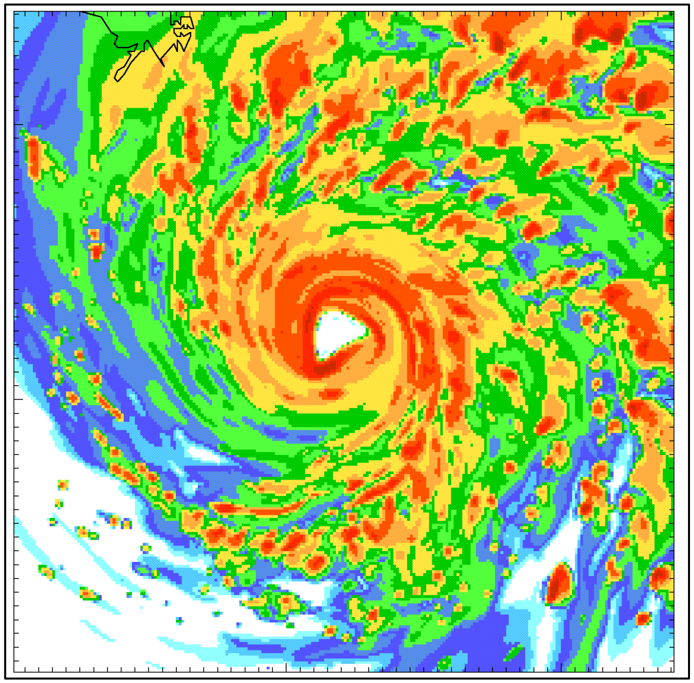
Introduction to the Weather Research & Forecast (WRF) System, a High-Resolution Atmospheric Model

Gary Clow
USGS / INSTAAR
clow@usgs.gov

CSDMS
COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

WRF Clinic Outline

1. *Introduction and Welcome*
2. *Overview of WRF Modeling System*
3. *Resources*
4. *Steps for Running WRF*
5. *Examples*
6. *Q & A*



Note: A Basic Model Interface (BMI) is currently being developed for WRF so it can be readily coupled with other models in the CSDMS system.

2. Overview of the WRF Modeling System

What is WRF?

2. Overview of the WRF Modeling System

What is WRF?

- State-of-the-art mesoscale atmospheric modeling system

    designed to serve both atmospheric research & NWP communities

    (flexible, modular, ...)

- Solves fully compressible non-hydrostatic Euler equations

    (conservation of mass, momentum, energy)

    designed for use at scales ranging from meters to 1000s of kilometers

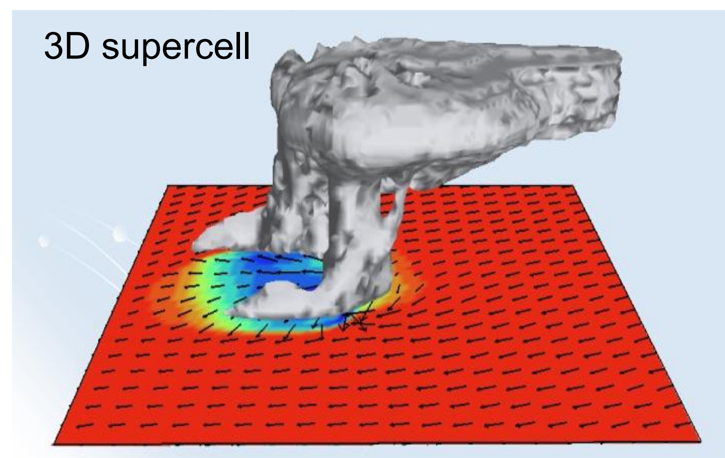
- Community model

    distributed development, centralized support

- Primary developers

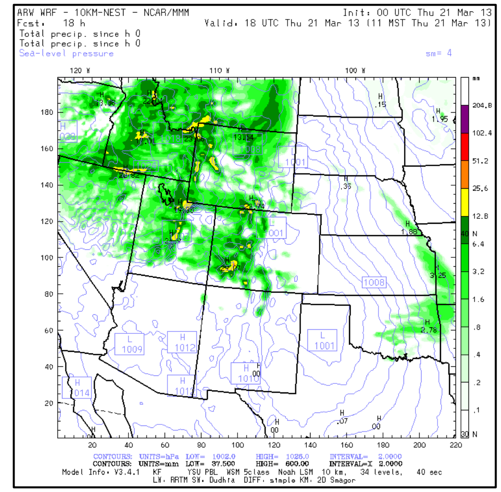
    NCAR, NOAA-ESRL, NOAA-NCEP

    + universities & govt agencies in U.S. and oversees



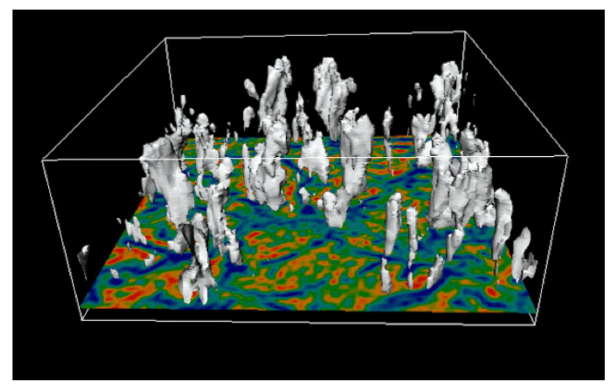
2. Overview of the WRF Modeling System

WRF Applications



- Real-time numerical weather prediction (NWP)
  - *Daily weather and severe storm forecasts by NOAA, AFWA, ...*
  - *Air-quality forecasts*
  - *Forest fires*
  - *Wind & solar forecasts for power utilities*

- Atmospheric Research
  - *Atmospheric physics / parameterization research*
  - *Real-time NWP and forecasting research*
  - *Regional climate and seasonal time-scale research*
  - *Landsurface interactions*
  - *Coupled-chemistry research*
  - *Idealized simulations at many scales*
    - *(e.g. mountain waves, convection, LES, ...)*
  - *Planetary research (Mars, Titan, ...)*



Convective Updraft (Moeng, NCAR)

2. Overview of the WRF Modeling System

WRF now comes in multiple flavors!

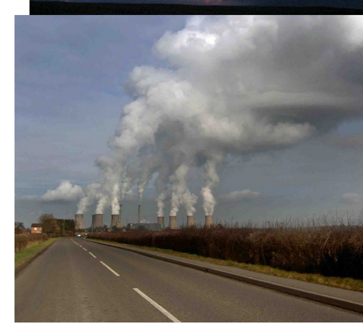
- 2 Dynamical Cores *(standard model)*

  ARW: Advanced Research WRF core → *supported by NCAR*

  NMM: Nonhydrostatic Mesoscale Model core → *supported by NOAA/NCEP*

- Specialized Versions of WRF

HWRF	*forecasts the track and intensity of tropical cyclones (NOAA)*
WRF-AHW	*WRF-ARW for hurricane research (NCAR)*
WRF-Fire	*2-way coupling of forest fire behavior with atmospheric dynamics*
WRF-Chem	*couples chemistry with WRF-ARW*
Polar WRF	*WRF-ARW modified for polar regions*
CWRF	*WRF-ARW modified for Regional Climate Modeling*
CLWRF	*WRF-ARW modified for Regional Climate Modeling*
planetWRF	*WRF-ARW modified for planetary research*



2. Overview of the WRF Modeling System

Who uses WRF?

- Operational forecast centers

    In the U.S. and other countries

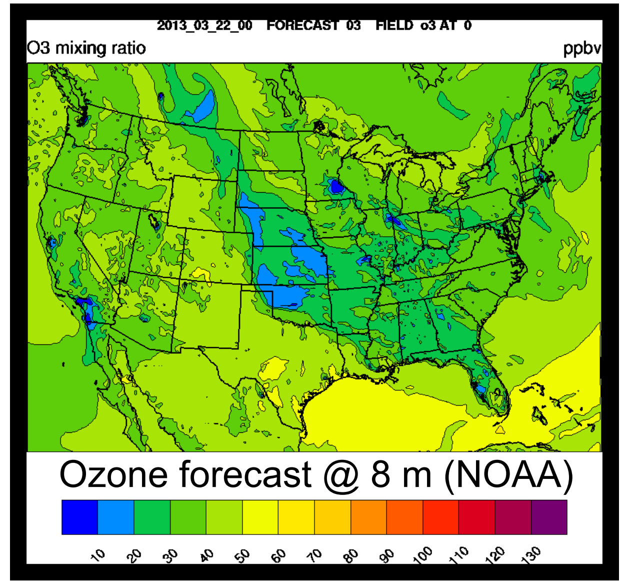
- Academic research scientists

    Atmospheric dynamics, physics, weather, climate ...

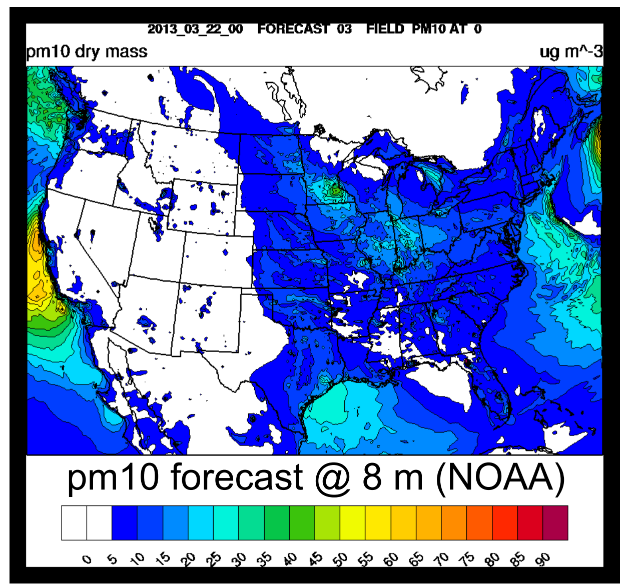
- Applications scientists

    Air quality, hydrology, utilities

There are currently over 20,000 users of WRF from 130 countries.



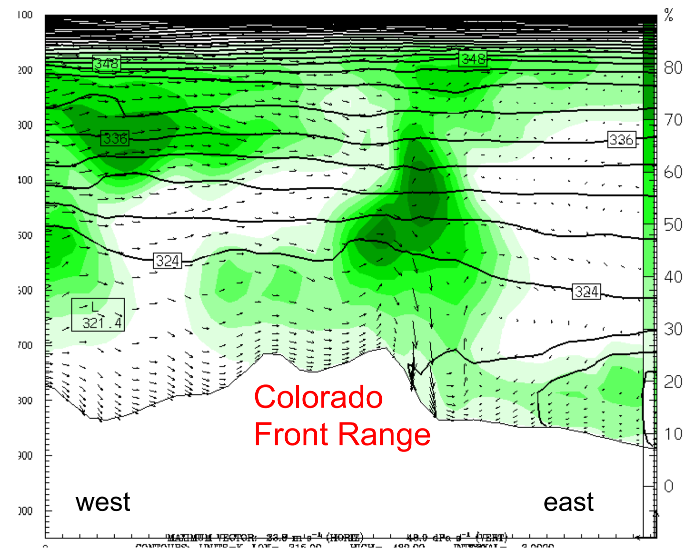
Ozone forecast @ 8 m (NOAA)

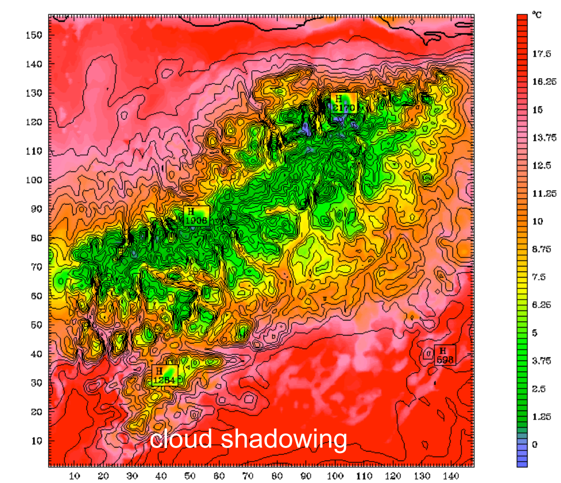


pm10 forecast @ 8 m (NOAA)

WRF Physics Modules & Coupling

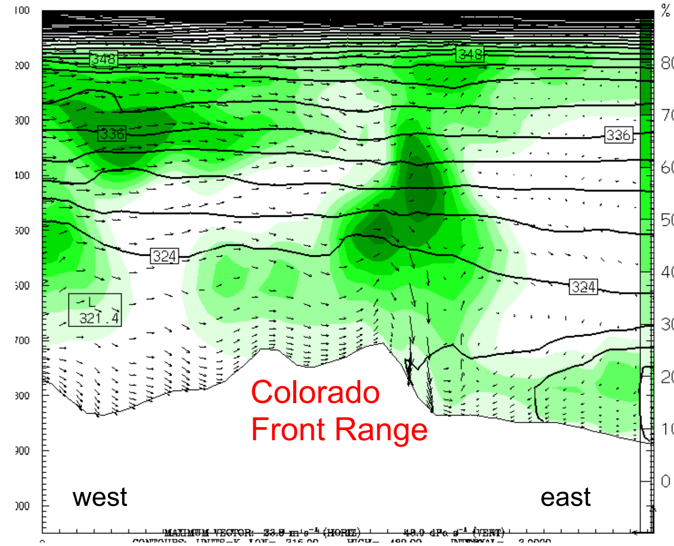
- **Dynamics Solver** – *integrates the compressible non-hydrostatic Euler equations (ARW, NMM)*
- Shortwave Radiation
- Longwave Radiation
- Cloud Microphysics
- Cumulus Cloud Parameterization *(dx > 10 km)*
- Planetary Boundary Layer *(dz > 100 m)*
- Land Surface Model





WRF Physics Modules & Coupling

Dynamics Solver – *integrates the compressible non-hydrostatic Euler equations (ARW, NMM)*



Shortwave Radiation

- *Dudhia, Goddard, CAM, RRTMG, FLG, GFDL*

Longwave Radiation

- *RRTM, CAM, RRTMG, Goddard, FLG, Held-Suarez, GFDL*

Cloud Microphysics

- *Kessler; Lin; NCEP; WSM 3,5,6 class; Eta; Goddard; Thompson; Milbrandt; Morrison; SBU-Ylin; WDM 5,6 class, NSSL 2-moment*

Cumulus Cloud Parameterization

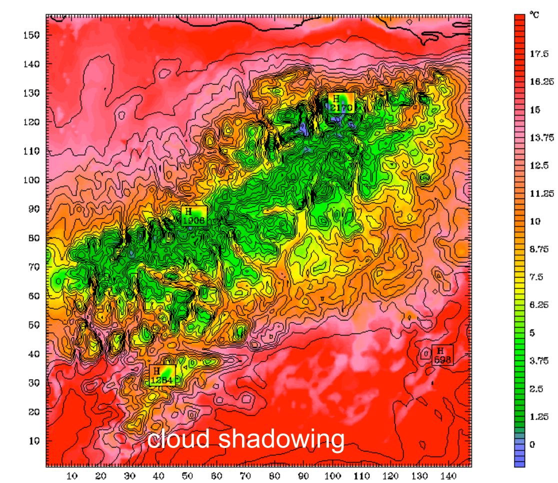
- *Kain-Fritsch, Betts-Miller-Janjic, Grell-Devenvi, Arakawa-Schubert, Grell-3, Tiedtke, Zhang-McFarlane, new SAS*

Planetary Boundary Layer

- *YSU, MYJ, GFS, QNSE, MYNNx, ACM2, BouLac, UW, TEMF, MRF*

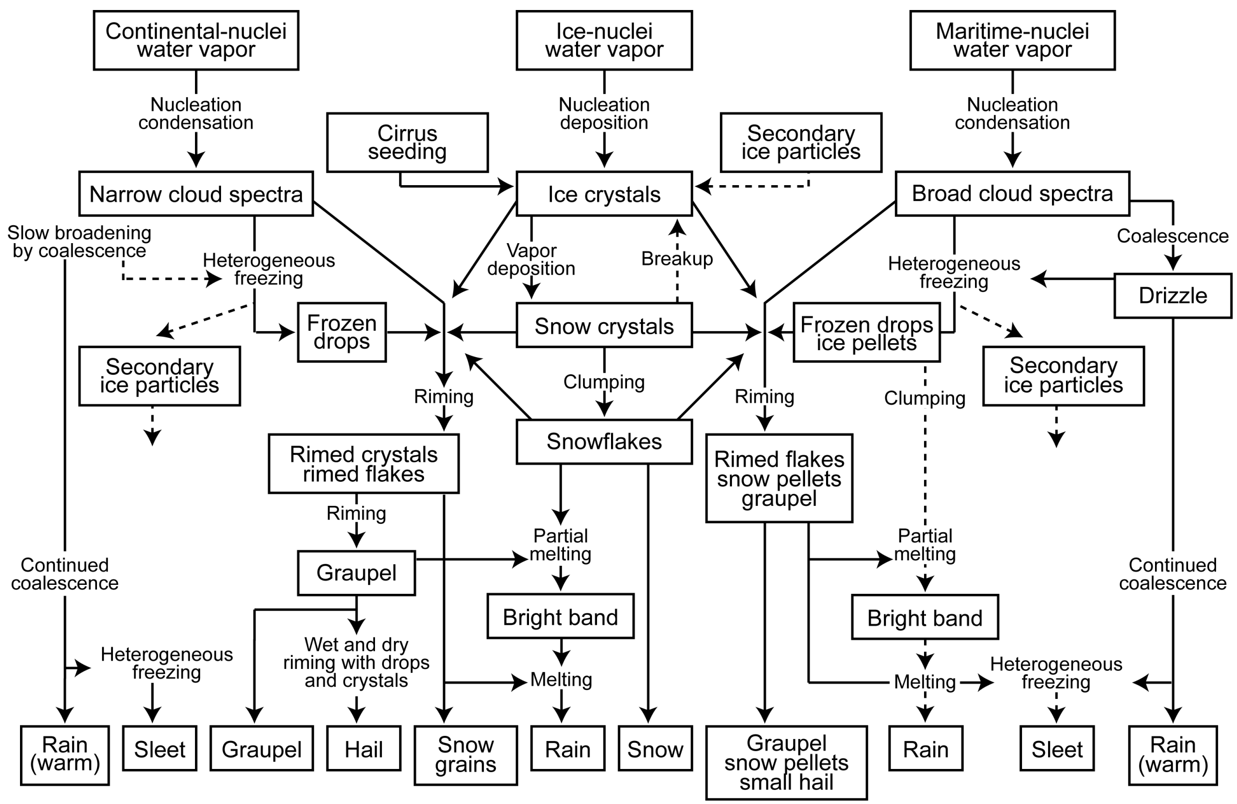
Land Surface Model

- *Noah LSM, RUC LSM, Pleim-Xiu LSM, NoahMP, SSiB, (CLM)*



WRF Physics Modules & Coupling

Cloud Microphysics - parameterizations



from Dudhia, Overview of WRF Physics

WRF Physics Modules & Coupling

Cloud Microphysics – schemes in v3.4

mp_physics	Scheme	Cores	Mass Variables	Number Variables
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW (Chem)	Qc Qr Qi Qs Qg	
3	WSM3	ARW	Qc Qr	
4	WSM5	ARW NMM	Qc Qr Qi Qs	
5	Eta (Ferrier)	ARW NMM	Qc Qr Qs (Qt*)	
6	WSM6	ARW NMM	Qc Qr Qi Qs Qg	
7	Goddard	ARW	Qc Qr Qi Qs Qg	
8	Thompson	ARW NMM	Qc Qr Qi Qs Qg	Ni Nr
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10	Morrison 2-mom	ARW (Chem)	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
13	SBU-YLin	ARW	Qc Qr Qi Qs	
14	WDM5	ARW	Qc Qr Qi Qs	Nn Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn Nc Nr
17	NSSL 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
18	NSSL 2-mom+ccn	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh Nn

from Dudhia, Overview of WRF Physics

WRF Physics Modules & Coupling

Cloud Microphysics

– interaction with Longwave Radiation schemes

ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	CO2*
1	RRTM	ARW NMM	Qc Qr Qi Qs Qg	1/0	330
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	yearly
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	379
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	337
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	345
31	Held-Suarez	ARW	none	none	none
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	fixed

from Dudhia, Overview of WRF Physics

WRF Physics Modules & Coupling

Cloud Microphysics

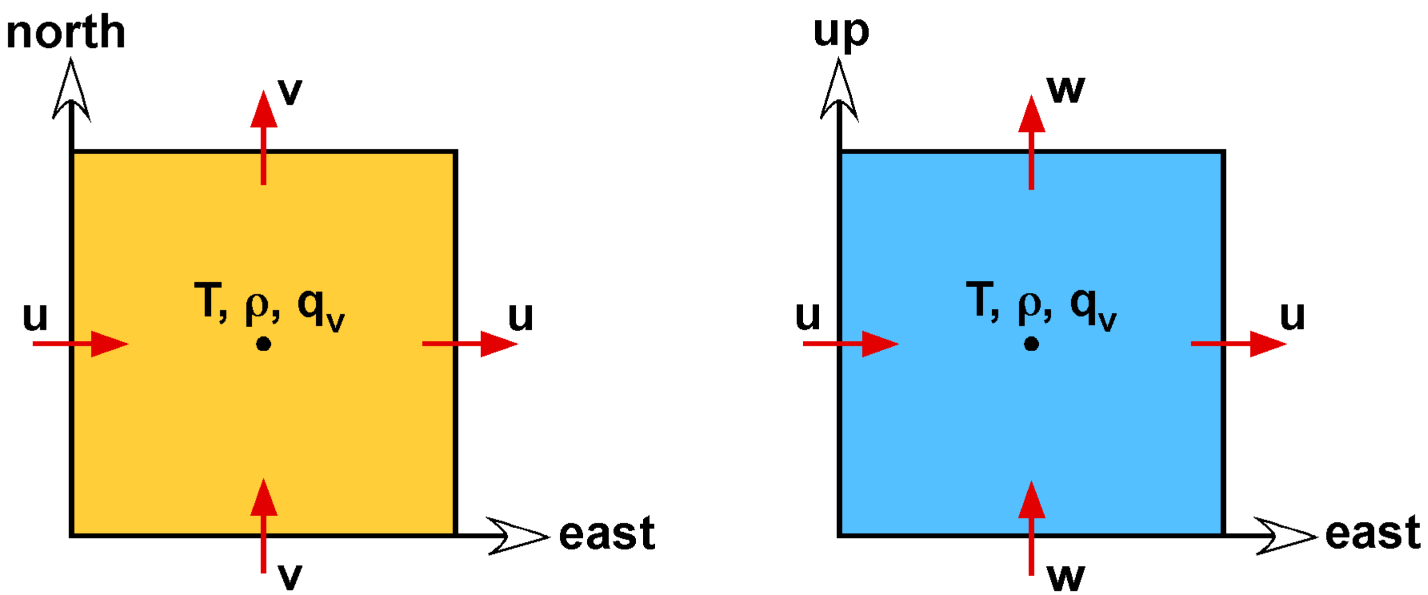
– interaction with Shortwave Radiation schemes

ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	Ozone
1	Dudhia	ARW NMM + Chem(PM2.5)	Qc Qr Qi Qs Qg	1/0	none
2	GSFC	ARW +Chem(τ)	Qc Qi	1/0	5 profiles
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	Lat/ month
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	1 profile
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	Lat/date

from Dudhia, Overview of WRF Physics

Spatial Discretization

Arakawa C-grid



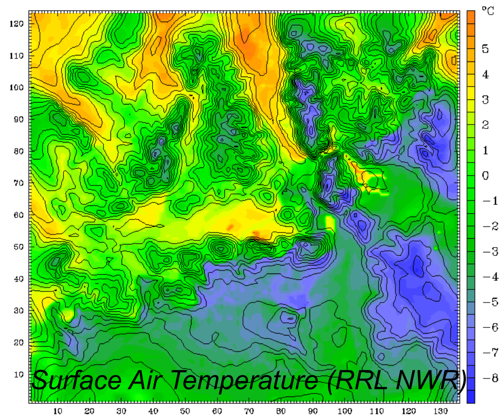
horizontal ***vertical***

WRF uses the flux-form of the Euler equations
(conserves mass, enthalpy, …)

WRF Output & Diagnostic Fields

Atmosphere, Precipitation

- air temperature
- pressure
- density
- water vapor density
- wind speed & direction
- vorticity
- convective instability
- precipitation (rain, sleet, graupel, hail, snow)
- convective vs. non-convective precip.
- column-integrated precipitable water
- cloud cover
- cloud ceiling
- cloud-top temperature



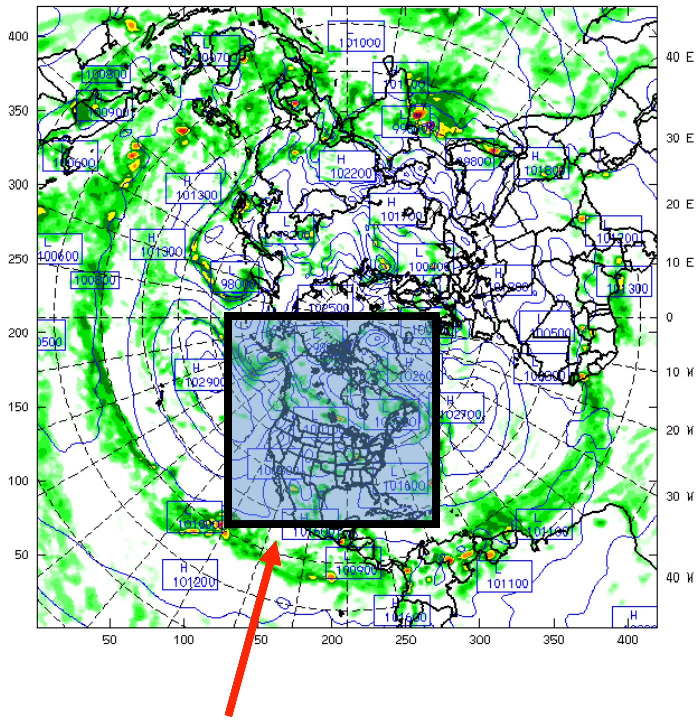
Near Surface

- surface skin temperature
- soil temperature
- snow depth
- snow water equivalent
- soil moisture
- soil liquid water
- downward shortwave flux @ sfc
- downward longwave flux @ sfc
- upward sensible heat flux @ sfc
- upward moisture flux @ sfc
- upward latent heat flux @ sfc
- ground heat flux
- wind shear
- surface friction velocity u*
- surface runoff
- underground runoff

Boundary & Initial Conditions

1) Retrospective Analyses

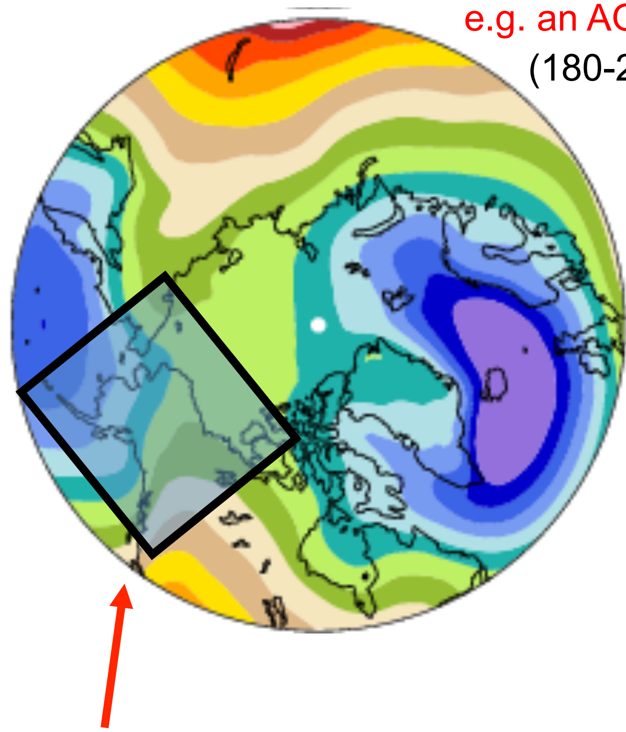
e.g. NCEP Global Analysis (110-250 km)



Nest WRF within observed large-scale circulation.

2) Future (or Past) Projections

e.g. an AOGCM (180-250 km)



Nest WRF within large-scale circulation projected by a global model.

Initial Conditions

- Lower Boundary

  elevation

  vegetation categories

  soil categories

  water categories (ocean, lake)

  albedo

  surface roughness

  surface pressure

  surface temperature (land & ocean)

  soil temperature

  soil moisture

  snow cover

  sea-ice coverage

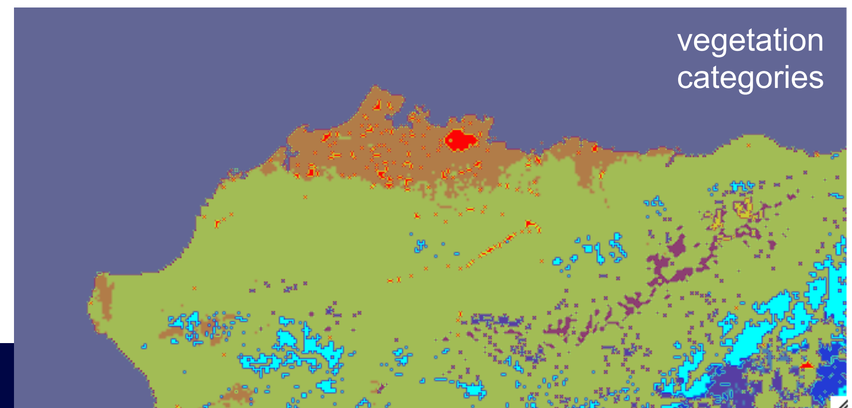
- 3D Fields

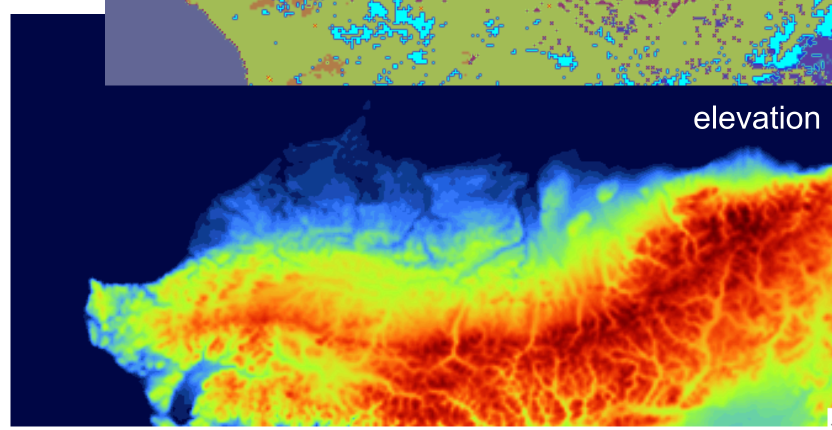
  air temperature

  winds

  relative humidity

  geopotential height





Boundary Conditions

- Lateral boundaries *(every 6 hours)*

  air temperature

  winds

  relative humidity

  geopotential height

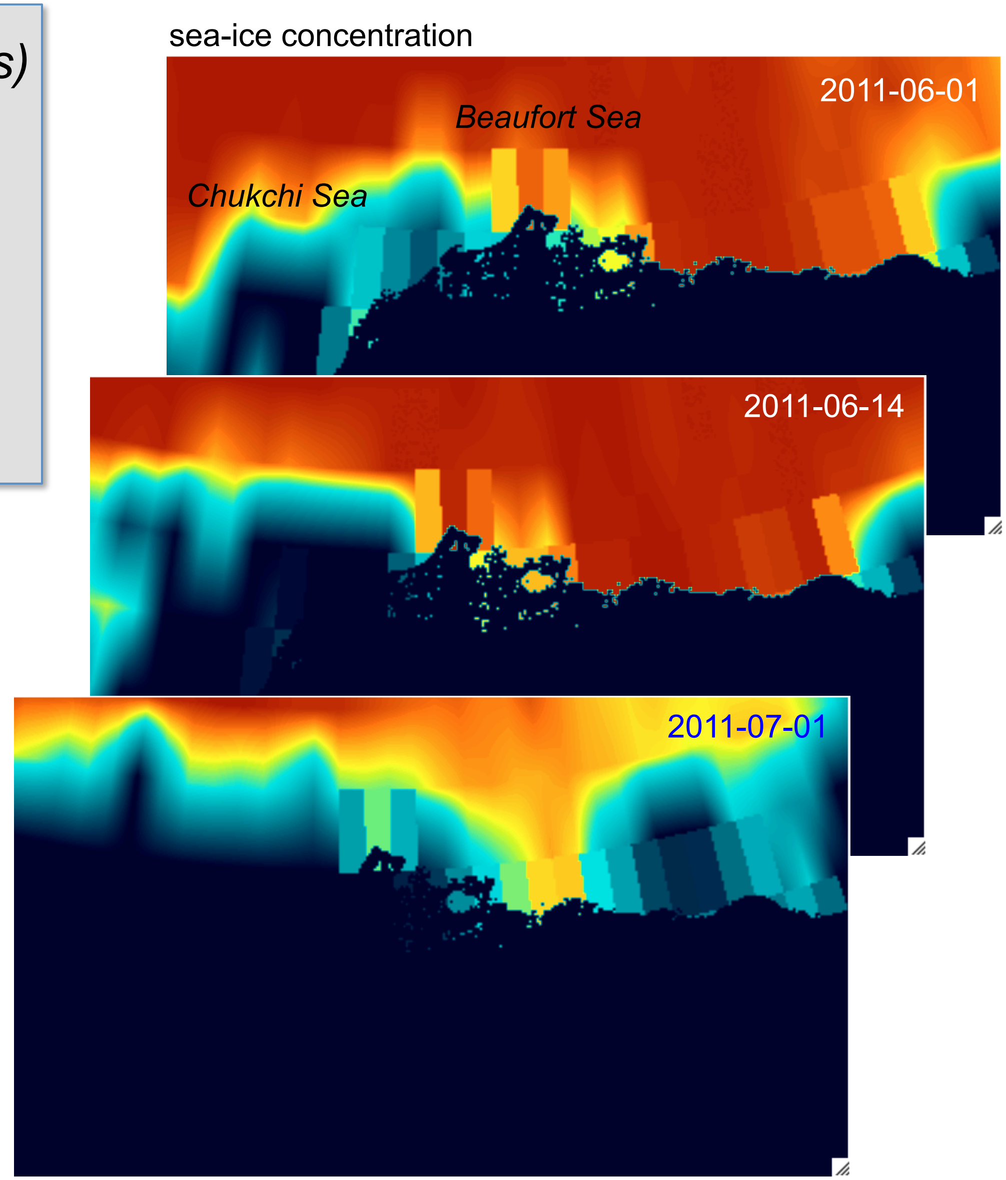
  surface pressure

- Lower boundary*

  SSTs

  sea-ice coverage

* for runs longer than 1 week



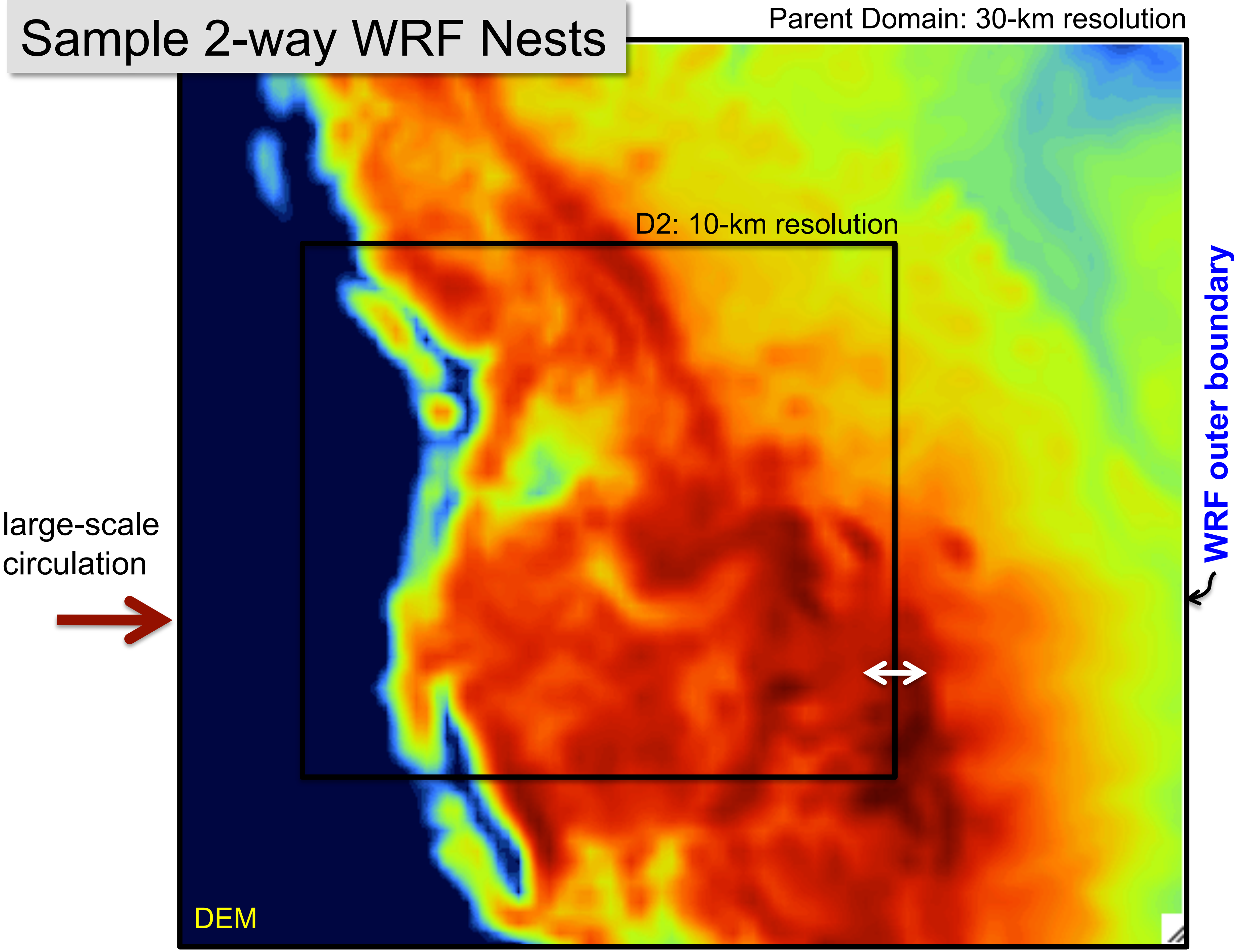
WRF Nesting Capability

Provides higher resolution in nested areas.

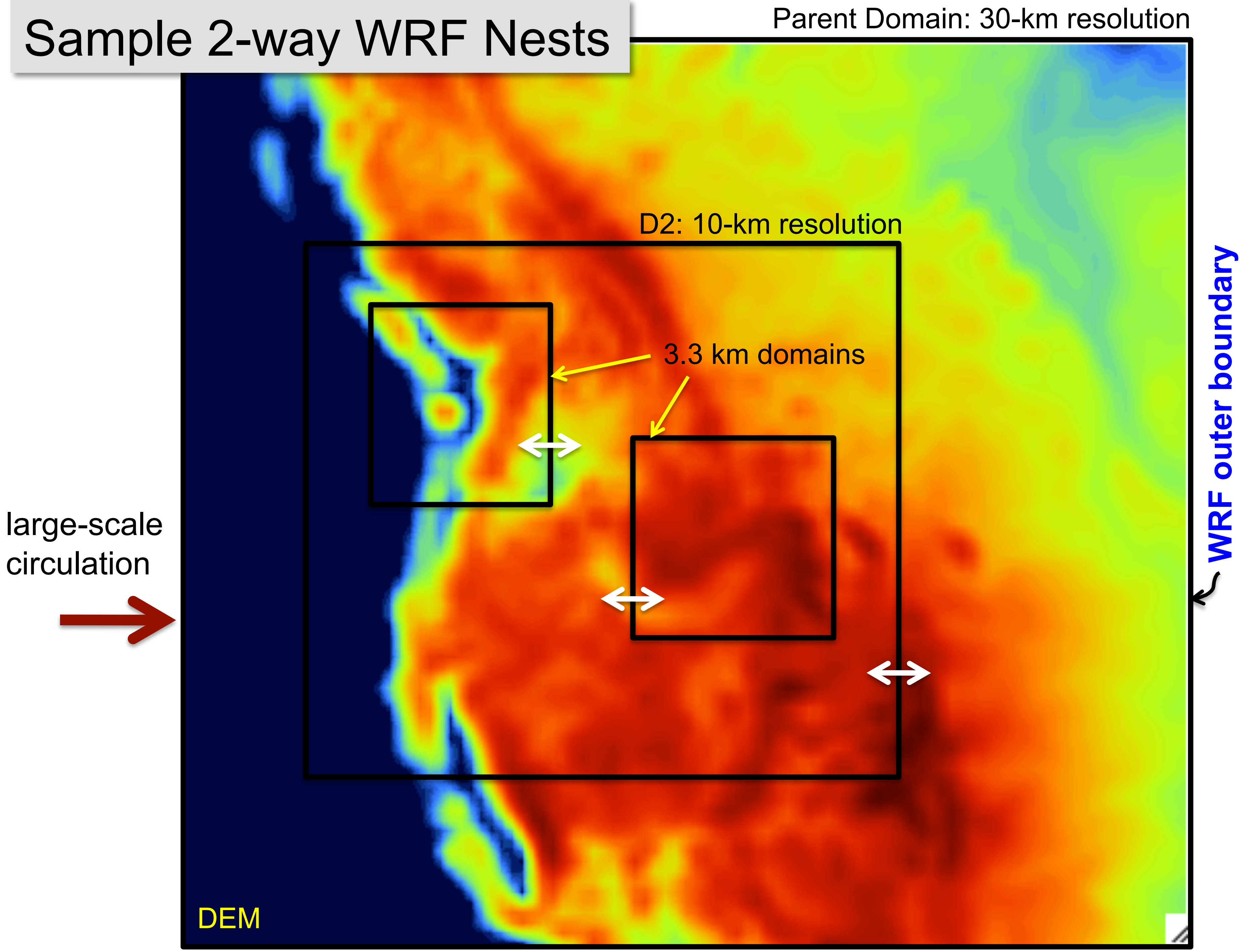
- 1-way
- 2-way interactive
- moving nest

Example 2-way: Red Rock Lakes NWR, Montana

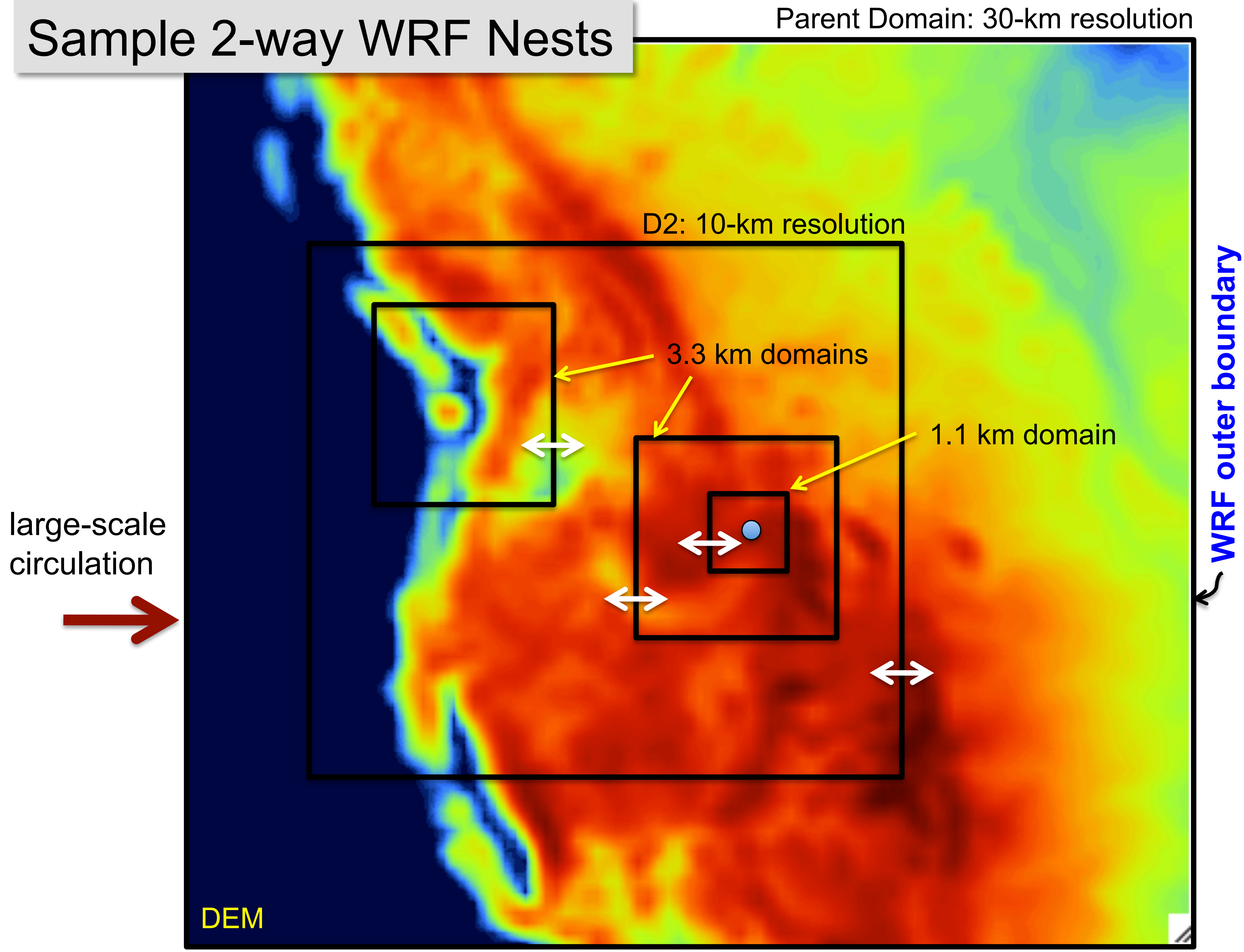
Sample 2-way WRF Nests



Sample 2-way WRF Nests

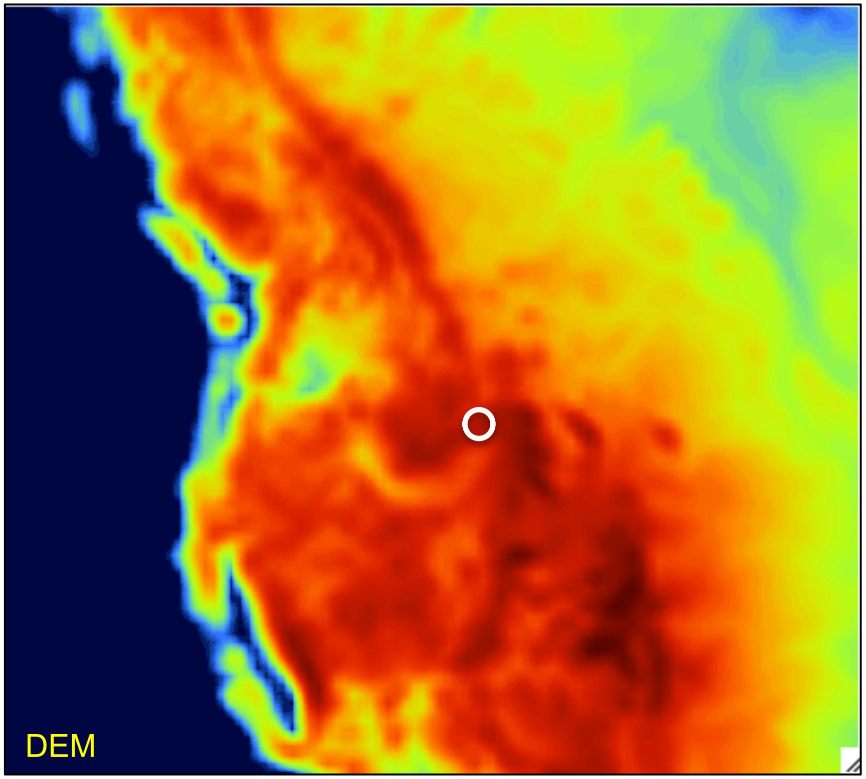


Sample 2-way WRF Nests



30 km

Parent Domain: 150 s

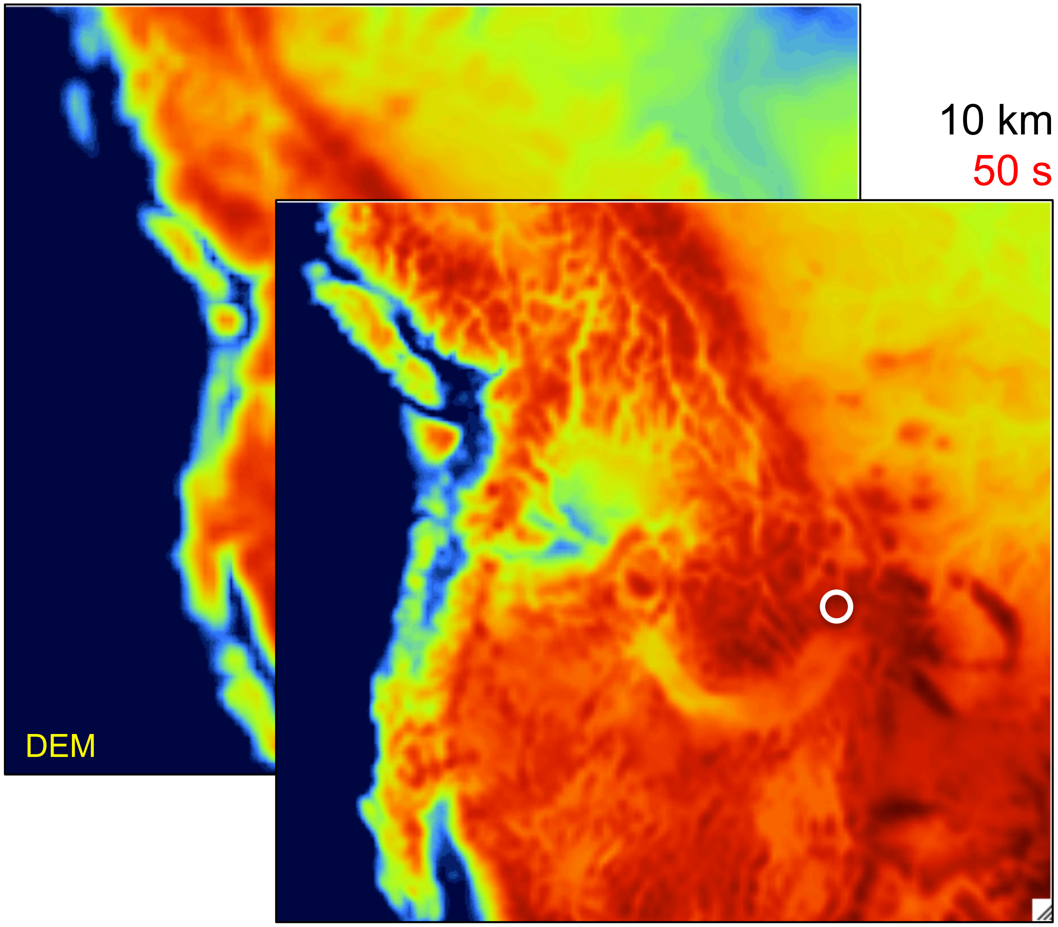


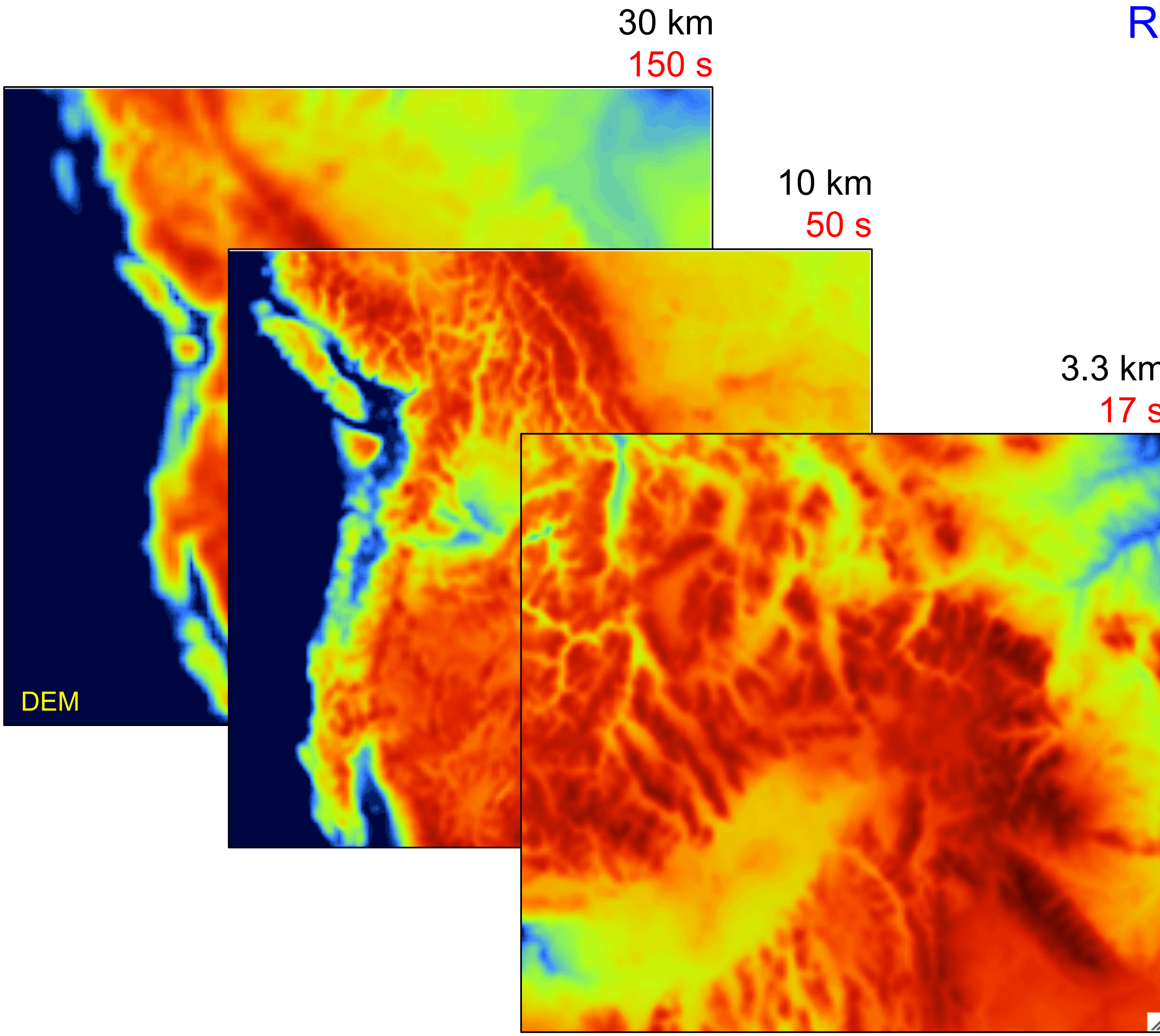
Red Rock Lakes NWR

Red Rock Lakes NWR

30 km
150 s

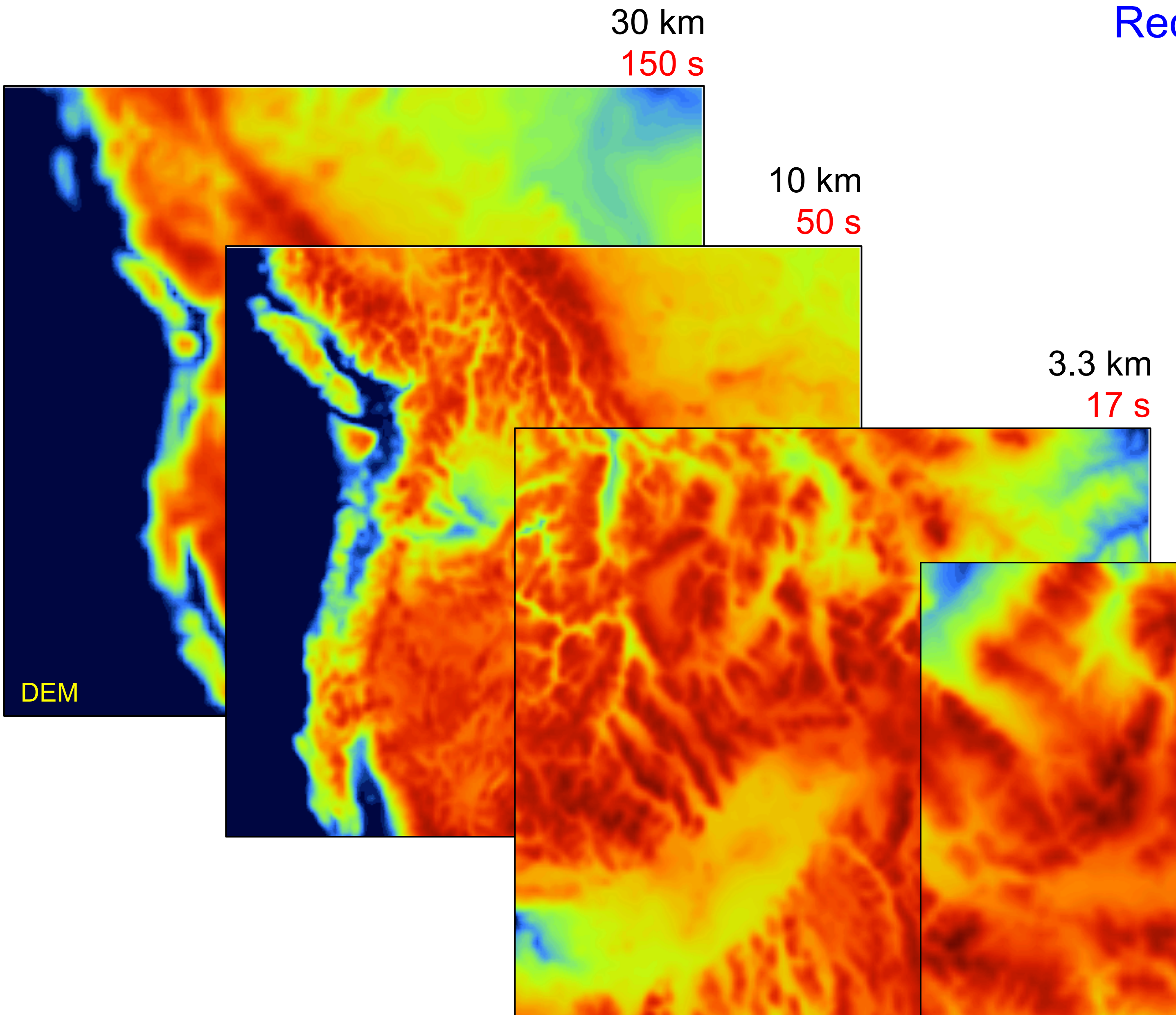
10 km
50 s

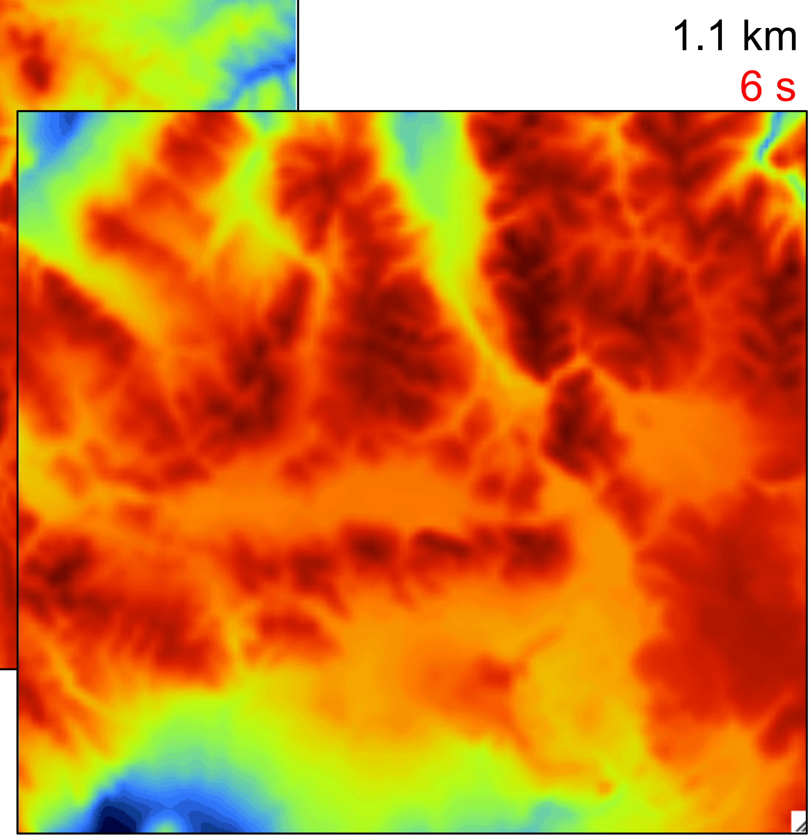




Red Rock Lakes NWR

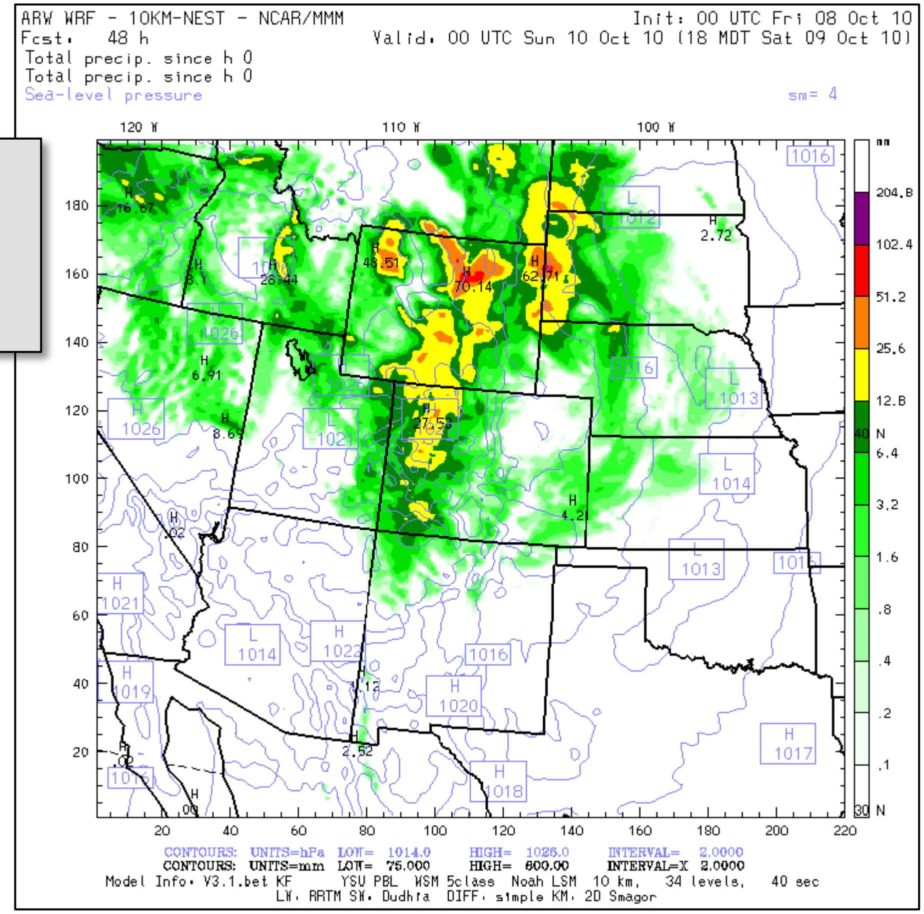
Red Rock Lakes NWR



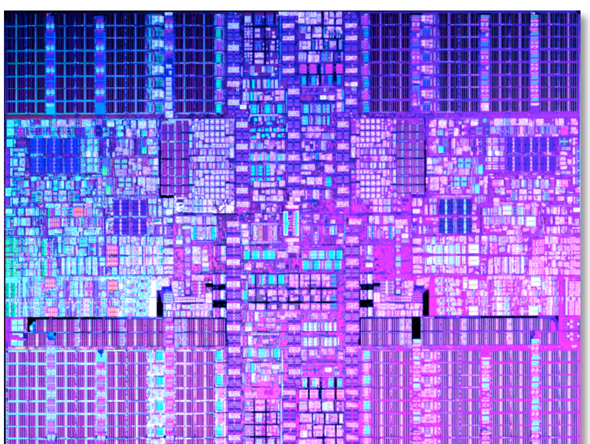


The Need for Parallel

A **48-hr WRF forecast** for the continental U.S. would take **52 hours** to calculate at 12-km resolution on a:



Dual core, 4.7 GHz chip
64-bit floating point precision
16 GB per processor
~ 6 Gflop/s (circa 2008)



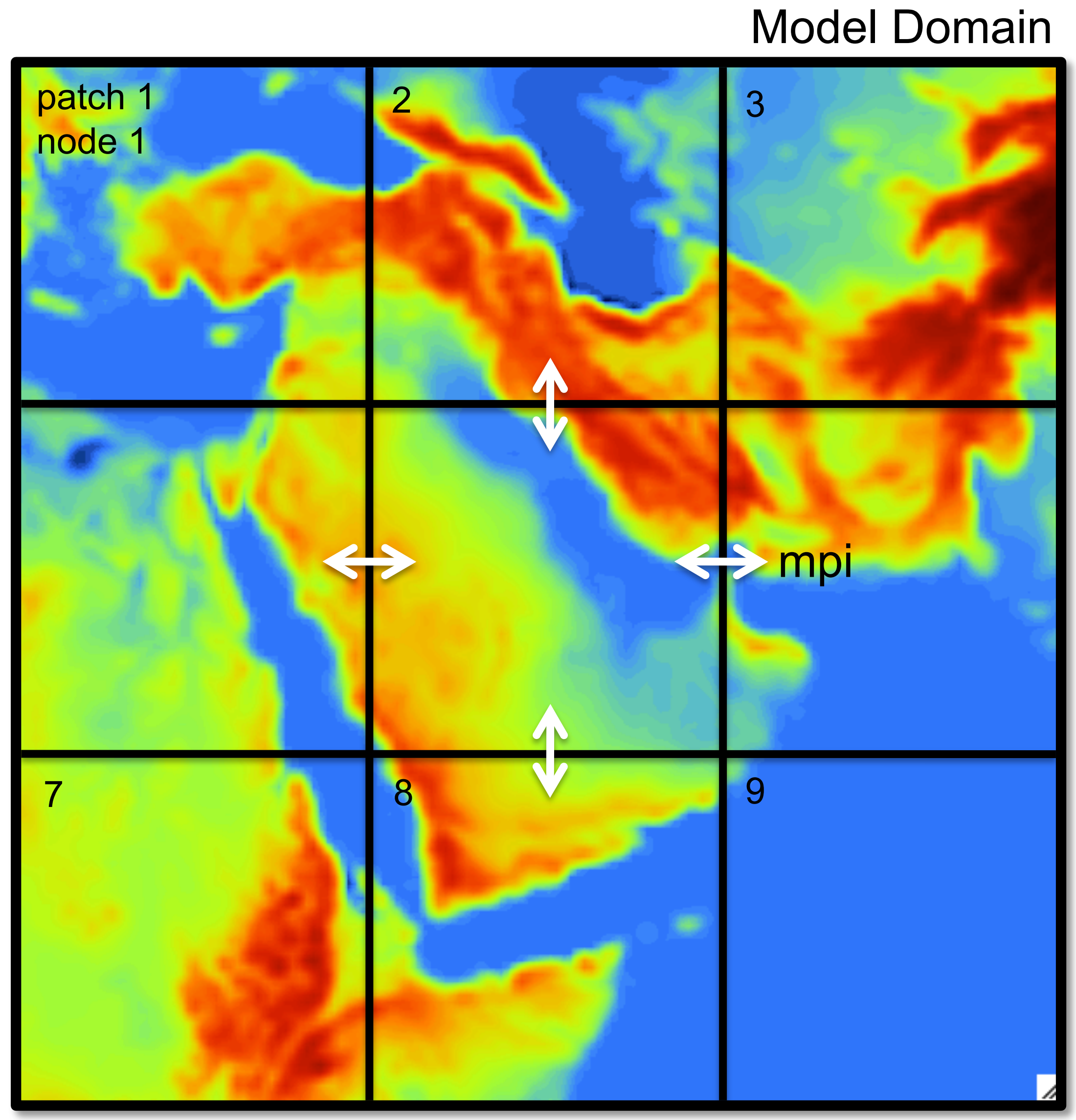
2 Levels of WRF Parallelism

Distributed Memory Parallel

- Model domain is decomposed into Patches, one for each distributed memory Node.

- Communication: MPI

Example: 9 available nodes,
9 patches

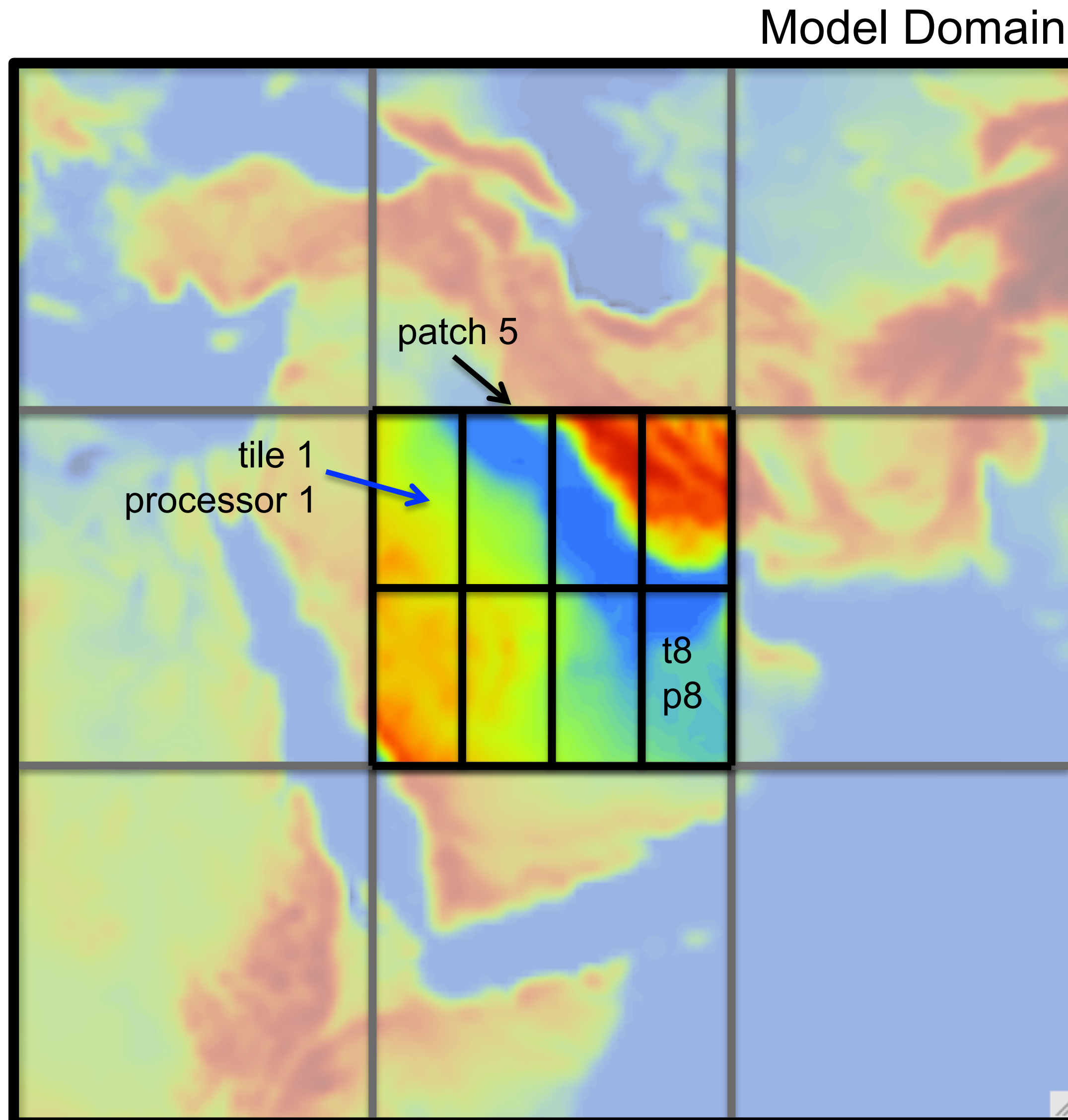


2 Levels of WRF Parallelism

Shared Memory Parallel

- Each patch is decomposed into Tiles, one for each shared memory processor.
- Communication: OpenMP

Example: 8 processors per node



2 Levels of WRF Parallelism

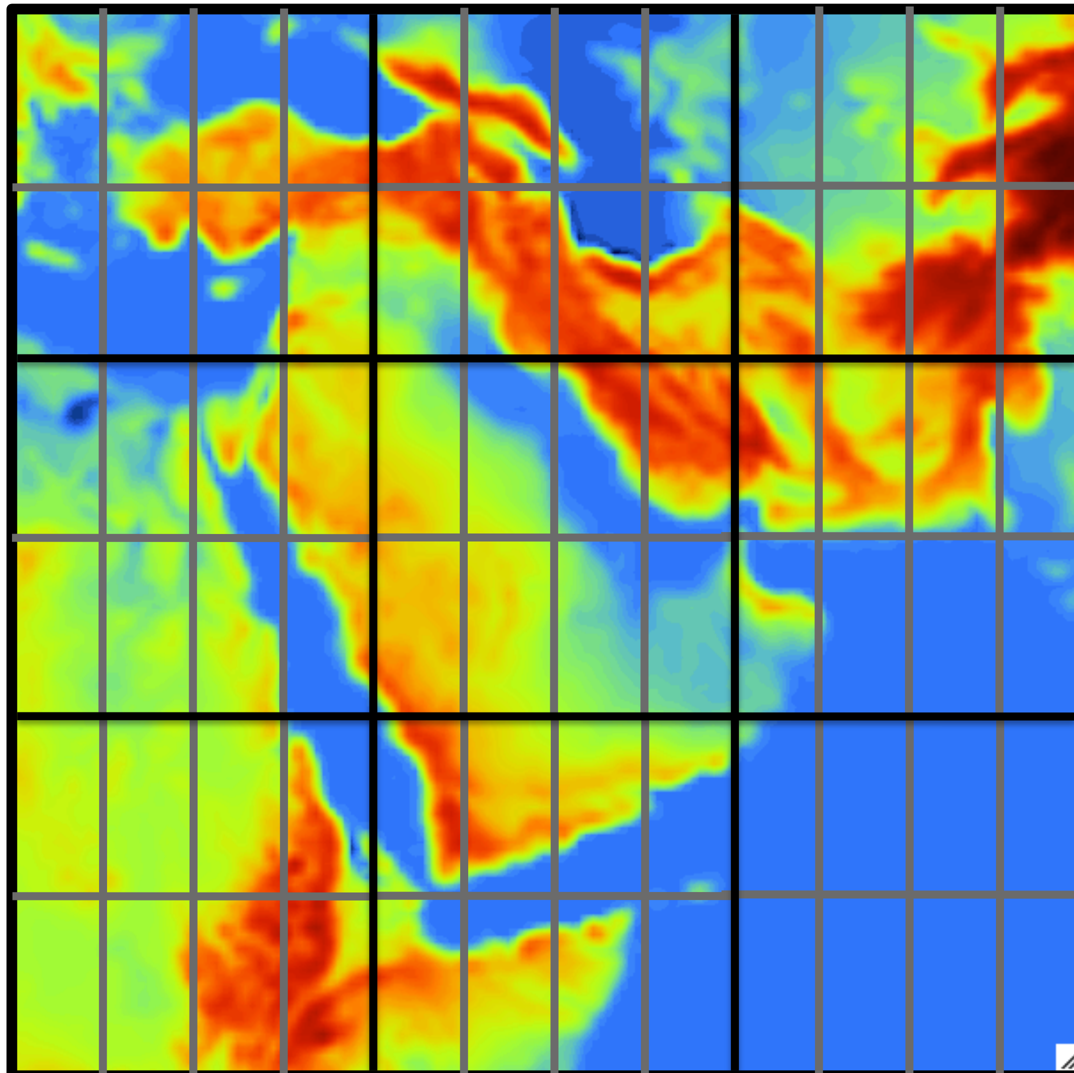
Shared + Distributed Memory Parallel

- Model domain is decomposed into Patches & Tiles.
- Communication:

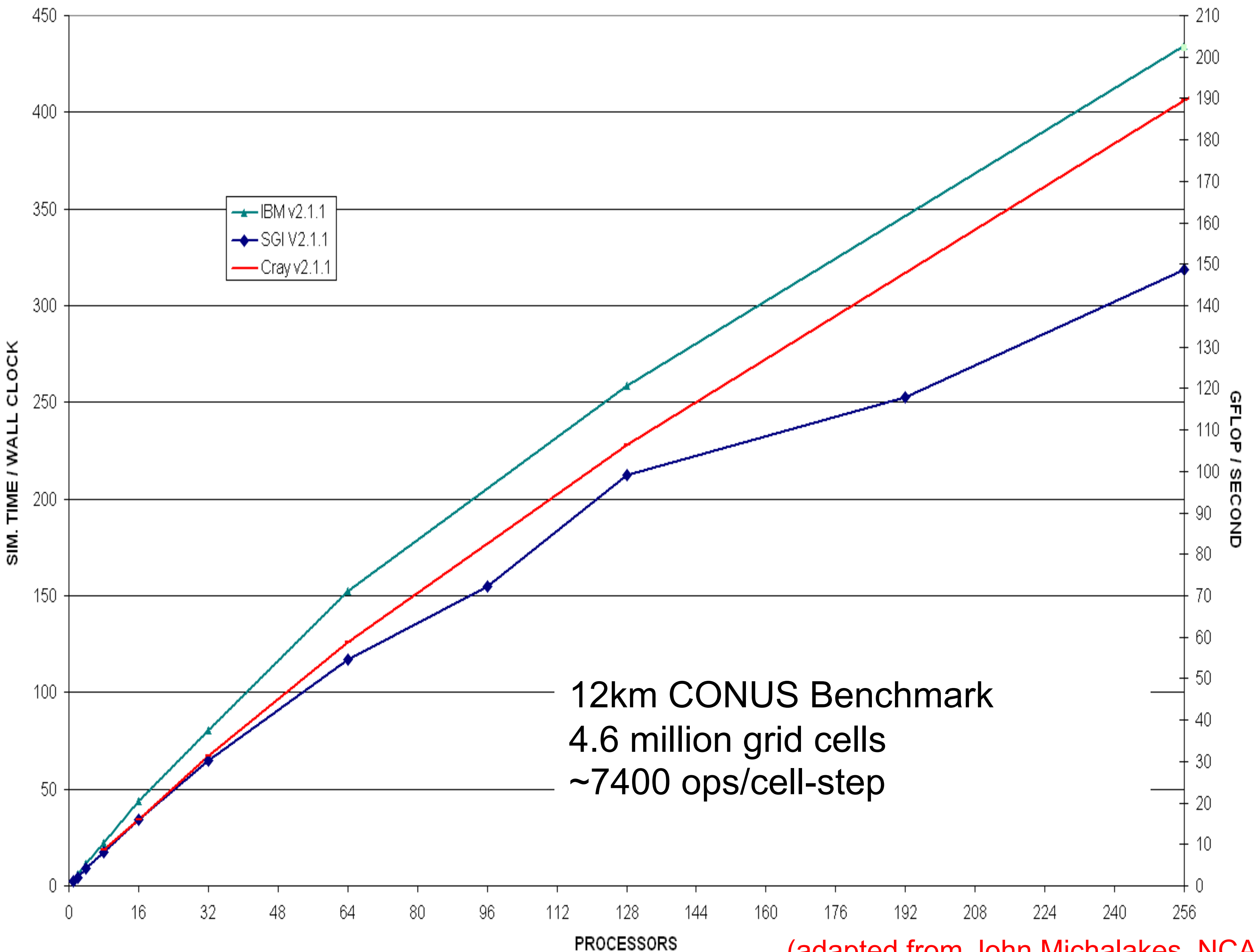
  OpenMP & MPI

Example: 9 available nodes,
72 processors

Model Domain

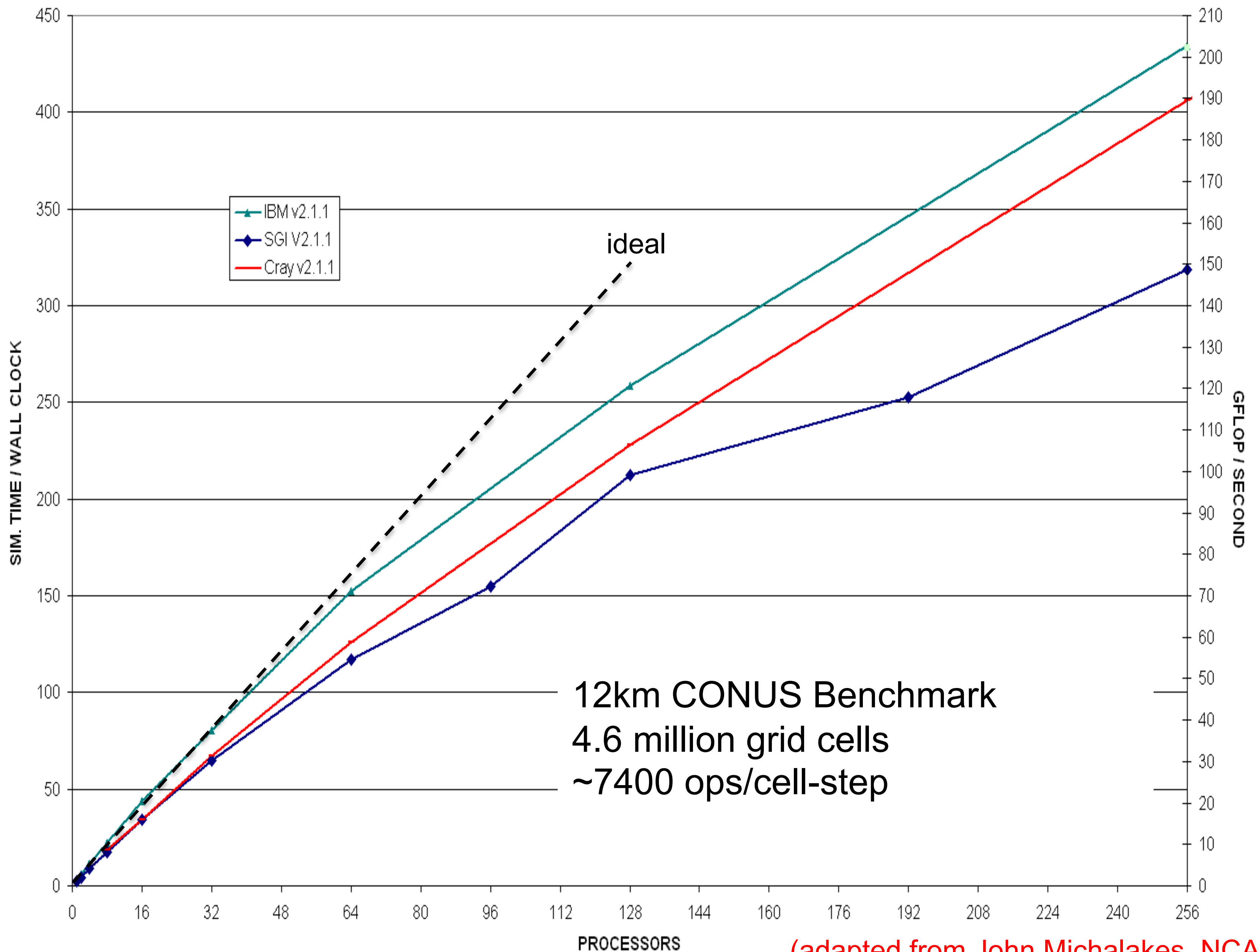


WRF Multiprocessor Performance



(adapted from John Michalakes, NCAR)

WRF Multiprocessor Performance



(adapted from John Michalakes, NCAR)

Software / Hardware Requirements

Platforms

Vendor	Hardware	OS
Cray	X1	UniCOS
Cray	AMD	Linux
IBM	Power Series	AIX
IBM	Power Series	Linux
SGI	IA64/Opteron	Linux
COTS*	IA32	Linux
COTS*	IA64/Opteron	Linux
Mac	Power Series	Darwin
Mac	Intel	Darwin
NEC	NEC	Linux

* commercial off the shelf

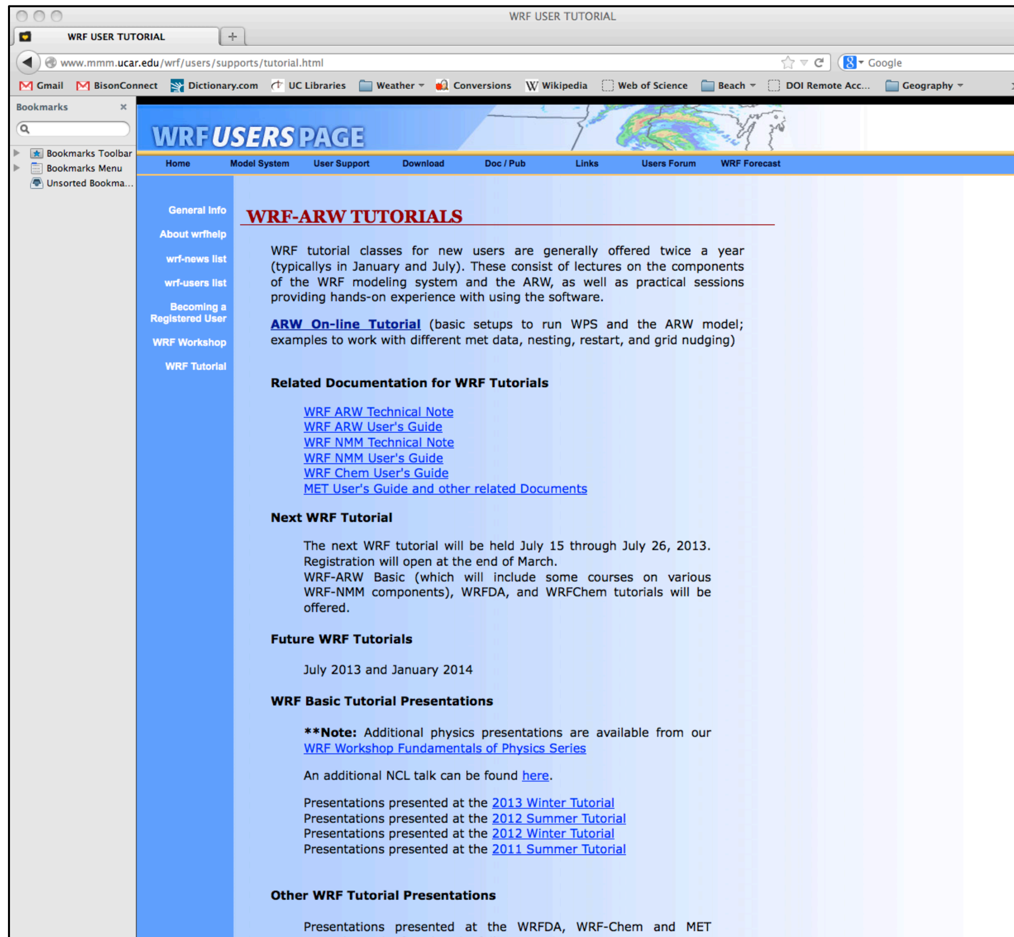
Software

- Fortran 90/95 compiler
- C compiler
- Perl
- netcdf library
- Public domain mpich for MPI
- NCAR Graphics is also handy

CSDMS HPCC (beach)

3. Resources

- *WRF model description and documentation*
- *WRF tutorials*
- *Links to model download site*
- *Links to site for downloading data needed to drive WRF*
- *Links to specialized WRF versions*
- *Real-time WRF forecasts*



3. Resources

- WRF home page

  http://www.wrf-model.org/index.php

- WRF-ARW user's page

  http://www.mmm.ucar.edu/wrf/users/

- WRF-NMM user's page

  http://www.dtcenter.org/wrf-nmm/users/

- WRF tutorials

  http://www.mmm.ucar.edu/wrf/users/supports/tutorial.html

- WRF source code

  http://www.mmm.ucar.edu/wrf/users/download/get_source.html

- Datasets for WRF

  http://rda.ucar.edu/

- Real-time WRF forecasts

  http://wrf-model.org/plots/realtime_main.php

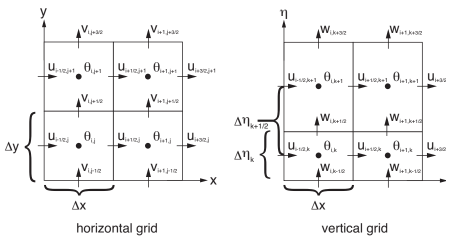


Figure 3.2: Horizontal and vertical grids of the ARW

where the discrete operator $\overline{a}^x$ denotes a linear interpolation operator. The grid lengths Δx and Δy are constant, hence in this case the operator reduces to $\overline{a}^x = (a_{i+1/2} + a_{i-1/2})/2$.

Using these definitions, we can write the spatially discrete acoustic step equations (3.7) – (3.12) as

$$\partial_t U'' + (m_x/m_y)\overline{(\alpha^{t^*}/\alpha_d^{t^*})}^x \Big[\overline{\mu_d^{t^*}}^x \Big(\overline{\alpha_d^{t^*}}^x \partial_x p''^\tau + \overline{\alpha_d''^\tau}^x \partial_x \overline{p} + \partial_x \overline{\phi''^\tau}^\eta \Big) + \partial_x \overline{\phi^{t^*}}^\eta \Big(\partial_\eta \overline{\overline{p''}^x}^\eta - \overline{\mu_d''}^x \Big)^\tau \Big] = R_U^{t^*} \tag{3.21}$$

$$\partial_t V'' + (m_y/m_x)\overline{(\alpha^{t^*}/\alpha_d^{t^*})}^y \Big[\overline{\mu_d^{t^*}}^y \Big(\overline{\alpha_d^{t^*}}^y \partial_y p''^\tau + \overline{\alpha_d''^\tau}^y \partial_y \overline{p} + \partial_y \overline{\phi''^\tau}^\eta \Big) + \partial_y \overline{\phi^{t^*}}^\eta \Big(\partial_\eta \overline{\overline{p''}^y}^\eta - \overline{\mu_d''}^y \Big)^\tau \Big] = R_V^{t^*} \tag{3.22}$$

$$\delta_\tau \mu_d'' + m_x m_y [\delta_x U'' + \delta_y V'']^{\tau+\Delta\tau} + m_y \delta_\eta \Omega''^{\tau+\Delta\tau} = R_\mu^{t^*} \tag{3.23}$$

$$\delta_\tau \Theta'' + m_x m_y [\delta_x (U'' \overline{\theta^{t^*}}^x) + \delta_y (V'' \overline{\theta^{t^*}}^y)]^{\tau+\Delta\tau} + m_y \delta_\eta (\Omega''^{\tau+\Delta\tau} \overline{\theta^{t^*}}^\eta) = {R_\Theta}^{t^*} \tag{3.24}$$

$$\delta_\tau W'' - m_y^{-1} g \overline{\Big\{ \overline{(\alpha/\alpha_d)^{t^*}}^\eta \Big[\delta_\eta (C \delta_\eta \phi'') + \delta_\eta \Big(\frac{c_s^2}{\alpha^{t^*}} \frac{\Theta''}{\Theta^{t^*}} \Big) \Big] - \mu_d'' \Big\}}^\tau = {R_W}^{t^*} \tag{3.25}$$

$$\delta_\tau \phi'' + \frac{1}{\mu_d^{t^*}} [m_y \Omega''^{\tau+\Delta\tau} \delta_\eta \overline{\phi^{t^*}}^\eta - m_y g \overline{W''}^\tau] = {R_\phi}^{t^*}, \tag{3.26}$$

where the discrete operator

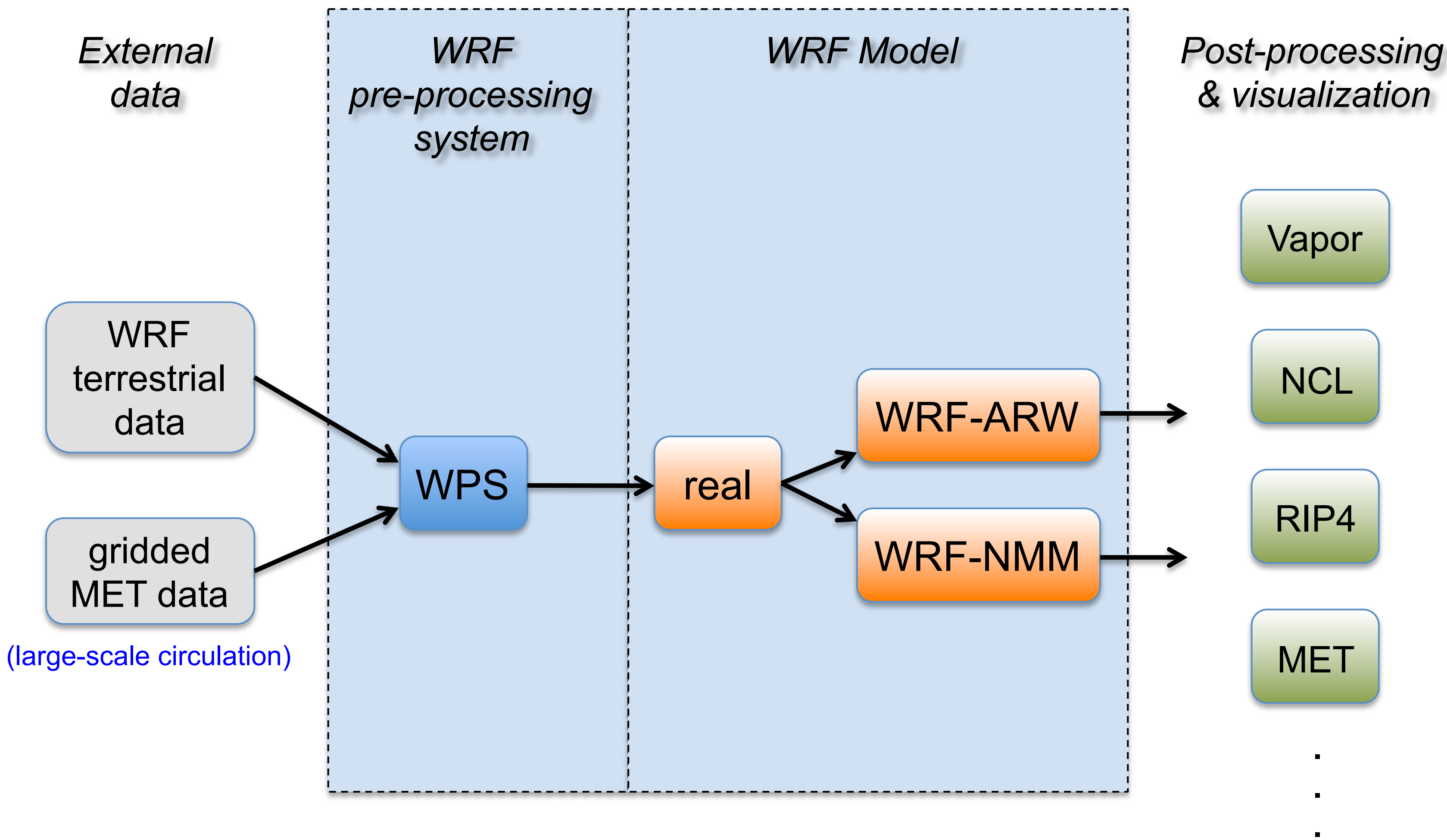
$$\delta_x a = \Delta x^{-1} (a_{i+1/2} - a_{i-1/2}) \tag{3.27}$$

with the operators δ_y and δ_η similarily defined. Additionally, the operator $\overline{a}^\eta$ is a vertical interpolation operator. Using the notation given for the vertically stretched grid depicted in

19

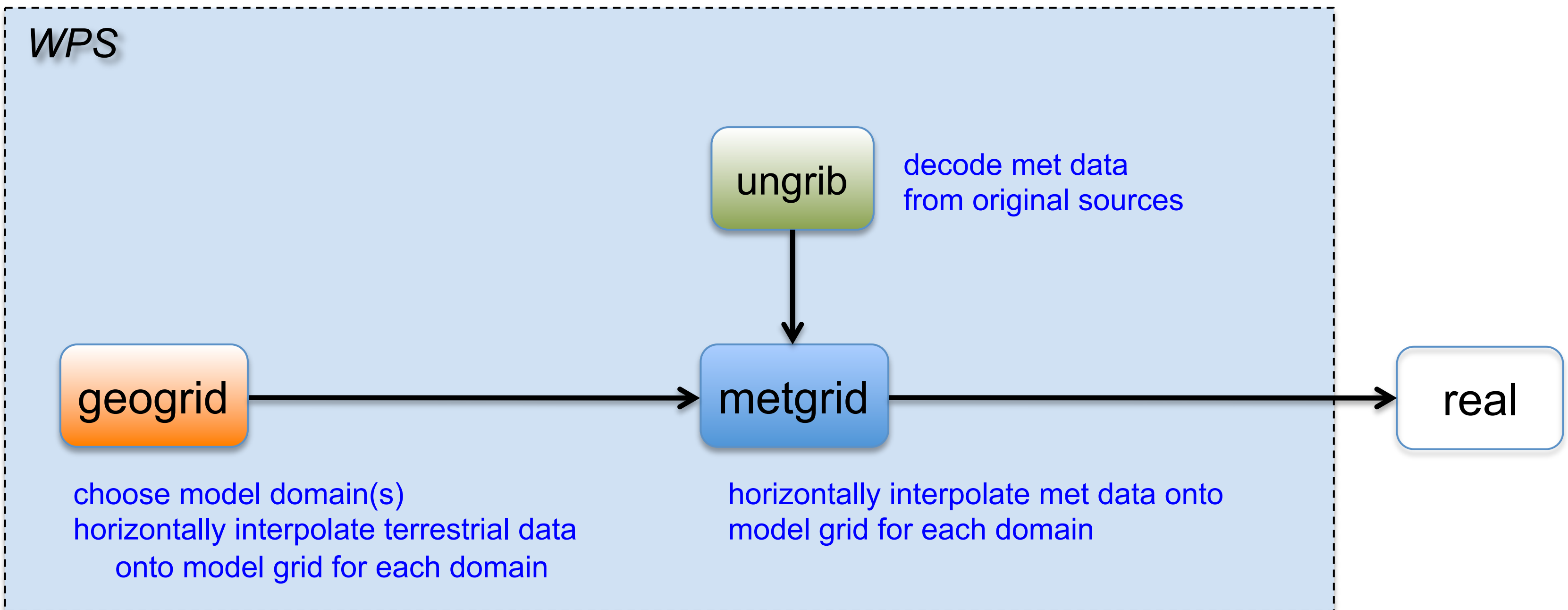
4. Steps for Running WRF

Simplified WRF Flow Chart



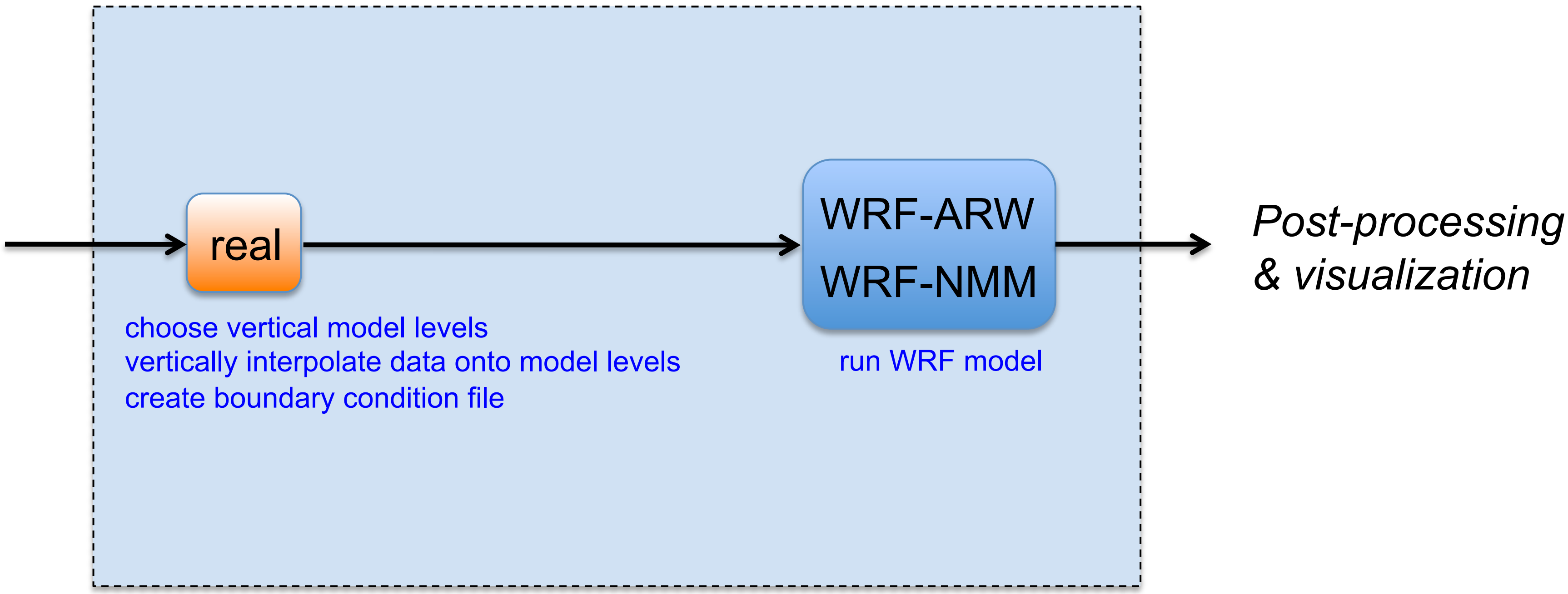
4. Steps for Running WRF

WRF Pre-processing System (WPS)



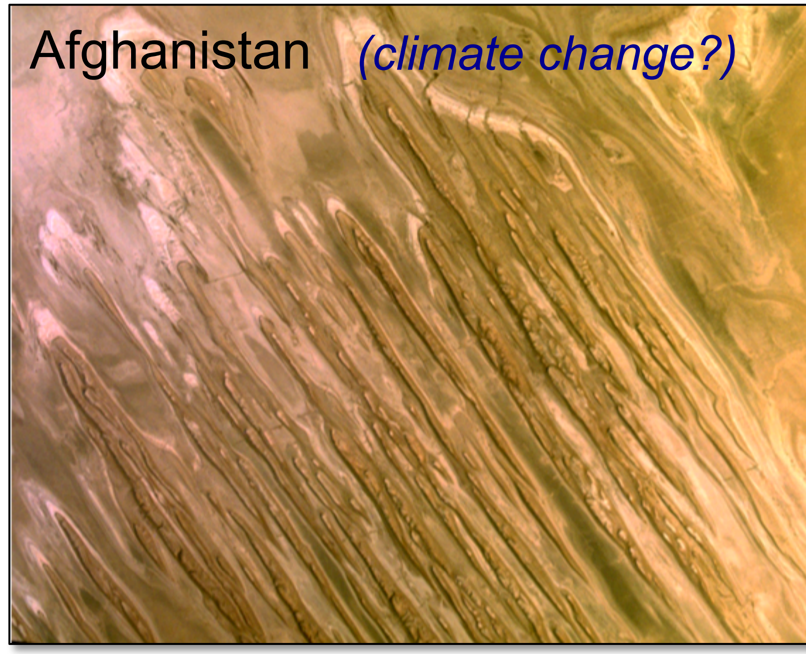
4. Steps for Running WRF

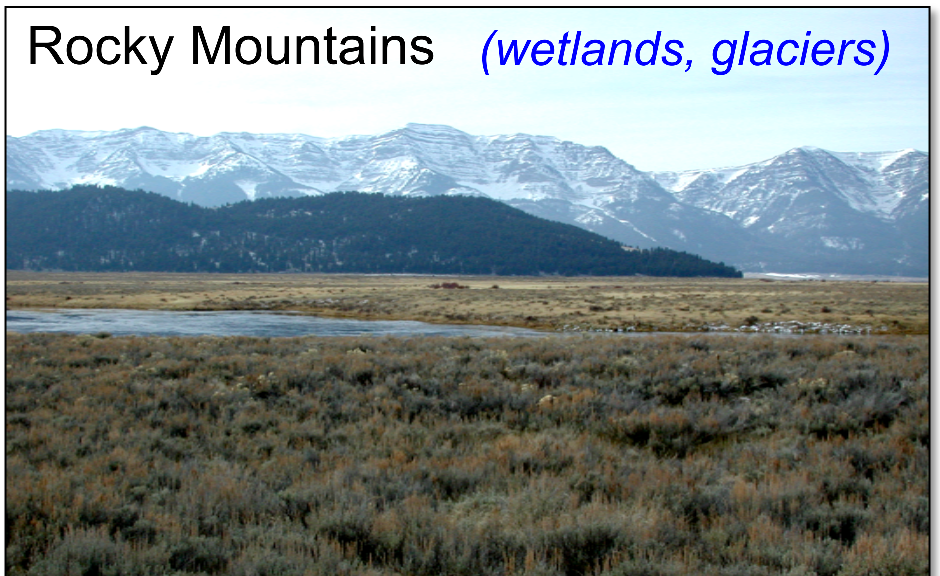
WRF Model

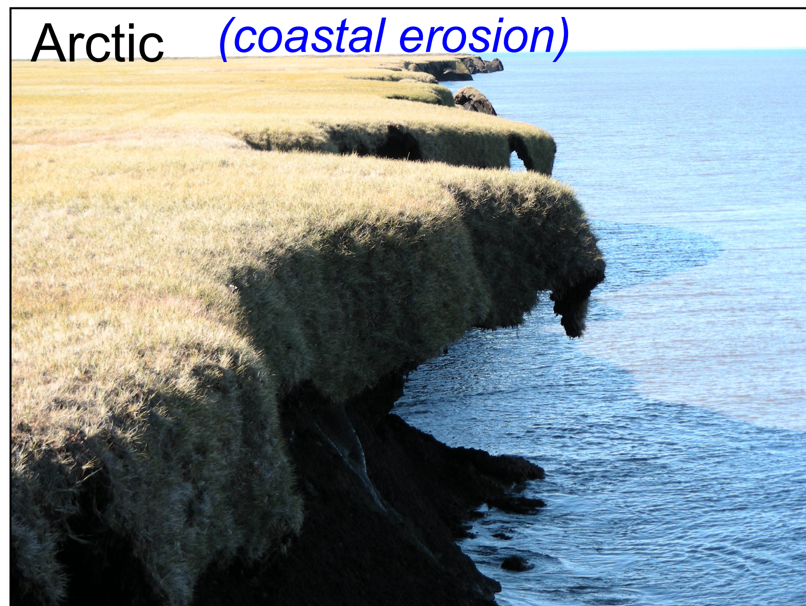


5. Examples


Mojave Desert *(dust storms, wind erosion)*


Afghanistan *(climate change?)*


Rocky Mountains *(wetlands, glaciers)*


Arctic *(coastal erosion)*


Thanks for coming to the WRF Clinic!
D. Lawrence