An Introduction to the WRF Modeling System

Wei Wang

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Mesoscale and Microscale Meteorology Laboratory, NCAR

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Outline

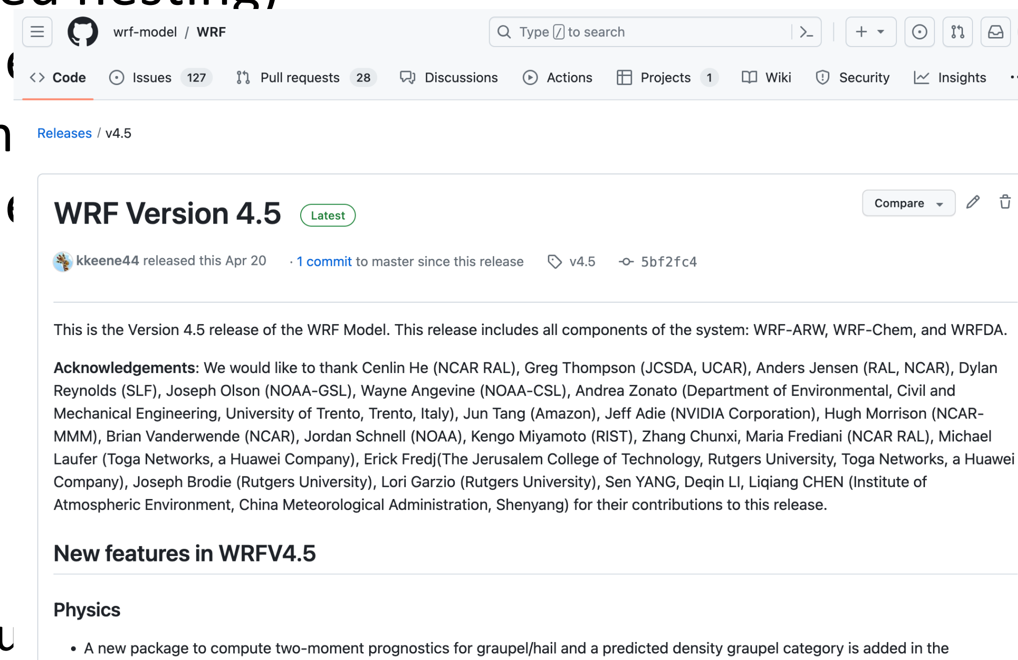
- What is WRF?
  - A brief history of WRF
  - WRF applications
- Some basic concepts about limited area modeling
- What does WRF look like to you, the user?
- What is covered in this tutorial?
- What should you expect to gain from this tutorial?

What is WRF?

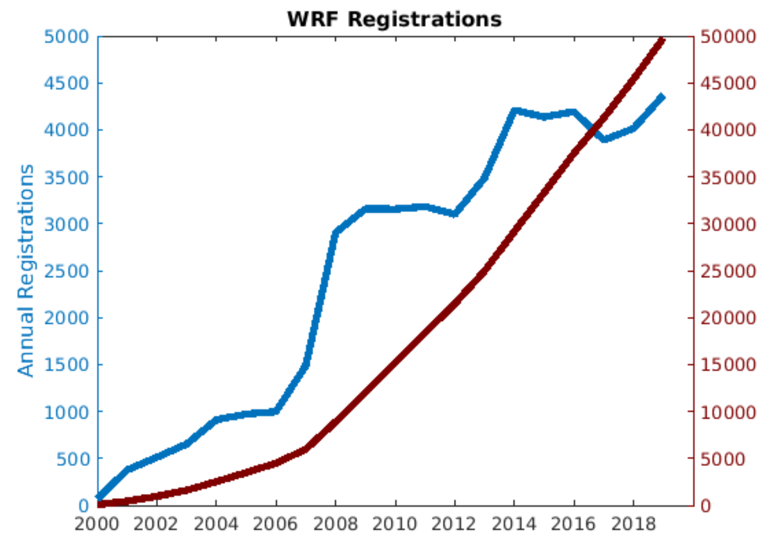
- WRF: Weather Research and Forecasting Model
- It is a supported "community model", i.e. a free and shared resource with distributed development and support
- Its early development was led by NCAR, NOAA/ESRL and NOAA/NCEP/EMC in early years with partnerships at AFWA, FAA, DOE/PNNL and collaborations with universities and other government agencies in the US and overseas.

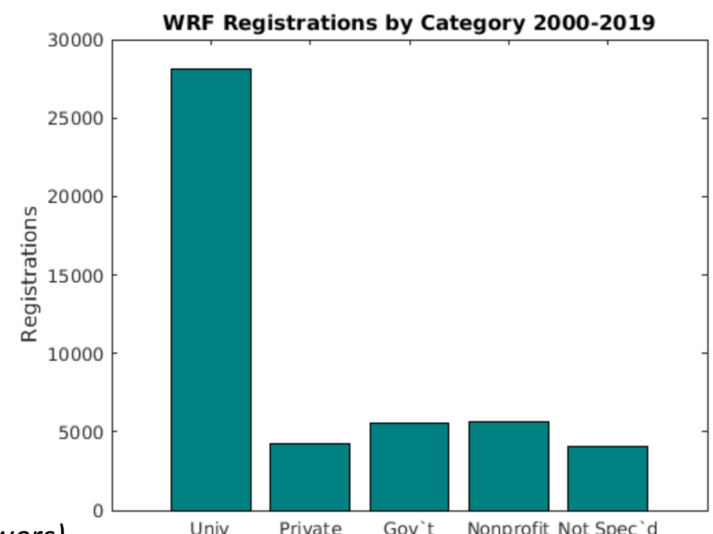
WRF Community Model

- Version 1.0 WRF was released December 2000
- Version 2.0: May 2004 (added nesting)
- Version 3.0: April 2008 (adde
- … (major releases in April, min
- Version 3.9: April 2017 (adde
  - Version 3.9.1 (August 2017)
- Version 4.0 (June 2018)
- Version 4.1 (April 2019)
- Version 4.2 (April 2020)
- Version 4.3 (May 2021)
  - Version 4.3.1, 4.3.2, 4.3.3 – bu
- Version 4.4 (April 2022)
  - Version 4.4.1, 4.4.2 – bug-fix releases
- Version 4.5 (April 2023) – last major release



WRF Users





As of June 2023:

No. of countries: 185

No. of users: 61,000

US: 19,090 (~ 31%)

Others: 41,910

(From Powers)

What is WRF-ARW?

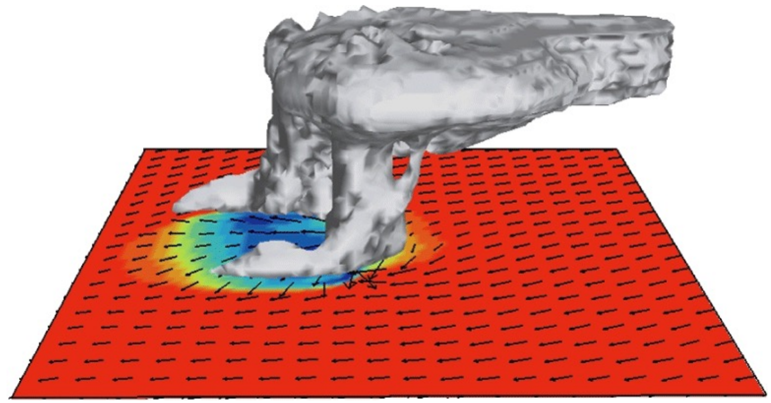
- WRF-ARW: The Advanced Research WRF (ARW)
  - WRF and WRF-ARW are synonymous.
  - Referring to its dynamical core: includes mostly advection, pressure-gradients, Coriolis, buoyancy, filters, diffusion, and time-stepping.
  - Since WRF v4.3.1, this is the only dynamical core.

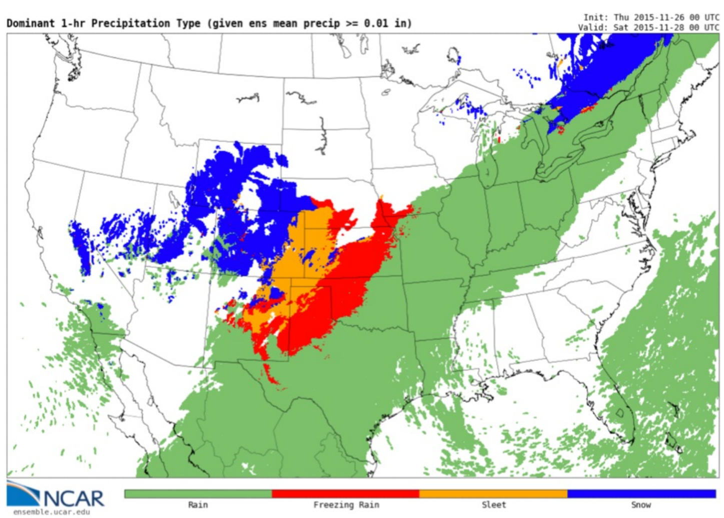
- WRF-ARW or WRF: its development, maintenance and support are centered at NCAR/MMM

What is WRF?

- A research tool:

Idealized simulations →



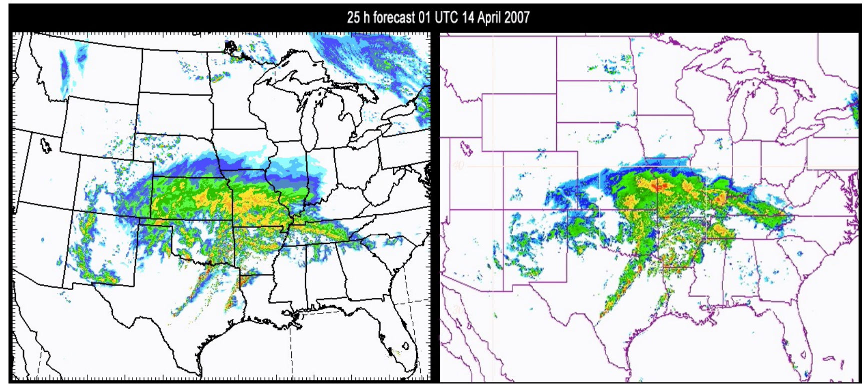


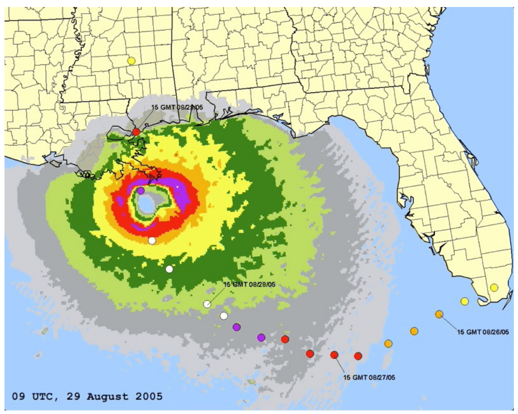
← Experimental real-time forecast

What is WRF?

- A research tool:

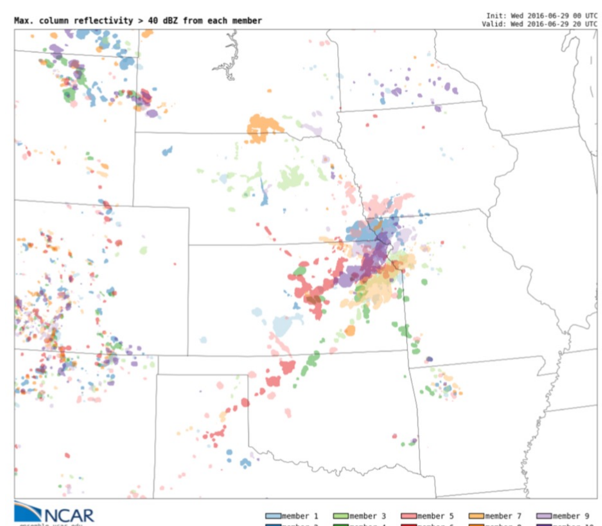
Convection forecast →





← High-resolution hurricane simulations

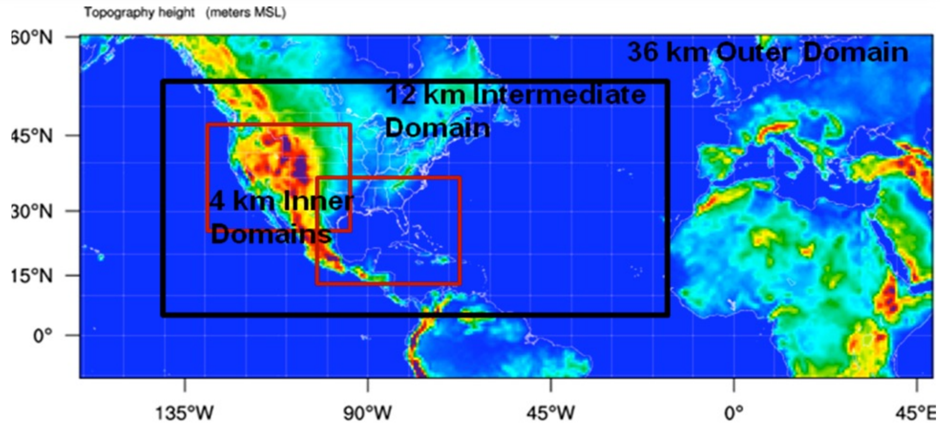
Development of ensemble forecasting technology →

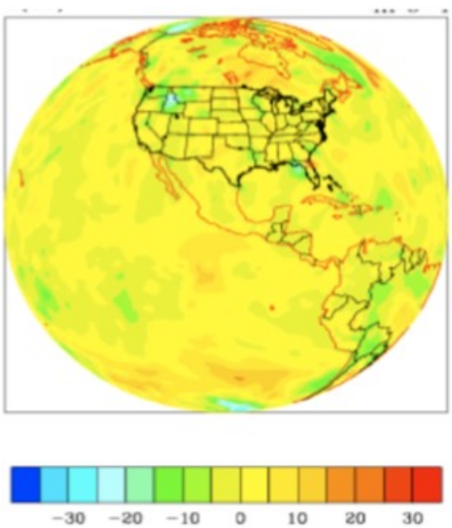


What is WRF?

- A research tool:

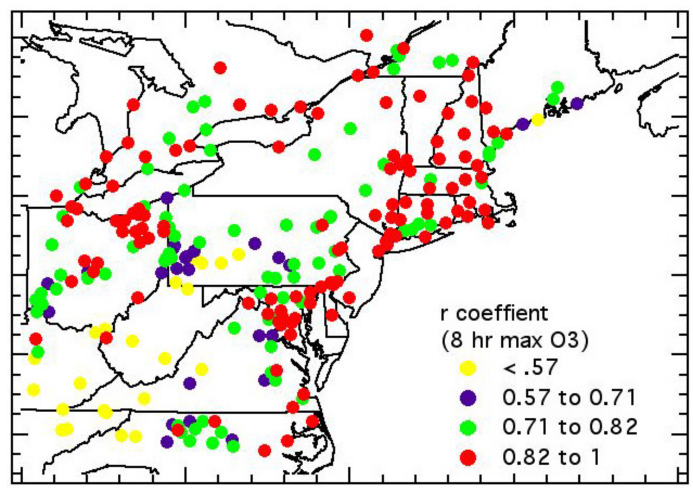
Regional Climate Modeling →





← Data assimilation (*analysis increments*)

WRF-Chemistry →
(*O3 forecast*)



What can WRF be used for?

- A tool for research
  - Develop and test physical parameterizations
  - Case-study research for specific weather events
  - Regional climate studies
  - Coupled-chemistry, fire, and hydrological applications
  - Data assimilation research
  - Teaching modeling and NWP

- A tool for numerical weather prediction
  - Hind-casting
  - Real-time (operational) forecasting
  - Forecasting for wind, solar and air quality (online and offline)

Some basic concepts

- How does a model work and what does time integration mean?

$$\frac{\Delta A}{\Delta t} = F(A)$$

ΔA = change in a forecast variable at a particular point in space

$F(A)$ = represents the dynamical and physical processes that can change the value of A

Δt = change in time

So a forecast at time N can be written as

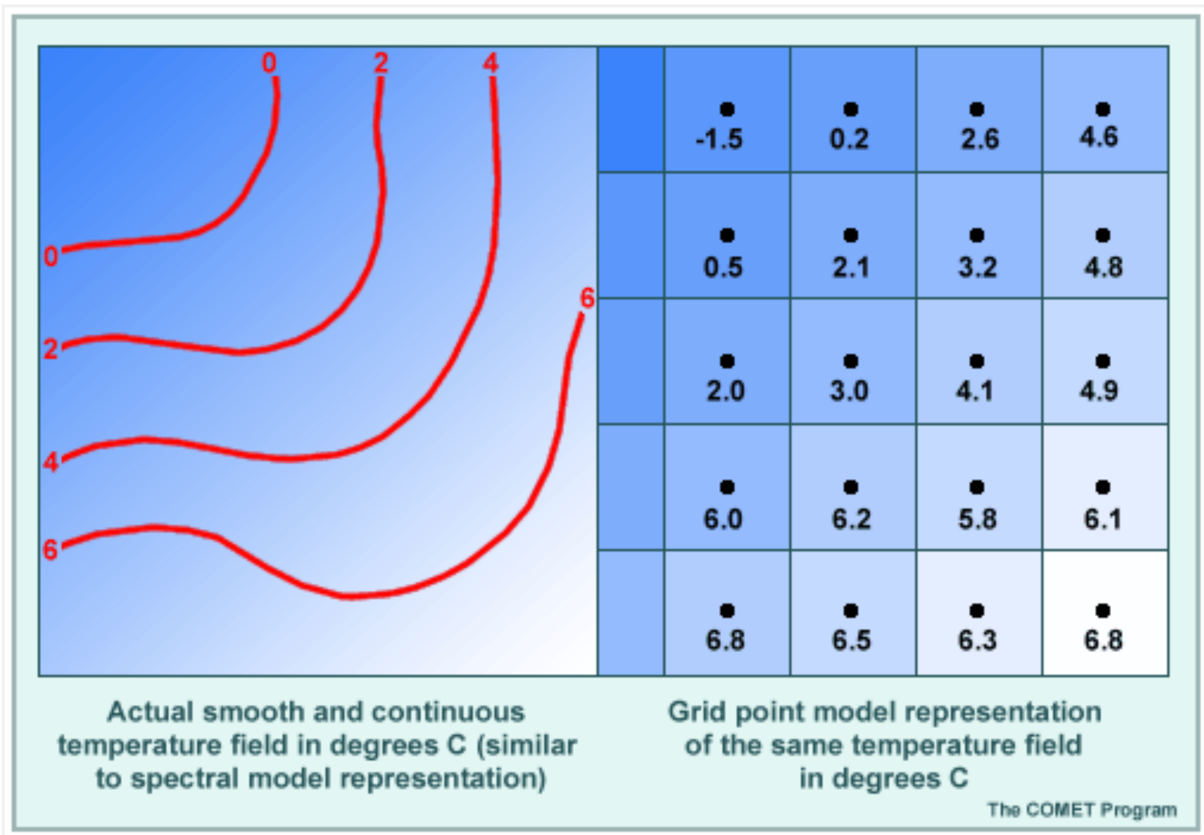
$$A^{n=1} = A^{n=0} + F(A^{n=0})\,\Delta t$$

$$A^{n+1} = A^{n} + F(A^{n})\,\Delta t$$

(adapted from COMET)

Some basic concepts

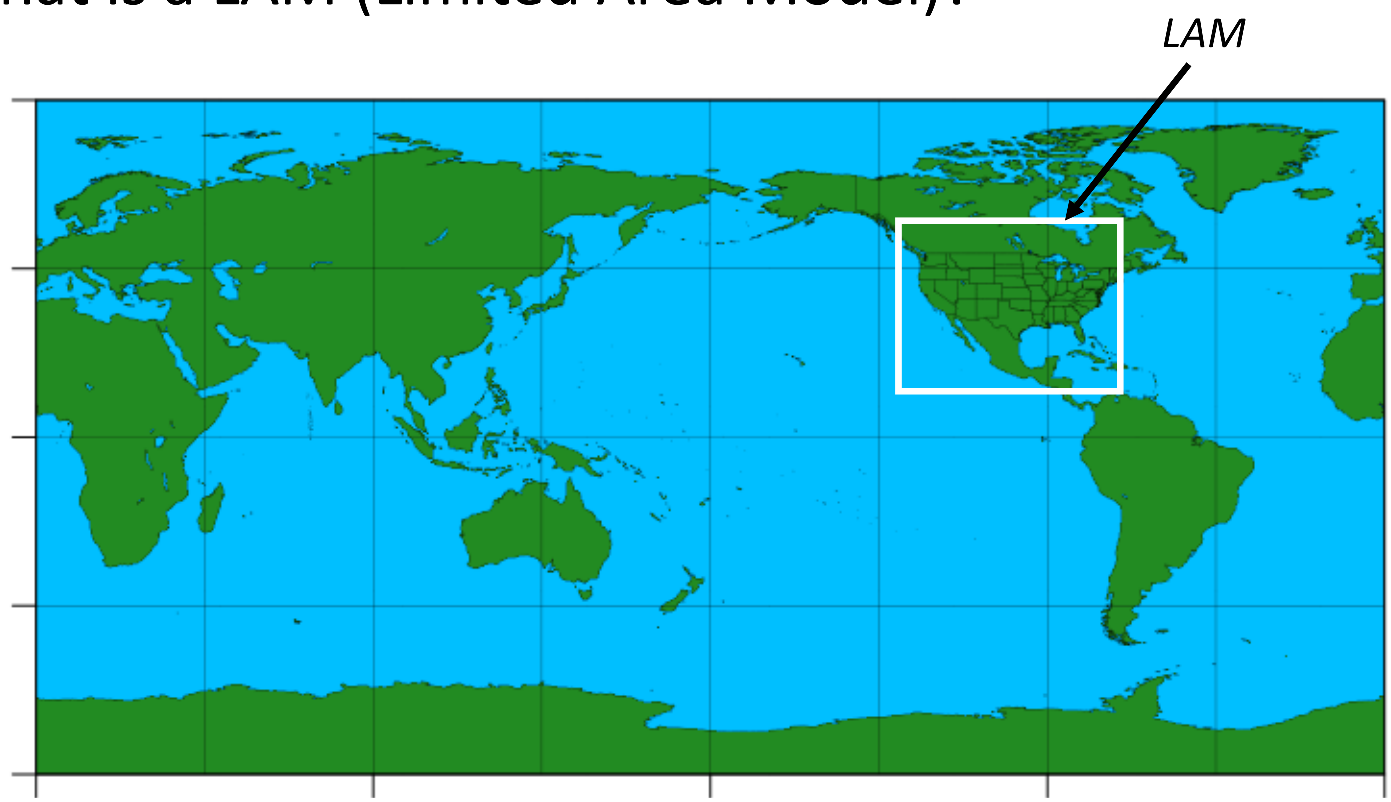
- How are data represented, and equations solved on a model grid?



(from COMET)

Some basic concepts

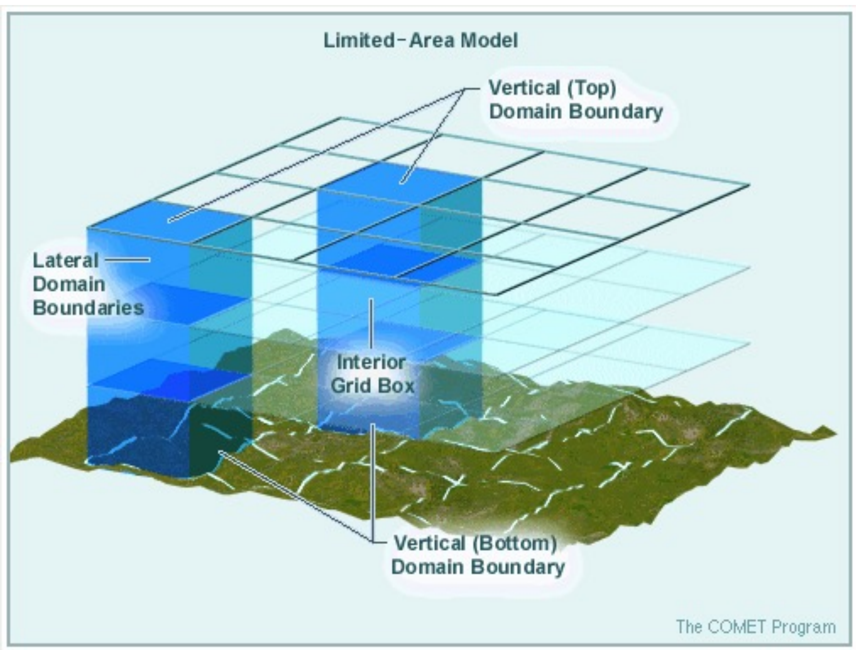
- What is a LAM (Limited Area Model)?

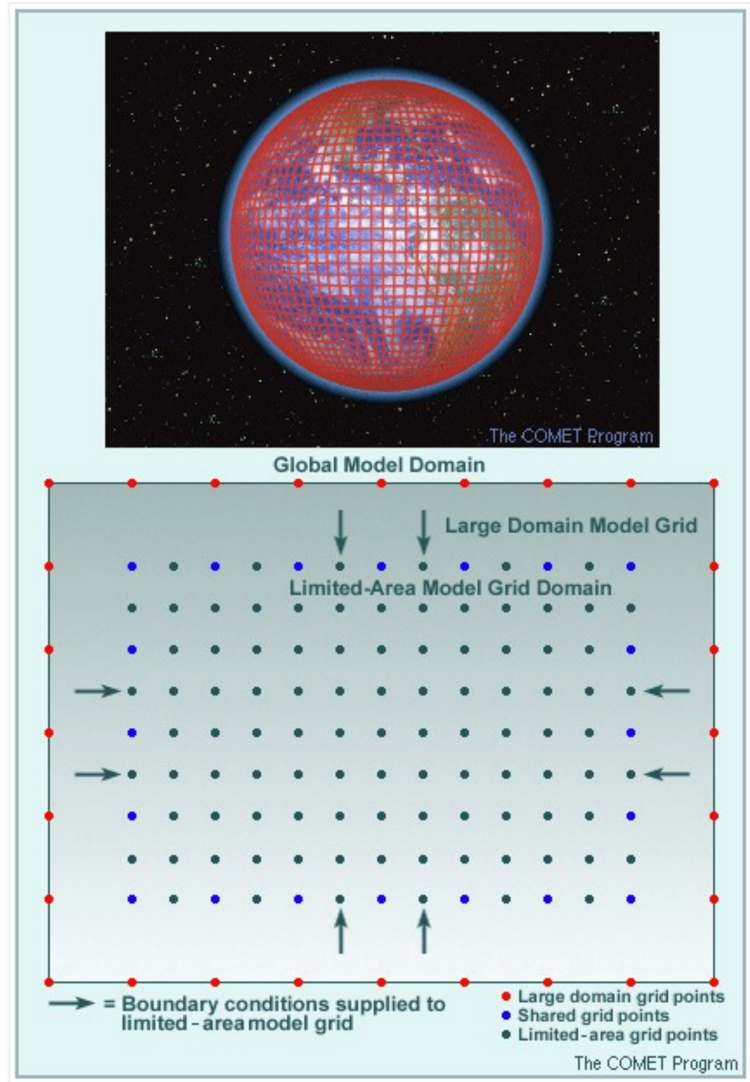


Global Model

Some basic concepts

- What is a LBC (lateral boundary condition)?

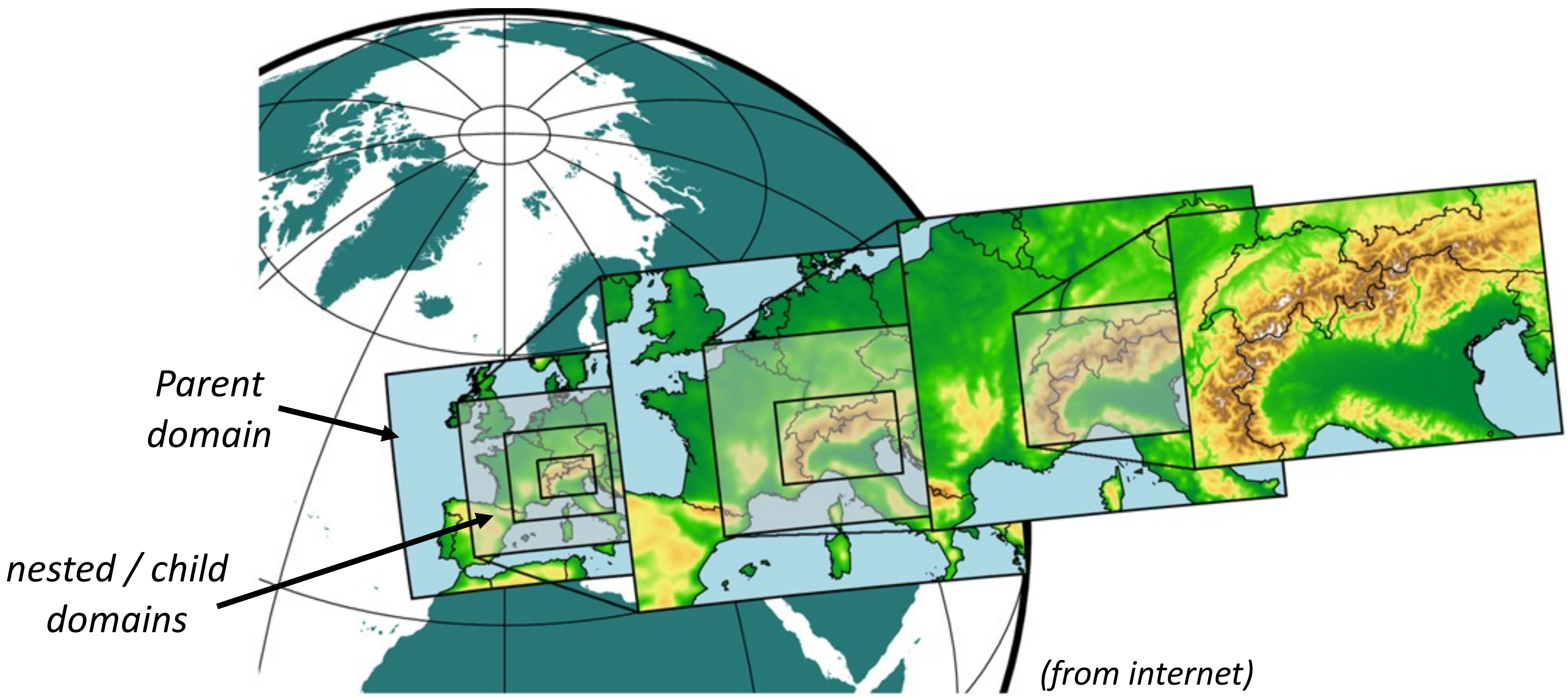




(from COMET)

Some basic concepts

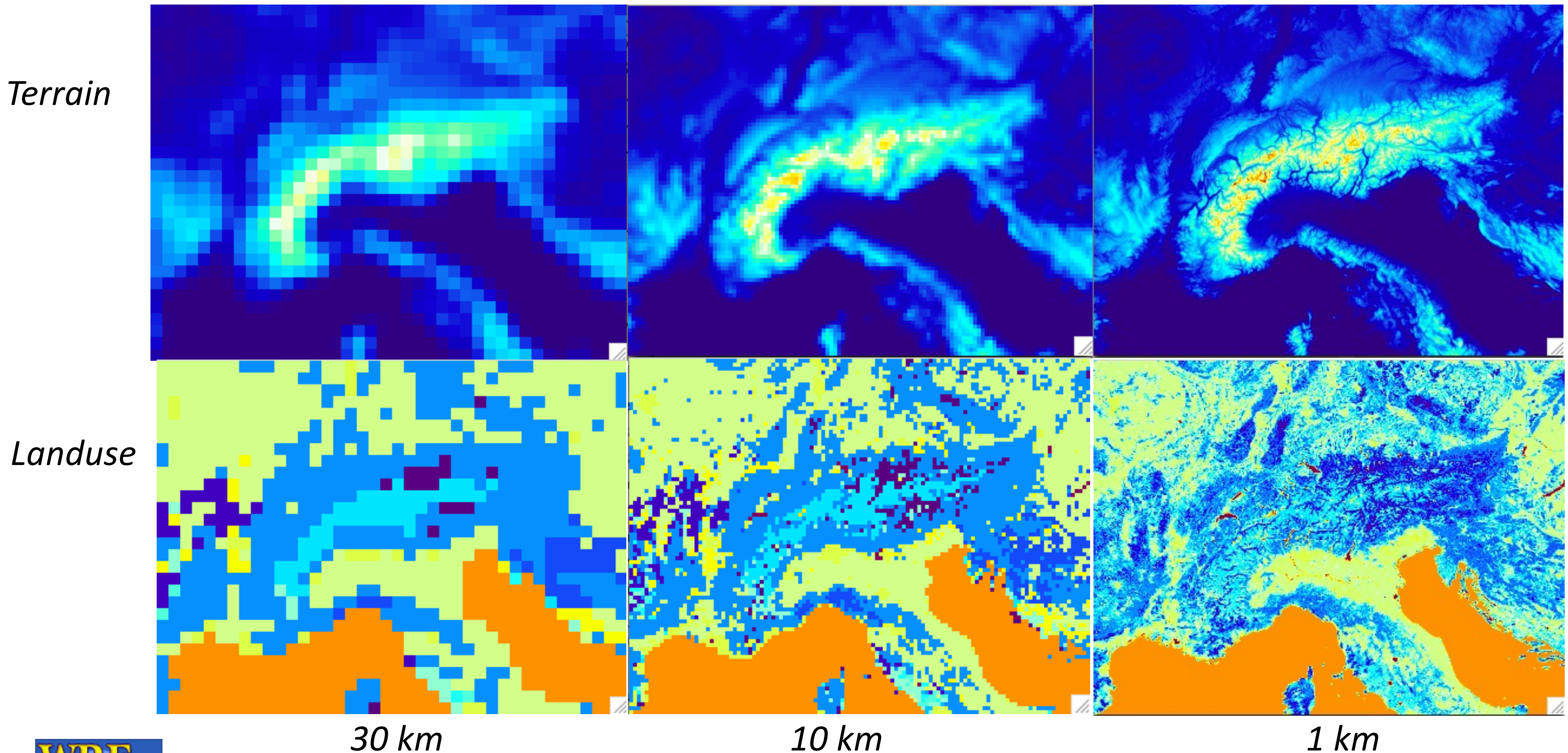
- Nesting in limited area model



(from internet)

Some basic concepts

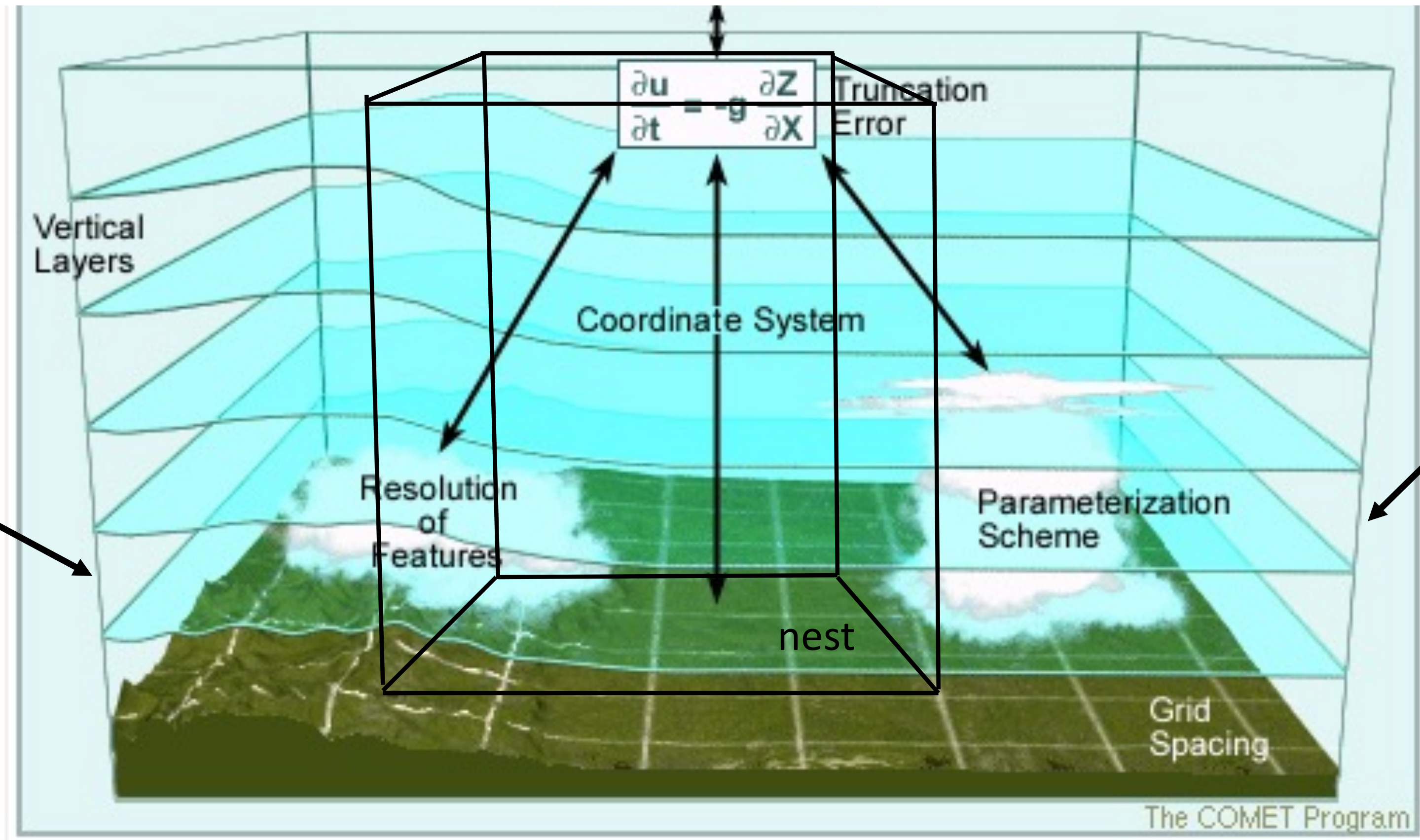
- Why nesting? An efficient way to obtain high resolution model solutions.



Some basic concepts

- A 3D view of LAM

Forcing from global models



Forcing from global models

(partially from COMET)

What does WRF look like to a user?

- A set of programs (mostly in Fortran) and executables
  - No GUI;
  - Command-line;
  - Simple graphic tools to use along the way.

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```
> tar -xf WRF-4.1.2.tar.gz
> cd WRF-4.1.2
> configure
> compile em_real >& compile.log &
> cd run/
> ln -s ../../WPS-4.1/met_em.d01.* .
> mpirun -np 4 real.exe
> ls -l wrfinput* wrfbdy*
> mpirun -np 8 wrf.exe
```

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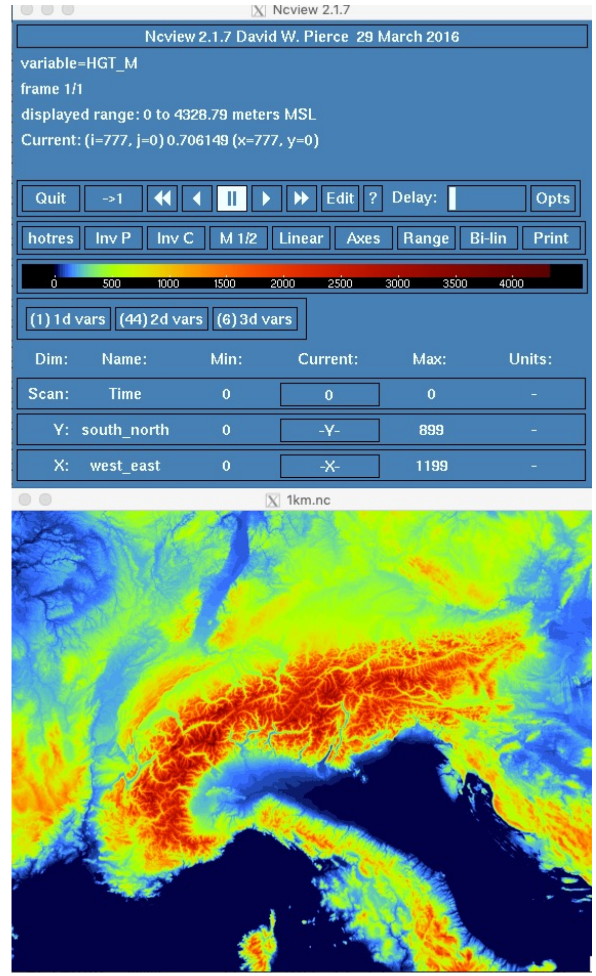
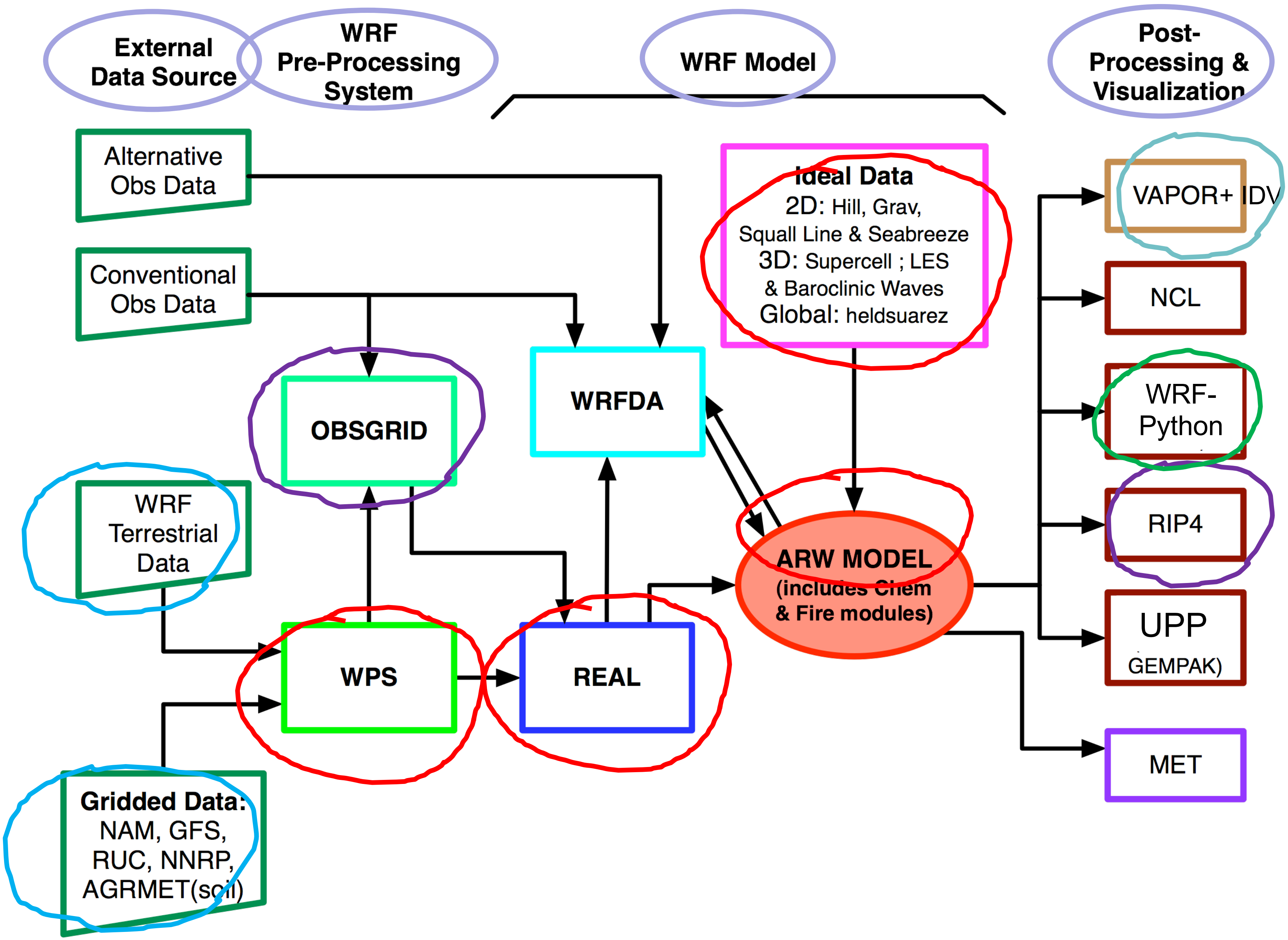


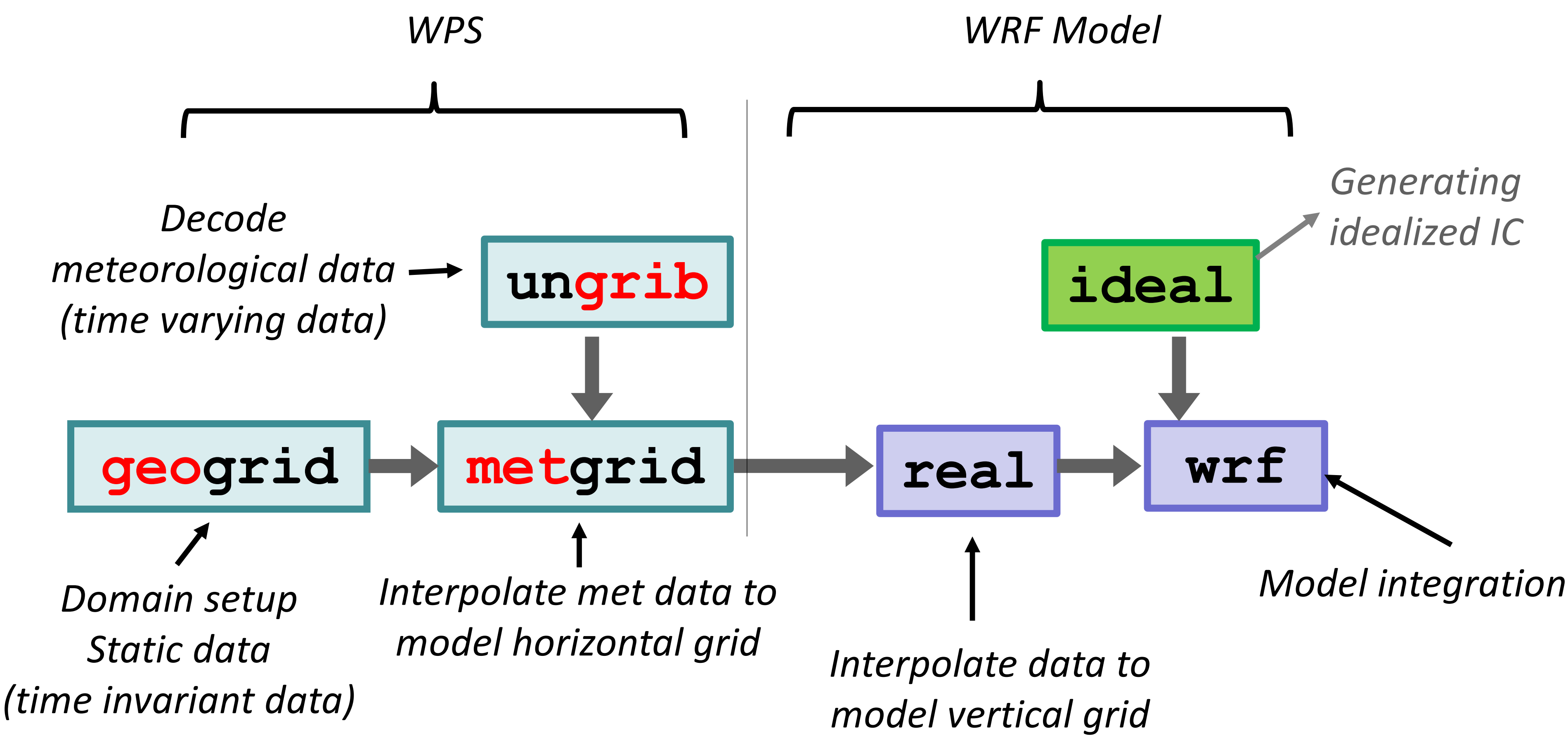
What does WRF look like to a user?

- A set of programs (mostly in Fortran) and executables
  - No GUI;
  - Command-line;
  - Simple graphic tools to use along the way.
- The modeling system programs have many functionalities
  - Many different ways to run a model;
  - Decisions needed at every step (input data, domain configuration, model options, etc.);
  - Best practices required.

WRF Modeling System Flow Chart



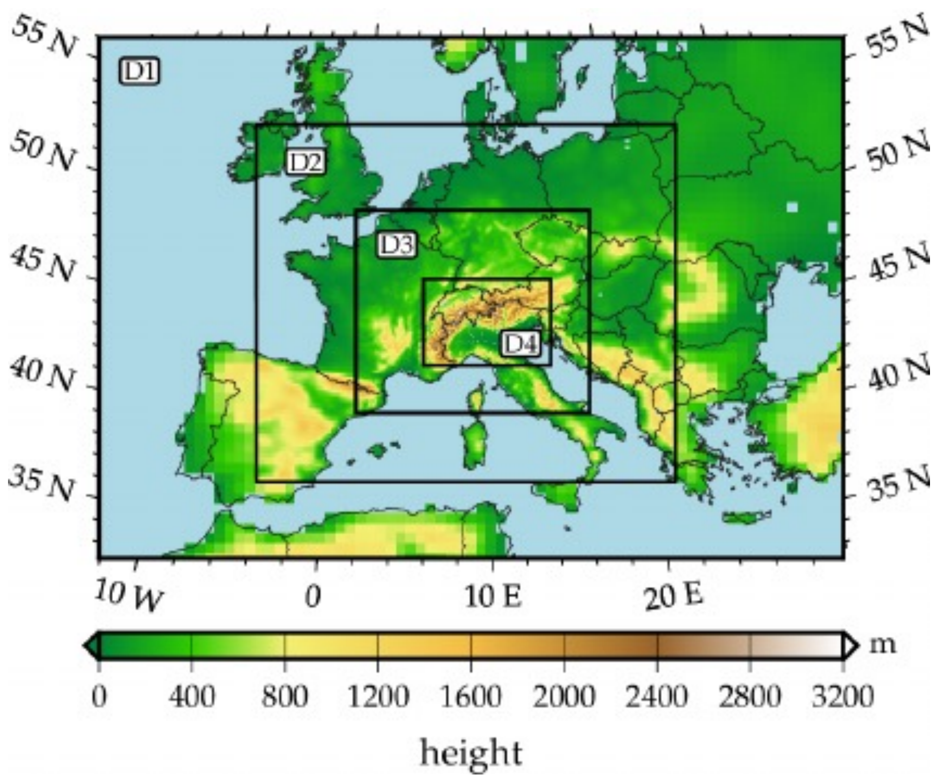
WPS and WRF Program Flow



For a real-data application

What will you learn in this tutorial?

a. Configuration of simulation domains



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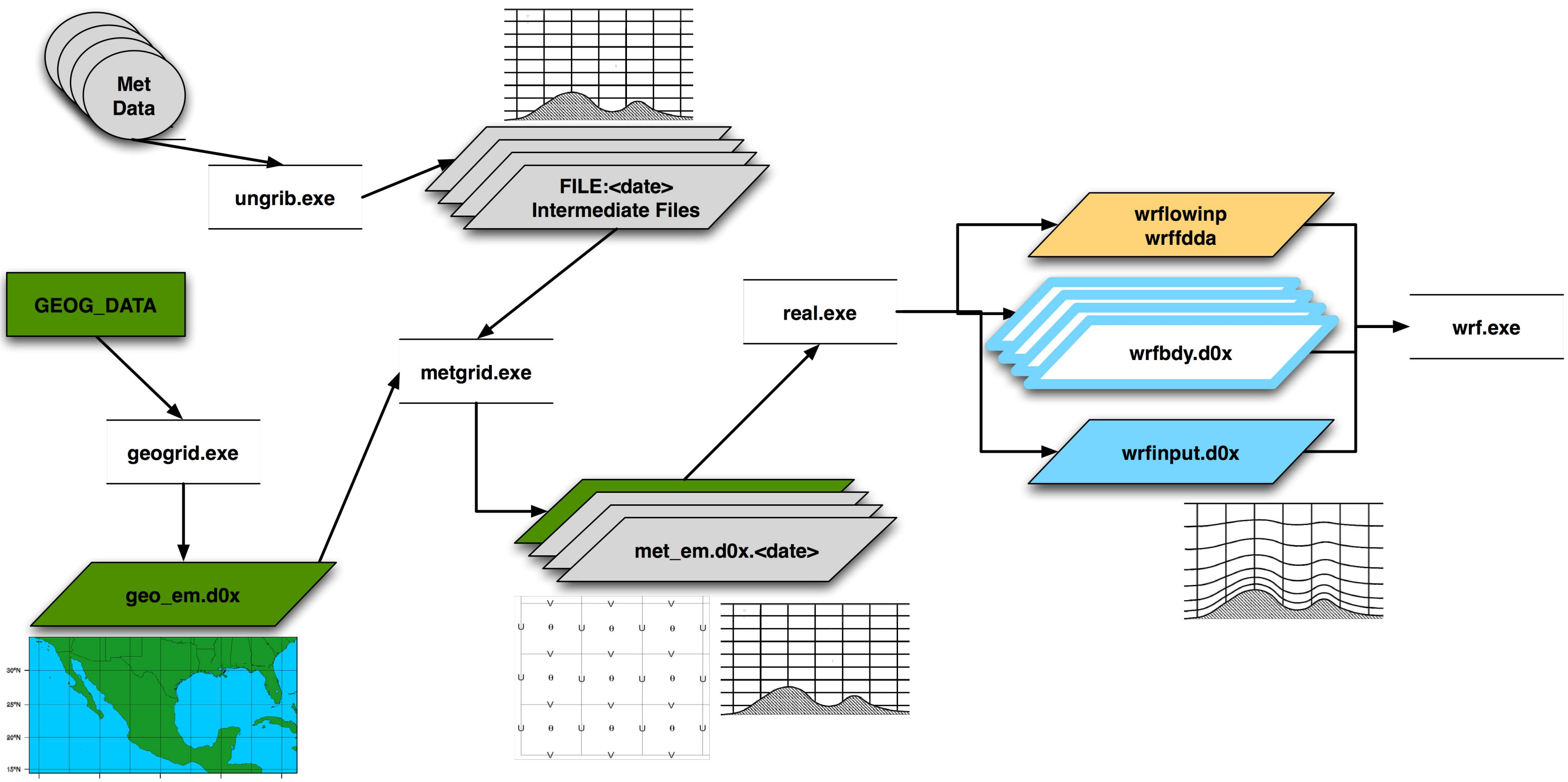

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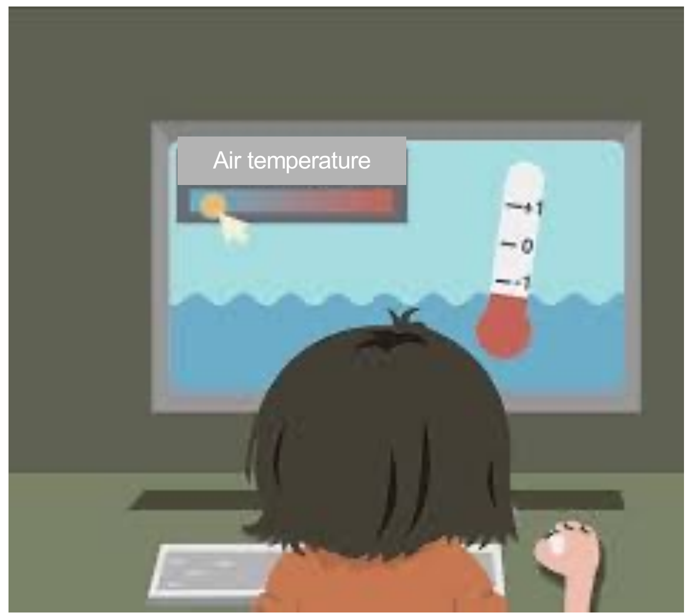
c. Running the model



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a. Configuration of simulation domains
b. Preparation of data for initial and boundary conditions
c. Running the model
d. Model internals:
    i. Dynamics: formulation of compressible, non-hydrostatic equations

$$\frac{\partial W}{\partial t}+g\left(\mu_d-\frac{\alpha}{\alpha_d}\frac{\partial p}{\partial \eta}\right) = -\frac{\partial Uw}{\partial x}-\frac{\partial \Omega w}{\partial \eta}$$

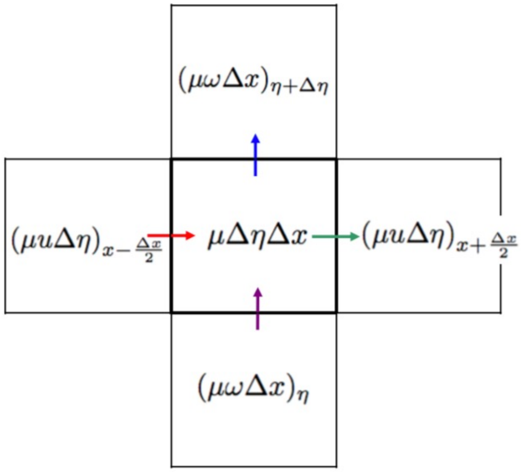
$$\frac{\partial \mu_d}{\partial t}+\frac{\partial U}{\partial x}+\frac{\partial \Omega}{\partial \eta} = 0$$

$$\frac{\partial \Theta}{\partial t}+\frac{\partial U\theta}{\partial x}+\frac{\partial \Omega\theta}{\partial \eta} = \mu Q$$

$$\frac{d\phi}{dt} = gw$$

What will you learn in this tutorial?

a. Configuration of simulation domains
b. Preparation of data for initial and boundary conditions
c. Running the model
d. Model internals:
    i. Dynamics: formulation of compressible, non-hydrostatic equations
    ii. Numerics: how to solve equations numerically



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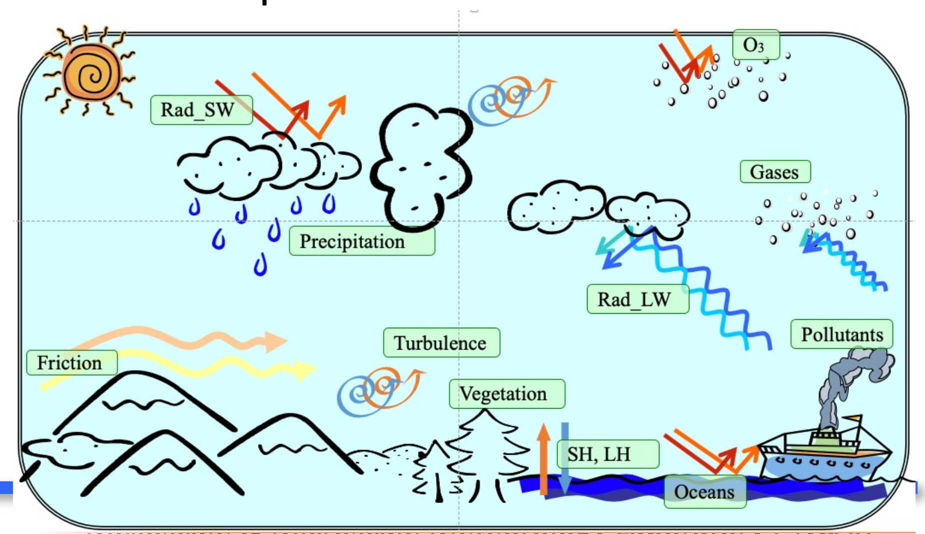

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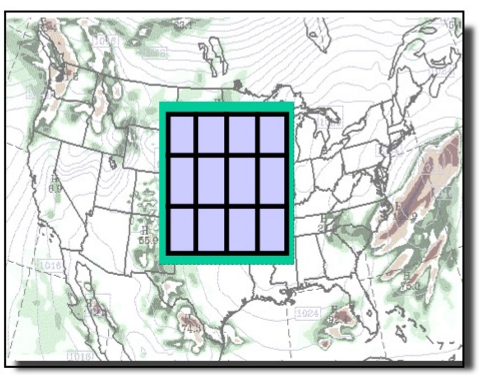
   iii. Physics: how are physical processes in the atmosphere are represented

   iv. Software and parallel computing



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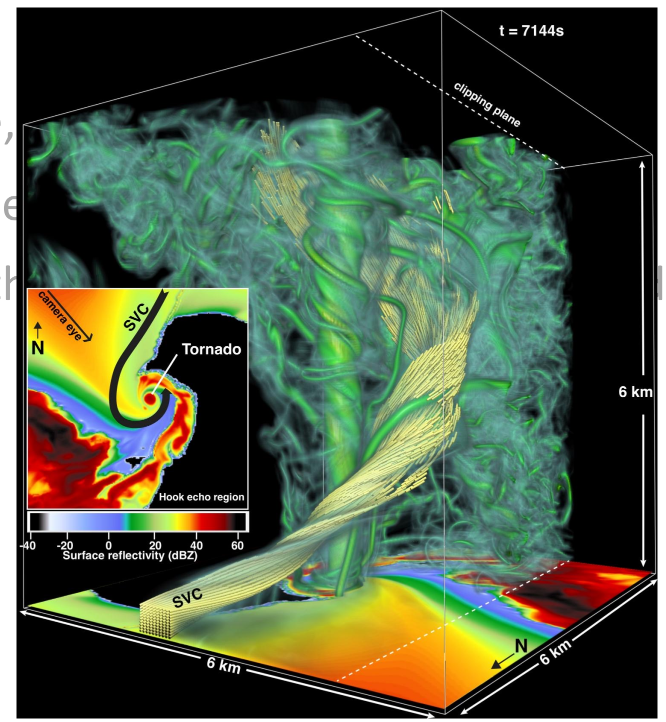
e. Tools to view and analyze model output



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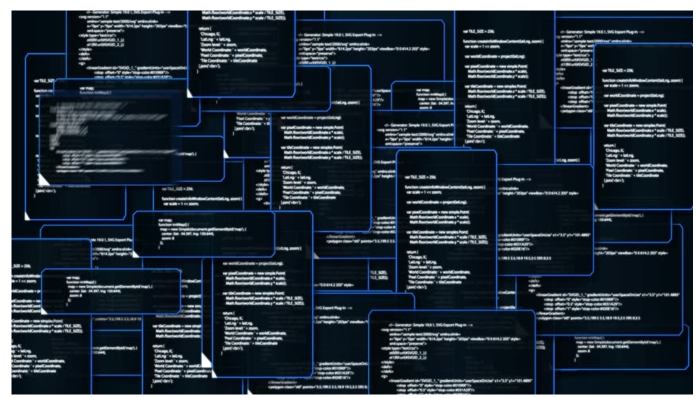
f. How to compile the modeling system code



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   iv. Software and parallel computing
e. Tools to view and analyze model output
f. How to compile the modeling system code
g. Best practices and verifying model output

What will you gain from this tutorial?

a. Knowledge needed to run WRF for basic applications
   i. Some understanding on how the model works
   ii. Familiarity with the process to run the model

b. Recognize what you learn here is a starting point
   i. Continue to learn after the tutorial
   ii. Read more and experiment
   iii. Practice, practice, and practice…

Reading (watch) Materials

Numerical Weather and Climate Prediction, 2011. By Thomas Warner, *Cambridge University Press*.

Warner, T., 2011. Quality assurance in atmospheric modeling. *Bull. Amer. Met. Soc. Dec. issue, p1601 – 1611.*

Stensrud, D., 2007. Parameterization Schemes: Keys to Understanding Numerical Weather Prediction Models. *Cambridge University Press*.

Haltiner G. and R. Williams, 1980. Numerical Prediction and Dynamic Meteorology. *Wiley*.

Hong, S-Y: Fundamentals in Atmospheric Modeling. *wrfhelp YouTube channel*.