VORTEX

WRF model overview

Introduction to Numerical Weather Prediction models

Numerical Weather Prediction model

Is a set of equations

solved using numerical approximations

and parametrizations,

applied to a specific domain

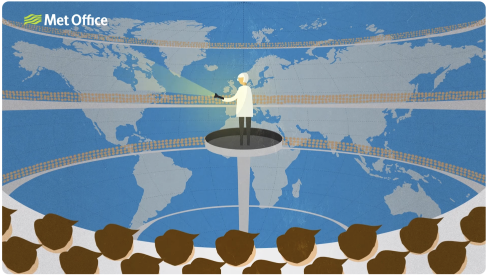
based on certain initial and boundary conditions

Numerical Weather Prediction model

1. Equations
2. Numerical approximations
3. Parametrizations
4. Domain
5. Initial and boundary conditions

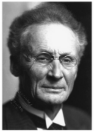
A bit of history

- In the 1920s, **Lewis Fry Richardson** following the primitive equations formulated by **Vilhelm Bjerknes** attempted the first atmospheric prediction:
  - Over two points in central Europe.
  - A six-hour forecast.
  - It took six weeks to produce by hand.
  - It was **wrong!** (error in initial conditions)



Richardson imagined a factory with 64,000 mathematicians calculating by hand the equations needed to forecast weather. **Credit:** Met Office

A bit of history


Vilhelm Bjerknes

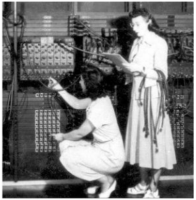

Lewis Fry Richardson

1920s

First attempt of
atmospheric prediction

1950

First successful
prediction using **ENIAC**


Klara Dan von Neumann

1980

ECMWF and **MetOffice**
start they global
forecast models

1987

Global Forecast
System is launched

1990s

NCAR and **NCEP** start
WRF model

2013

NCAR launches
MPAS model

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Governing equations

- Conservation of momentum (Newton's laws)
  - 3 equations for accelerations of 3D wind ($F = ma$)
- Conservation of mass
  - 1 equation for conservation of air (mass continuity)
  - 1 equation for conservation of water
- Conservation of energy
  - 1 equation for the first law of thermodynamics ($\Delta U = Q - W$)
- Equation of state
  - Ideal gas law ($PV = nRT$)

Primitive equations

- East-West wind:

$$\frac{\partial u}{\partial t} = \eta v - \frac{\partial \Phi}{\partial x} - c_p \theta \frac{\partial \pi}{\partial x} - z \frac{\partial u}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial x}$$

- North-South wind:

$$\frac{\partial v}{\partial t} = -\eta \frac{u}{v} - \frac{\partial \Phi}{\partial y} - c_p \theta \frac{\partial \pi}{\partial y} - z \frac{\partial v}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial y}$$

- Temperature:

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}$$

- Precipitable water:

$$\frac{\delta W}{\partial t} = u \frac{\partial W}{\partial x} + v \frac{\partial W}{\partial y} + w \frac{\partial W}{\partial z}$$

- Pressure:

$$\frac{\partial}{\partial t} \frac{\partial p}{\partial \sigma} = u \frac{\partial}{\partial x} x \frac{\partial p}{\partial \sigma} + v \frac{\partial}{\partial y} y \frac{\partial p}{\partial \sigma} + w \frac{\partial}{\partial z} z \frac{\partial p}{\partial \sigma}$$

Navier-Stokes

- Conservation momentum and mass can be reformulated as a set of nonlinear partial differential equations known as **Navier–Stokes**

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{\nabla P}{\rho} + \mu \nabla^2 u$$

- These set of equations relate the velocity (u), pressure (P), density (ρ) and viscosity (μ) of a flowing fluid.
- For the three-dimensional system, there is not a general analytical solution (Navier–Stokes existence and smoothness problem)

Advection

- Conservation of momentum for one dimension wind accelerated by pressure gradient:

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x}$$

- Computers cannot solve even this simple calculus equation, only arithmetic operations.
- These derivatives can be translated into algebraic equations using numerical methods.

Taylor series

- The **Taylor series** approximates a function using a sum of polynomial terms. Differential equations can be integrated numerically.

$$f(x_0+h) = f(x_0)+\frac{f'(x_0)}{1!}h+\frac{f^{(2)}(x_0)}{2!}h^2+\cdots+\frac{f^{(n)}(x_0)}{n!}h^n+R_n(x),$$

- Truncation is inevitable, given that the sum is infinite.
- The omitted terms during truncation contribute to one of the inherent approximation errors.

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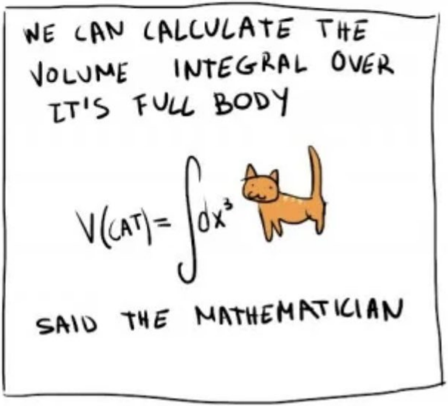
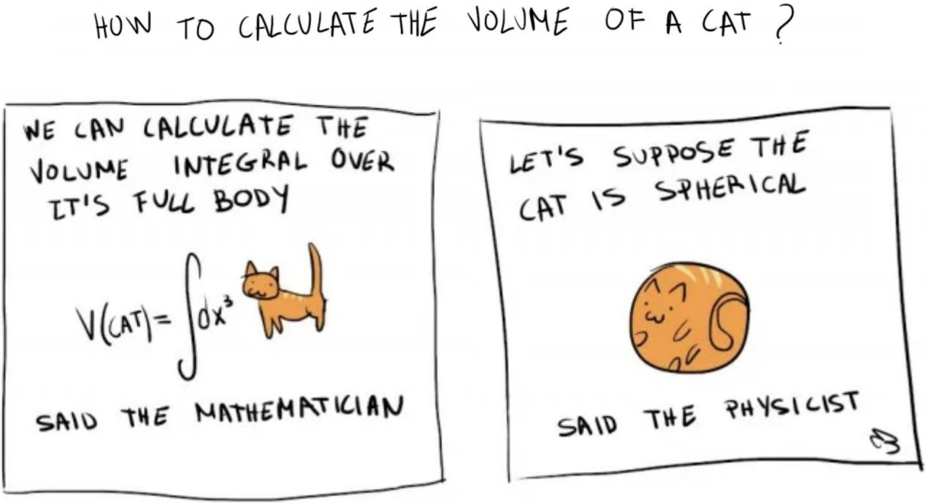
HOW TO CALCULATE THE VOLUME OF A CAT ?

HOW TO CALCULATE THE VOLUME OF A CAT ?





Credit: Adventures of a Schrödinger's cat

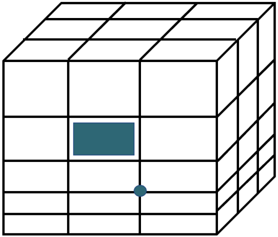
Model discretization

- Finite differences allow to approximate differential equations.
- The continuity of reality must be broken into a finite number of steps

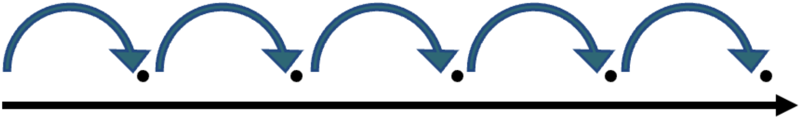
Continuous reality

Discreted model

Model discretization



- Spatial domain is discretized as a three-dimensional computational grid with mesh between its points.
- The parameters can be located either at the points or at the centers of the meshes of the grid.



- Time is not a continuous variable, the calculations jumping from one step to the next.

Reynolds decomposition

- Even if the primitive equations are solved numerically in a limited area, atmospheric processes at a scale smaller than the grid interval are omitted (subgrid)
- Reynolds averaging separates the resolvable and unresolvable scales of motion in the equations.
- Variables may be decomposed into mean and perturbation components.

$$u(x, y, z, t) = \overline{u(x, y, z)} + u'(x, y, z, t)$$

- These turbulent subgrid-scale fluxes need to be approximated (closure problem)

Turbulence and TKE

- Turbulence is fluid motion characterized by chaotic changes in pressure and flow velocity.
- It is caused by excessive kinetic energy, leading to the formation of vortices and eddies.
- Turbulence Intensity is defined as the standard deviation of the wind speed (σM) divided by the average speed (M):

$$TI = \frac{\sigma M}{\overline{M}}, M = \sqrt{u^2 + v^2}$$

- Turbulence Kinetic Energy (TKE) is the mean kinetic energy per unit mass associated with eddies in turbulent flow.

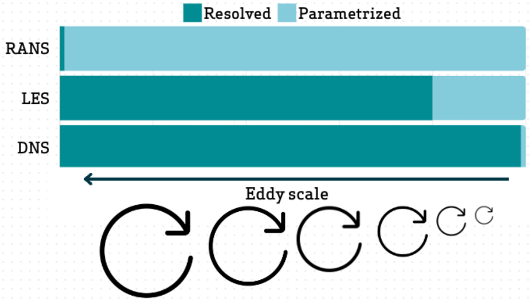
$$TKE = \frac{1}{2}(\sigma u^2 + \sigma v^2 + \sigma w^2)$$

- Both variables are approximately related by the equation:

$$TI \approx \frac{\sqrt{2 \cdot TKE}}{\overline{M}}$$

Computational Fluid Dynamics

- **Reynolds-Averaged Navier-Stokes** (RANS) models solve the non-turbulent part of the motion and parametrizes the eddies in the turbulence kinetic energy (TKE)
- **Large-Eddy Simulations** (LES) The algorithm resolves large eddies, the smaller are parameterized.
- **Direct Numerical Simulation** (DNS) models resolve explicitly all of the turbulent motion (grids with $\Delta x < 1m$)



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Parametrizations

Some meteorological processes are too small, too brief or too complex to be explicitly represented.

- Microphysics
- Cumulus
- Radiation
- Surface layer
- Planetary Bounday Layer

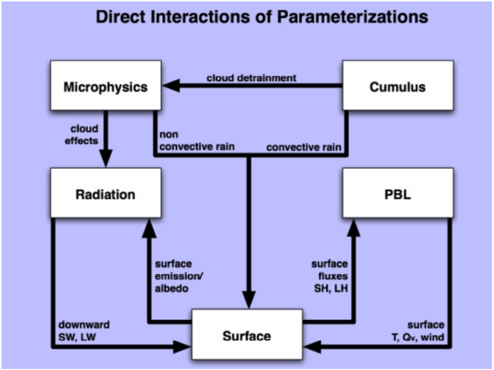
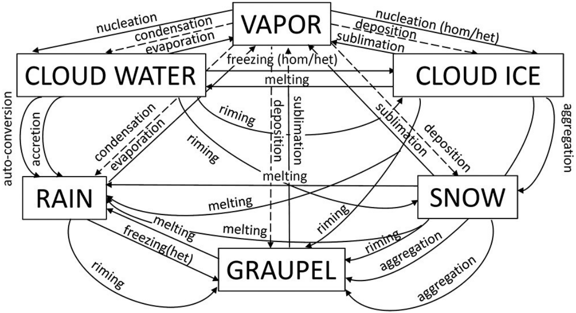


Diagram showing interactions between various physics components.
Credit: A Description of the Advanced Research WRF Model Version 4.3

Microphysics

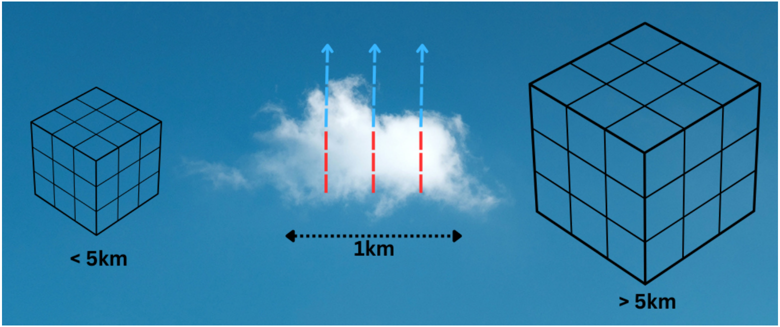
- Processes among hydrometeors affect temperature and relative humidity
- Schemes consider between 3 up to 6 classes of hydrometeors.



Tatsuya Seiki, Woosub Roh & Masaki Satoh (2022) Cloud Microphysics in Global Cloud Resolving Models, Atmosphere-Ocean, 60:3-4, 477-505, DOI: 10.1080/07055900.2022.2075310

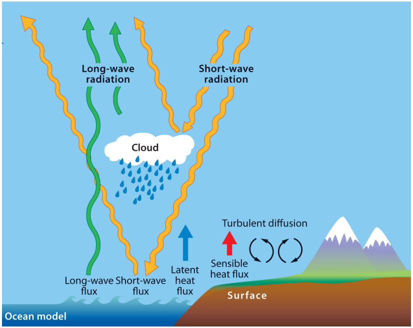
Cumulus

- Cumulus clouds have a size of less than 1km
- Models with $\leqq$ 5 km grids can resolve convective clouds. Still the microphysical processes need to be parameterized.
- Models with $>$ 5km grids need parameterize convective updrafts.
- The schemes are intended to represent vertical fluxes (bottom of the column is warmer than the top)



Radiation

Atmospheric temperature changes due to radiative flux divergence.

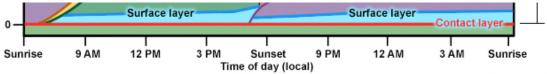


Adapted from parameterizations in the IFS model. ECMWF Glenn Carver 2020

- Upward longwave radiative flux from the ground is determined by the **land-use** and the ground skin temperature.
- For shortwave radiation, the upward flux is the reflection due to surface **albedo**.
- Most schemes use pre-set look-up tables to represent processes.

Surface layer

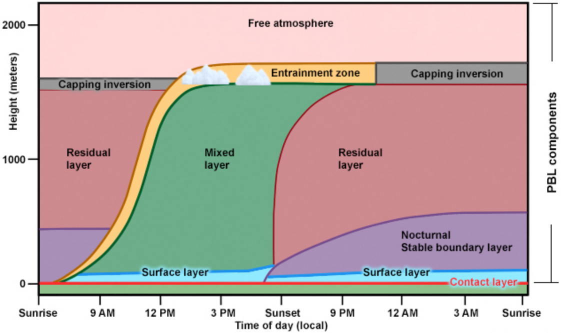
- The surface layer is the lowest 10% of the Boundary layer where the turbulent fluxes are approximately constant with height.
- The surface layer schemes calculate surface **heat** and **moisture** fluxes that are used as a lower input in PBL.
- This calculation depends on the surface aerodynamic **roughness** lengths, which are based on the landuse type, specified by dataset tables.
- Some surface layer schemes must be run in conjunction with PBL schemes



Credit: MetEd, UCAR

Planetary Boundary Layer

- PBL schemes parametrize the vertical sub-grid-scale turbulent fluxes due to eddies in the whole atmospheric column.
- Provide profiles of wind and temperature where the model does not resolve.



Credit: MetEd, UCAR

Planetary Boundary Layer

Most used schemes:

- **YSU (Yonsei University)** Nonlocal scheme that considers advective mixing. It does not calculate TKE but estimates PBL height (accurate for diurnal growth)
- **MYJ (Mellor-Yamada-Janjic)** Local mixing scheme that computes TKE and PBL height.
- **MYNN (Mellor-Yamada-Nakanishi-Niino)** Similar to MYJ with better representation of vertical moisture gradients. Includes a parametrization **Fitch** to compute wakes from wind farms.

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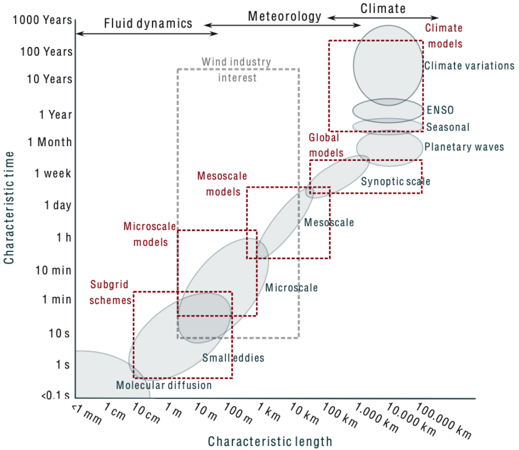
Domain size

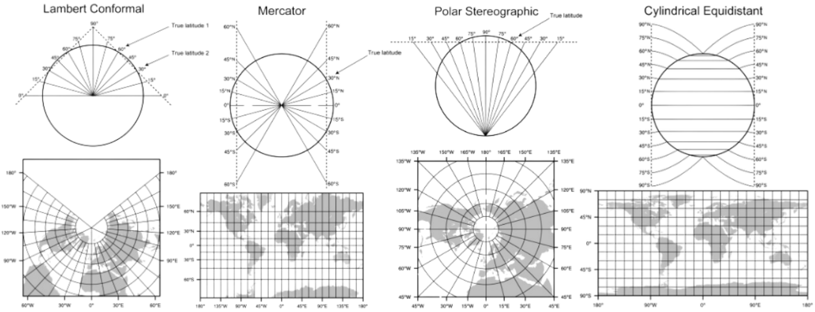
- Models can be either **Global** (GFS) or **Regional** (WRF)
- Regional models can use finer grids and resolve smaller-scale meteorological phenomena



Credit: Alex Montornès, Vortex LES white paper

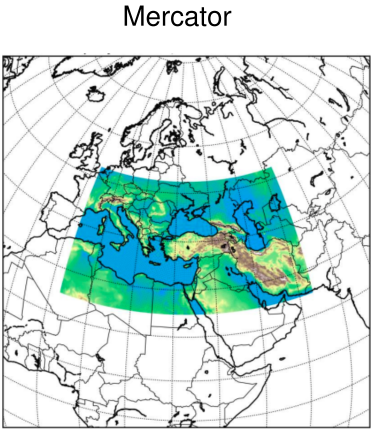
Map projection

- The Earth is roughly an ellipsoid (datum WGS84)
- WRF model domain is defined by plane rectangles
- A map projection has to be used:



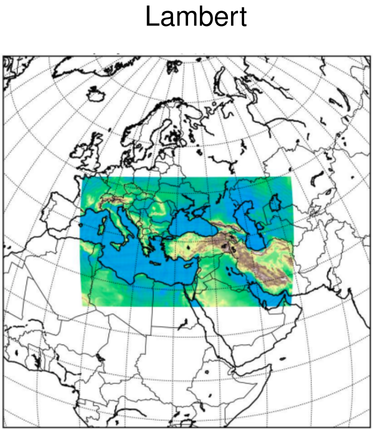
Credit: Kelly Kleene, The WRF Preprocessing System

Map projection



Mercator

For a 12km grid, Mercator yields cell sizes ranging from 9.9km to 14.6km



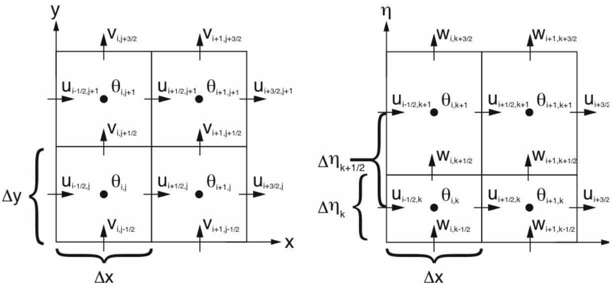
Lambert

For a 12km grid, Lambert has cell sizes between 11.7km and 12.1km

Credit: Kelly Kleene, The WRF Preprocessing System

Spatial grid

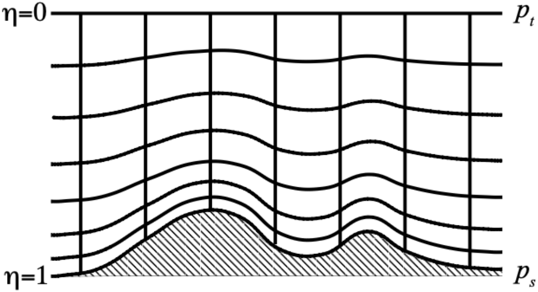
- Scalar thermodynamical variables (temperature, pressure,...) are located at the mass point, the center of the cell θ.
- Components of the wind velocity vector are located at the center of each face (u, v, w) staggered in x, y, η
- The vertical grid length is not constant, usually is shorter near the surface.



Horizontal (Arakawa C-grid staggering) and vertical grids of the WRF model.
Credit: A Description of the Advanced Research WRF Model Version 4.3

Spatial grid

- Vertical coordinate is the normalized hydrostatic pressure, η
- This coordinate is terrain following.
- η is 1 at the Earth's surface, 0 at the top of the atmosphere.

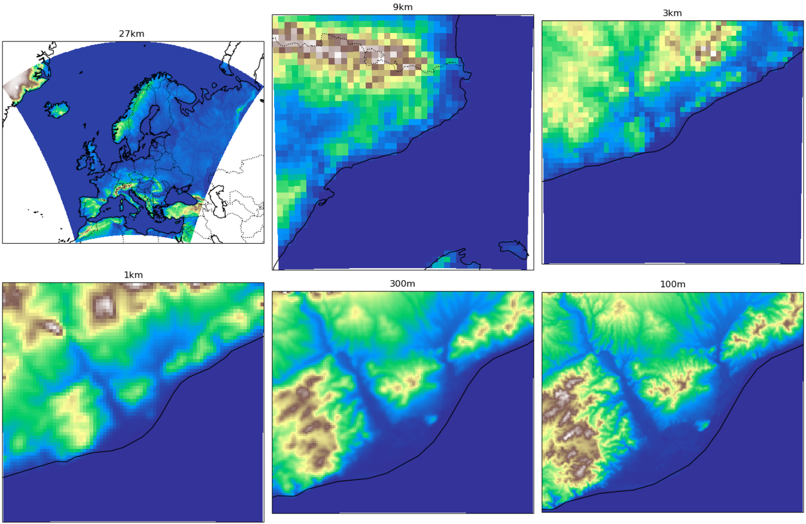


$$\eta = \frac{p_d - p_t}{p_s - p_t}$$

p_d: pressure of dry air
p_s: p_d at the surface
p_t: p_d at the top

WRF model η coordinate. **Credit:** A Description of the Advanced Research WRF Model Version 4.3

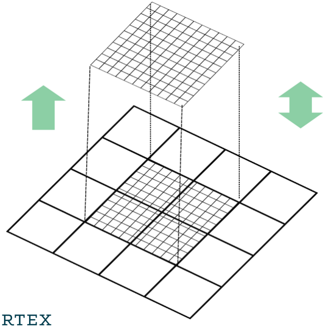
Resolution

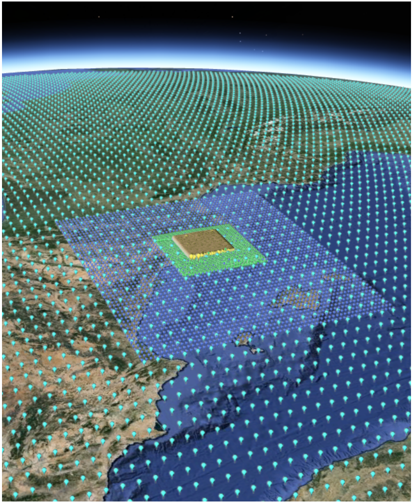


Nesting

WRF model often uses a 3:1 nesting ratio.

- **One-way** Information flows from the parent domain to the nested domain
- **Two-way** Data is exchanged between the two domains





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Initialization

Initialization includes real data and static terrestrial fields:

- Surface and 3-dimensional temperature (K), pressure (Pa), relative humidity (%), geopotential height (m) and horizontal wind speed (m/s)
- 2-dimensional albedo, Coriolis parameters, terrain elevation, vegetation/land-use type and land/water mask.

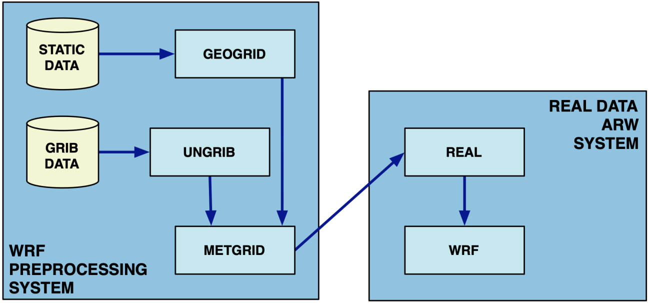

Diagram of WPS and ARW.**Credit:** A Description of the Advanced Research WRF Model Version 4.3

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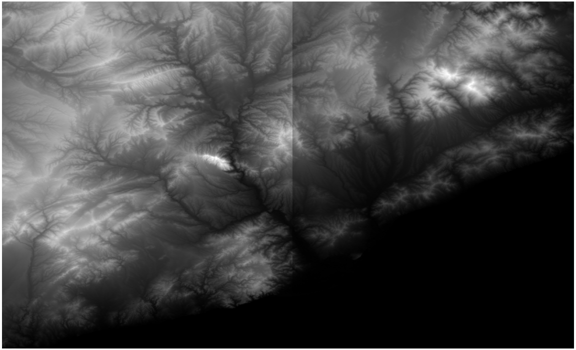
Topography

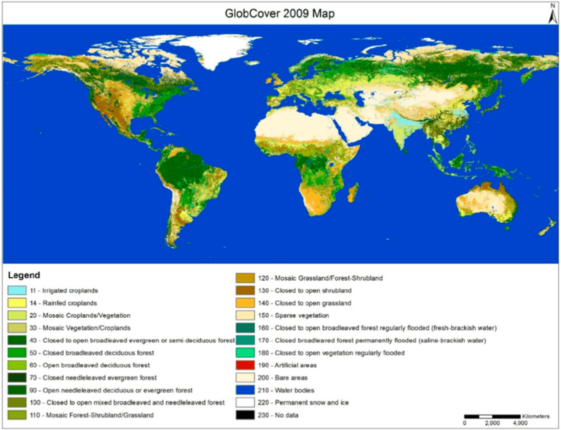
- The Shuttle Radar Topography Mission has a resolution of 90m (30m available since 2014).
- Digital Elevation Data arranged in tiles covering one by one degree of latitude and longitude



SRTM tiles N41E001 and N41E002

Land Use

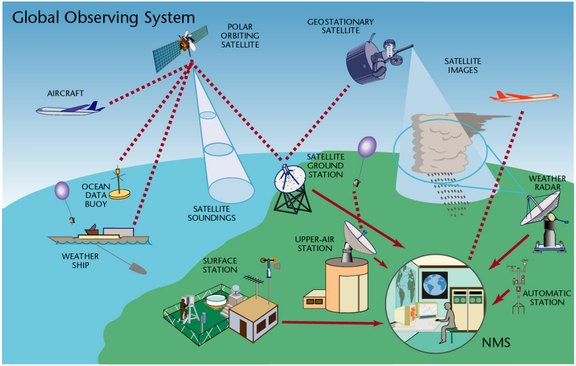
- Globcover dataset has a spatial resolution of 300m.
- Land is classified in 22 different land cover classes.
- Land cover also determines roughness and albedo.



Credit: Congalton, R. et al. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis

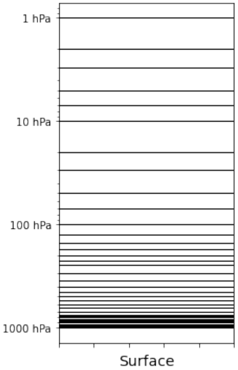
Reanalysis

- Observations are unevenly distributed and have errors
- Reanalysis combines past short-range weather forecasts with observations through data assimilation.
- Reanalysis fills the gaps in observations in a way that is consistent in time



Observation components of the Global Observing System **Credit**: WMO

Reanalysis



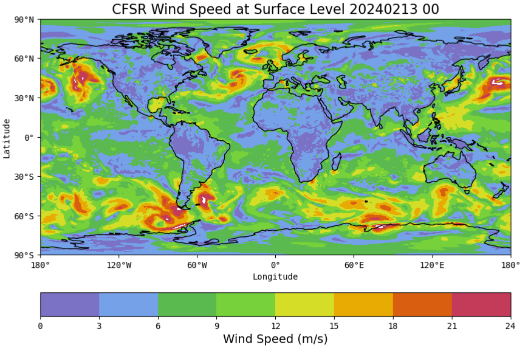
- Reanalysis are stored in binary formats GRIB (CFSR, ERA5) and NetCDF (MERRA2)
- Data contain 3-dimensional variables needed by NWP models (T, P, RH, Φ, u, v,etc.)

Bottom level available with surface variables:

Dataset	Wind	Temperature
ERA5	100m, 10m	2m
MERRA2	50m, 10m	2m
CFSR	10m	2m

CFSR

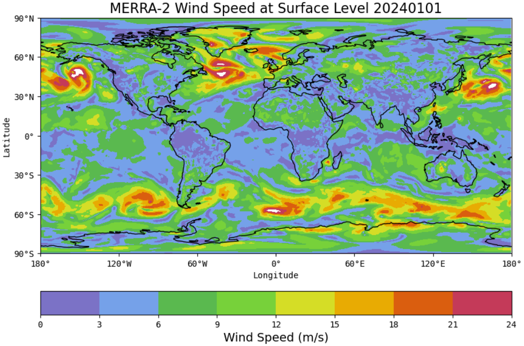
- Climate Forecast System Reanalysis (CFSR) was released by NCEP (NOAA) in 2010.
- Spatial resolution is 0.5 by 0.5 degrees of latitude and longitude with 37 vertical levels (64 model).
- Temporal resolution of 6 hours (00, 06, 12 and 18 UTC) extending from 1979 up to present (CFSv2, updated daily).



https://nomads.ncep.noaa.gov/pub/data/nccf/com/cfs/prod/cdas.20240213/cdas1.t00z.pgrbhanl.grib2

MERRA2

- The second Modern-Era Retrospective analysis for Research and Applications was released by NASA in 2016.
- Spatial resolution is 0.625 degrees of longitude by 0.5 degrees of latitude with 42 vertical levels (72 model).
- Temporal resolution of 6 hours (00, 06, 12 and 18 UTC) extending from 1980 up to present, updated monthly.

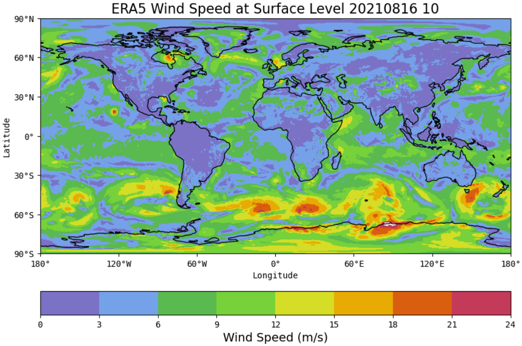


MERRA-2 Wind Speed at Surface Level 20240101

https://goldsmr5.gesdisc.eosdis.nasa.gov/data/MERRA2/M2I6NVANA.5.12.4/2024/01/MERRA2_3d_Nv.20240101.nc4

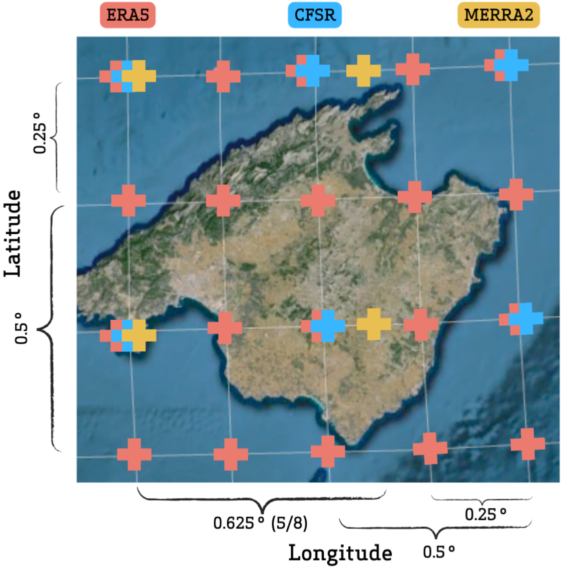
ERA5

- ERA5 was released by the European Centre for Medium-Range Weather Forecasts (ECMWF) in 2018.
- Spatial resolution is 0.25 by 0.25 degrees of latitude and longitude with 37 vertical levels (137 model)
- Temporal resolution is hourly extending from 1940 up to present, updated daily (ERA5-T 5 days of delay)



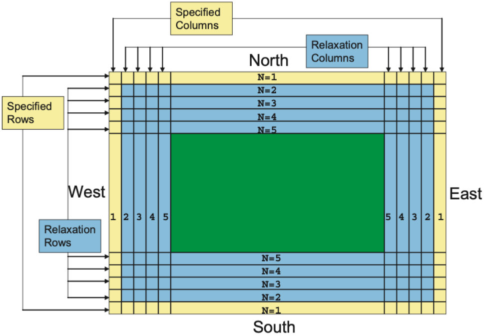
https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels

Reanalysis



Lateral Boundary Conditions

- Inner domains use the parent domain as boundary conditions.
- Model has to provide lateral conditions for outer-most domain
- Specified zone: interpolation from an external analysis
- Relaxation zone: where the model is nudged or relaxed towards the large-scale analysis.



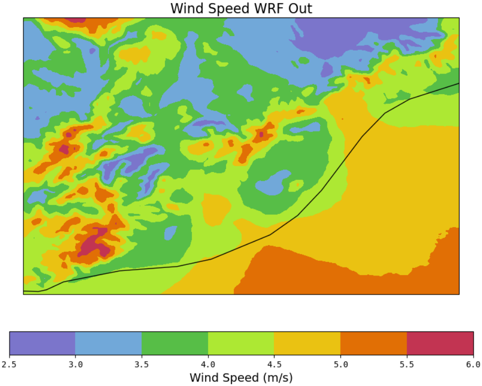
Lateral Boundary conditions. **Credit:** A Description of the Advanced Research WRF Model Version 4.3

Nudging

- Nudging is a method of keeping simulations close to observations or reanalysis data.
- Three types:
    - Grid: Forces the model towards the observations grid-point by grid-point.
    - Observational: Forces the model locally.
    - Spectral: Decomposes the difference fields spectrally

Output

- WRF output data is typically stored in netCDF files.
- The three-dimensional variables are the staggered grid.
- *wrfout_to_cf.ncl* translates values in NetCDF Climate and Forecast (CF) compliant format



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