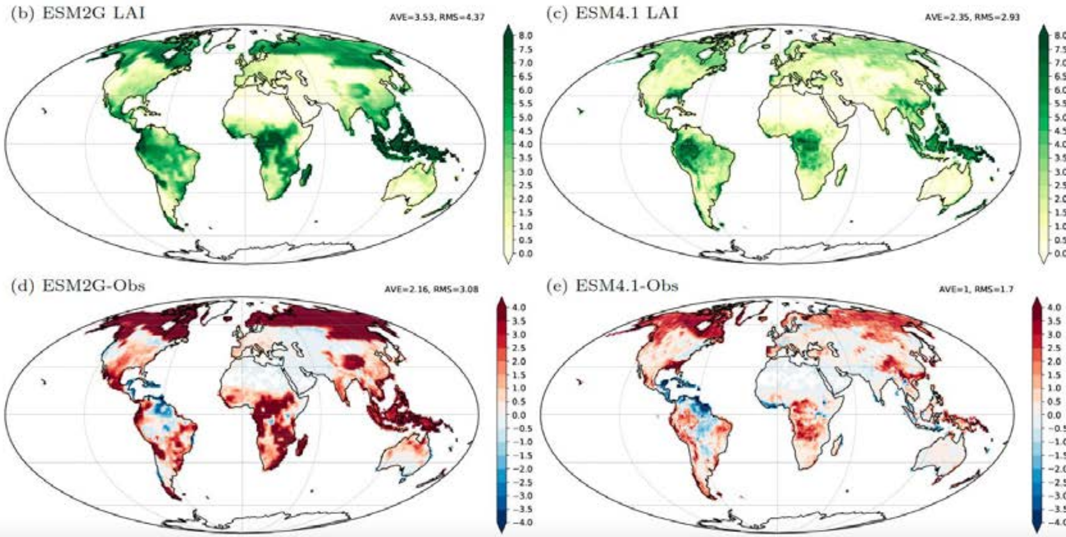
Vertical & Horizontal Canopy Heterogeneity: Perfect Plasticity Approximation



$$1 = \sum_{j=1}^{k} \int_{z^*}^{\infty} N_j(z) A_j(z^*, z)\, dz$$

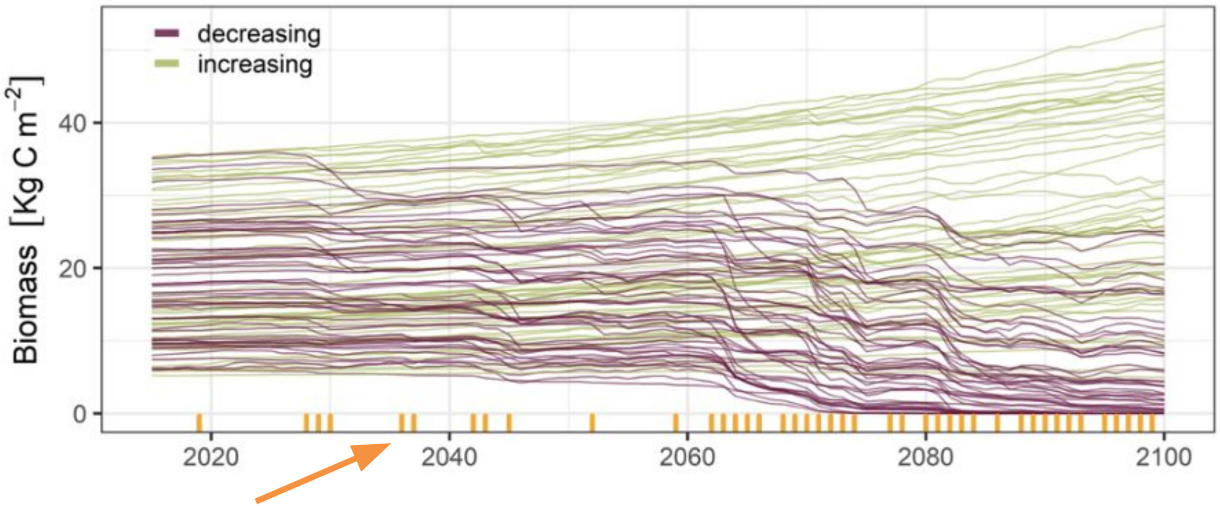
- trees are plastic: the total of the exposed crown areas is equal to the ground area;
- there is a prognostic *canopy height* Z^* su[ch] that any foliage above Z^* is in the canopy with all other foliage in the understory.

- ❖ *PPA enables ecological heterogeneity*
- ❖ *Global implementation: e.g. GFDL ESM4.1/LM4.1 in CMIP6*
- ❖ *Size and age structure predicted*



Shevliakova et al, 2024, Martinez Cano et al, 2020
Weng et al., 2015, Srtigul et al. 2008

ESM4.1 projects an abrupt decline in tree density in Amazon in low-mitigation scenarios due to increased fire and reduced competitiveness



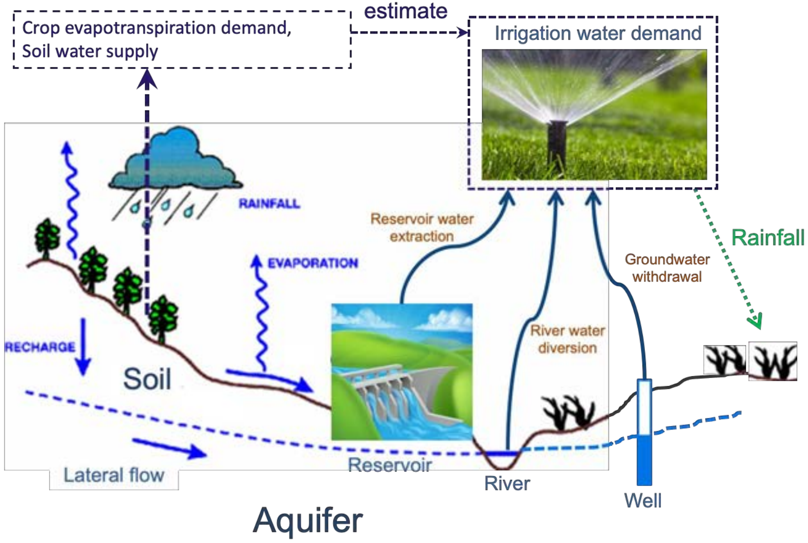
Simulated fires. Each line represents a grid cell currently occupied by tropical forest. Purple lines show forest dying after fire

- Pronounced biomass losses under SSP5-8.5 and SSP3-7 after 2060 due to increased wildfire lead to nearly collapse of forests at many locations in Amazon.
- Without Amazon forest carbon sinks global Paris Agreement goals are much harder to attain

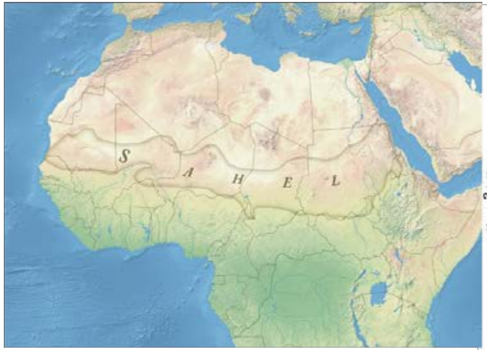
Martinez Cano et al., PNAS, 2023

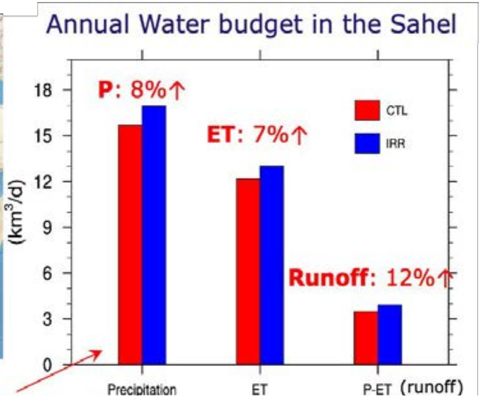
Water management processes have local and remote implications for climate change

Implementation of irrigation in GFDL Land models



Irrigation outside Africa affects water availability in the Sahel through remote effects



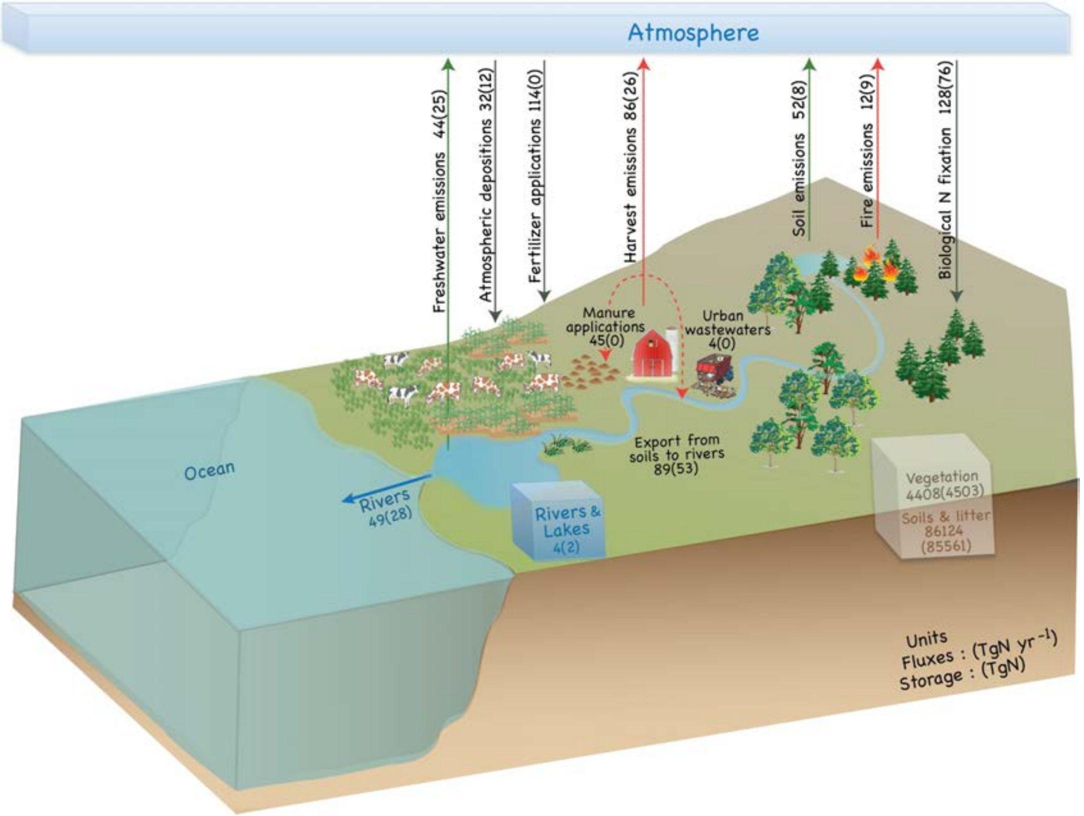


ESM2M Simulations without irrigation and with prognostic irrigation schemes us

Zeng et al. 2022

GFDL Land Model LM3-TAN (Terrestrial and Aquatic Nitrogen)

- **LM3**: Coupled terrestrial-river-lake water, energy, and/or C-N dynamics
- **TAN**: Linking terrestrial and freshwater N dynamics (Lee et al., 2014)
- Recent findings (Lee et al 2024) :
  - Fertilizer usage is the primary determinant of future river N loads.
  - Fertilizer applications to produce bioenergy in climate mitigation scenarios cause larger load increases than in the highest emission scenario.



Simulated land **C budget** includes LU flux **as the Managed Land Proxy**

Δ land (C) =

- Gross LU C emissions from clearing/deforestation

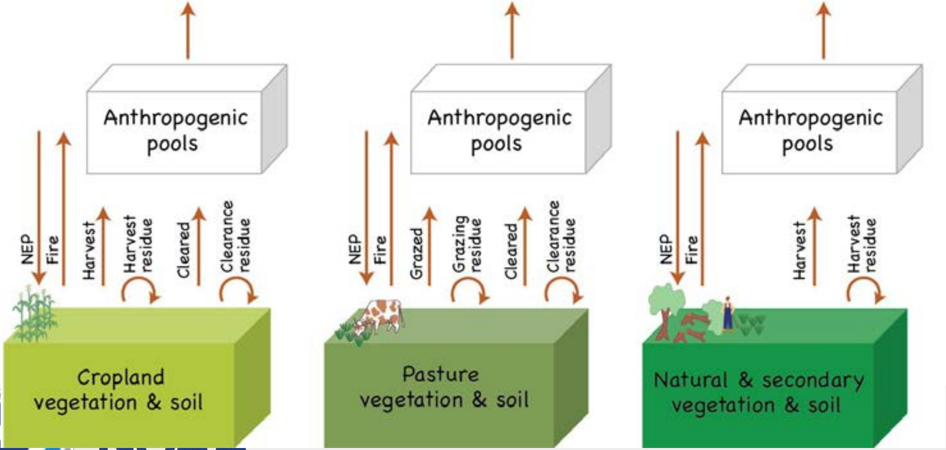
- Gross emissions from wood and ag. harvesting

+ *NEP - Fire on second. lands, croplands, & pasture*

+ NEP - Fire on natural lands

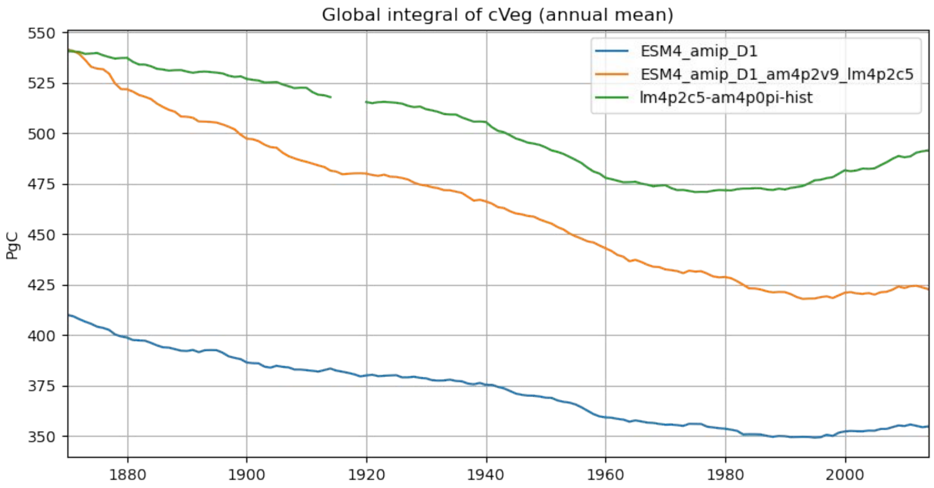
Net C flux on managed lands

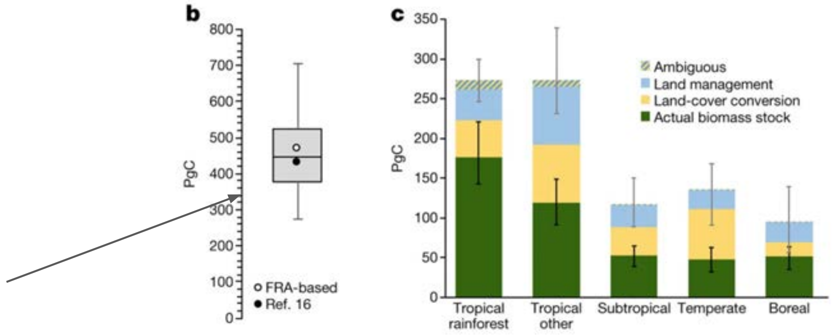
Biosphere sinks and sources



- GFDL ESMs
  - separate soil C on different land uses and report losses from soils and Net Ecosystem Production (NEP) by land-use category
  - separate secondary and primary vegetation and report the regrowth of secondary vegetation
- New prognostic crop calendars
- Rangelands in addition to pastures, revising grazing

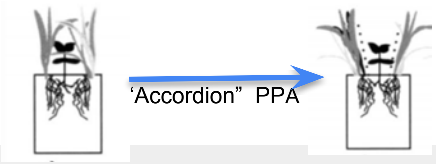
Vegetation dynamics and moisture exchanges with soil improve biomass biases



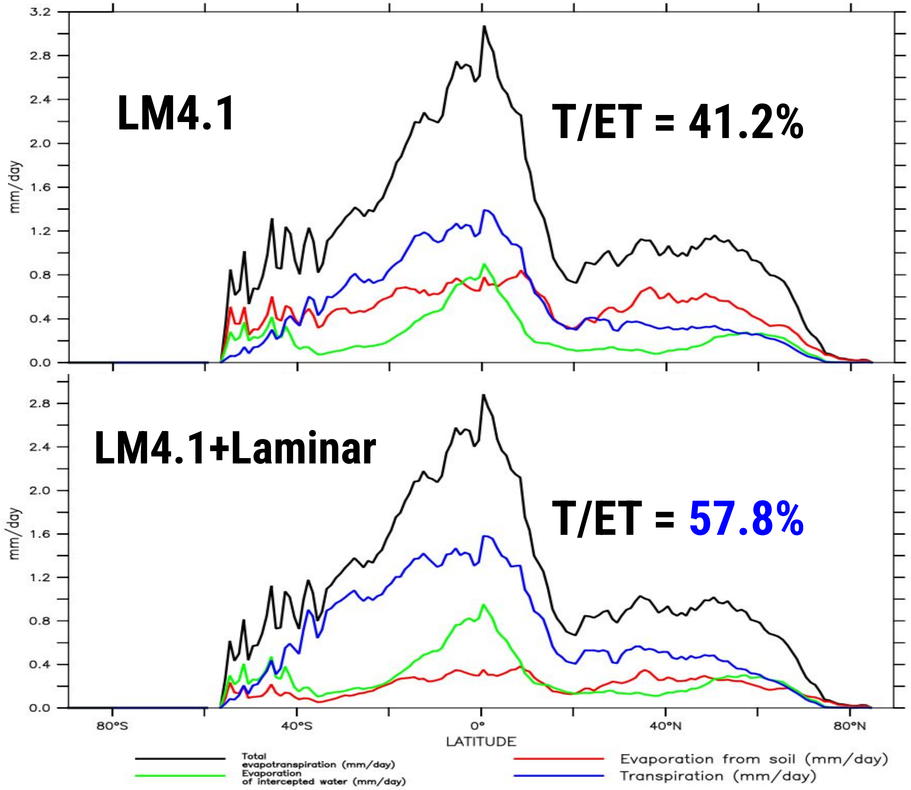


Erb et al 2017

- Tree line
- Laminar soil resistance
- Grass-seedling competition for light



Zonal-mean Effect of Laminar Resistance on Soil Evaporation



Results from standalone land model driven by the forcing from AM4p0

- Observationally-based estimates of Wei et al. (2017) indicate T/ET (Transpiration to EvapoTranspiration) value of 57.2%
- Laminar resistance formulation brings the model number very close to that estimate, mostly due to reduction in direct evaporation from soil (red curve), although there is some slight increase in transpiration too.
- Longer-term effects include vegetation feedback, with vegetation reacting to more available soil moisture.

Malyshev, in prep

Preliminary Global LM4.2-GIMICS Results

Ito et al. (2020)

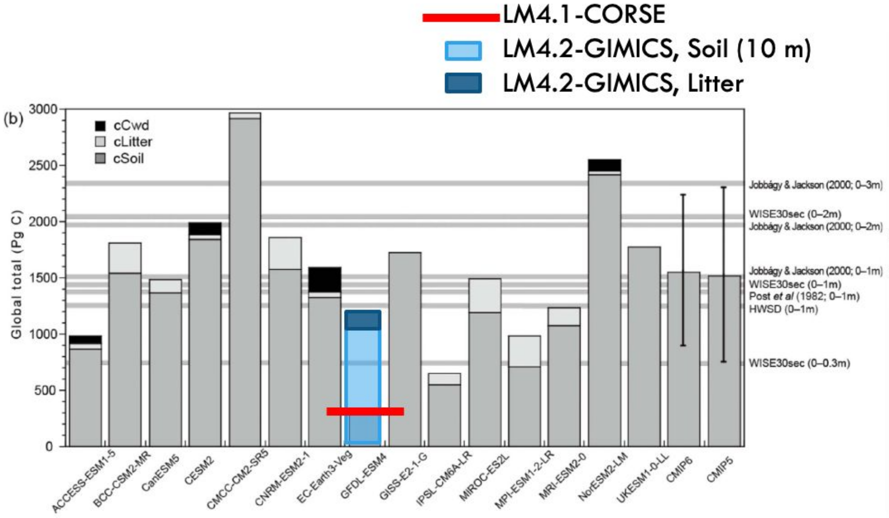
- Observational data shown by grey horizontal bars
- 15 CMIP land model results in the 2000s
  - — Soil: 1413±688
  - — Litter: 185±88 (11.9, 1.7-27.8% of soil)
  - — Total: 1553±672

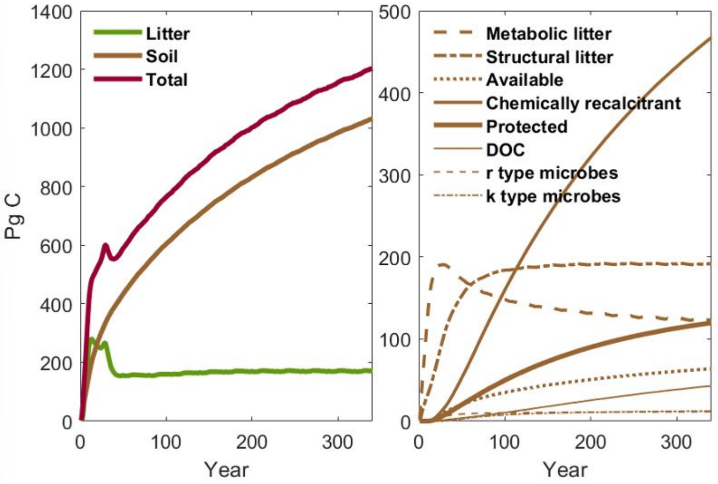
Viscarra Roseel & Hicks (2015); Xu et al. (2013)

- HOC (Cc): ~46-60%; ROC (Cp): 25-33%; POC (Ca): 12-23%
- Microbes: 2 (0.5-5)% of soil

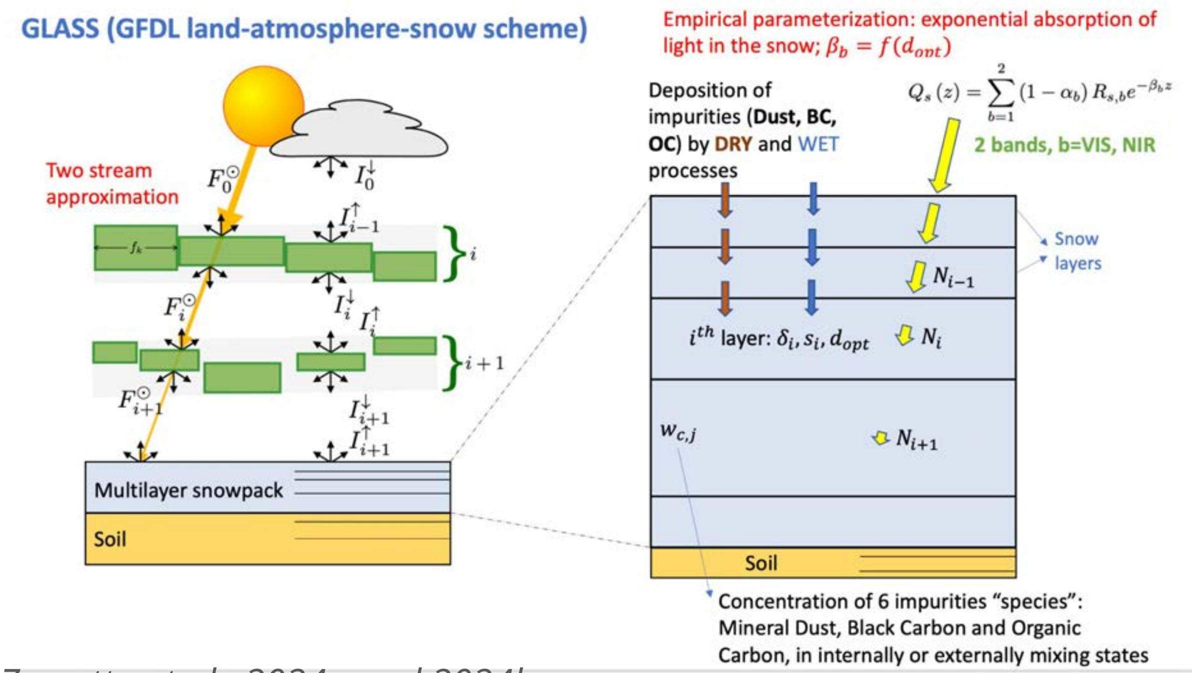
LM4.2-GIMICS

- On going global spin-up simulation



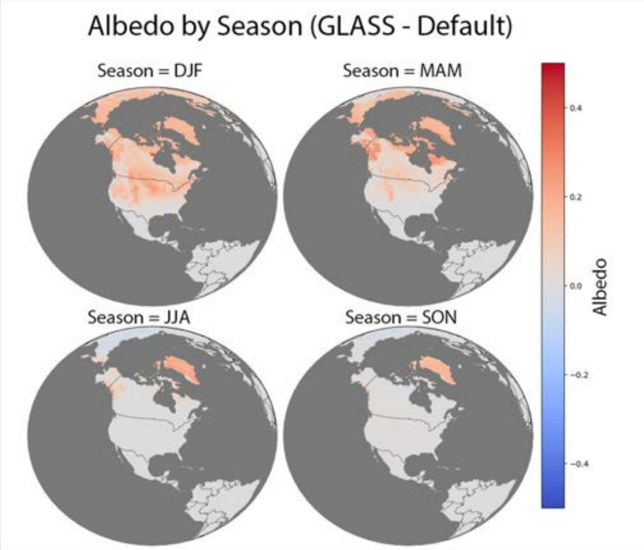


New snow model with impurities GLASS



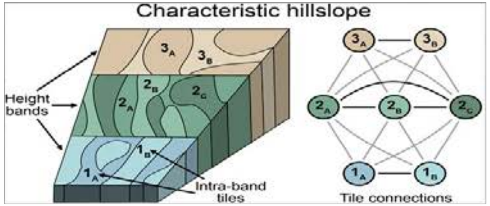
Zorzetto et al., 2024a and 2024b

Simulations with AM4.2/LM4.2

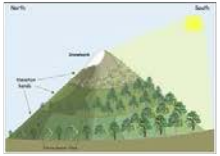


Predicting climate vulnerabilities & hazards in the ESM framework

- Too much or too little water interacting with natural and managed ecosystems: hydrological & ecological droughts, fires, floods, etc.
- LM4.2 – hydrological cycle at the stakeholder-relevant scale

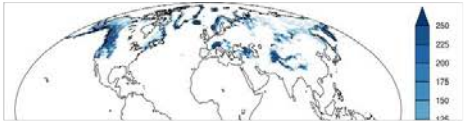


Chaney et al 2018

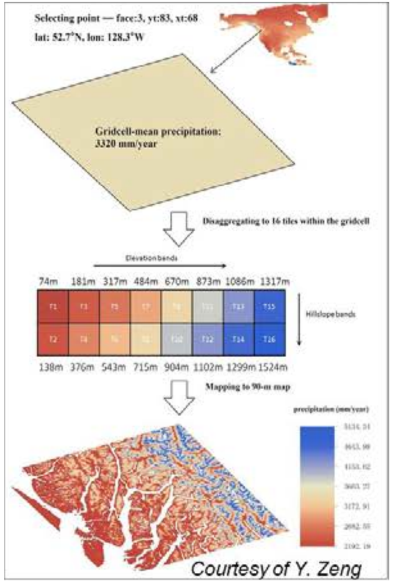


1. Mountain Shading
Zorzetto et al., 2023

Difference in snow between high and lowlands

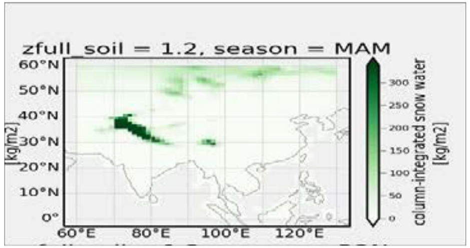


In-lie orographic scaling of P, T, q

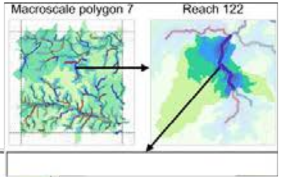


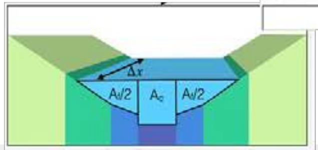
Courtesy of Y. Zeng

Dynamics of snow with aging impurities - GLAS



Scaling streams/river ridges and coupling with groundwater





Chaney et al 2021

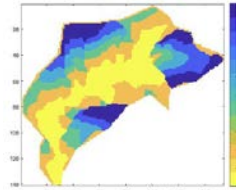
LM4.2 -SHARC

Providence Creek, Sierra Nevada (NV)

❖ Soil, Hillslope Aquifer, and River Contin

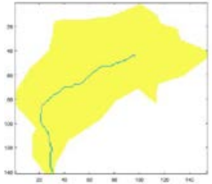
- Unsaturated soil–groundwater vertical inter
  - Water transport

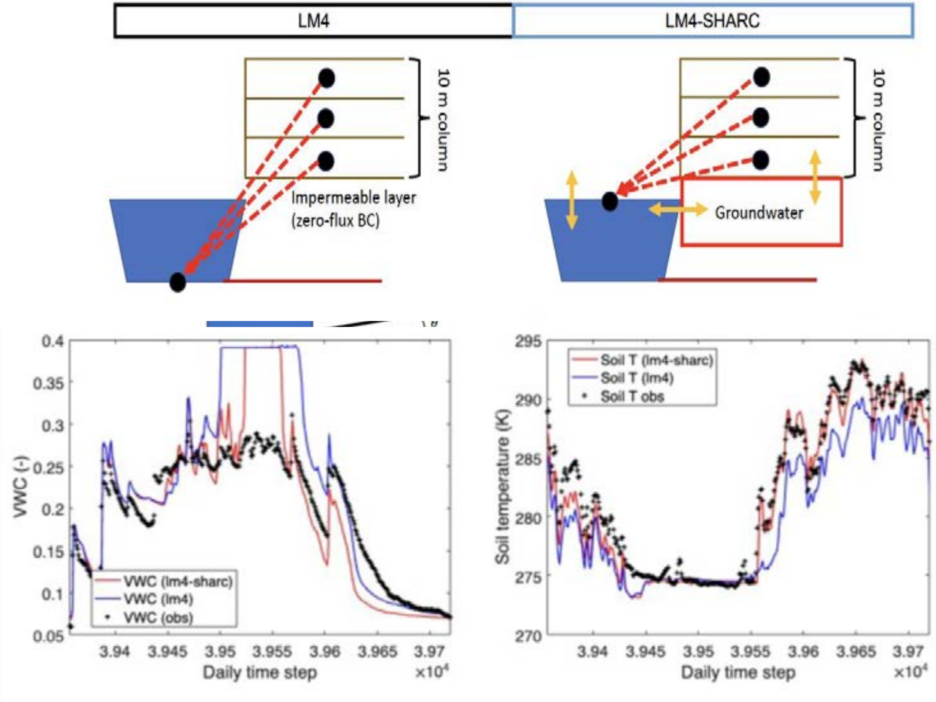
- Soil tiles



- Hillslopes

- Stream flowline





NEW RIVER ROUTING

- Two-way coupling with tiles
- Reach-based subgrid
- Inlet-outlet reaches form continental networks
- kinematic wave approach

Chaney et al 2021

Hong et al, 2024 in rev

Year 2009


Geosci. Model Dev., 17, 5191–5224, 2024
https://doi.org/10.5194/gmd-17-5191-2024

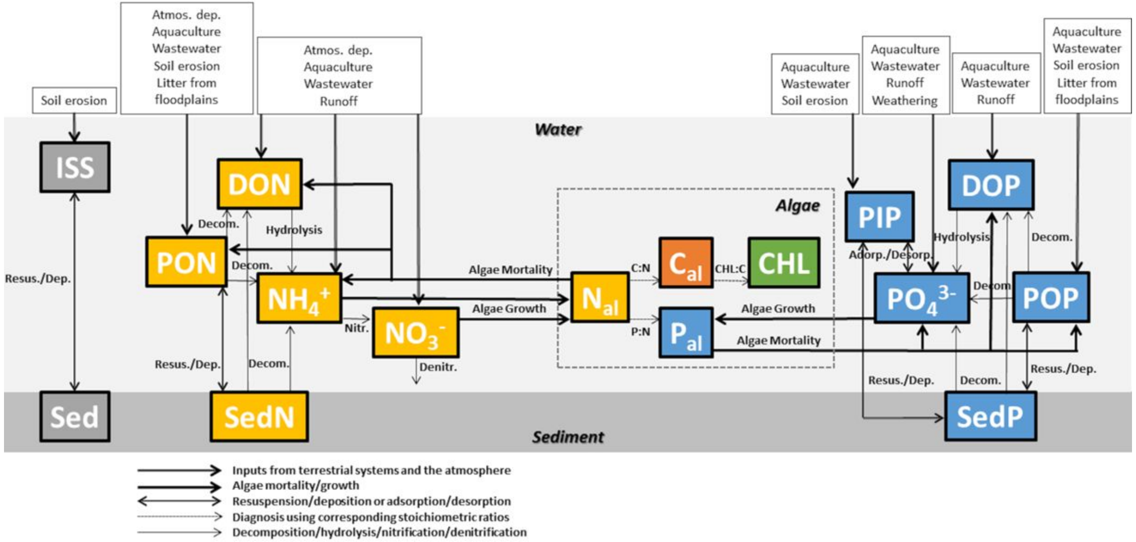
Geoscientific Model Development
Open Access
EGU
Model description paper

Linking global terrestrial and ocean biogeochemistry with process-based, coupled freshwater algae–nutrient–solid dynamics in LM3-FANSY v1.0

Minjin Lee[1], Charles A. Stock[2], John P. Dunne[2], and Elena Shevliakova[2]

LM3-FANSY (Freshwater Algae, Nutrient, and Solid Cycling and Yields)

A baseline for eventual linking of global terrestrial and ocean biogeochemistry in next generation Earth System Models

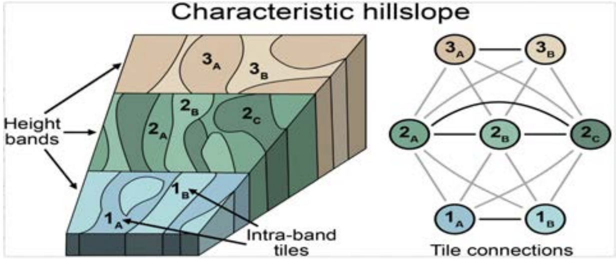


simulates SS, N, and P in multiple forms (particulate /dissolved, organic/inorganic) and units (yield, load, and concentration) across globally distributed large rivers, with an accuracy comparable to other global empirical models.

Towards prognostic wetland methane emissions

prognostic wetlands (SHARC) + soil C (GIMICS) + CH_4 with microbes

LM4.2 – hydrological cycle



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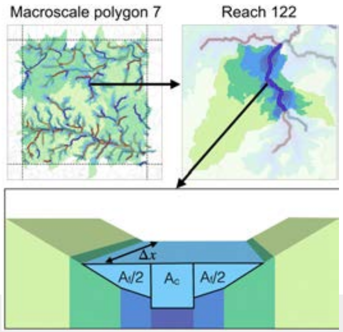

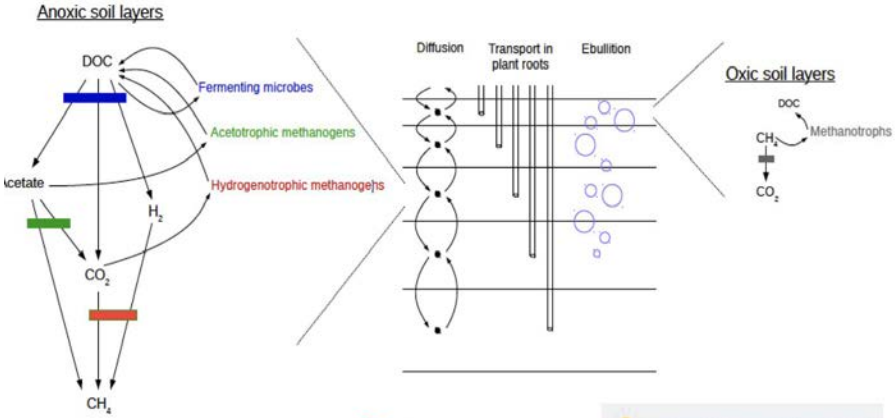

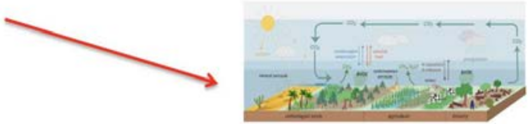

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