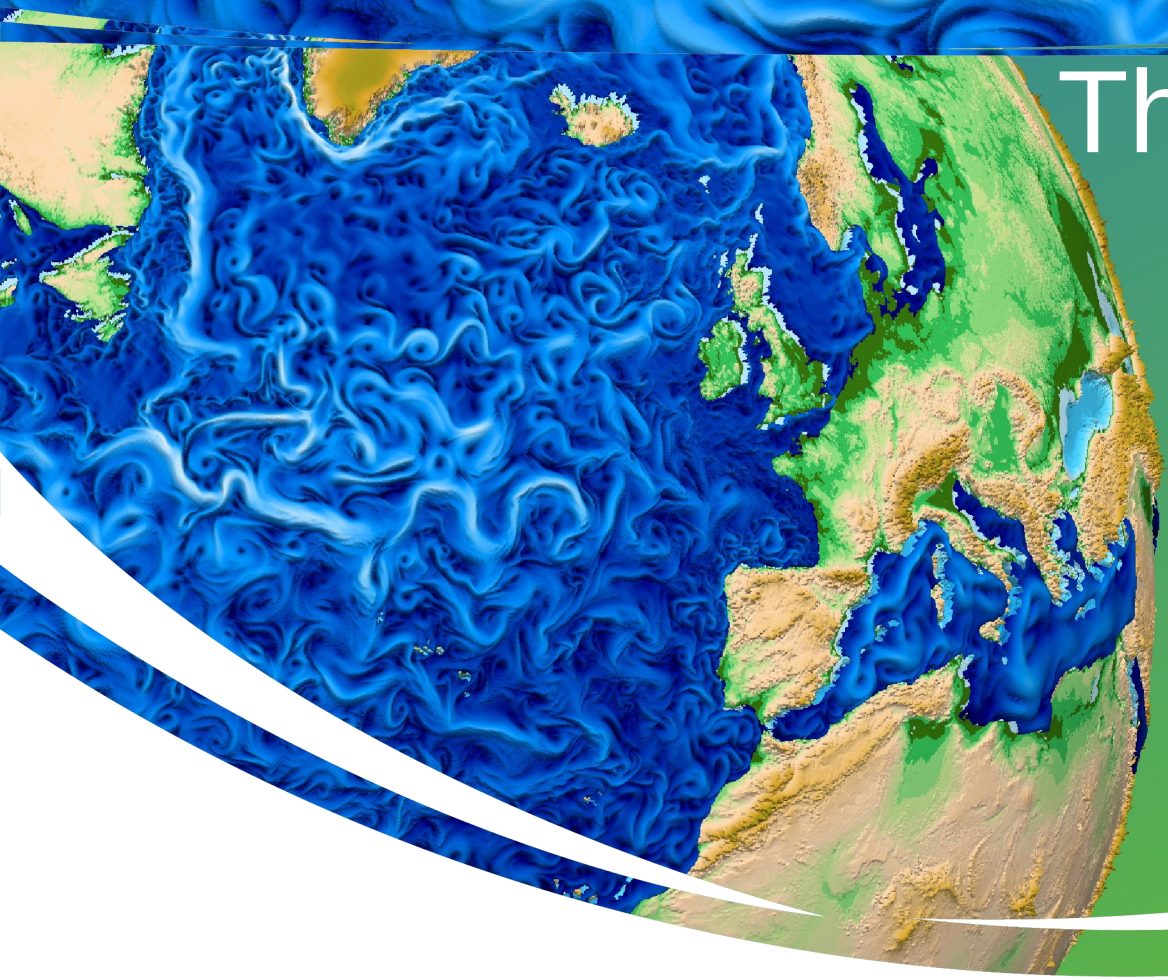
SAND2023-08025C

E3SM Energy Exascale Earth System Model



The Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM)

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Outline

1. What is SCREAM?
2. Why build a global storm-resolving model (GSRM)?
3. What did we find?
4. Challenges/Conclusions

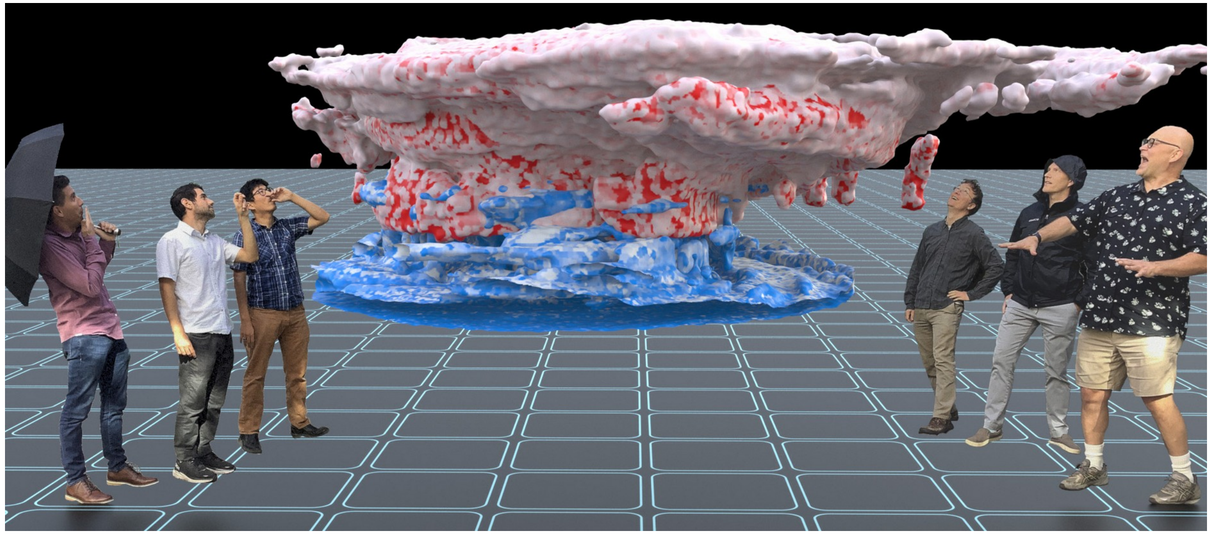

Fig: Some SCREAM members really getting inside the model

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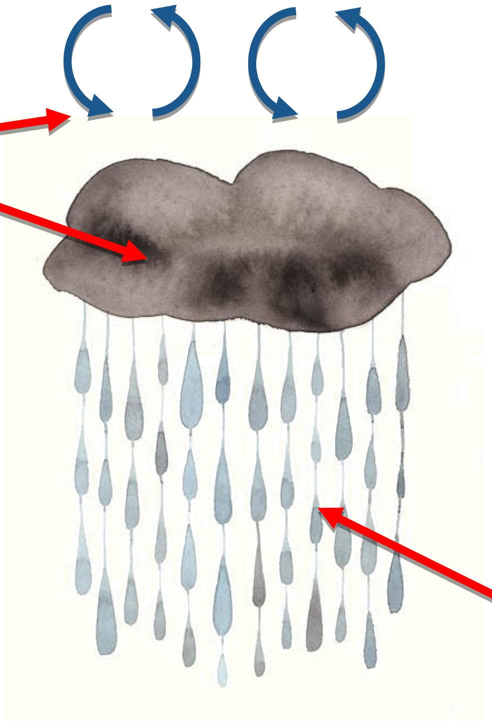
What's in SCREAM?

~~parameterized convection~~

Turbulence and **cloud formation** handled by the Simple Higher-Order Closure (**SHOC)**



Resolved-scale **fluid dynamics** treated by a non-hydrostatic Spectral Element (**SE**) approach

Radiation handled by a C++ port of the **RTE+RRTMGP** package

Aerosol effects will be prescribed in initial implementation

Microphysical processes handled by Predicted Particle Properties (**P3)** scheme

* Using coarser grid for physics parameterizations (Hannah et al., 2021, JAMES) *

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Useful Tools

- Doubly-Periodic (DP) mode is an economical way to develop and test SCREAM. It:
  - runs the full model on a rectangular plane
  - takes advantage of E3SM's library of ~30 ARM case studies

See: Bogenschutz et al. "Horizontal Resolution Sensitivity of SCREAM in a Doubly-Periodic Configuration"

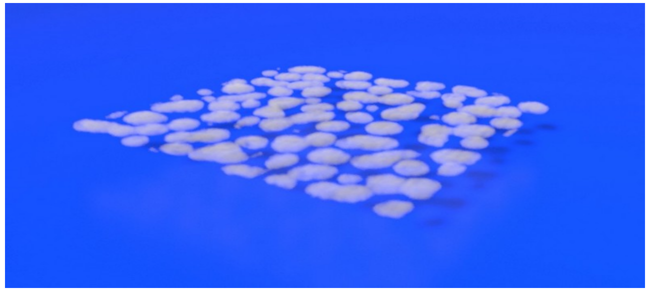
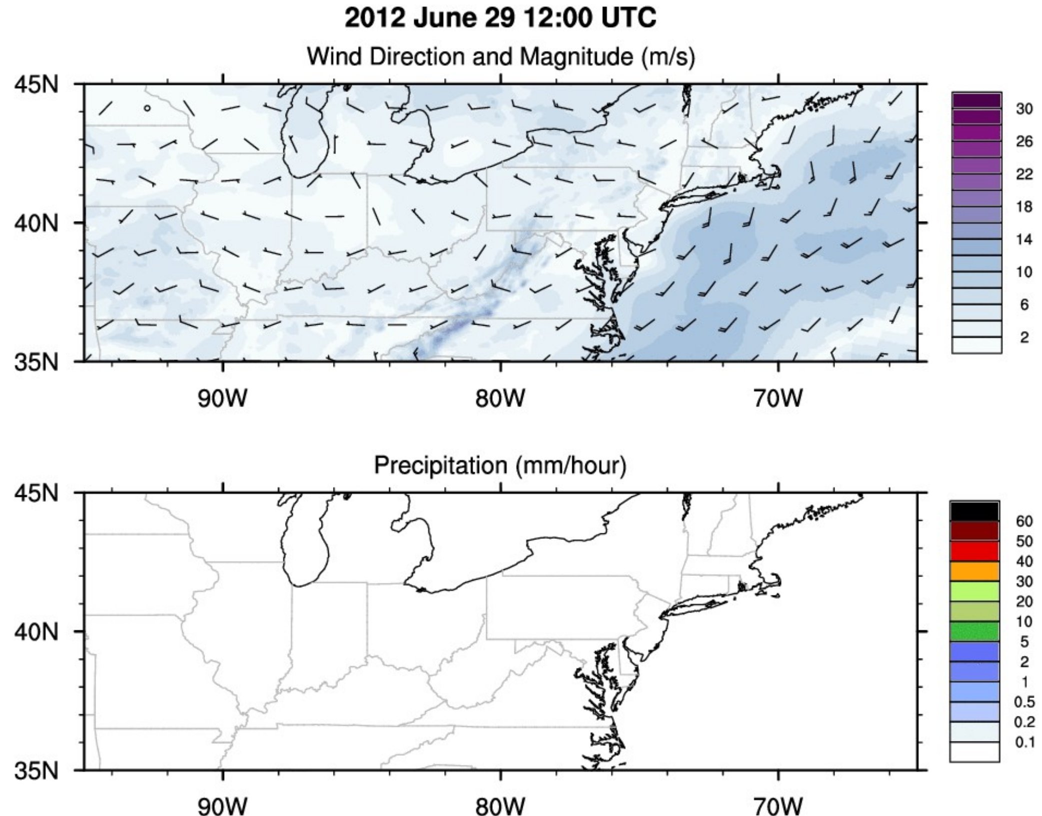


Fig: DP in action



- SCREAM can also run in regionally-refined mode (RRM) with fine in a small region and coarse elsewhere

See: Liu et al. "The June 2012 North American Derecho: A Testbed for Evaluating Regional and Global Climate Modeling Systems at Cloud-Resolving Scales"

Fig: June 29th 2012 derecho over the Midwest/Mid-Atlantic US as simulated by SCREAM at 3 km.

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Why GSRMs? Why Now?

- Exascale computers are fast enough to do km-scale climate simulations
  - SCREAM runs at 0.6 SYPD on Summit
  - We should exceed 1 SYPD on Frontier
- The GPUs in exascale computers only help for very large problem size (see figure)
  - Conventional GCMs won't be accelerated at all

Caveat: NICAM has been doing these runs since 2004

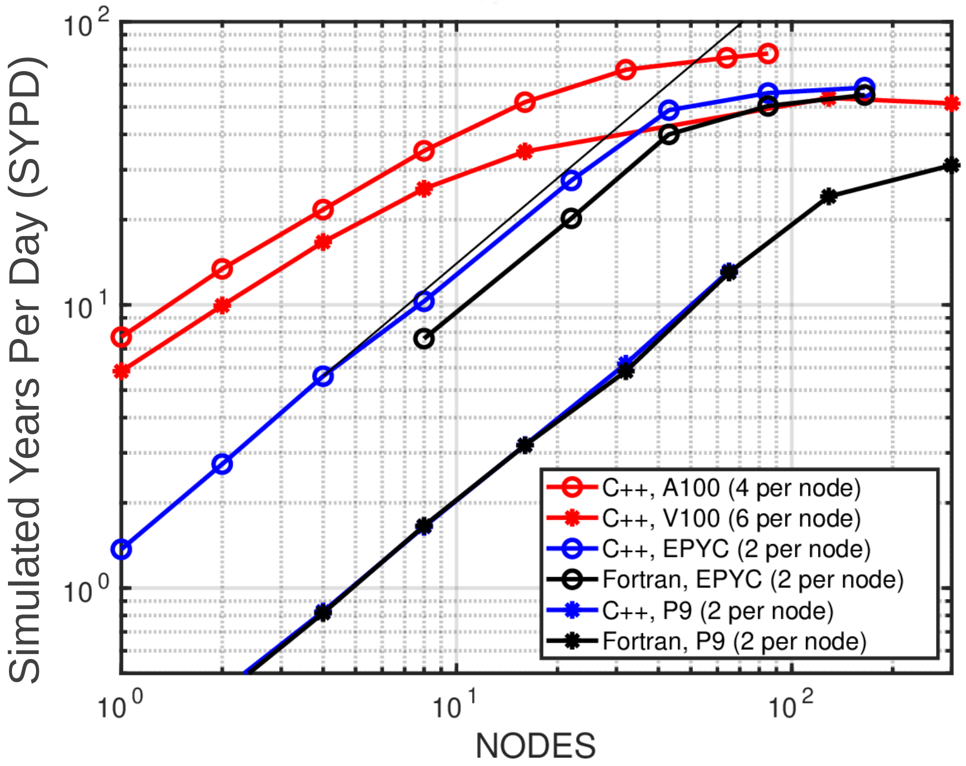

*Fig: SCREAM throughput at **dx=100 km** as a function of number of nodes used. Output was turned off.*

Why GSRMs? Why Now?

Physical Motivations:

- **Deep convection** is critical but has proven hard to parameterize
  - But partially-resolved convection is also a problem!
- **Global coverage** is needed to capture upscale effects of local improvements
- Accurate hydrology predictions require **fine-scale topography**
- Many interactions are too small to resolve and aren't parameterized

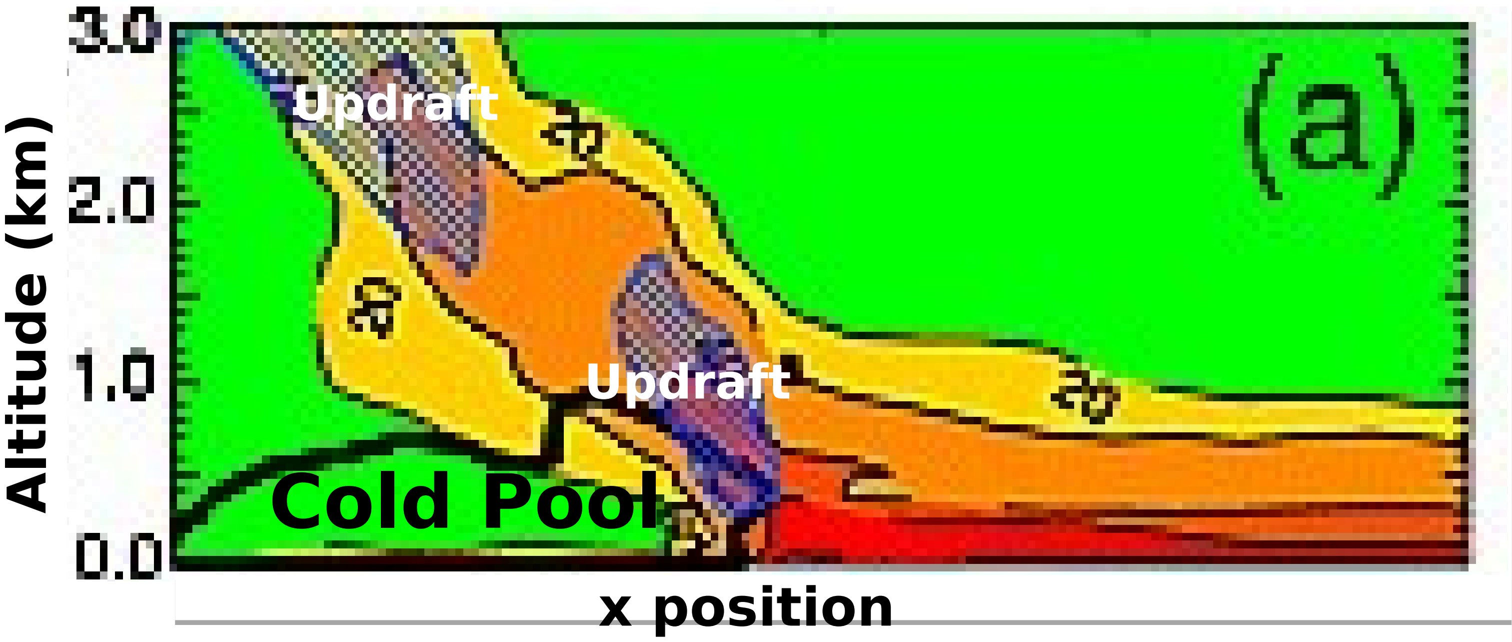

Fig: Snapshot of DMS concentration (green=low, red=high) in a 2d CRM of oceanic deep convection (domain =256 km, Δx = 1 km). Neglecting the spatial pattern of DMS reduced convective transport by 50%. From Devine et al, 2006 GRL, pointed out by Ken Carslaw

Why GSRMs? *Our* Experience

- Results from SCREAMv0 DYAMOND2 simulation (40 days starting Jan 20, 2020)
- As expected, precipitation is much better at dx=3 km
  - diurnal cycle (shown)
  - intensity/frequency
  - vertical structure
  - orographic impact

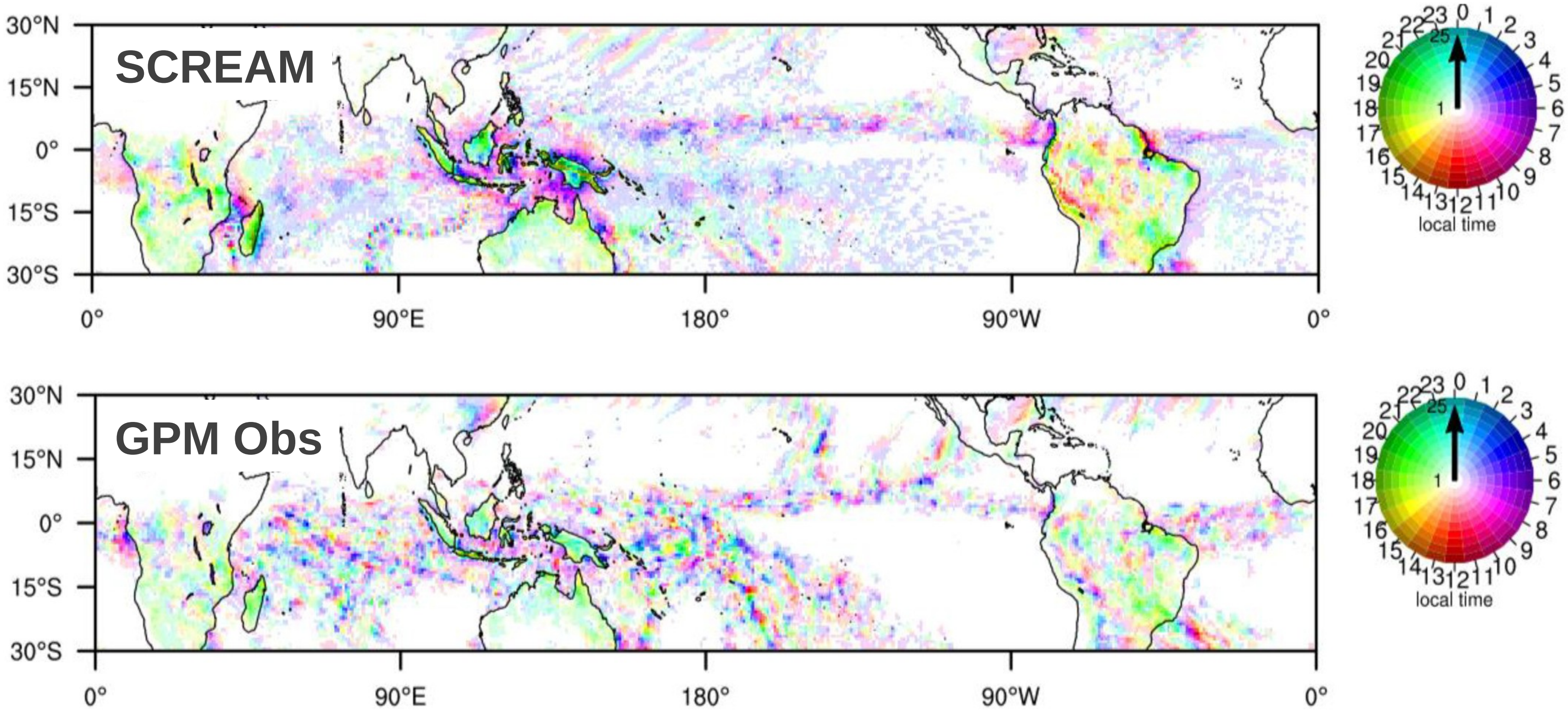

Fig: Diurnal cycle of tropical precipitation averaged over the last 30 days of DYAMOND2. Hue indicates time of peak precipitation and intensity indicates diurnal amplitude. Amplitudes less than 1 mm day^{-1} are colored white and colors saturate at 25 mm day^{-1}. From Caldwell et al., (JAMES, 2021)

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Why GSRMs? *Our* Experience

- Our ability to capture cloud structures is impressive
- Showing cold air outbreaks here but tropical + extra-tropical cyclones are also well-represented

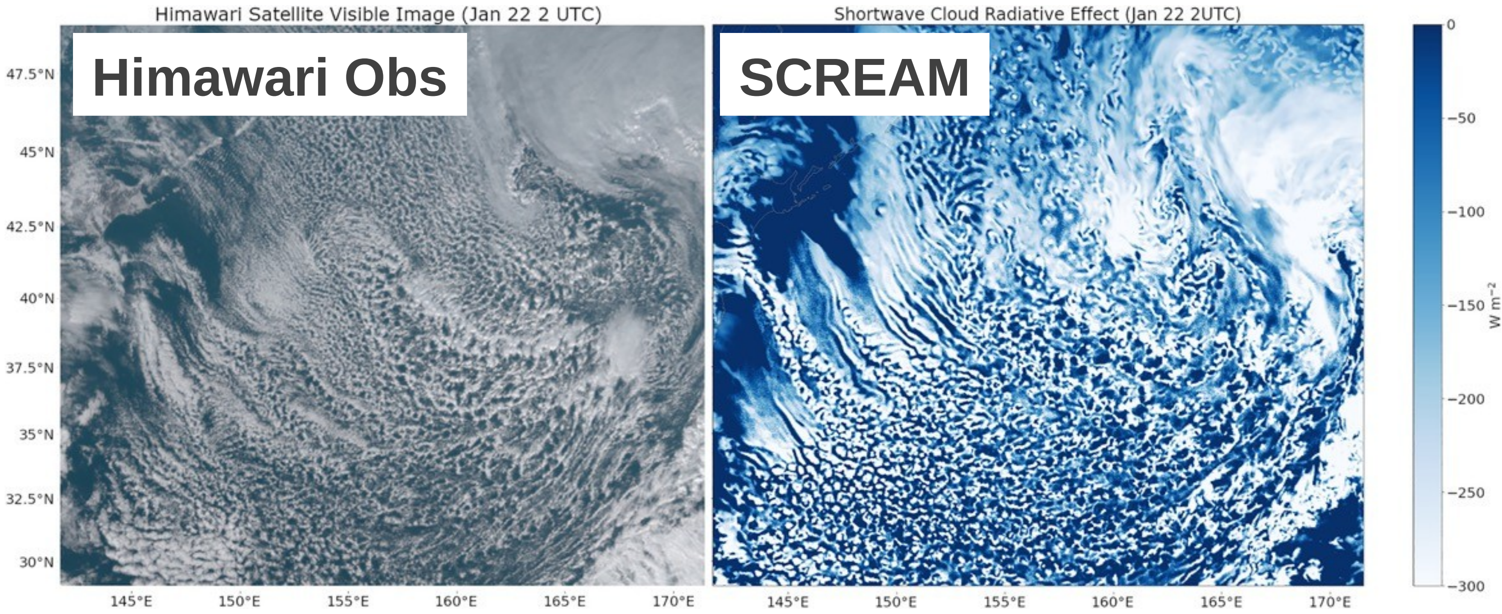

Fig: Cold-air outbreak off Siberia on January 22, 2020 at 2:00:00 UTC (~local noon) from a Himawari visible satellite image (left) and shortwave cloud radiative effect from SCREAMv0 (right). Visualization is over a region bounded by 29°–49°N and 141.5° to 171.5°E. From Caldwell et al., (JAMES, 2021)

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GSRMs… Not Perfect Yet

- SCREAM struggles to aggregate tropical convection (see Fig)

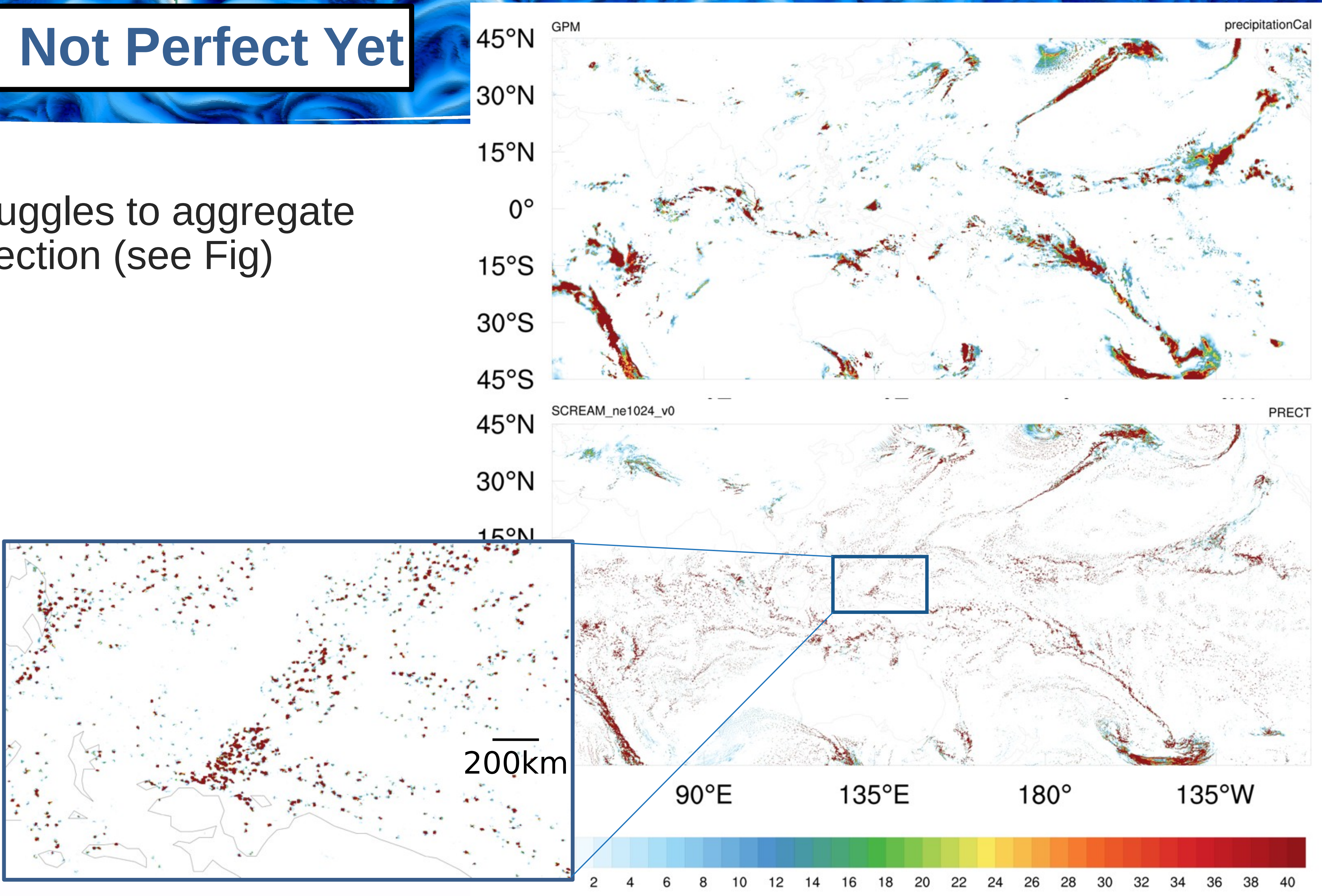

Fig: Snapshot of precipitation on Jan 21 2020 at 0 UTC from GPM obs (top) and EAMxx (bottom)

…Though We Have Been Improving

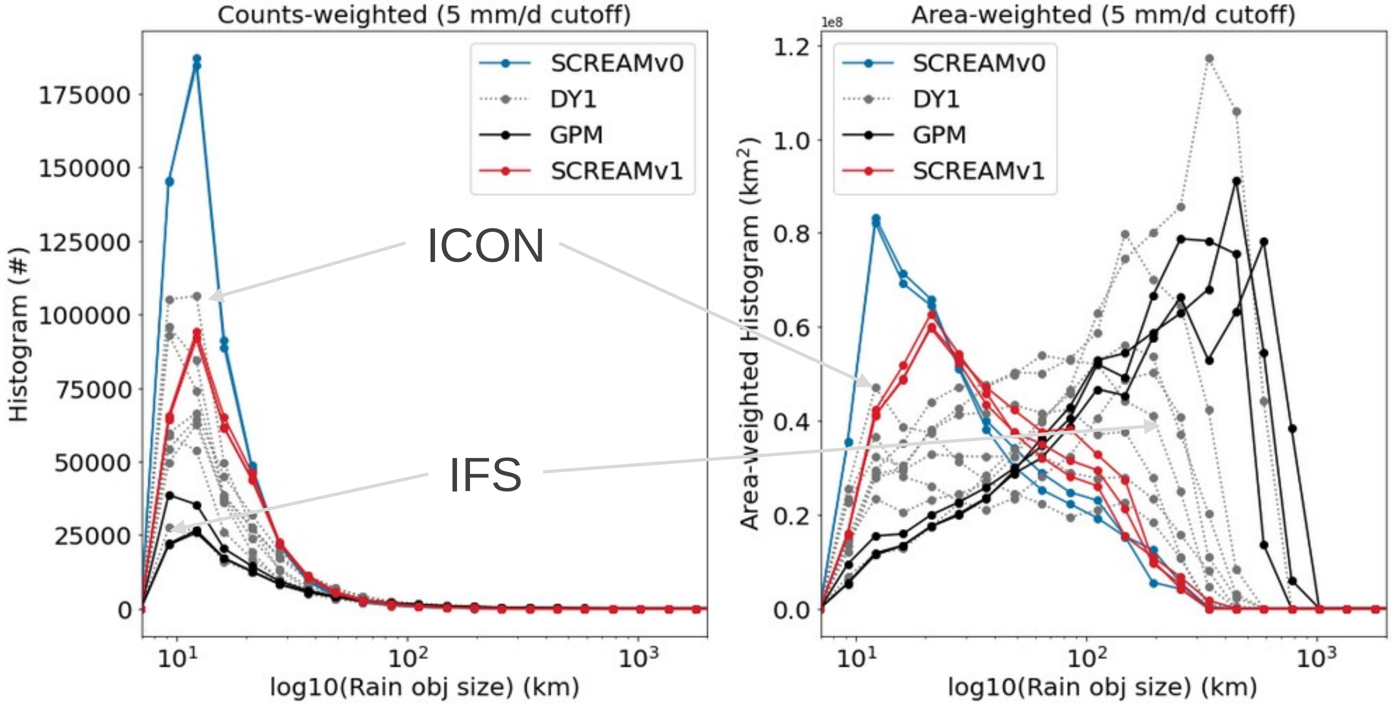

Fig: Frequency (left) and area (right) of convective events as a function of their size (x axis). Note SCREAMv0 (F90) is from DYAMOND2 (winter), SCREAMv1 (C++) is from Oct 2013, and other lines are from DYAMOND1 (summer) model runs.

- Our new implementation has less popcorn than our DYAMOND2 contribution
  - Due partially to removing subgrid rain enhancement
  - Popcorn is still a problem

Other Imperfections

Precipitation biases:

- Double ITCZ/anemic SPCZ
- latitude/width of convergence zone isn’t quite right
- West Pacific + Indian Ocean are too dry
- NW Atlantic has a persistent wet bias

Other issues:

- Night-time warm bias over land
- extreme cold snaps

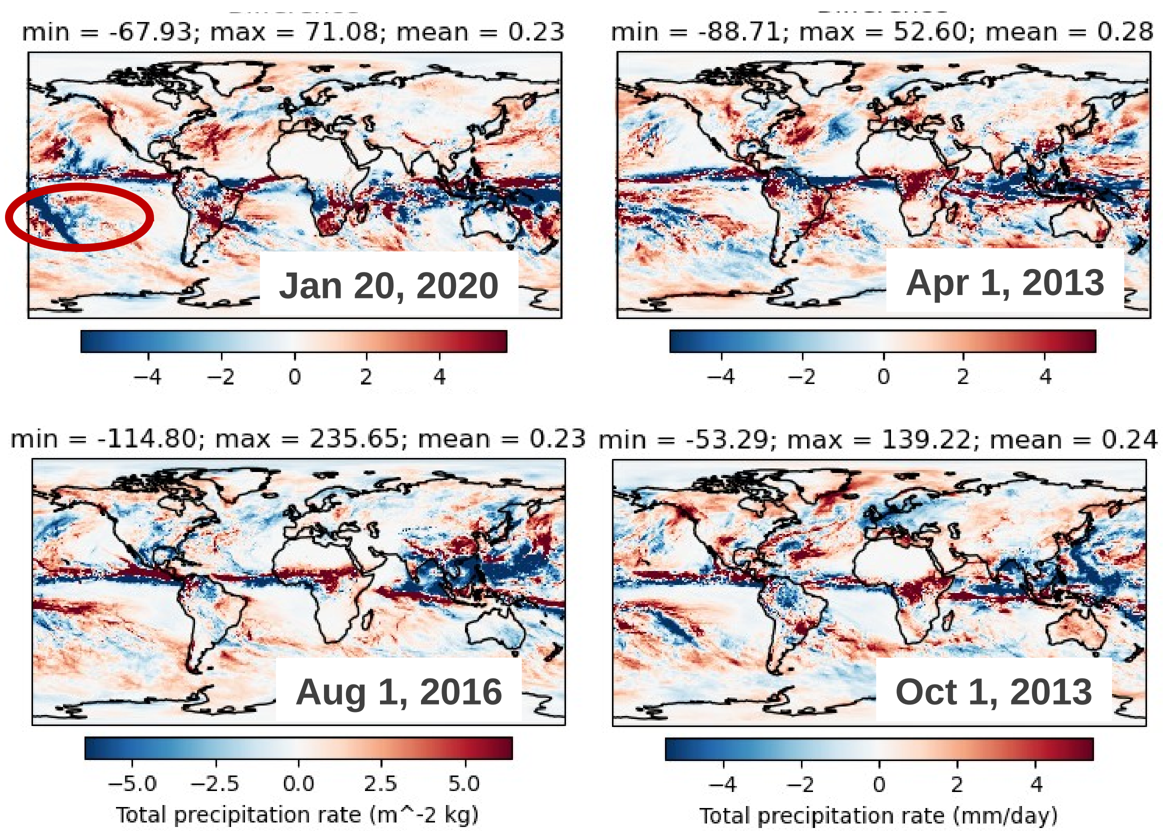

Fig: SCREAMv1 precipitation bias (using ERA5 as truth) averaged over all 40 days starting on listed dates. DYAMOND2 and DYAMOND1 are on the top and bottom left, respectively

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Challenge: Long Simulations

- We can get 1 SYPD on DOE's exascale computers… but only 10 yrs per annual allocation!
  - Climate forecasts require PDFs of extremes and significance testing which we can't get from 10 yrs
  - model tuning is hard when you can't afford to run
- Possible solutions:
  - Wait for faster computers (but more competition)
  - Use AI to emulate your GSRM (recent work by Bretherton, Yuval, Pritchard, etc)
  - Test resolution sensitivity, then use the coarsest resolution you can get away with
  - Focus on idealized runs (next slide)

Fig: An atmospheric river making landfall on the US West Coast as simulated by SCREAM

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GSRMs: Built for Idealization

- Climate and aerosol sensitivity can be reasonably(?) approximated from short, idealized, fixed-SST simulations
  - **Net feedback** can be computed from 1 yr fixed-SST & SST+4K "Cess" runs (Cess et al., 1990 JGR, Ringer et al., 2014 GRL, Qin et al., 2022 JGR)
  - **Effective forcing** of CO_2 change can be assessed from similar paired experiments (Hansen et al., 2005 JGR)
  - **Aerosol sensitivity** can be computed from a pair of 15 mo nudged runs (Kooperman et al., 2012 JGR)
  - **Anthropogenic impact** on a **single storm** can be assessed from pseudo-global warming storylines (Shepard et al., 2018 Clim Change)

But is GSRM climate sensitivity any better? We still can't resolve boundary-layer clouds (which have huge radiative impact)!

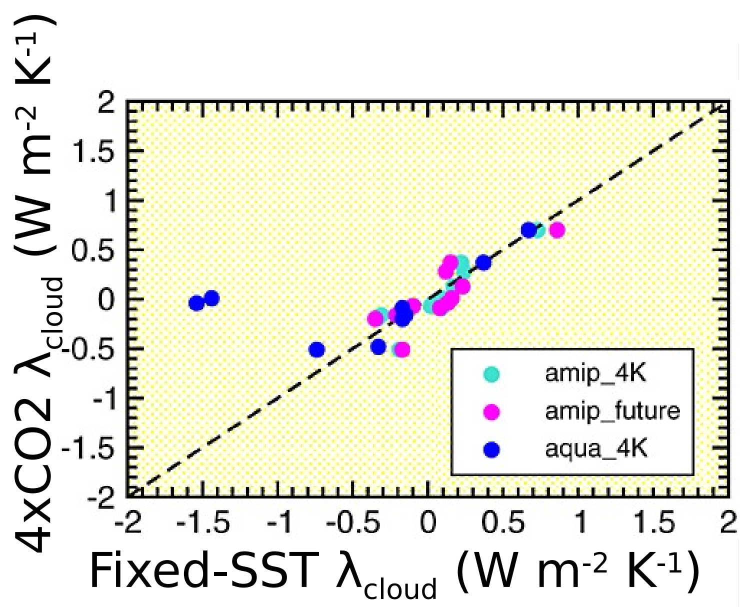


Fig: Cloud feedback from full-complexity (y-axis) versus fixed SST simulations in CMIP5. Adapted from Ringer et al, (2014 GRL).

Challenge: Drowning in Data

- Saving cloud-resolving output globally is unsustainable (see figure)
- Possible Solutions:
  - **Regional output** - only save fine-scale information at observation sites (Mark Webb idea)
  - Write **Coarsened output** for large-scale analysis (Chris Bretherton idea)
  - **Data compression… ** or half precision?
  - **Temporal subsampling** – Only save high frequency output for short periods
  - **Compute statistics online**
    - Output monthly PDFs
    - Composite over particular regimes

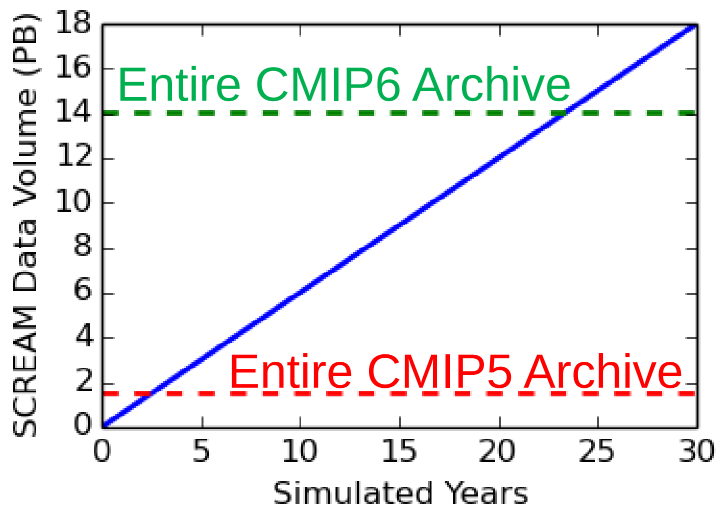


Fig: SCREAM data holdings as a function of simulation length assuming 50TB/simulated month

GSRM Grand Challenges

1. How can GSRMs provide *real-world* predictions (requiring statistical significance and frequency of extreme events)?

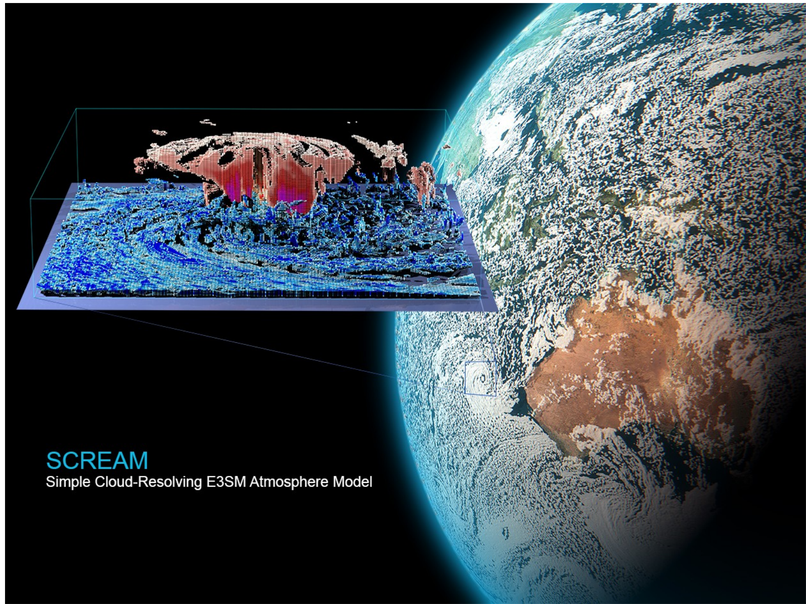
2. What are the *upscale* benefits of GSRMs? Why aren't regional models good enough?

3. Is GSRM climate *sensitivity* better than for GCMs? If not, why bother?

4. How should we handle partially-resolved convection?

5. How should we tackle the technical challenges (how to store output, how to tune, etc)?

6. We need input data (particularly land surface datasets) at km-scale.



Conclusions

- Exascale computers make km-scale climate simulations possible… with a big enough allocation and disk space
- GSRMs solve a lot of – but not all – classic biases in GCMs
  - Precipitation and clouds generally look better
  - Boundary-layer clouds are still anemic
  - West Pacific clouds and precipitation needs work
  - Gray-zone convection impairs cloud aggregation
- GSRMs come with a whole new set of challenges to overcome