Introduction to Meteorological Process Modeling and WRF Post-Processing

Lecture 1

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Lecture Objective and Learning Outcomes

Lecture objective

To introduce the purpose of numerical atmospheric modelling and the WRF model, its basic concepts and the full workflow from input data to visualization.

Learning outcomes

By the end of this lecture, students will be able to:

1. explain why numerical models are needed in addition to observations;
2. describe what WRF is and distinguish its two dynamic cores, ARW and NMM;
3. define a model grid, a limited-area model and nesting;
4. name the stages of the WRF workflow (geogrid, ungrib, metgrid, real, wrf) and the role of each program;
5. identify the main input and output files of each stage.

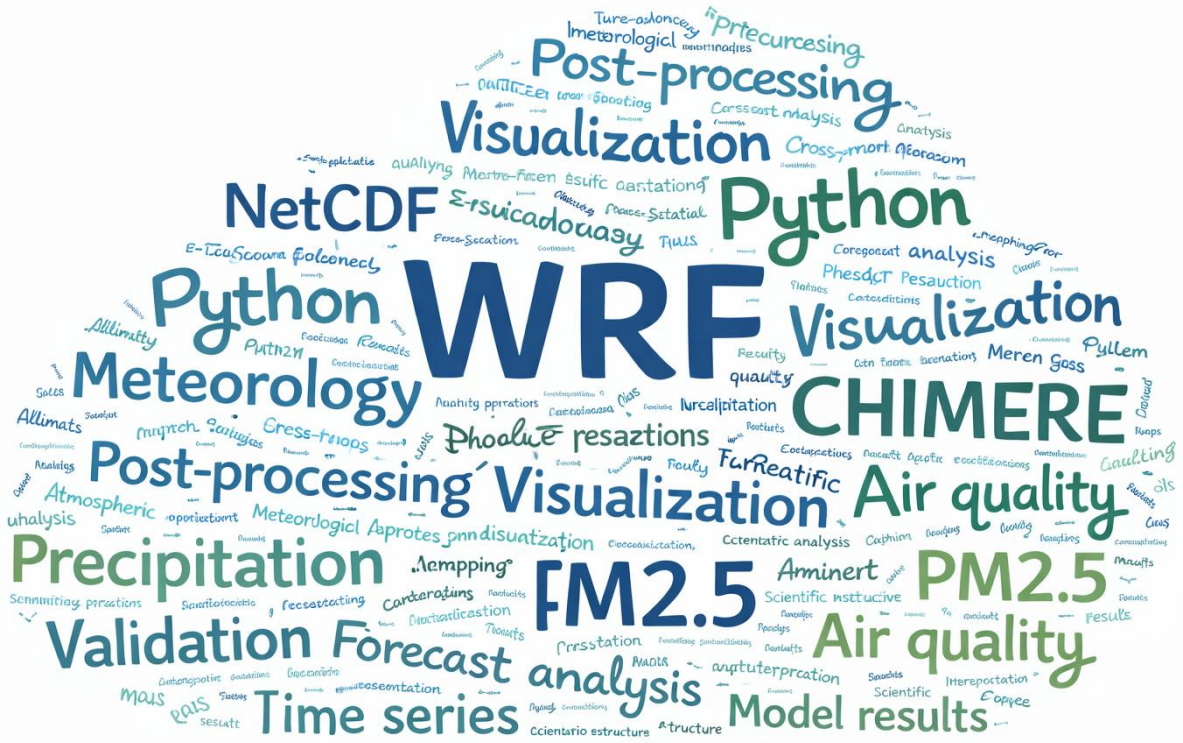
Agenda

- Why atmospheric models are needed
- What WRF is and how it evolved
- Dynamic cores: ARW and NMM
- Basic concepts: model grid, limited-area models, nesting
- The modelling ecosystem and the WRF workflow
- From model output to visualization





Course Outline



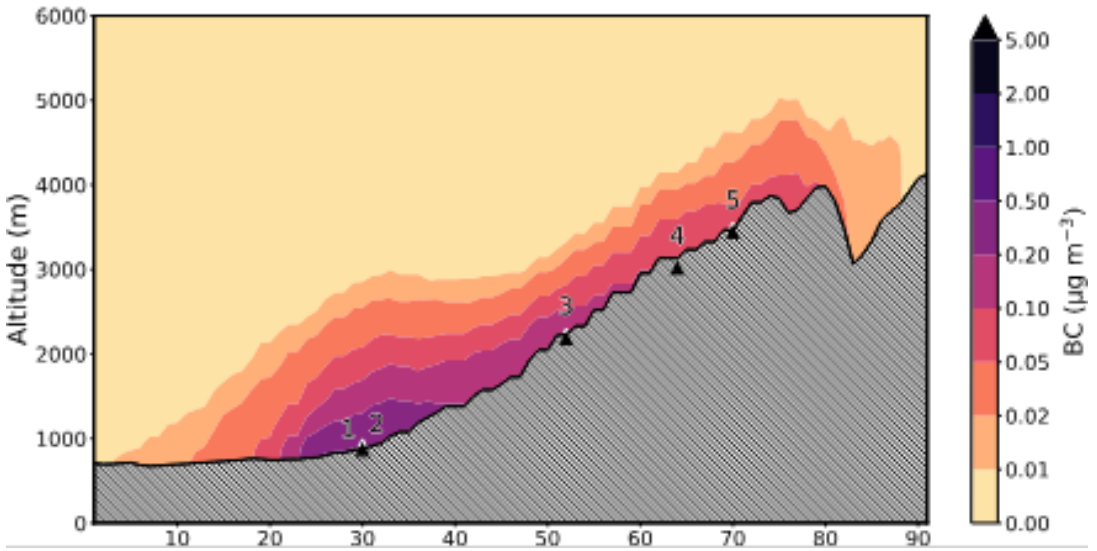
- Introduction to WRF modelling
- NetCDF structure
- Mapping meteorological fields
- Vertical structure of atmosphere
- Vertical cross-sections
- Model validation
- Introduction to CHIMERE
- Air quality-meteorology interactions
- Scenario analysis

Why Do We Need Atmospheric Models?

- Limitations of Observations
  - Meteorological stations provide point measurements
  - Satellite data do not capture full vertical structure
  - Many processes cannot be directly measured
- Complexity of the Atmosphere
  - Nonlinear interactions between dynamics and physics
  - Multiscale processes (local → regional → global)
  - Rapid temporal variability
- Role of Numerical Models
  - Provide continuous 4D fields (x, y, z, time)
  - Help interpret atmospheric mechanisms
  - Support forecasting and environmental analysis

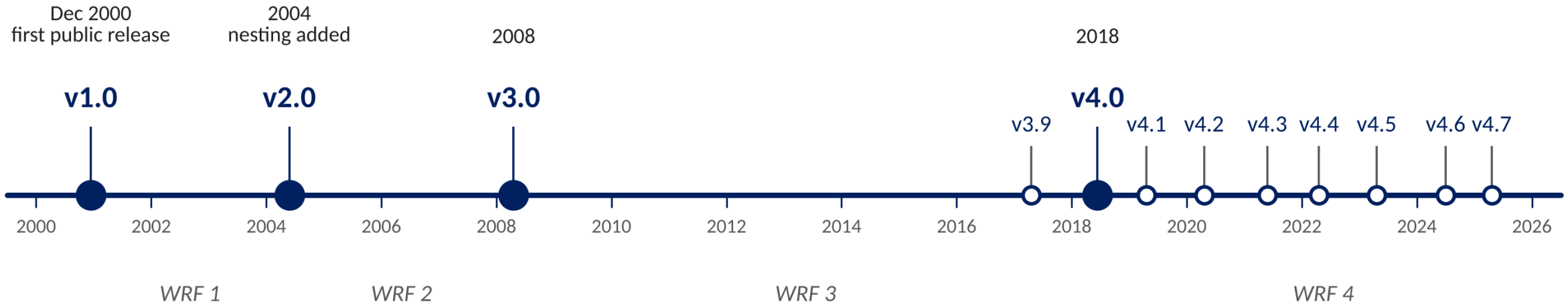
Examples of model applications:

- Mountain meteorology
- Air pollution transport
- Extreme weather events



What is WRF?

- **WRF:** Weather Research and Forecasting Model
- A free, open-source community model developed by NCAR, NOAA/ESRL and NOAA/NCEP/EMC in partnership with universities and government agencies



WRF: Global Community and Dynamic Cores



In 2020: 184 countries

ARW – Advanced Research WRF

Developed at NCAR

Research flexibility

The core used in this course

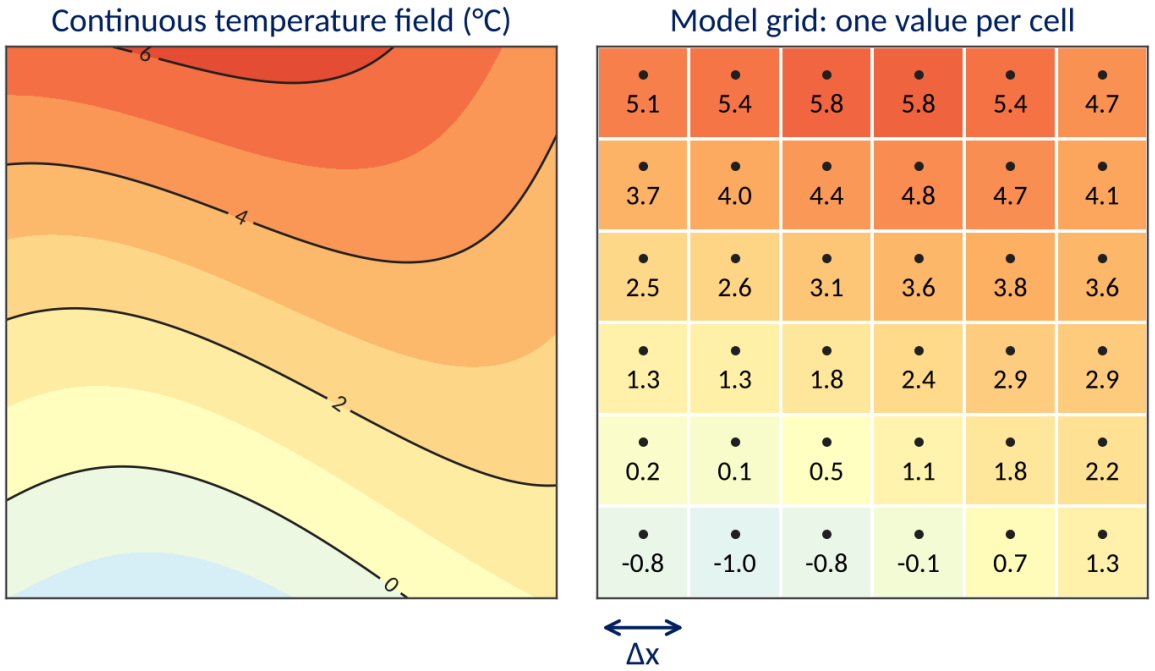
NMM – Nonhydrostatic Mesoscale Model

Developed at NCEP

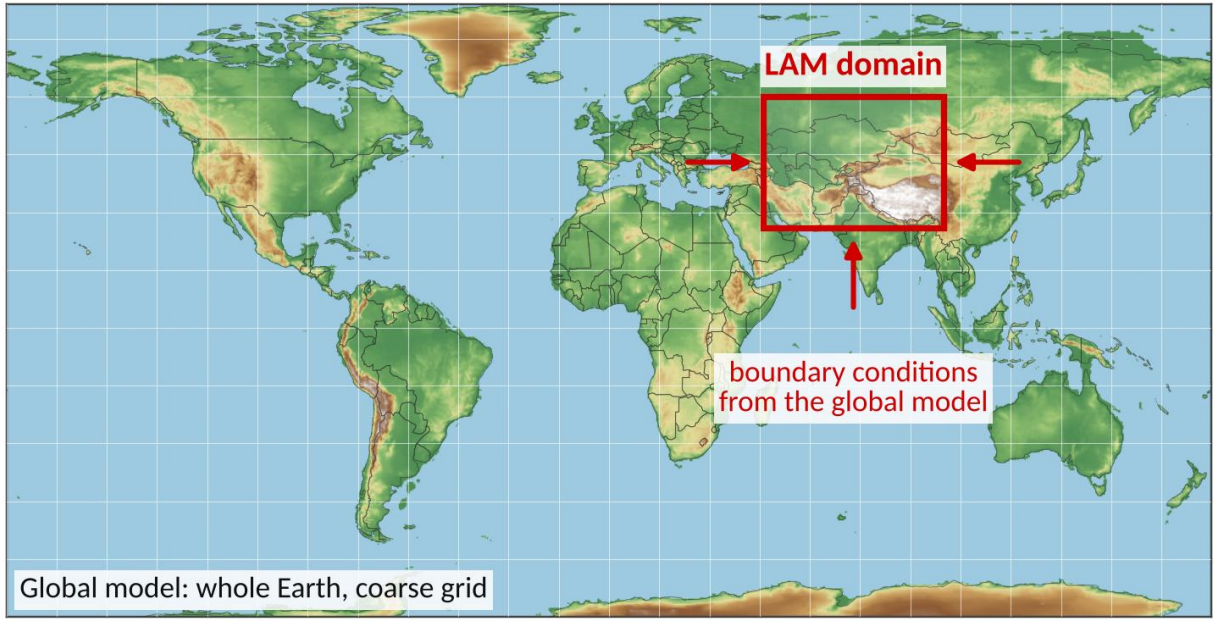
Operational forecasting efficiency

Some Basic Concepts

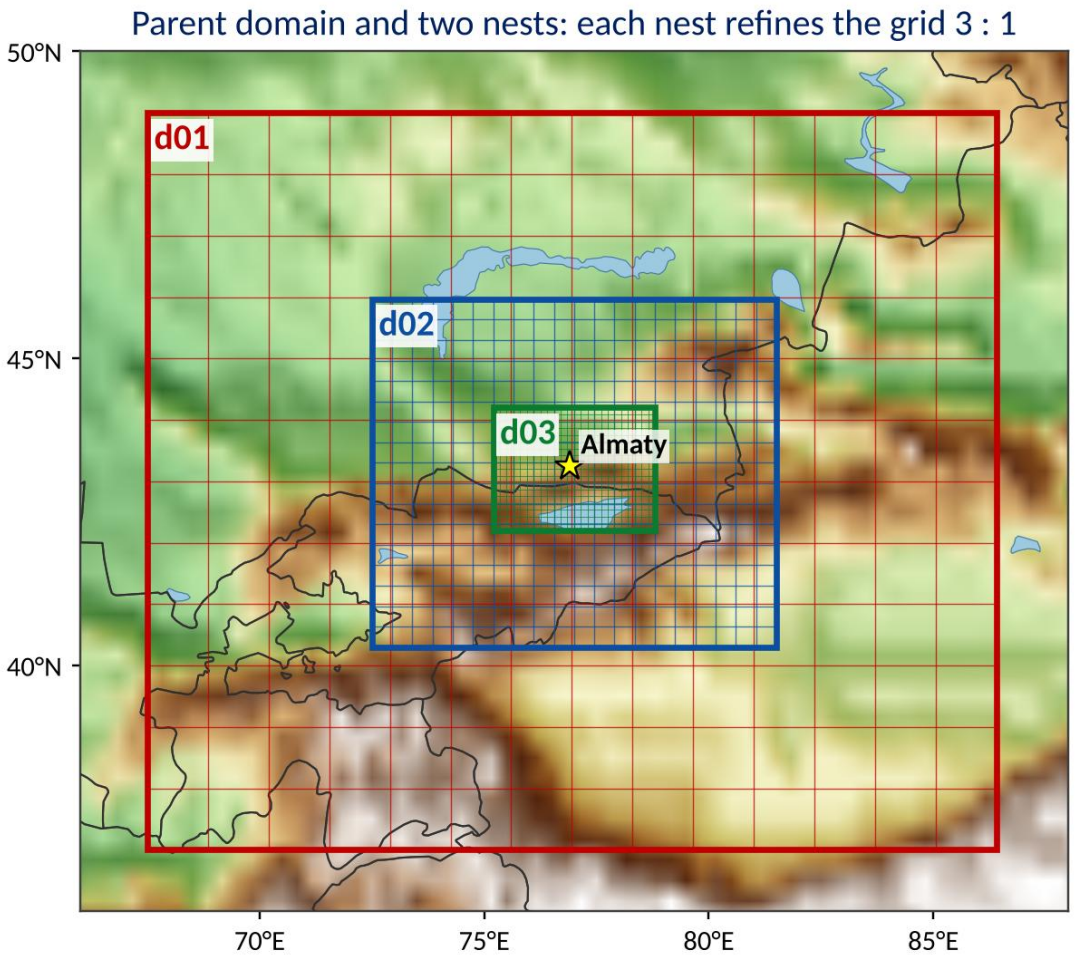
Equations are solved and data are presented on a model grid

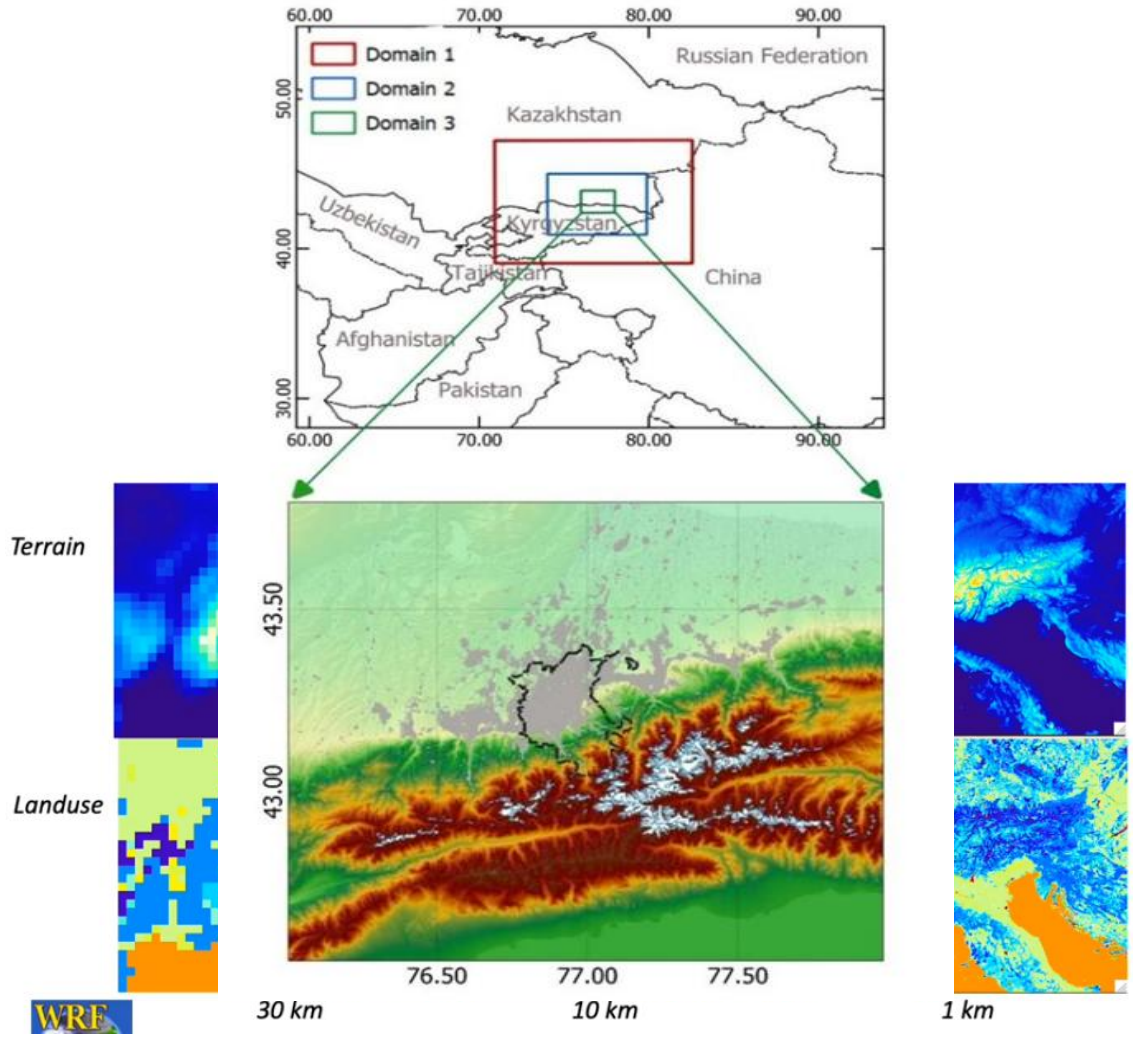


Limited Area Model (LAM) – where we choose the boundary conditions



Nesting


Parent domain and two nests: each nest refines the grid 3 : 1
50°N
45°N
40°N
70°E
75°E
80°E
85°E
d01
d02
d03
Almaty


60.00
70.00
80.00
90.00
50.00
40.00
30.00
Domain 1
Domain 2
Domain 3
Russian Federation
Kazakhstan
Uzbekistan
Kyrgyzstan
Tajikistan
China
Afghanistan
Pakistan
Terrain
Landuse
43.50
43.00
76.50
77.00
77.50
30 km
10 km
1 km
WRF

The Modelling Ecosystem

I. PRE-PROCESSING (WPS)

- Preparation of input data
- Prepare geographical fields
- Horizontal interpolation

Key File
Inter
met_em files

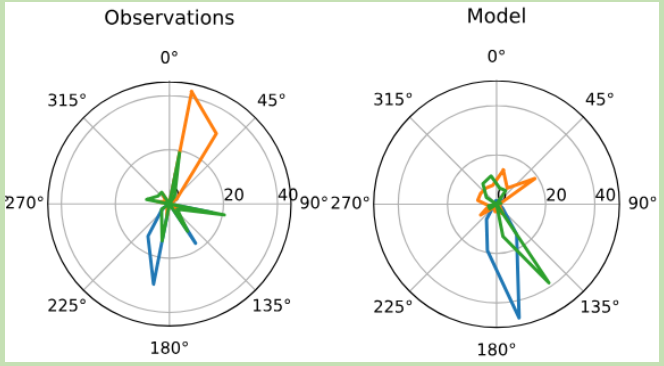
II. SIMULATION (WRF)

- Vertical interpolation (real.exe)
- Time-step integration
- Physical parameterizations
- Generation of model output

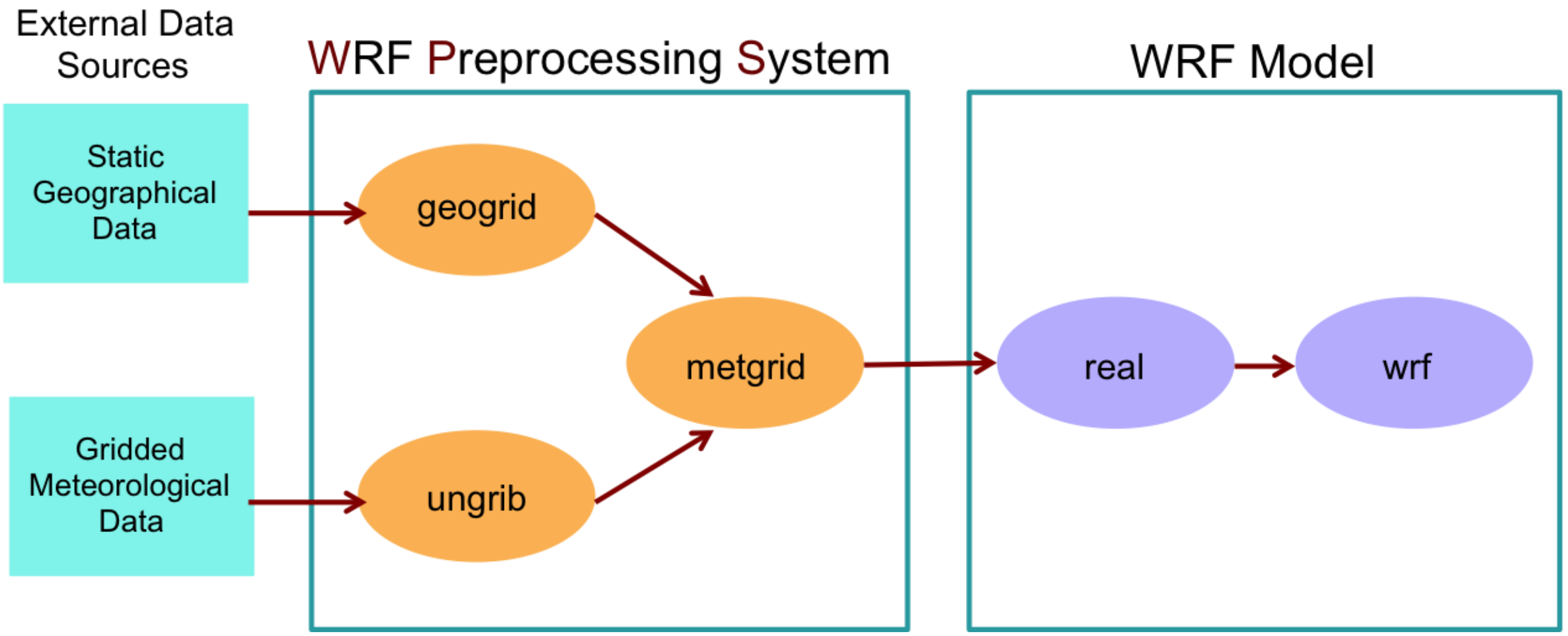
Key File
Inter
wrfout files

III. VISUALIZATION

- Data extraction and diagnostics
- Mapping and analysis
- Scientific interpretation



WRF Workflow



WRF Workflow

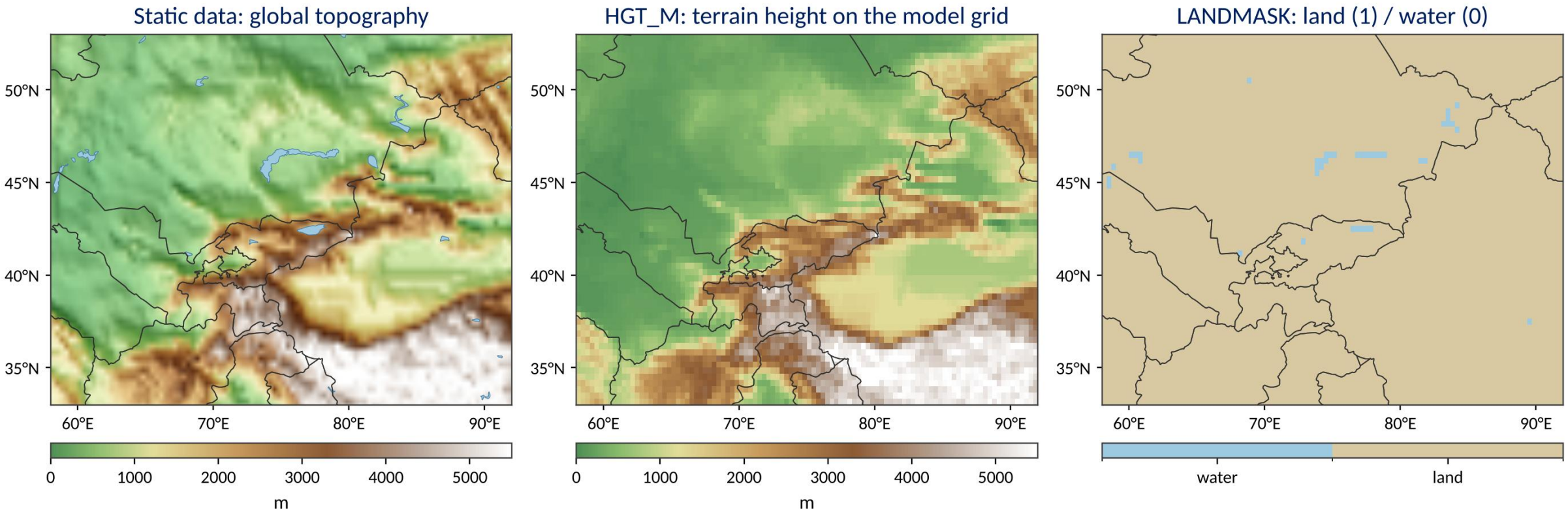
WPS

- **geogrid.exe** creates terrestrial data from static geographic data that is obtained from an external data source.
- **ungrib.exe** unpacks GRIB meteorological data and packs it into an intermediate file format.
- **metgrid.exe** interpolates the meteorological data horizontally onto your model domain. Output from metgrid.exe is used as input to WRF (through the real.exe program).

WRF

- **real.exe** vertically interpolates the data onto the model coordinates.
- **wrf.exe** generates the model forecast.

The stage: GEOGRID



geogrid.exe → geo_em.d01.nc Also: LU_INDEX (land use), SOILCTOP (soil type), ALBEDO12M, GREENFRAC, LAI12M

Time-independent: run once for each domain configuration

The stage: UNGRIB

Input: GRIB2 files (e.g. GFS 0.25°)

- `gfs.t00z.pgrb2.0p25.f000`
- `gfs.t00z.pgrb2.0p25.f003`
- `gfs.t00z.pgrb2.0p25.f006`
- `gfs.t00z.pgrb2.0p25.f009`

packed binary records, hundreds of fields per file

dates and time interval

`namelist.wps`

ungrib.exe

Vtable.GFS: which fields to extract

Param	Level	Name	Units	Description
11	100	TT	K	Temperature
33	100	UU	m s-1	U wind
34	100	VV	m s-1	V wind
52	100	RH	%	Relative humidity
7	100	HGT	m	Height
1	1	PSFC	Pa	Surface pressure

Output: intermediate files, one per time

- `FILE:2023-10-27_00`
- `FILE:2023-10-27_03`
- `FILE:2023-10-27_06`
- `FILE:2023-10-27_09`

only the fields WRF needs, still on the original lat–lon grid

The stage: METGRID

from geogrid: the model grid

`geo_em.d01.nc`

from ungrib: meteorological fields

`FILE:2023-10-27_00`

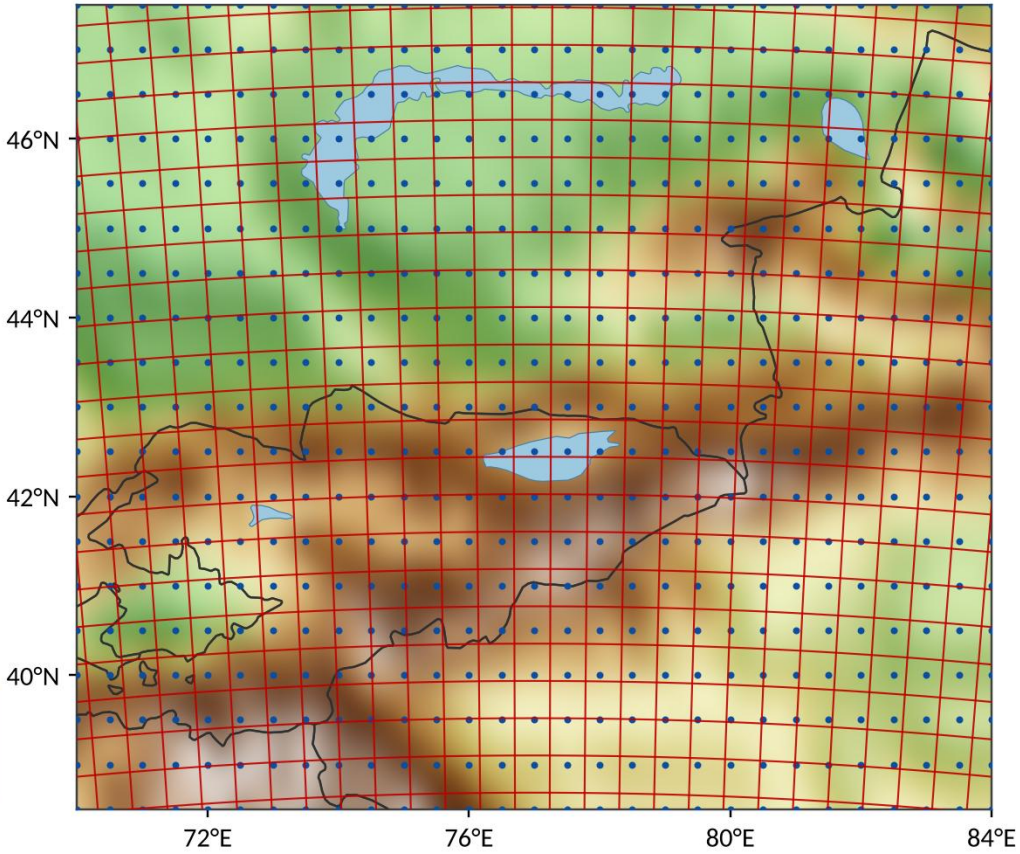
metgrid.exe

horizontal interpolation
(rules in METGRID.TBL)

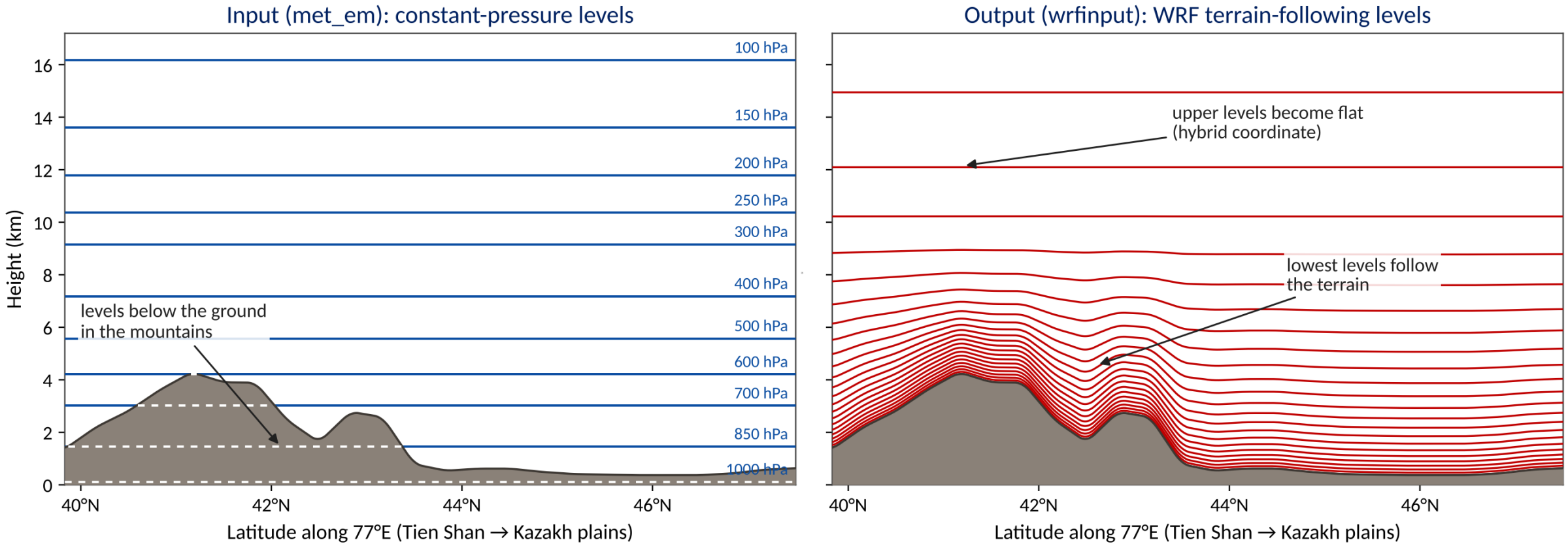
`met_em.d01.2023-10-27_00:00:00.nc`

one NetCDF file per time and per domain

Input points on a regular lat–lon grid (blue)
are interpolated to the model grid (red)



The stage: REAL and WRF



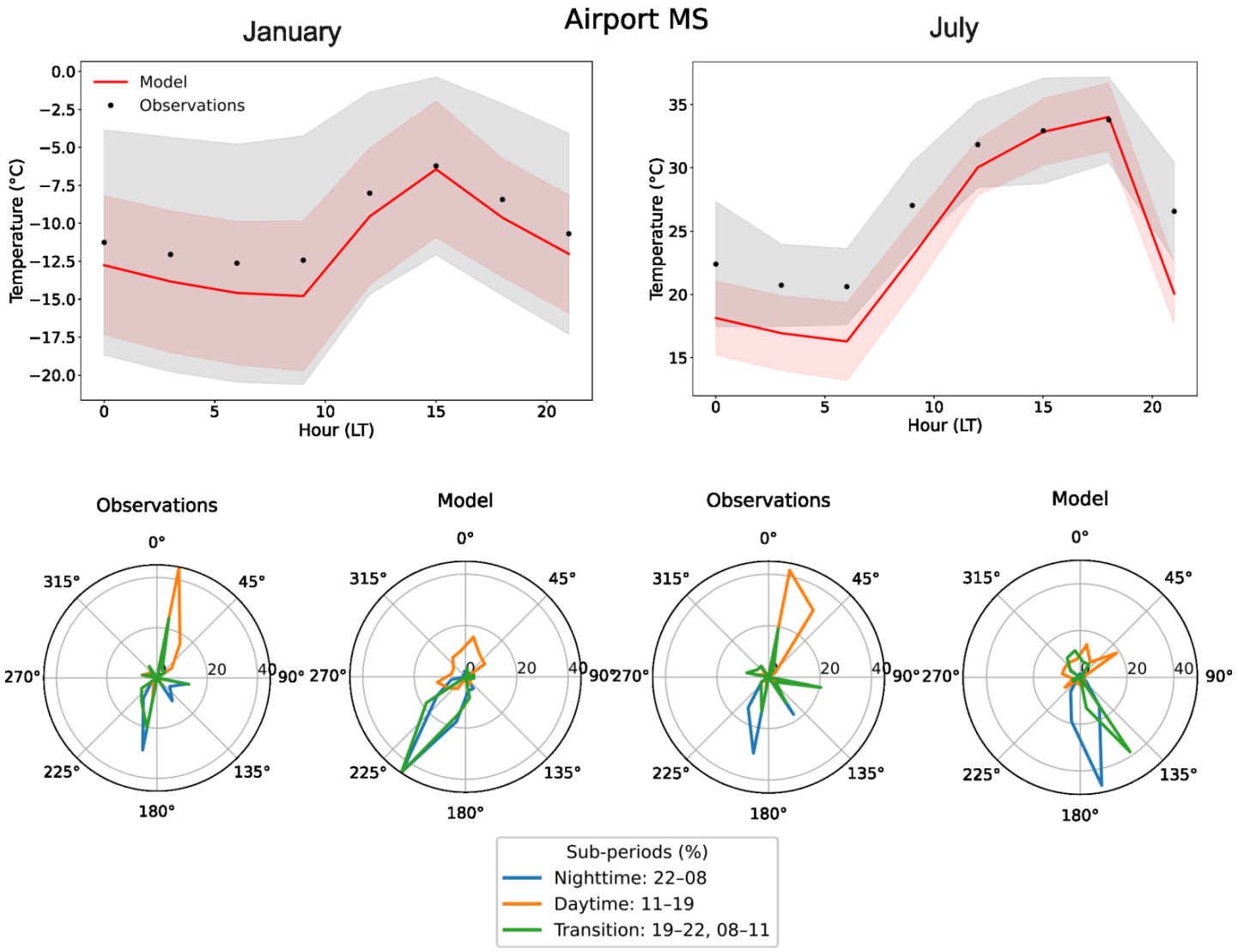
real.exe

wrfinput_d01 (initial) + wrfbdy_d01 (boundary conditions)

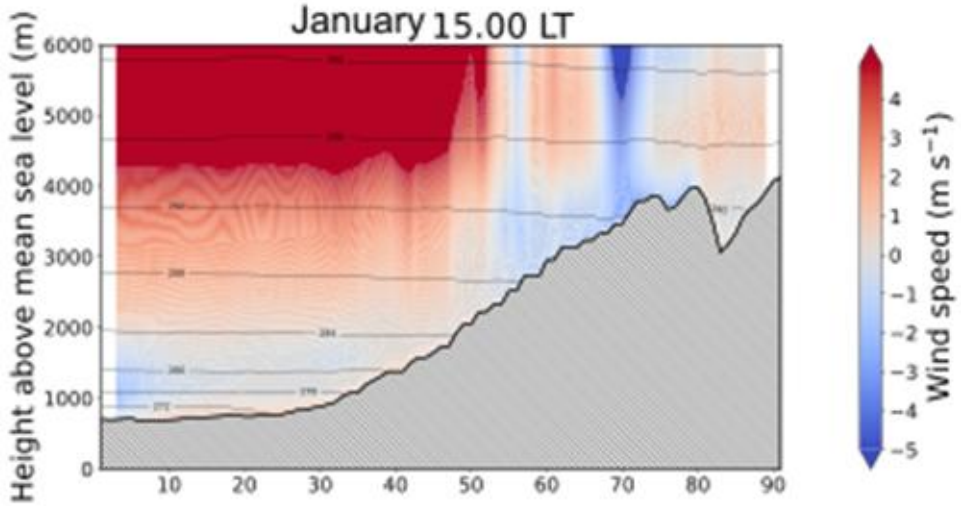
wrf.exe

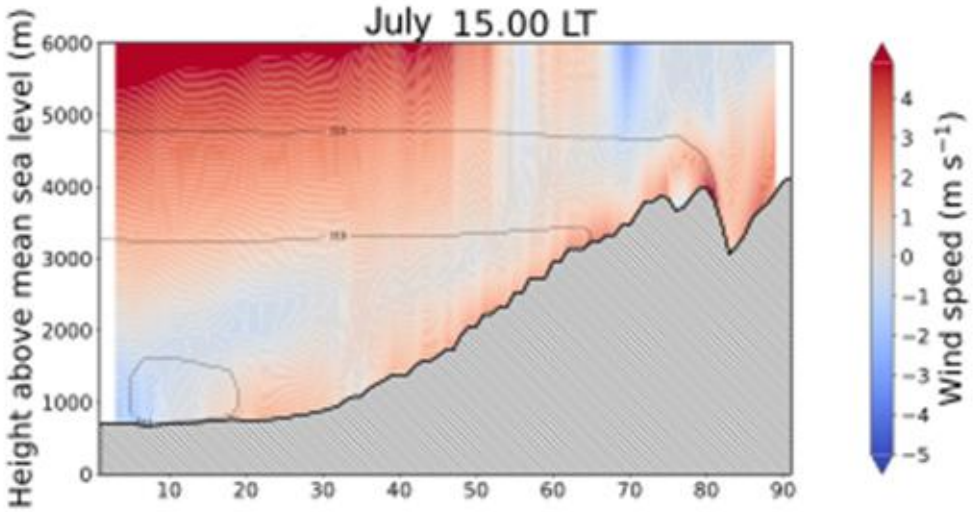
wrfout_d01_2023-10-27_00:00:00 (NetCDF output)

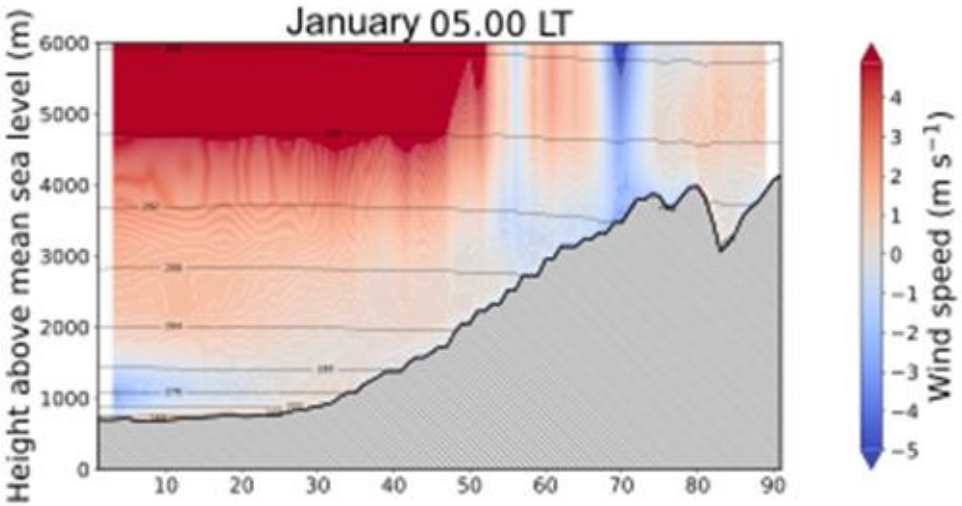
Visualization: Model vs Observations

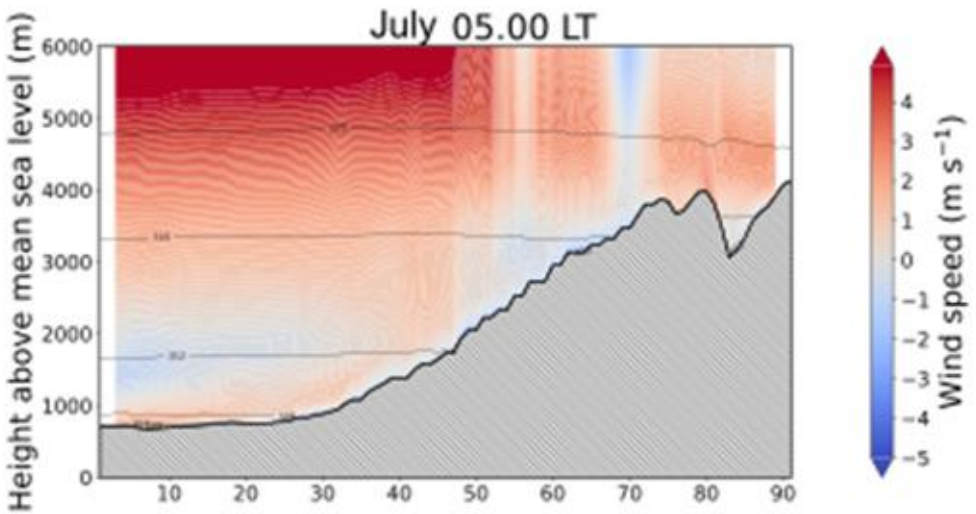


Visualization: Vertical Cross-Sections









Conclusion

Key points

1. Observations are limited in space and in the vertical; models provide continuous 4-D fields (x, y, z, time).
2. WRF is a free, open-source community model; this course uses the ARW core.
3. A limited-area model needs boundary conditions; nesting increases the resolution over the area of interest.
4. WPS prepares the input: geogrid (static fields), ungrib (GRIB to intermediate files), metgrid (horizontal interpolation).
5. real.exe interpolates vertically and creates wrfinput and wrfbdy; wrf.exe produces the wrfout files.
6. Post-processing turns model output into maps, cross-sections and comparisons with observations.

Self-Check Questions

1. Why can observations alone not describe the state of the atmosphere completely?
2. What is the difference between the ARW and NMM dynamic cores?
3. What is a limited-area model, and why does it need boundary conditions?
4. What is nesting, and when is it used?
5. What does each of the three WPS programs do?
6. What is the difference between real.exe and wrf.exe, and which files does each produce?

What You Will Be Able to Do

- Analyze atmospheric fields
- Build vertical cross-sections
- Study boundary layer processes
- Link meteorology with air quality

- Thank you for your attention!

References

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6. Figure data: NOAA National Geophysical Data Center, ETOPO global relief model; Natural Earth, naturalearthdata.com.