Numerical Modeling

(Separate notes accompany this PowerPoint)

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Outline

- Numerical Models
- NWP
- WRF

What are numerical models?

A numerical model numerically integrates a set equations for a volume of the atmosphere, which is divided into a series of material volumes, called the grid mesh.

“Model” of the atmosphere

- Take equations that describe atmospheric processes
- Convert them into a form where they can programmed into a computer
- Solve the equations so that this software representation of the atmosphere evolves within the computer
- This is called a “model” of the atmosphere

Example of solving equation

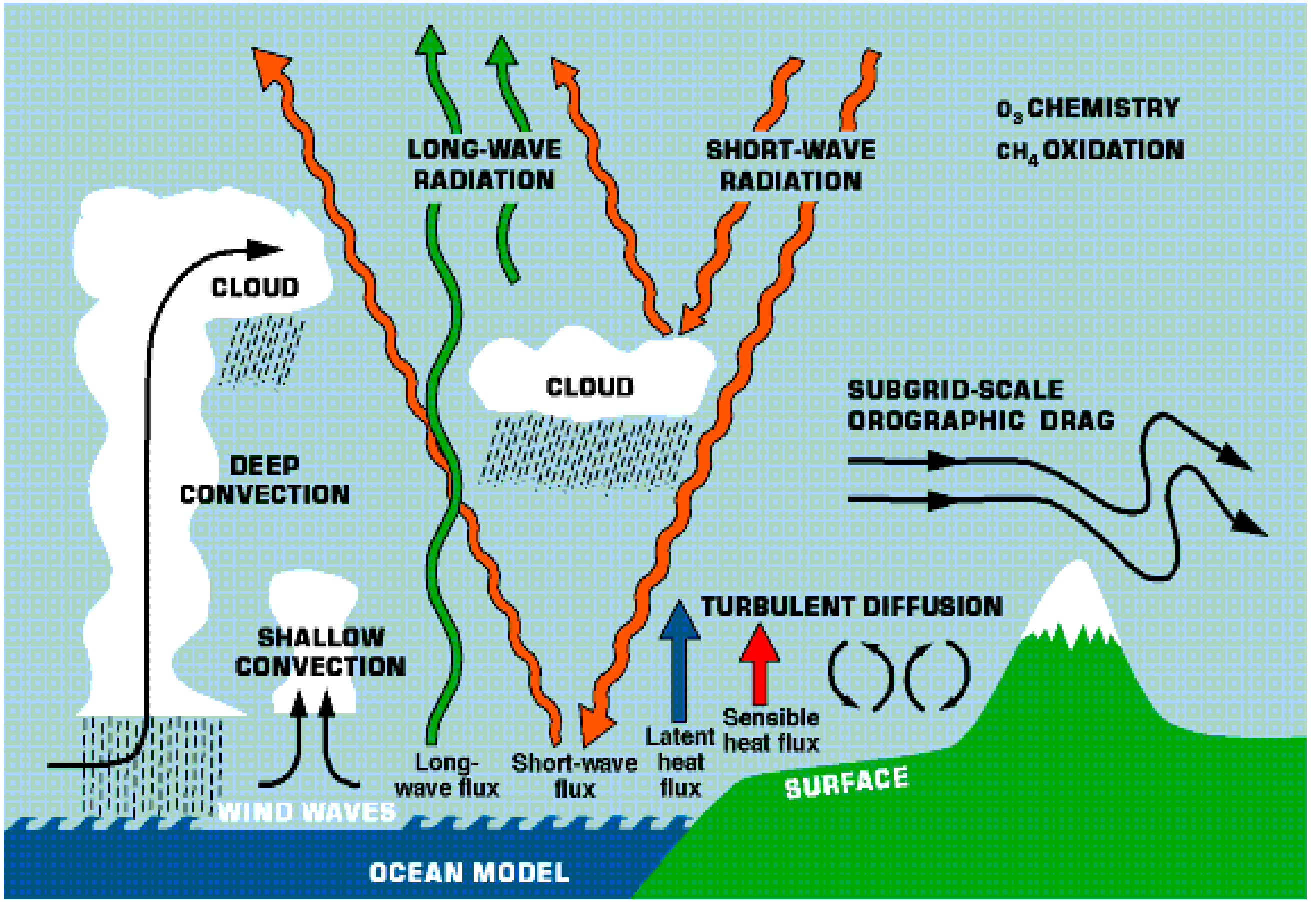
- $\frac{T_{\{change\}}}{time} = solar + IR\ (gain) + IR\ (loss) + conduction + convection + evaporation + condensation + advection$

So – “solving” the equation implies estimating the terms on the right hand side, adding them up and obtaining rate of change of temperature.

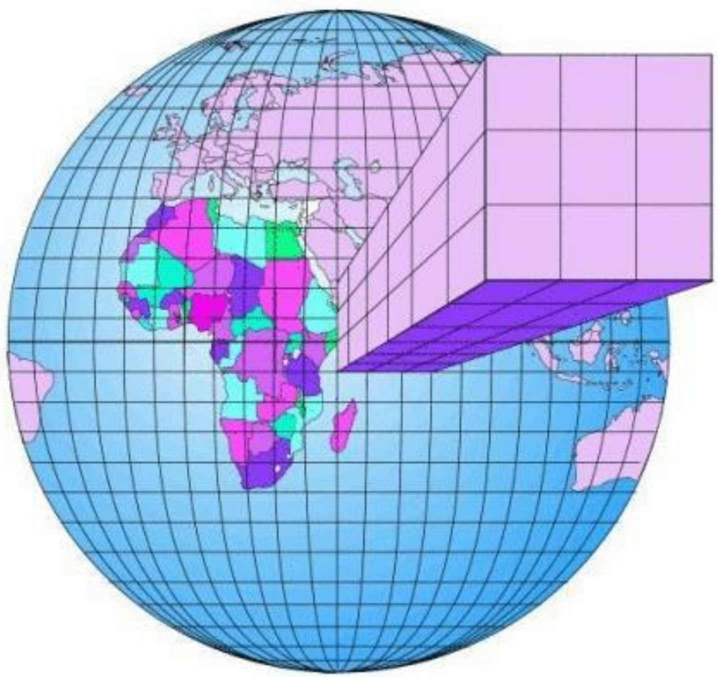
Similar Equations are solved for

- East-west wind component
- North-south wind component
- Specific humidity (or RH)
- Pressure
- Cloud water
- Rain/snow water

Schematic of processes that generally require parameterization



Low resolution grid mesh for a global model



Some Basics

- Matter of interest (e.g. atmosphere) is assumed to be continuous
- Modeling material volume
- Material volume has bulk properties of density, temperature, velocity, etc

Putting the ideas in perspective

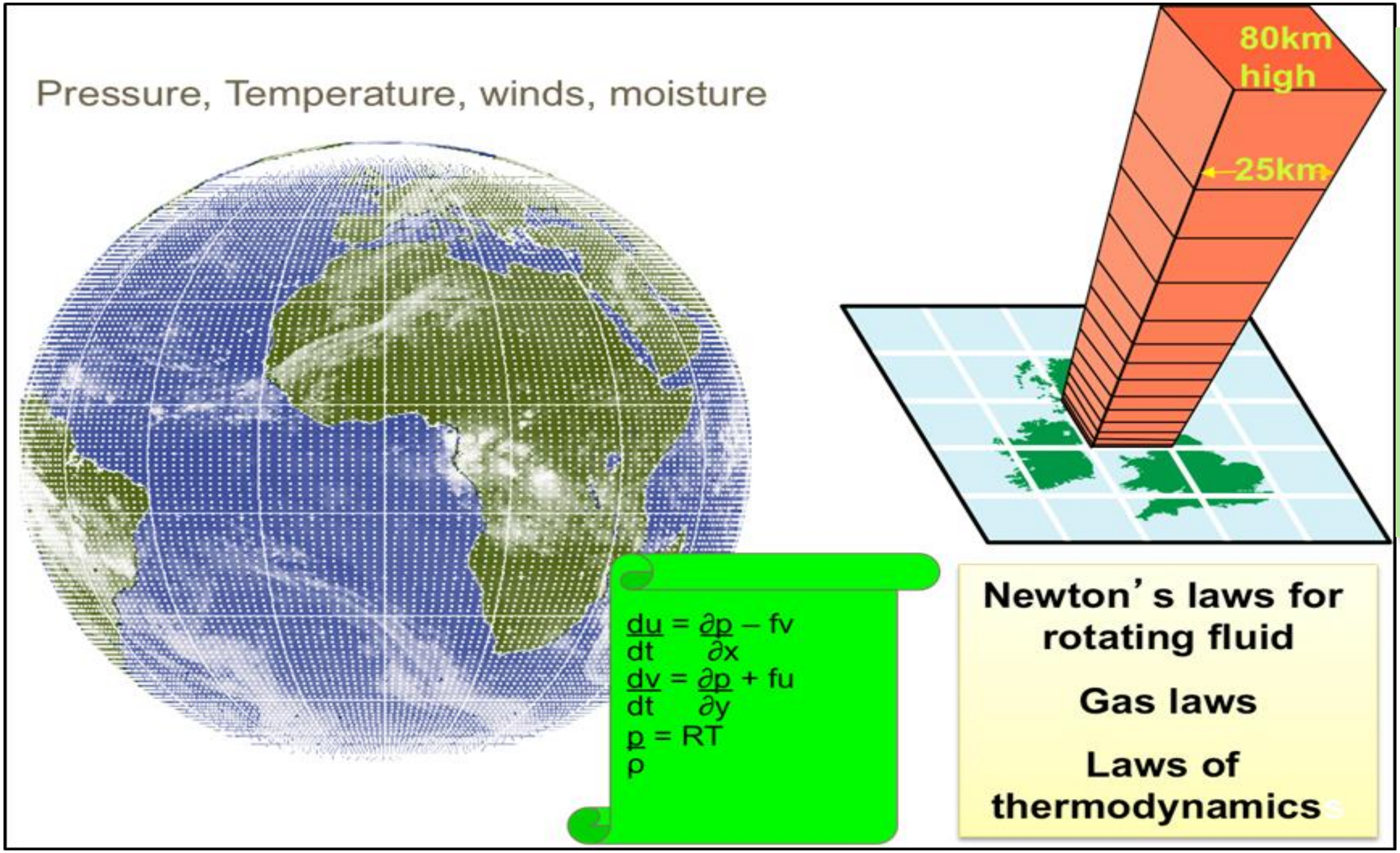


Figure 10.5: Model horizontal and vertical grids on the sphere used to solve the fluid equations to provide a numerical weather forecast. The dimensions and grid spacings are from the Met Office Unified Model (MetUM) used for global NWP (Circa August 2013).

Source: The Forecasters' Handbook chp 10

Two Types of Models

- Global – grid covers the entire atmosphere of Earth (global models)
- Limited area – grid covers a region of the atmosphere such as continent, sub-continent or city (limited area models).

Types of Models

- Global Climate Models (GCMs)
- Regional Models/Limited Area Models (LAMs) or Mesoscale Models
- Cloud Resolving Models (CRM)

Element's of a model(1)

- The basic coordinate system
  - Longitude, latitude, sigma, time
- Meteorological variables
  - Wind, temperature, pressure,moisture content, etc at every level at each grid point
- The governing equations

Governing Equations

- Conservation of momentum (Newton's laws)
  - 3 equations for accelerations of 3-d 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
- Relationship among p, V, and T
  - 1 equation of state (ideal gas law)

Elements of a model (2)

- Physical processes
  - Boundary conditions (Lower, Upper, Lateral)
  - Surface Characteristics (Topography, Land-Sea)
  - Horizontal Diffusion
  - Boundary Layer
  - Heat Transfer Processes
  - Moisture and Precipitation

Uses of Atmospheric Models

- Daily weather prediction (models are allowed to run into the future for 1-10 days)
- Climate prediction (models are allowed to run for years
  - "what if" experiments, e.g. what will happen if we double CO_2?
  - Simply let the model run forward
- Research – You can study the model solution when you do not have good observations of real atmosphere

What is NWP (1)?

A method of weather forecasting that employs:

- A set of equations that describe the flow of fluids,
- Which is translated into computer code,
- Combined with parameterizations of other processes,
- Then applied on a specific domain,
- And integrated, based on initial conditions and conditions at the domains’ boundaries

What is NWP (2)?

A method of weather forecasting that employs:

- Governing equations
- Numerical methods
  - Finite difference (based on Taylor series)
  - Finite volume (based on fluxes in and out of volume)
  - Spectral (calculated in Fourier space)
- Parameterizations
- Domains
- Initial and boundary conditions

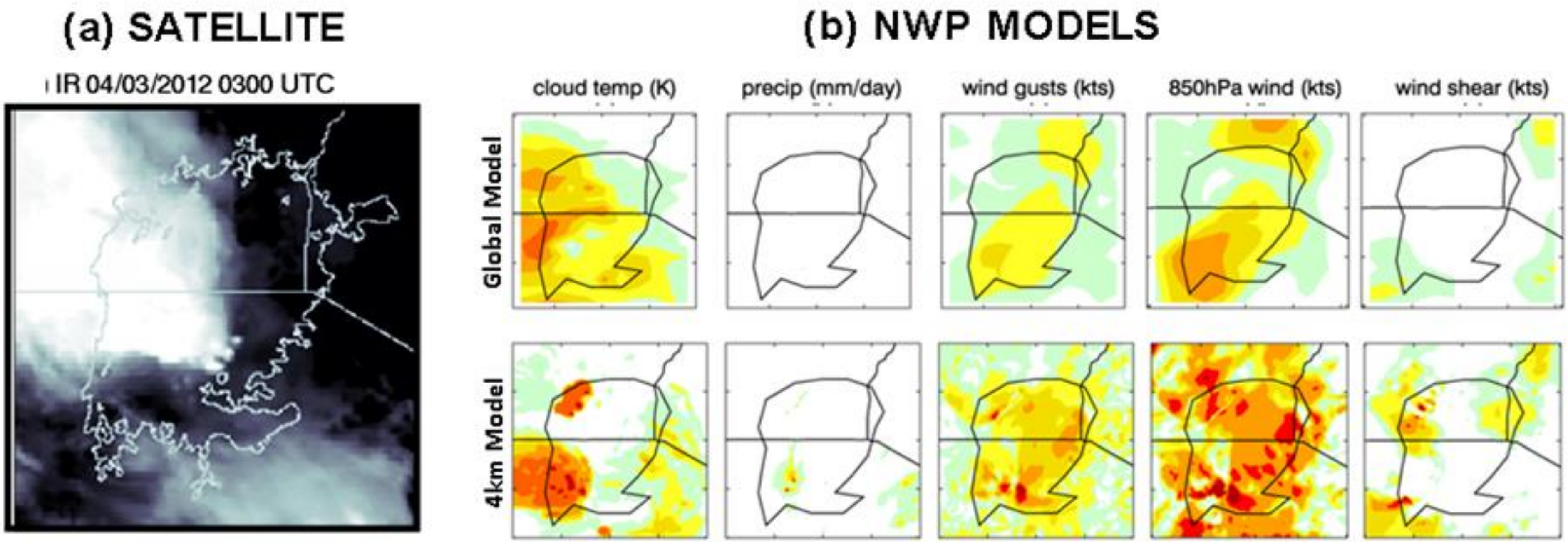


Figure 10.22: Case Study of Lake Victoria storm from 4th March 2012: (a) Satellite IR imagery (b) Met Office NWP operational model performance for Global and 4 km models. (Reproduced from Fig. 7, 8 and 9 of Chamberlain et al. (2013)

Source: The Forecasters' Handbook chp 10

Introduction to WRF Model

- Weather Research and Forecasting Model
- Different WRF Models with same architecture but different core codes
  - ARW (Advanced Research WRF) at NCAR
  - NMM (Non-Hydrostatic Mesoscale Model) at NCEP
    - Based on Eta Model's code

Architecture of WRF Model

DRIVER	- Manages execution over nested grids - Controls input/output - Top-level control over parallel processing
MEDIATOR	- Makes calls to parallel mechanisms
MODEL	- Contains numerics and physics - Performs model computations

Suitability

- Idealized simulations (e.g. LES, convection, baroclinic waves)
- Parameterization research
- Data assimilation research
- Forecast research
- Real-time NWP
- Coupled-model applications
- Teaching
- Climate Simulation

Grand Vision for WRF Model

- From the start, WRF was intended to be used for both research and operations
  - Shorten time between research developments in NWP and application to operations
  - Increase communication and understanding between research and operational communities

Platforms for WRF Model

- Can be run on a variety of platforms: single processor, shared or distributed memory

Remarks

- The WRF Model is state-of-the-art in operational mesoscale NWP, free, has a large user community sharing knowledge, has a technical support team at NCAR

- WRF Tutorial presentations in PPT and PDF
  http://www.mmm.ucar.edu/wrf/users/supports/tutorial.html

- WRF technical paper
  http://www.mmm.ucar.edu/wrf/users/pub-doc.html

Thank you

Extras

Numerics in WRF Model

- The WRF Model's numerics are higher order than MM5's, so they contain more terms and better approximate the governing equations
  - Horizontal advection: 5^{th} order
  - Vertical advection: 3^{rd} order
  - Temporal integration: 3^{rd} order

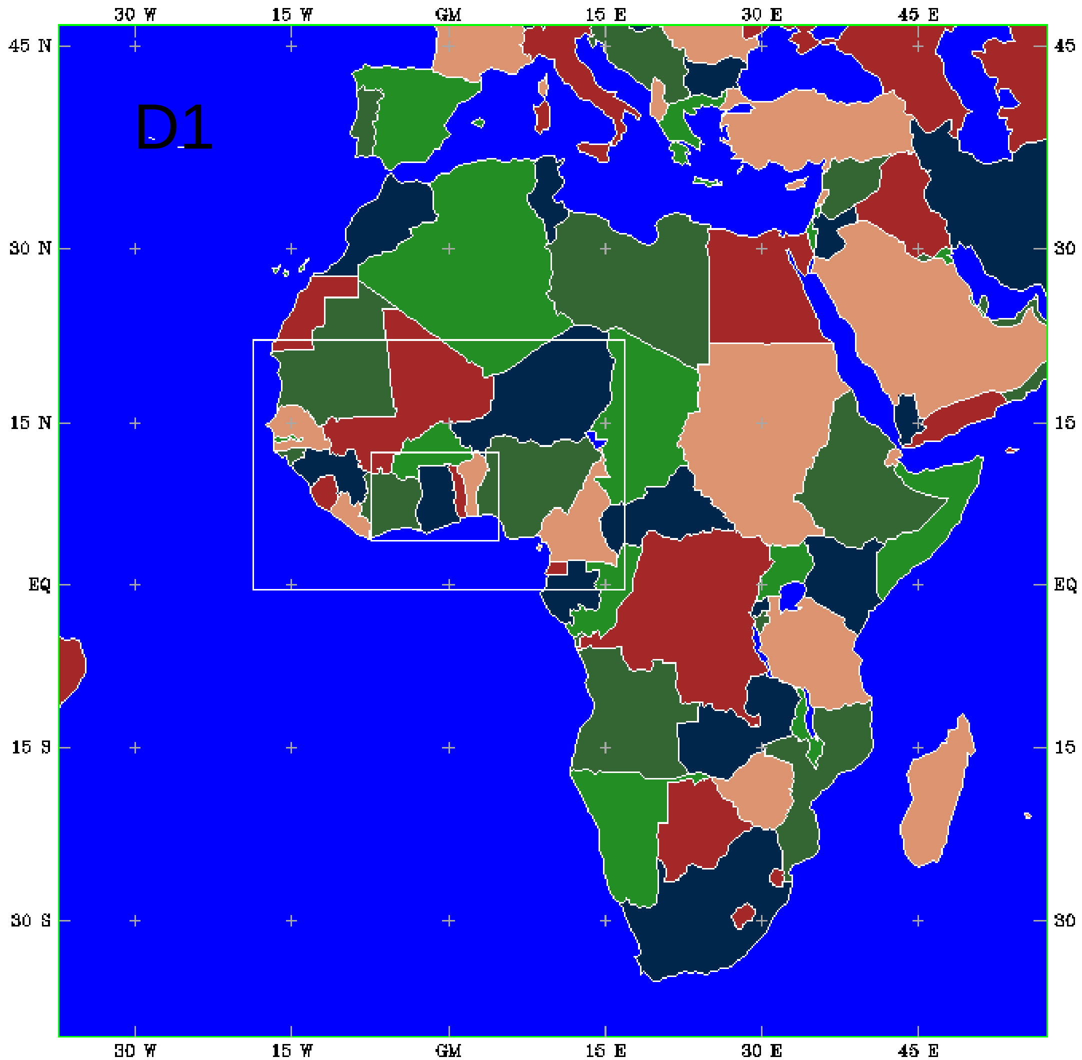
Domains

Three domains
2-way nested

DX=
40.5/13.5/4.5 km

Dimensions
D1: 261x261x36
D2: 184x295x36
D3: 208x301x36

D1 is largest domain
D3 is smallest domain



Governing Equations

Higher order advection schemes, which lead to a higher effective resolution than in many other NWP models

- Almost every model uses a slightly different set of equations.

- Why?
  - Application to different parts of the world
  - Focus on different atmospheric processes
  - Application to different time and spatial scales
  - Ambiguity and uncertainty in formulations
  - Tailoring to different uses

Governing Equations

- The WRF Model is one of the first cloud-scale models designed to conserve mass, momentum, and energy.

- But…
  - Water is only perfectly conserved if positive definite advection (available since V2.2) is used
  - Momentum and energy are not numerically conserved
  - Momentum is not really conserved because it is a staggered variable, and so can't use the mass conservation property accurately

ARW Solver (1)

- **Equations: Fully compressible, Euler nonhydrostatic with a run-time hydrostatic option available. Conservative for scalar variables.**
- **Prognostic Variables: Velocity components u and v in Cartesian coordinate, vertical velocity w, perturbation potential temperature, perturbation geopotential, and perturbation surface pressure of dry air. Optionally, turbulent kinetic energy and any number of scalars such as water vapor mixing ratio, rain/snow mixing ratio, and cloud water/ice mixing ratio.**
- **Vertical Coordinate: Terrain-following hydrostatic-pressure, with vertical grid stretching permitted. Top of the model is a constant pressure surface.**
- **Horizontal Grid: Arakawa C-grid staggering.**
- **Time Integration: Time-split integration using a 3rd order Runge-Kutta scheme with smaller time step for acoustic and gravity-wave modes.**
-

ARW Solver (2)

- **Initial Conditions: Three dimensional for real-data, and one-, two- and three-dimensional using idealized data. A number of test cases are provided.**
- **Lateral Boundary Conditions: Periodic, open, symmetric, and specified options available.**
- **Top Boundary Conditions: Gravity wave absorbing (diffusion or Rayleigh damping). w = 0 top boundary condition at constant pressure level.**
- **Bottom Boundary Conditions: Physical or free-slip.**

ARW Solver (3)

- Spatial Discretization: 2nd to 6th order advection options in horizontal and vertical.
- Turbulent Mixing and Model Filters: Sub-grid scale turbulence formulation in both coordinate and physical space. Divergence damping, external-mode filtering, vertically implicit acoustic step off-centering. Explicit filter option also available.

- Earth's Rotation: Full Coriolis terms included.
- Mapping to Sphere: Three map projections are supported for real-data simulation: polar stereographic, Lambert-conformal, and Mercator. Curvature terms included.
- Nesting: One-way, two-way, and moving nests

Model Physics

- **Microphysics: Bulk schemes ranging from simplified physics suitable for mesoscale modeling to sophisticated mixed-phase physics suitable for cloud-resolving modeling.**
- **Cumulus parameterizations: Adjustment and mass-flux schemes for mesoscale modeling including NWP.**
- **Surface physics: Multi-layer land surface models ranging from a simple thermal model to full vegetation and soil moisture models, including snow cover and sea ice.**
- **Planetary boundary layer physics: Turbulent kinetic energy prediction or non-local K schemes.**
- **Atmospheric radiation physics: Longwave and shortwave schemes with multiple spectral bands and a simple shortwave scheme. Cloud effects and surface fluxes are included**