Thanks for the award …

Julio Bacmeister and Peter Lauritzen (CGD/NCAR)

CESM Summer Workshop, June 12, 2023

National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977


Brian Dobbins
Isaac Davis
Patrick Callaghan
John Truesdale
Brian Eaton

Funding acknowledgements

CAM (Community Atmosphere Model) would not be where it is today without:

- **NSF base funding**
- **CAM7 funding (e.g., streamlining variable resolution applications, CESM in the cloud, …)**
- **CESM Simpler Models funding**
- **Climate Process Teams**
  (CLUBB EDMF, CLUBB momentum transport, coupling to land)
- **NCAR PBL Reinvestment**
- **SIMA funding**
- **…**

Is low(er) resolution climate modeling dead?

Julio Bacmeister and Peter Lauritzen (CGD/NCAR)

CESM Summer Workshop, June 12, 2023

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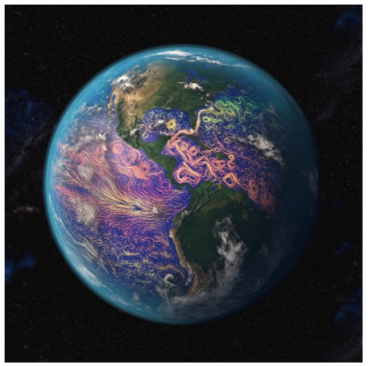
Gavin Schmidt - https://www.realclimate.org/

Mmm-k scale climate models

25 JUN 2022 BY GAVIN



Ocean eddy visualization (Karsten Schnieder)

Two opinion pieces (Slingo et al., and Hewitt et al.) and a supportive Nature Climate Change editorial were published this week, extolling the prospects for what they call "k-scale" climate modeling. These are models that would have grid boxes around 1 to 2 km in the horizontal – some 50 times smaller than what was used in the CMIP6 models. This would be an enormous technical challenge and, while it undoubtedly would propel the science forward, the proclaimed benefits and timeline are perhaps being somewhat oversold.

Ambitious partnership needed for reliable climate prediction

Julia Slingo, Paul Bates, Peter Bauer, Stephen Belcher, Tim Palmer, Graeme Stephens, Bjorn Stevens, Thomas Stocker & Georg Teutsch

Nature Climate Change **12**, 499–503 (2022) | Cite this article

Current global climate models struggle to represent precipitation and related extreme events, with serious implications for the physical evidence base to support climate actions. A leap to kilometre-scale models could overcome this shortcoming but requires collaboration on an unprecedented scale.

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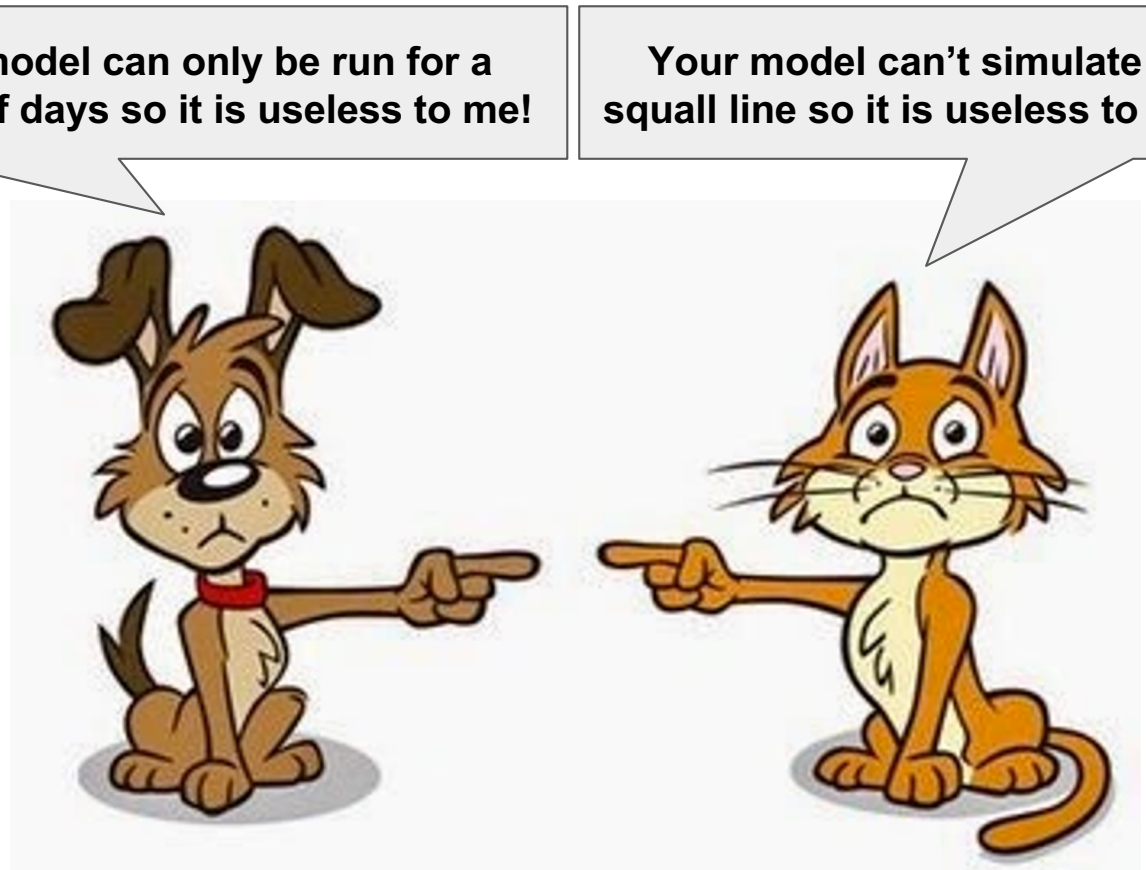

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Climate model dogs mission(s)

Two missions - broadly speaking

- **Provide community model for a variety of climate applications**
  - ***Need for lower res models is clear***

- **Provide state-of-the-art climate information to stakeholders**
  - ***We will argue that lower res models are needed here as well***

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Climate model dogs mission(s)

Provide projections of climate change to stakeholders. What is needed?

- **Tuned climate model with an adequate representation of climate mean** (TOA balance, SWCF, precip, large scale circulation, ..., come to the AMWG for details ...). **Tuning can be costly (less so for 3km models?)**
- **Ensembles to quantify spread** (e.g., LENS1, LENS2 ~30-50 members)
- **Provide information at a spatial scale that is meaningful to stakeholders** (km scale?)

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Climate model dogs mission(s)

Provide projections of climate change to stakeholders. What is needed?

- **Tuned climate model wit**
  climate mean (TOA balance
  to the AMWG for details ...)
- **Ensembles to quantif**
- **Provide information at a**
  stakeholders (km scale?)

Computational cost of Large ensembles (50+ members):

Each run for ~250 years (1850 to 2100)

⇒ ~12.5 K years of simulation!

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Climate model dogs mission(s)

To assess variability (uncertainties) in the coupled system you need an ensemble

- **An example: TC projections for end of 21st Century using LENS1 to estimate variability**

For more background: Bacmeister et al. (2018), in ***Climatic Change***

Thanks to Nan Rosenbloom and Susan Bates

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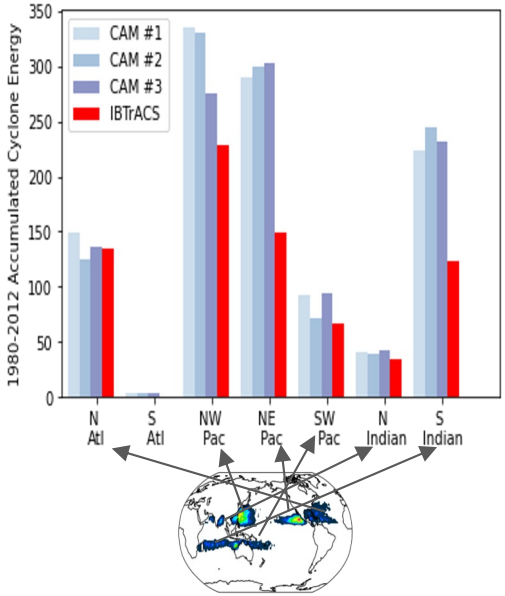
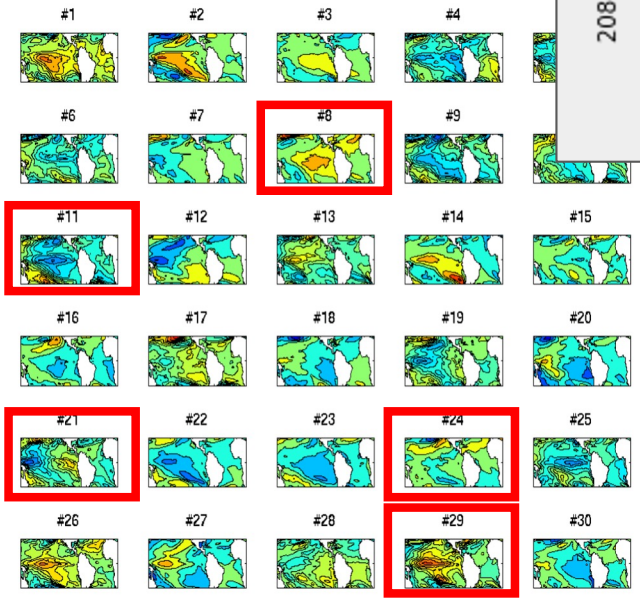
1979-2012 Accumulated Cyclone Energy (ACE) by basin



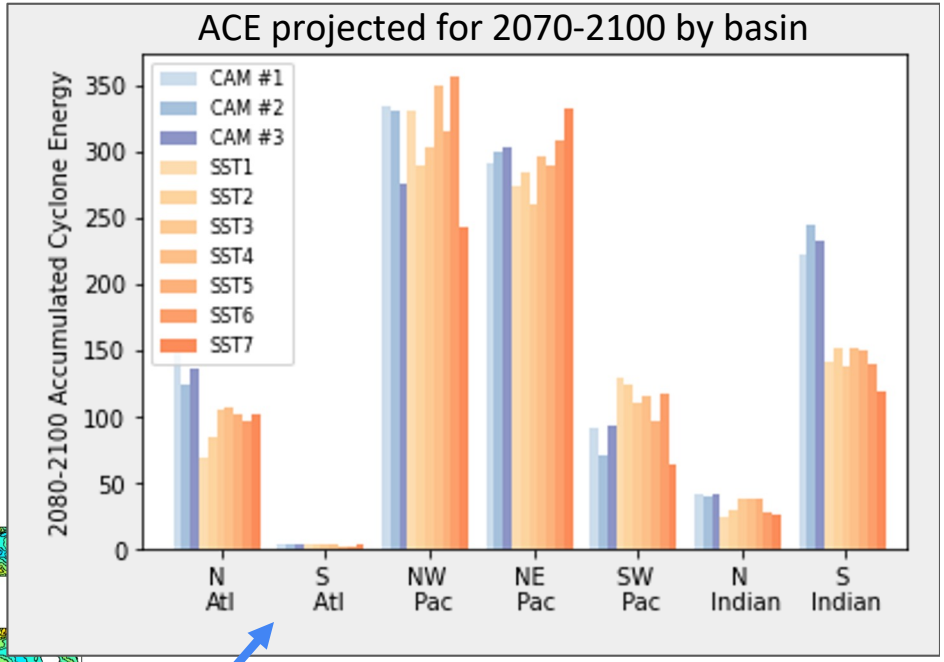
Single SST (present day observed) - atmos only variability

Bias Corrected LENS1 SSTs 2070-2100 (deviation from LENS1 mean) under RCP8.5.

Pick 5 (+ LENS1 mean, and a CMIP5 RCP8.5)--> 7 SSTs



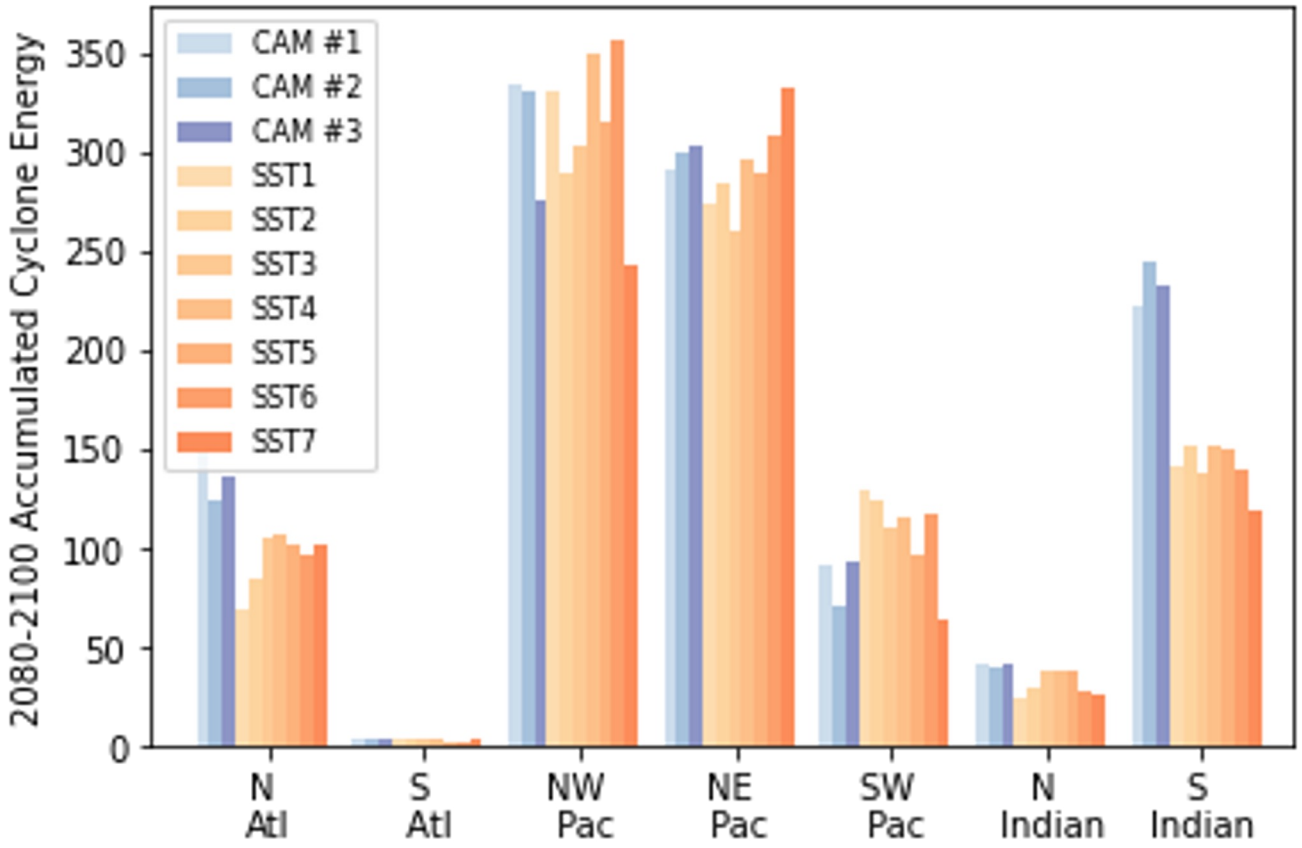
ACE projected for 2070-2100 by basin



"Time-slice" runs at 25km resolution forced with 7 bias corrected SSTs taken from large ensemble (LENS1)

LENS1: Kay et al (2015), *BAMS*
LENS2: Rodgers et al (2022) *Earth System Dynamics*

ACE projected for 2070-2100 by basin



Spread due to SST variability appears substantially larger than atmos only variability

Projected change in TC activity can change sign depending on SST projection

Projected 30-year means - not just ENSO

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Climate model dogs mission(s)

High-resolution simulated climate is not always better than low-resolution

- Example: precipitation

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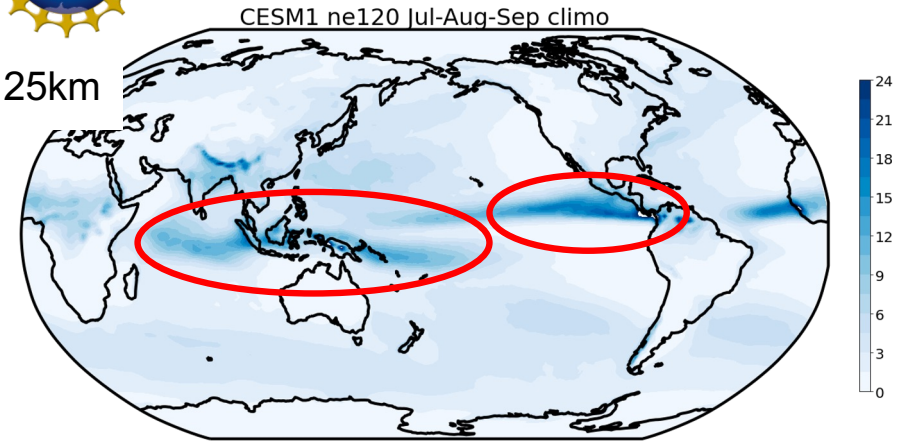
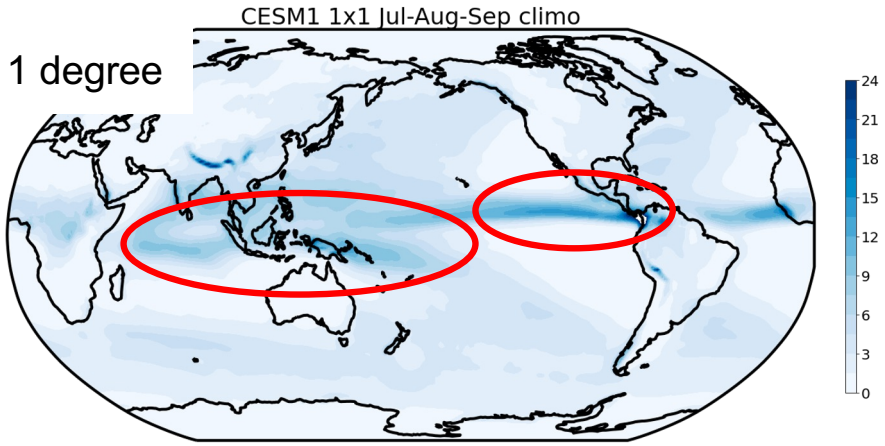


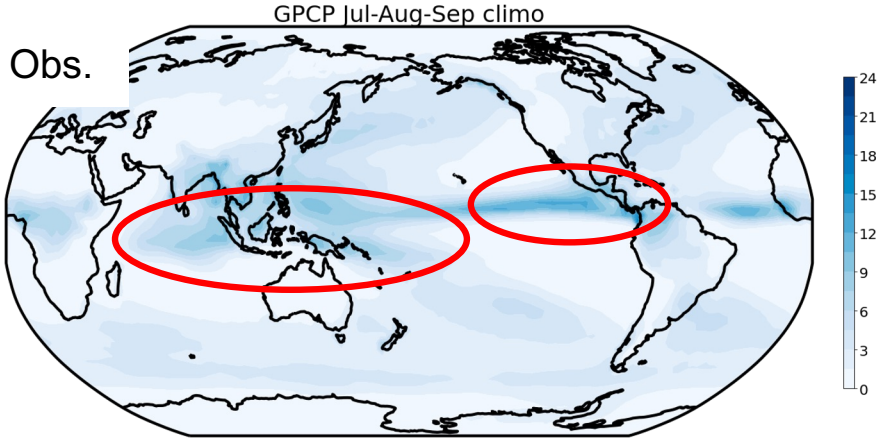
25km

ITCZ biases and “doubling” intensify at 25km:

- Tunable by increasing deep-scheme activity, but experience with CAM indicates this nearly eliminates TC activity



1 degree



Obs.

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Climate model dogs mission(s)

Is ~3km a “breakthrough” resolution ?

We only have indications not an answer due to length of available simulations

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Climate model dogs mission(s)

- **We've argued that providing well-tuned climate and reliable estimates of variability will require >10K SY (maybe much more). Probably not doable at ~3km globally:**

Hence, to get to stakeholder scales we need downscaling
(probably dynamic downscaling)

- **Ensembl… …y spread** (e.g., LENS1, LENS2 ~30-50 members)
- **Provide information at a spatial scale that is meaningful to stakeholders** (km scale?)

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Climate model dogs mission(s)

Downscaling works!

- Examples: South America, Greenland

Like AI - you need good boundary dataset for downscaling, similar to AI which needs good training data!

i.e. downscaling is here to stay until we get 32768 times speed-up …

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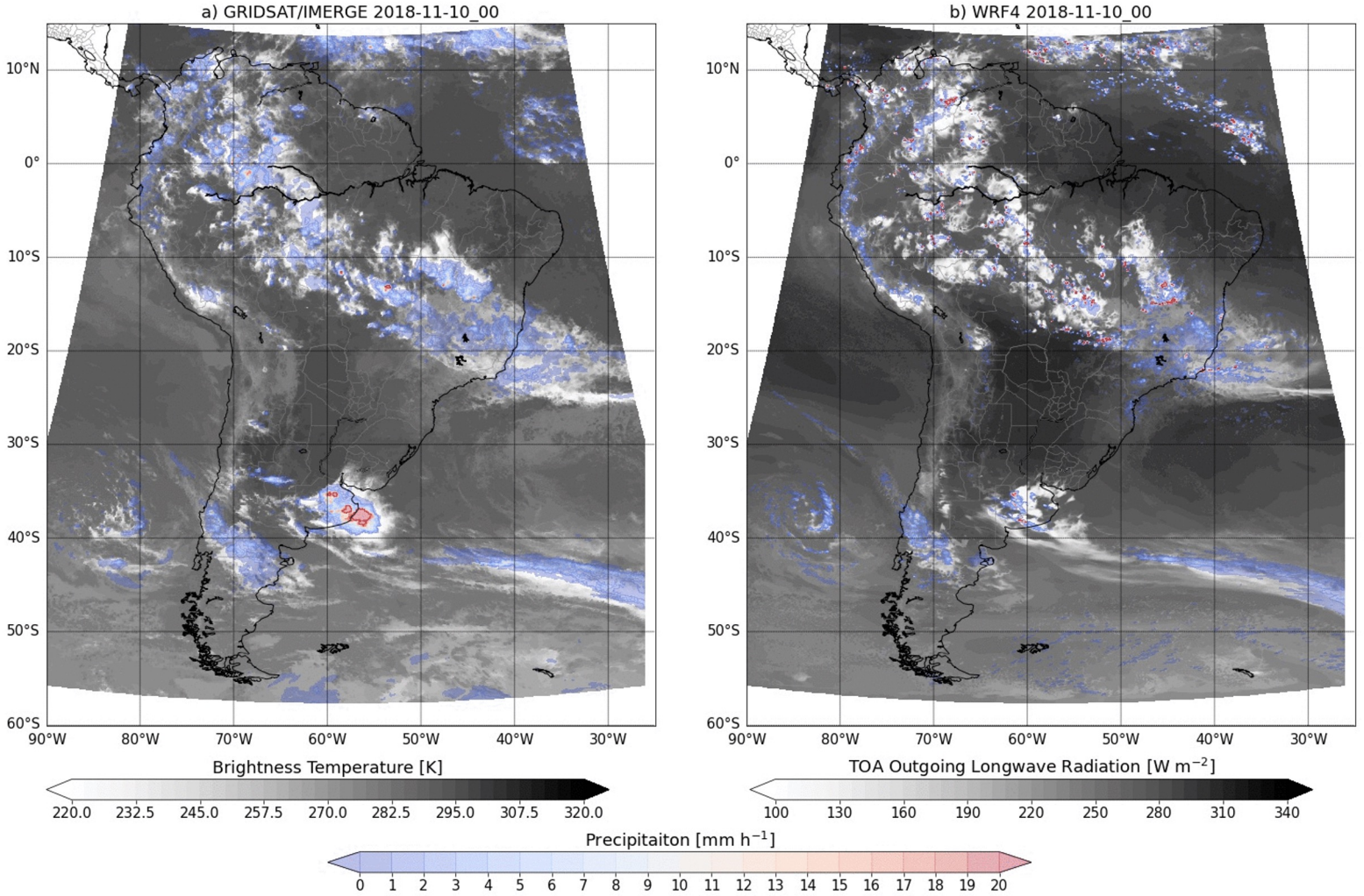
Traditional downscaling: regional WRF forced w/ ERA

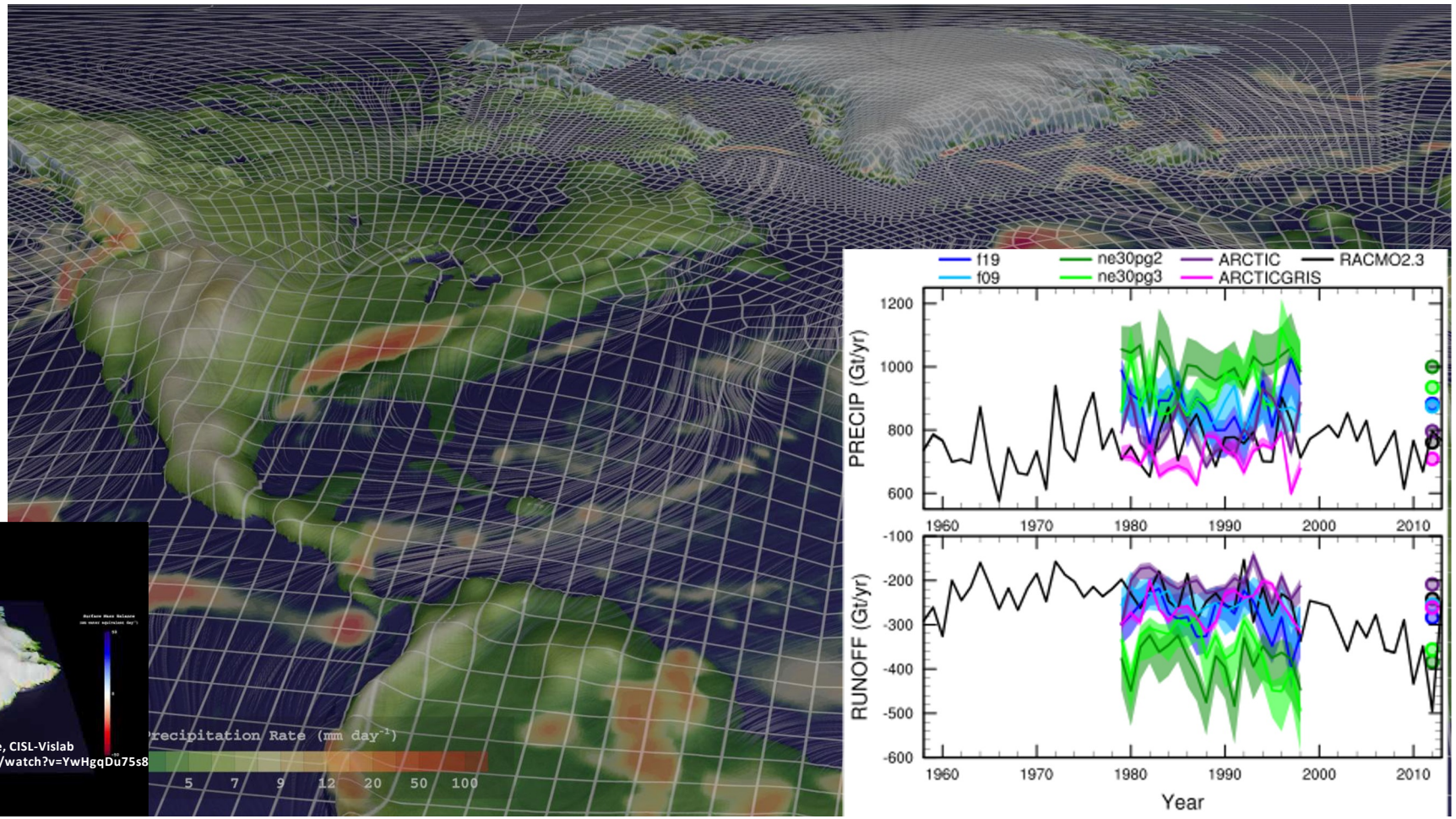
Animation courtesy of Andreas Prein (MMM/NCAR)

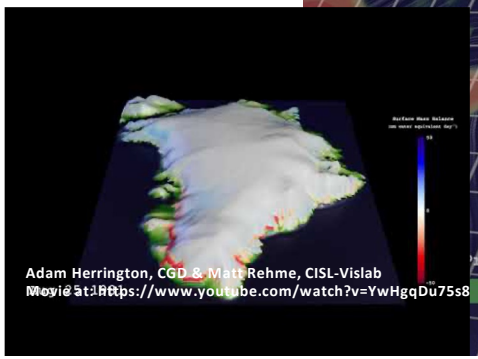


Point:

Works well if boundary data is high quality!

Dynamic downscaling with mesh-refinement: Coupled regional climate in global CESM





Some recommendations/questions

- **Pacific regional refinement / limited area to examine ITCZ biases with longer ~3km runs**
- **High resolution or variable resolution medium ensembles (~10 members)**

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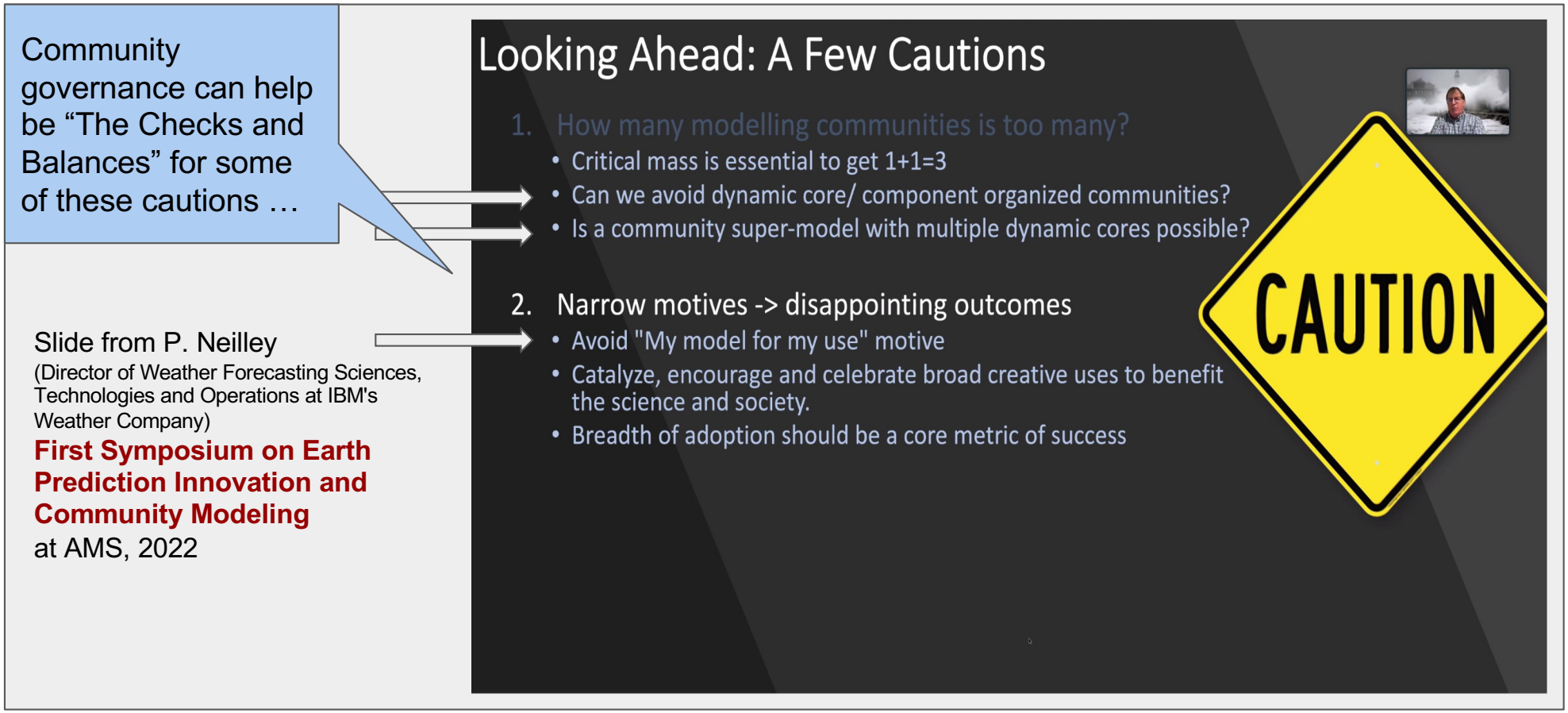
Community governance can help be “The Checks and Balances” for some of these cautions …

Slide from P. Neilley
(Director of Weather Forecasting Sciences, Technologies and Operations at IBM's Weather Company)
First Symposium on Earth Prediction Innovation and Community Modeling
at AMS, 2022



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Climate Model dog wishlist:

- **A flexible modeling system where we can perform:**

  - global low and high resolution simulations (~200km to km scale),
  - easily configurable dynamical downscaling (traditional nesting and mesh-refinement),
  - LES capability for parameterization development!

- **Unified workflows and diagnostics!**

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Climate Model dog wishlist:

Sounds easy or even banal!

It is actually very very hard when you start assessing what it would take:

For example, try and setup new resolution in a modeling system:

1. **How to define/make grid?** (especially variable resolution - is there a community tool?)
2. **Input datasets?** (forcing datasets, topography, …)
3. **Balanced initial condition?** (is your initial condition procedure/software dynamical core agnostic or just designed for "your" model/application? Remember: not just atmosphere but also spinning up land initial conditions etc.)
4. **What physics to use?** (depends model top, horizontal resolution, time-scale, region, …)
5. **Tuning?** (is your tuning parameter/namelist generation scale aware?)
6. **"Known unknowns" will appear** (memory footprint issues, slow throughput issues, stability issues, …)
7. **Maybe even "unknown unknowns"!**
8. **Diagnostics** (inline zonal means, output size, analysis software/workflows, …)

There are efforts within CESM and SIMA (System for Integrated Modeling of the Atmosphere) towards unified infrastructures …

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Climate Model dog wishlist:

Lets not forget about 1st principles

- **Towards a true multi-phase/component fluid formulation (in CESM)**
- **Thermodynamic consistency in physics packages**
- **Missing processes: Enthalpy flux, frictional heating of falling precipitation, drag of falling precipitation, …**

For in depth discussion see Lauritzen et al. (2022):
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022MS003117

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Climate Model dog wishlist:

Non-column physics

Gravity wave cone?
Convection non-local?
Radiation?
AI?

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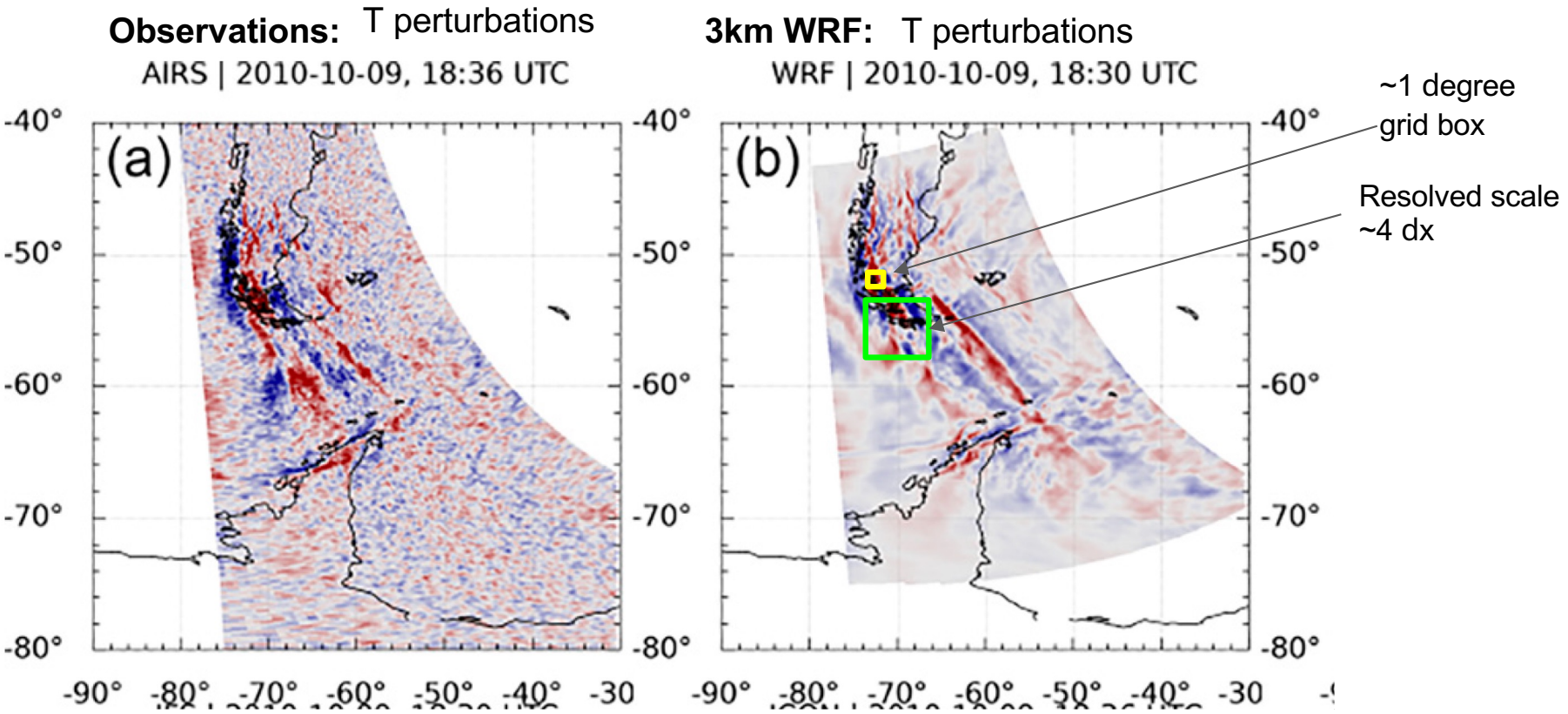
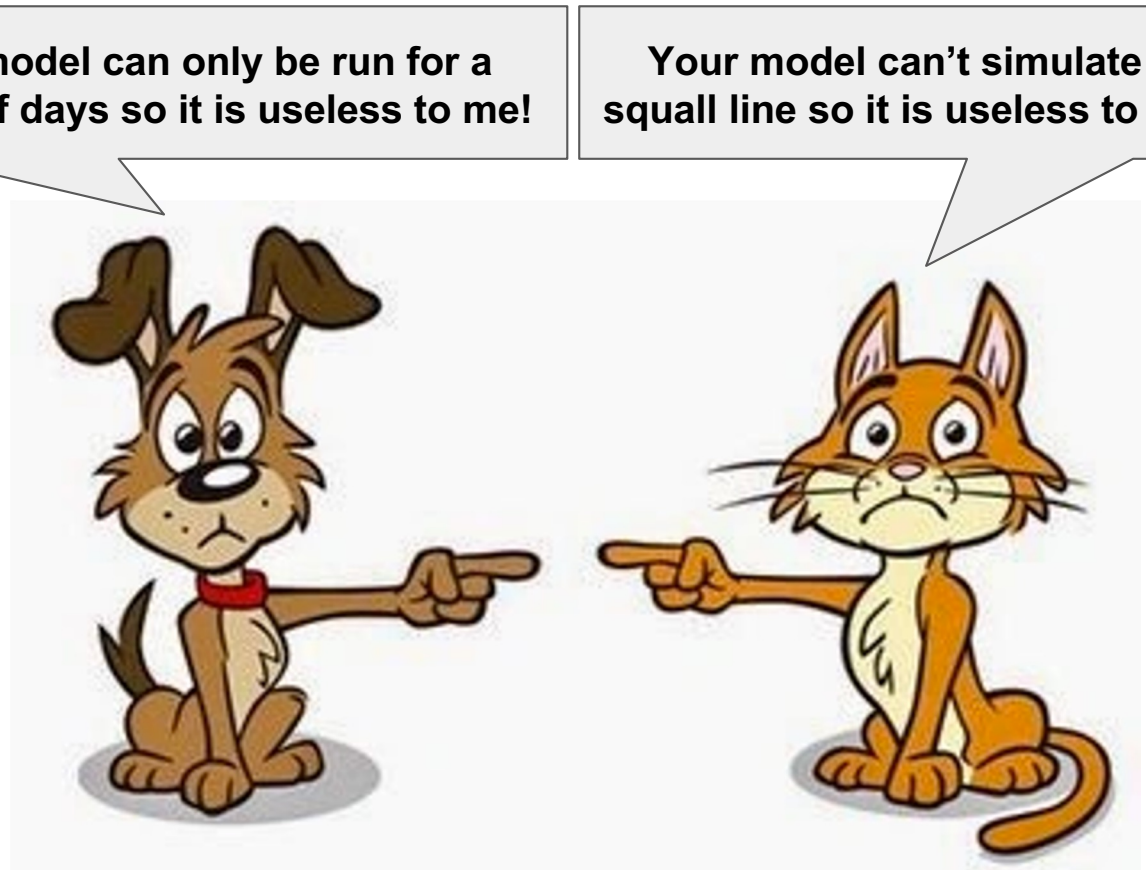
Example: Orographic gravity waves



From Kruse et al (2022) in JAS

Even at 1 degree column physics is a bad approximation!



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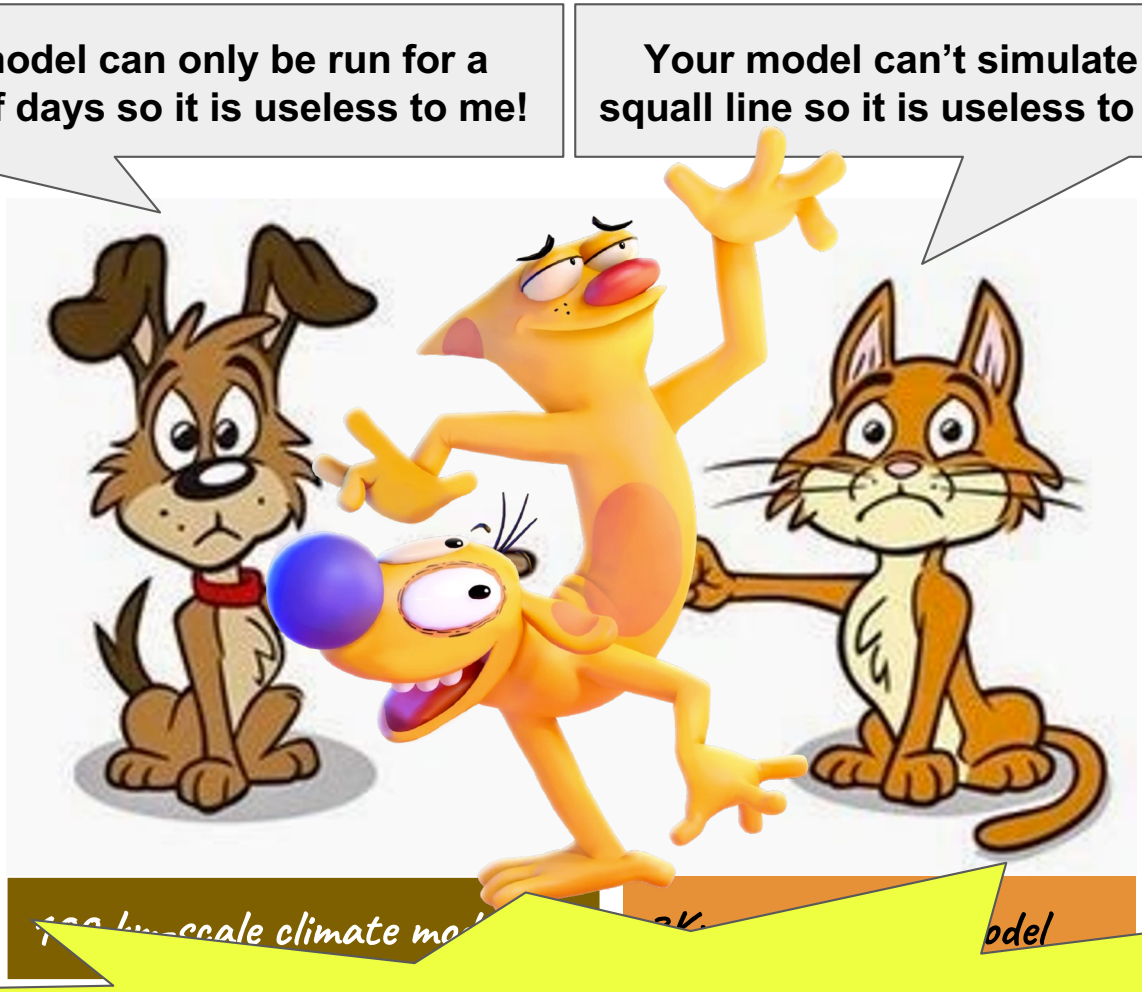

Let's create the dog-cat
- should we call it the "dat" or "dot"?

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Supplementary slides

CAM physics total energy formula

No condensate loading, constant latent heats, no enthalpy flux terms

$$\frac{\partial}{\partial t}\iiint \rho^{(d)}\Big\{K+\Phi_s+c_p^{(d)}T+\sum_{\ell\in\mathcal{L}_{H_2O}} m^{(\ell)}\Big[K+\Phi_s+\underbrace{c_p^{(\ell)}\left(T-T_{00}\right)+h_{00}^{(ice)}}_{\text{moist enthalpy terms}}\Big]$$

$$\mathcal{L}_{H_2O}\equiv\{wv\}$$

$$+\underbrace{m^{(wv)}L_{s,00}+m^{(liq)}L_{f,00}}_{\text{latent heat terms}}\Big\}dA\,dz=$$

$$c_p^{(\ell)}=c_p^{(d)}$$

$$\iint\Big\{\underbrace{\sum_{\ell\in\mathcal{L}_{H_2O}} F_{net}^{(\ell)}\left[c_p^{(\ell)}\left(\tilde{T}_s-T_{00}\right)+h_{00}^{(ice)}\right]}_{\text{enthalpy flux}}$$

$$+\underbrace{F_{net}^{(wv)}L_{s,00}+F_{net}^{(liq)}L_{f,00}}_{\text{latent heat flux}}+F_{net}^{(turb,rad)}\Big\}dA, \qquad (1)$$

We are working towards undoing these simplifying assumptions ….

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No

Towards enthalpy flux in CESM3

New steps towards enthalpy fluxes in CESM3 completed:
(CAM needs to move to variable latent heats to "match" MOM6)

- **Change spectral-element dynamical core to use variable latent heats (see Lauritzen et al., 2018) - DONE**
- **Change CAM physics to incl. all condensates in pressure - DONE (possibly important for high res applications as well)**
- **Change CAM physics to use variable latent heats - step 1 of 2 DONE**
- **Pass enthalpy flux to other components (MOM6 straight forward, land and ice less obvious) - ???**

We are working towards undoing these simplifying assumptions ….

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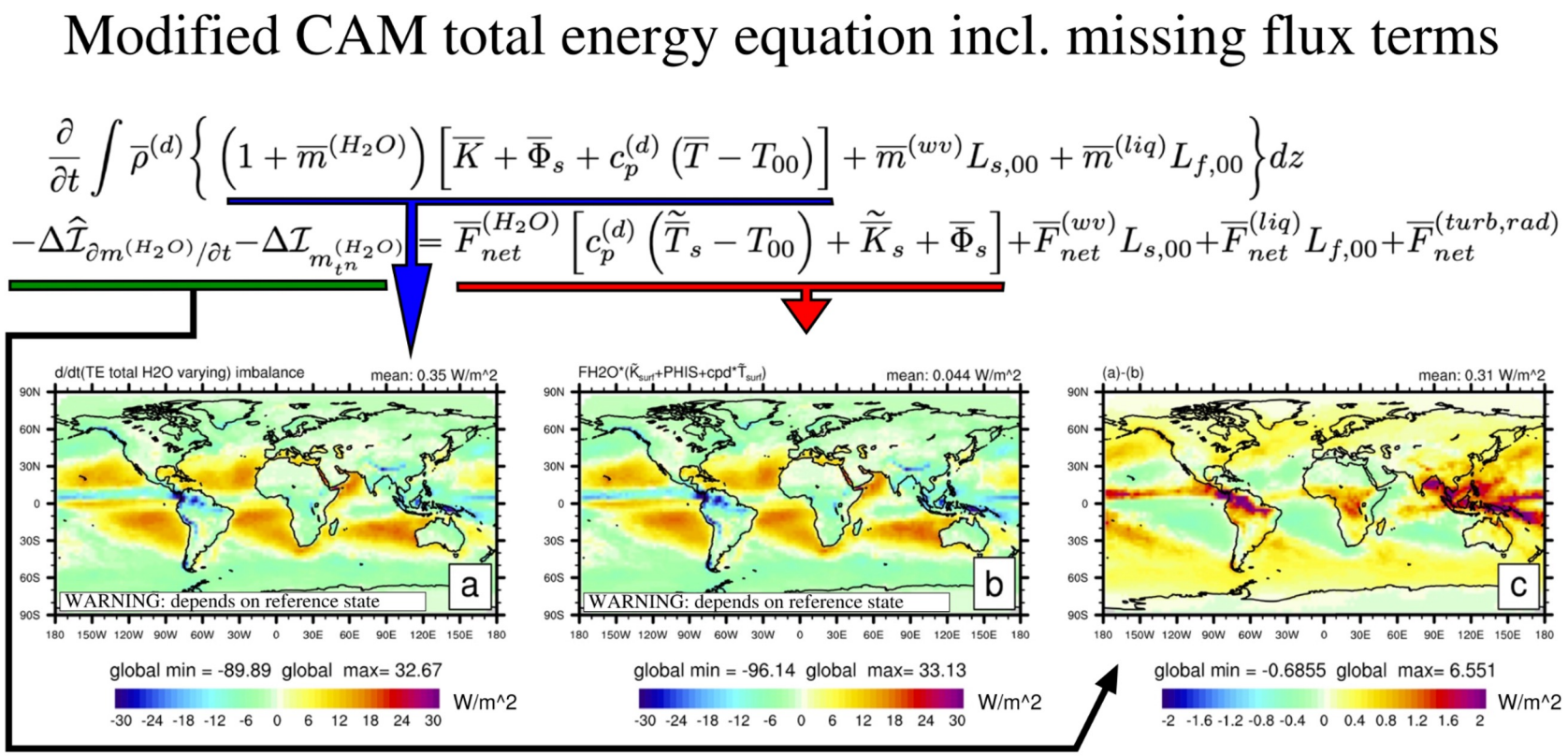

Figure 6. Modified (consistent) CAM total energy equation terms in W/m^2: (a) Imbalance introduced by "dry-mass adjustment" using all forms of water in the kinetic, geopotential and enthalpy terms, (b) missing flux terms, and (c) is the difference between (a and b). Note that the imbalance is locally much reduced when using the modified total energy equation. Also, the imbalance does not depend on the reference state (as should always be the case).

Climate model dogs mission

Provide projections of clima
needed?

- **Tuned climate mod**
  climate mean (TOA balance
  to the AMWG for details ...) **tha**
  Day)

- **Ensembles to quantify sp**

- **Provide information at a spatial scale that is meaningful to stakeholders** (km scale?)

Computational cost of tuning a climate model:
(does not incl. basic parameterization and dynamical core development)

Example, for the development of CAM6 ~300 model versions were used; each run ~100 years

⇒ ~30K years of simulation!

Counterargument: Maybe at 3km you won't need to do as much tuning.

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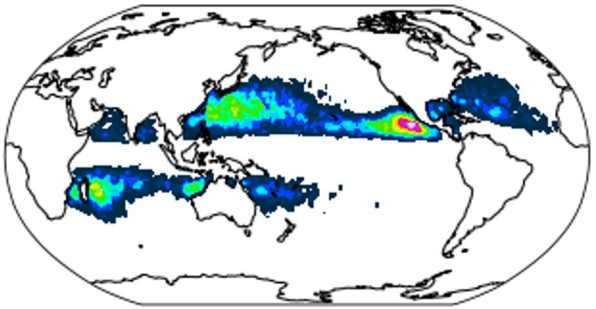
CESM1 quarter degree (~25km) climate simulations.

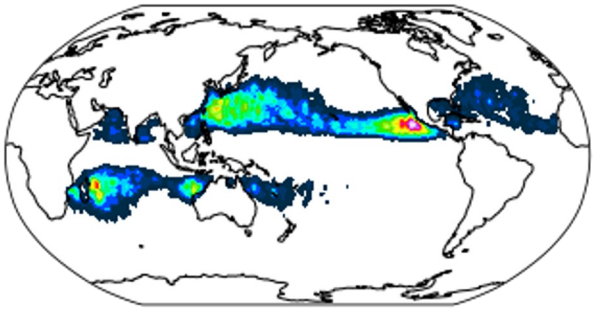
This slide: 3 member ensemble forced with observed SSTs

1979-2012 Accumulated Cyclone Energy (ACE) density

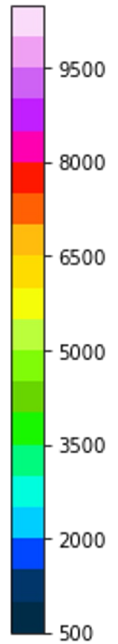
Ens. Member #1



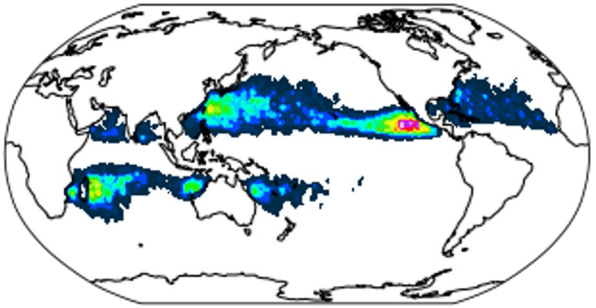
Ens. Member #2



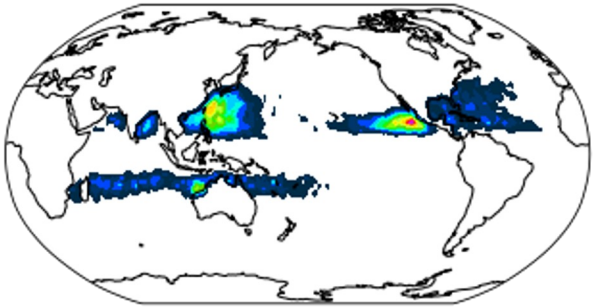
ACE ~ wind^2



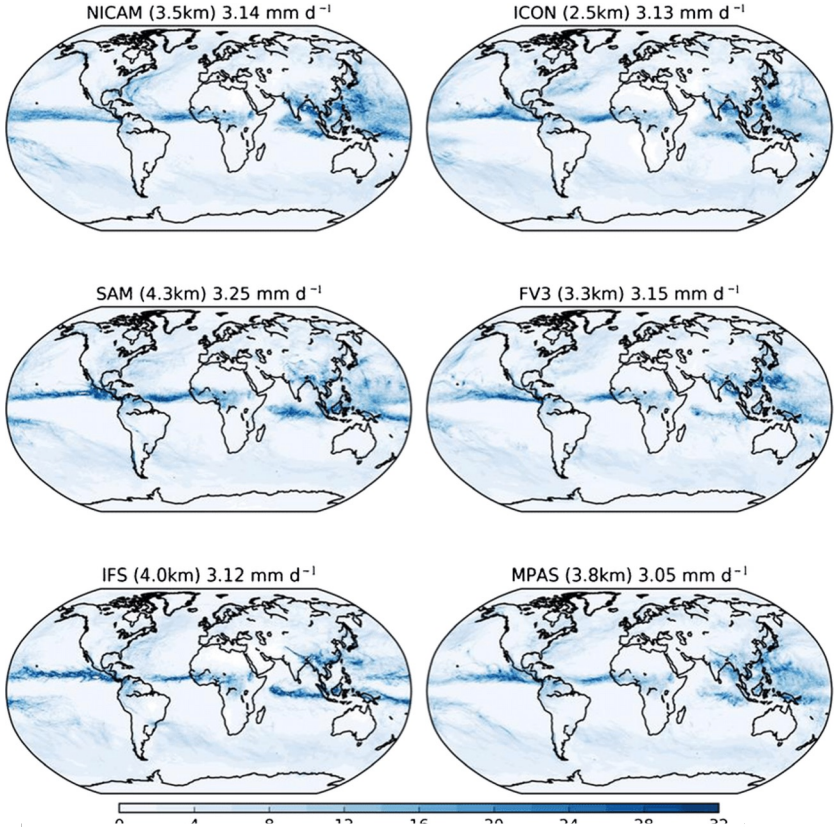
Ens. Member #3



Obs: IBTrACS 1980-2022



DYAMOND precipitation Aug 10-Sep 10 2016



Current Climate Change Reports
https://doi.org/10.1007/s40641-019-00131-0

CONVECTION AND CLIMATE (C MULLER, SECTION EDITOR)

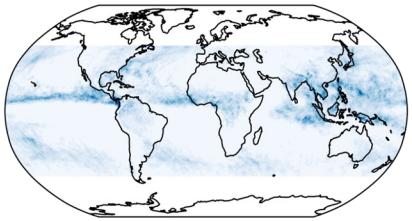
Check for updates

Global Cloud-Resolving Models

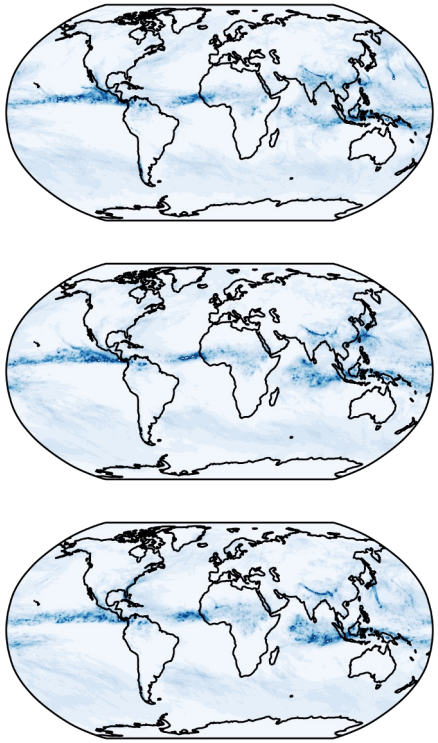
Masaki Satoh[1] · Bjorn Stevens[2] · Falko Judt[3] · Marat Khairoutdinov[4] · Shian-Jiann Lin[5] · William M. Putman[6] · Peter Düben[7]

Observed:

TRMM Aug 10-Sep 10 2016

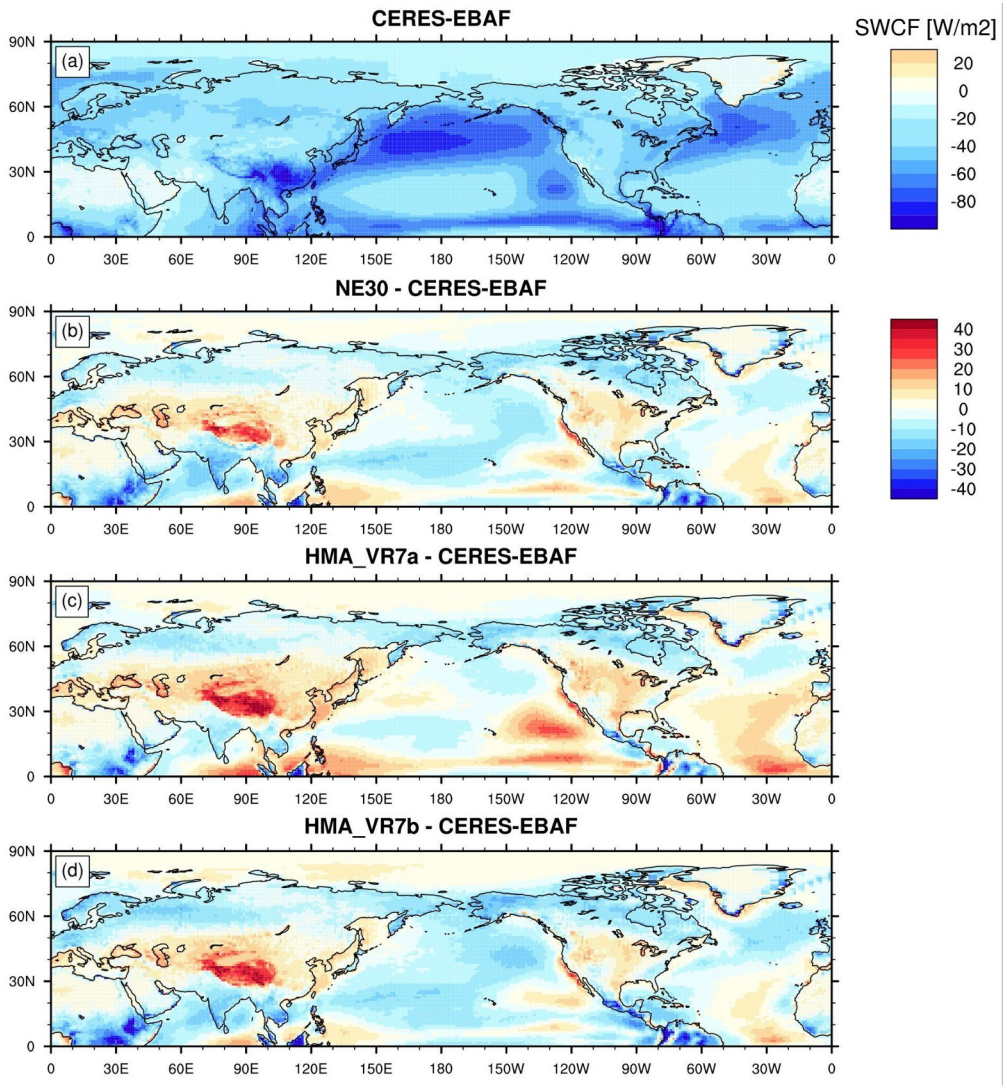


Sample August precip from 25km CESM (***not same year as DYAMOND***, similar ENSO indices)



Difficult to make definite statements based on 30d simulation

- Discernible inter-model spread - why? (MPAS looks pretty good)
- Hints of increased ITCZ biases at ~3km (plotting projection not optimal for seeing this)



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Some recommendations/questions

- **Pacific regional refinement / limited area to examine ITCZ biases**
- **High resolution (~25km) ensembles (~10 members)**
- **Where and what resolution is enough to capture the phenomenon/process you are interested in? (refinement in ocean and/or atmosphere? Which is more important?) [iHESP, Justin Small]**

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