Introduction to the WRF Weather Model

and the ISOR/Belgingur Operational and on Demand Forecast Solution

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Outline of this talk

* Introduction
  * What is ISOR/Belgingur
  * Atmospheric modeling
* The WRF modeling system
  * Pre-processing
  * Model physics
  * Running the model and data visualization
* The ISOR/Belgingur forecasting suite
  * Introduction
  * Demonstration

Where we came from

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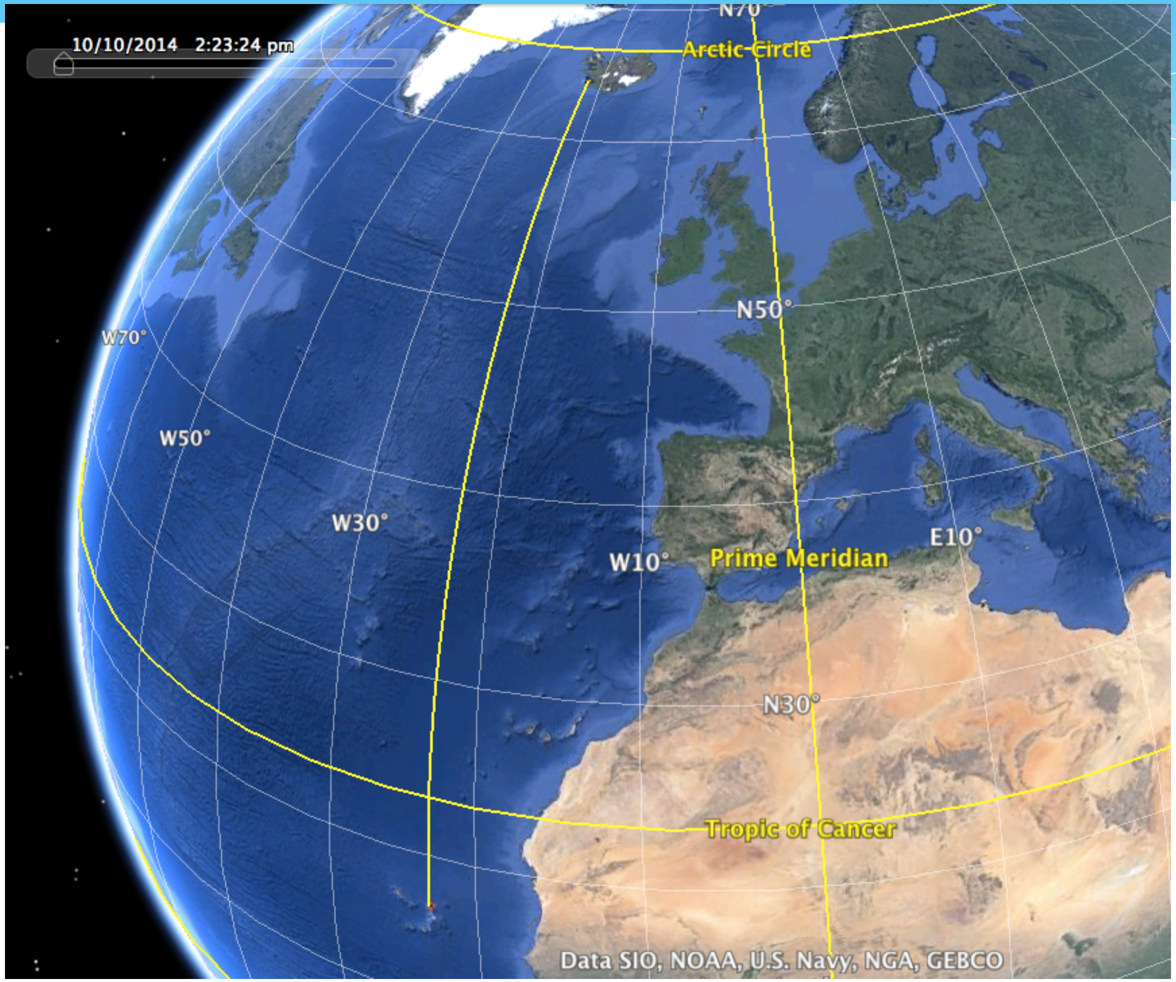
Where we went ☺



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About ISOR (aka Iceland Geosurvey)

* Established in 2003 when the GeoScience Division of the National Energy Authority of Iceland was spun off as a separate entity
* A self-financing, state-owned, non-profit institution
* More then six decades of continuous experience in the field of geothermal and hydropower research and development
* Provides over half of the teaching staff of the UNU Geothermal Training Programme, operated since 1979

About Belgingur

* Founded in 2001 – www.belgingur.eu
* Mixed private and governmental ownership
  * 90% private
  * 10% owned by ISOR (aka Iceland Geosurvey)
* Strong tradition in atmospheric research
  * Atmospheric flow in complex terrain
  * Dynamical downscaling of global climate data
* Operational forecasts since 2004
  * www.belgingur.is
* On-Demand forecasts since 2012
  * SARWeather – www.sarweather.com

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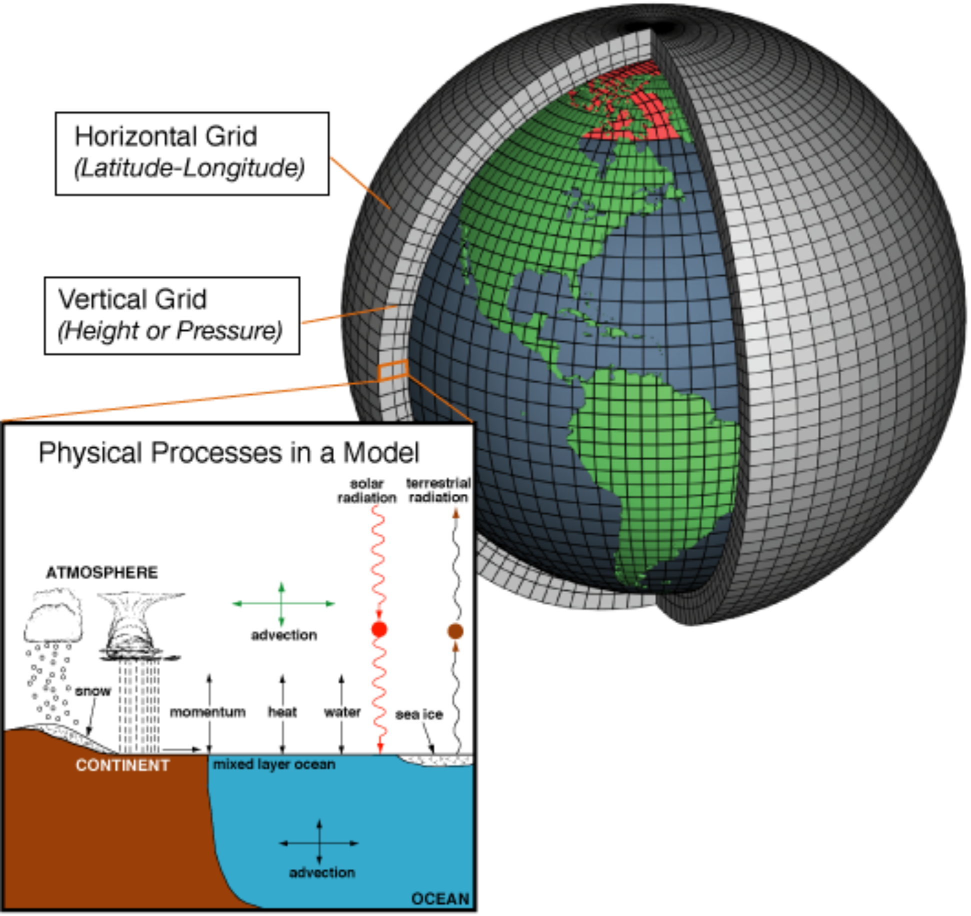
Our network

* Long time collaborators with
  * NOAA/ESRL in Boulder, USA
  * ISOR, Iceland
  * The Icelandic Meteorological Office
  * University of Bergen, Norway
  * University of Iceland and Reykjavík University, Iceland
* Service provider for
  * GDACS – Global Disaster and Alerts Coordination System
    * SARWeather On-Demand forecasts
  * Landsvirkjun – The Icelandic Power Company
  * Vegagerðin – The Icelandic Road Authorities
  * The Icelandic Meteorological Office (2004-2012)
  * Eneco Ltd., the Netherlands
  * 365 Media, Iceland

Atmospheric models



Set of equations that describe the atmospheric flow and need to be integrated forward in time to produce a weather forecast

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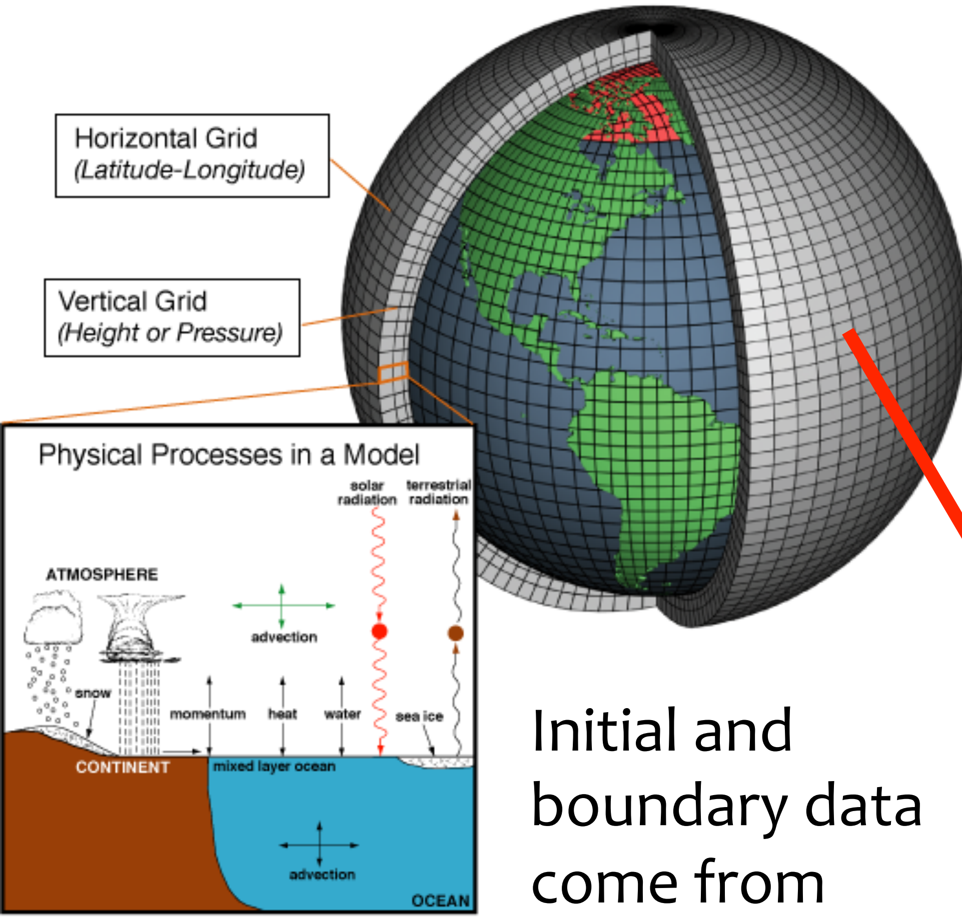
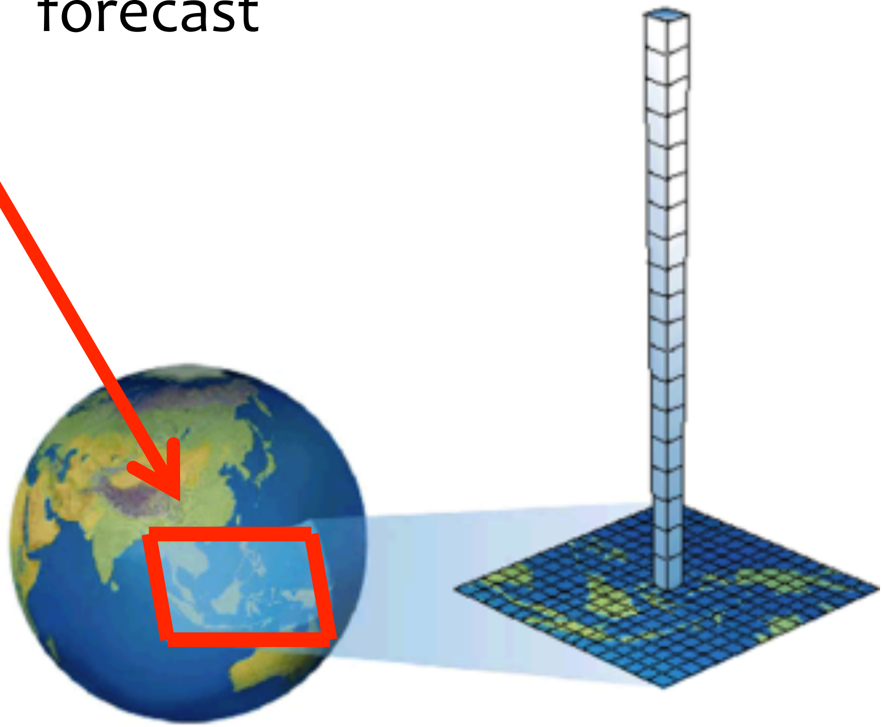
Atmospheric models



Set of equations that describe the atmospheric flow and need to be integrated forward in time to produce a weather forecast

Initial and boundary data come from global models

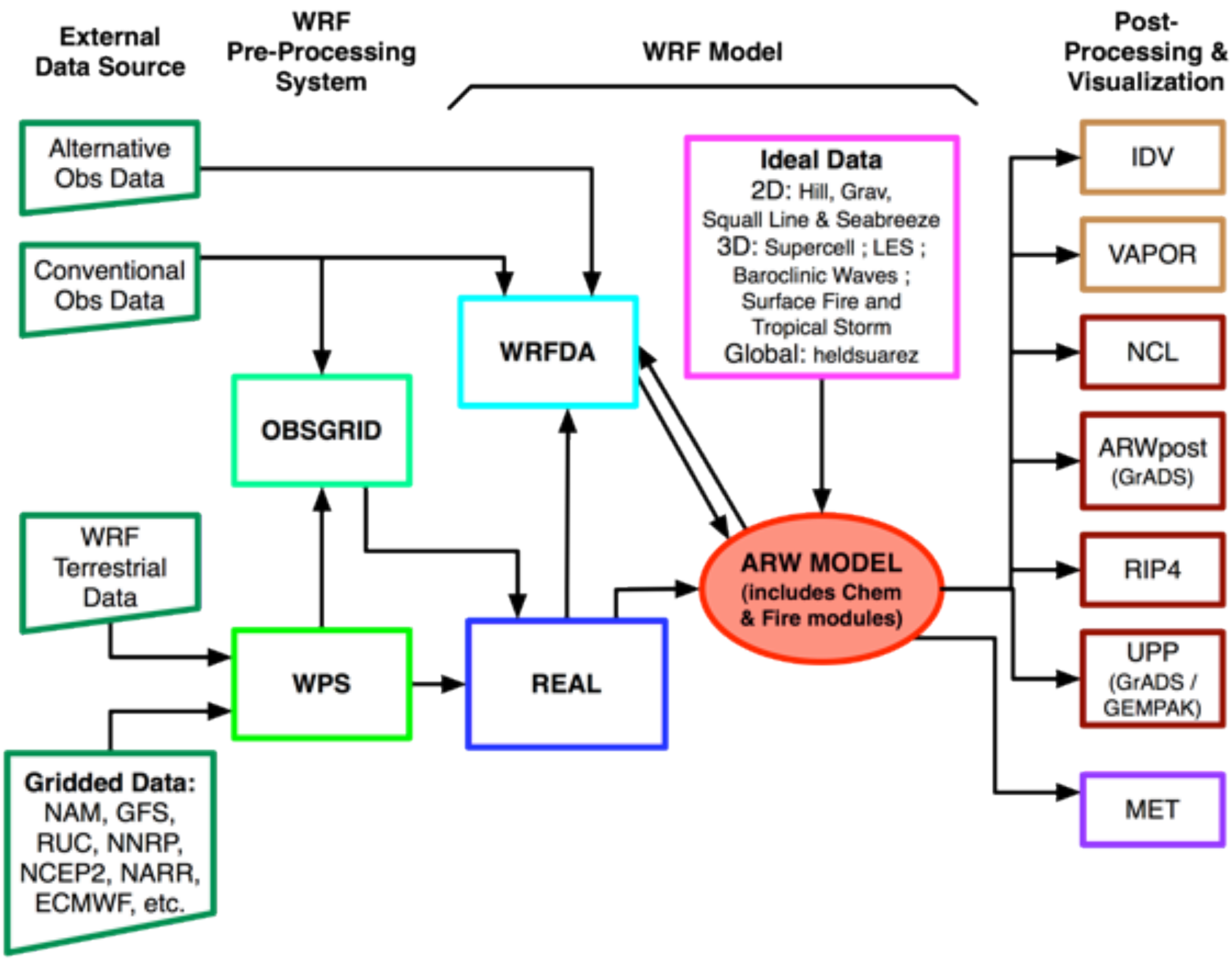


Regional

The WRF atmospheric model

- Open source model developed in collaboration of
  - NCAR, NOAA, AFWA, NRL, Univ. of Oklahoma & FAA
- Five development teams with sixteen workgroups
  - More than 160 official developer
  - Additional development by academic and governmental institutions in the US and abroad
  - Very large user community (>20.000), excellent support
- Non-hydrostatic
- Regional and global applications
- Wide range of scales for both real time and idealized applications
  - Optional data assimilation (3D-VAR, 4D-VAR, and FDDA)
  - Has been modified for volcanic applications
  - Includes a dust module (re-suspension of dust/ash)

WRF modeling system flow chart



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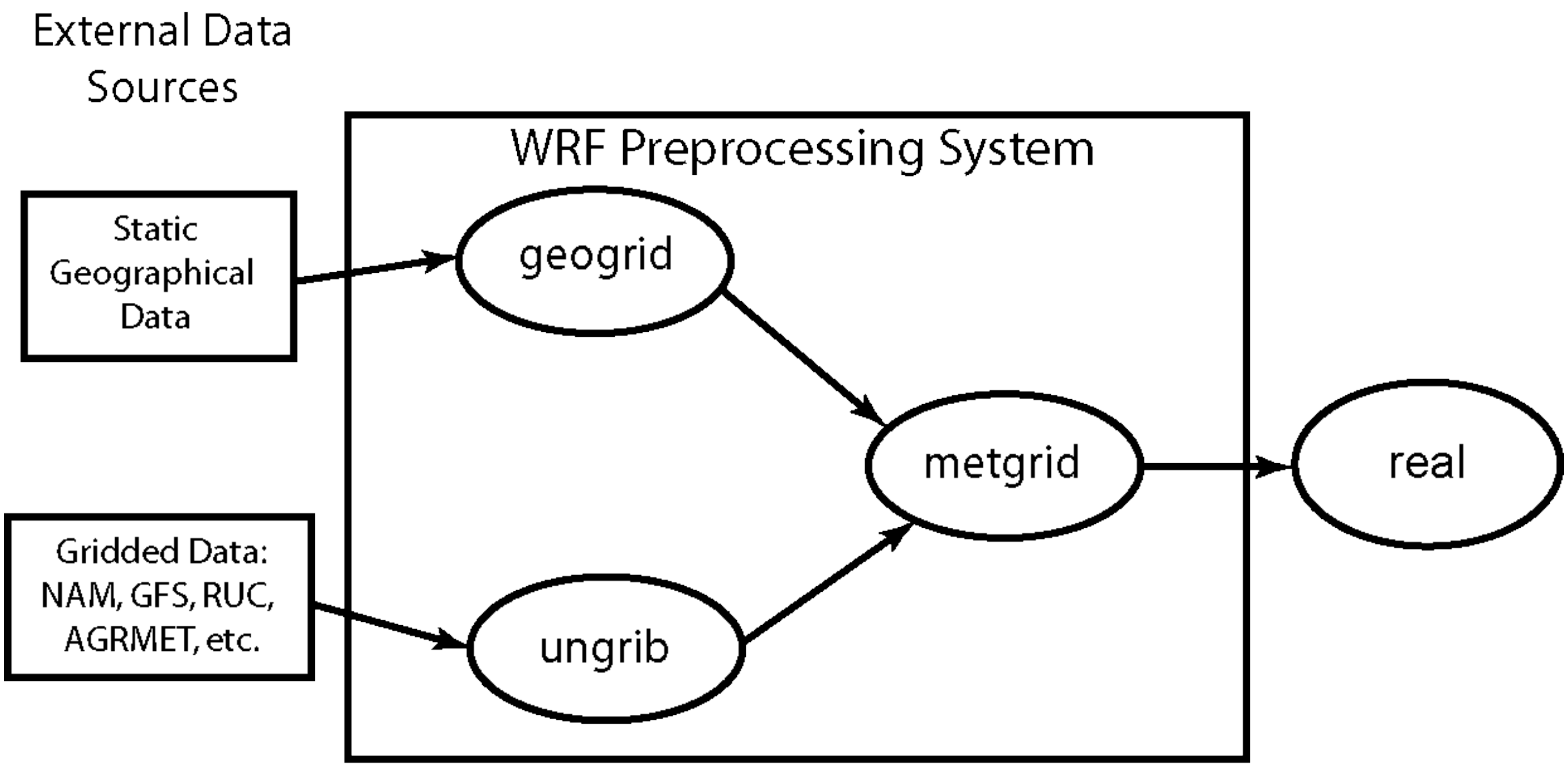
WPS - the WRF Pre-processing system

- The purpose of WPS is to prepare input to WRF for real-data simulations:
  1. Defines simulation coarse domain and ARW nested domains
  2. Computes latitude, longitude, map scale factors, and Coriolis parameters at every grid point
  3. Interpolates time-invariant terrestrial data to simulation grids (e.g., terrain height and soil type)
  4. Interpolates time-varying meteorological fields from another model onto simulation domains

WPS flow chart



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Courtesy of Michael Duda @ NCAR

WPS - overview

- geogrid (think **geo**graphical)
  - Define size/location of model domains and interpolate static terrestrial fields to simulation grids
- ungrib (think **un+grib**)
  - Extract meteorological fields from GRIB files
- metgrid (think **met**eorological)
  - Horizontally interpolate meteorological fields (from ungrib) to simulation grids (defined by geogrid)

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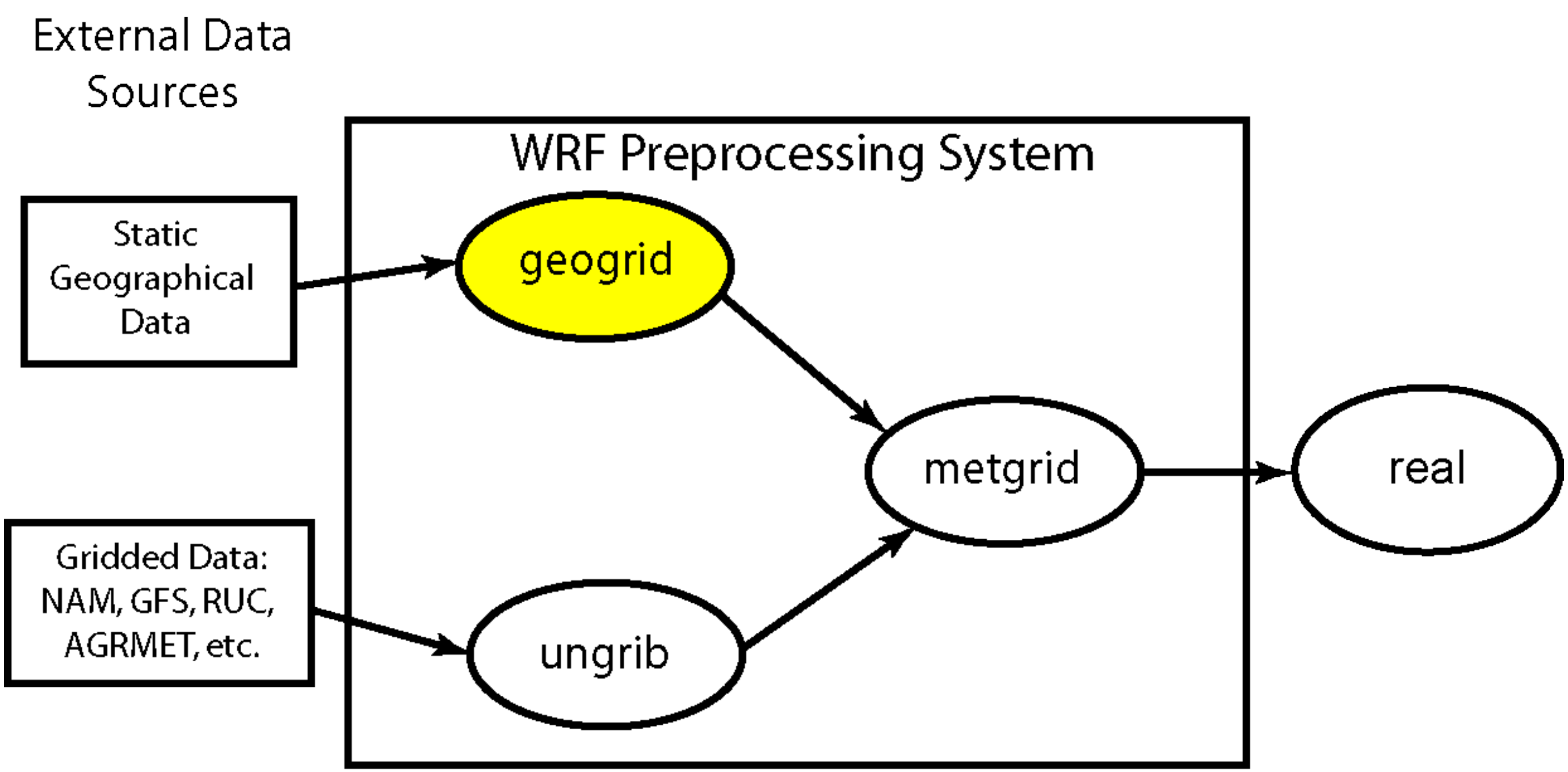
The *geogrid* program



geogrid: think <u>geo</u>graphical

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Courtesy of Michael Duda @ NCAR

The *geogrid* program

- For WRF model domains, geogrid defines:
  - Map projection (all domains must use the same projection)
  - Geographic location of domains - Dimensions of domains
- Geogrid provides values for static (time-invariant) fields at each model grid point
  - Compute latitude, longitude, map scale factor, and Coriolis parameters at each grid point
  - Horizontally interpolate static terrestrial data (e.g., topography height, land use category, soil type, vegetation fraction, monthly surface albedo)

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Geogrid: Nesting basics

- A nested domain is a domain that is wholly contained within its parent domain and that receives information from its parent, and that may also feed information back to its parent
  - A nested domain has exactly one parent
  - A domain may have one or more children
- 2-way nests on the same nesting level must not overlap in coverage!

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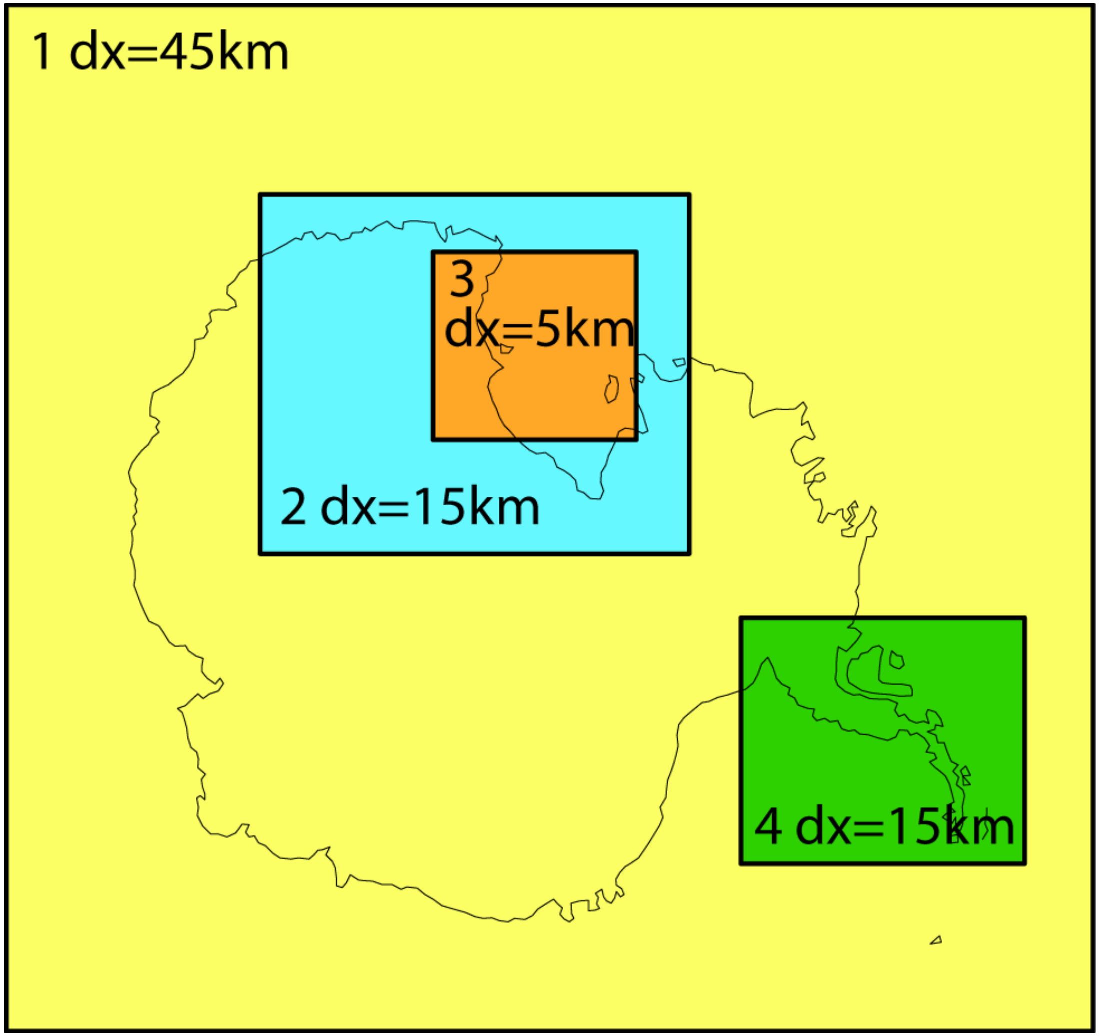
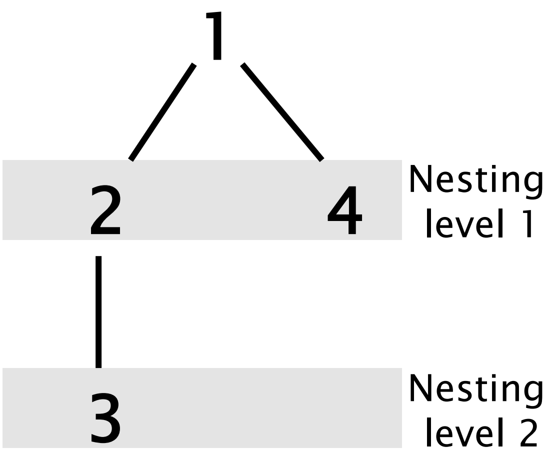
Geogrid: Nesting example

Example configuration using four domains



Each domain is assign a domain ID #



Nesting structure shown as a tree for the domains at left

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Geogrid: Interpolating static fields

- Given definitions of all computational grids, geogrid interpolates terrestrial, time-invariant fields
  - Topography height
  - Land use categories
  - Soil type (top layer & bottom layer)
  - Annual mean soil temperature
  - Monthly vegetation fraction
  - Monthly surface albedo

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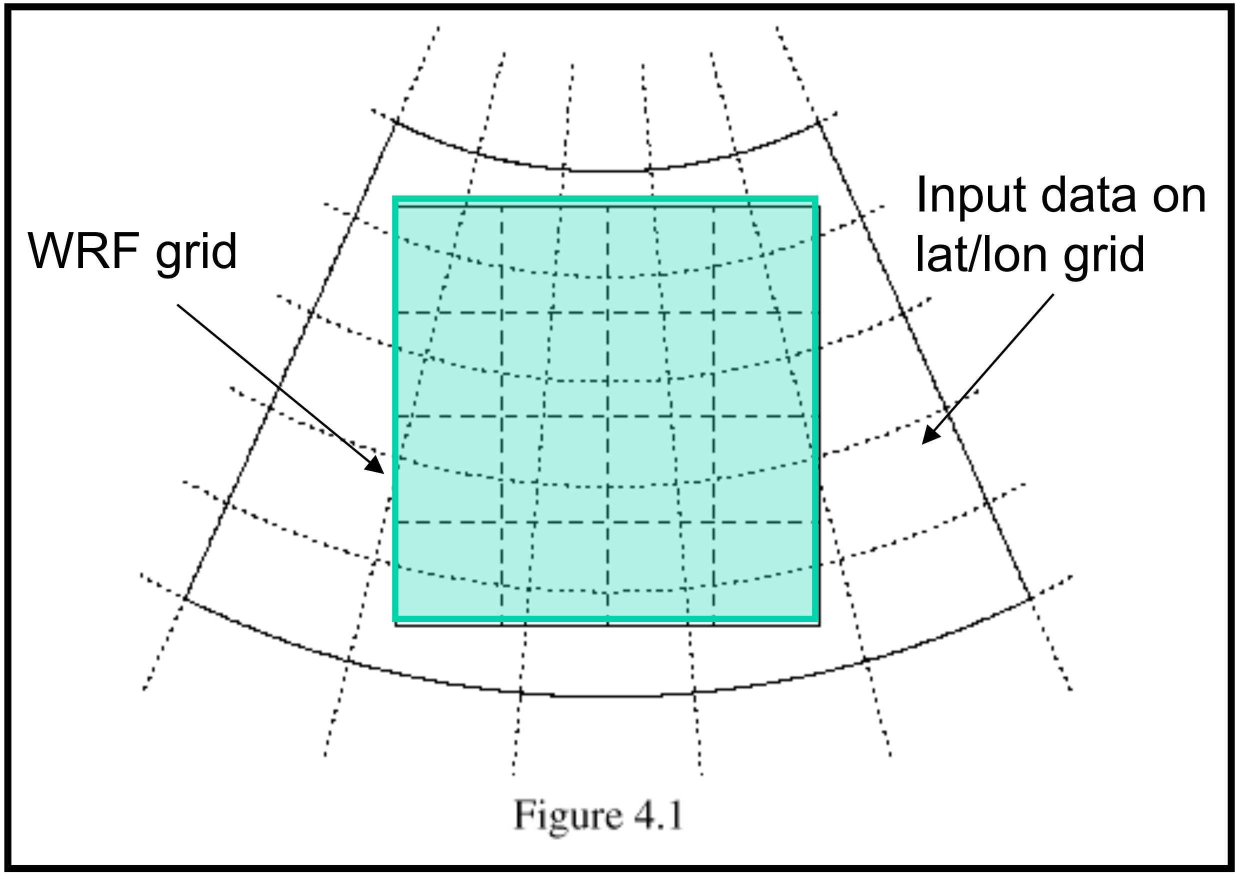
Geogrid: Interpolating static fields



In general, source data are given on a different projection from the model grid

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Geogrid: Output

- The parameters defining each domain, plus interpolated static fields, are written using the WRF I/O
  - One file per domain for ARW
- Filenames: geo_em.d0n.nc
  - (where n is the domain ID number)
- Example:
  - geo_em.d01.nc
  - geo_em.d02.nc (nest)
  - geo_em.d03.nc (nest)

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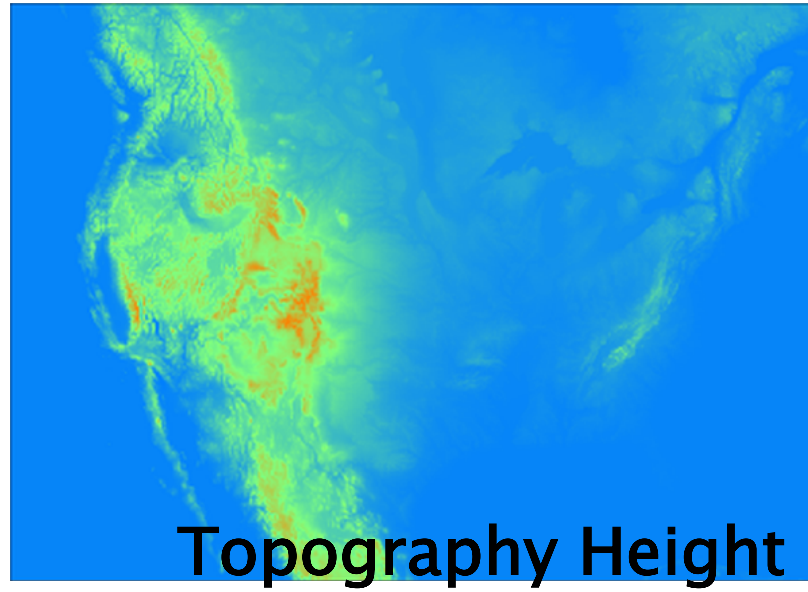
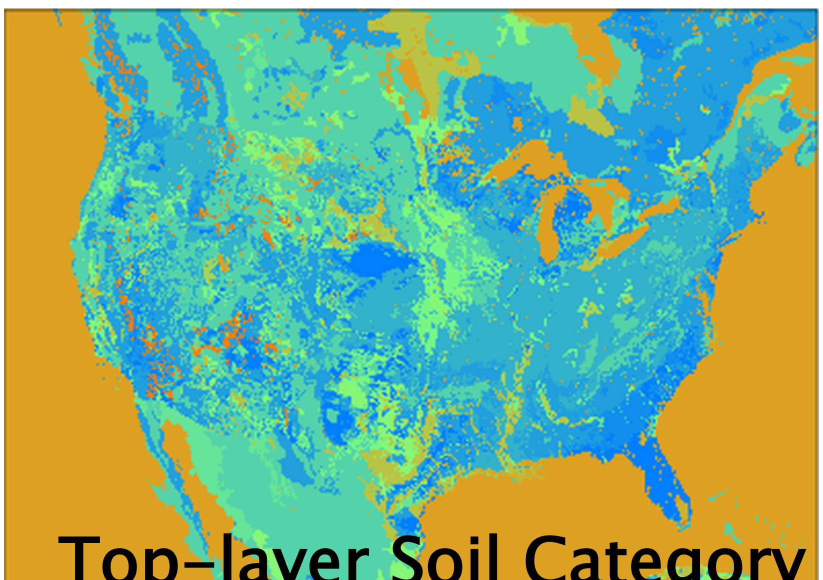
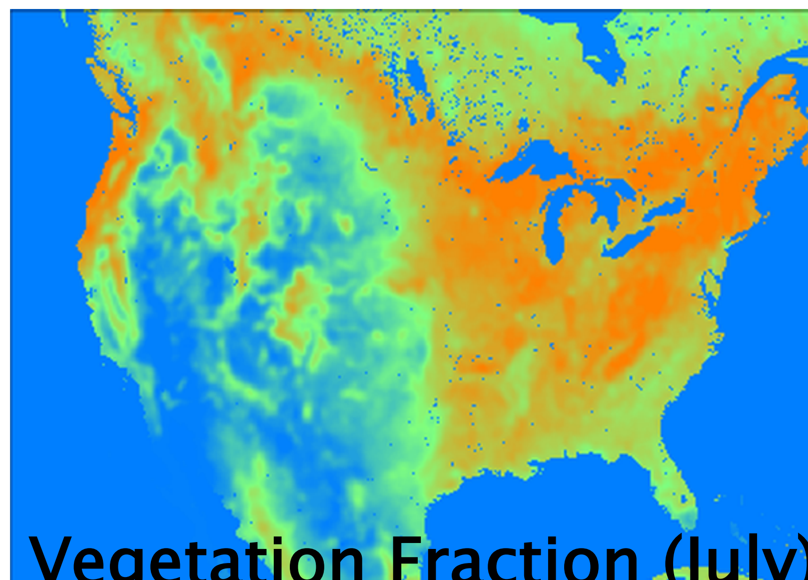
Geogrid: Example output fields

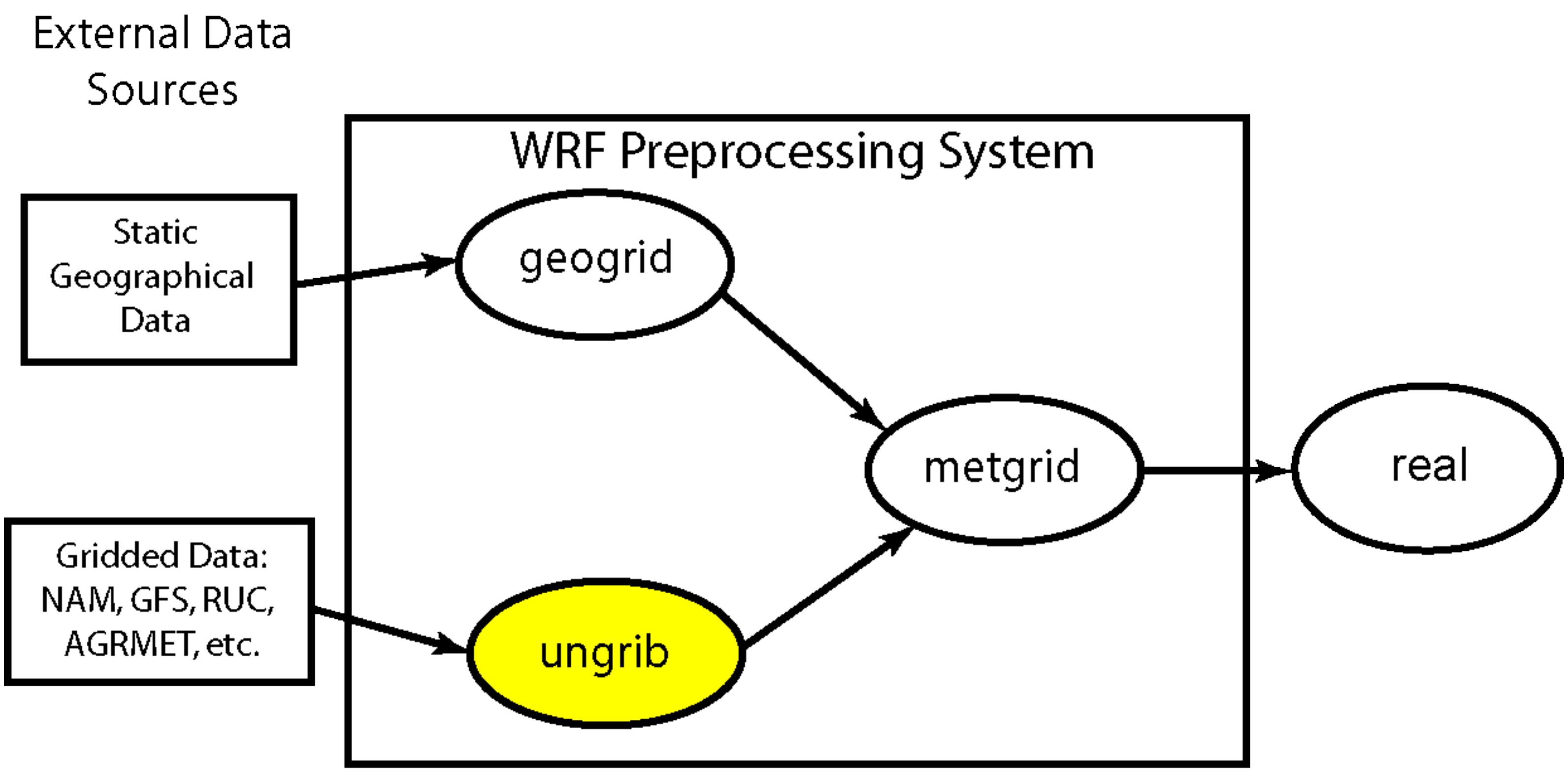






Courtesy of Michael Duda @ NCAR

The *ungrib* program



ungrib: think un+grib

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The *ungrib* program

- Read GRIB Edition 1 and GRIB Edition 2 files
- Extract meteorological fields
- If necessary, derive required fields from related ones
  - E.g., compute RH from T, P, and Q
- Write requested fields to an intermediate file format

Uses Vtables (Vartibal tables) to identify which fields to extract

- Vtables are files that give the GRIB codes for fields to be extracted from GRIB input files
- One Vtable for each source of data
- Vtables are provided for: NAM 104, NAM 212, GFS, AGRMET, and others

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Ungrib: Intermediate file format

- After extracting fields listed in Vtable, ungrib writes those fields to intermediate format
- For meteorological data sets not in GRIB format, the user may write to intermediate format directly
  - Allows WPS to ingest new data sources (basic programming required of user)
  - Simple intermediate file format is easily read/written using routines from WPS (read_met_module.F and write_met_module.F)
- Output files named FILE:YYYY-MM-DD_HH
  - YYYY is year of data in the file; MM is month; DD is day; HH is hour
  - All times are UTC

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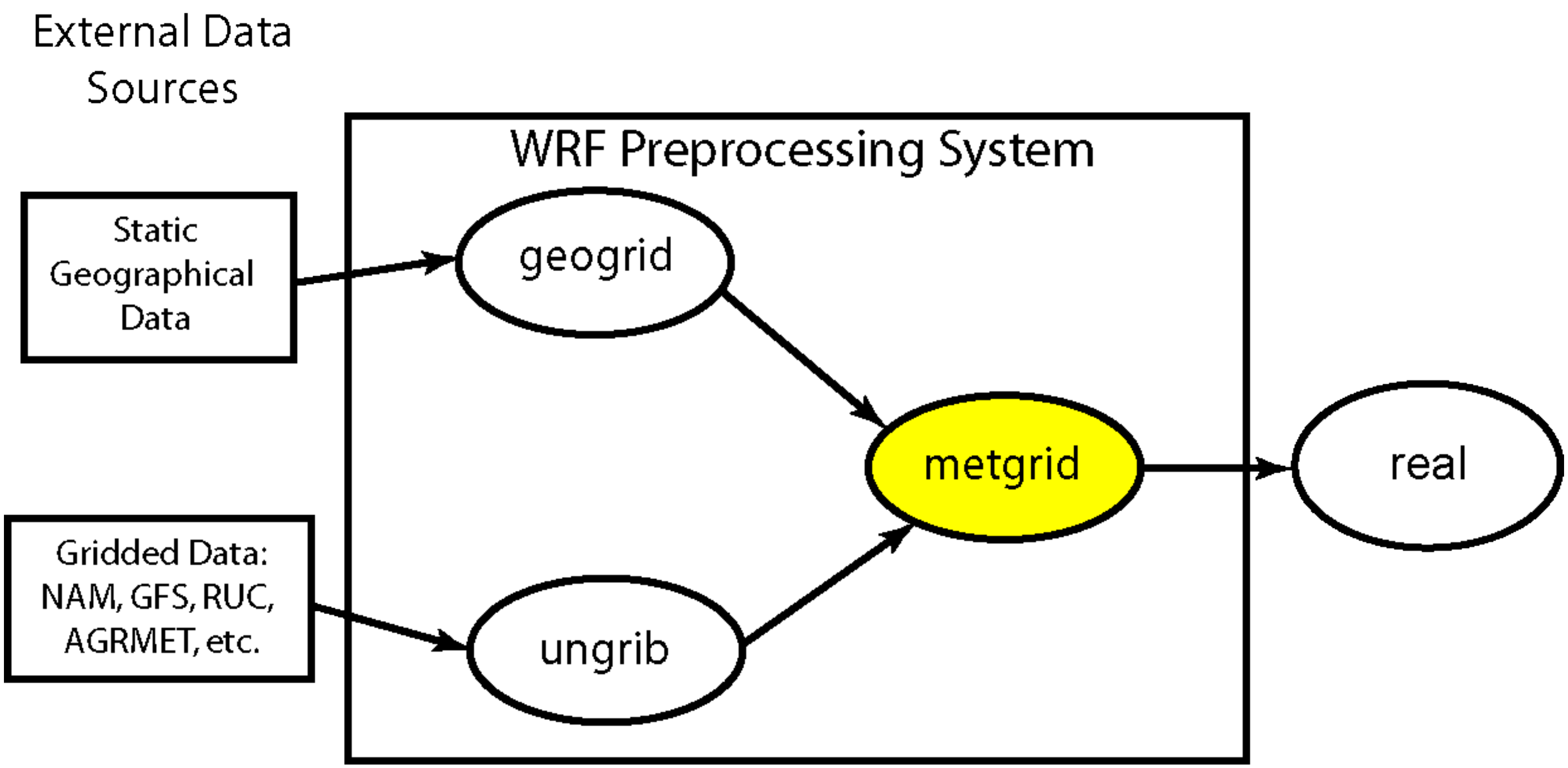
The *metgrid* program



metgrid: think meteorological

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Courtesy of Michael Duda @ NCAR

The *metgrid* program

- Horizontally interpolate meteorological
- data (extracted by ungrib) to simulation domains (defined by geogrid)
    - Masked interpolation for masked fields
    - Can process both isobaric and native vertical coordinate data sets
- Rotate winds to WRF grid
    - i.e., rotate so that U-component is parallel to x- axis, V-component is parallel to y-axis

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Metgrid: Masked interpolation

- Masked fields may only have valid data at a subset of grid points
  - E.g., SST field only valid on water points
- When metgrid interpolates masked fields, it must know which points are invalid (masked)
  - Can use separate mask field (e.g., LANDSEA)
  - Can rely on special values (e.g., $1{\times}10^{30}$) in field itself to identify masked grid points

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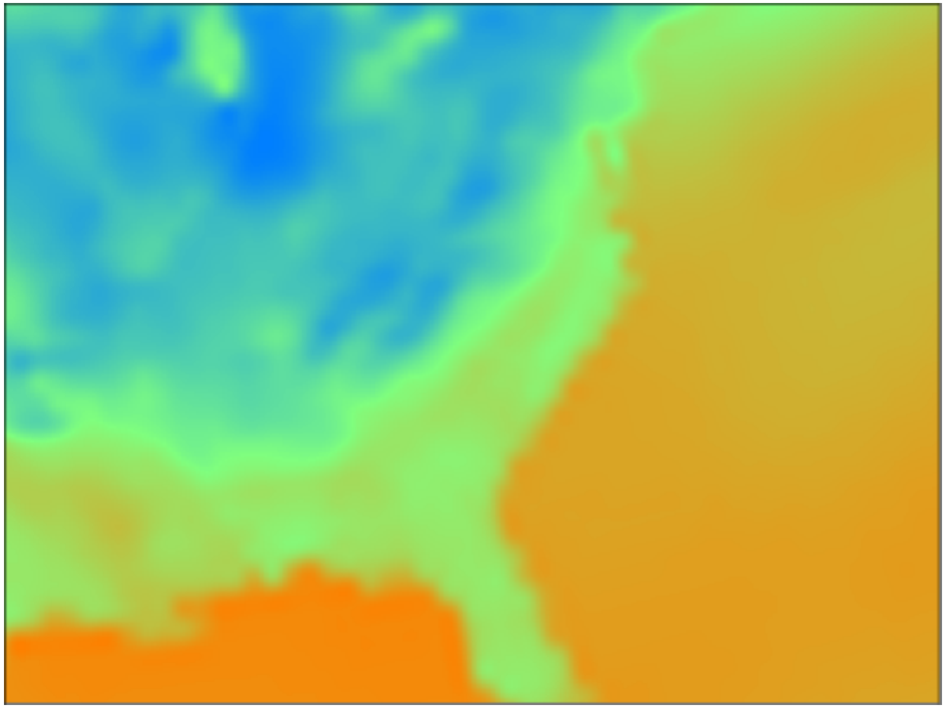
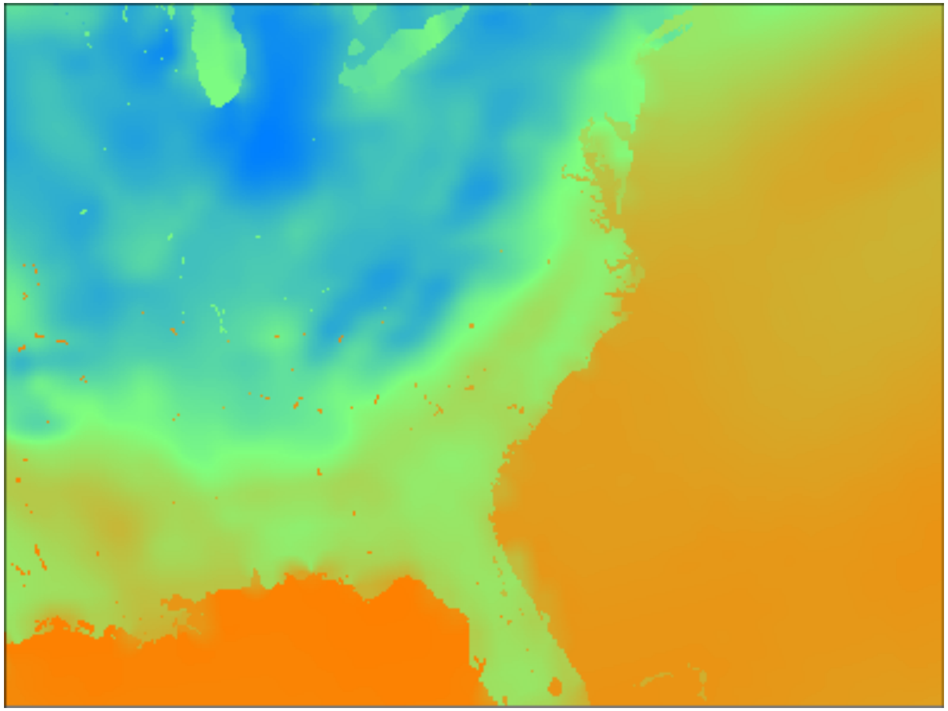
Example: Masked interpolation





Skin temperature field inter-polated from GFS 0.5-deg field with no mask using a sixteen-point interpolator

Skin temperature field interpolated using masks: GFS water points interpolated to model water points, GFS land points interpolated to model land points

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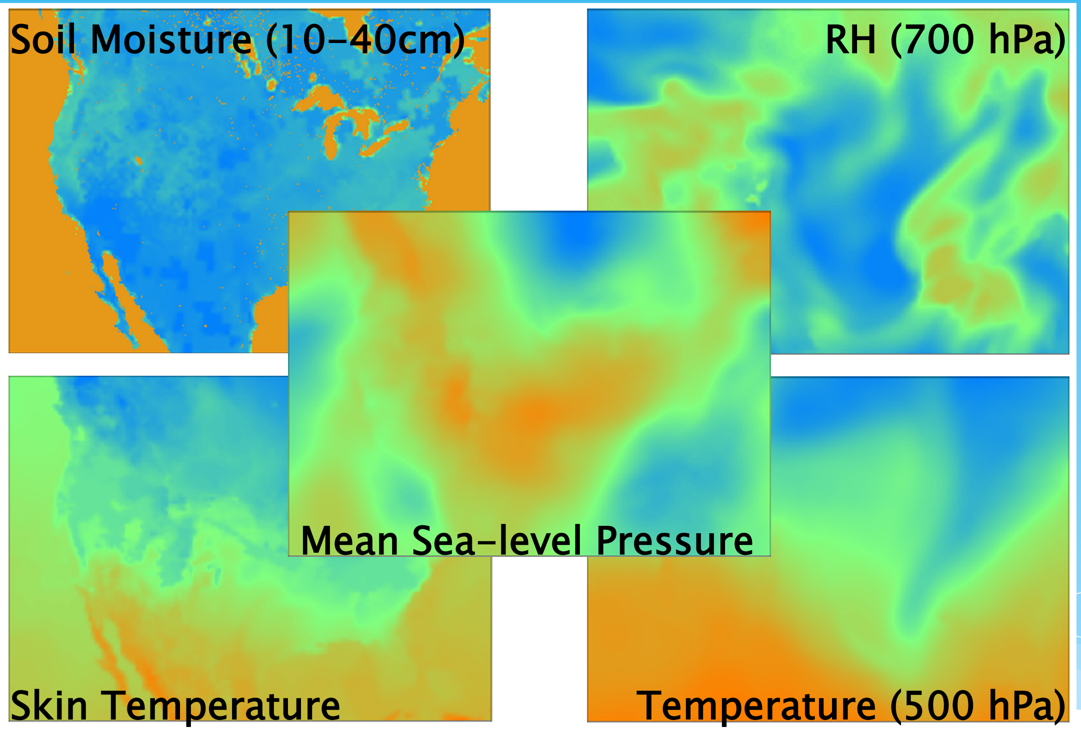
Courtesy of Michael Duda @ NCAR

Metgrid: Model output

- For all domains; one file per time period
- Files contain static fields from geogrid plus interpolated meteorological fields
- Filenames: ARW: met_em.d0*n*.YYYY-MM-DD_HH:mm:ss.nc

(where *n* is the domain ID number)



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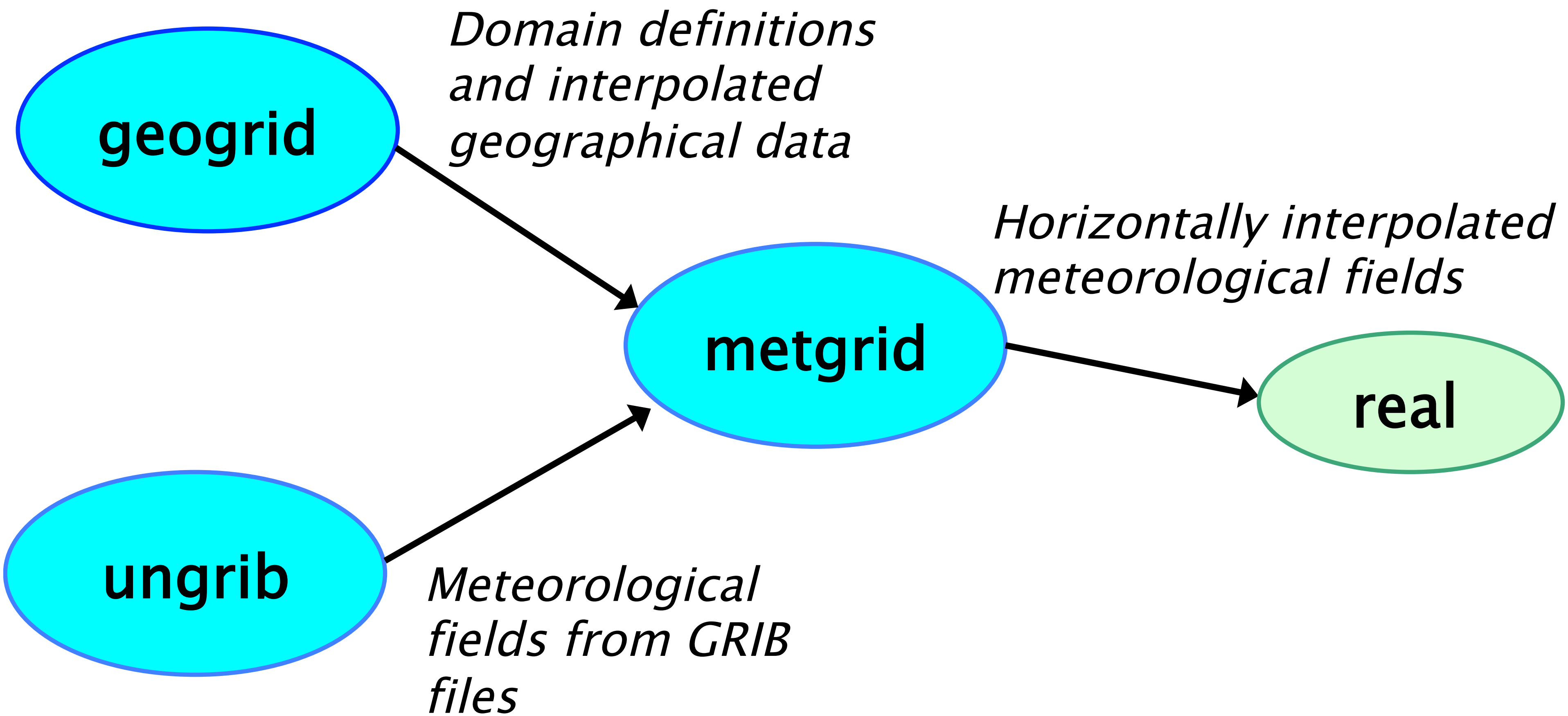
WPS summary

Vertical interpolation to WRF sigma levels is performed in the real program



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WRF physics

- Radiation
  - Longwave (ra_lw_physics)
  - Shortwave (ra_sw_physics)
- Surface
  - Surface layer (sf_sfclay_physics)
  - Land/water surface (sf_surface_physics)
- PBL (bl_pbl_physics)
- Turbulence/Diffusion (diff_opt, km_opt)
- Cumulus parameterizatio (cu_physics)
- Microphysics (mp_physics)

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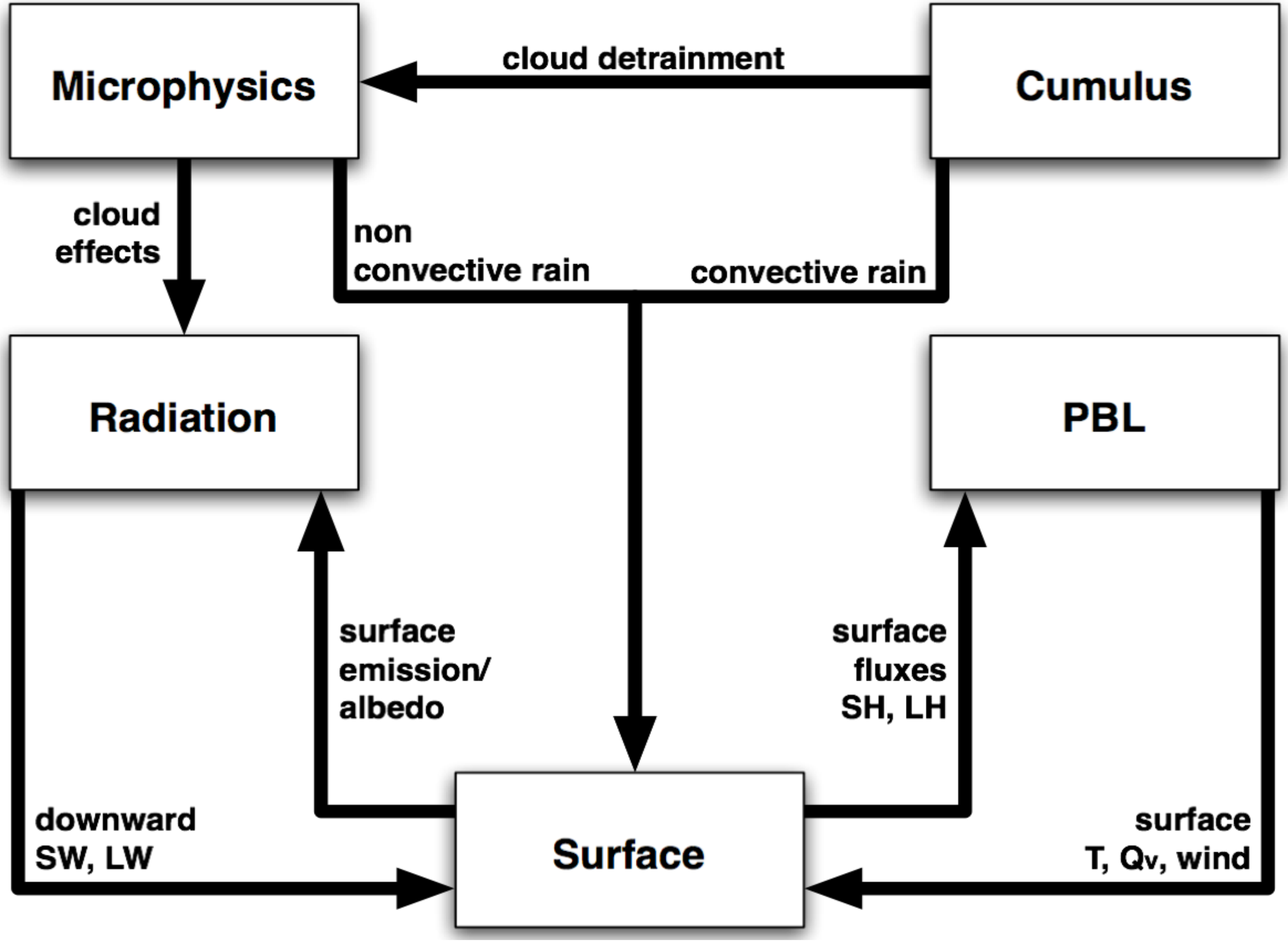
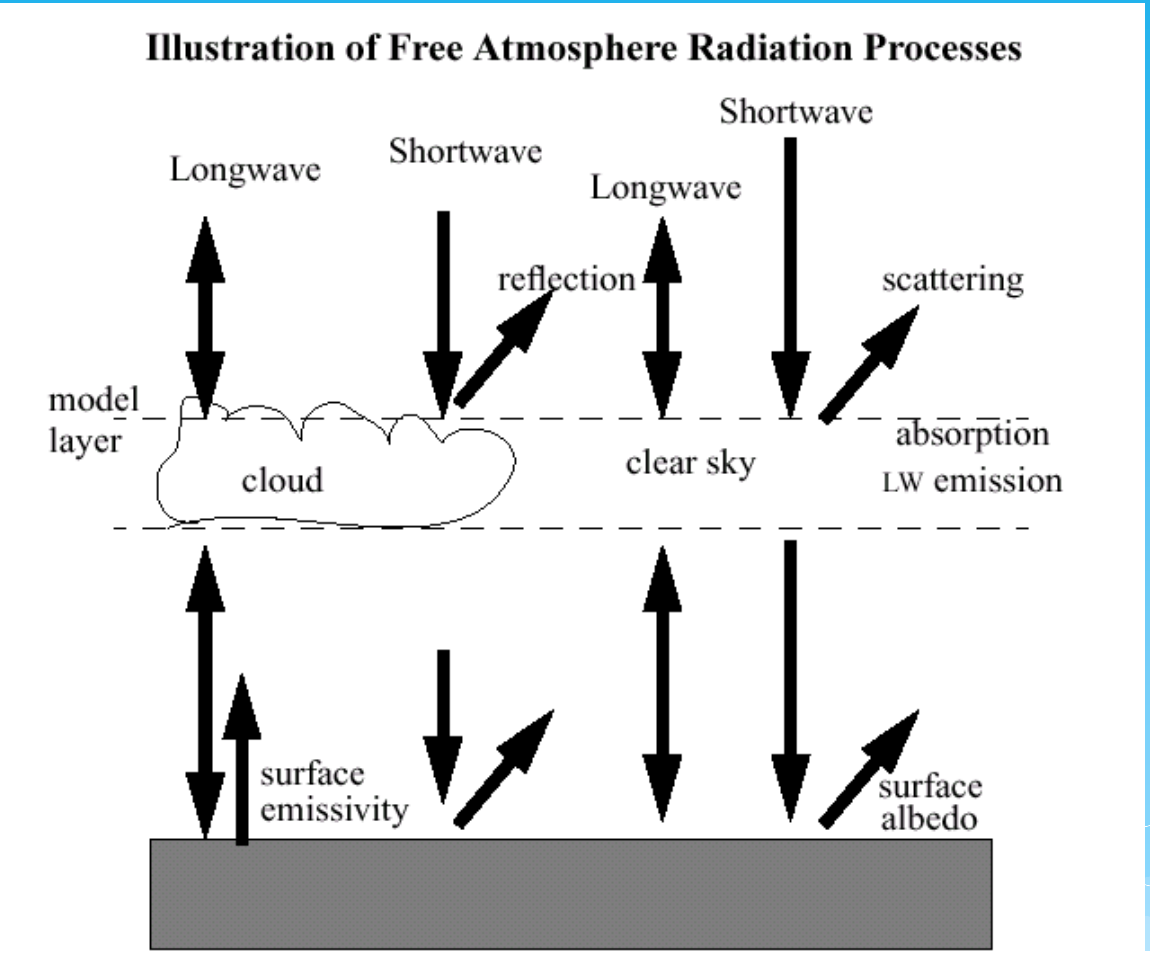
WRF physics – direct interaction of parameterizations



Courtesy of Jimy Dudhia @ NCAR

Radiation

Provides atmospheric temperature tendency profiles and surface radiative fluxes



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Courtesy of Jimy Dudhia @ NCAR

Long wave radiation

- Compute clear-sky and cloud upward and downward radiation fluxes
  - Consider IR emissions from model layers
  - Surface emissivity based on land-type
  - Flux divergence leads to cooling in a model layer
  - Downward flux at surface is important in land energy budget
  - IR radiation generally leads to cooling in clear air (~2 K/day), stronger cooling at cloud tops and warming at cloud base

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Short wave radiation

- Computes clear-sky and cloudy solar fluxes
- Includes annual and diurnal solar cycles
- Most schemes consider downward and upward (reflected) fluxes
    - Note that the Dudhia scheme has only downward fluxes
- Primarily a warming effect in clear sky
- Important component of the surface energy balance

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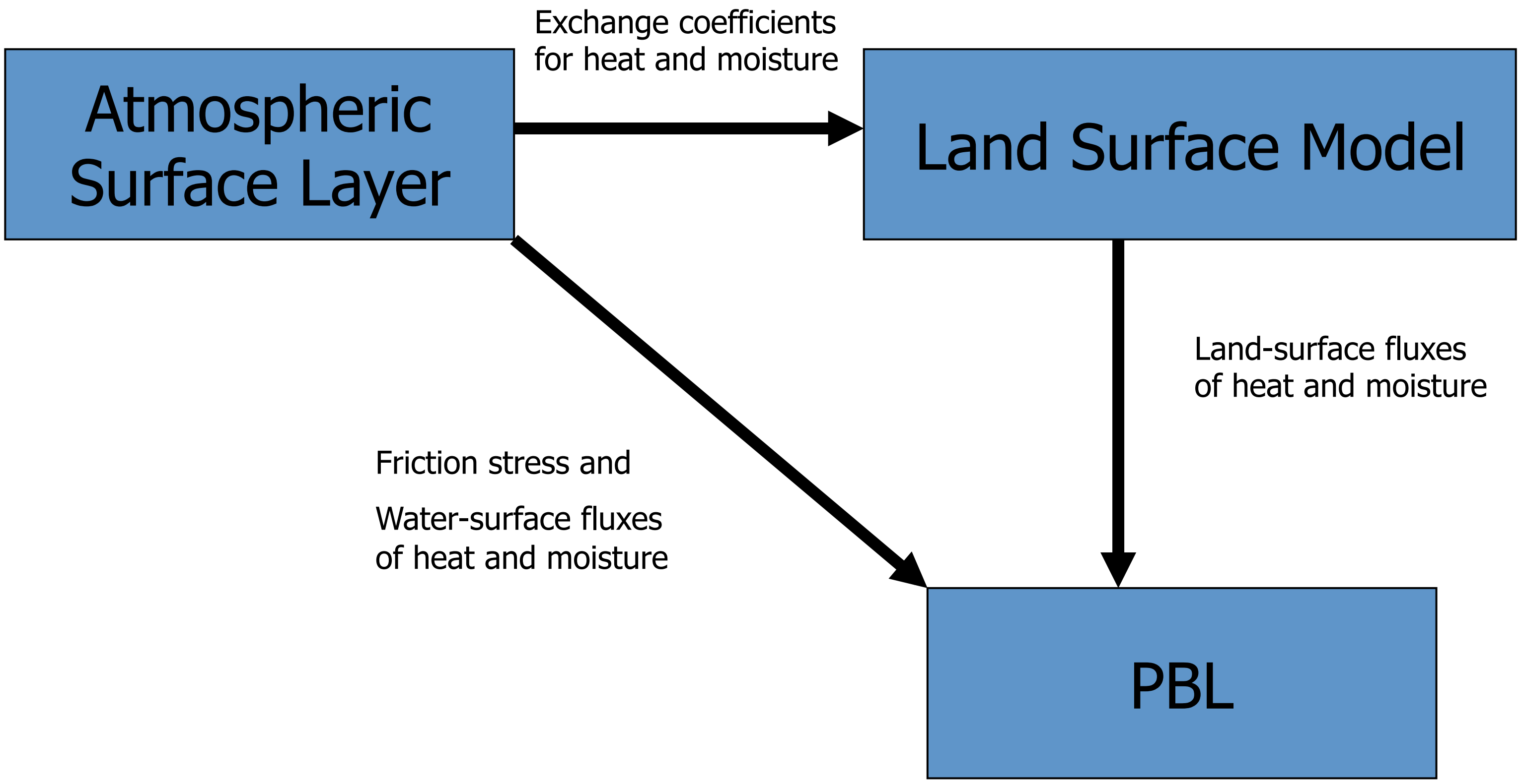
Surface physics components



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WRF surface layer options

- Use similarity theory to determine the exchange coefficients and diagnostics of 2m T and q and 10m winds
- Provide exchange coefficients to land-surface models
- Provide friction velocity to PBL schemes
- Proved surface fluxes over water points
- Schemes have variations in stability functions and roughness lenghts

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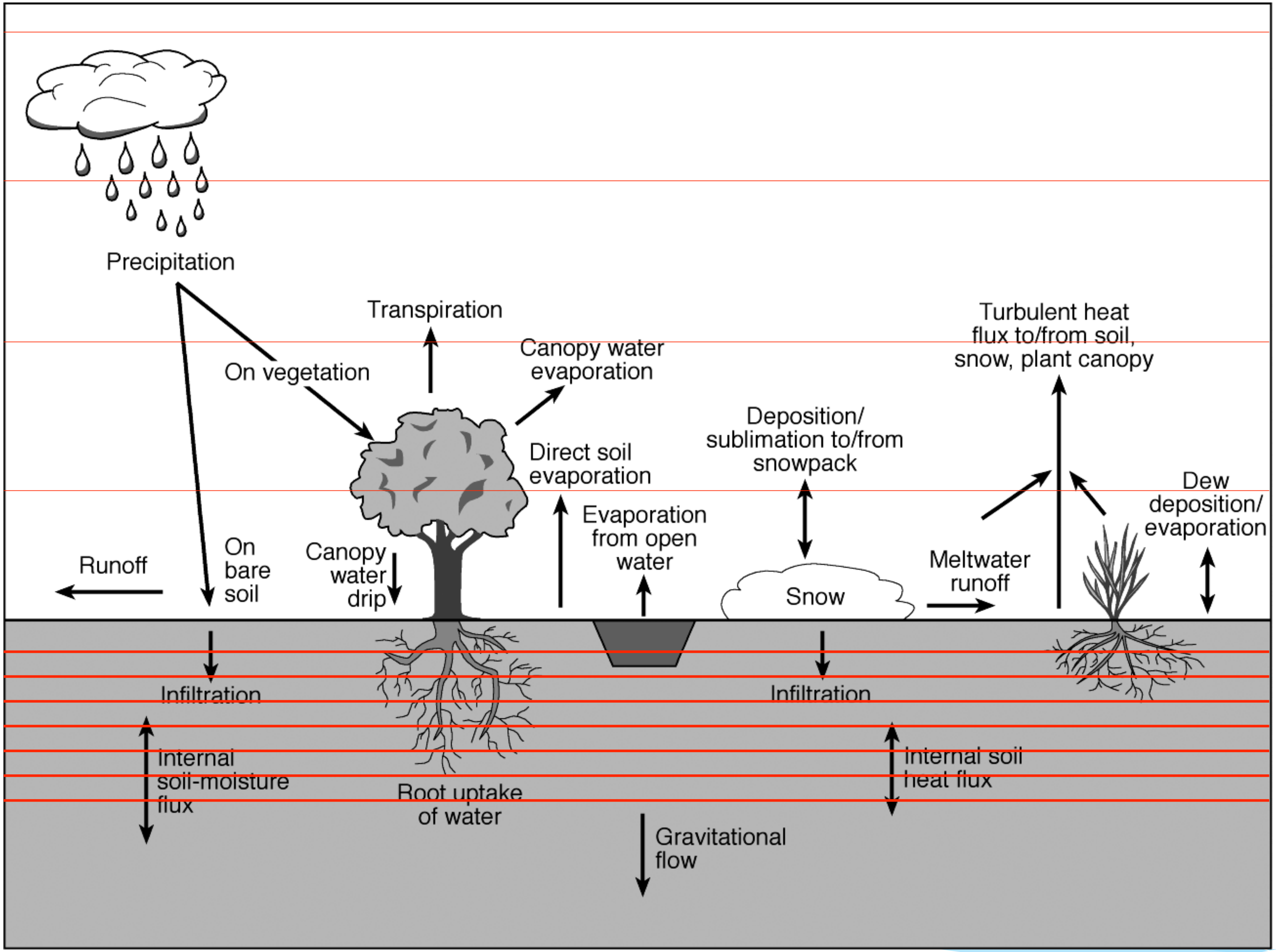
WRF land-surface models



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Courtesy of Jimy Dudhia @ NCAR

WRF land-surface models

- Driven by surface energy and water fluxes
- Predicts soil temperature and soil moisture in layers (4 for Noah and NoahMP, 6 for RUC, 2 for PX and 3 for SSiB)
- Predicts snow water equivalent on ground. May be in layers (NoahMP, RUC, and SSiB)
- May predict canopy moisture only (Noah, RUC) or temperature only (SSiB) or both (NoahMP)

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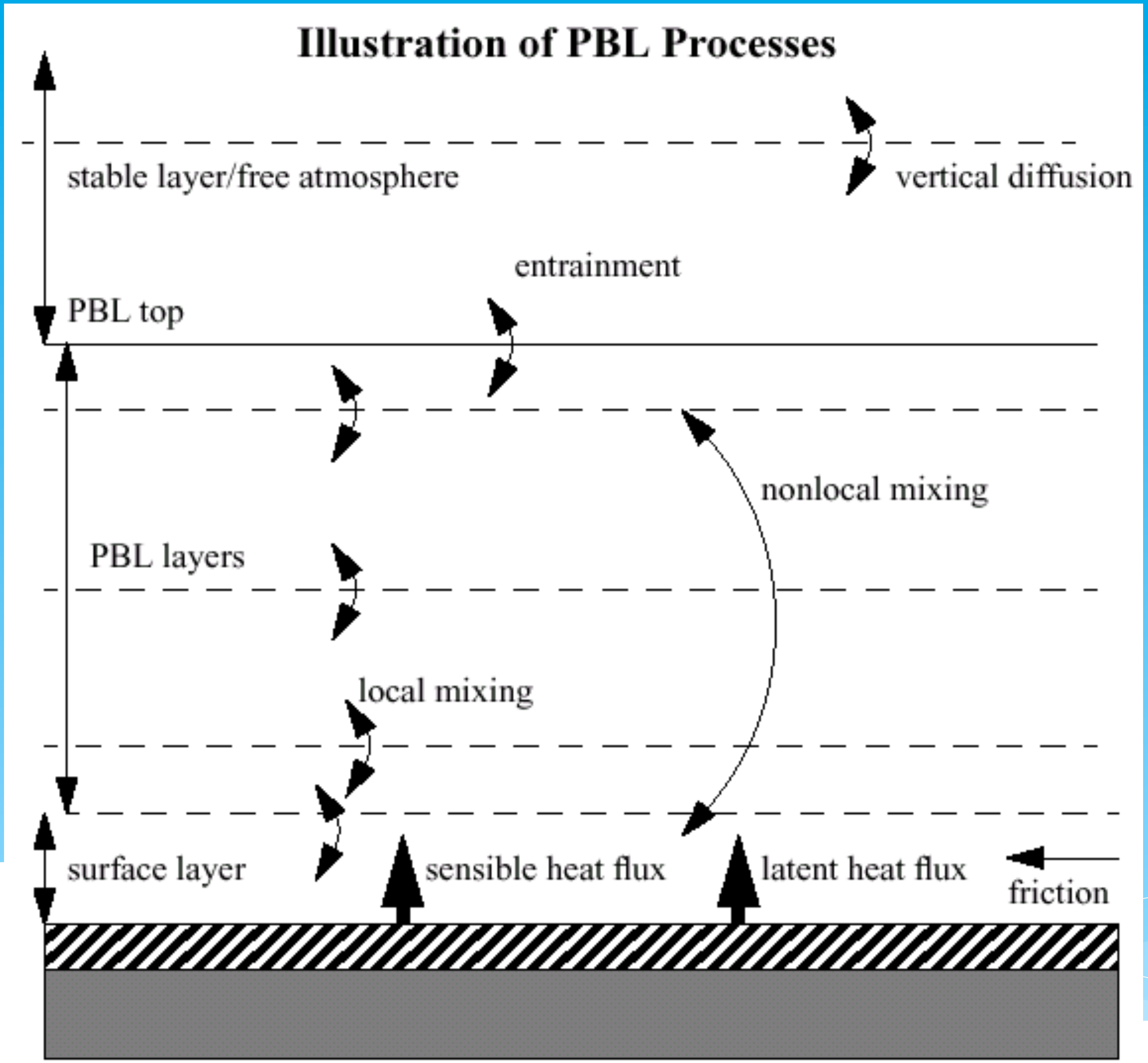
Planetary boundary layer



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Courtesy of Jimy Dudhia @ NCAR

WRF PBL options

- Purpose is to distribute surface fluxes with boundary layer eddy fluxes and to allow for PBL growth by entrainment
- Classes of PBL schemes are:
  - Turbulent kinetic energy prediction (Mellor-Yamada Janjic, MYNN, Bougeault-Lacarre, TEMF, QNSE, CAM UW)
  - Diagnostic non-local (YSU, GFS, MRF, ACM2)
- Above the PBL all these schemes also do vertical diffusion due to turbulence

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WRF PBL options

- PBL schemes can be used for most grid sizes when surface fluxes are present
- Lowest level should be in the surface layer
  - Important for surface (2m, 10m) diagnostic interpolation
- With ACM2, GFS and MRF schemes, lowest full level should be 0.99 or 0.995, not too close to 1
- TKE schemes can use thinner surface layers
- Assumes that PBL eddies are not resolved
- At grid size dx << 1km this assumption breaks down
  - Can use 3d diffusion instead of a PBL scheme in WRF Version 3 (coupled to surface physics)
  - Works best when dx and dz are comparable

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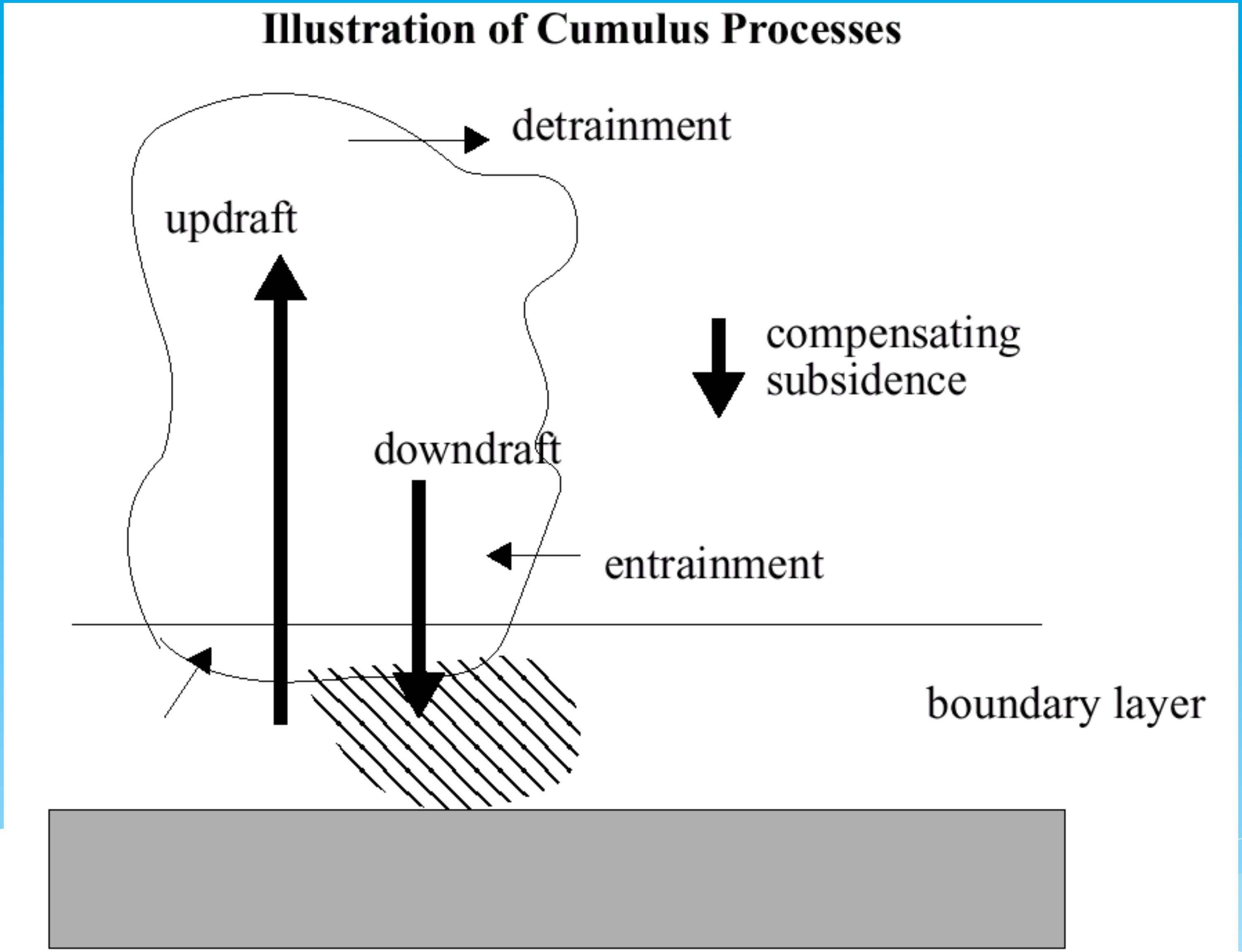
Cumulus parameterization



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Courtesy of Jimy Dudhia @ NCAR

Cumulus schemes

- Used for grid columns that completely contain convective clouds
- Re-distribute air in column to account for vertical convective fluxes
  - Updrafts take boundary layer air upwards
  - Downdrafts take mid-level air downwards
- Schemes have to determine
  - When to trigger a convective column
  - How fast to make the convection act
- Clouds only activate in columns that meet certain criteria
  - Presence of some CAPE in sounding
  - Not too much convective inhibition (CIN) in sounding
  - Minimum cloud depth from parcel ascent

Microphysics schemes

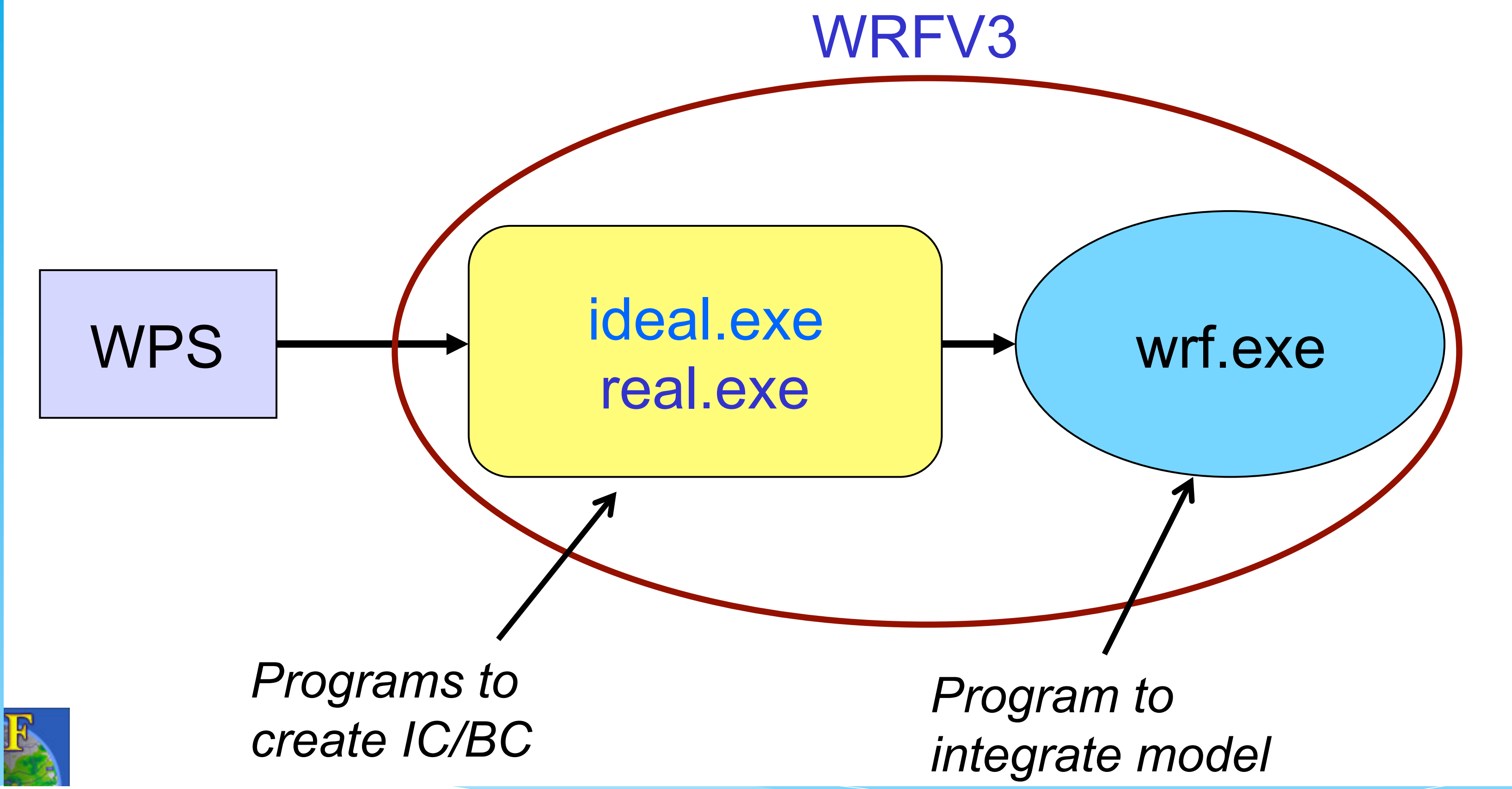
- Range of levels of sophistication
  - Warm rain (i.e. no ice) – idealized
  - Simple ice (3 arrays)
  - Mesoscale (5 arrays, no graupel)
  - Cloud scale single-moment (6 arrays, with graupel)
  - Double moment (8-13 arrays)
  - Spectral Bin (120-240 arrays)
- Latent heat release from
  - Condensation, evaporation, deposition, sublimation, freesing, and melting
- Particle types
  - Cloud water, raind drops, ice crystals, snow, graupel, hail
- Processes
  - Aggregation, accretion, growth, and fall-out

Microphysics: Single vs. double moment schemes

- Single-moment schemes have one prediction equation for mass (kg/kg) per species (Qr, Qs, etc.) with particle size distribution being derived from fixed parameters
- Double-moment (DM) schemes add a prediction equation for number concentration (#/kg) per DM species (Nr, Ns, etc.)
  - DM schemes may only be double-moment for a few species
  - DM schemes allow for additional processes such as size-sorting during fall-out and sometimes aerosol (CCN) effects

Running the WRF model

WRF system flowchart



Courtesy of Wei Wang @ NCAR

Running the WRF model

- cd to run/ or one of the test case directories
- Move or link WPS output files to the directory for real-data cases
- Edit namelist.input file for the appropriate grid and times of the case
- Run a initialization program (real.exe)
- Run model executable, wrf.exe

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What is a namelist?

- A Fortran namelist contains a list of runtime options for the code to read in during its execution. Use of a namelist allows one to change runtime configuration without the need to recompile the source code.
- Fortran90 namelist has very specific format, so edit with care:

```
&namelist-record      - start
/                     - end
```

- As a general rule:
  - Multiple columns: domain dependent
  - Single column: value valid for all domains
- A namelist file may contain a number of records

What is a namelist?

namelist record **&time_control**

```
run_days             = 0,
run_hours            = 24,
run_minutes          = 0,
run_seconds          = 0,
start_year           = 2000, 2000, 2000,
start_month          = 01,   01,   01,
start_day            = 24,   24,   24,
start_hour           = 12,   12,   12,
start_minute         = 00,   00,   00,
start_second         = 00,   00,   00,
end_year             = 2000, 2000, 2000
end_month            = 01,   01,   01,
end_day              = 25,   25,   25,
end_hour             = 12,   12,   12,
end_minute           = 00,   00,   00,
end_second           = 00,   00,   00,
interval_seconds     = 21600
history_interval     = 180,  60,   60,
frames_per_outfile   = 1000, 1000, 1000,
restart_interval     = 360,
restart              = .true.,
```

domain 1 option

nest options

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How to check model output?

- Use ncdump:
  - ncdump –h wrfout_d0?_<date>

  to get the header information
  - ncdump –v Times wrfout_d0?_<date>

  to check output time
  - ncdump –v Uwrfout_d0?_<date>

  to chech a particular variable (U, in this case)

- Use ncview to quickly plot variables
- Plethora of other software tools
  - NCL
  - RIP4
  - Grads
  - Python

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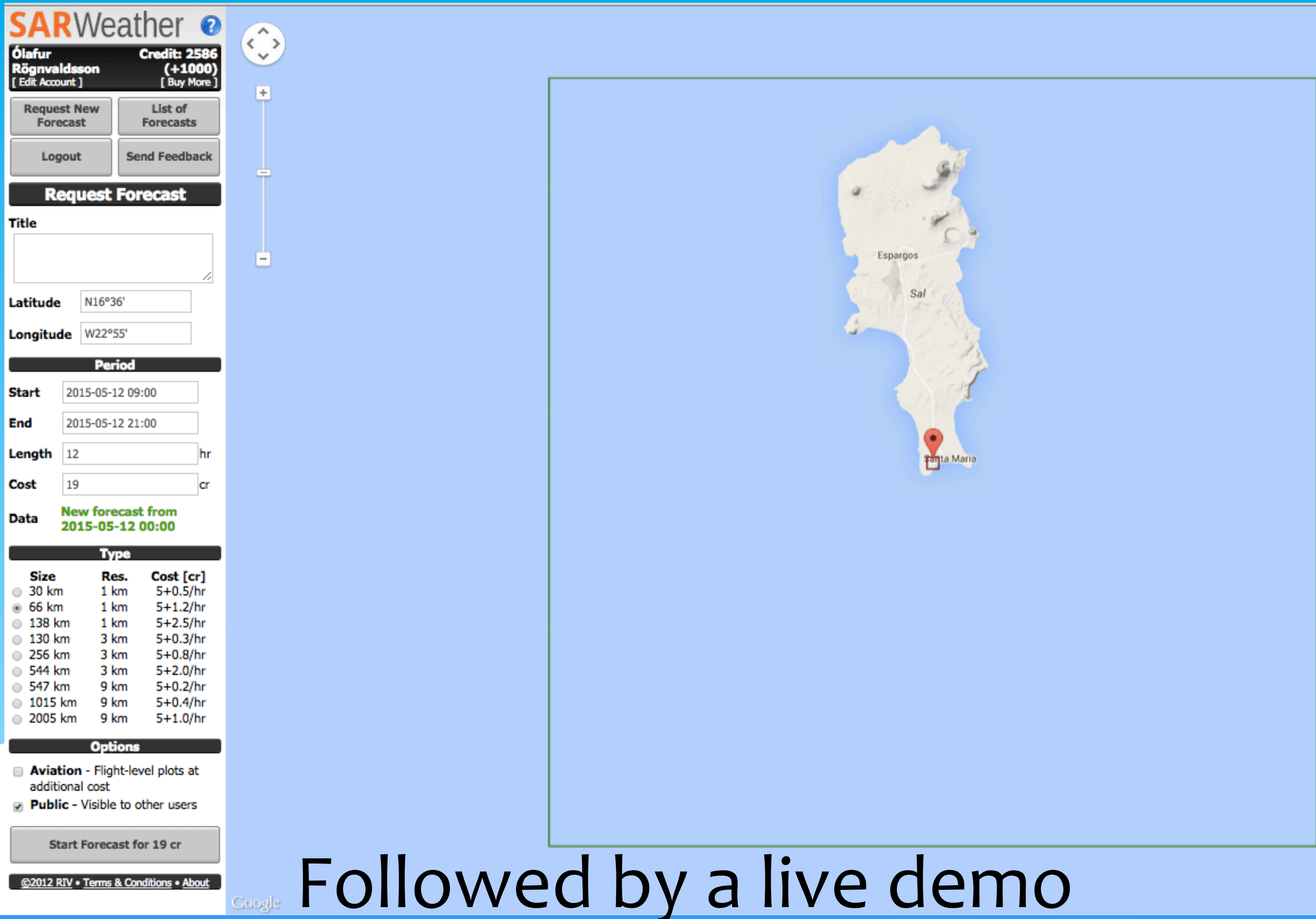
ISOR/Belgingur WOD system

Historical overview in one slide



Followed by a live demo

2007-2008: Lobbyism, applications, etc. etc.

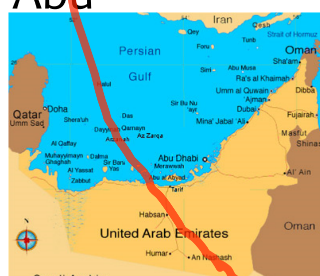
2007: Flight of the SUMO

2007: Idea emerges

January 2010: Haiti

2009: Cash starts flowing

Spring 2010: USAR conference in Abu Dhabi



Spring/summer 2010: Eruption in Mt. Eyjafjallajökull

2009-2010: Code like the wind

May 2010: GDACS annual meeting

GDACS
Global Disaster Alert and Coordination System

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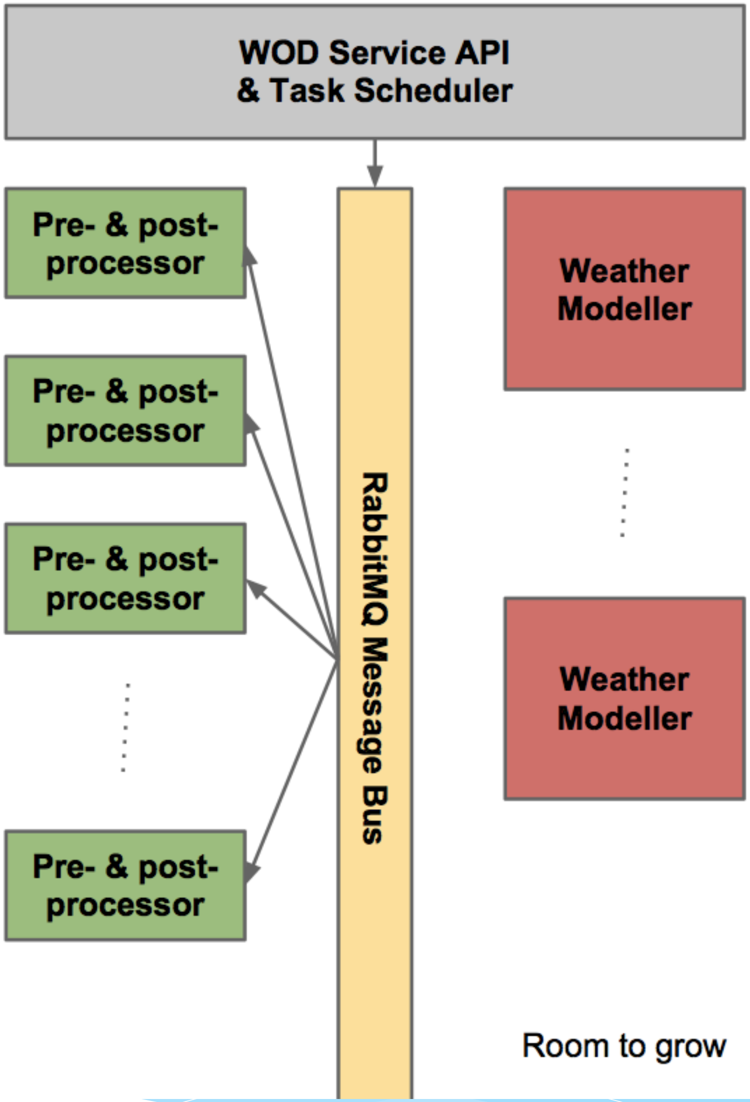
WOD Workflow

1. WOD API breaks request into tasks
2. Pre-processing starts immediately
3. Weather modellers started as needed
4. Post-processing tasks run in parallel with modeller
5. Output available ASAP



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Another live demo!!!

Forecast On Demand
Three layer cake

Open source atmospheric model and input data

Customized Output, e.g.
Search And Rescue
(SARWeather)
Wind Energy
Road Authorities

Forecast On Demand software stack

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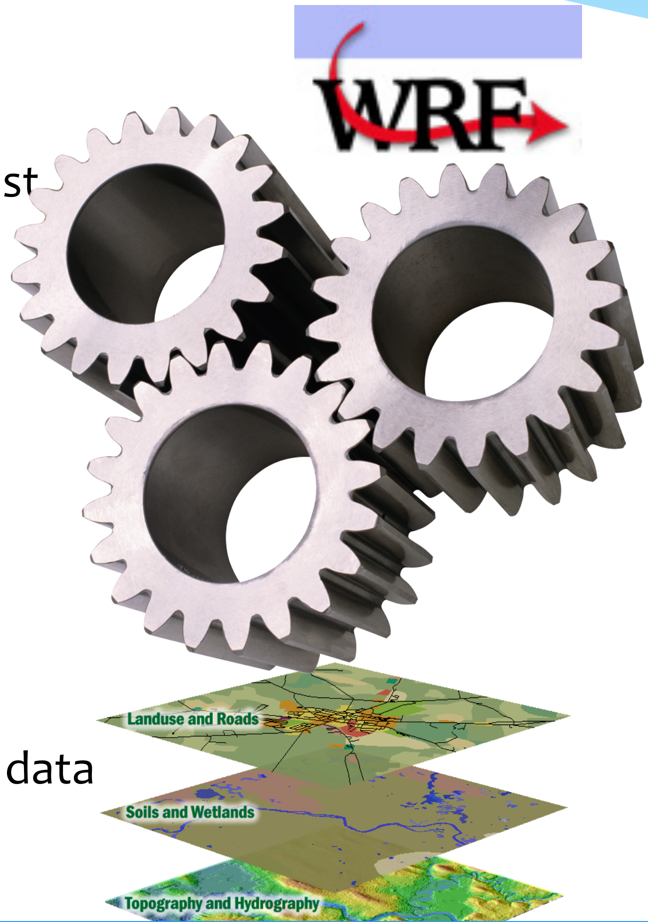
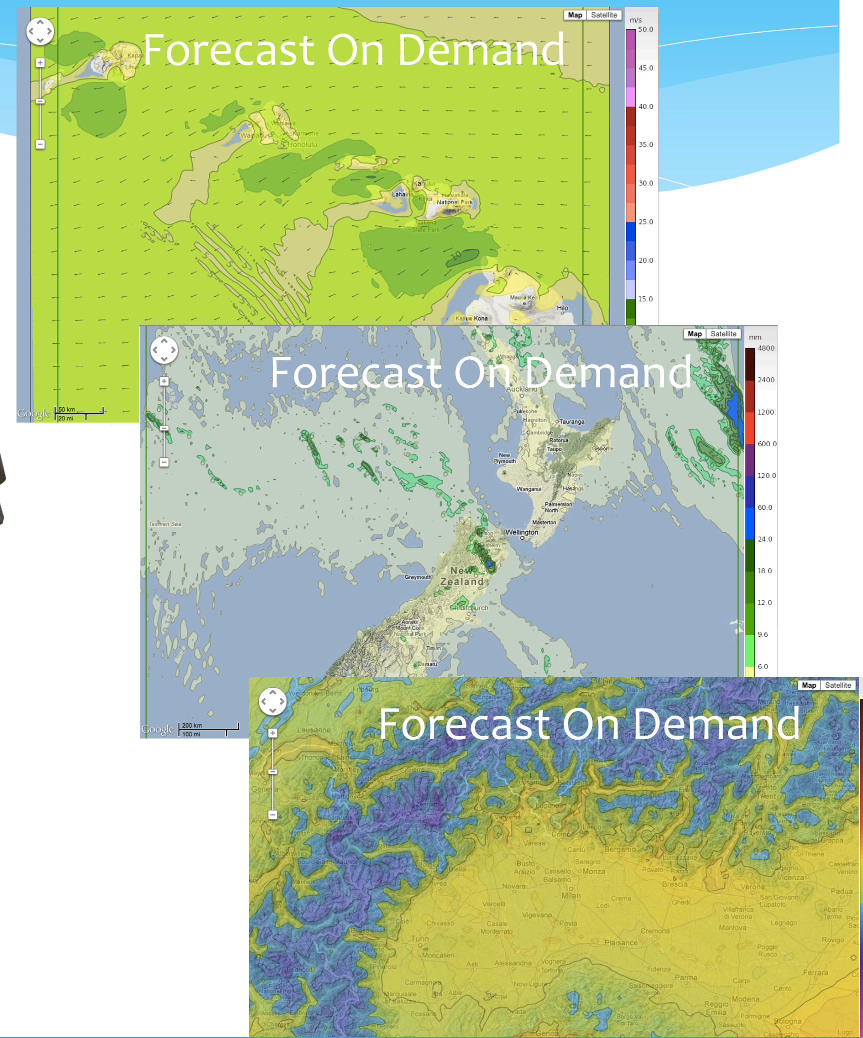
Dataflow
static and dynamic data

New global forecast every 6 hours





Static geographic data

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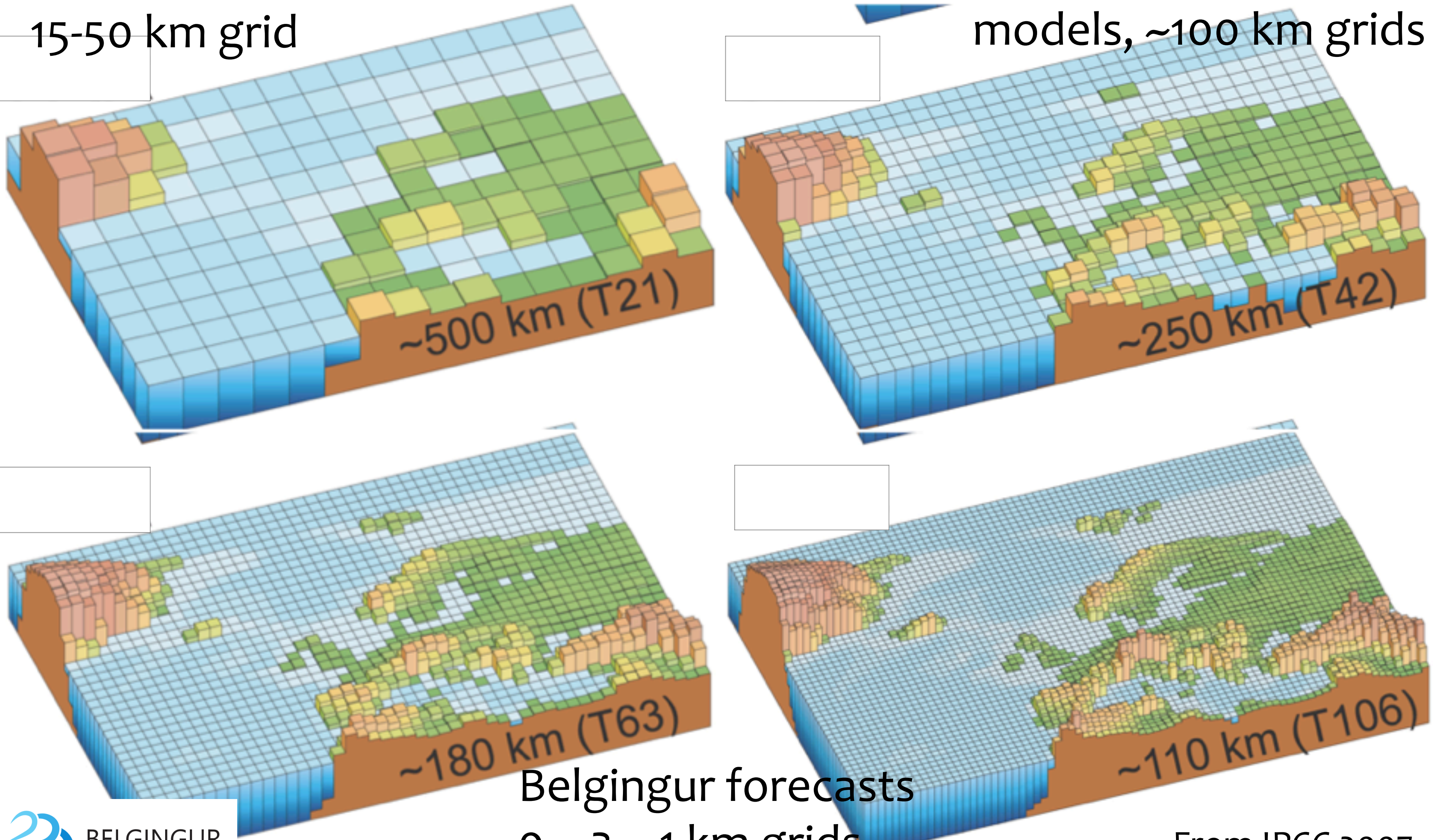
Importance of high resolution

Global forecasts
15-50 km grid

Current climate
models, ~100 km grids



Belgingur forecasts
9 – 3 – 1 km grids

From IPCC 2007

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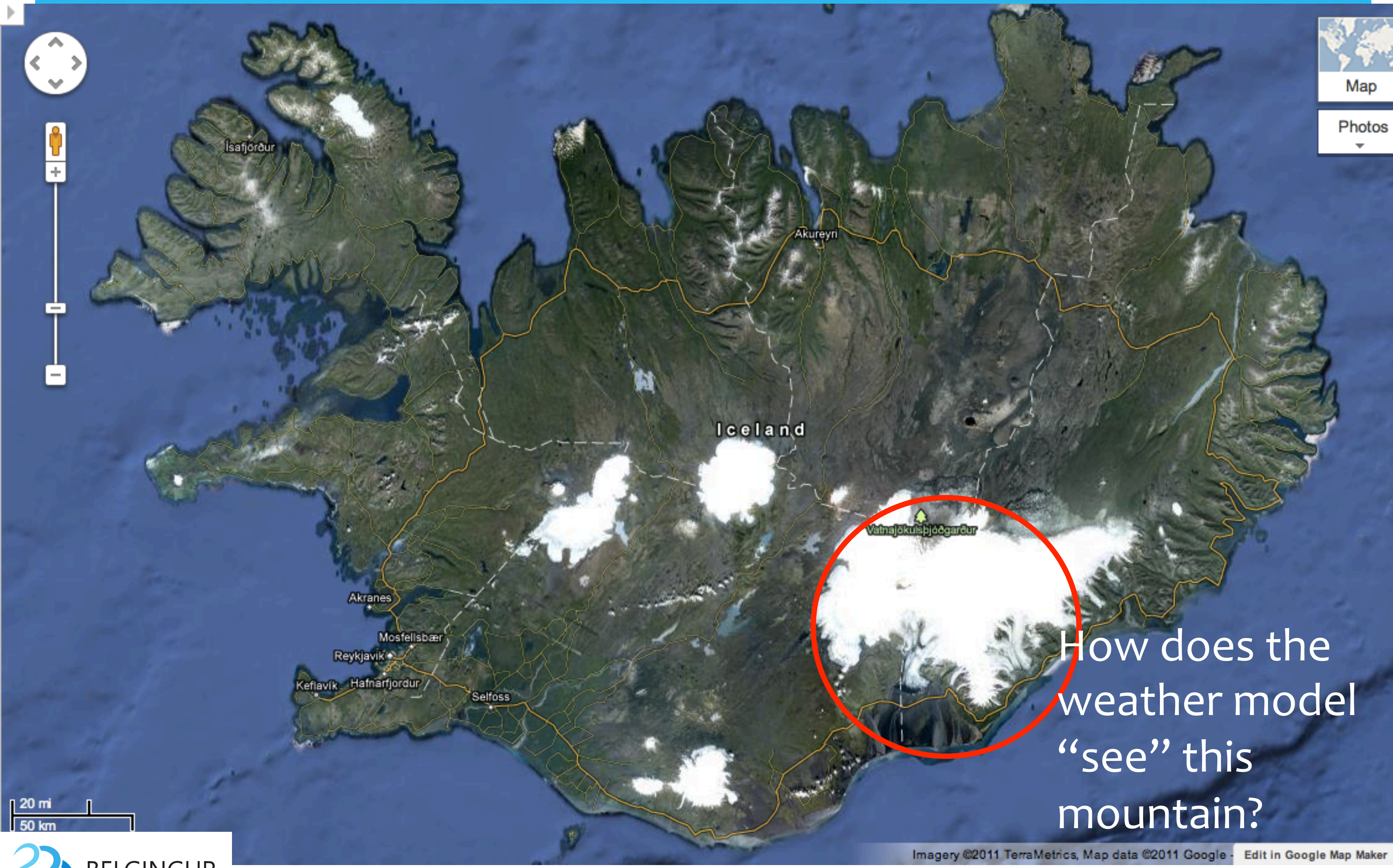
Importance of high resolution



How does the weather model "see" this mountain?

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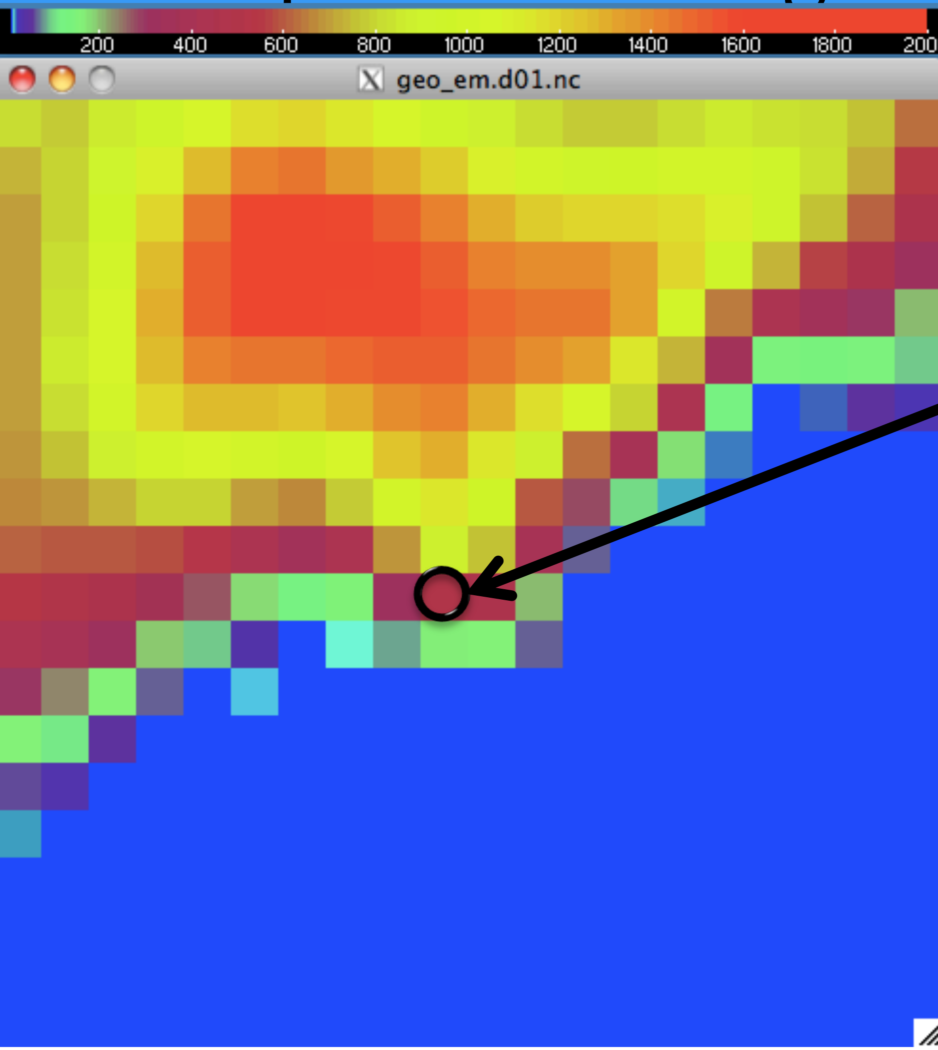
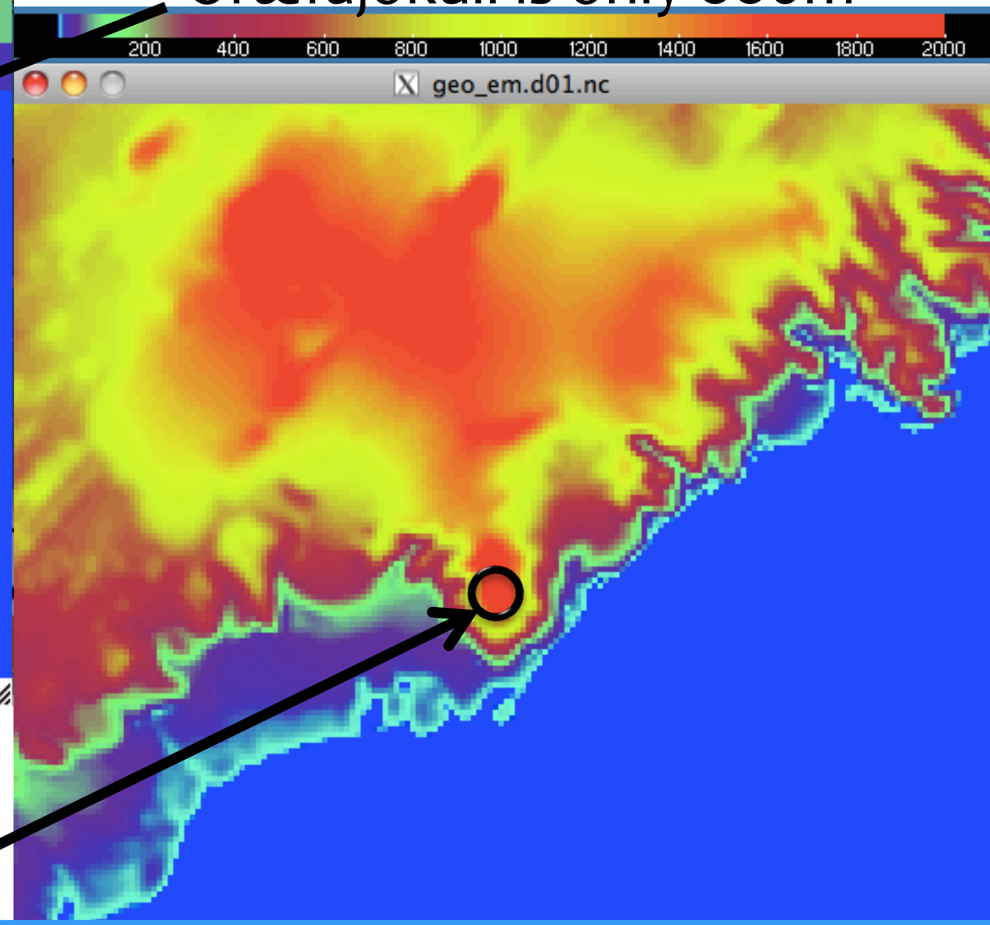
Importance of high resolution

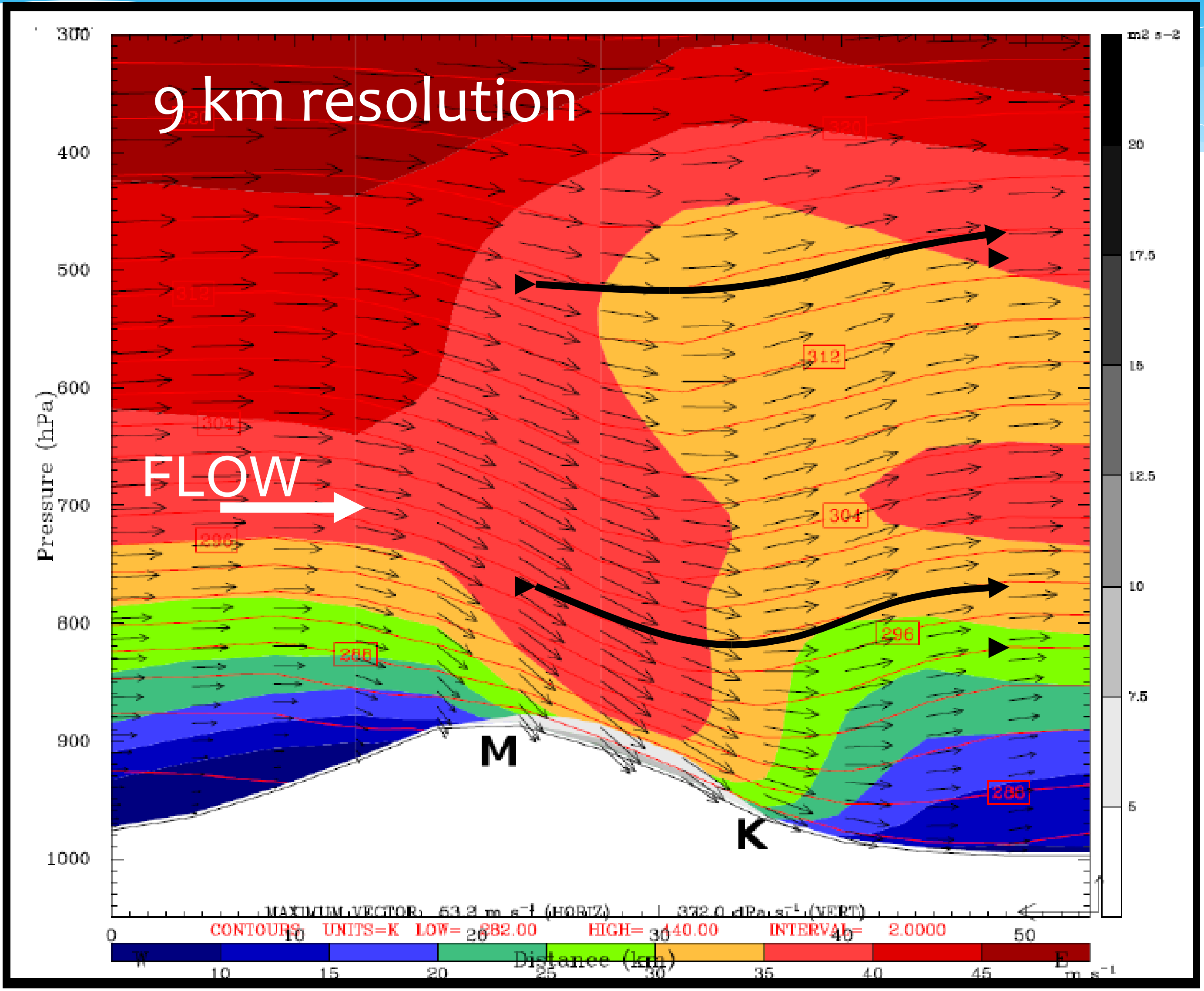


Vatnajökull icecap, max height is 1675m. Top height of Mt. Öræfajökull is only 880m



At 1km resolution the max height is 2020m. Top height of Mt. Öræfajökull is now 1945m

Importance of high resolution



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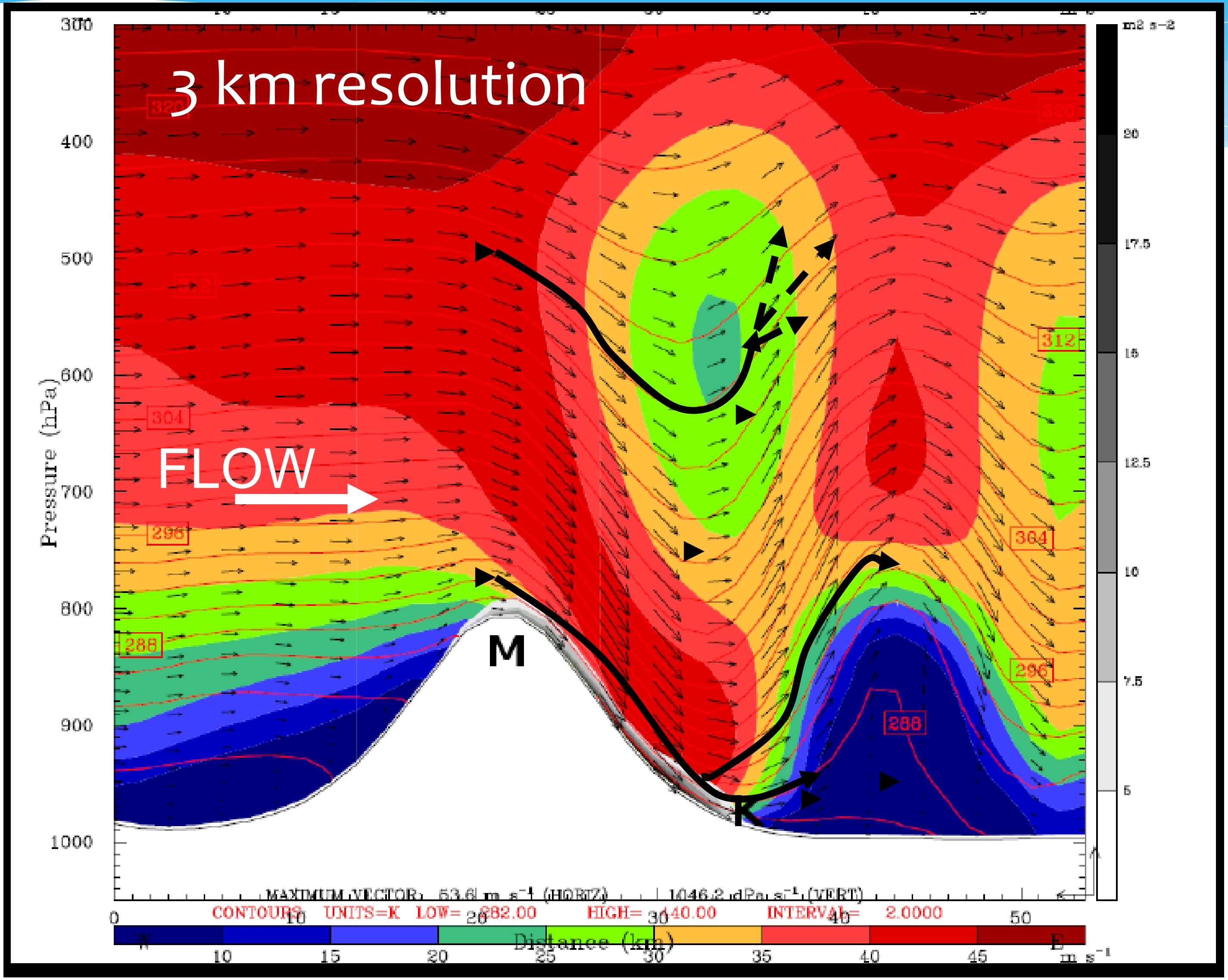
Importance of high resolution



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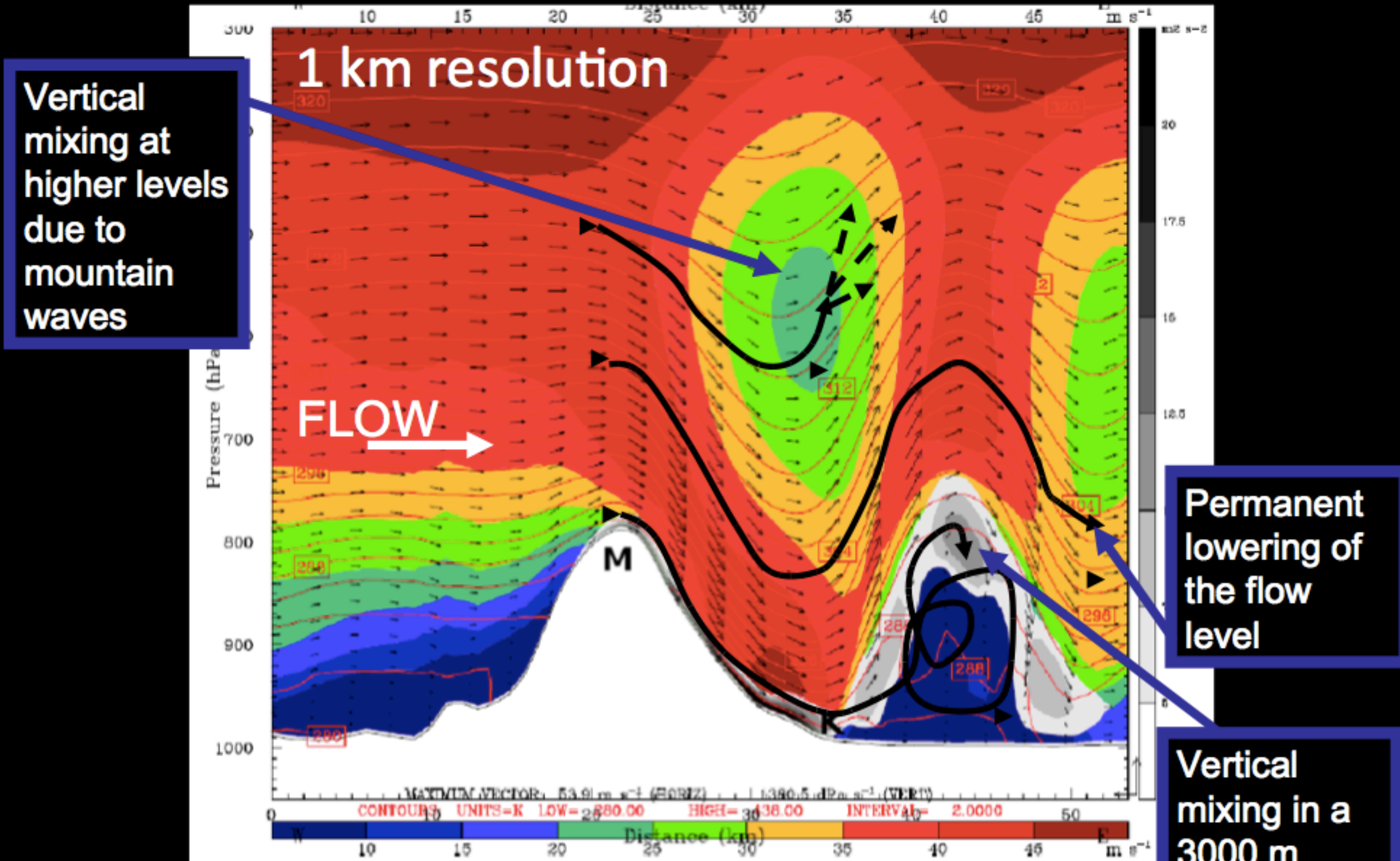
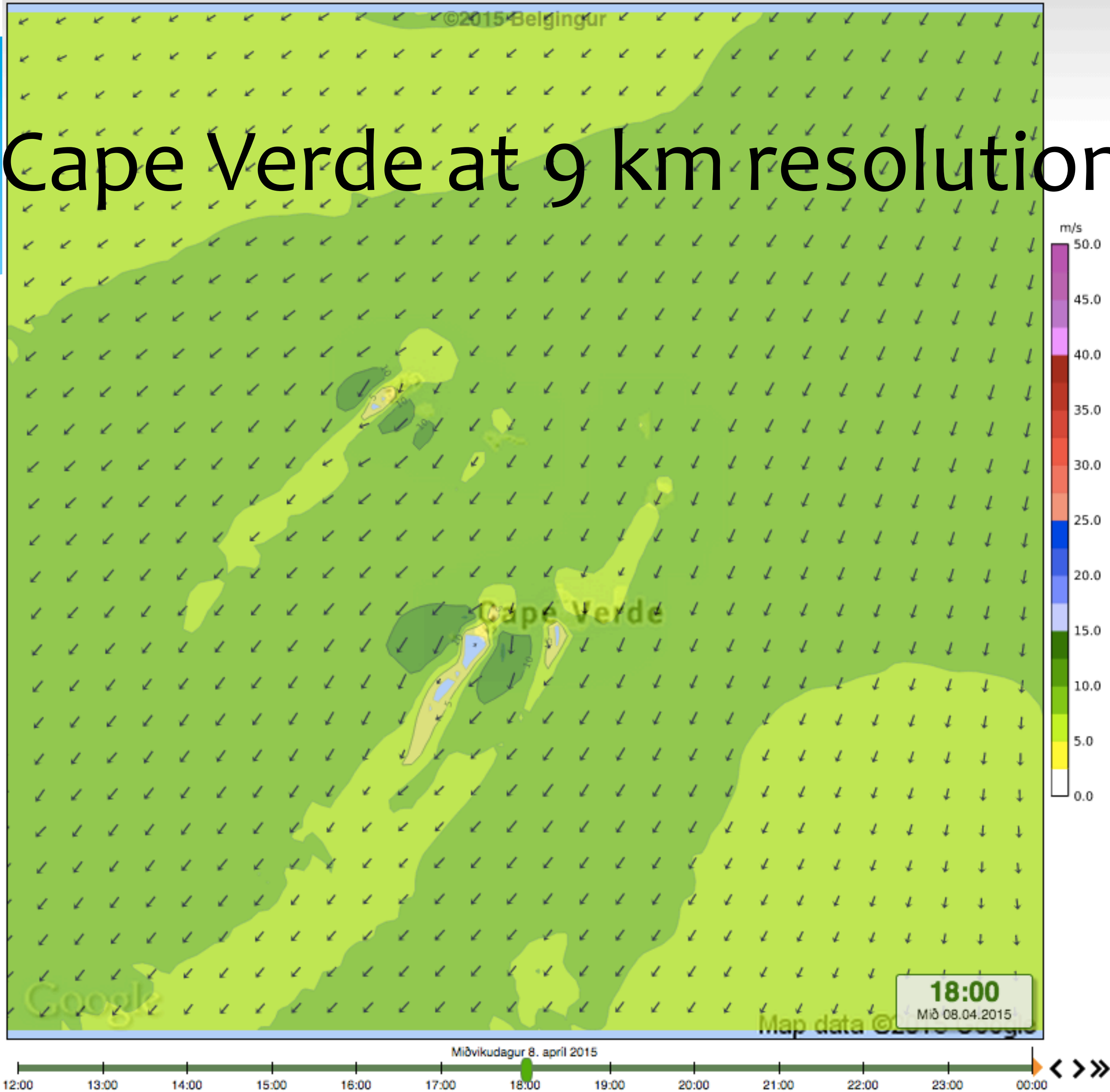
Importance of high resolution

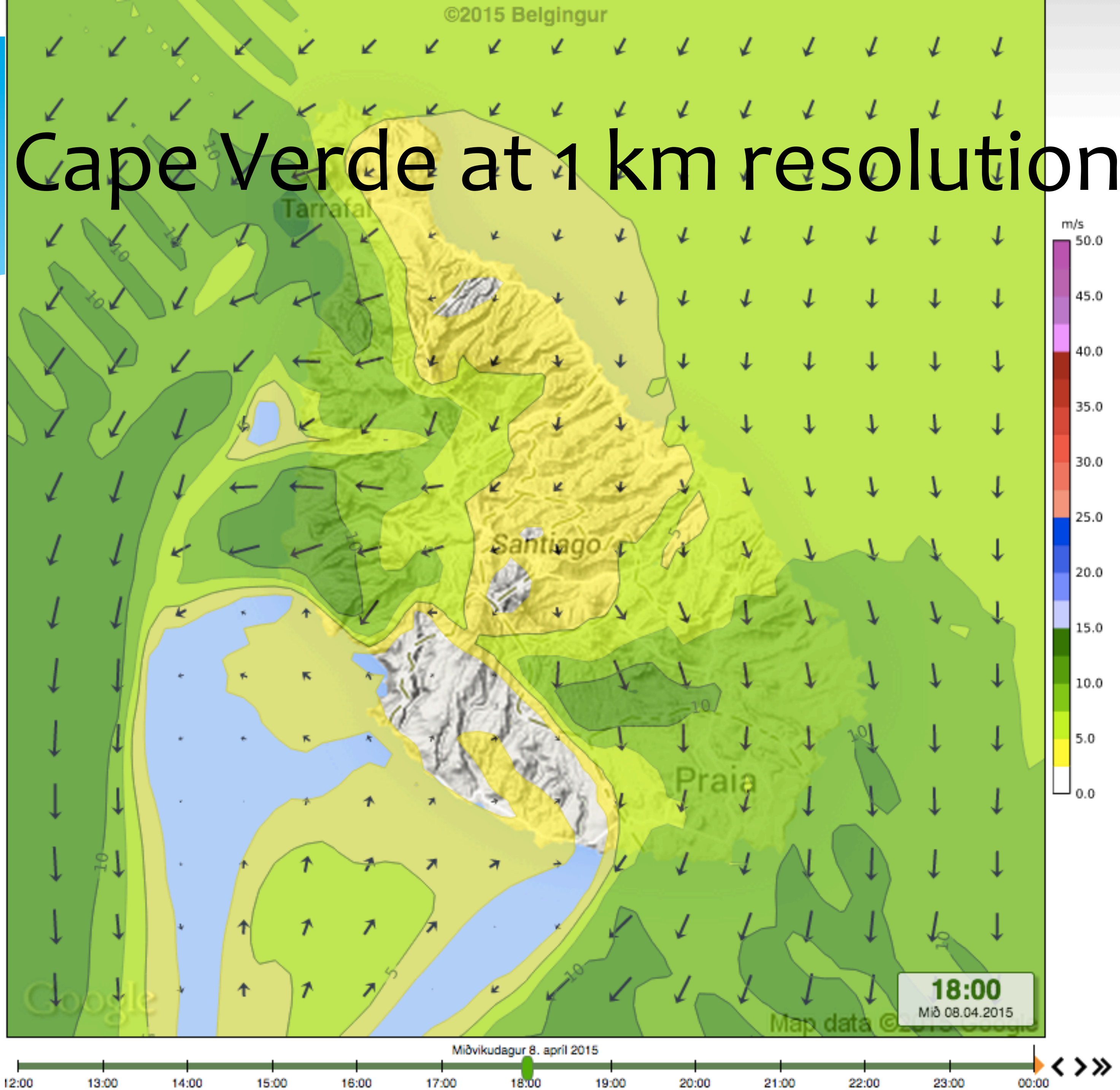


None of these important features are visible at dx=9km, or at resolutions of many current forecast models!

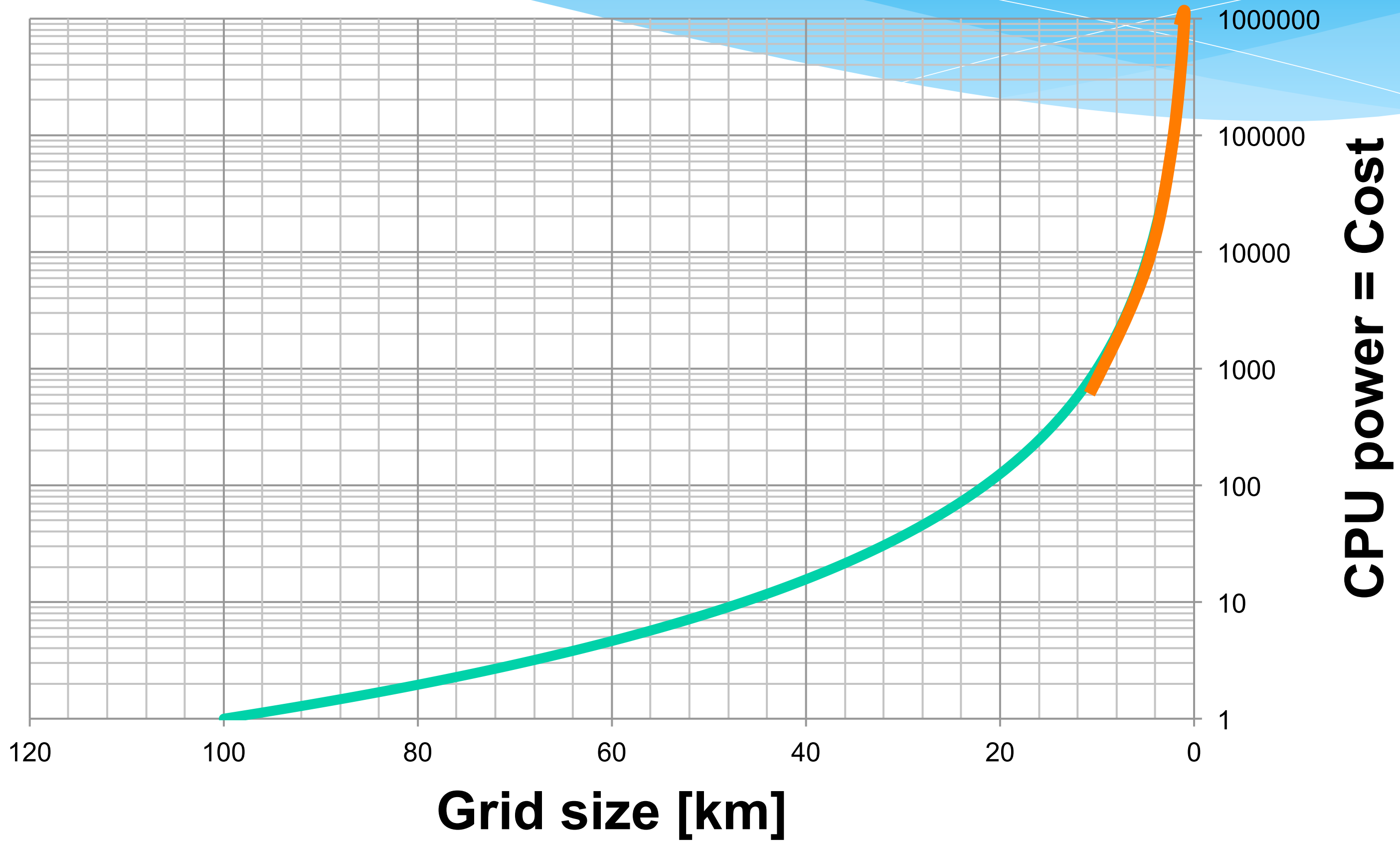
Cape Verde at 9 km resolution



Cape Verde at 1 km resolution



Why not always use 1km resolution?



Need 1000-times more CPU power to simulate a 1 km resolution forecast than a 10 km one for the same region!

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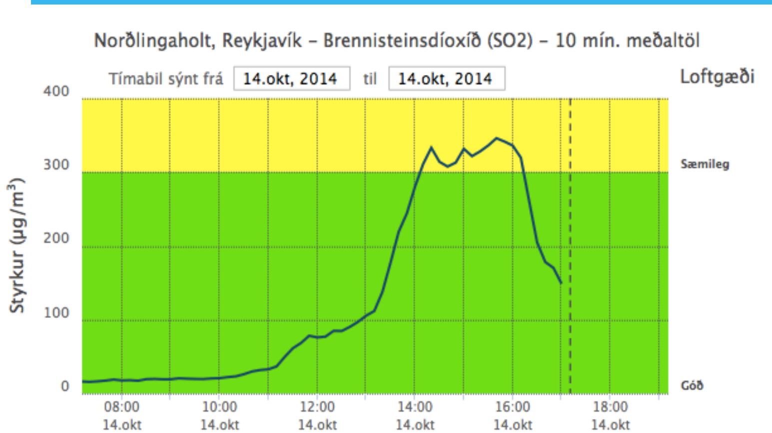
The WRF-Chem model

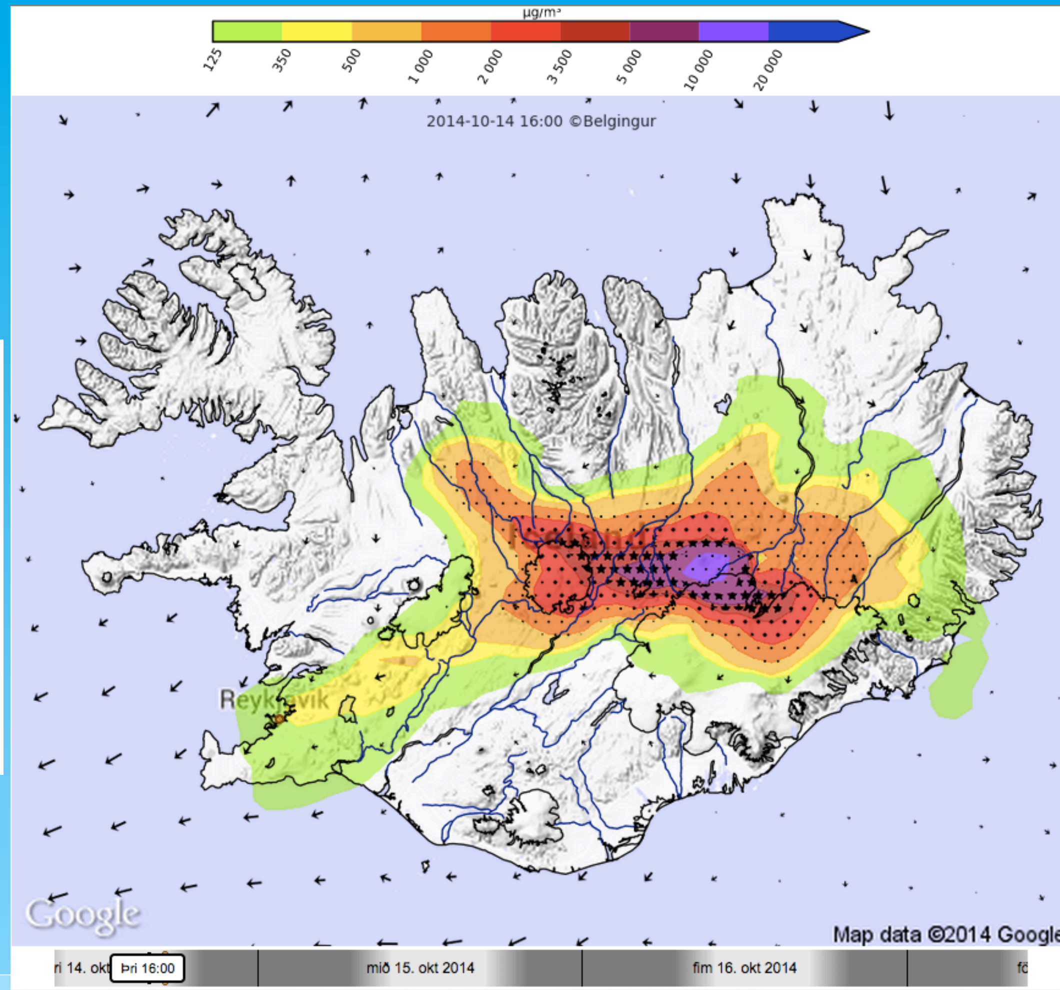
- Open source addition to the WRF model
  - Development is led by NOAA
- Potential to to simulate the coupling between dynamics, radiation and chemistry
  - Capable of both on-line and off-line modeling
- Simulate and forecast the dispersion of chemical constituents and/or other airborne pollutants
  - e.g. SO_2 and volcanic ash

SO_2 forecasts

SO_2 forecast for 16 UTC
2014-10-14

Strength of SO_2 in Reykjavík is ~350 µg/m³





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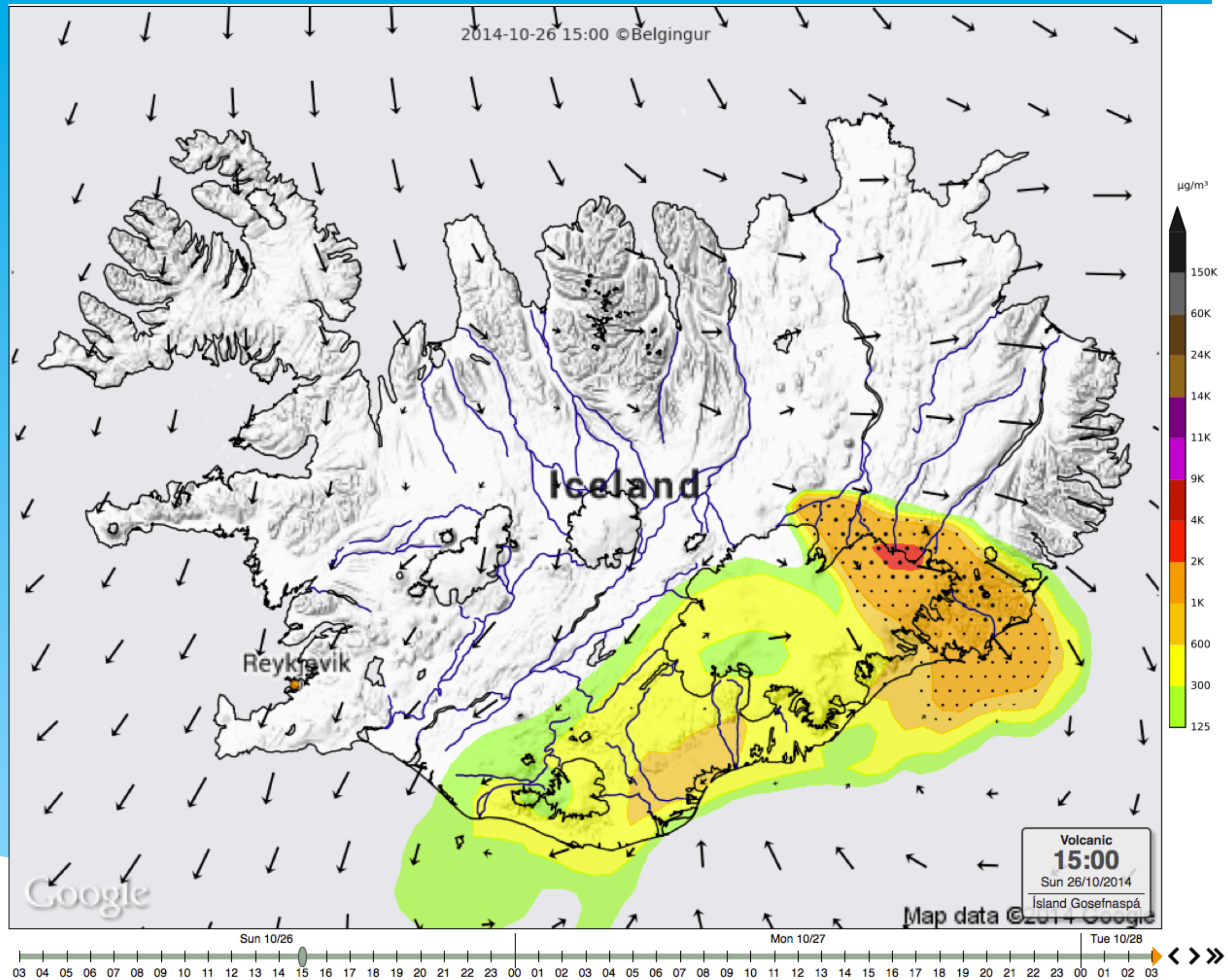
SO_2 forecasts

SO_2 forecast for 15 UTC 2014-10-26

Strength of SO_2 around Höfn í Hornafirði between 3000-7000 µg/m³



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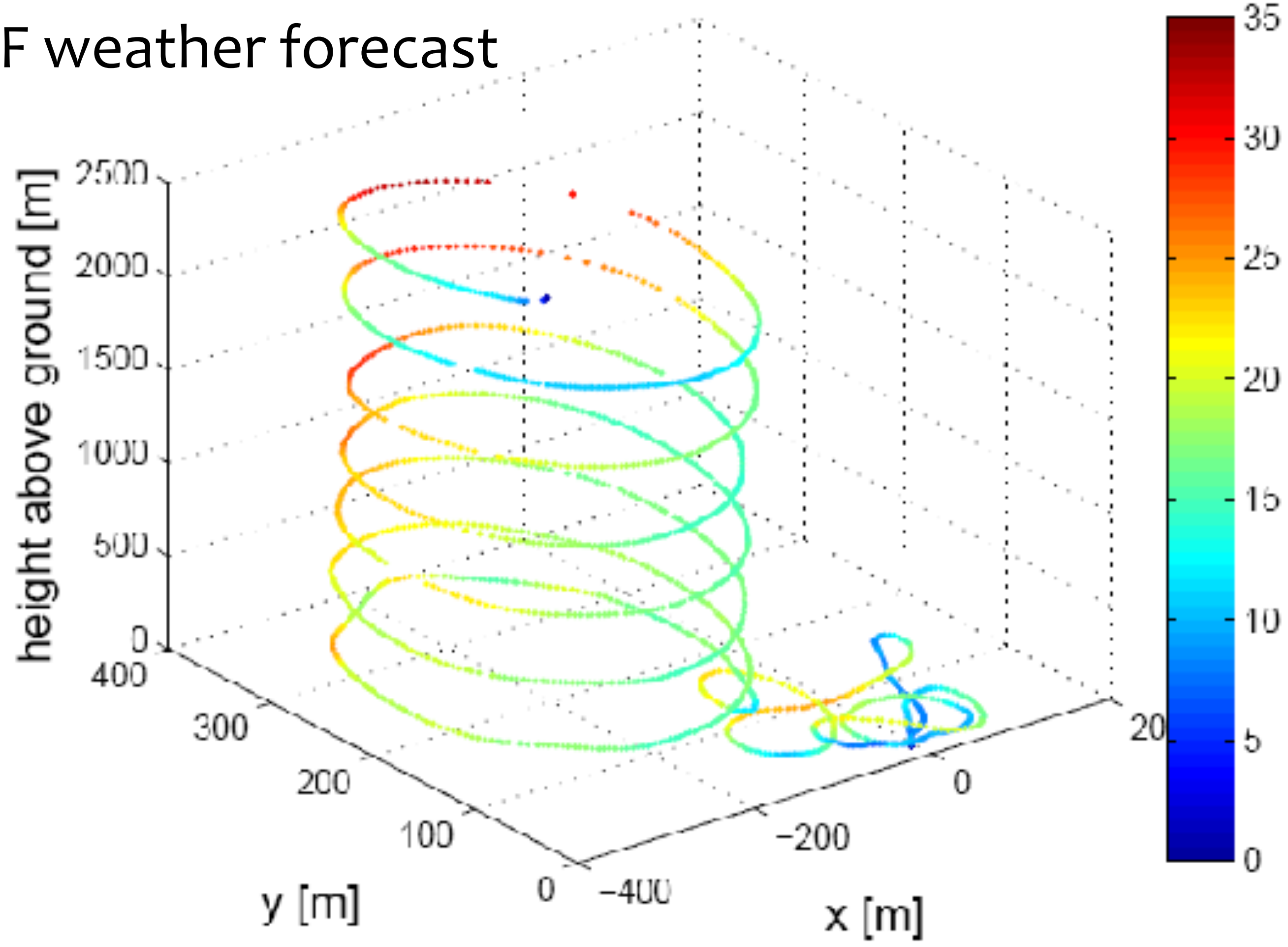
SUMO and WRF

The SUMO (Small Unmanned Meteorological Observer) can measure winds, humidity, pressure, and temperature in a vertical profile up 4km height

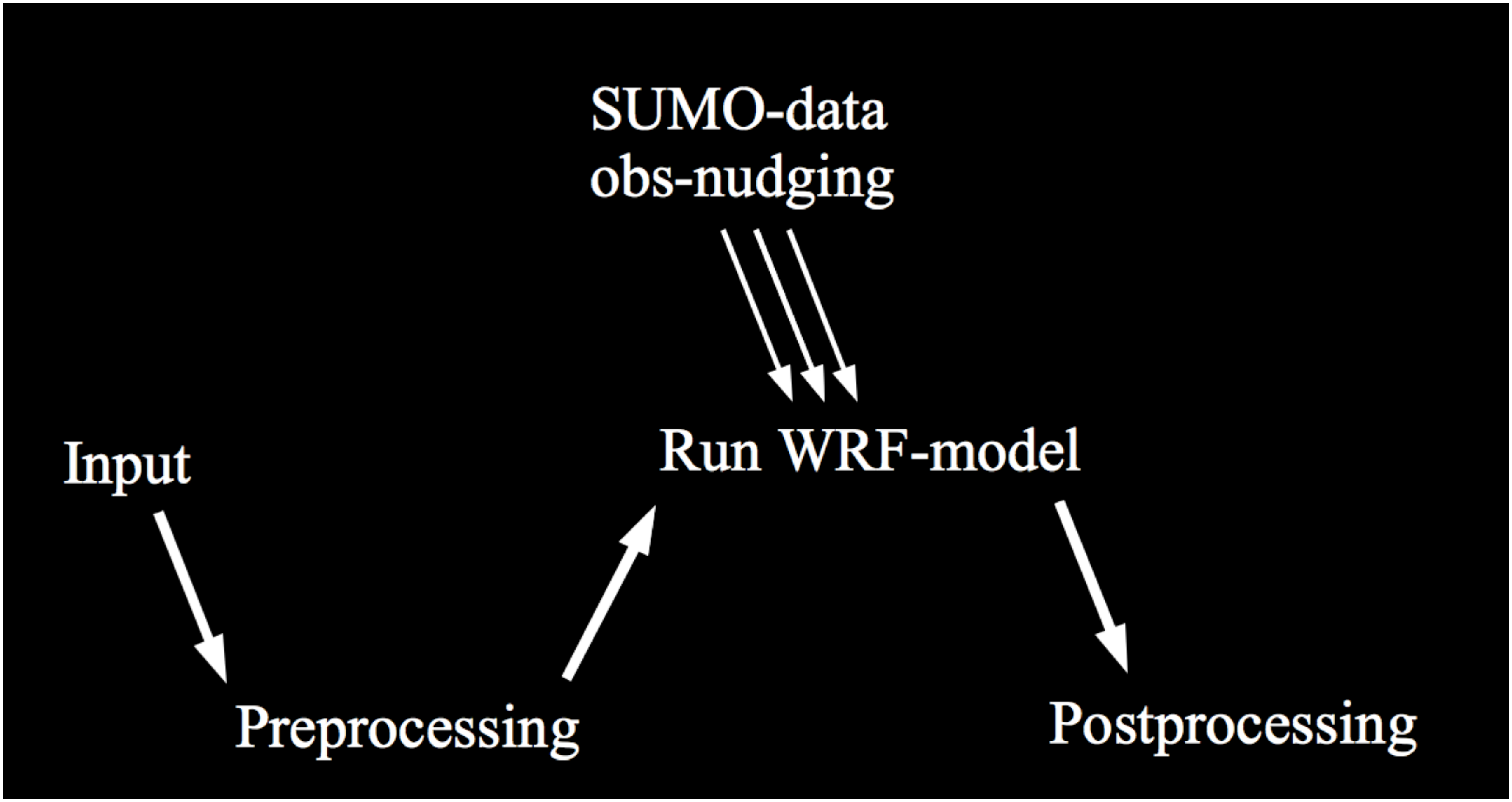
SUMO and WRF

This data can be assimilated with the WRF weather forecast



SUMO and WRF

The SUMO-data is incorporated into the WRF-simulation, via obs-nudging



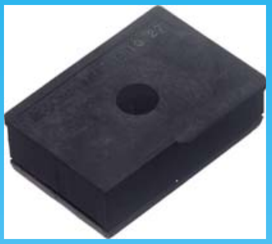
Additional sensors

The SUMO has been equipped with an optical dust sensor

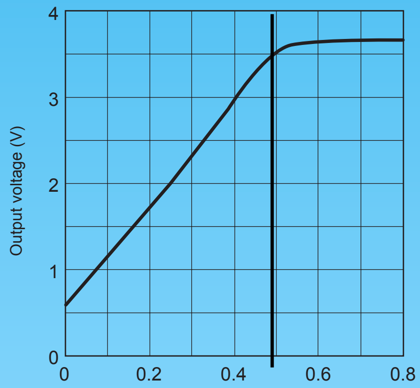
GP2Y1010AU0F is a dust sensor by optical sensing system:

- An infrared emitting diode (IRED) and an phototransistor are diagonally arranged into the device
- It detects the reflected light of dust in air
- Especially effective to detect very fine particle
- In addition it can distinguish smoke from house dust by pulse pattern of output voltage

Compact Optical Dust Sensor



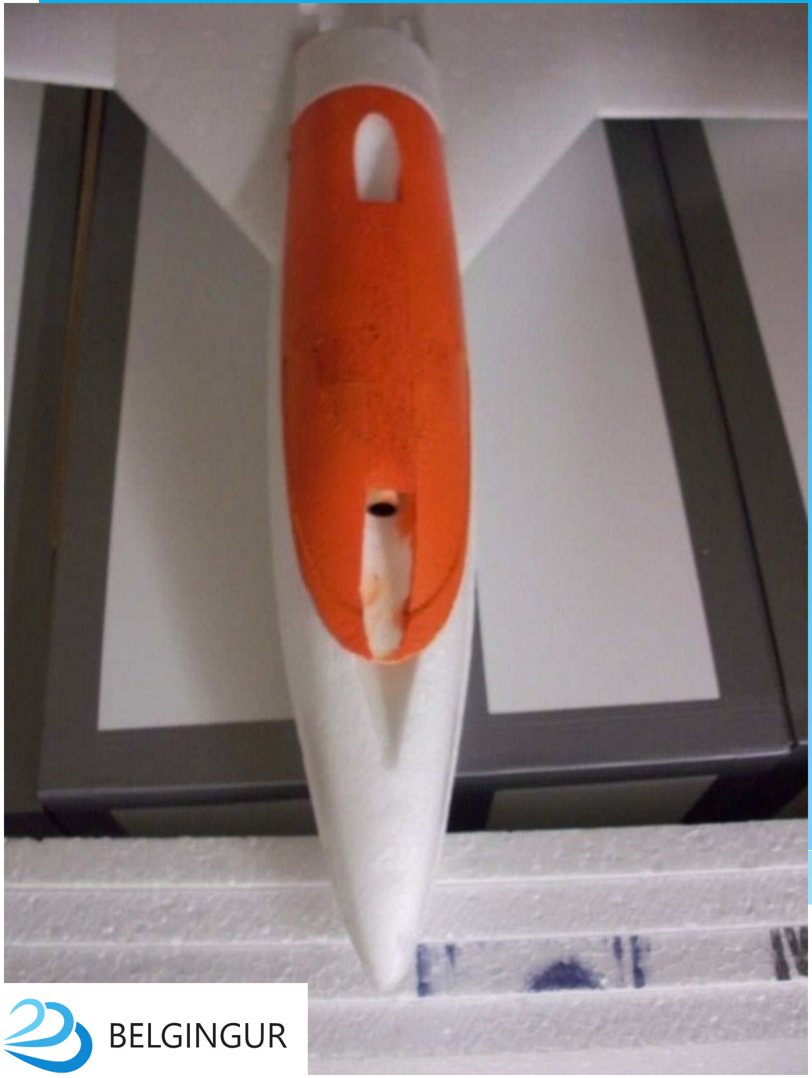
Output Voltage vs. Dust Density

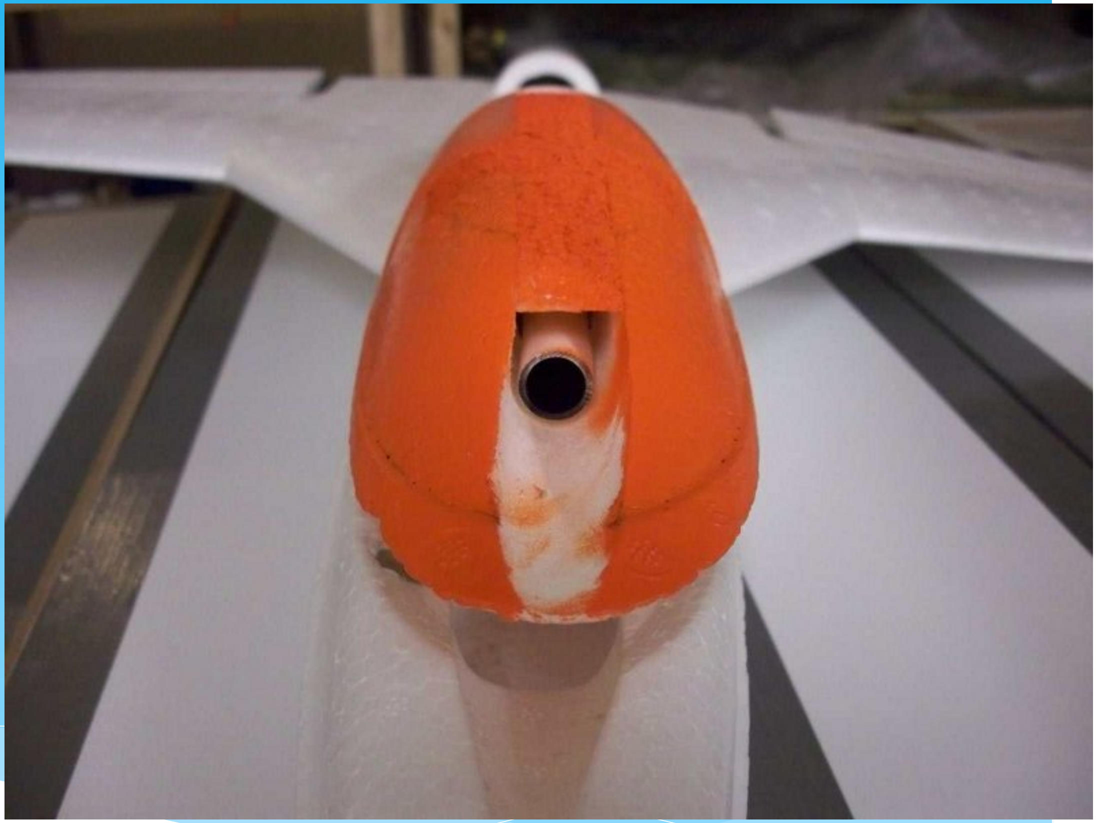


Saturation at about 500μg/m³

Preliminary results

The SUMO dust sensor has been tested in France and Iceland





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