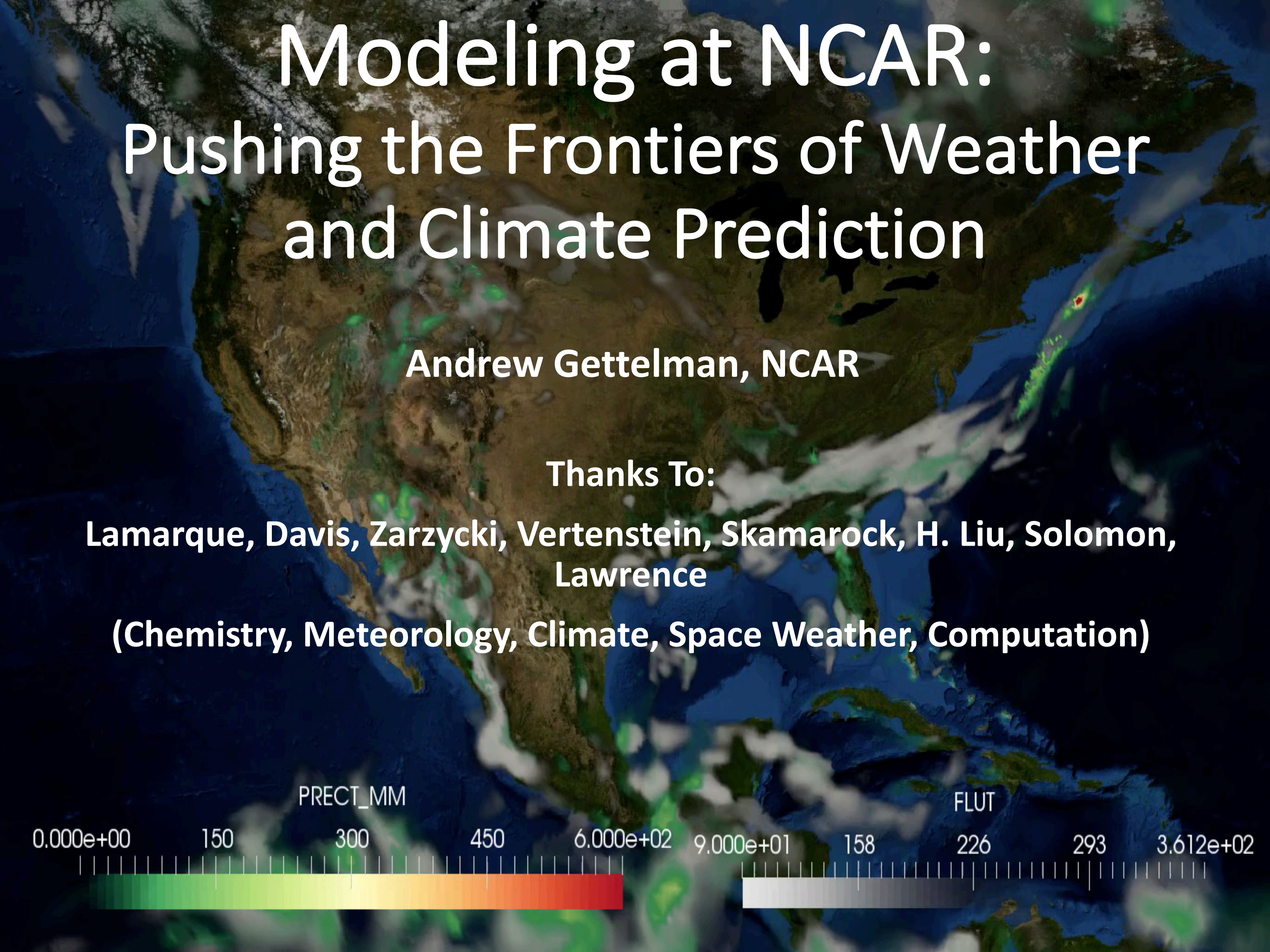
Modeling at NCAR:
Pushing the Frontiers of Weather and Climate Prediction

Andrew Gettelman, NCAR

Thanks To:

Lamarque, Davis, Zarzycki, Vertenstein, Skamarock, H. Liu, Solomon, Lawrence

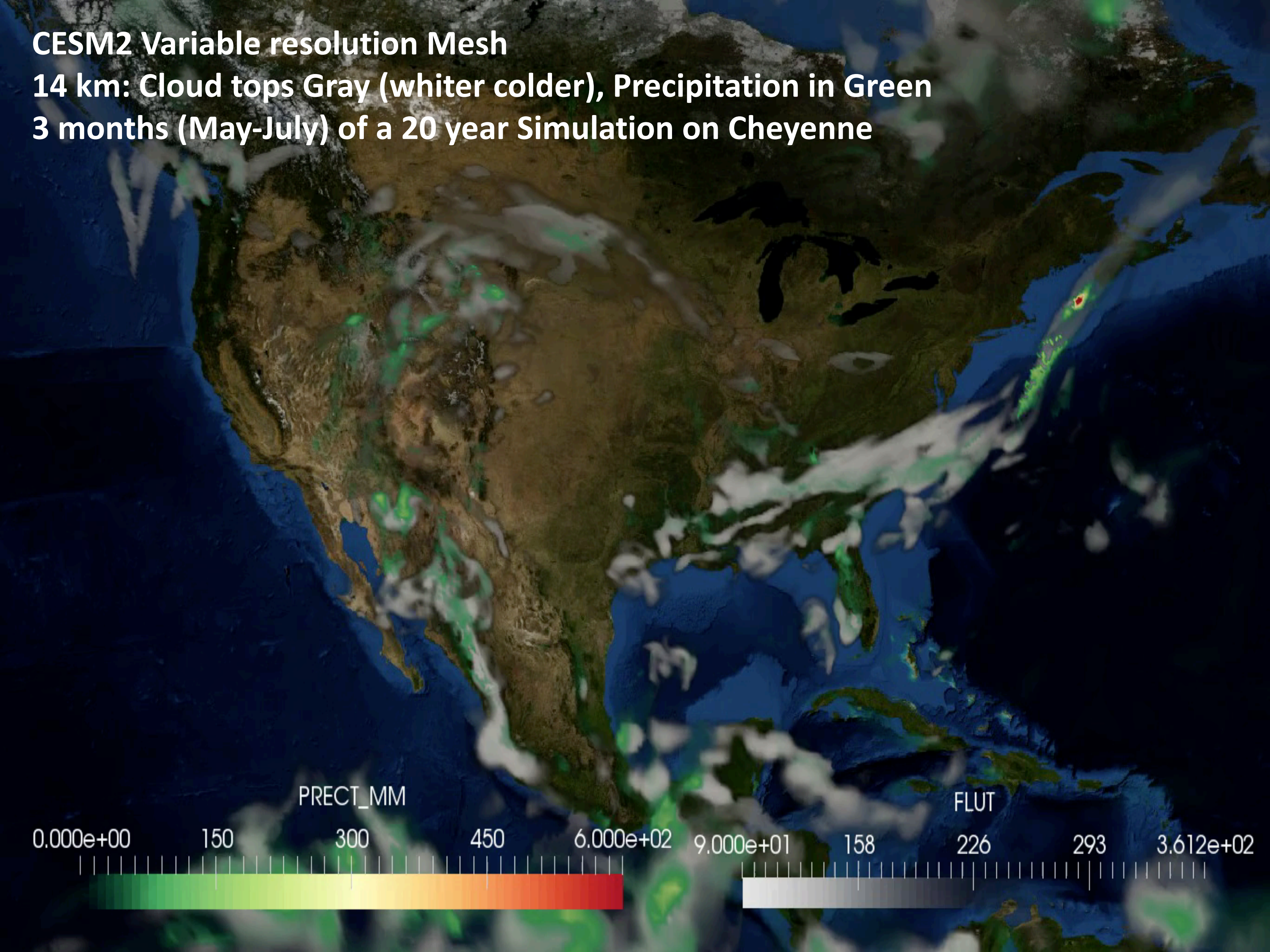
(Chemistry, Meteorology, Climate, Space Weather, Computation)



CESM2 Variable resolution Mesh

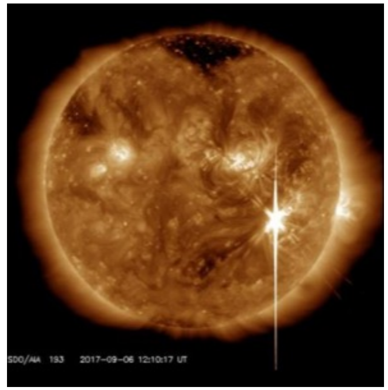
14 km: Cloud tops Gray (whiter colder), Precipitation in Green

3 months (May-July) of a 20 year Simulation on Cheyenne



Motivation

‘Last Week in N. America’



Largest Solar Flare in 10 years, Sep 6

‘No one is killed by the global average mean temperature’

Climate change is how the tails are going to change

How did we get here? Where are we going?
Outline

- Who Am I? Why am I representing NCAR?
- Intro: Modeling the Earth System
- NCAR Community Modeling Tools
- Elements Of Community Modeling
    - Infrastructure, Evaluation and Analysis
- Towards a Unified System
- Summary and Next Steps

Note: Just showing a few sponsors. But lots of contributors!

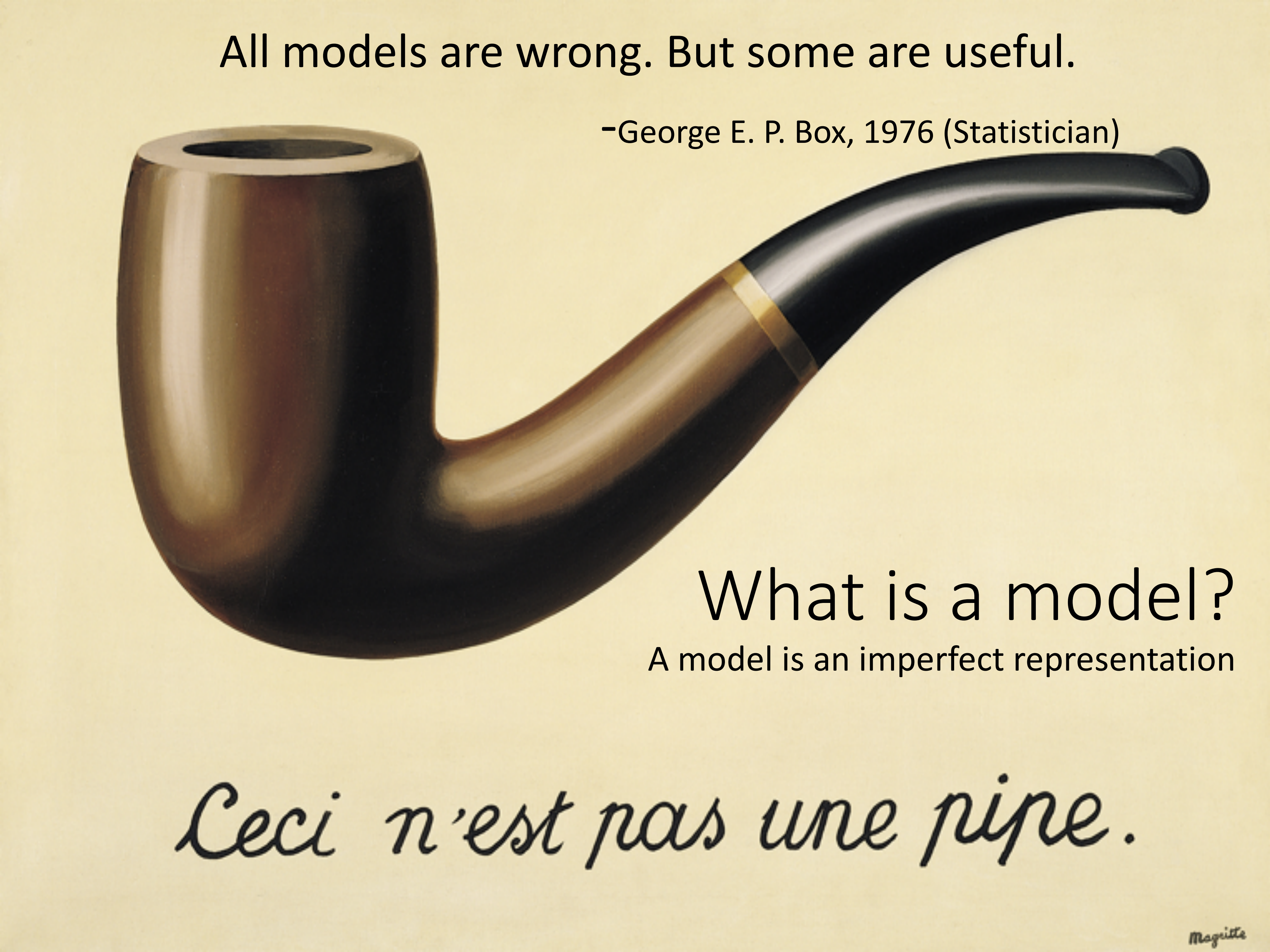

Ceci n'est pas une pipe.
Magritte

All models are wrong. But some are useful.

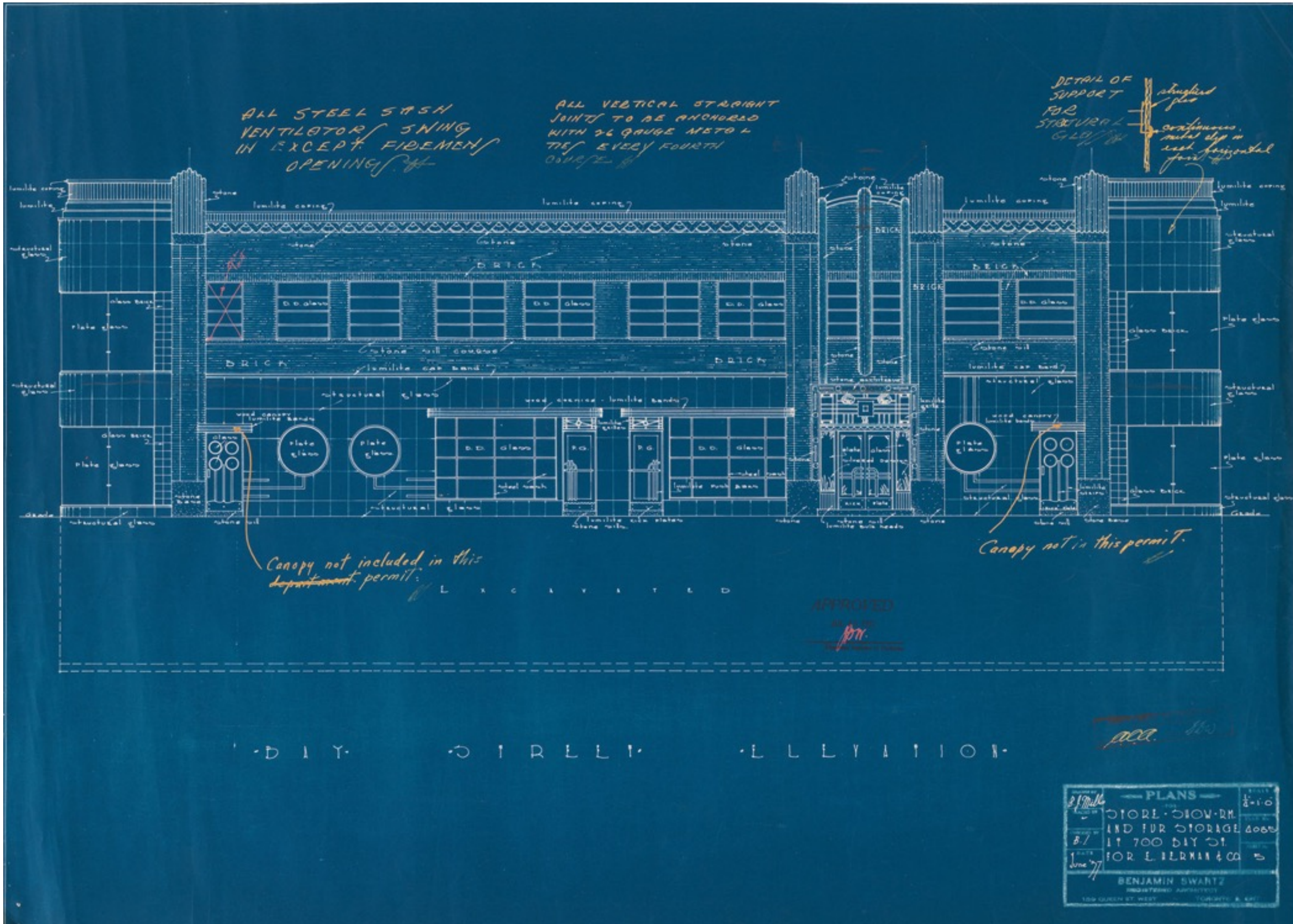
-George E. P. Box, 1976 (Statistician)

What is a model?

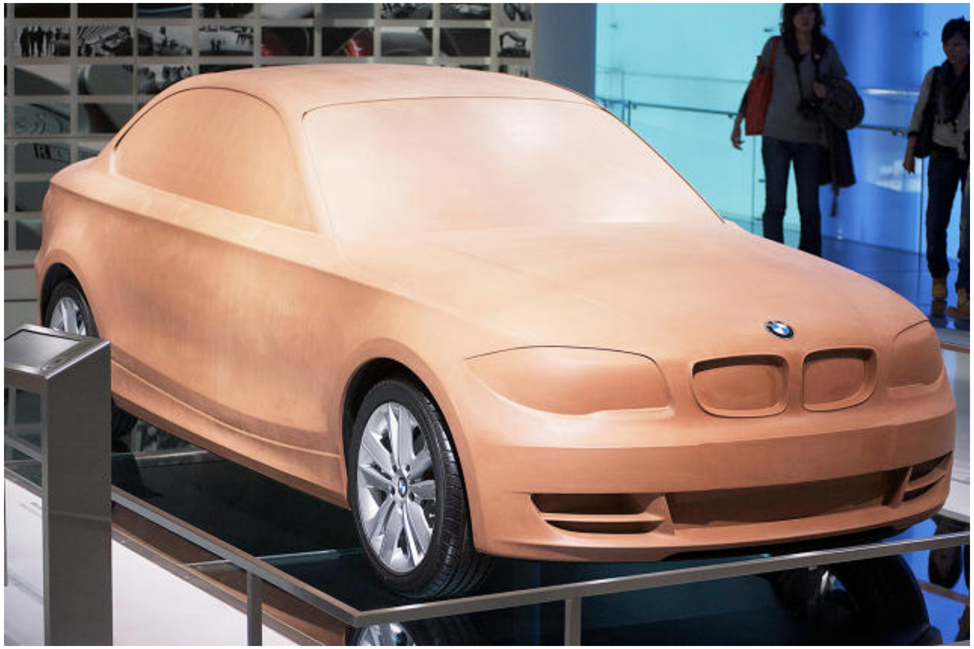
A model is an imperfect representation



Model of a Building



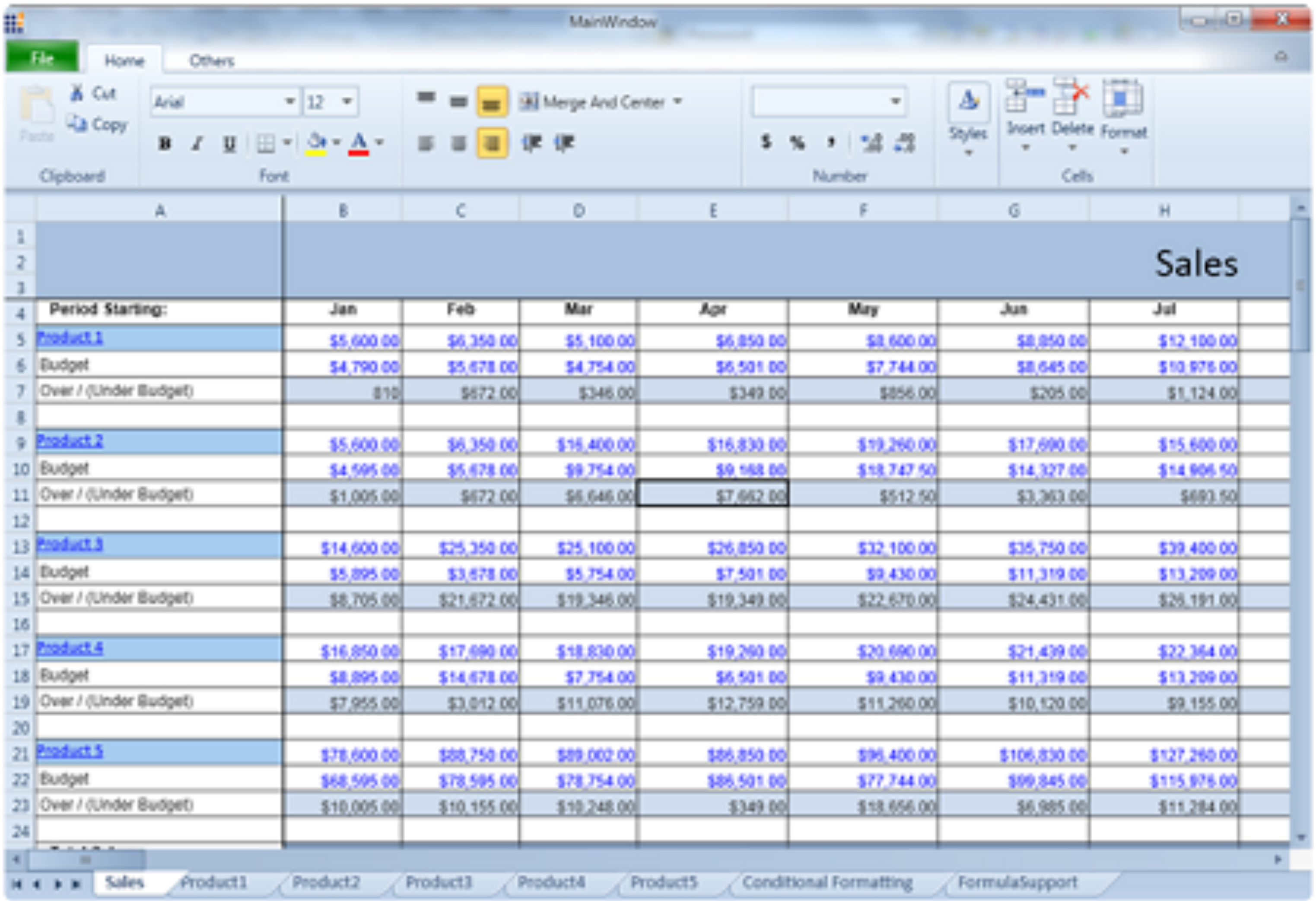
Models of a Car



Physical Model of San Francisco Bay

Numerical Model

Spreadsheet: 0 dimensions



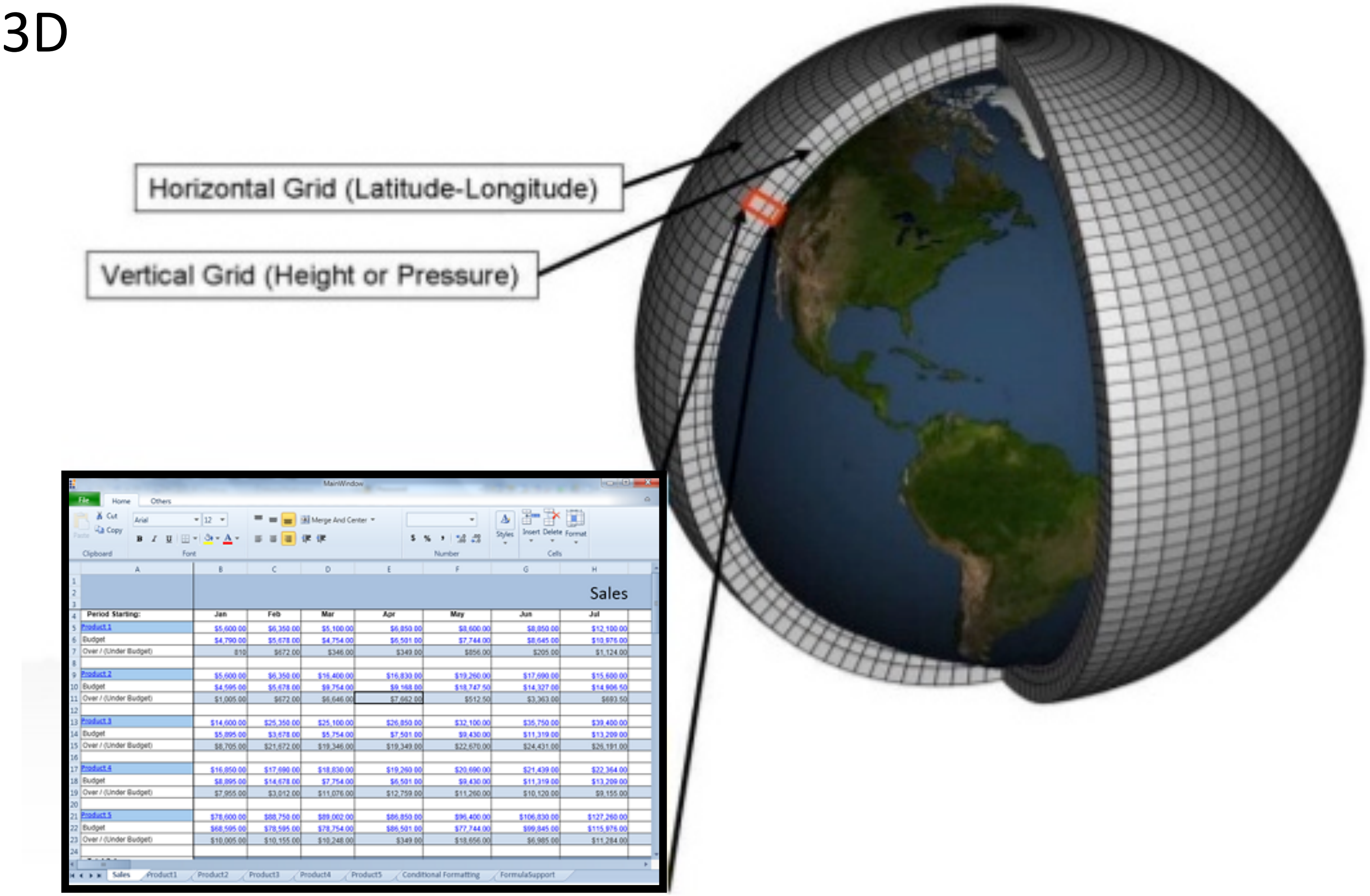
Period Starting:	Jan	Feb	Mar	Apr	May	Jun	Jul
Product 1	$5,600.00	$6,350.00	$5,100.00	$6,850.00	$8,600.00	$8,850.00	$12,100.00
Budget	$4,790.00	$5,678.00	$4,754.00	$6,501.00	$7,744.00	$8,645.00	$10,976.00
Over / (Under Budget)	810	$672.00	$346.00	$349.00	$856.00	$205.00	$1,124.00
Product 2	$5,600.00	$6,350.00	$16,400.00	$16,830.00	$19,260.00	$17,690.00	$15,600.00
Budget	$4,595.00	$5,678.00	$9,754.00	$9,168.00	$18,747.50	$14,327.00	$14,906.50
Over / (Under Budget)	$1,005.00	$672.00	$6,646.00	$7,662.00	$512.50	$3,363.00	$693.50
Product 3	$14,600.00	$25,350.00	$25,100.00	$26,850.00	$32,100.00	$35,750.00	$39,400.00
Budget	$5,895.00	$3,678.00	$5,754.00	$7,501.00	$9,430.00	$11,319.00	$13,209.00
Over / (Under Budget)	$8,705.00	$21,672.00	$19,346.00	$19,349.00	$22,670.00	$24,431.00	$26,191.00
Product 4	$16,850.00	$17,690.00	$18,830.00	$19,260.00	$20,690.00	$21,439.00	$22,364.00
Budget	$8,895.00	$14,678.00	$7,754.00	$6,501.00	$9,430.00	$11,319.00	$13,209.00
Over / (Under Budget)	$7,955.00	$3,012.00	$11,076.00	$12,759.00	$11,260.00	$10,120.00	$9,155.00
Product 5	$78,600.00	$88,750.00	$89,002.00	$86,850.00	$96,400.00	$106,830.00	$127,260.00
Budget	$68,595.00	$78,595.00	$78,754.00	$86,501.00	$77,744.00	$99,845.00	$115,976.00
Over / (Under Budget)	$10,005.00	$10,155.00	$10,248.00	$349.00	$18,656.00	$6,985.00	$11,284.00

What is a Weather/Climate Model?

A numerical model of budgets (mass, energy)

Governed by equations (physical Laws)

Points in 3D

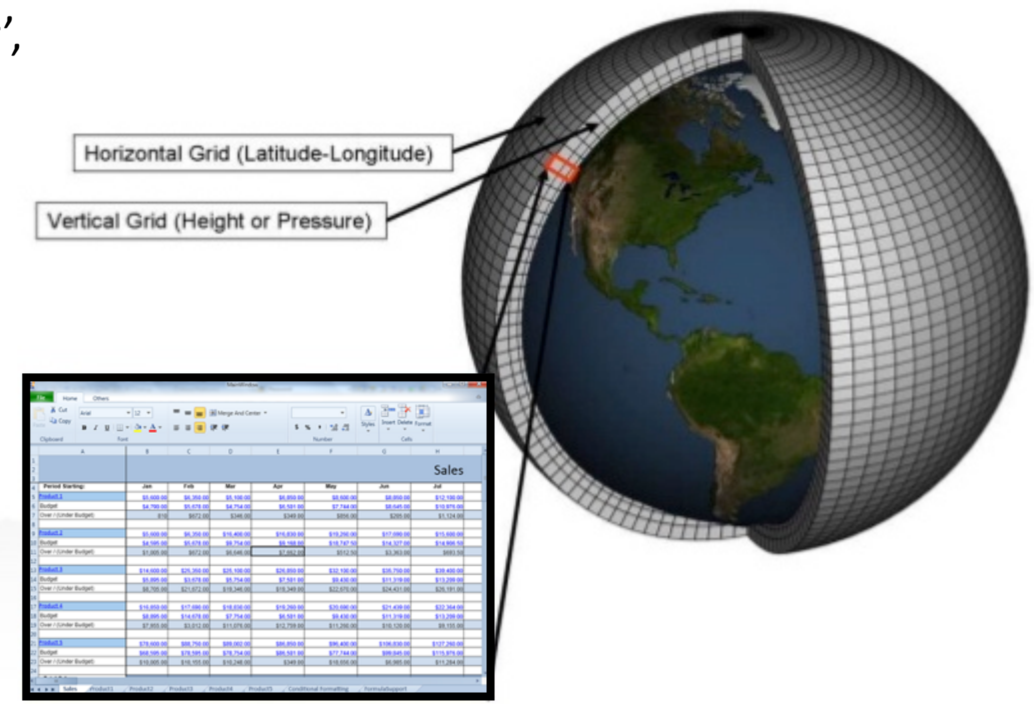


Earth System Modeling

An accounting exercise constrained by physical laws

How does a geophysical model work?

- A giant spreadsheet. Entries for ‘water’, ’heat’, ‘salt’, ‘carbon’, ‘wind’
- Account for each process in each box (water in a cloud)
- Solve process equations each point
- Advance in time (and move variables around in space)
- Repeat



Common Problems:

- Processes hard to describe at the right scale (imperfect)
- Need to derive physical laws at the right scale (need observations)

This defines a finite element model of a physical system

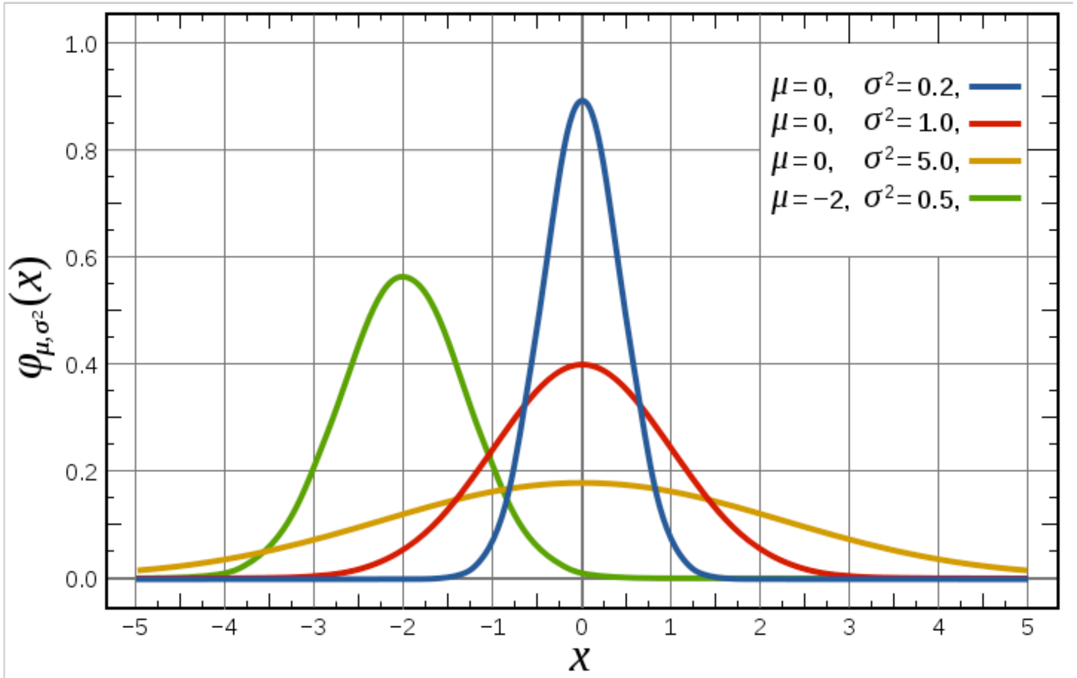
Weather v. Climate Modeling

Climate is what you Expect, Weather is what you get

- Climate = distribution of possible weather (probability)
- Weather = Chaos
  - Chaos theory developed by a meteorologist (Ed Lorenz, 1961)
  - Simple model to explain why the weather is not predictable

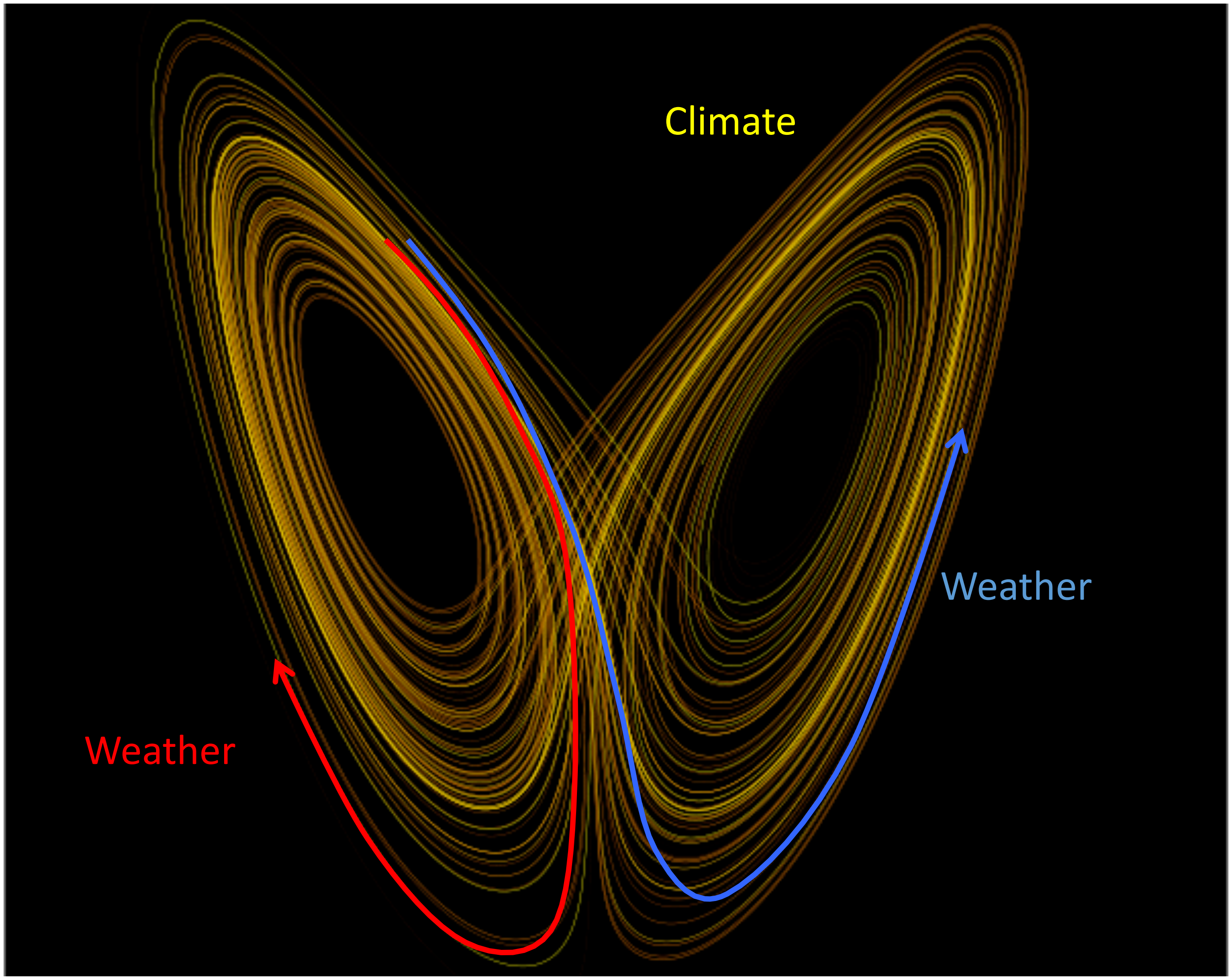
Weather: Initial conditions critical
Climate: Independent of initial conditions

Note: 'mean' of Blue, Red and Yellow distributions are the same, but climate is different



Chaos Theory: Lorenz Attractor

Pattern (climate) is stable
Nearby trajectories can be different (weather)



NCAR Community Models

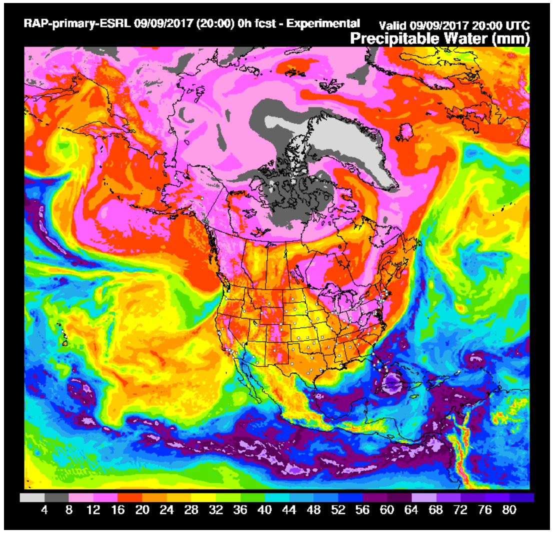
What is ‘available’ Now

Community = Released and Supported

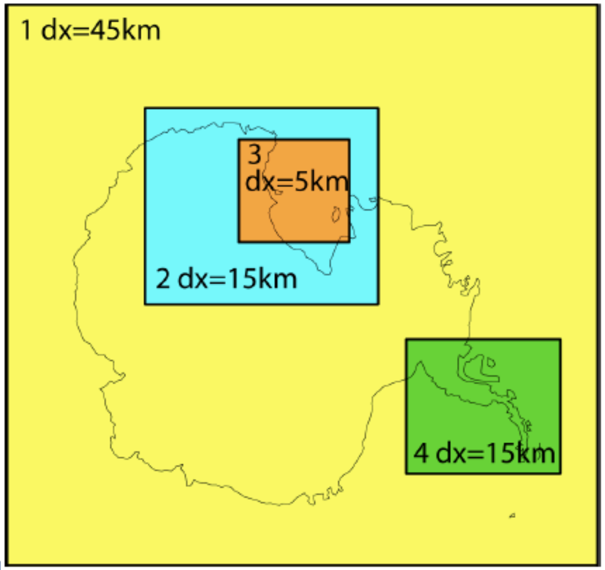
- WRF: Weather, Air Pollution
- CESM: Climate, Chemistry, Carbon, Land
- WACCM-X: Space Weather
- Hydrology Modeling
- Integrated Assessment
- Analysis Tools

Weather Research & Forecast Model

- Limited Area Mesoscale Model
- ARW and NMM dynamical cores
- Data Assimilation options (nudged)
- Wide array of available physical parameterizations
- Nesting possible
- Used for Research and Forecasting



WRF – RAP 15km
Real Time Forecast
(Total Column H_2O)

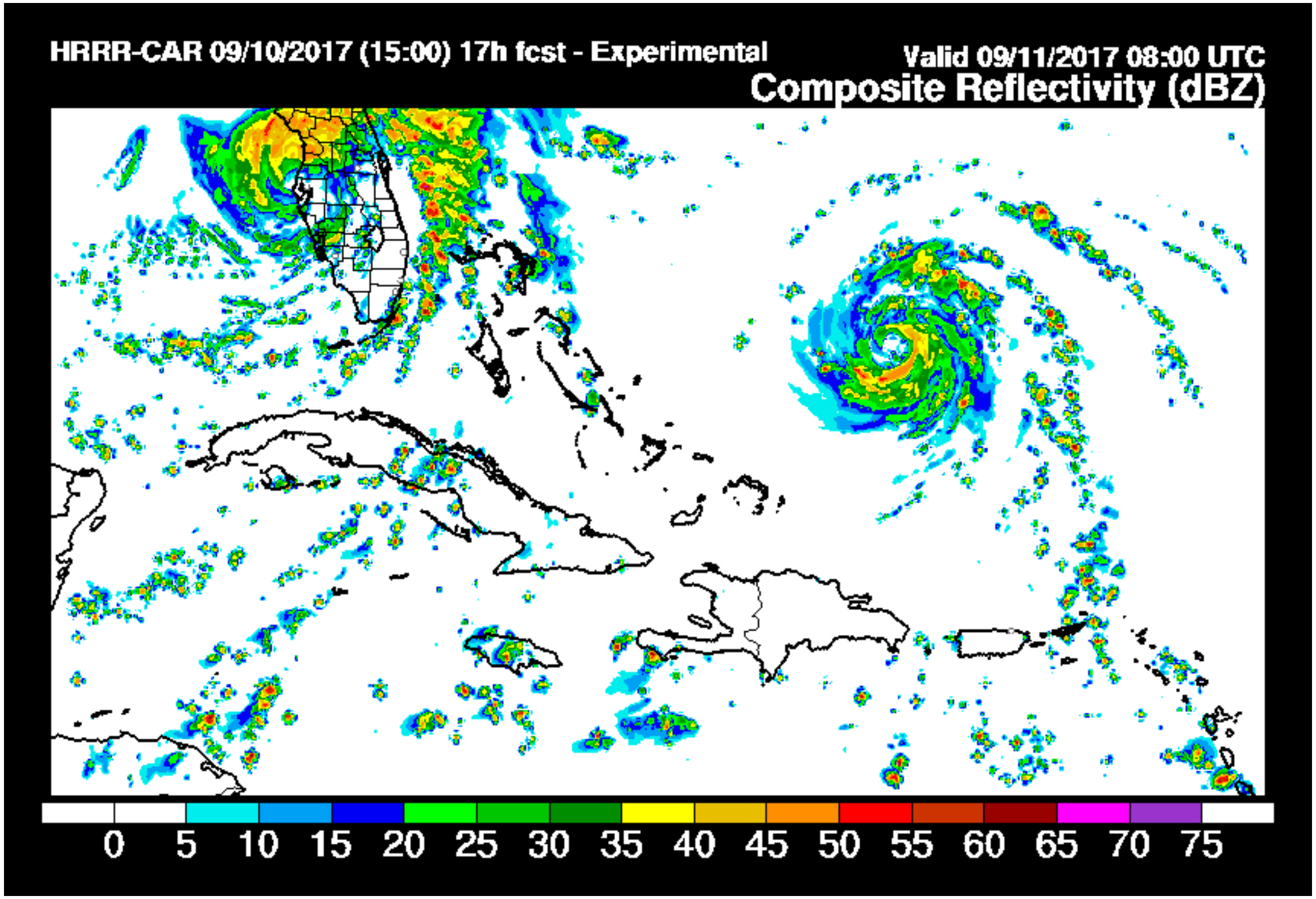


WRF Nested Grids for Antarctica

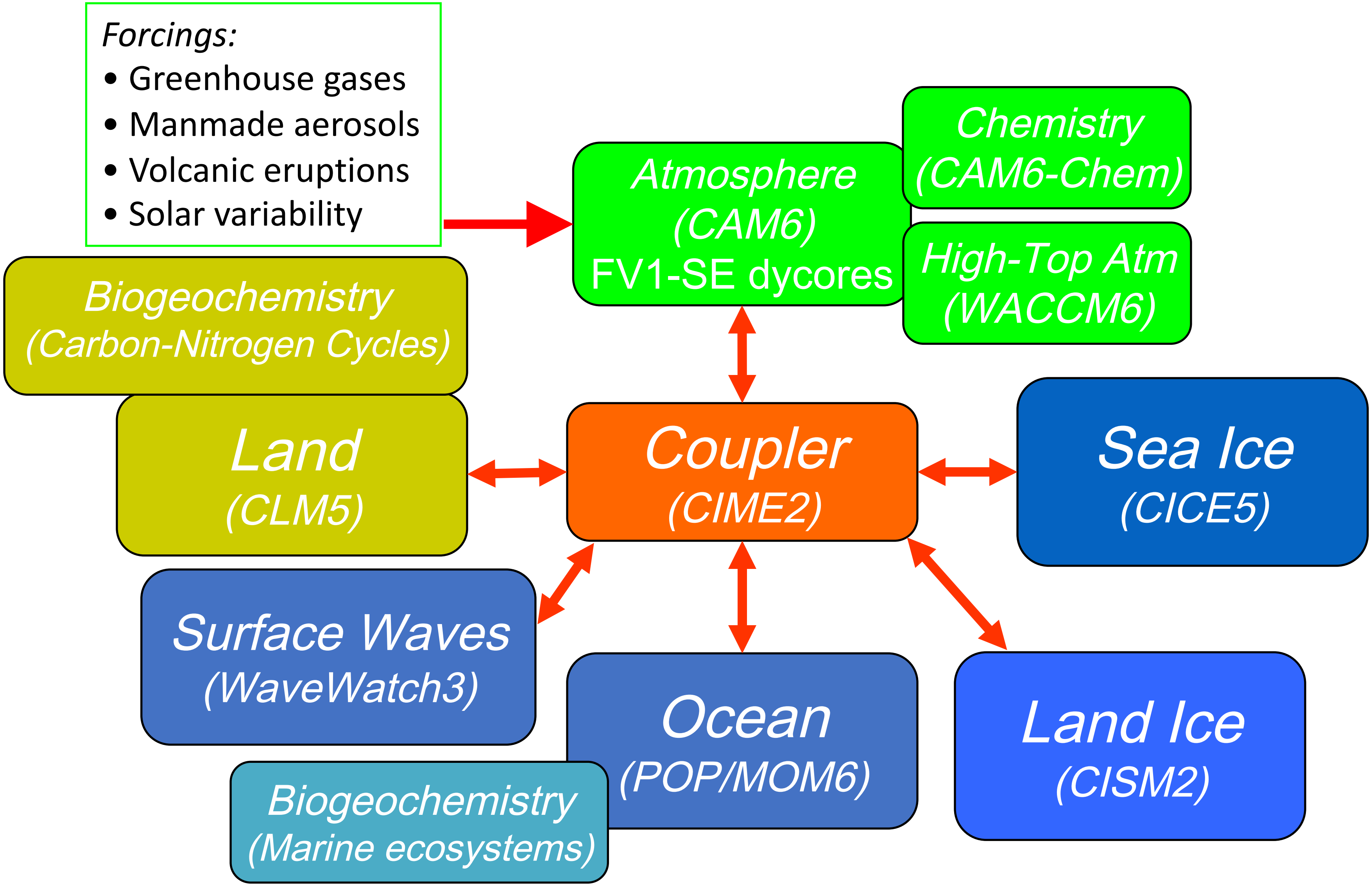
Weather Research & Forecast Model

Used extensively for NWP around the world

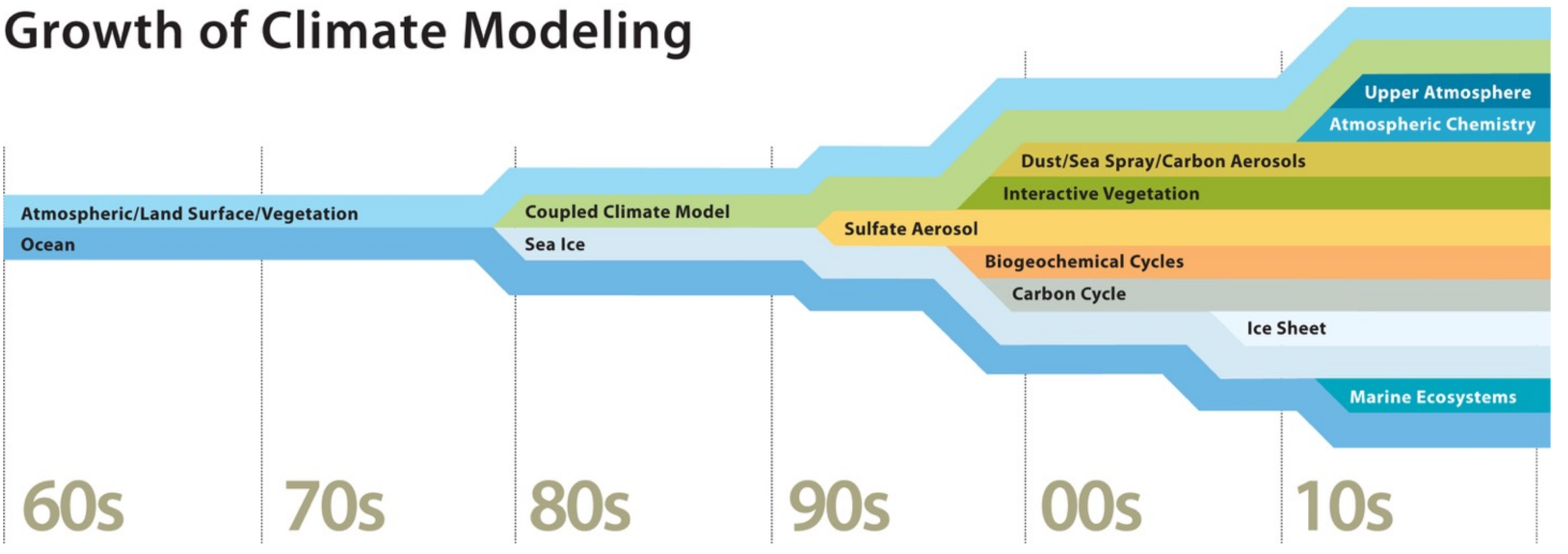
- High-Resolution Rapid Refresh (HRRR) model: 3km over US. Modified WRF with data assimilation
- Example: 17 hr forecast for now



Community Earth System Model



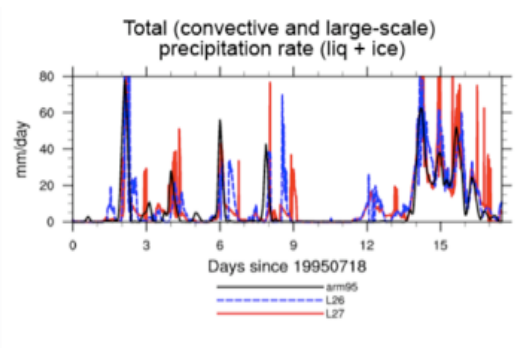
ESMs: Adding Complexity



CESM supports a range of climate science goals through a *Single Model Code Base*

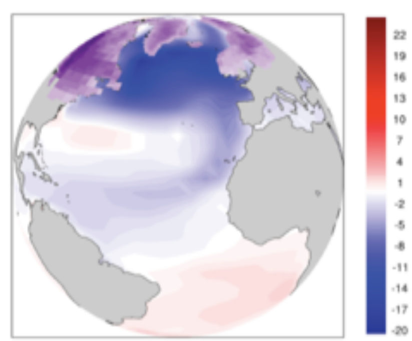
Desktop

Single column/
Coarse resolution:
Physics development

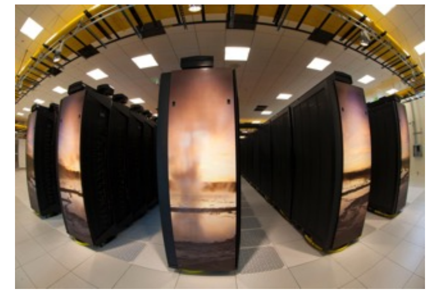


Small cluster

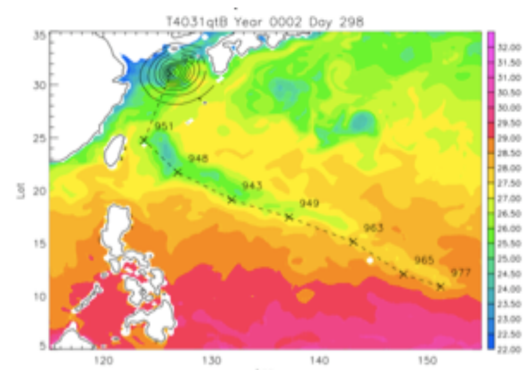
Lower resolution:
Paleo/Large Ensemble
University research



HPC

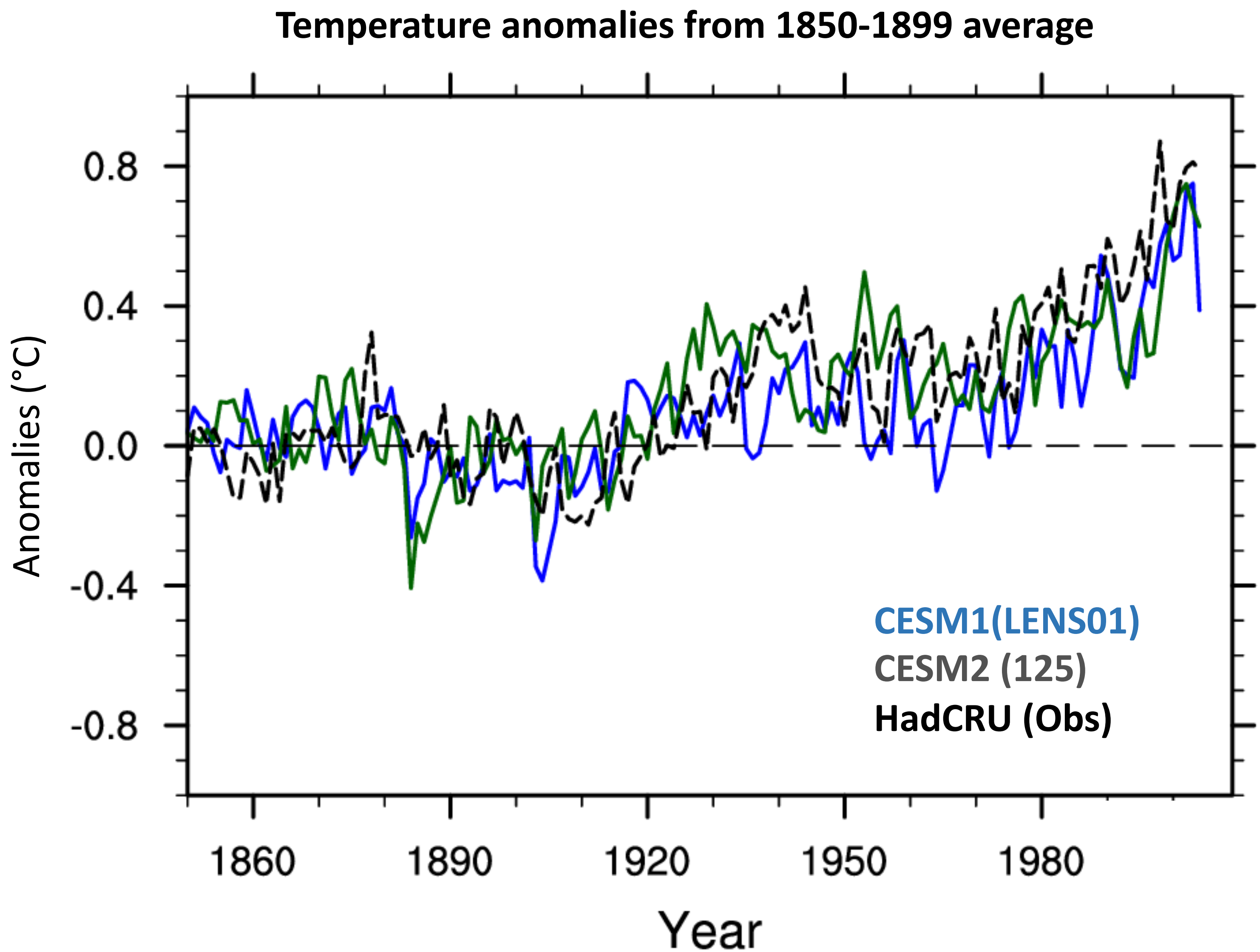


Higher resolution:
CMIP
Breakthrough Science

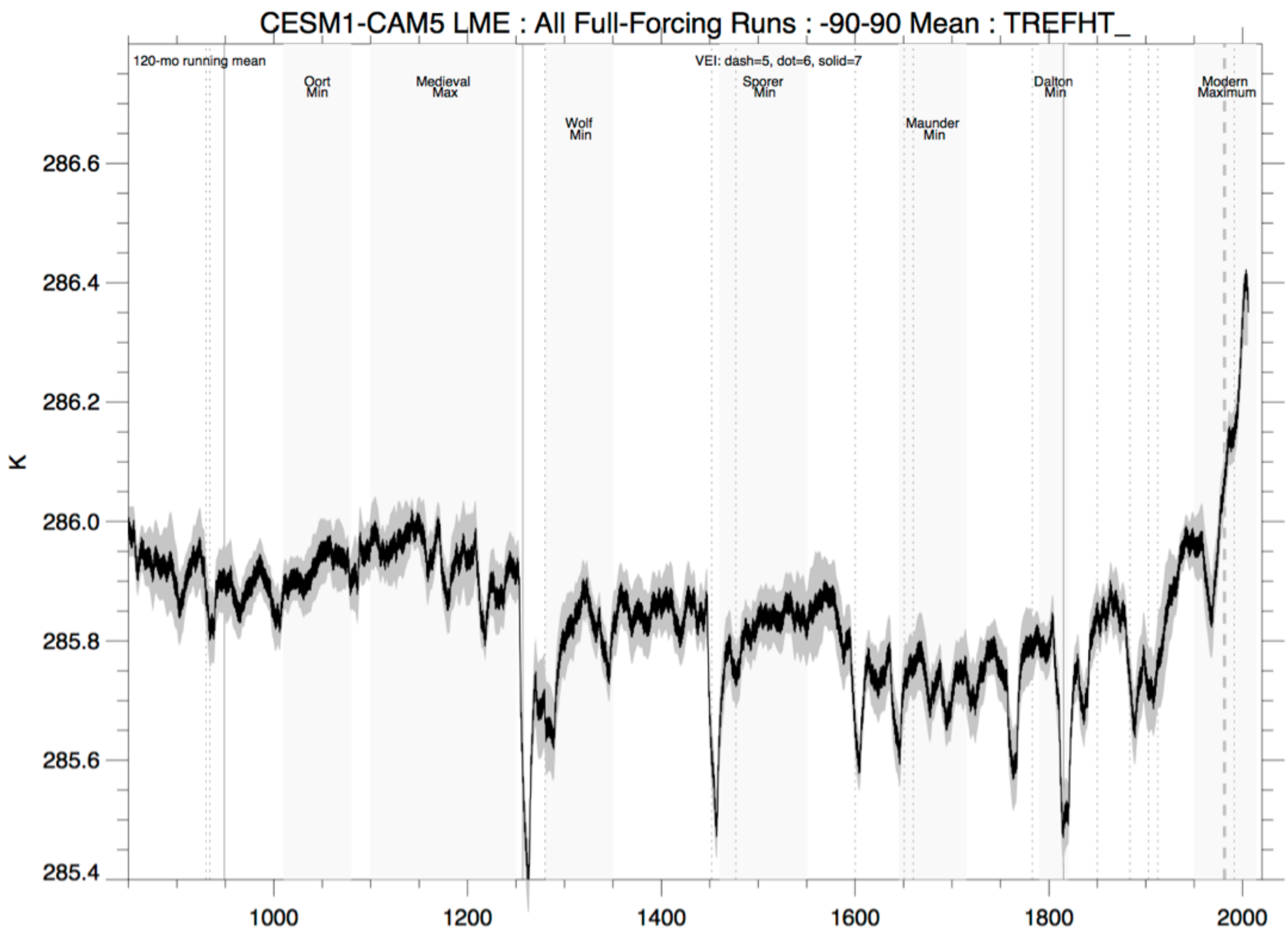


CESM1,CESM2α

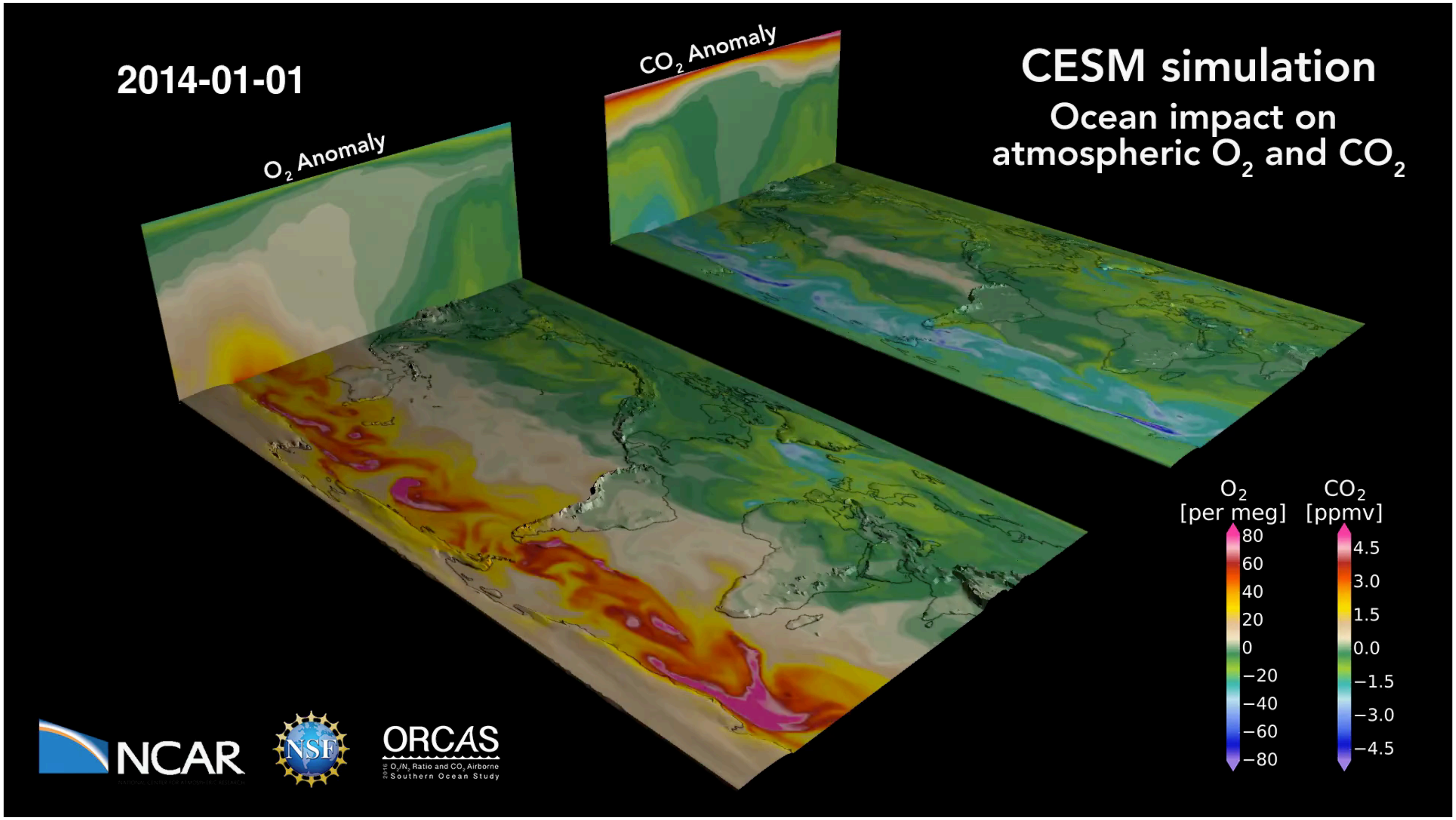
20[th] Century Global T_s Anomalies



Last Millennium, CESM1 860-2010

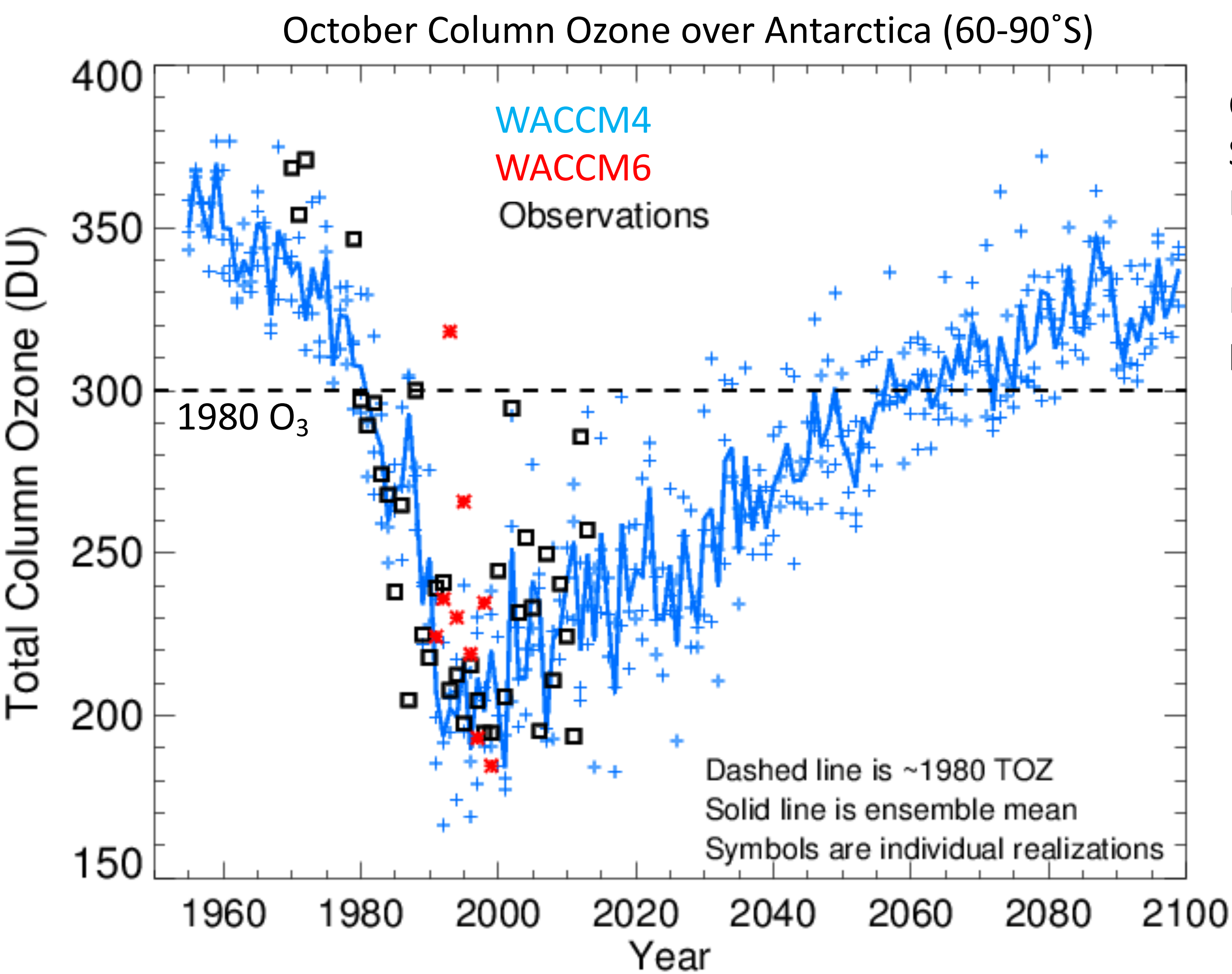


CESM Coupled Carbon Cycle



Movie from M. Long and T. Scheitlin

WACCM: CESM with Chemistry
Monitoring and Predicting the Ozone Hole



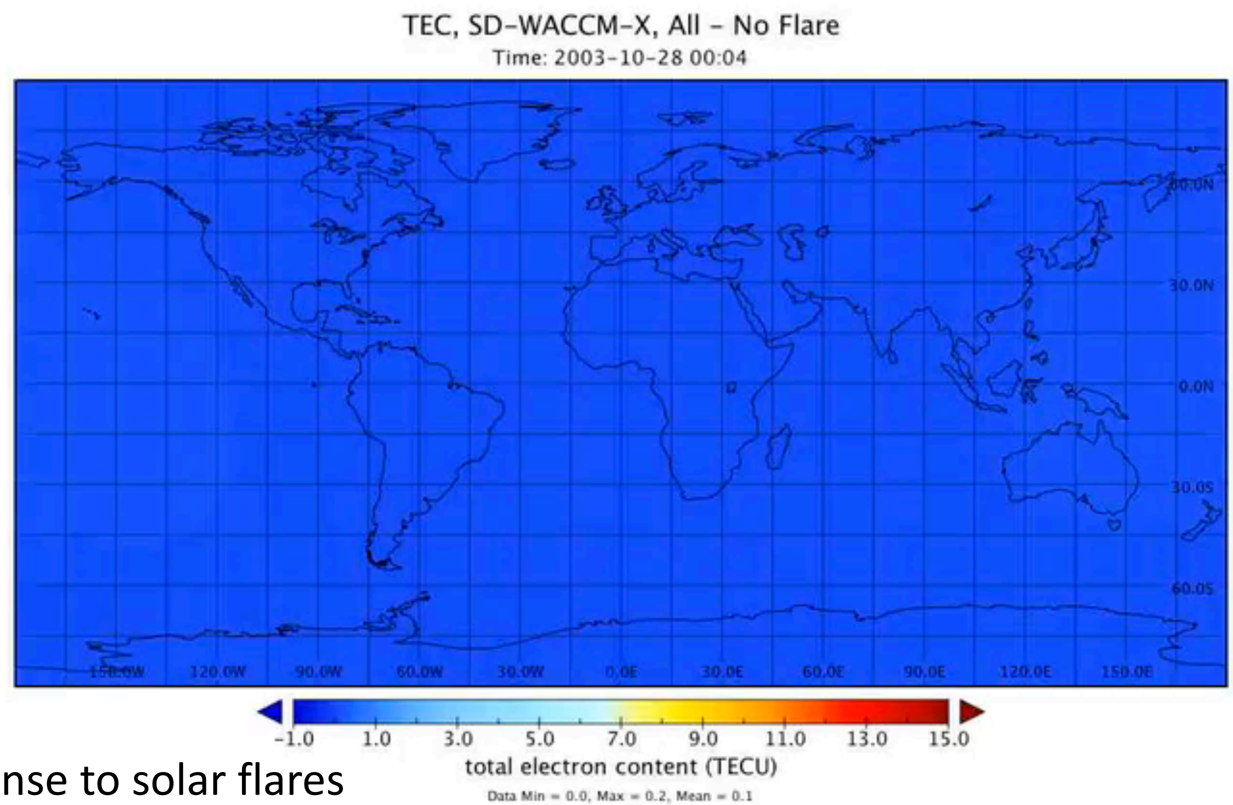
CESM + Chemistry + Stratosphere & Mesosphere

Key part of chemical prediction

Space Weather (WACCM-X)

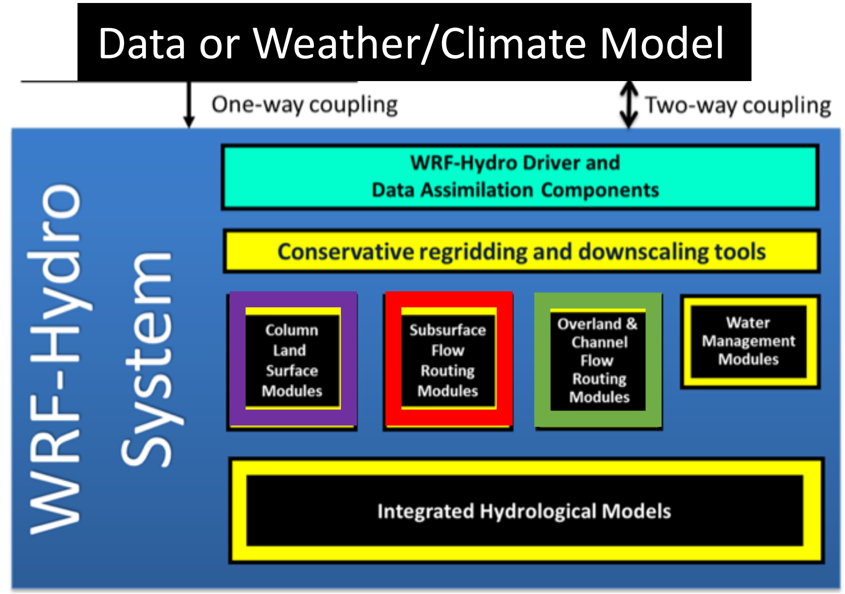
Whole Atmosphere Community Climate Model-eXtended

- Coupled WACCM (CESM+ Chemistry)
- Include thermosphere-ionosphere model (TIE-GCM)
- Represent surface to 500km

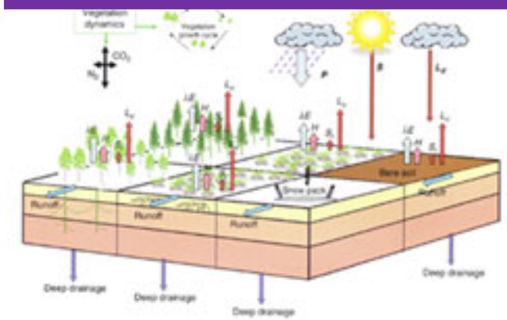


WACCM-X Ionosphere:
total electron content response to solar flares

Hydrology Modeling
WRF: Land Surface + Hydro

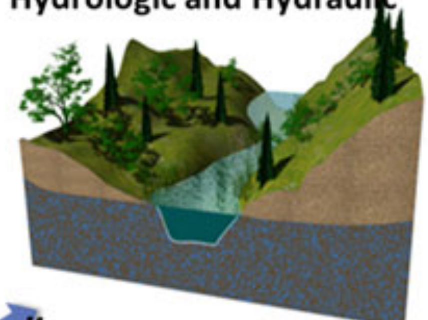


Column Land Surface Models:



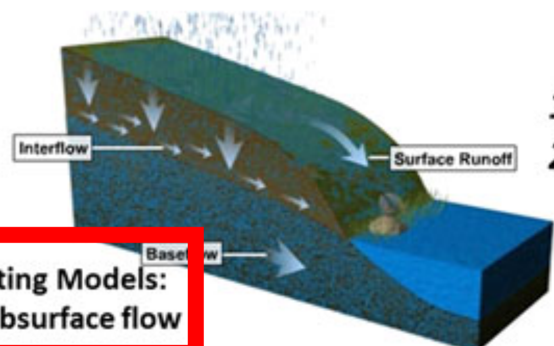
Output Variables:
Evapotranspiration
Soil moisture/Soil Ice
Snowpack/snowmelt
Runoff
Radiation Exchange
Energy Fluxes
Plant Water Stress

Channel & Reservoir Routing Models:
Hydrologic and Hydraulic



Output Variables:
Streamflow
River Stage
Flow Velocity
Reservoir Storage
& Discharge

2-way coupling



1-way coupling or 2-way coupling

Terrain Routing Models: Overland, subsurface flow

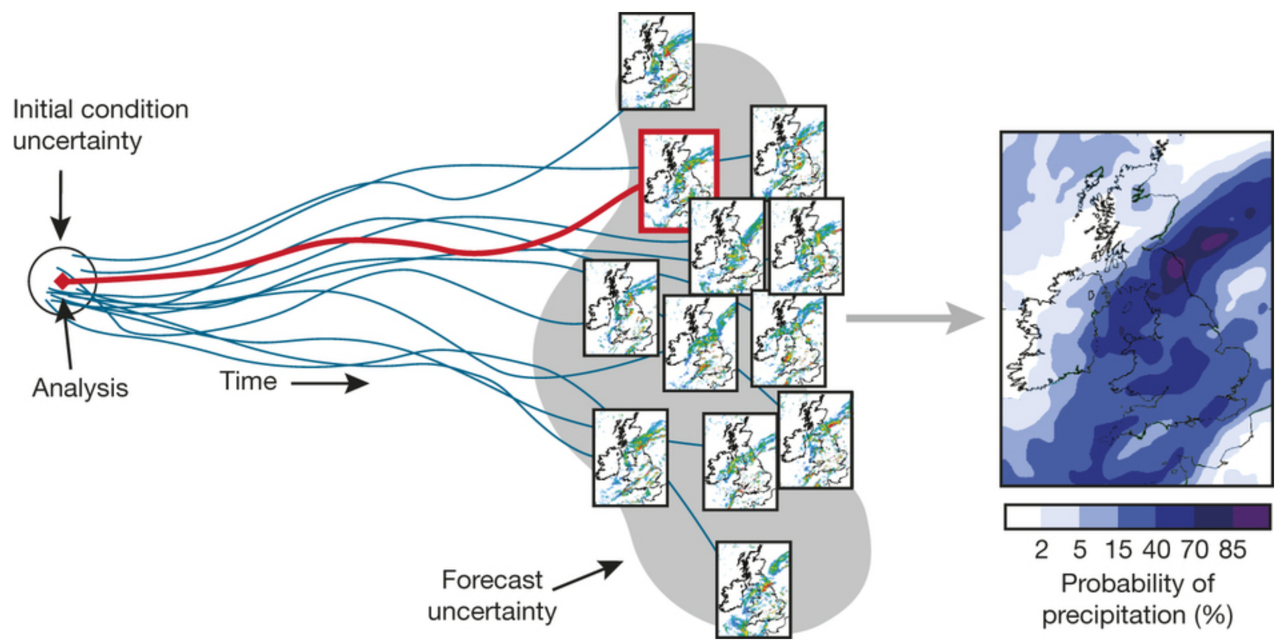
Output Variables:
Stream Inflow, Surface Water Depth, Groundwater Depth, Soil Moisture

Data Assimilation
’Initialized’ Forecast Experiments

- WRF-DA: Community DA system
- DART: NCAR Based Ensemble Kalman Filter (CESM)

Assimilation Schematic

DART
- Run Ensemble members
- Compare to Observations
- Find Increments
- Apply increments
- Repeat



Elements of Community Modeling

- Software Engineering: Robust frameworks
- Portability (different architectures)
- Analysis: Community Data (Climate Data Guide)
- Diagnostic Tools (Climate Variability, Diagnostics), CMIP6 analysis framework
- Infrastructure: Hardware and Data systems (PIO, storage). [Dave Hart talk later in the week]
- Community Governance
- Community Development (WRF, CESM examples; community develops)

Software/Infrastructure Support

- NCAR Professional software engineers
  - Groups ‘embedded’ close to scientists
- Software Engineering (design)
  - Strive for ‘robust’ code, robust compile and run scripts
- Frameworks and APIs
  - Defined interfaces
- Code management
  - Repositories, moving towards open source
- Testing
  - Verification Testing, basic bug testing, run testing
- Portability
  - Verification, Testing on different machines, compliers
  - Support for different architectures limited

NCAR UCAR **ClimateDataGuide** *inform • compare • discover*

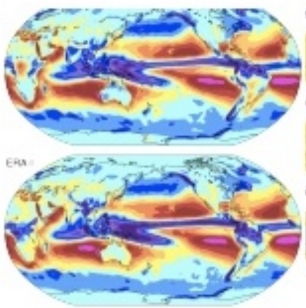
CLIMATE DATA | ANALYSIS TOOLS | MODEL EVALUATION | EXPERT CONTRIBUTORS | ABOUT | Site-wide Search >>

Data Discovery Guided by Experts > >

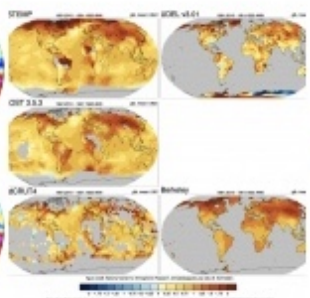
Search and access 194 data sets covering the Atmosphere, Ocean, Land and more. Explore climate indices, reanalyses and satellite data and understand their application to climate model metrics. This is the only data portal that combines data discovery, metadata, figures and world-class expertise on the strengths, limitations and applications of climate data. Discover it now.

Data Set Overviews > >

Compare the attributes, strengths and limitations of multiple data sets.

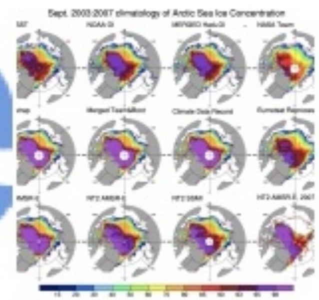


Atmospheric Reanalysis: Overview & Comparison Tables



Global Temperature Data Sets: Overview & Comparison Table

Precipitation Data Sets: Overview & Comparison table



Sea Ice Concentration data: Overview, Comparison table and graphs

68
data experts have contributed to the Climate Data Guide

JOIN US

Multiply the impact of your work by announcing new data sets and sharing your knowledge of the strengths, limitations and applications of particular data sets.

Ways to make an impact

Become a registered user of this site

Contribute a data set & assessment

Post a comment to any data set page

https://climatedataguide.ucar.edu/

Community Model Diagnostics

Example:
Atmosphere

Set Description

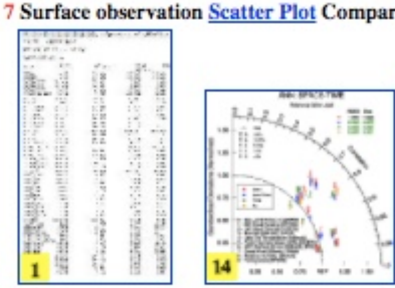
1 Tables of ANN, DJF, JJA, global and regional means and RMSE.
2 Line plots of annual implied northward transports.
3 Line plots of DJF, JJA and ANN zonal means
4 Vertical contour plots of DJF, JJA and ANN zonal means
4a Vertical (XZ) contour plots of DJF, JJA and ANN meridional means
5 Horizontal contour plots of DJF, JJA and ANN means
6 Horizontal vector plots of DJF, JJA and ANN means
7 Polar contour and vector plots of DJF, JJA and ANN means
8 Annual cycle contour plots of zonal means
9 Horizontal contour plots of DJF-JJA differences
10 Annual cycle line plots of global means
11 Pacific annual cycle, Scatter plot plots
12 Vertical profile plots from 17 selected stations
13 Cloud simulators plots
14 Taylor Diagram plots
15 Annual Cycle at Select Stations plots
16 Budget Terms at Select Stations plots

WACCM Set Description

1 Vertical contour plots of DJF, MAM, JJA, SON and ANN zonal means (vertical log scale)

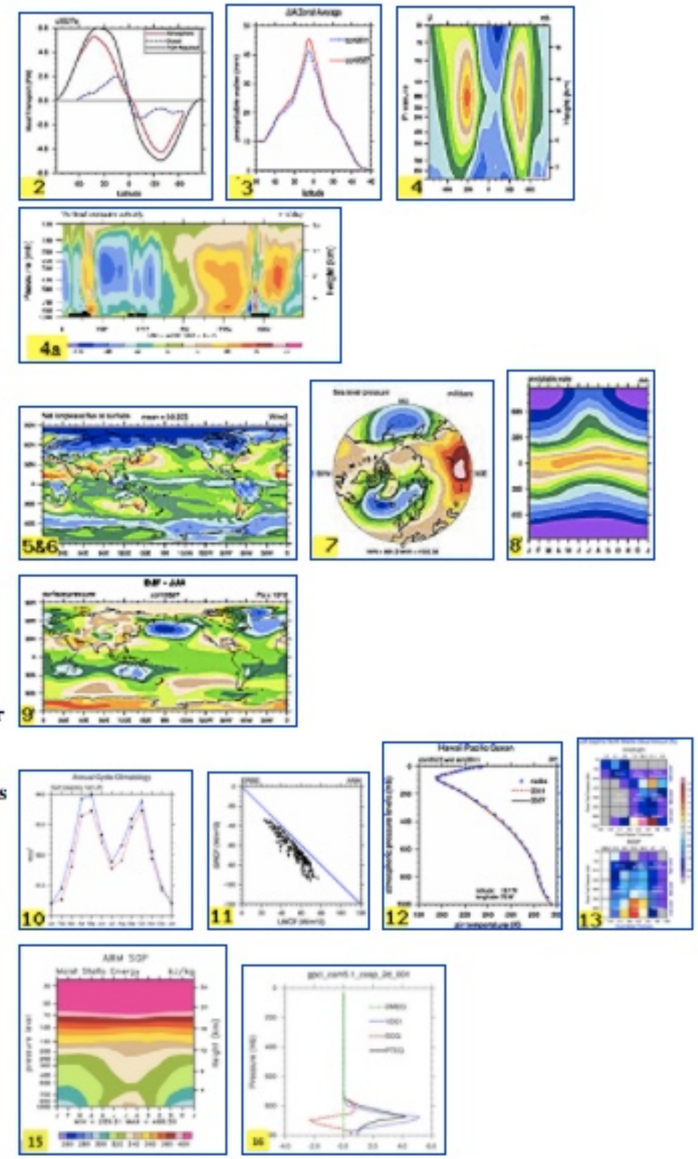
Chemistry Set Description

1 Tables / Chemistry of ANN global budgets
2 Vertical Contour Plots contour plots of DJF, MAM, JJA, SON and ANN zonal means
3 Ozone Climatology Comparisons Profiles, Seasonal Cycle and Taylor Diagram
4 Column O3 and CO lon/lat Comparisons to satellite data
5 Vertical Profile Profiles Comparisons to NOAA Aircraft observations
6 Vertical Profile Profiles Comparisons to Emmons Aircraft climatology
7 Surface observation Scatter Plot Comparisons to IMROVE



TABLES METRICS

Click on Plot Type



Community Infrastructure

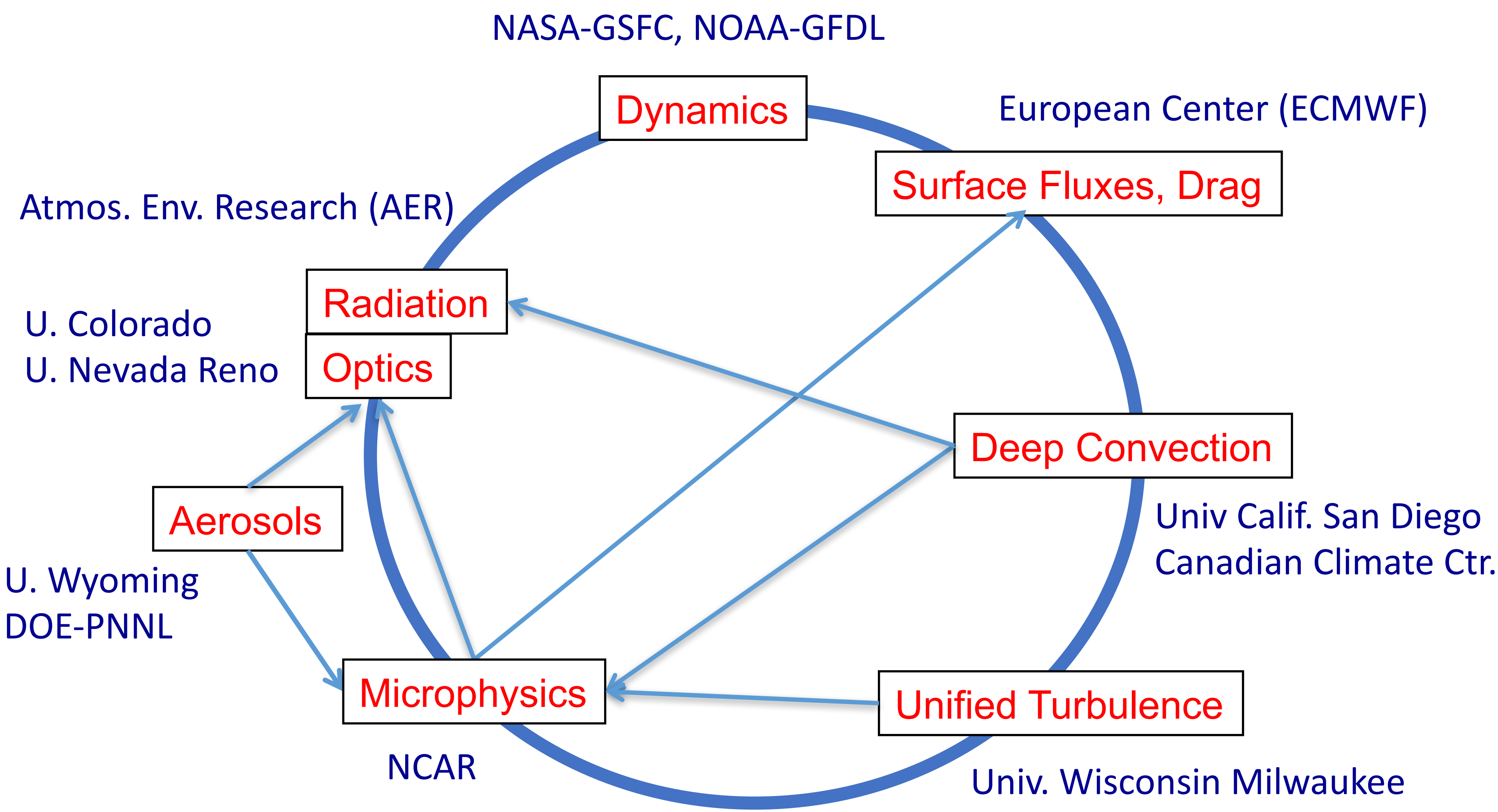
- Earth System Grid
  - Sharing model data with the community
- CMIP6 Analysis Server
  - Host model output for the community
  - Prototype for CMIP5
  - See discussion later in the week
- Community Tutorials (Human Infrastructure)
  - CESM = 80 scientists/students
  - WRF = 2x80 scientists/students
  - On line tutorials as well

Community Model Governance

Community Development

Community Atmosphere Model (CAM6)

Code from many different collaborators



Towards a Unified Framework

Now and Next Steps

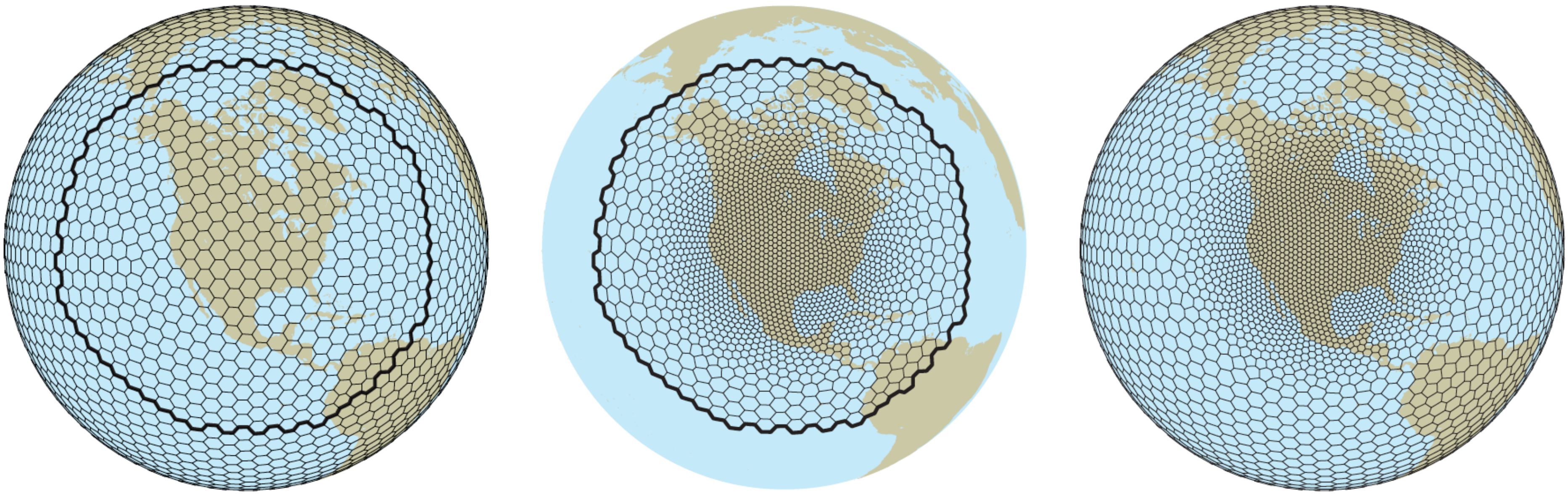
- MPAS + WRF: more flexibility for weather
- High Resolution CESM: Variable Mesh
- CESM-MPAS: Weather to climate
- WACCM-X Space Weather in the same system
- Community Terrestrial Systems Model
- CIME: common framework for modeling & Interoperable physics
- Unifying pieces (Chemistry, Clouds, Land)

MPAS
Model for Prediction Across Scales

Los Alamos NATIONAL LABORATORY EST. 1943

U.S. DEPARTMENT OF ENERGY | Office of Science

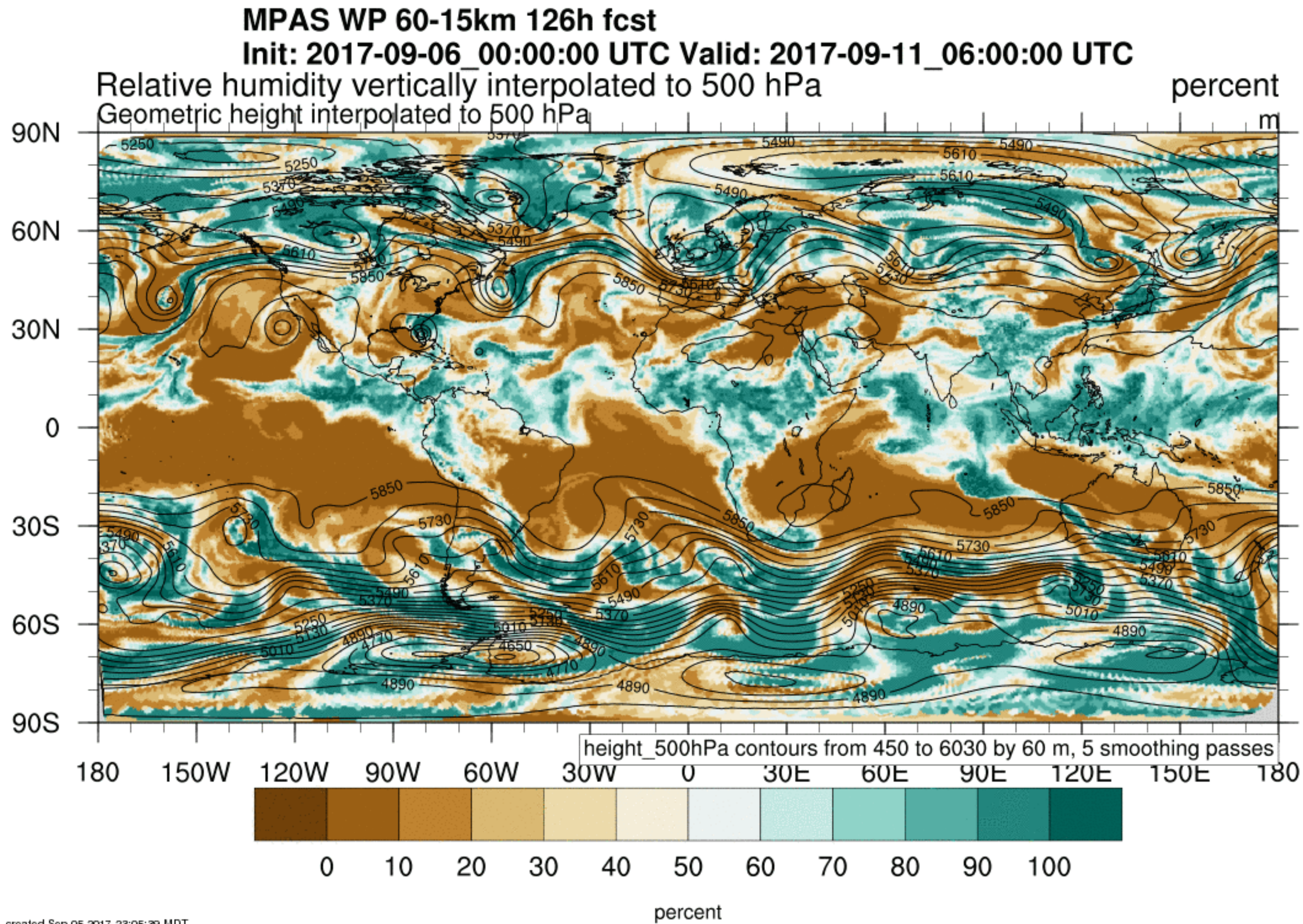
UNIFORM **REGIONAL** **VARIABLE**



MPAS: Next Generation Dynamical Core (Variable Mesh)
Coupled to limited sets (suites) of physical parameterizations
Usually run in global mode, with a variable (not nested) mesh
Typically refined mesh is a ‘mesoscale’ (3-20km)
Use parameterization methods from the mesoscale (WRF)

MPAS: Forecasts

5 day forecast for now. Initialized Thursday, 0Z.   60km with 15km over U.S.
Lines= 500hPa Geopotential Height, Colors: 500hPa Relative humidity



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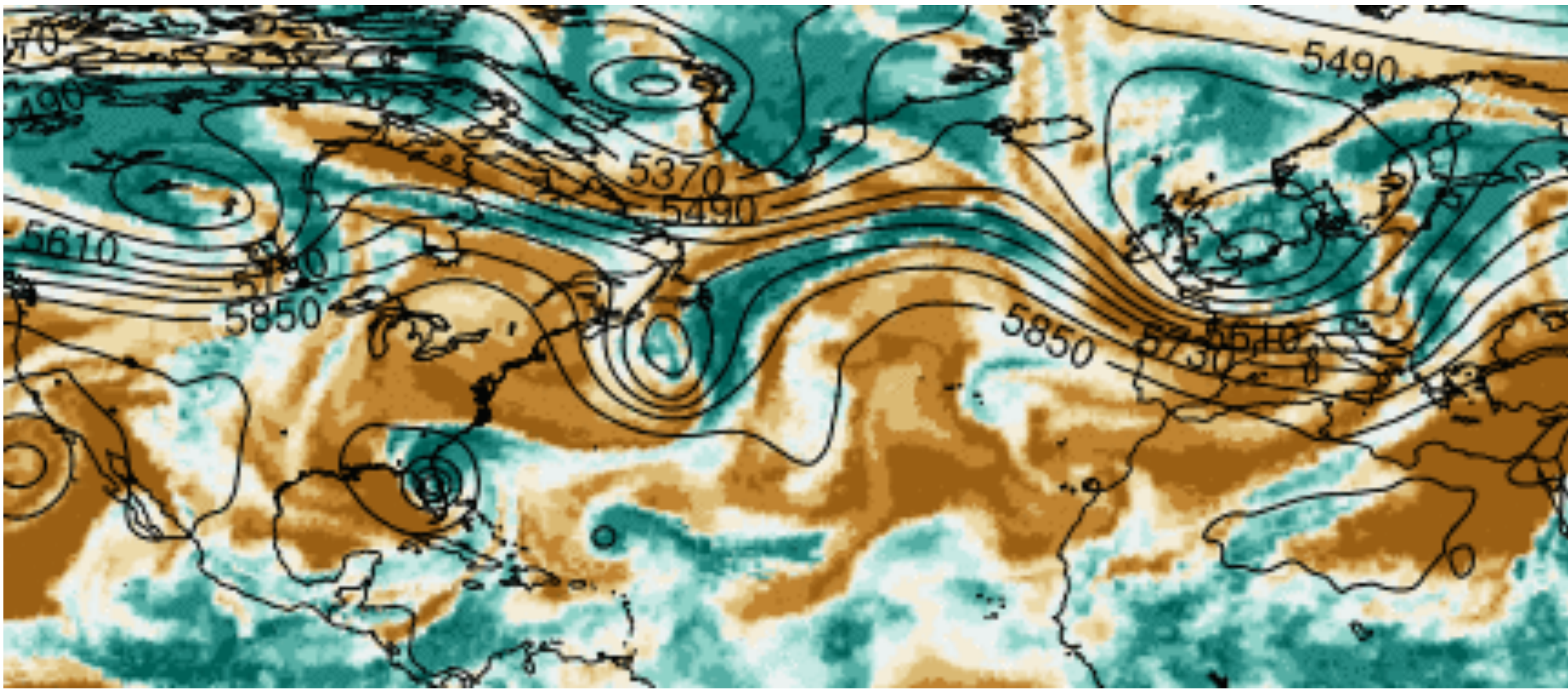
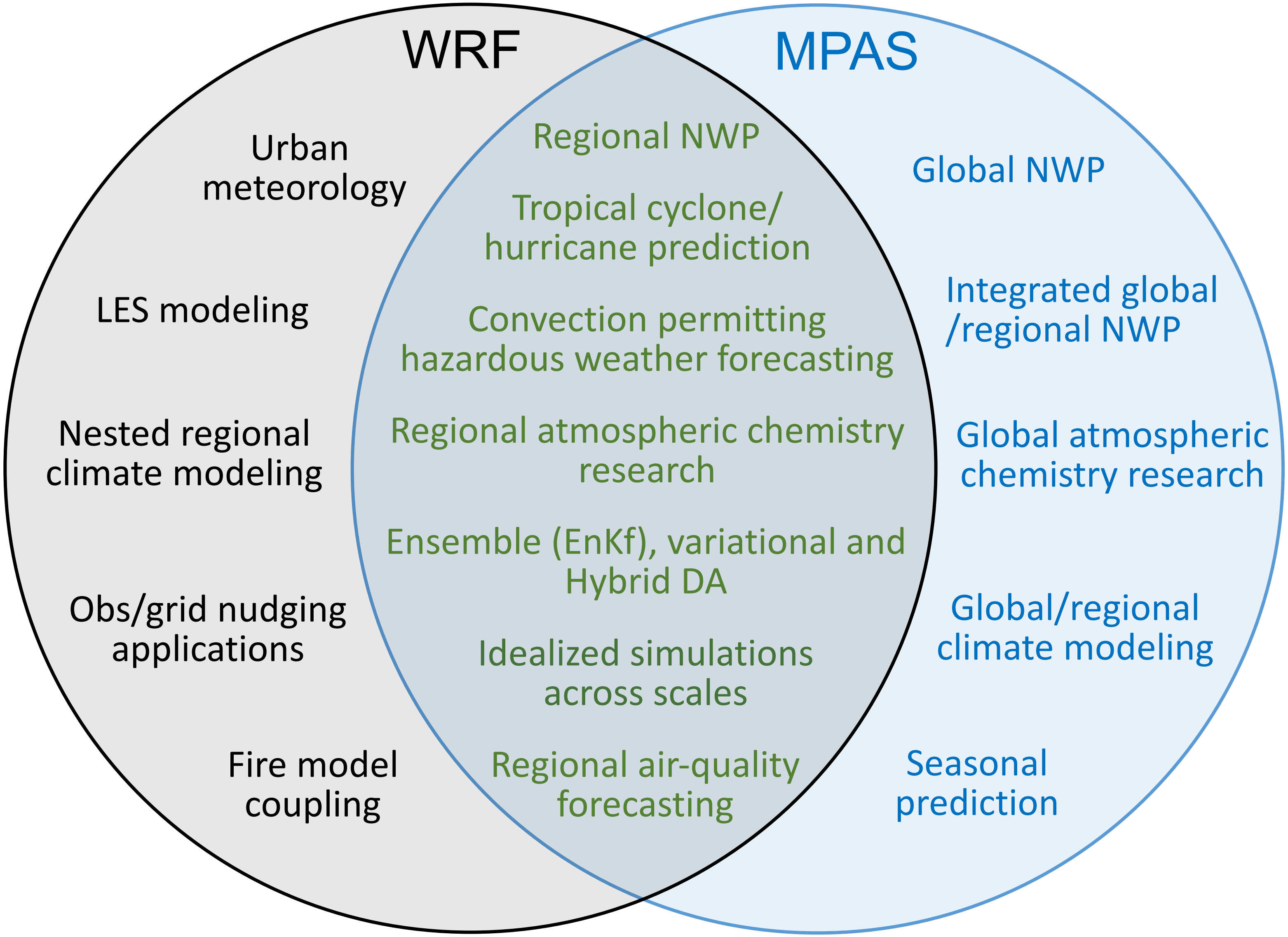


Irma | Annecy

WRF and MPAS Development Plans



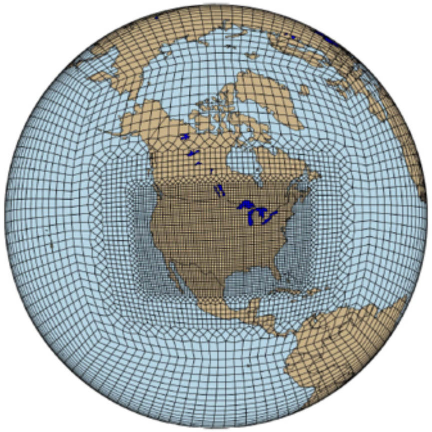
Goal: Common Physics and DA & Common Code Repository (and development) for WRF, MPAS

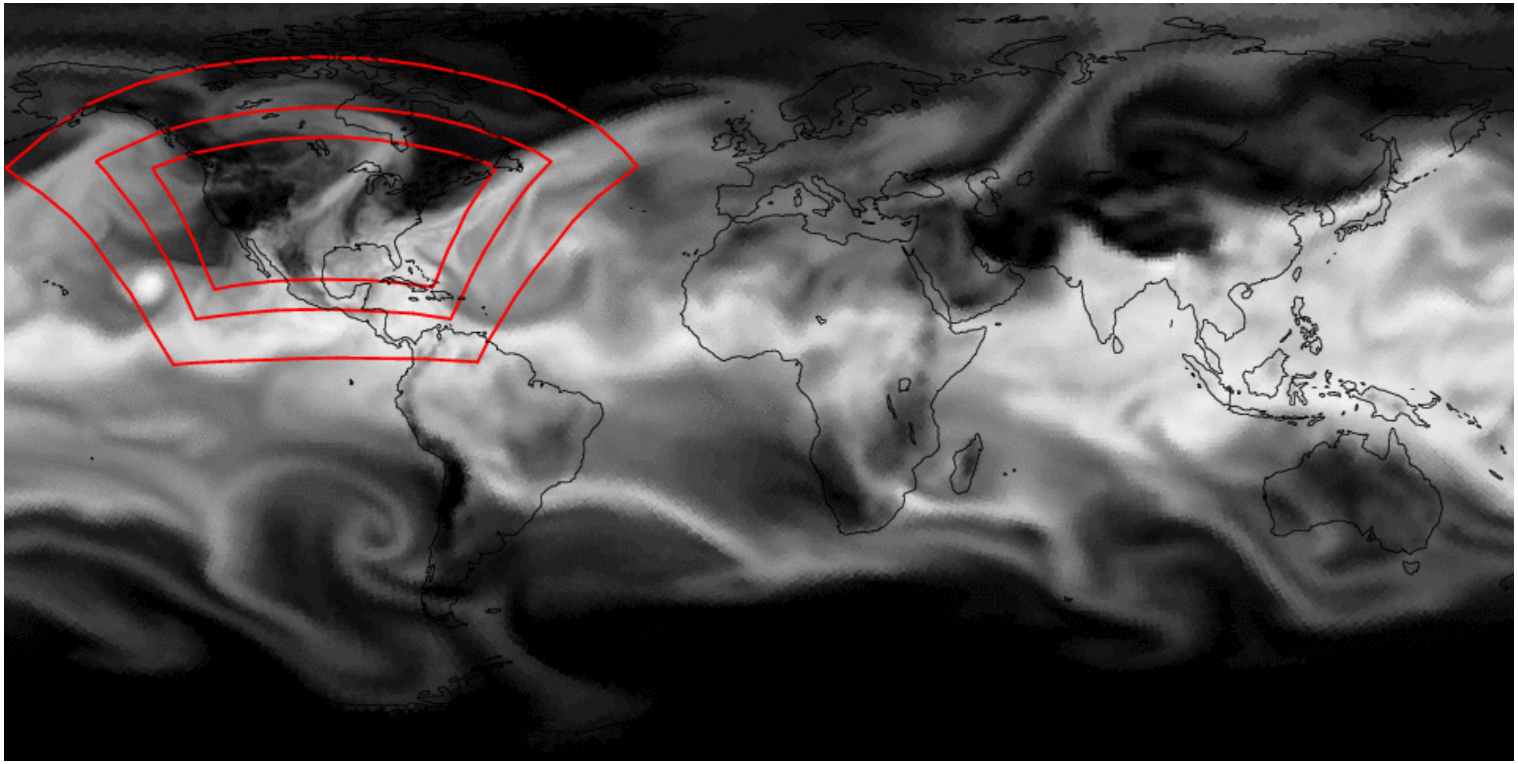
CESM

Regional refinement to the Mesoscale

Regional-refinement in CAM6 (AMIP) with the Spectral Element (SE) and MPAS dynamical cores

Testing down to 3km over US (here 14km)

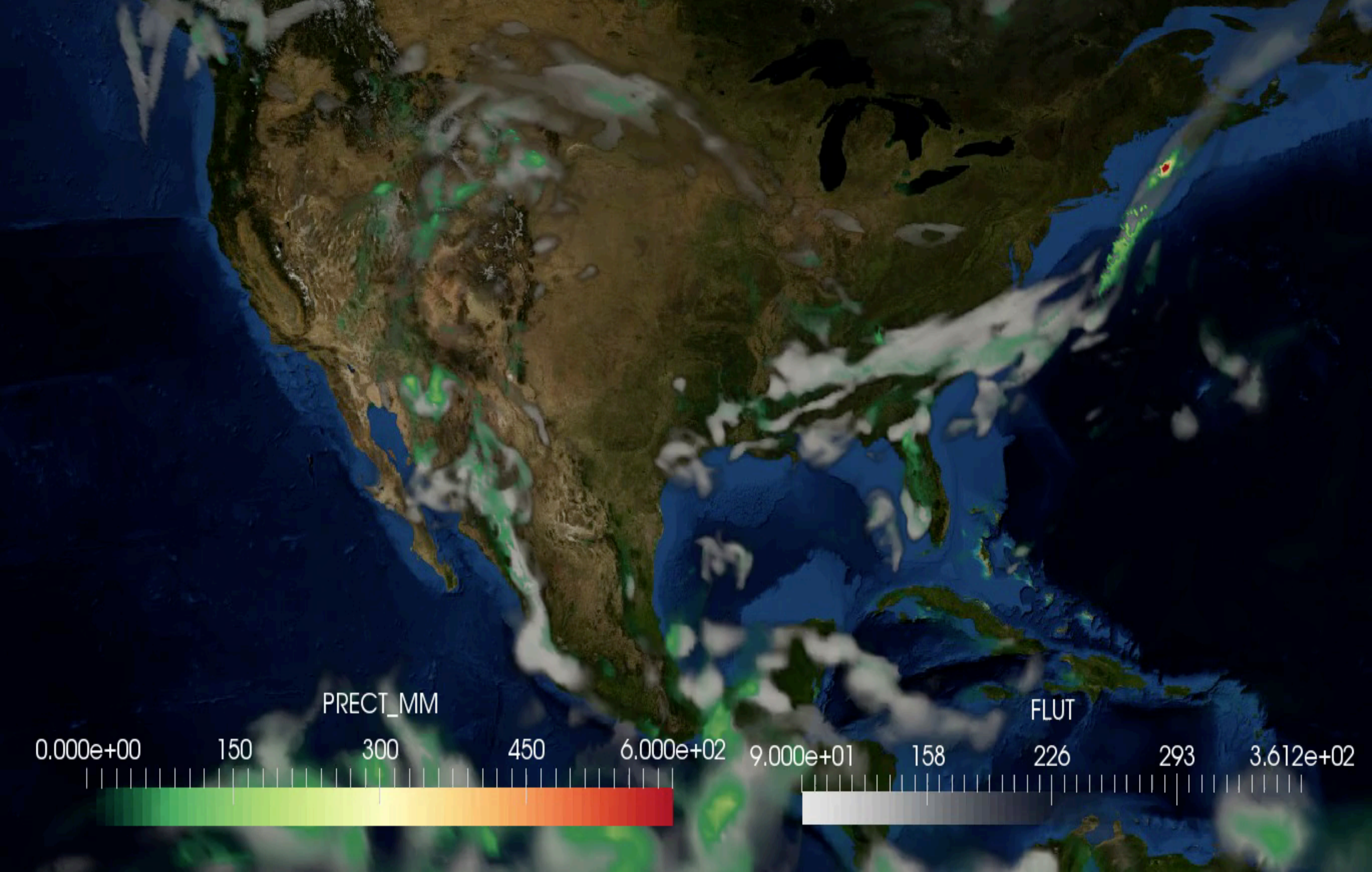




Precipitable water Sept 23-Oct 3, 111 km -> 14 km

Slide from C. Zarzycki

CESM2 Variable resolution Mesh (CESM-SE & CESM-MPAS)
14 km: Cloud tops Gray (whiter colder), Precipitation in Green
3 months (May-July) of a 20 year Simulation on Cheyenne

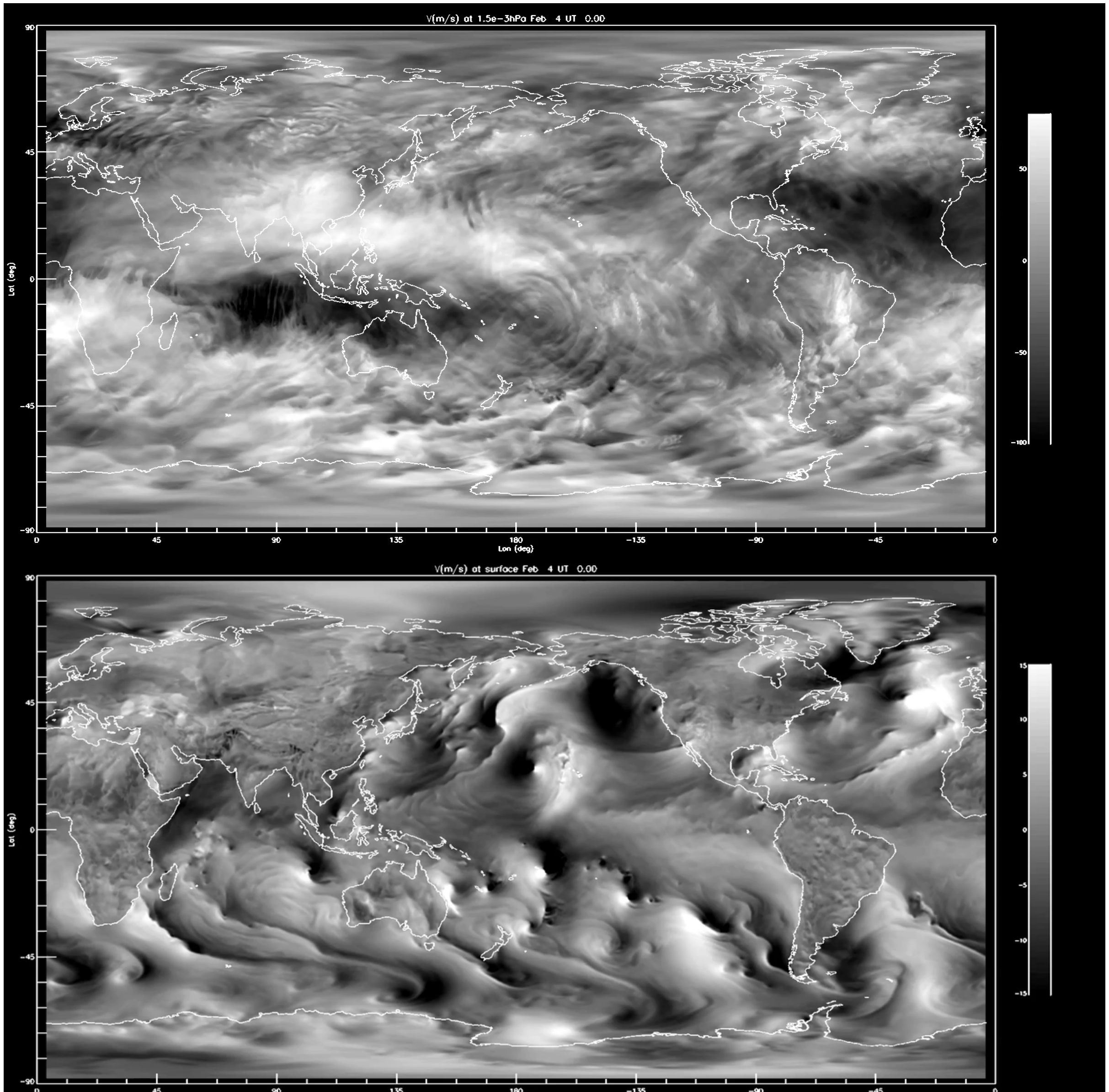


WACCM-X 2.0

Unified Geo-space Modeling

Lower Thermosphere

Surface



Response of Thermosphere to Surface wave forcing

25km global version of CESM WACCM-X

500m vertical resolution to 140km

10K cores on NWSC Yellowstone

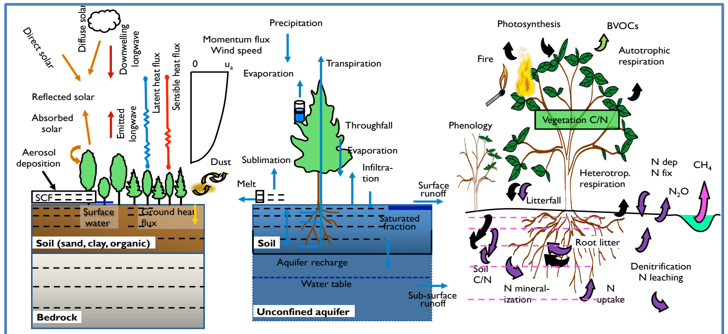
3 days of simulation shown

Liu et al., 2014

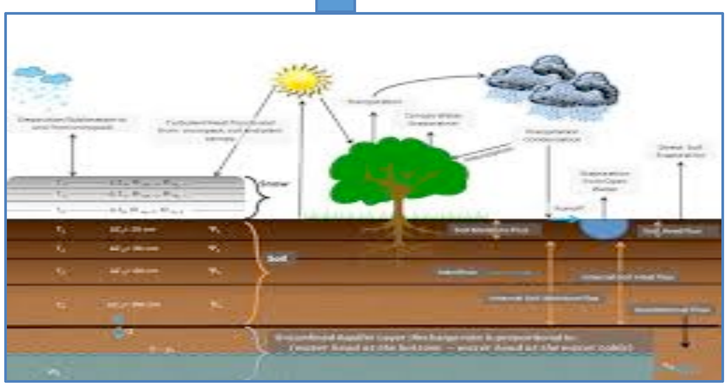
Community Terrestrial Systems Model (CTSM)

for research and prediction in climate, weather, water, and ecosystems

CLM (CGD)



CTSM

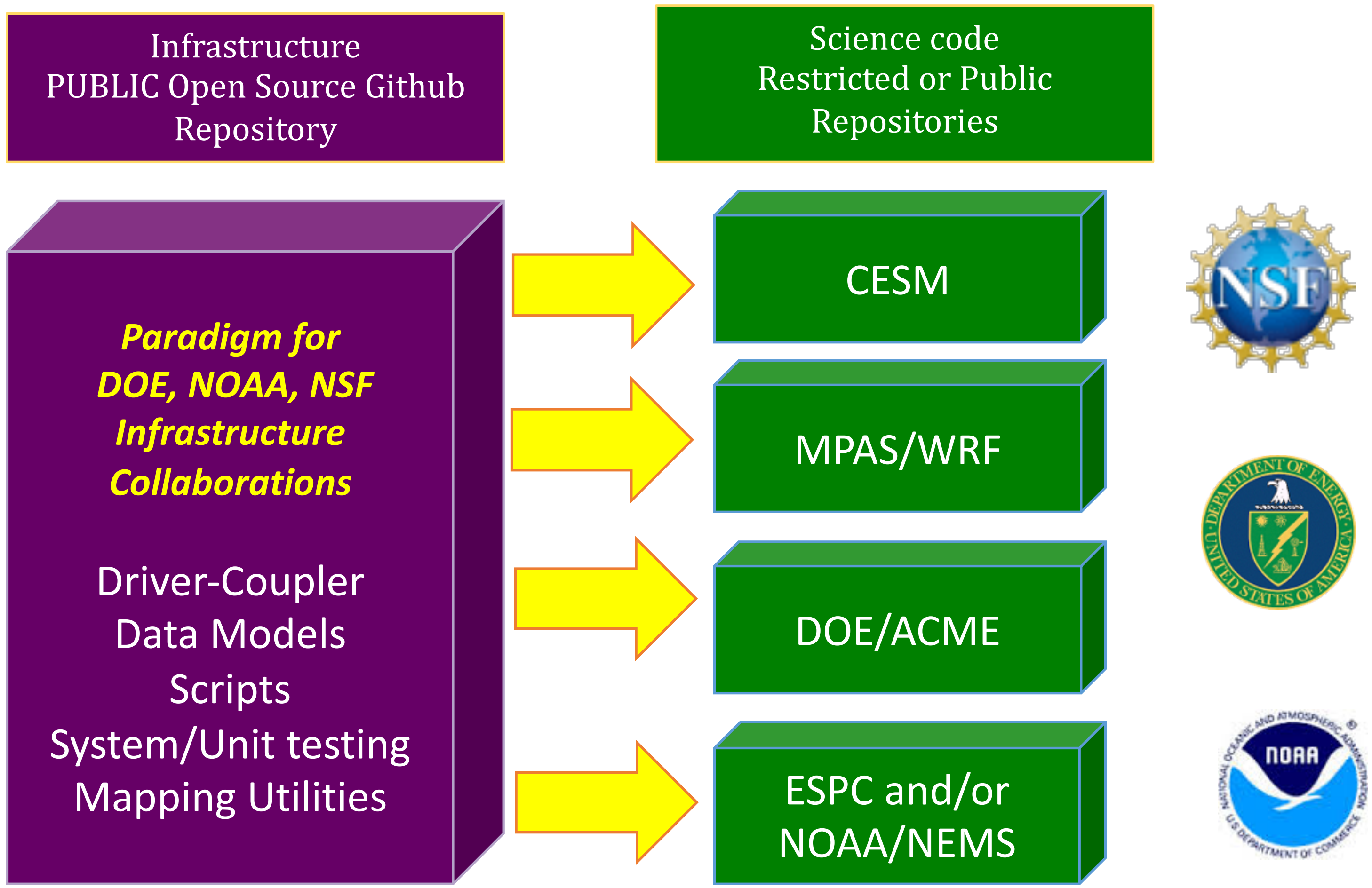


Noah-MP, WRF-Hydro (RAL)

Unify land modeling across NCAR/UCAR

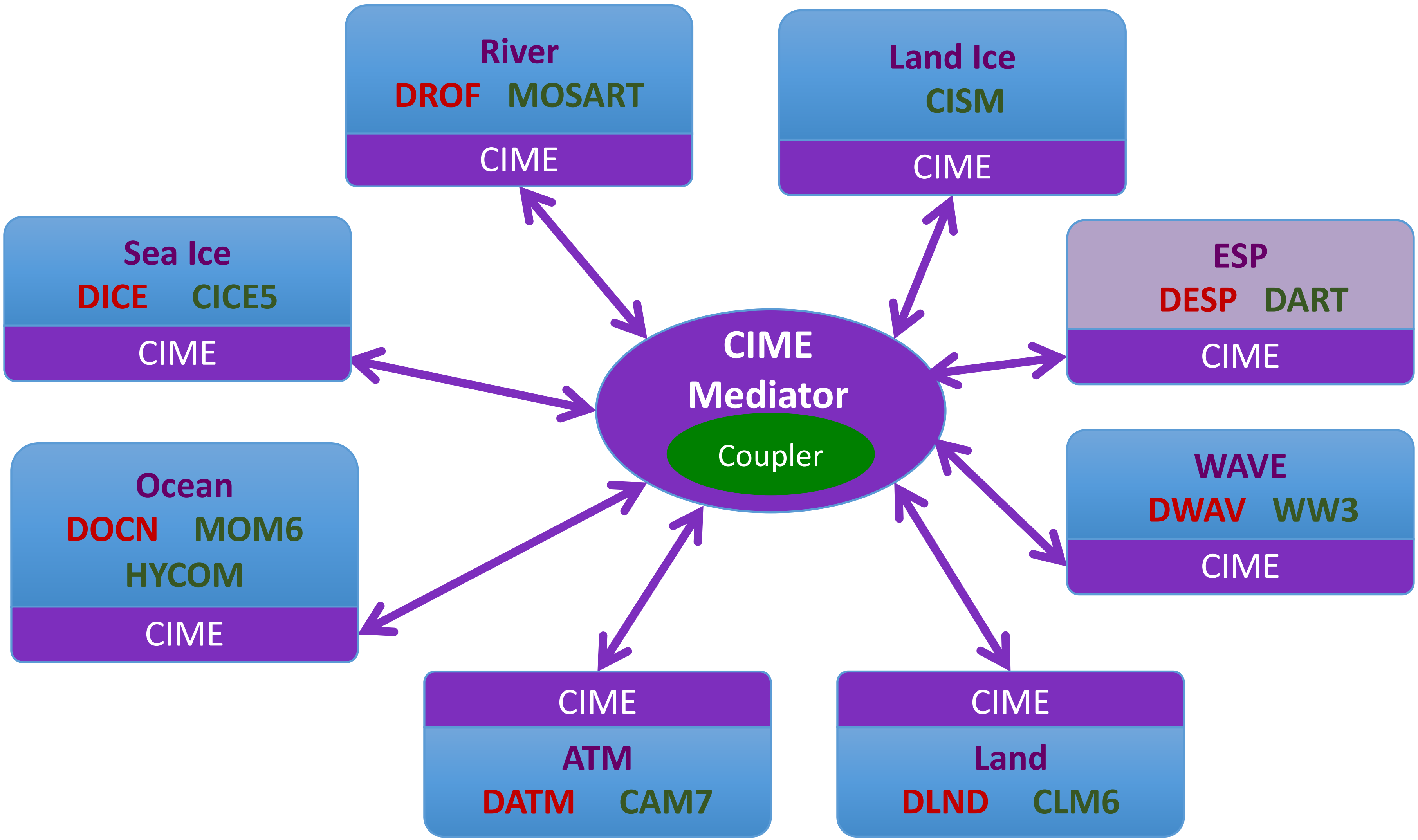
- Better use of NCAR and community resources
- Accelerate advances, minimize duplication of effort, centralized support
- Increase flexibility and robustness of process representation, spatial discretization, and numerical solution
- Enable better hypothesis-driven science
- Integrate land modeling research community

CIME: Common Infrastructure for Modeling Earth
(new python-based CESM infrastructure)



addresses needs of multiple efforts

Moving Forwards: New CIME Driver/Mediator will enable community collaboration



Bringing it all together

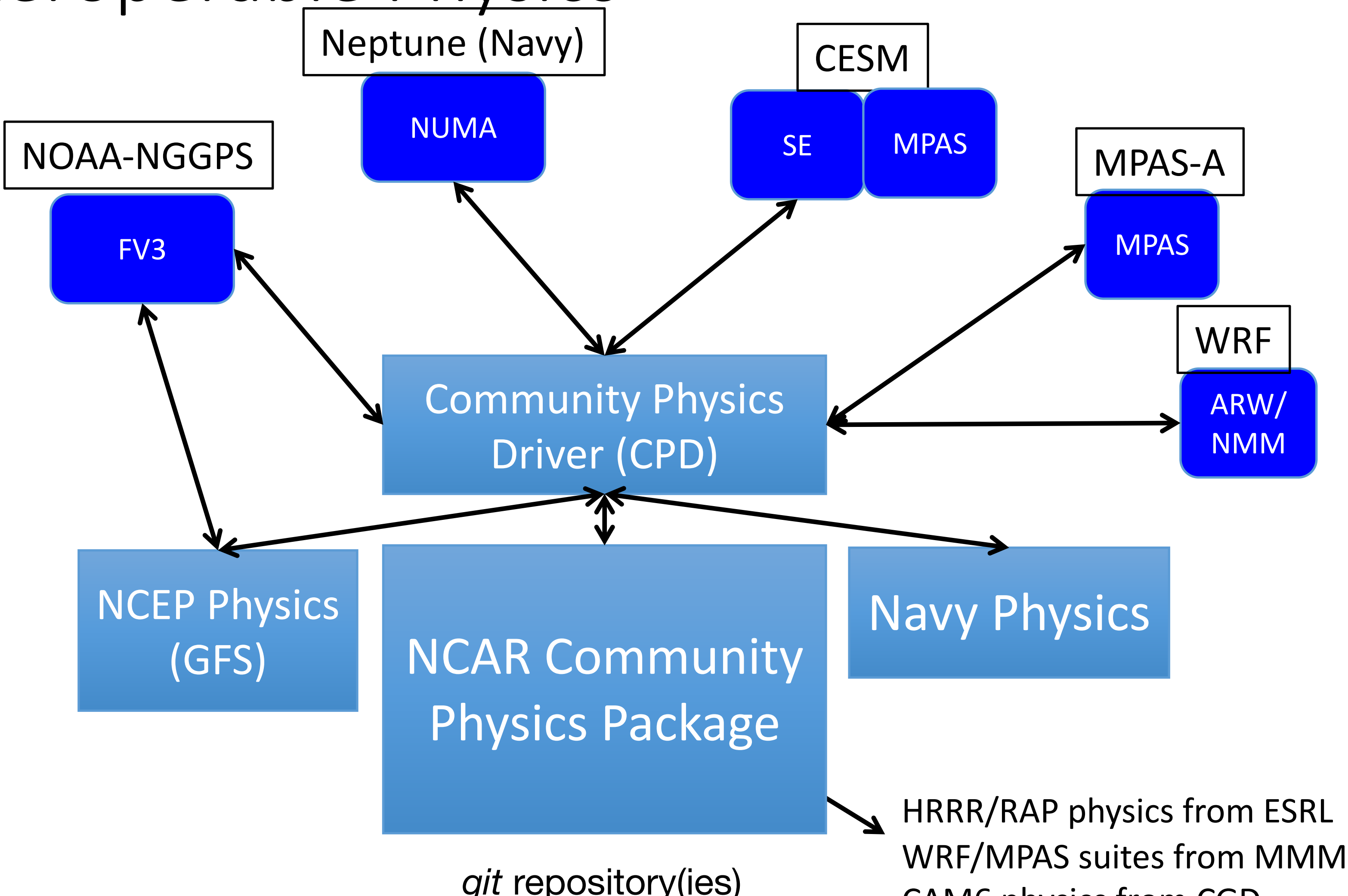
- Common Framework
  - ‘Architecture’, Coupling (CIME)
- Atmosphere
  - Common Driver (Framework, API)
  - Common Physics packages: goal ‘work across scales’
- Land: Sequence of linked models
  - Water, soil model
  - Ecosystems
  - Hydrology, Runoff

Interoperable 'components'

- Hierarchy of models from simple to complex
- Danger: trying to do too many things
- Robust releases of defined models
    - Limited definitions for community
    - More options for development, exploration

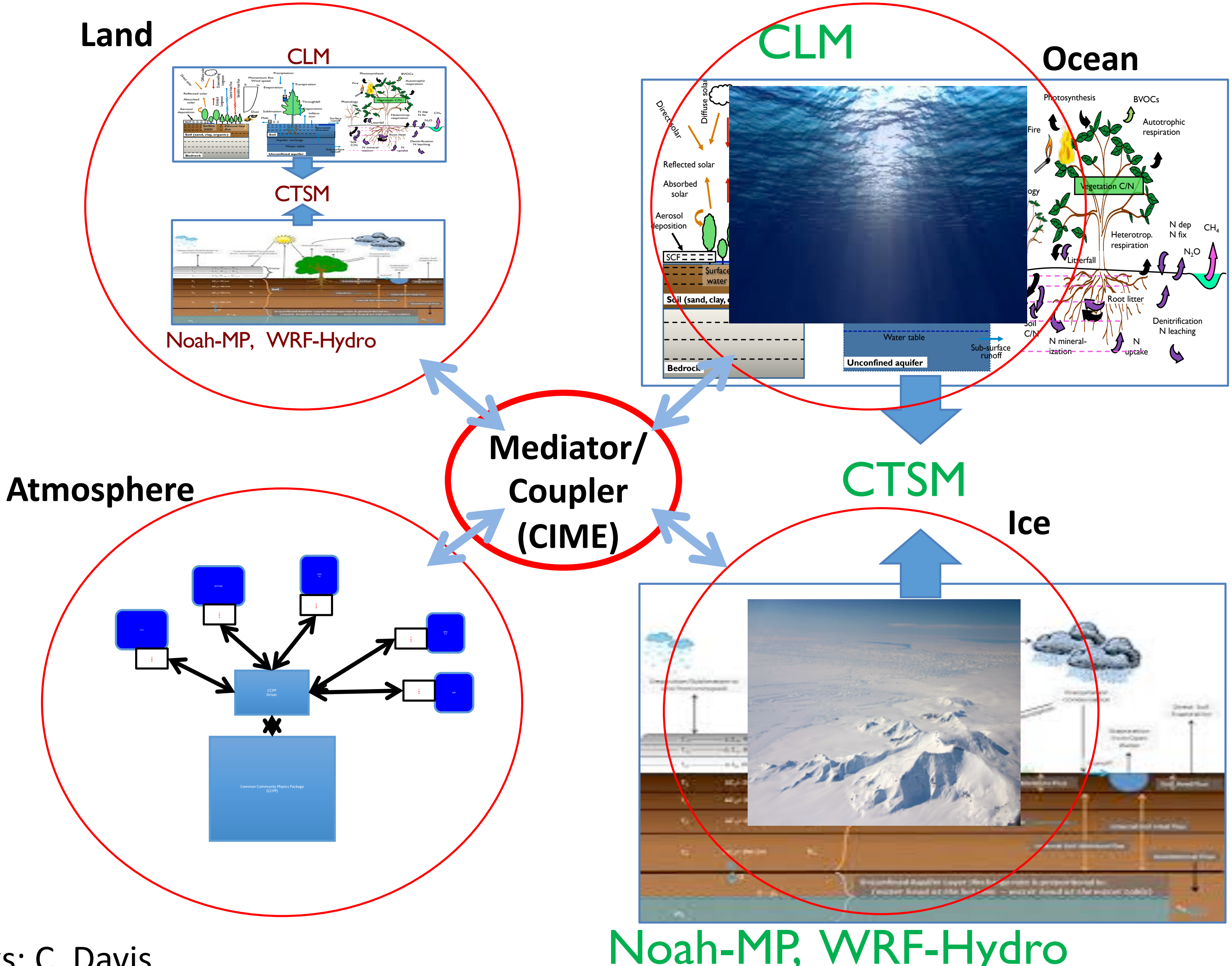


Atmosphere: Interoperable Physics



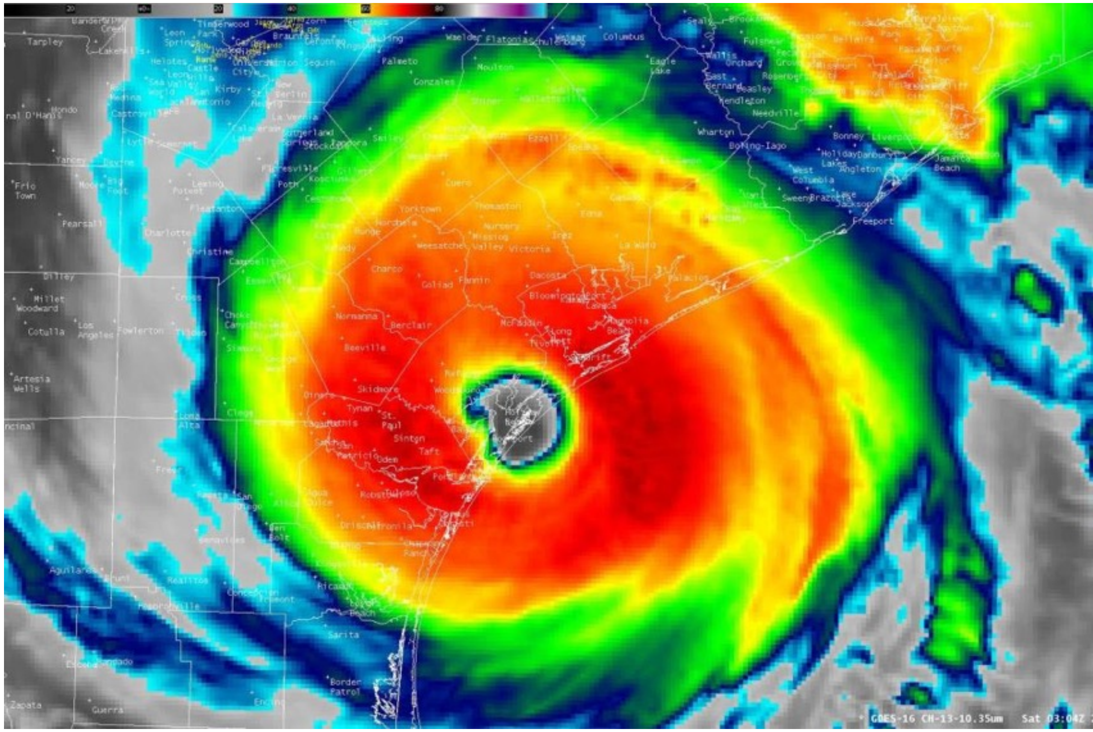
Weather: Physics orbits around the dycore (multiple physics)
Climate: Dycore orbits around the physics (one physics)

Earth-System Modeling: System of Ecosystems



Thanks: C. Davis

Simulate This
Hurricane Harvey

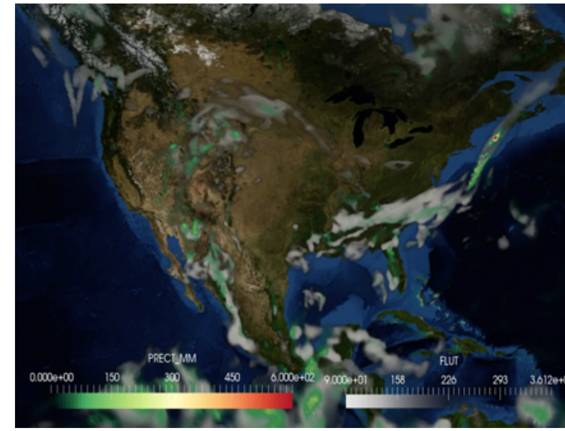


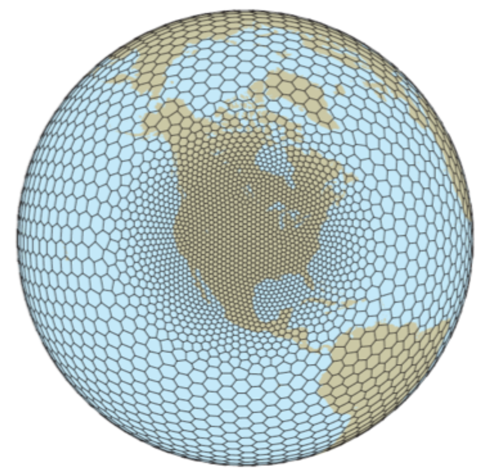
Harvey, 27 Aug 2017

- Forecast/Hindcast:
  - Coupled model (ocean and atmosphere)
  - Data assimilation (initialized)
  - High Resolution Regional (15km, or even 3km)
  - Land surface and Hydrology (runoff, flooding) model
- Understanding/Simulating current storms necessary for:
  - Forecasts of future events (Weather)
  - Prediction of climate change impacts on Hurricanes

Getting There Fast

- 15km Hydrostatic CESM2-SE
- Non-hydrostatic CESM2-MPAS
  - Above simulations available next year
  - Gettelman et al, Zarzycki et al
- Testing: 3km CESM2+MPAS
  - Modified physical parameterizations
  - Global coupled model framework
  - Do simulations make sense?
  - Similar to WRF forecast capability
- Can we go from global ←→ local
  - Not now. But conceptually possible.
  - Closer than you might think





Summary

- NCAR community modeling spans seconds to centuries
- Tools are growing together: Seamless prediction
  - From weather to climate and back
- Future is a ’common framework’ (not one model)
  - Getting there fast
  - Scientifically exciting: now testing 3km CESM-MPAS
- Community is key at all levels
  - Strategic planning, governance, development, analysis
  - Collaboration with other centers (e.g NOAA, NASA, DOE, ECMWF)

Way Forward
What does this mean for hardware/software?

- Inter-operable software, working with community
  - Efficient and portable code
- Higher resolution = more data
  - Shorter forecasts = throw out data
  - Balance of computations v. data storage
- Does this mean we are headed to the cloud?
  - Already staying at a center for data/output (not moving data)
  - Will computation go there next?
- People or machine limited?
  - Software engineering well below industry standard (FTE/lines of code)
  - More human resources = faster development
  - So, merge with other communities to expand (Weather ←→ Climate)
- New Architectures
  - New code is expensive to write (or rewrite)
  - Millions of lines of ‘legacy code’
- New methods possible
  - Emulation, machine learning, ‘training’