Multi-Scale Modeling of Hydrologic and Biogeochemical Processes in Arctic Ecosystems

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Introduction

- As Arctic temperatures rise, the timing, rate, and chemical form of the release of previously frozen carbon is a critical uncertainty in understanding the trajectory of the Earth's climate system.
- Prediction will require accurate representation of surface and subsurface thermo-hydrologic responses to the degradation of permafrost and thawing subsurface ice bodies, as ecological and biogeochemical processes controlling the carbon dynamics depend critically on temperature and soil moisture.
- The NGEE–Arctic team is working to conduct an iterative sequence of simulations of permafrost-affected landscapes using the Community Land Model (CLM) and PFLOTRAN (a massively parallel hydrology and reactive transport code) using nested computational domains spanning global, intermediate, and fine scales, in the context of an upscaling/downscaling framework:

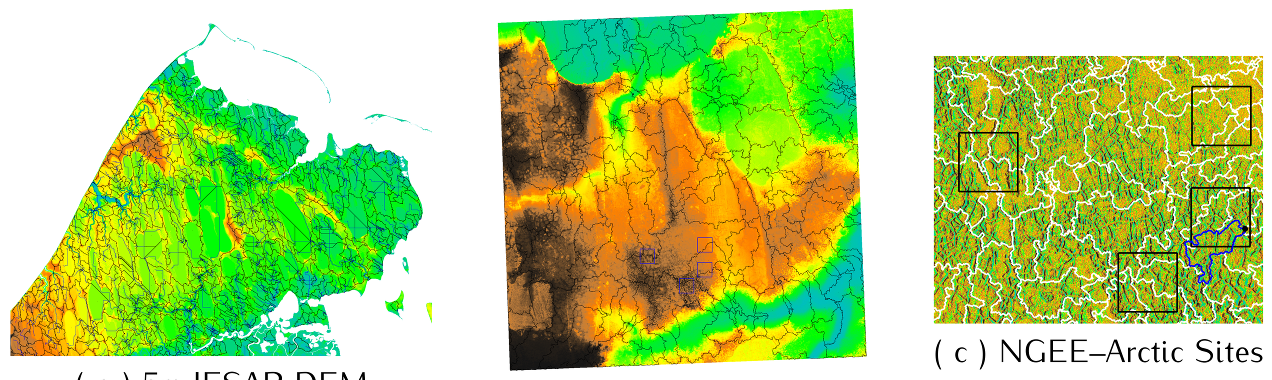
Figure 1: *A zoom-in through five orders of magnitude near Barrow, AK. The yellow boxes show the area enlarged at the next finer scale.*

- *Upscaled* results from fine-scale, process resolving models inform process representations at the global climate model scale.
- *Downscaled* results from the global climate model scale provide appropriate large-scale context for simulations conducted at finer scales.

- The ultimate goal is to develop appropriate parameterizations of Arctic eco-climatological processes at the scale of a high-resolution Earth System Model (ESM) grid cell (nominally 30 × 30 km in size).

Study Area

- The study site is located near Barrow, Alaska (71.3225°N, −156.626° W) on the North Slope of Alaska (Figure 2). Four observation plots are located in different hydrologic and geomorphologic settings.
- Field plots were selected to sample the Alaskan tundra across polygon age and soil moisture gradients (Figure 2(c)).
- Extensive field and laboratory campaigns are being conducted at these sites to provide observations to force, calibrate and validate the models.

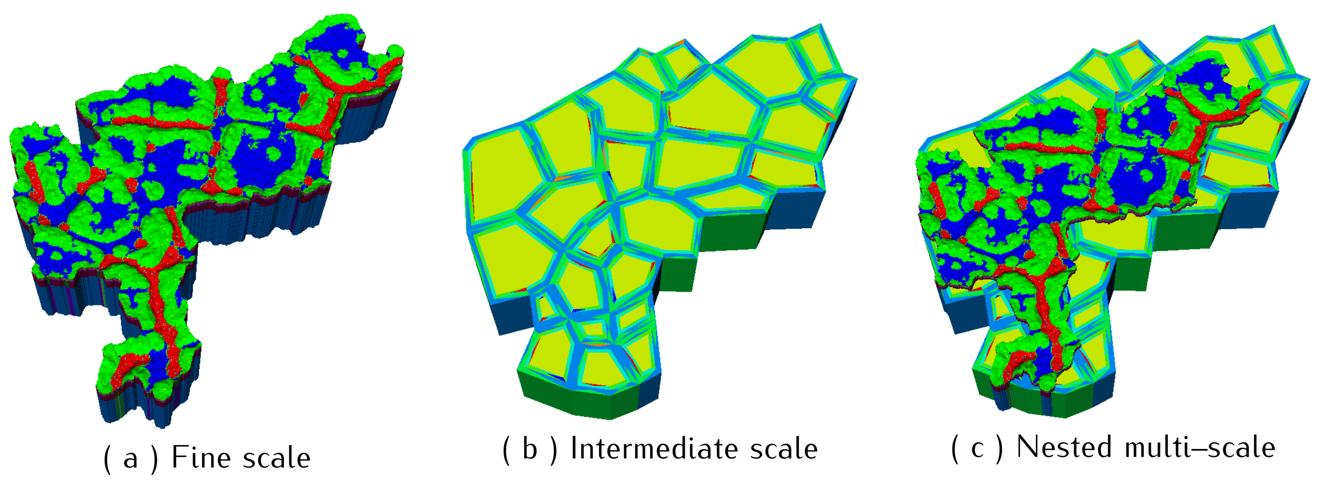


(a) 5m IFSAR DEM (b) 0.25m LiDAR BEO, AK (c) NGEE–Arctic Sites

Figure 2: *NGEE–Arctic sites in Barrow, AK are laid across the key geomorphic features of the landscape which are the building blocks for the multi-scale modeling framework.*

Subsurface Permafrost Hydrology

- A three-phase model of subsurface flow and heat transport has been added to PFLOTRAN.
- Simulations of seasonal freeze/thaw at NGEE-Arctic sites has been conducted at two scales for a watershed at BEO.
  - *Domain:* Area: 4327.5 m^2 with a vertical extent of 5.5 m
  - *Fine Scale:* Unstructured TIN mesh based on 0.25m LiDAR DEM (Total Cells = 4,493,184) (Figure 3(a))
  - *Intermediate Scale:* Geomorphological unit based mesh that captures centers/ridges/troughs of polyons in a coarser mesh (Total Cells = 40,032) (Figure 3(b))
  - *Parameters:* Point measurements of soil hydraulic and thermal properties from the NGEE sites were combined with remote sensing based remote sensing classifications to develop spatially heterogeneous fields of soil properties in the model
  - *Forcings:* Simulations were forced using ground surface temperatures from Circumpolar Active Layer Monitoring (CALM) sites and Evapotranspiration data from Barrow ARM site
  - *Validation:* Permafrost thaw depth and subsurface temperatures data sets from NGEE sites are being employed for validation of the models



(a) Fine scale (b) Intermediate scale (c) Nested multi–scale

Figure 3: *NGEE–Arctic sites in Barrow, AK are laid across the key geomorphic features of the landscape which are the building blocks for the multi-scale modeling framework.*

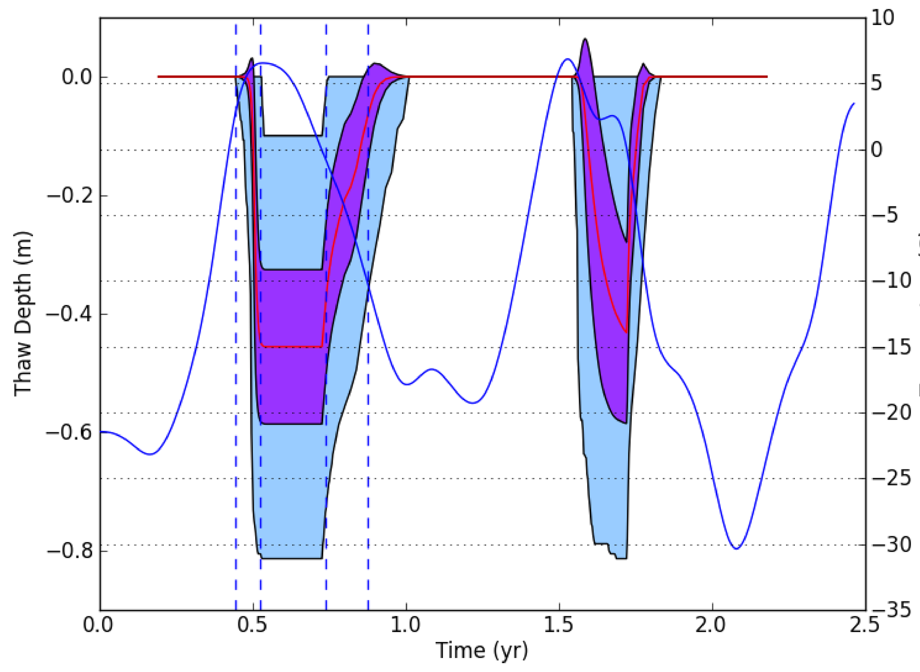
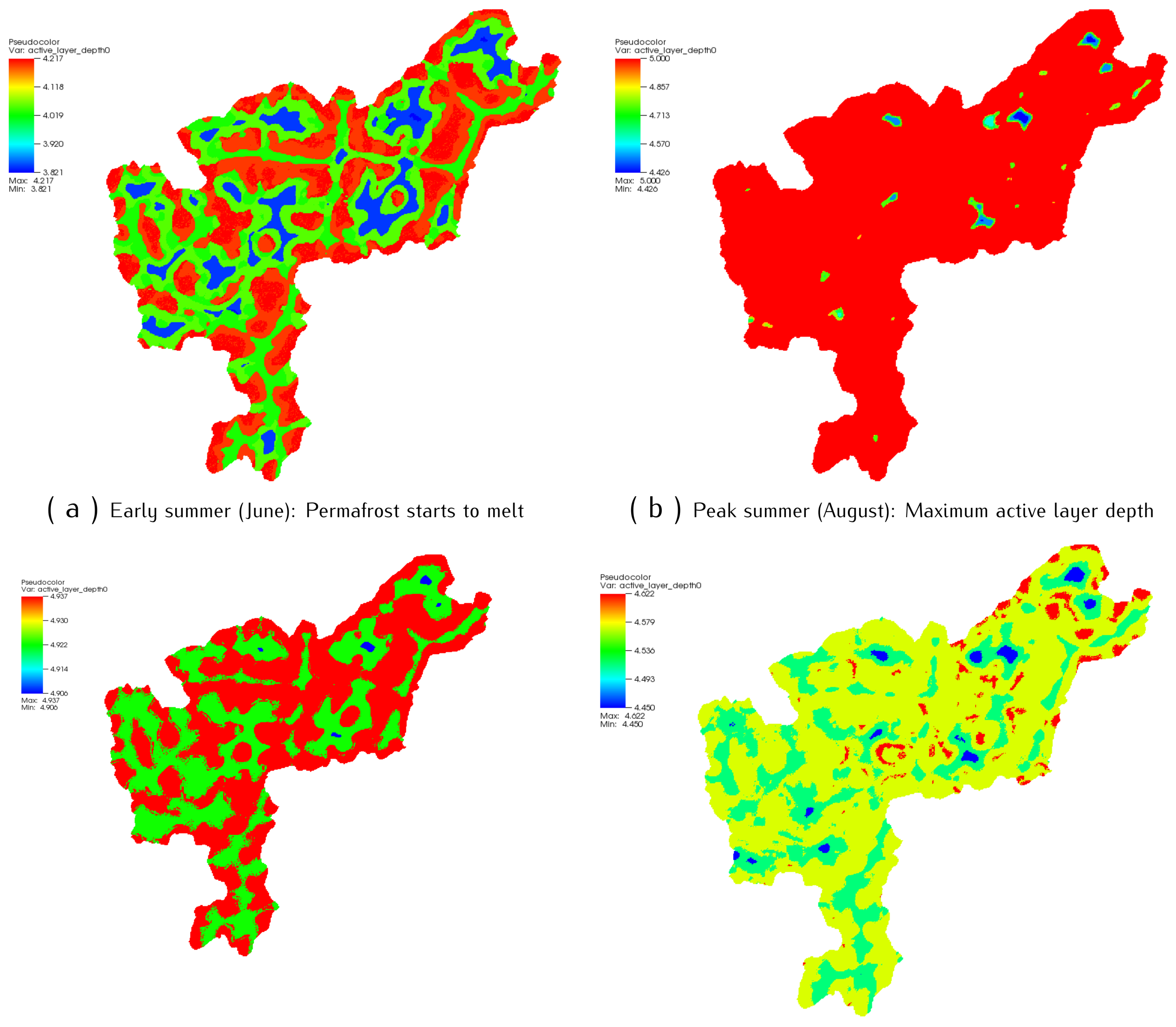


Figure 4: *Simulated thaw of permafrost layer*



(a) Early summer (June): Permafrost starts to melt (b) Peak summer (August): Maximum active layer depth

(c) Later Summer (October): Active layer starting to freeze (d) Early Winter (December): Active layer nearly frozen

Figure 5: *Simulation of permafrost active layer dynamics using PFLOTRAN*

Coupled Below-ground Thermal-Hydrology and C-N Biogeochemistry, Physical-chemistry and Transport by Coupled CLM-PFLOTRAN

- PFLOTRAN possess capabilities to represent general biogeochemical/physical-chemical reactions, which are tightly coupled to thermal-hydrology and a transport model.
- CLM45-CN reaction network has been implemented in PFLOTRAN along with a new plant N uptake algorithm.
- A fully explicit soil N reactive-transport network has also been developed. Degassing-dissolving of GHG species from the soil C-N reactions are included in the reactive-transport network.
- Fully coupled CLM-PFLOTRAN hydrology and beogeochemistry model is being deployed for simulations and evaluations at NGEE-Arctic research sites at Barrow, AK.

Implementation of CLM-CN+ Reaction Network in Coupled CLM-PFLOTRAN

- The classic CLM45-CN biogeochemical (BGC) reactions (Thornton et al., 2005) has been implemented in PFLOTRAN.
- Unlike CLM-CN, plant N uptake algorithm in PFLOTRAN has is regulated by the plant growth demand as potential N uptake, which competes with soil immobilization for N nutrients.
- The reaction networks has been evaluated at the NGEE-Arctic research sites at Barrow, AK for polygonal landscape (low-centered-polygon, LCP; High-centered-polygon, HCP; and Transitions).
- The coupled CLM-PFLOTRAN simulates a very constrained plant LAI and thus soil litter C stocks, compared to CLM model (Figure 6). Except for the lower LAI in the coupled simulations, the spatial differences among landscape positions compares better with observations, i.e., high LAI in those low elevation region.

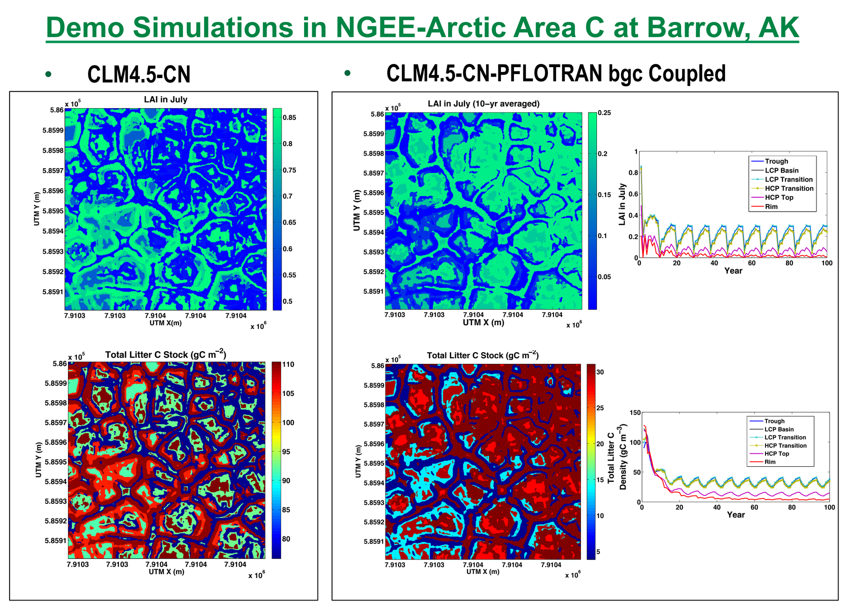


Figure 6: *Comparison of CLM4.5-CN and CLM4.5-CN-PFLOTRAN(bgc) simulations in NGEE-Arctic field site Area C, Barrow, AK*

Soil Nitrogen Reactive-Transport Network

- A general soil N nitrification-denifitrication algorithms, including gaseous emissions (Parton et al. 1996; Dickinson et al. 2002) has been implemented in PFLOTRAN (Figure 7).
- Model includes soil adsorption of NH^{4+} generated from nitrification or sink.
- Allows simulation of N leaching
- Coupled of hydrological-biogeochemical model (CLM-PFLOTRAN (Richards/bgc), the right panel of Figure 7), shows lower amount of NH^{4+} and $NO^{3-}N$ in upper soil layers while some accumulation in the lower layers, compared to the BGC only mode.
- However, when NH^{4+} adsorption is incorporated, the soil NH^{4+} solution concentration is significantly reduced and thus less transport with water flow are expected (the left panel of Figure 7).

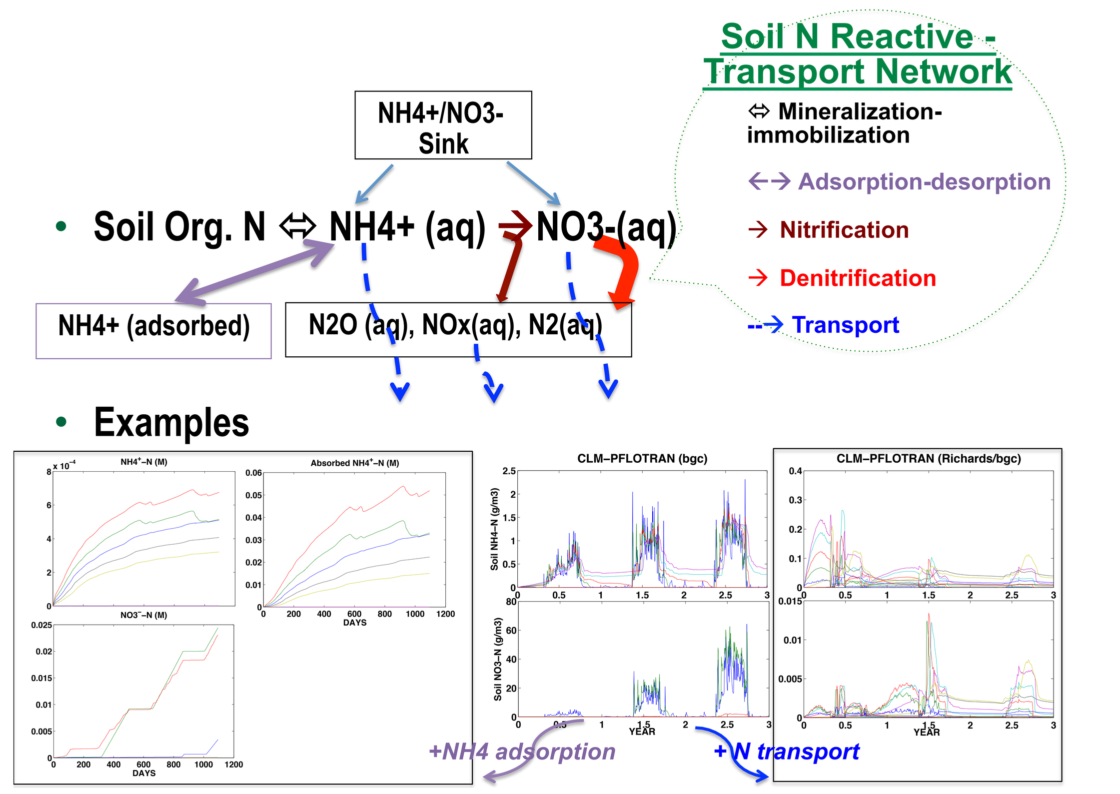


Figure 7: *A schematic view of soil N reactive-transport network and preliminary simulations of CLM-PFLOTRAN*

Gaseous Species at Soil-Air Interface: Degassing and Dissolving

- Chemical reactions are assumed to be in aqueous solution, so trace gas productions from soil C-N network are first in aqueous phase, and possibly reacts with other soil solution chemical species. By incorporating well-developed $CO_2/N_2O/N_2$ solubility algorithms, soil solution-air gas dissolving-degassing modules have been developed in PFLOTRAN (Figure 8).
- If no barrier exists between below-ground soil air and atmosphere, equilibrium air exchange between soil-atmosphere is modeled (and further development of soil air transport module in PFLOTRAN is in progress).
- Compared to the seasonal dynamics of soil CO_2 respiration, soil CO_2 fluxes to atmosphere shows a few spikes in spring probably due to soil thawing caused CO_2 release accumulated in freezing period (the left-low panel in Figure 8).
- Gas dissolving-degassing module would allow simulating of geological C and other GHG sequestrations.

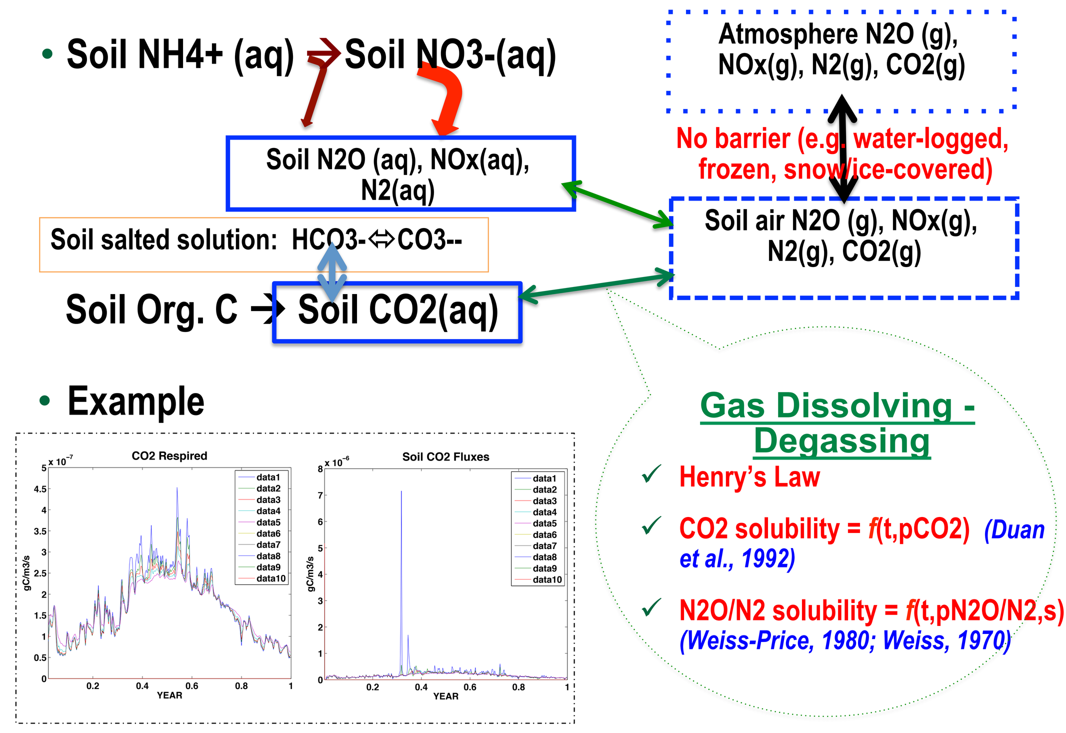


Figure 8: *Soil C-N gas species degassing and dissolving*

Summary

- CLM-PFLOTRAN modeling framework allows for multi-scale modeling of Arctic ecohydrologic processes from fine (sub-meter) scale to intermediate (individual landscape positions/polygons) scale to global scales.
- PFLOTRAN simulates three phase thermal hydrology of permfrost domianted landscapes.
- Comprehensive below-ground C and N biogeochemical network has been developed and implemented.
- Model calibration and validation using observations are underway.

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