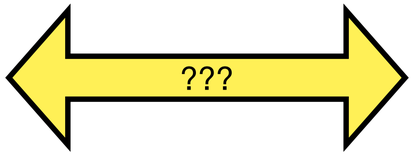
Leveraging the model-observations partnership for advancing process understanding

Charlotte DeMott, Colorado State University

image credit: NOAA



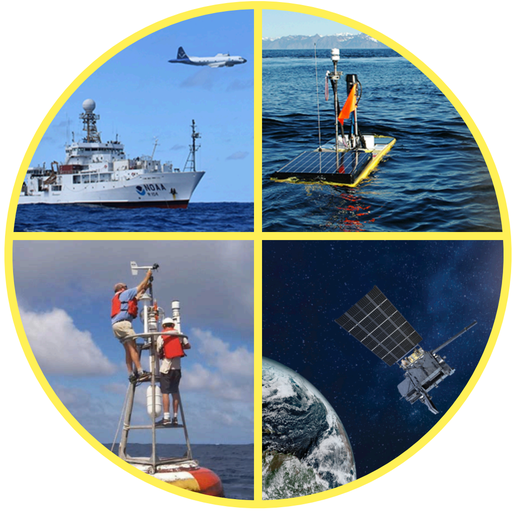


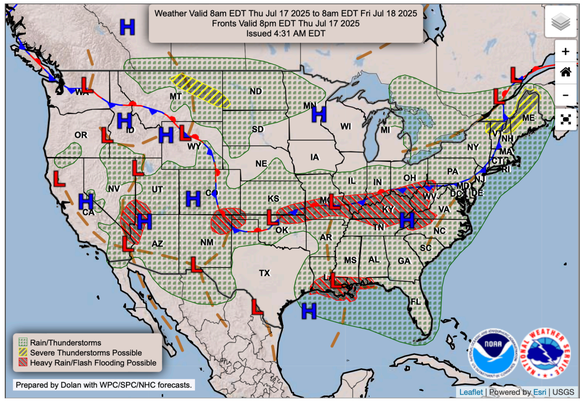
image credits: NOAA, NDBC

US CLIVAR Summit POS Panel Breakout 22 July 2025 Boulder, CO

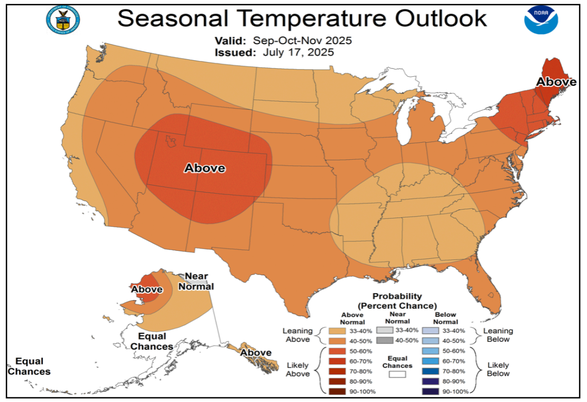
Why do we model?

- to predict the future
- to protect life, resources, infrastructure, economic activity

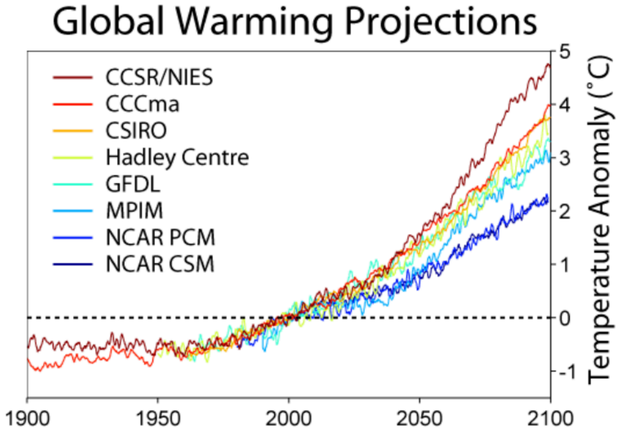
hours to days



seasons



decades



How do we model?

- set the initial state
- integrate the governing equations:
  - conservation of momentum, energy, mass, water

Basic Equations

Conservation of momentum:

$$\frac{\partial \vec{V}}{\partial t} = -(\vec{V} \bullet \nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega} \times \vec{V} + \nabla \bullet (k_m \nabla \vec{V}) - \vec{F}_d$$

Conservation of energy:

$$\rho c_p \frac{\partial T}{\partial t} = -\rho c_p (\vec{V} \bullet \nabla)T - \nabla \bullet \vec{R} + \nabla \bullet (k_T \nabla T) + C + S$$

Conservation of mass:

$$\frac{\partial \rho}{\partial t} = -(\vec{V} \bullet \nabla)\rho - \rho(\nabla \bullet \vec{V})$$

Conservation of H_2O (vapor, liquid, solid):

$$\frac{\partial q}{\partial t} = -(\vec{V} \bullet \nabla)q + \nabla \bullet (k_q \nabla q) + S_q + E$$

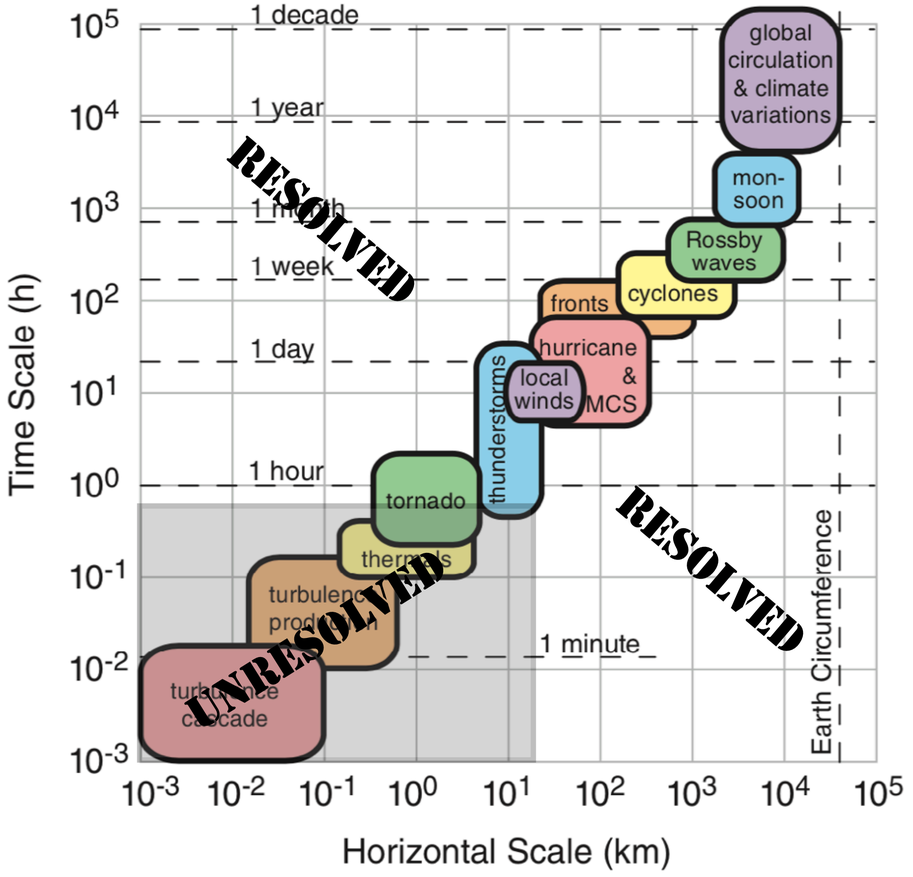
Equation of state:

$$p = \rho R_d T$$

V = velocity
T = temperature
p = pressure
ρ = density
q = specific humidity
g = gravity
Ω = rotation of earth
F_d = drag force of earth
R = radiation vector
C = conductive heating
c_p = heat capacity, const. p
E = evaporation
S = latent heating
S_q = phase-change source
k = diffusion coefficients
R_d = dry air gas constant

Challenges…

- ***data assimilation***: setting the initial state
- ***parameterization***: continuous equations, discrete representations
  - the need to represent subgridscale processes
- ***evaluation***: how well do models perform?
- ***understanding***: what processes regulate the flow of energy across scales?



adapted from Stull 2017

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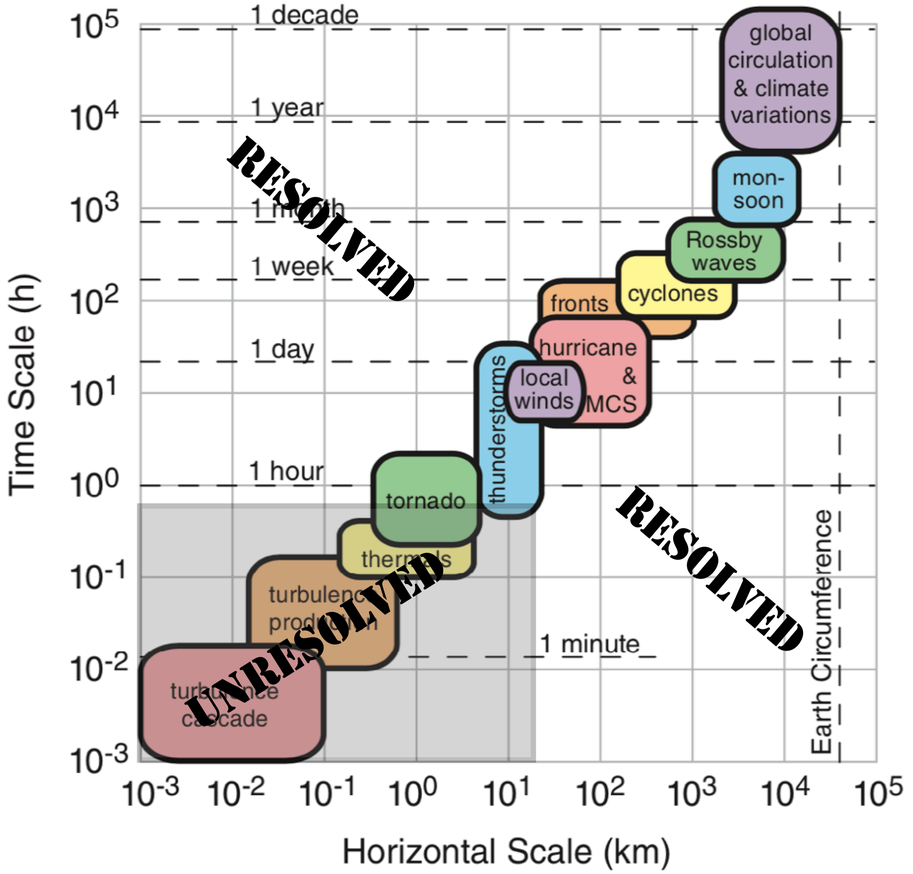
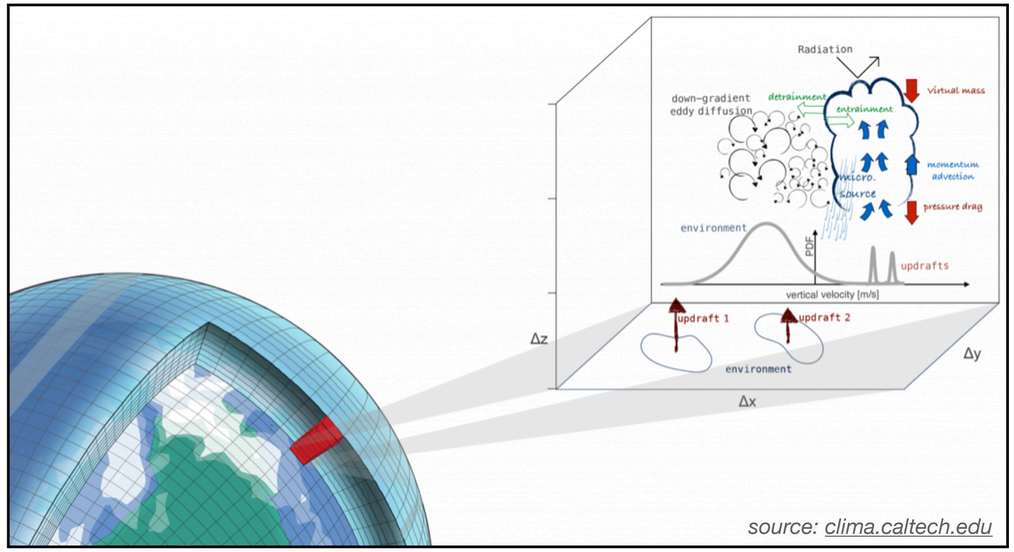


adapted from Stull 2017

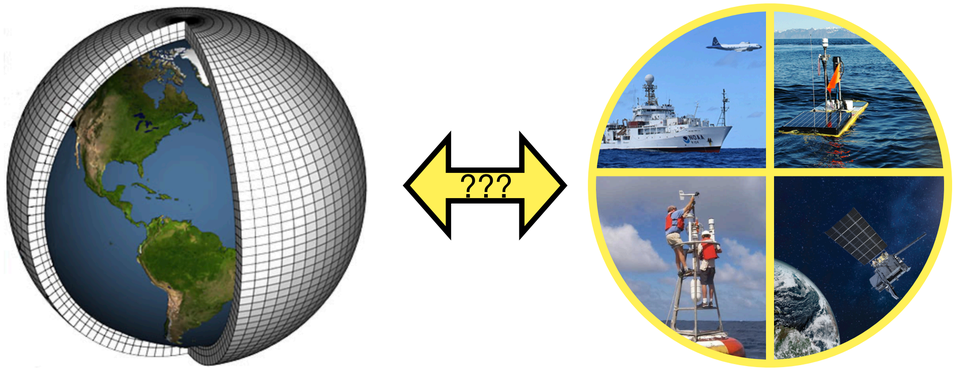
Observations:

- ***parameterization***: direct measurement of subgridscale processes (field campaigns)
- ***evaluation***: direct measurement or retrieval of key variables across time and space scales
- ***understanding***: how do small-scale (unresolved) processes vary under large-scale (resolved) forcing?



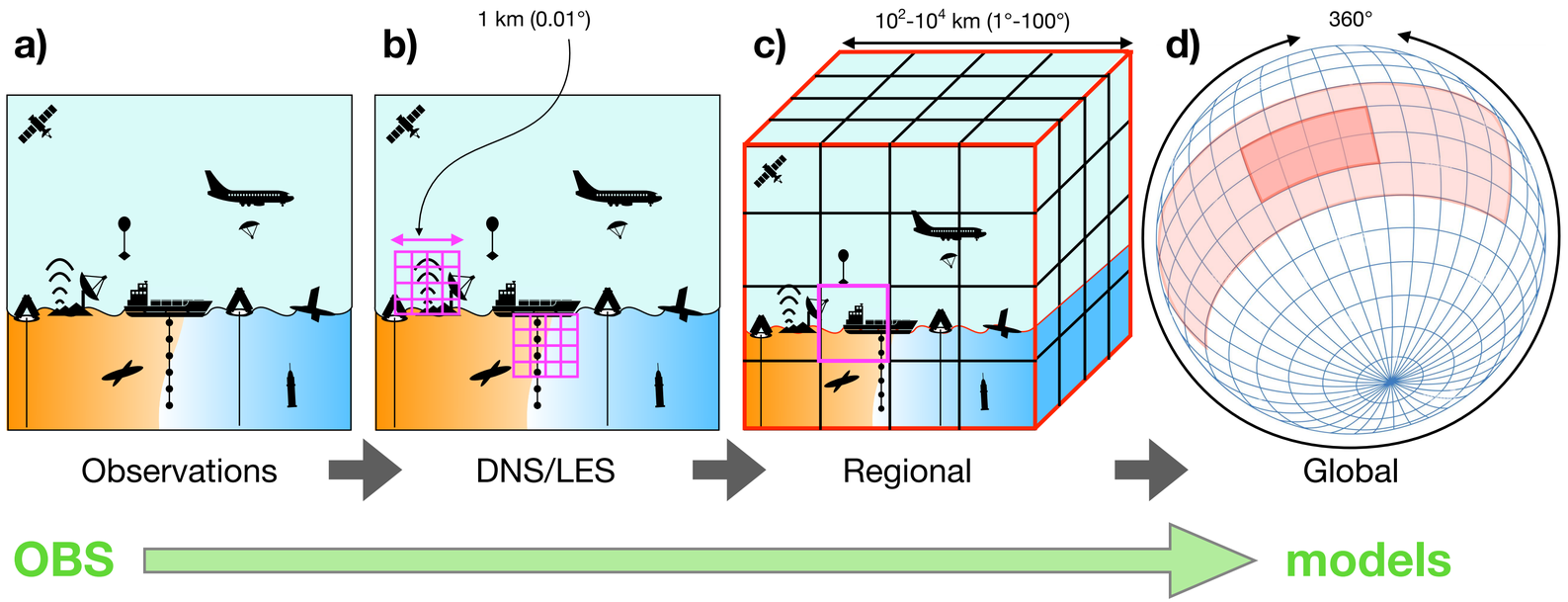
Model-OBS partnership?

- how do we leverage fine-scale measurements from spatially spare and short-duration process studies?
- how do we assess the representativeness of field measurements for model development?



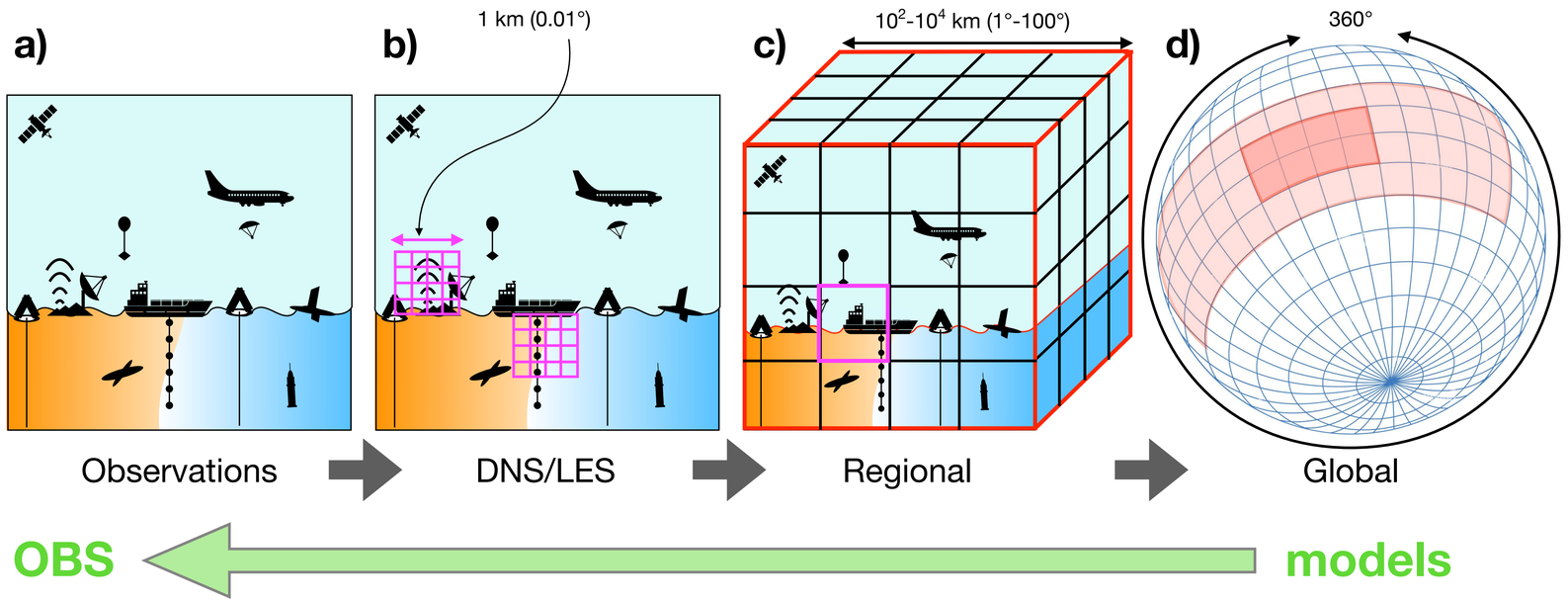
source: clima.caltech.edu

Model hierarchies



- OBS-to-models:
  - ***LES/DNS***: generate subgrid statistics, develop/refine parameterizations
  - ***Regional***: do new parameterizations improve initialized regional simulation?
  - ***Global***: how well do new parameterizations perform in other regimes?

Model hierarchies



- models-to-OBS:
  - ***Global***: where, when, why of largest biases? (model vs OBS budget studies)
  - ***Regional***: test sensitivity to parameterization assumptions/formulations
  - ***LES/DNS***: design and assess process study sampling strategies

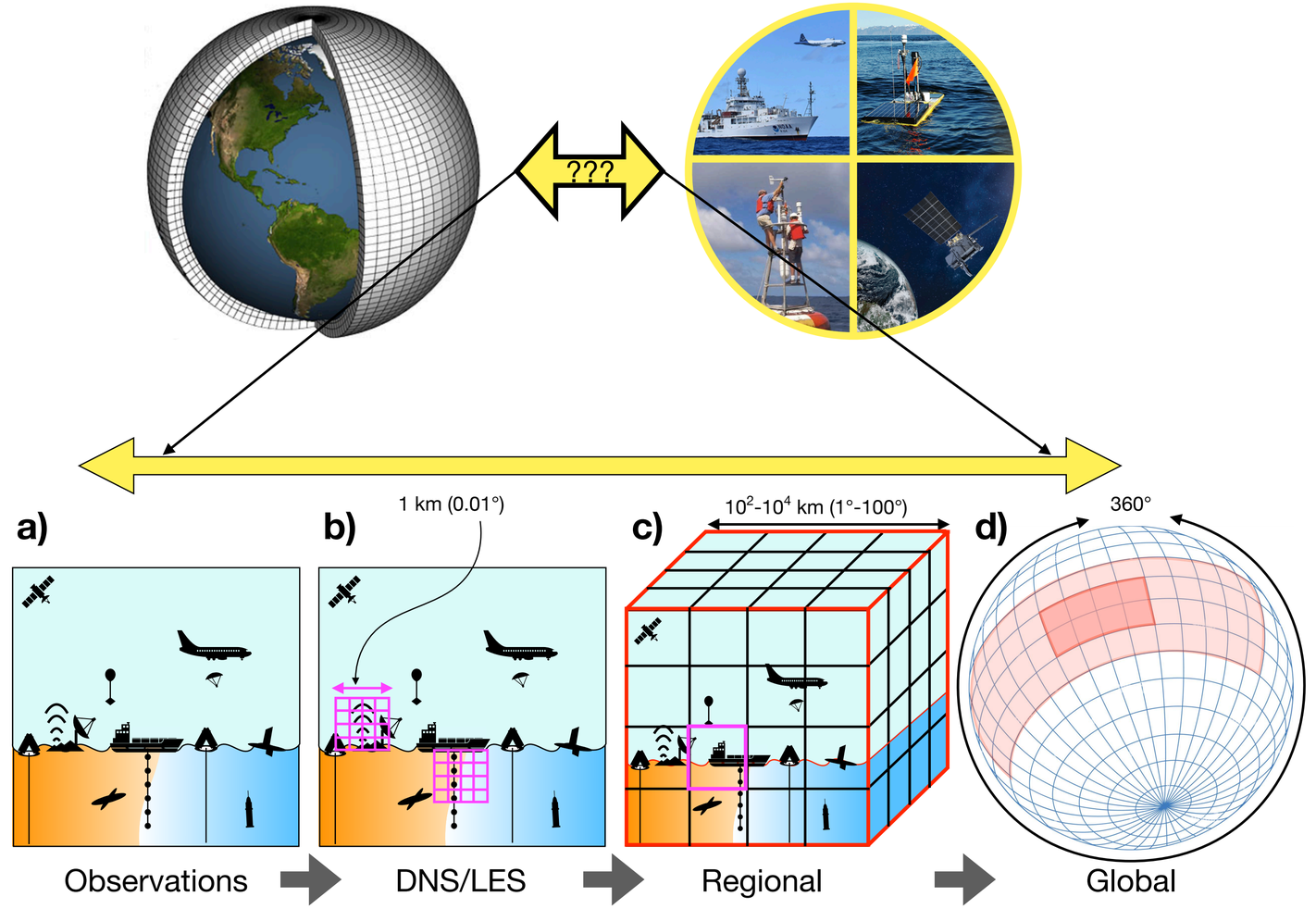
Model-observer interaction

e.g., WCRP Global Kilomenter-scale Hackathon

- ***what***: a dispersed collection of modeling and process diagnostics experts
- ***why***: global collaboration to develop best practices for model-obs comparison
- ***topics***: TCs, MCSs, inter-scale energy transfer, extrememm precipitation, air-sea interactions, aerosol effects, urban climate impacts, AI applications

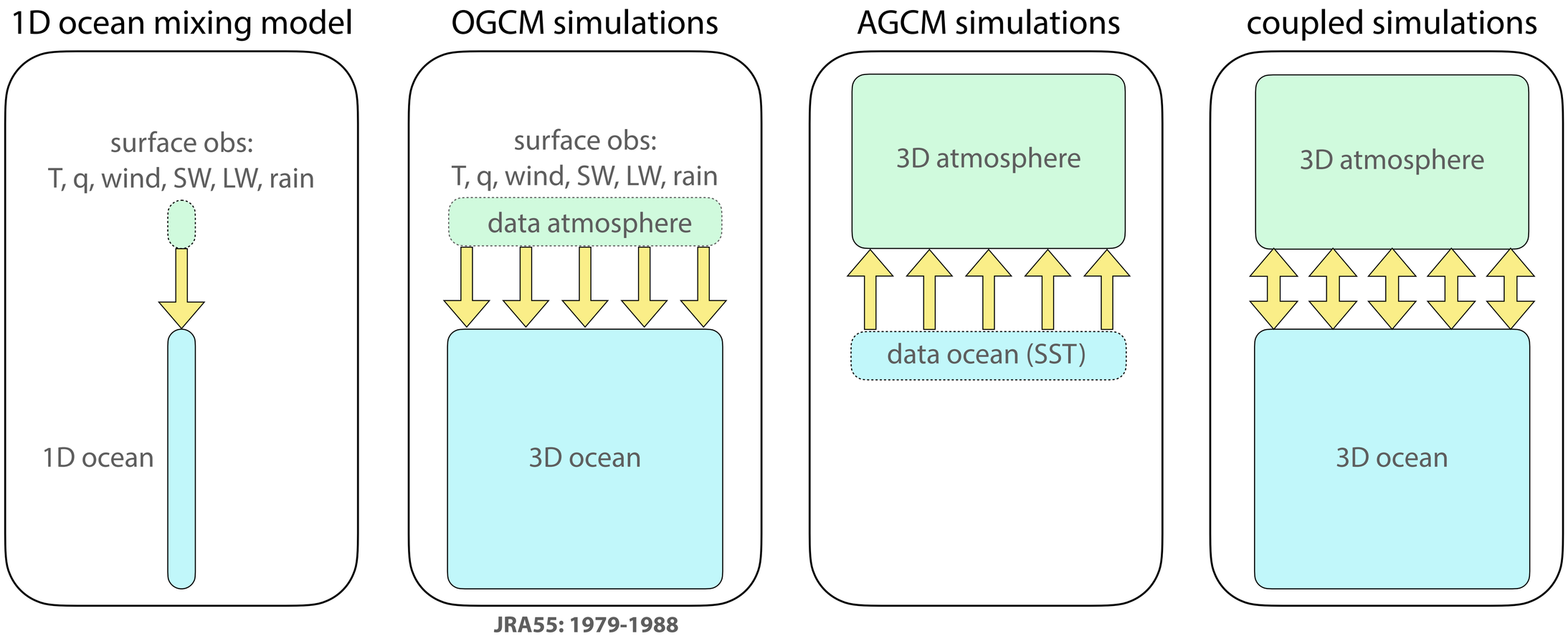
Summary

- observations are key for model assessment and improvement
- hierarchical modeling can help assess representativeness of observations
- model-observer collaborations can help optimize the model assessment exercise



extra slides

understanding flux algorithm effects: a model hierarchy approach



JRA55: 1979-1988