Peculiarities & Disasters in Weather CFD

CFD2018 - 26th Annual Conference of the Canadian CFD Society
10 - 12 June 2018

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Topics:

1. Peculiarities of Meteorological vs. Engineering CFD
2. Some weather Disasters:
   - thunderstorms
   - tornadoes
   - forest-fire smoke
   - floods
   - hurricanes
   - climate change
   - blizzards
   - hazards to wind turbines

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Tim Chui
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Marjolein Ribberink
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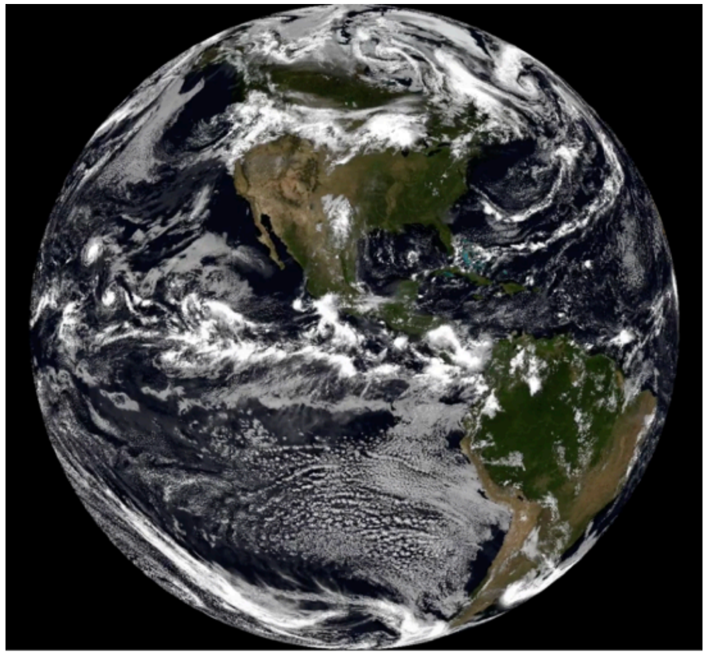
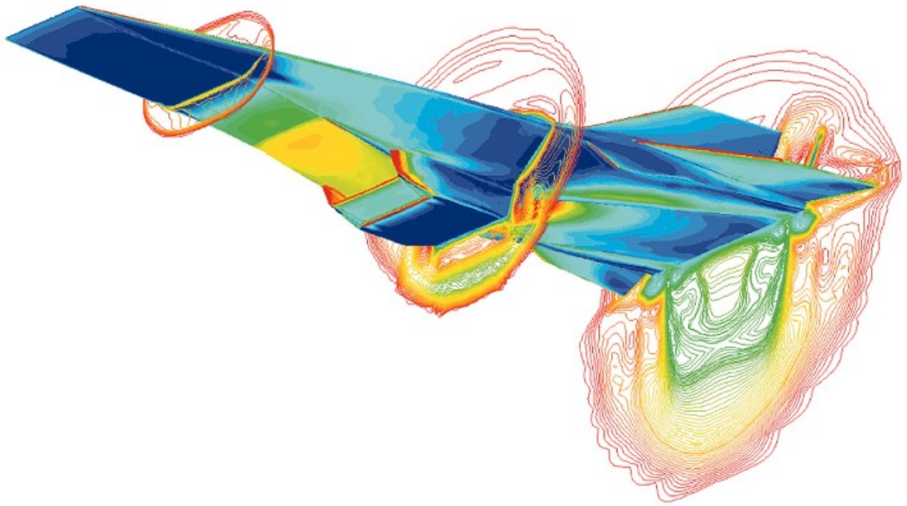
Roland Schigas
Greg West
Eve Wicksteed
Tatjana Zenker

Peculiarities of CFD of Weather

Peculiarities of weather CFD relative to engineering CFD.



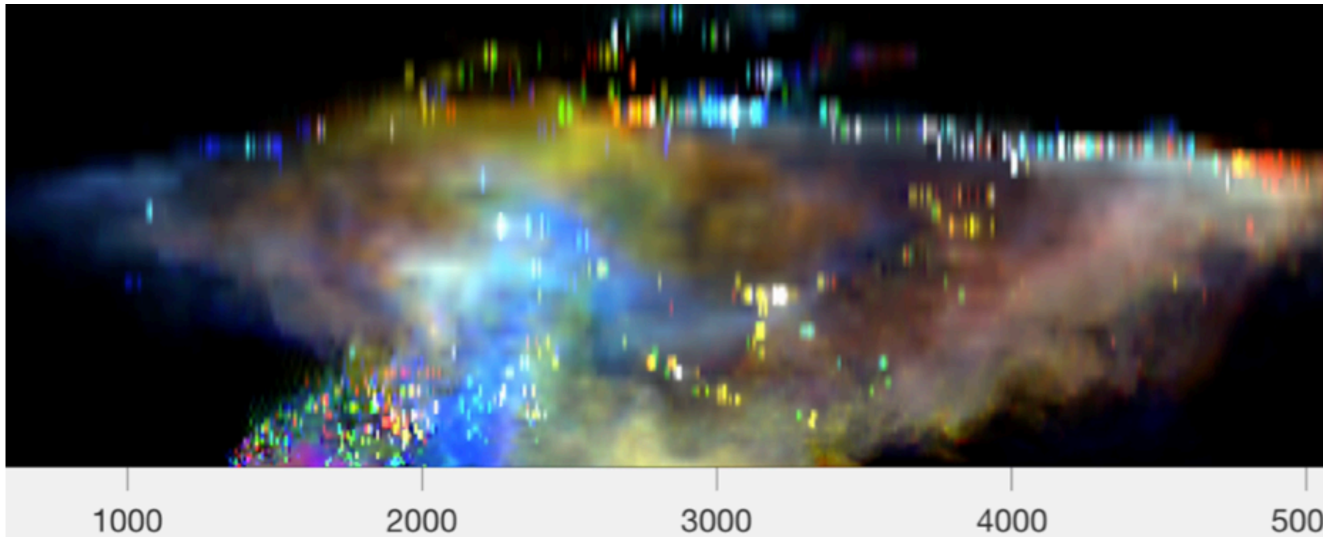
https://www.gfdl.noaa.gov/fv3/



X43A - Mach 7. By NASA - Armstrong Flight Research Center. Photo ID: ED97-43968-1., Public Domain, https://commons.wikimedia.org/w/index.php?curid=717133

Weather Disasters that can be simulated/forecast?

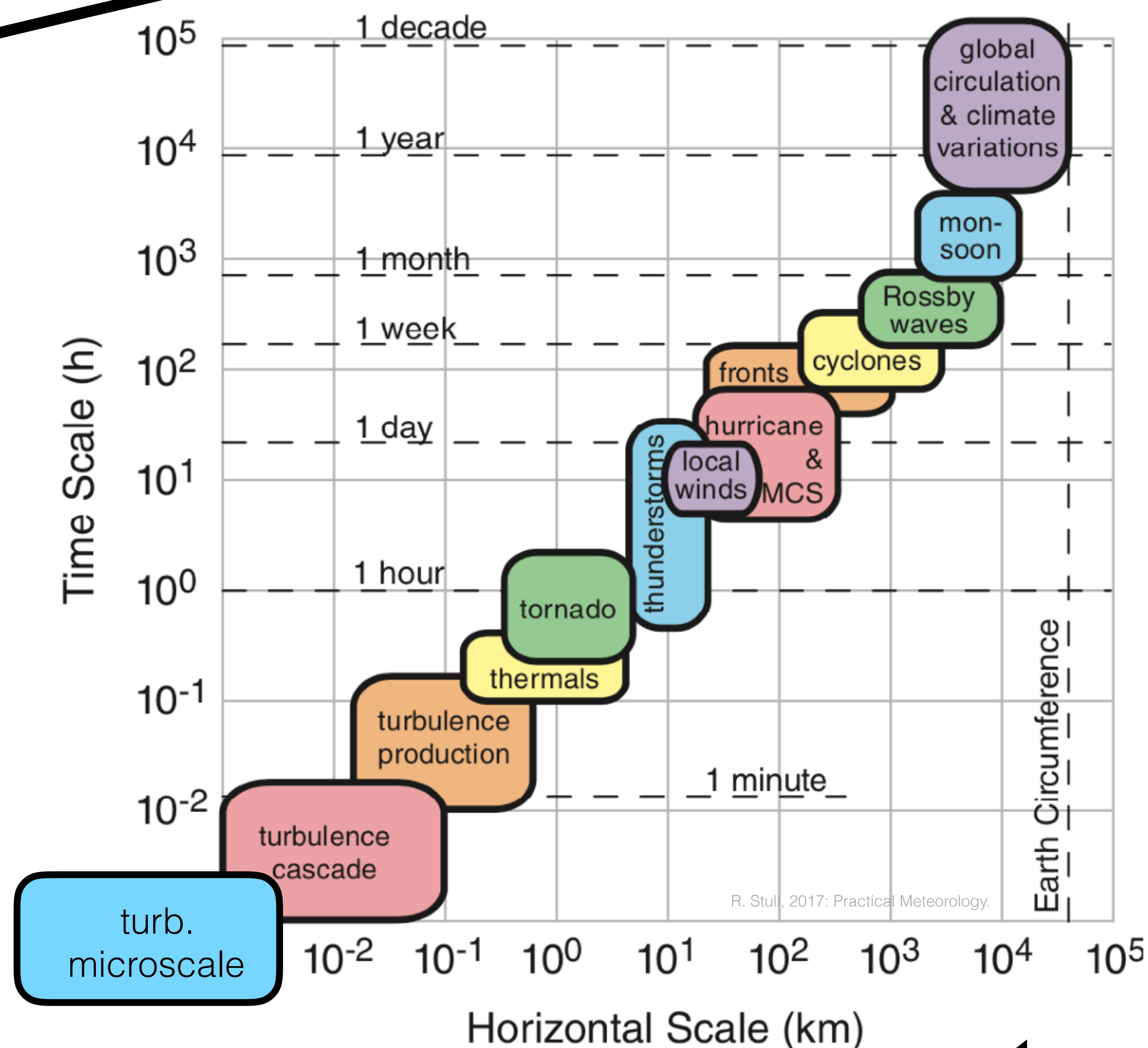
Visualization by David Bock, NCSA. See http://lantern.ncsa.illinois.edu/Vis/XSEDE/XSEDE15/Bock_Leigh.mov



Frans Liqui Lung. UBC & Delft

Large Range of Length Scales (L)

Special relationship between time and space scales of weather phenomena.



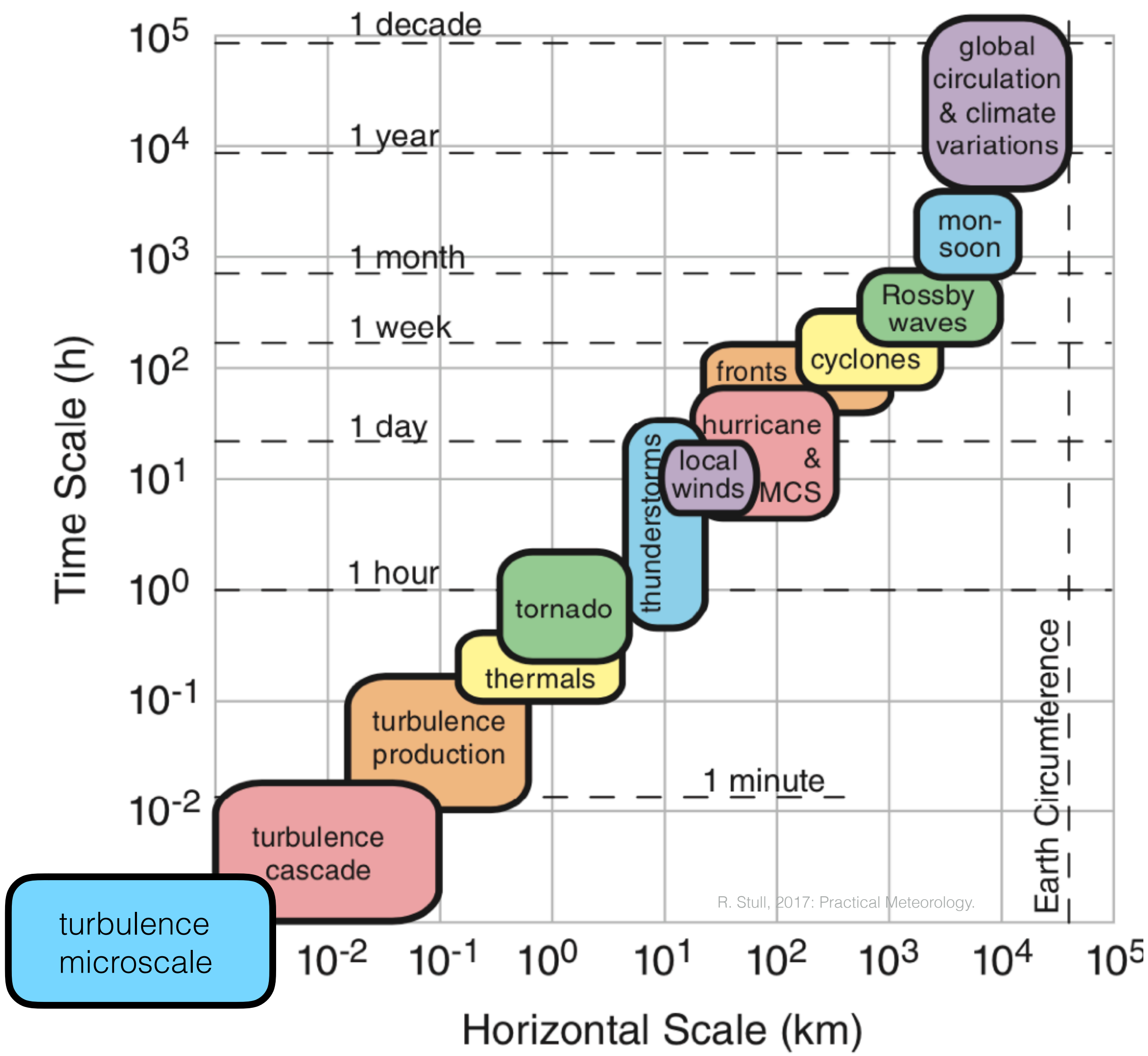
Weather has same **small** scale (Kolmogorov microscale) as in engineering for air ...

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \approx 1\ \text{mm}$$

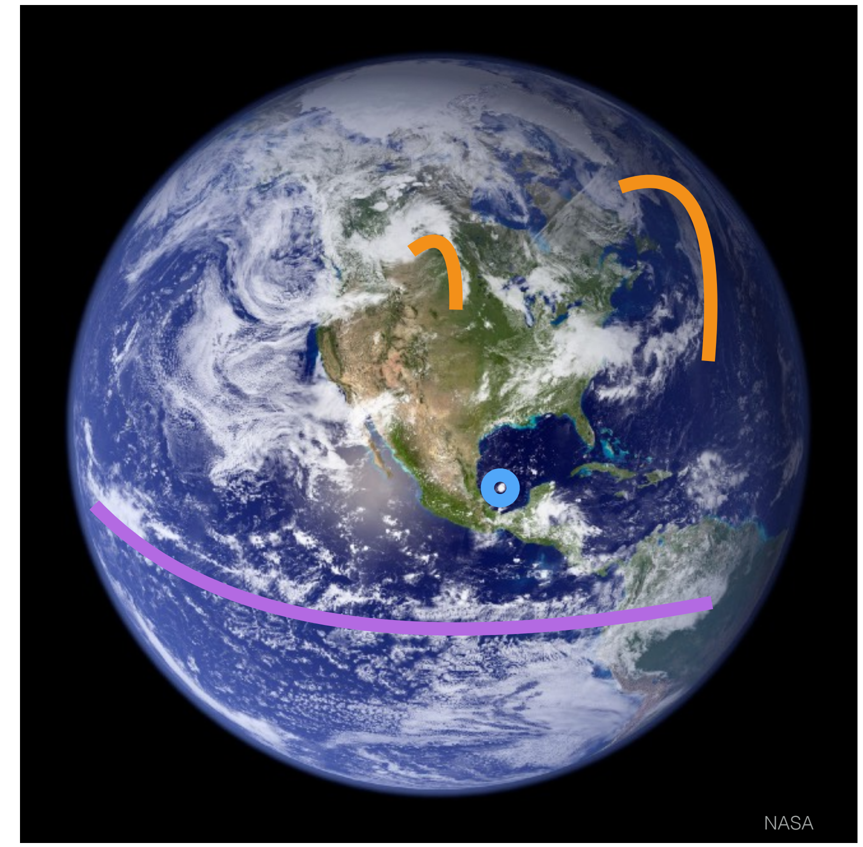
...but weather has much-larger **large** scales (≈10^3 km)

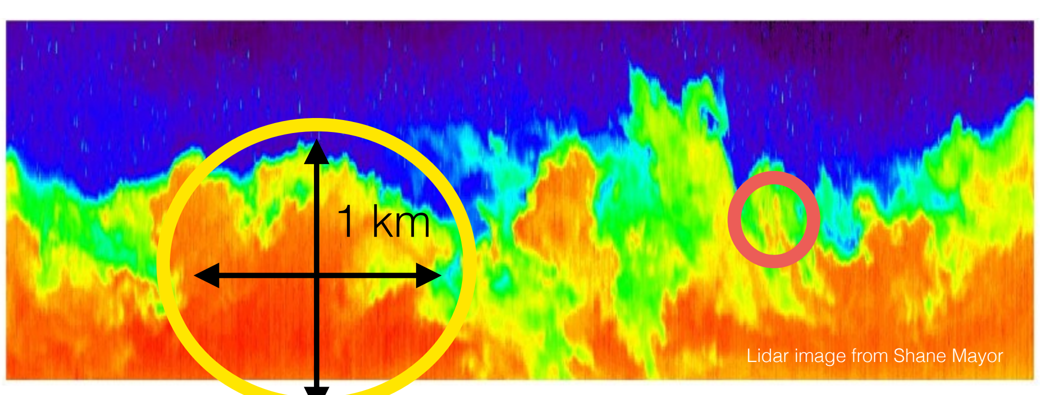
ν = kinematic viscosity, ε = TKE dissipation rate.

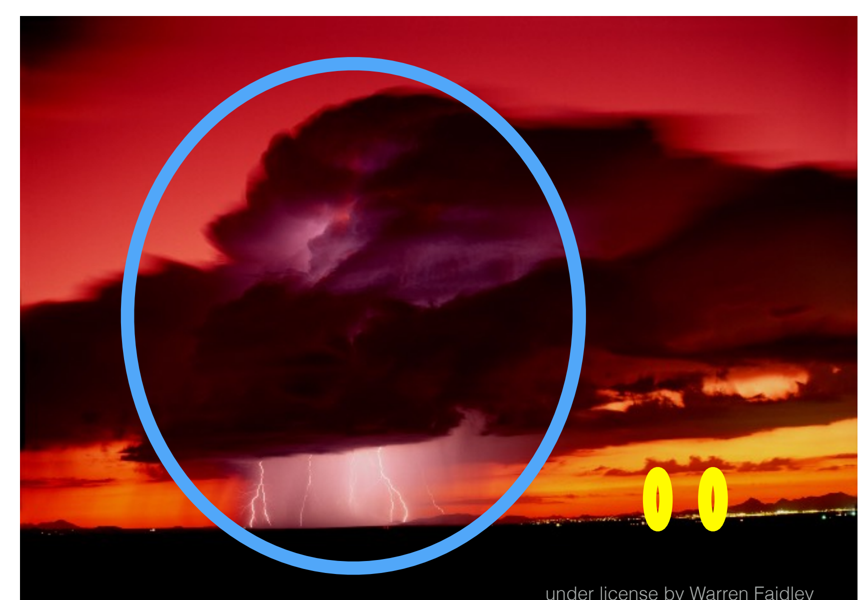
Superposition of All Length-scales. No spectral gap.



Scales of Motion in the Atmosphere







Predictability is Limited by Time Scale (t)

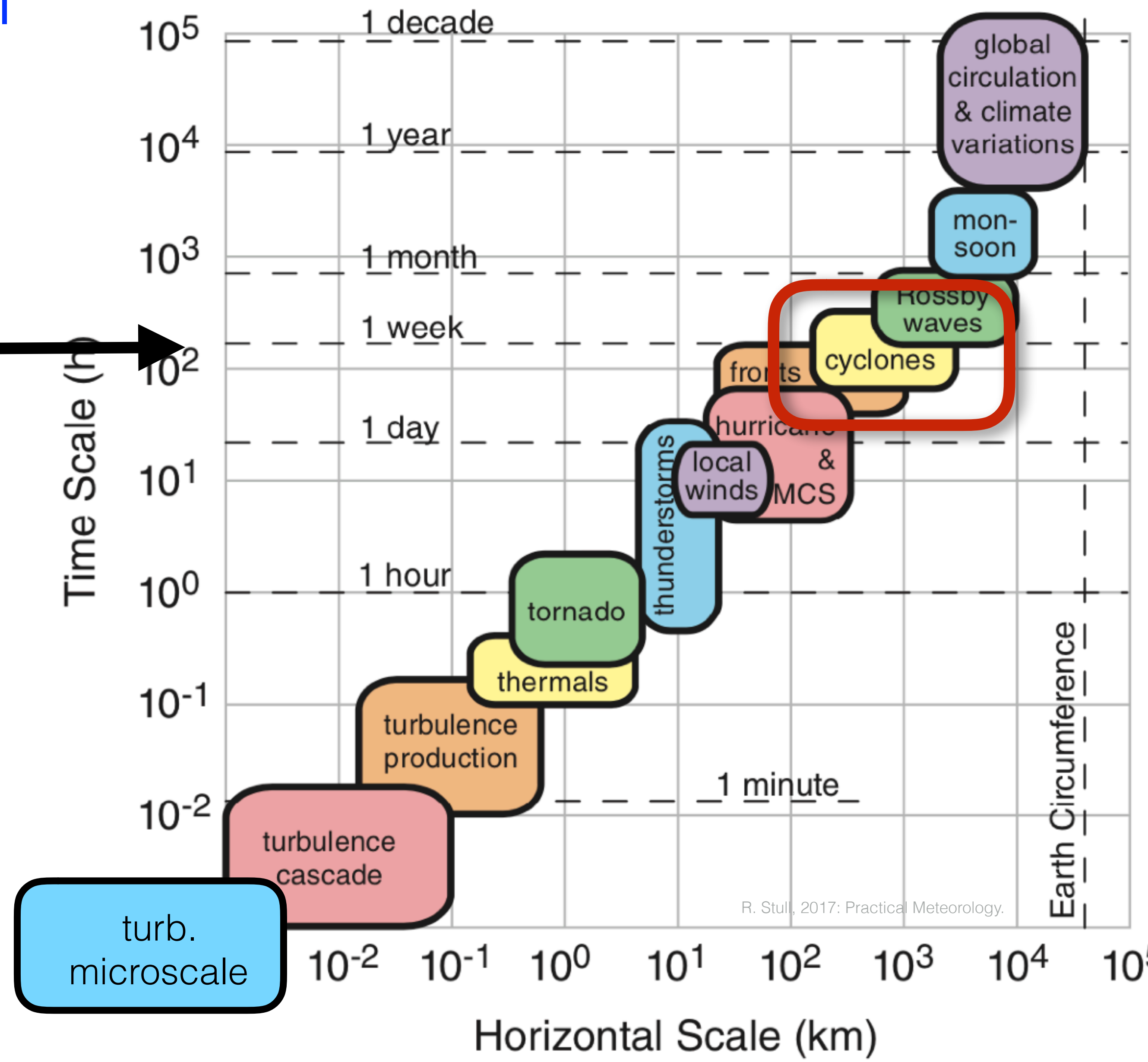
Predictability: Realistic vs. Real

Example: Starting with a real cyclone ICs as observed in the atmosphere, forecast skill for that **real** cyclone diminishes to nil after about 1 week.

Beyond 1 week, **realistic**-looking cyclones still appear in the forecast, but at the wrong locations and times and intensities.

But realistic forecasts are useful for a different reason: on average these phenomena transport realistic amounts of heat, moisture, momentum on larger scales. (Good for climate models & other simulations.)

Similar limits of predictability for phenomena of all time scales.



Turbulence is Not a Function of Reynolds Number

...because the Reynolds Number (Re) is so large, due to large length scales and small molecular viscosity

$$\mathrm{Re} = \frac{\rho U L}{\mu} \approx 10^{7} - 10^{10}$$

- Thus, atmosphere would always turbulent if we considered only inertia & viscosity.
- We can neglect molecular viscosity.

But atmos. turbulence is a modulated by the Richardson number (Ri)

$$Ri = \frac{g}{\theta} \frac{\Delta\theta / \Delta z}{(\Delta U / \Delta z)^{2}}$$

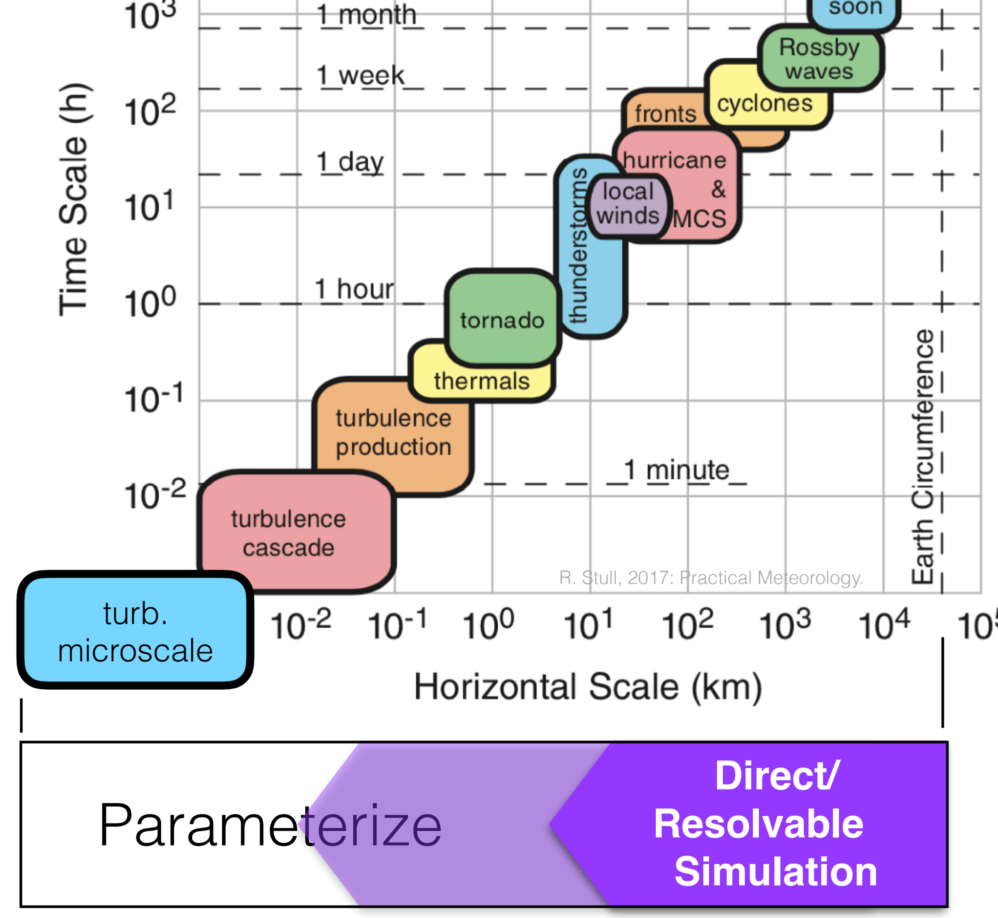
...indicating the damping effect of static stability [vertical potential temperature (θ) structure] vs. the TKE generation by wind shear (ΔU/Δz).

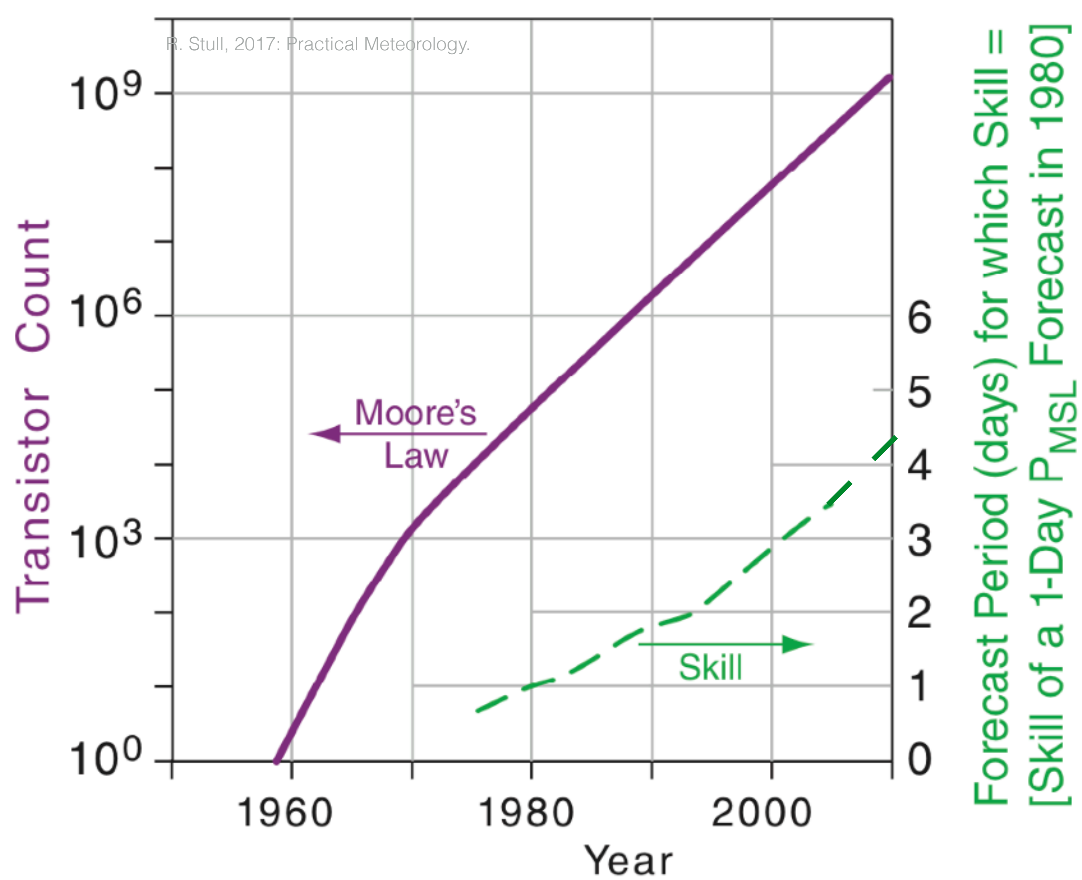
ρ = air density, U = wind speed, L = length scale, μ = molecular viscosity, g = accel. due to gravity, T = temperature, z = height, θ=T+(9.8K/km)·z.

Large range of scales requires more computing power than is available / affordable

Weather CFD is called
Numerical Weather Prediction (NWP)

Thus we are forced to approximate (parameterize) the effects of small scales.



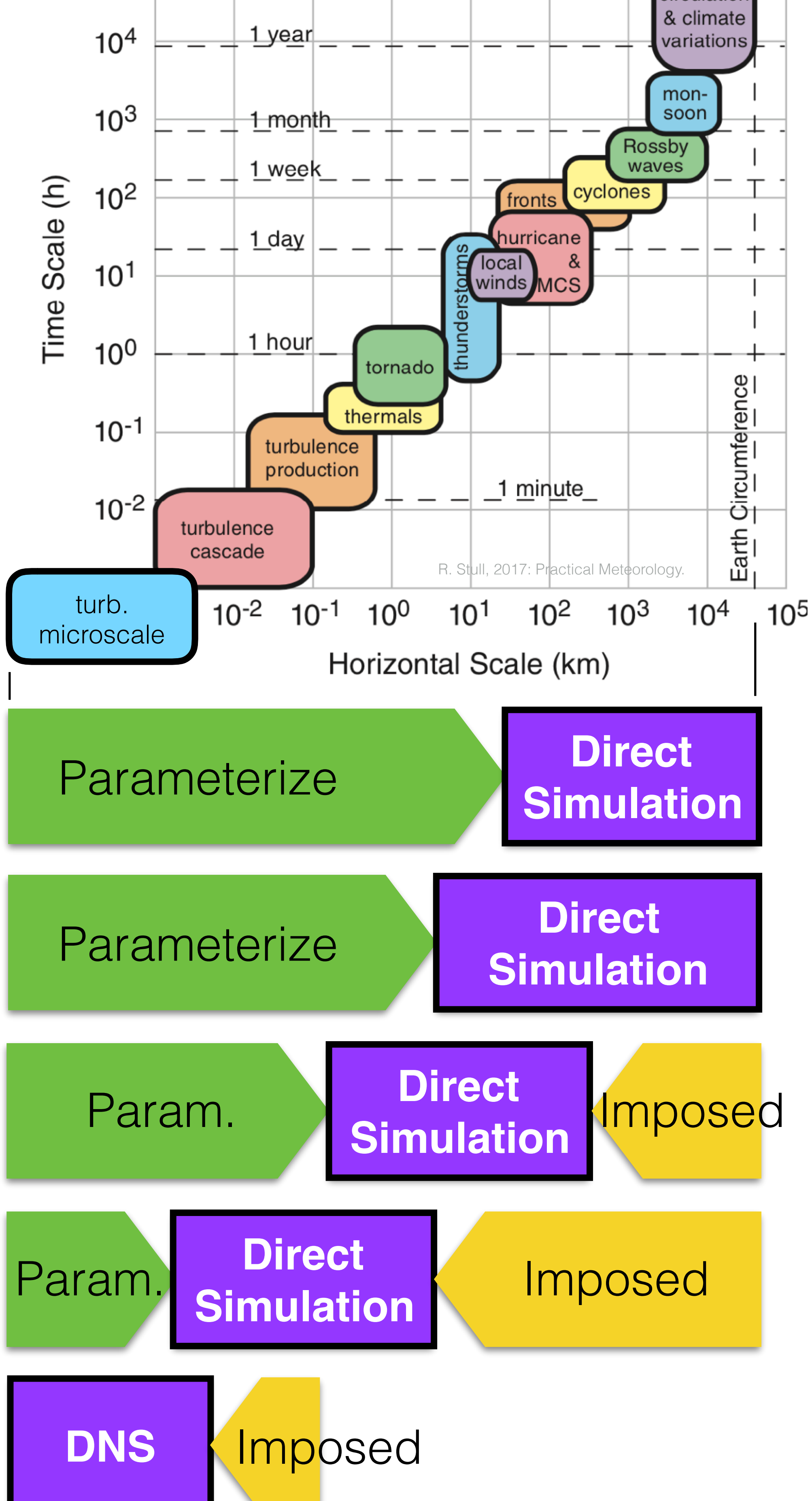


- 1970s-present:
  NWP forecast skill increased with growth in computer power, as described by Moore's law.

Parameterization is being pushed to smaller scales.

PMSL = atmospheric Pressure at mean sea level

Divide & Conquer



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  (simulates net effect of many scales)
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  (real-time operational forecasts)
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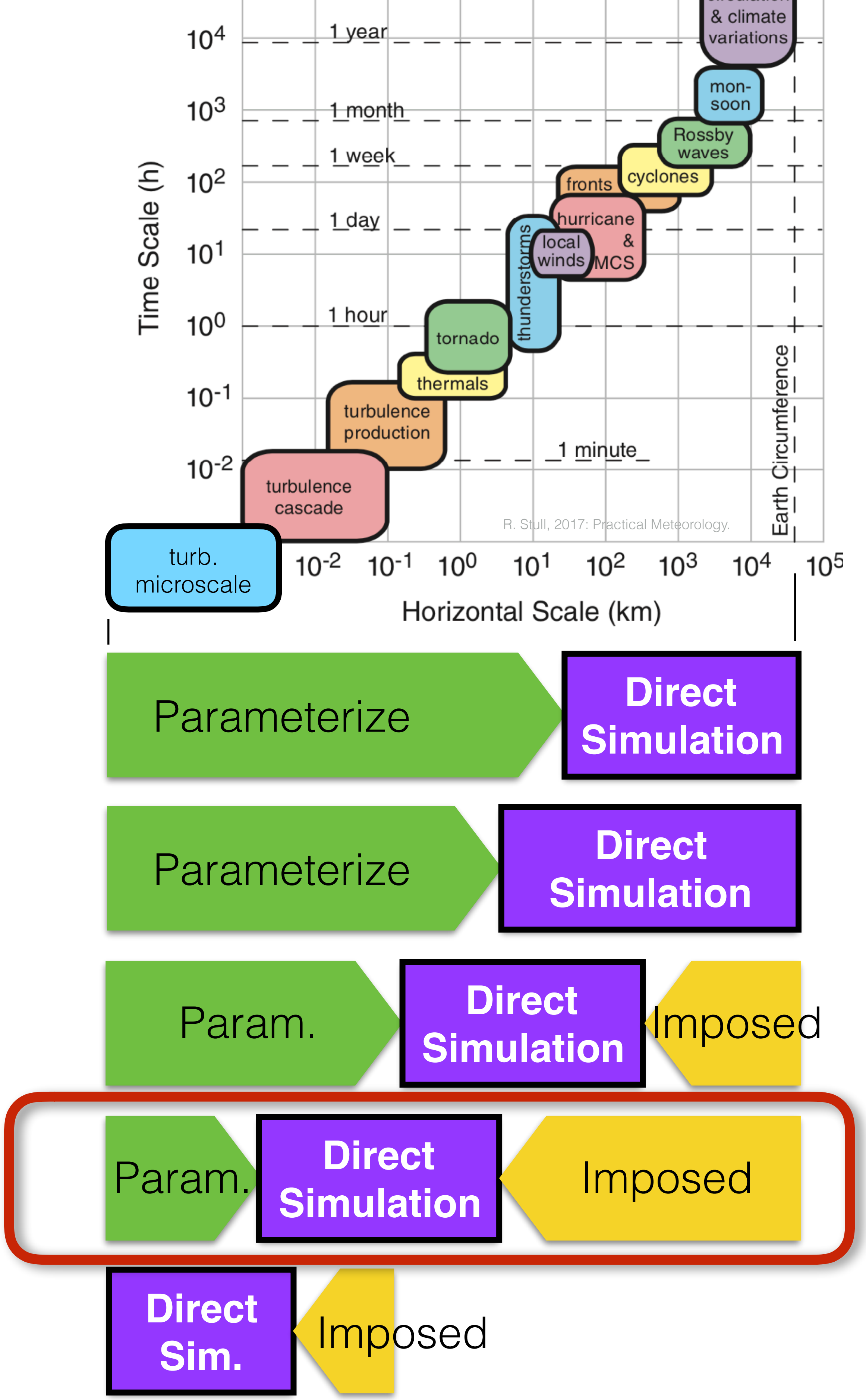
  (but getting closer to real-time)
- Atmos.Boundary Layer Simulations
  (bottom 2 km of atmosphere)
- Engineering Simulations

BCs = boundary conditions, ICs = initial conditions. DNS = Direct Num. Simulation. Atmos. Boundary Layer (ABL) = bottom 2 km of atmosphere

1. Boundary Layers & Turbulence



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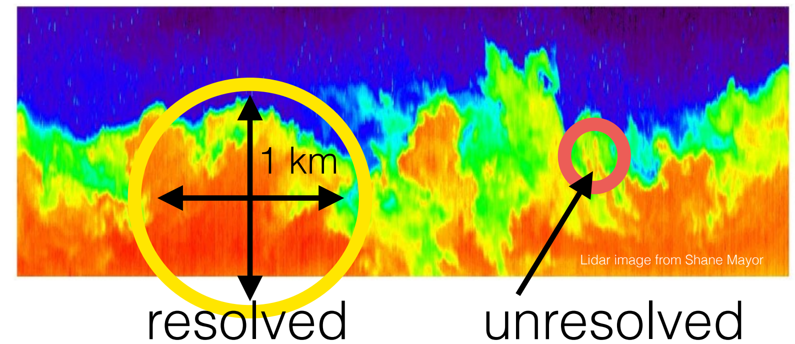
Large Eddy Simulation (LES) - realistic looking, but not real

- Boundary Layer Observations



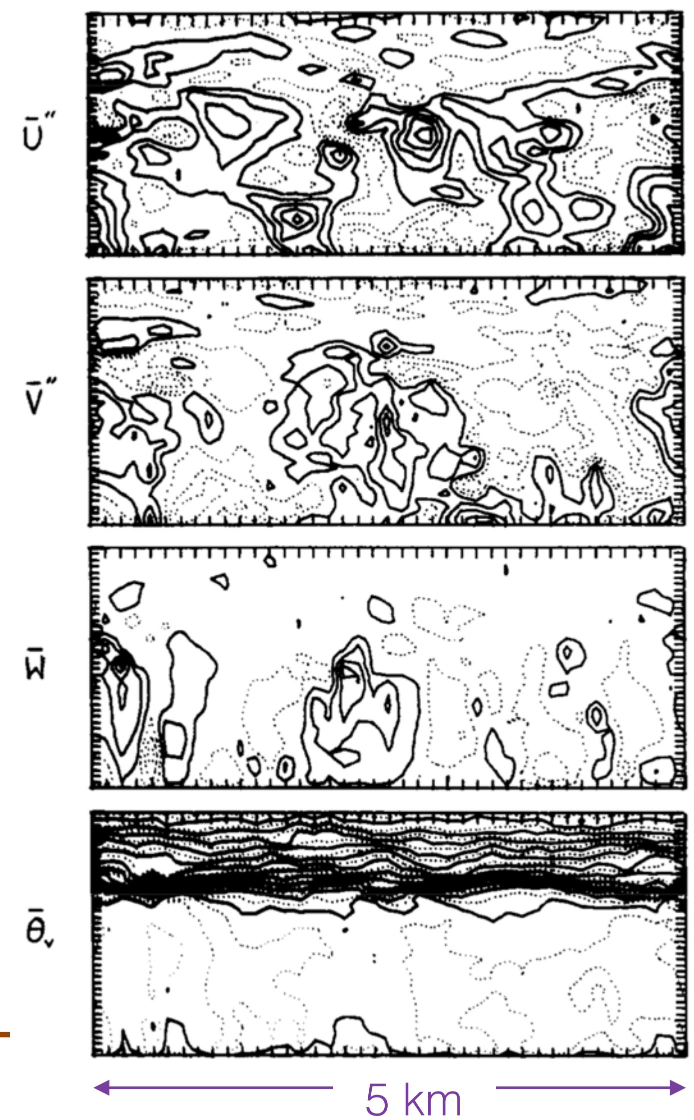
observed by laser radar (lidar). red = more pollution/ scatterers

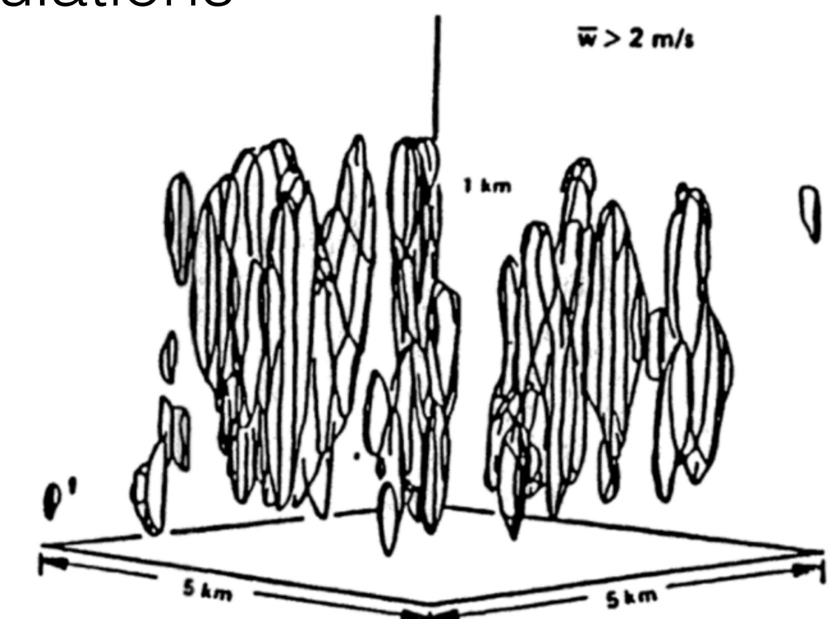
LES: Developed 50 years ago by Jim Deardorff at NCAR for convection in the atmospheric boundary layer (ABL).

Smallest resolvable scales were limited by computer power (i.e., were not very small).

$\Delta x = \Delta y = 125$ m and $\Delta z = 50$ m in domain (x, y, z) = 5 x 5 x 2 km. $(40)^3$ grid points = 6.4×10^4 grid points.

- Boundary Layer Simulations





Moeng, 1984, NCAR/AR-83, 57-58.

Not trying to forecast each thermal or turbulent eddy. But trying to forecast their net effect on transport of heat, pollutants, etc.

Deardorff, 1974, Bound. Layer Meteorology, 7, 199-226.

Disasters: 2017 Forest Fire Season in British Columbia

Image courtesy of BC Wildfire Service. https://www.facebook.com/BCForestFireInfo/videos/10155384746680673/

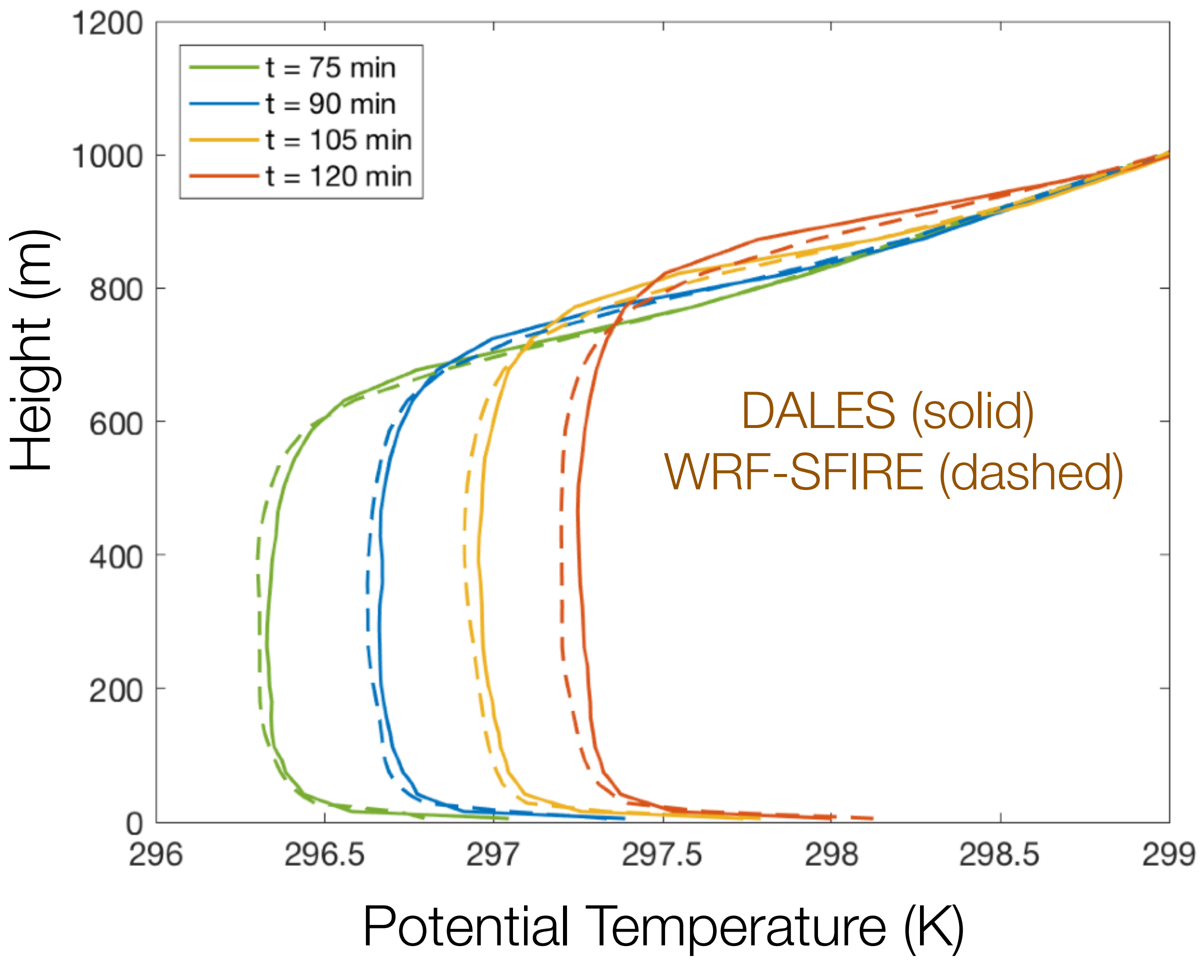
Over 65 provincial parks closed. Dozens of highways closed. Dozens of towns evacuated.

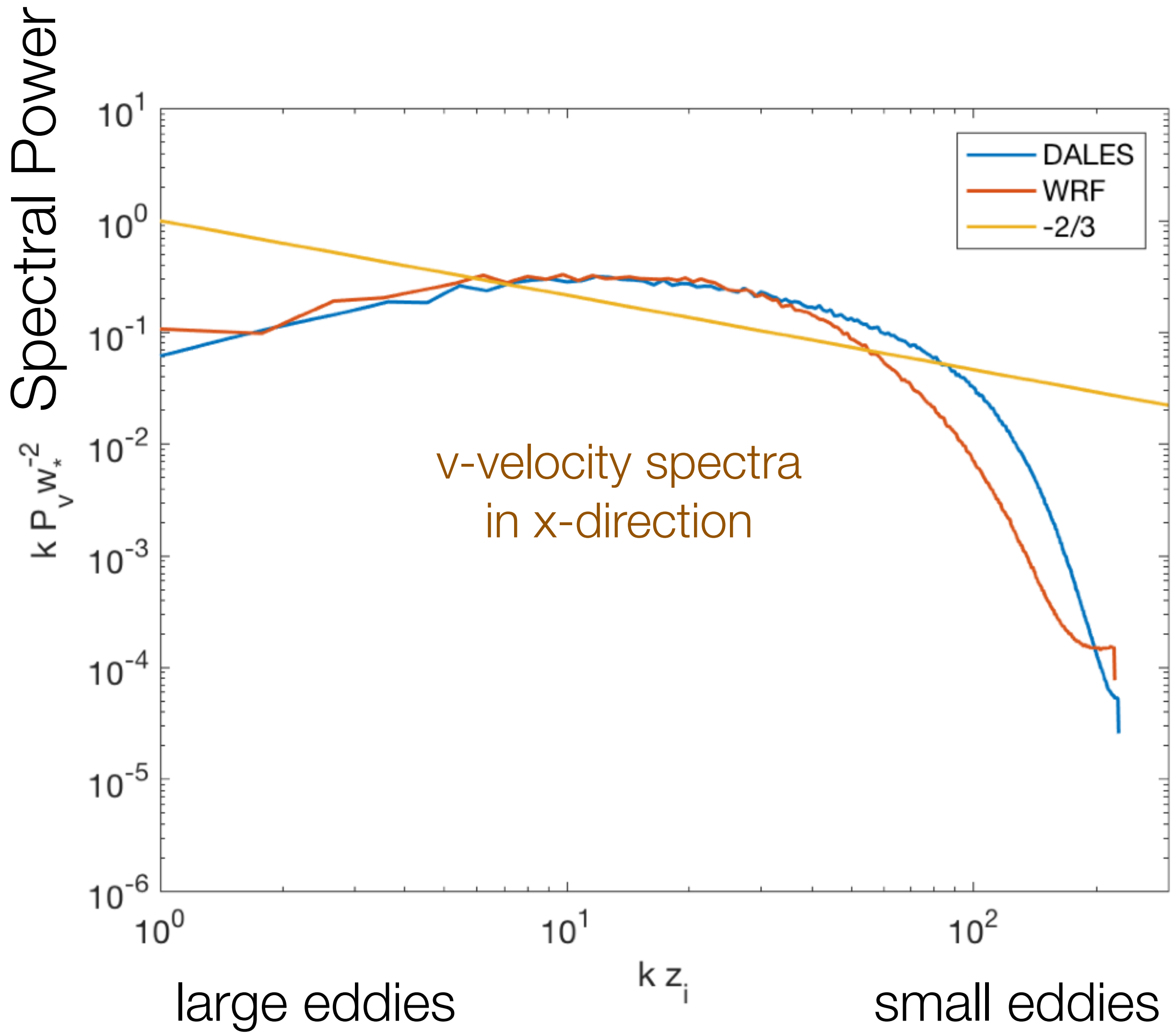
Large-Eddy Simulation (LES) Community Models - present day

DALES = Dutch Atmospheric LES	WRF-SFIRE = coupled Weather Research & Forecast and FIRE-spread
DALES	**WRF-SFIRE**
Non-hydrostatic	Non-hydrostatic
Boussinesq approximation	Fully compressible
FFT Pressure solver	Prognostic P eq.
Imposed net zero vertical velocity	
Cartesian height levels	Pressure eta levels
Subgrid Turb.: K theory based on TKE	Subgrid Turb: 3-D 1.5 order TKE closure
Handles multiple tracers	Moisture is surrogate for smoke emissions
Flat terrain or simple linear slope only	Complex terrain
Δx = 10 m	Δx = 40 m for WRF, with 4 m for SFIRE
55 layers in vertical, up to 2.8 km	50 layers in vertical, up to 2.5 km
Cyclic lateral boundary conditions	Cyclic lateral boundary conditions
Fireline approximated by enhanced surface heat flux	Models fire spread & heat & H_2O
Infinitely long fireline	Finite length fireline
800 x 300 x 55 grid points in x, y, z = 1.32×10^7 total	300 x 150 x 50 grid points in x, y, z = 2.25×10^6 total

Model Comparison of PBL Evolution

LES spin-up comparison by Frans Liqui Lung at UBC & Delft

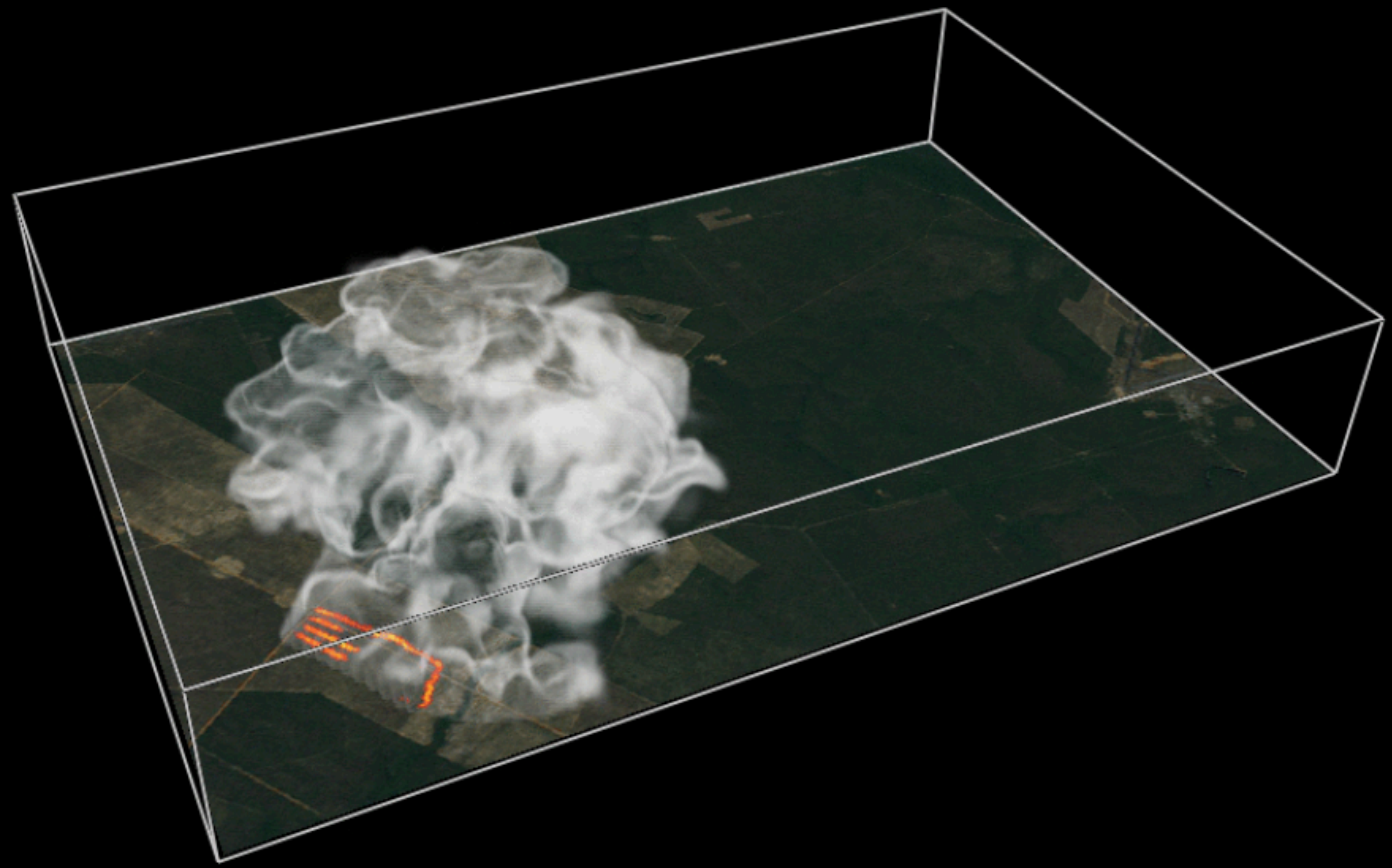




Large-Eddy Simulation (WRF-SFIRE): first experiments

Research by Nadya Moisseeva at UBC.

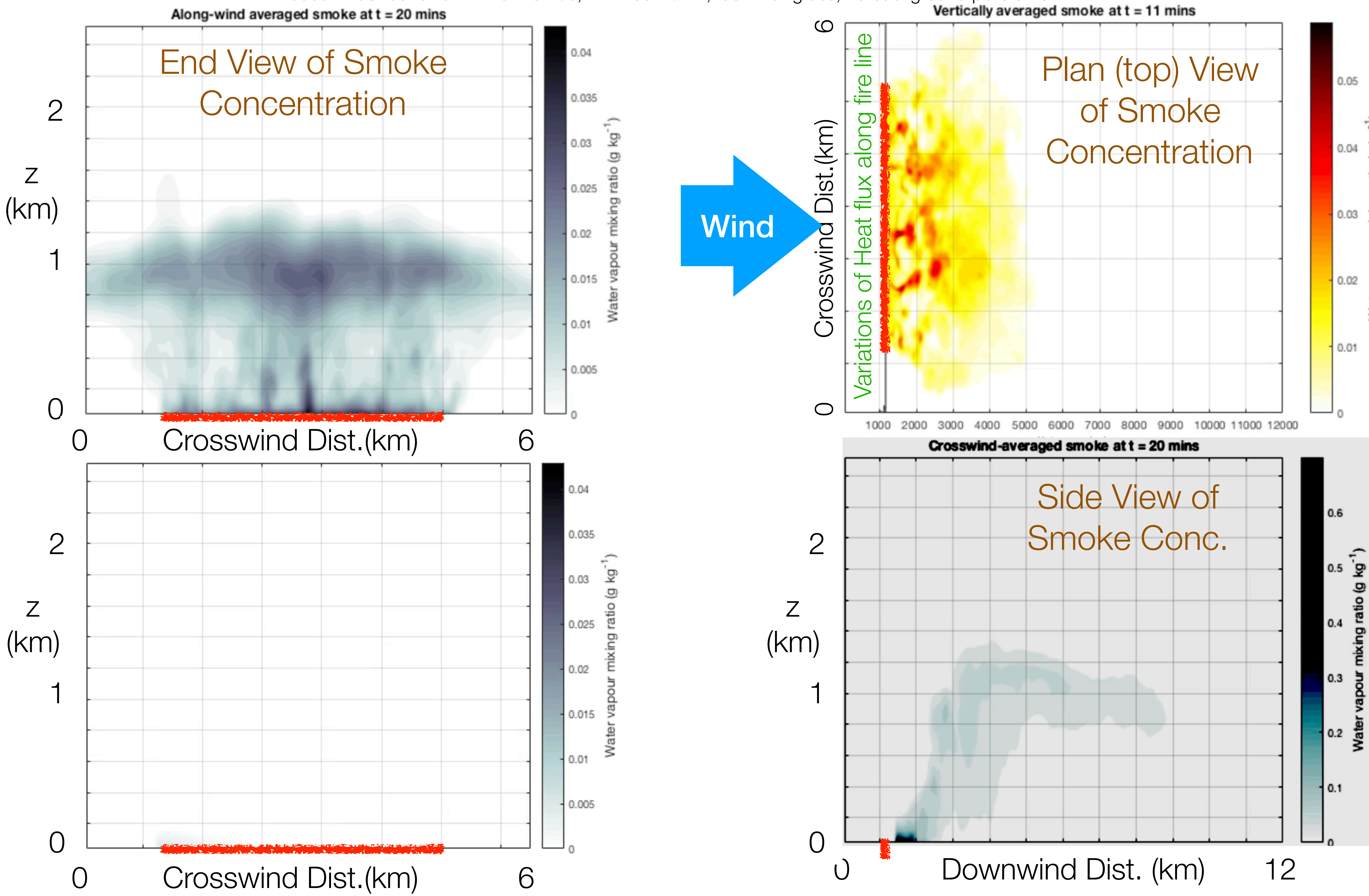
- Simulating the prescribed burn: RxCADRE 2012 (Nov 10, 2012 – Elgin Air Force Base, Florida) two large lots (shrub/forest). Surface/air measurements of emissions, including H_2O vapor



WRF-SFIRE

Convective-Structures.   LES runs by Nadya Moisseeva. Analysis by Rosie Howard at UBC

Case: W6S400F3R0 = wind = 6 m/s, H = 400 W/m2, fuel = tall grass, no background pollutants



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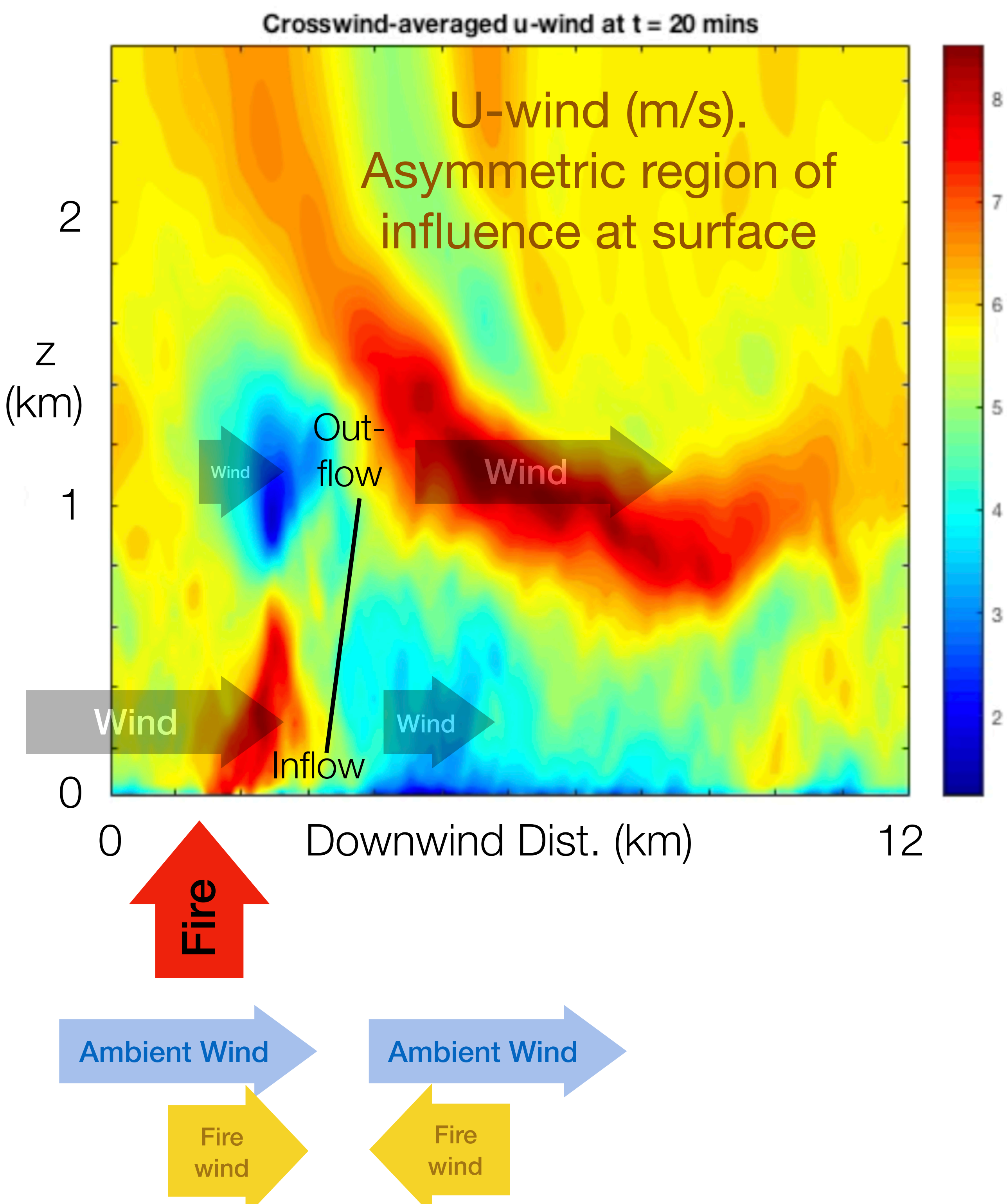
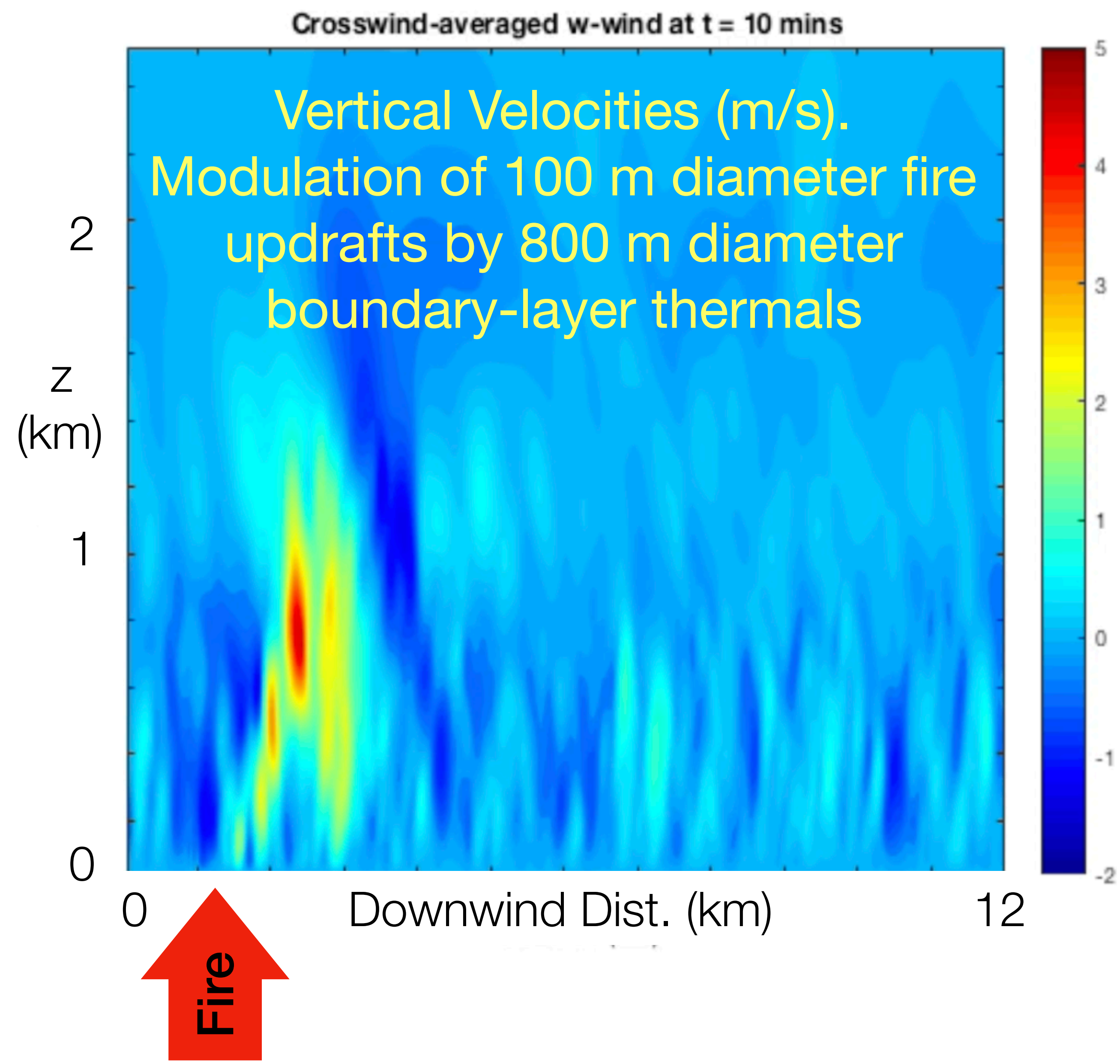
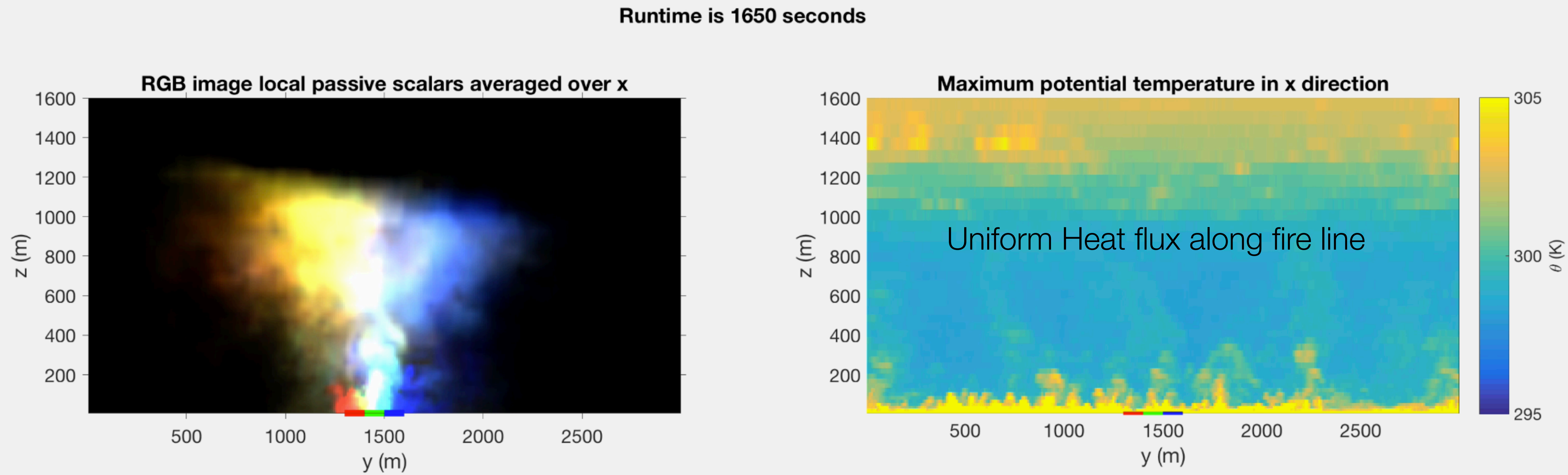


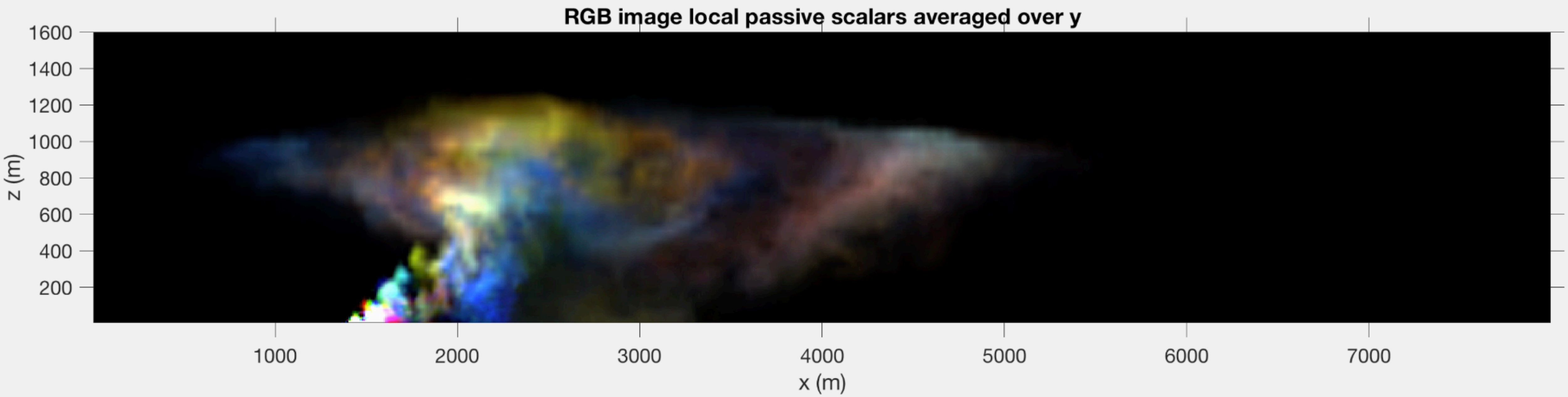


DALES

Fire-convection Structures.   Analysis by Frans Liqui Lung at UBC & Delft

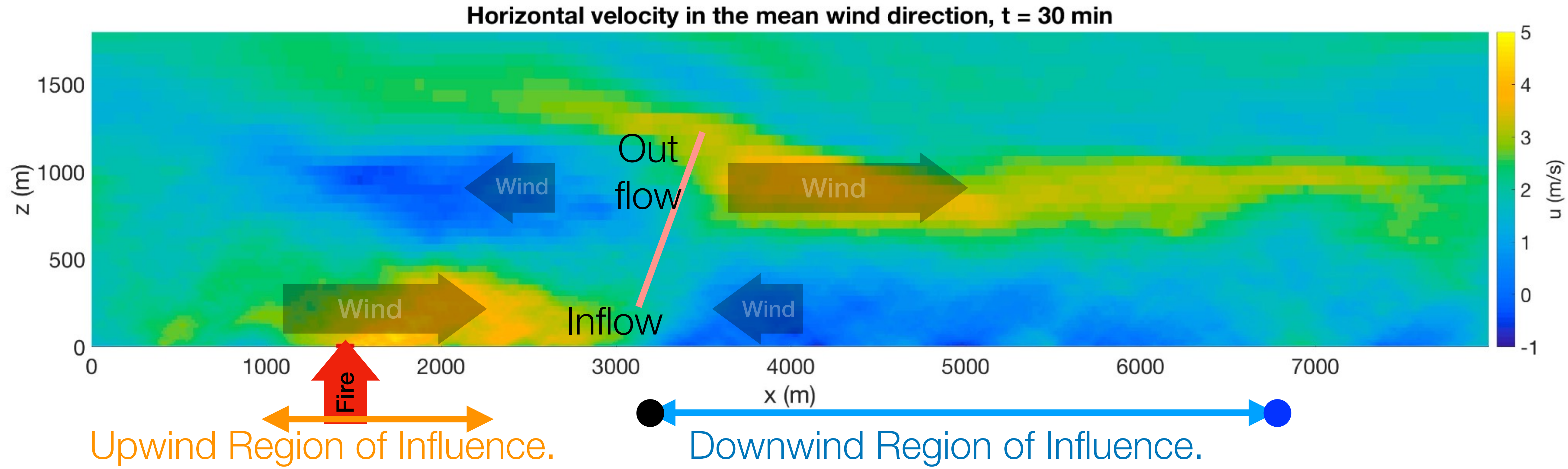


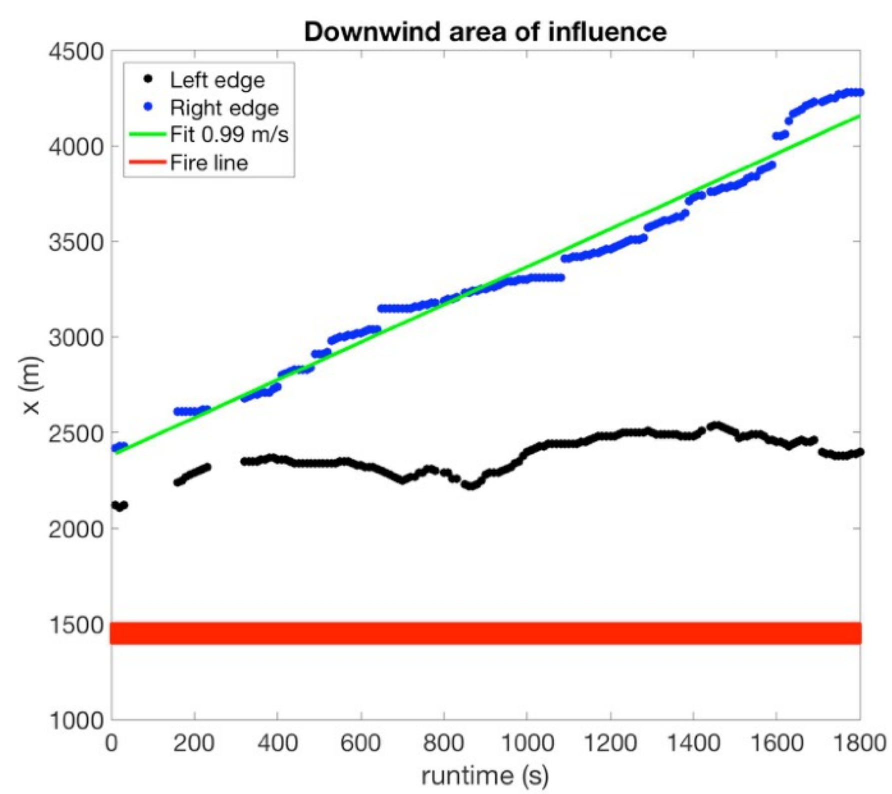
Absolute Concentrations. But emitted from very small portion of fire line.



DALES

Region of Influence. Analysis by Frans Liqui Lung at UBC & Delft





Mean wind is 2 m/s.

Heat flux of fire plume is 8 K m/s.

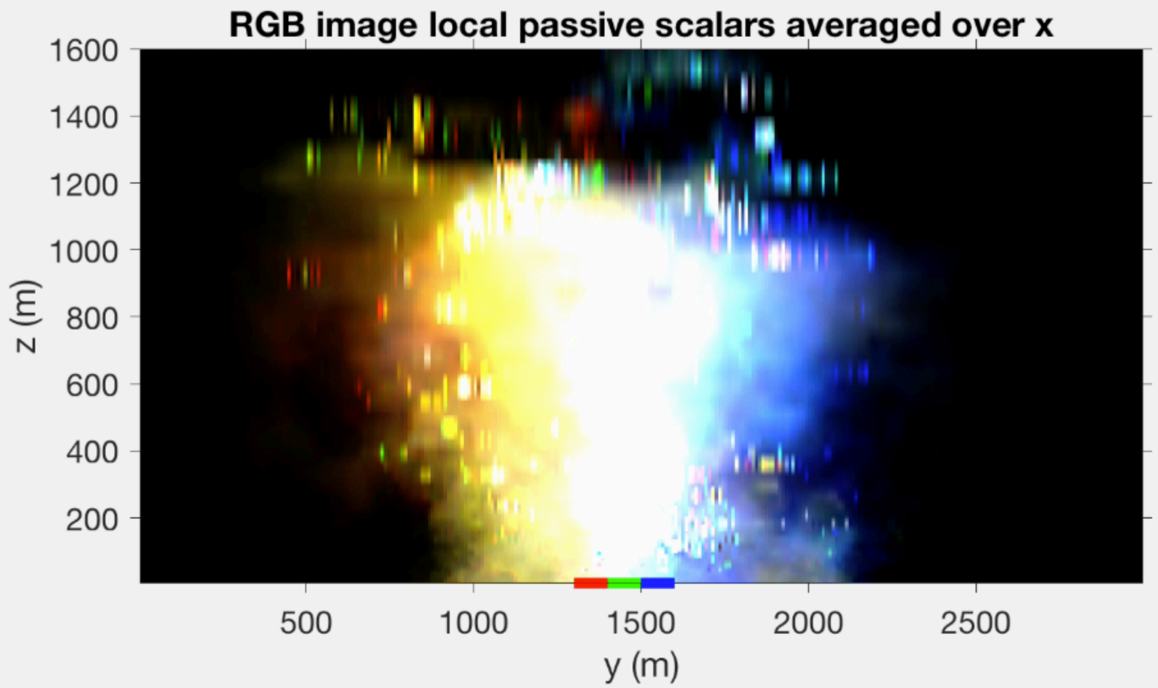
Heat flux of environment is 0.2 K m/s.

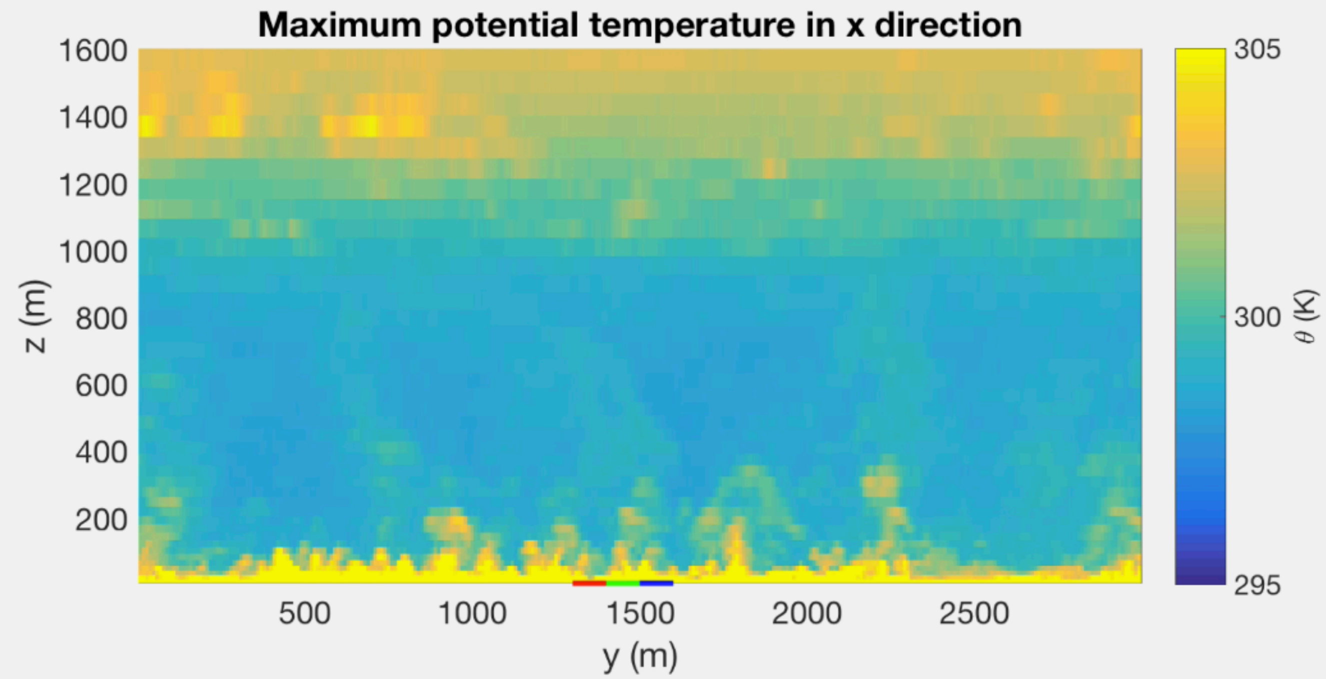
Width of fire line is 100 meters.

DALES

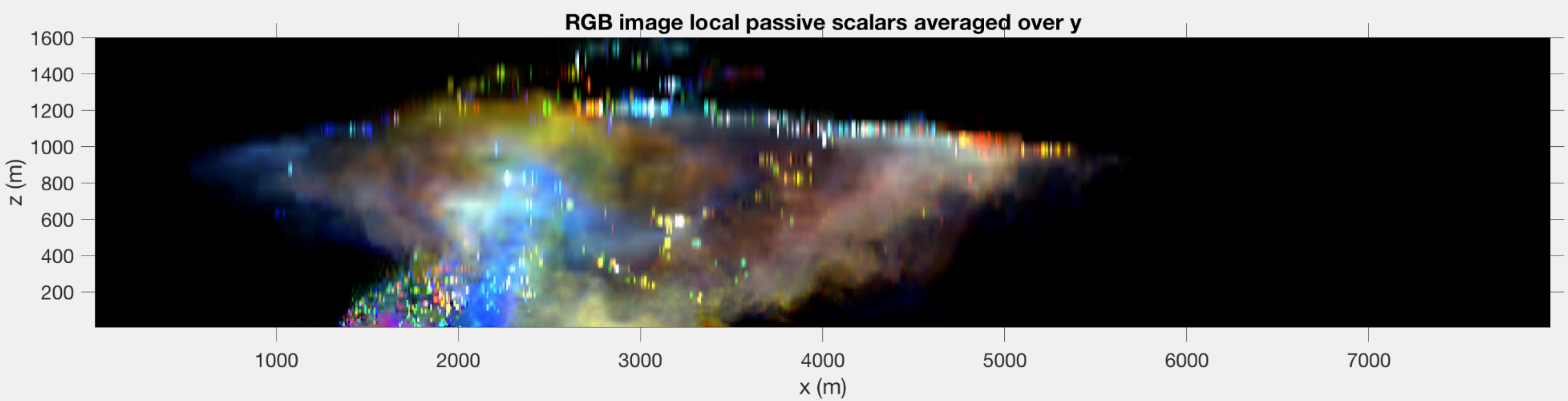
Convective-Structures. Analysis by Frans Liqui Lung at UBC & Delft

Runtime is 1650 seconds

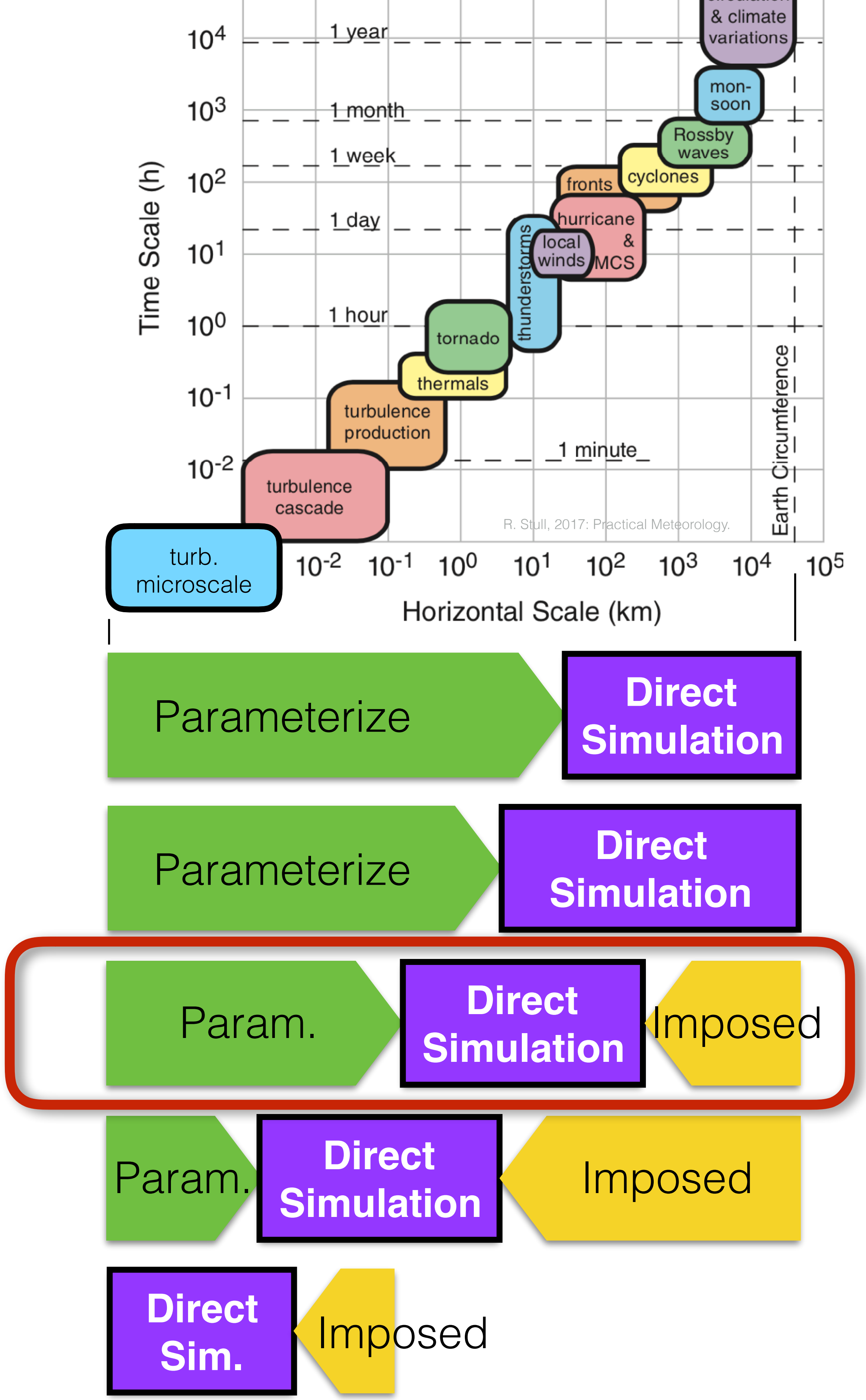




Relative (percentage) Concentration. Reveals backflow toward fireline at surface



Storm Simulations



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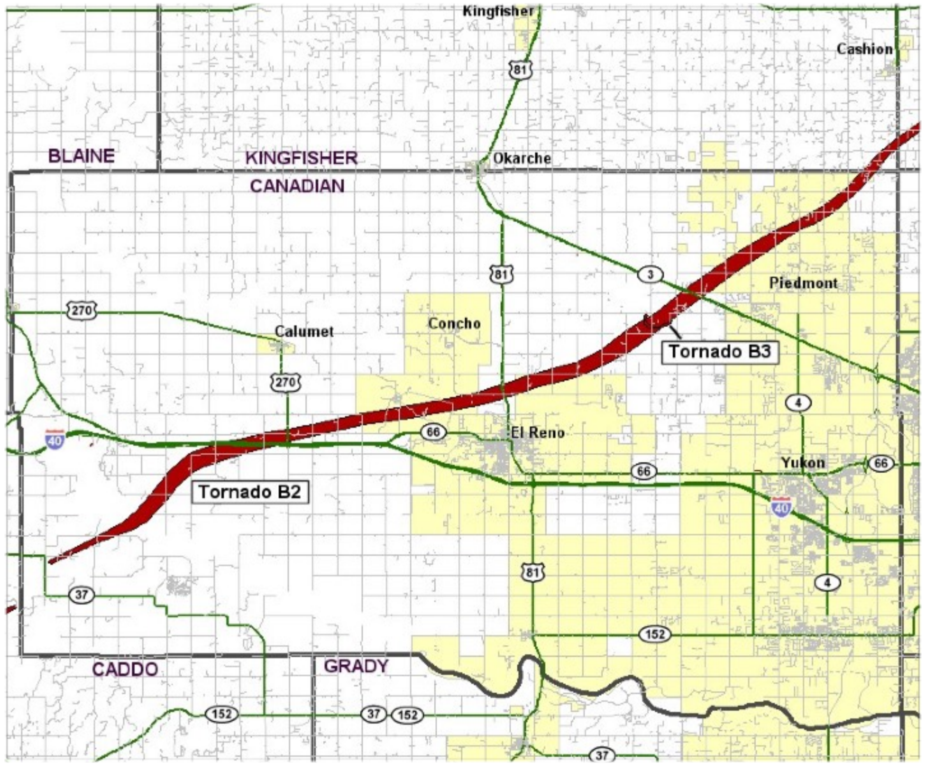
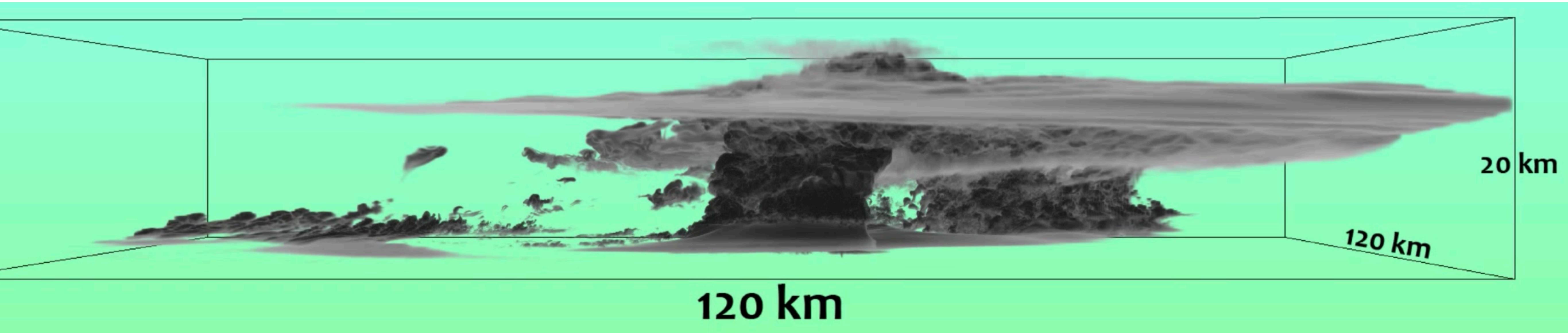
Disaster: EF5 Tornado in Oklahoma

24 May 2011, Calumet–El Reno–Piedmont–Guthrie



Tornadic Thunderstorm Simulation

Leigh Orf, U. Wisc. CIMSS. Images from his presentations. See https://www.youtube.com/watch?v=7UjdFg4UWpk



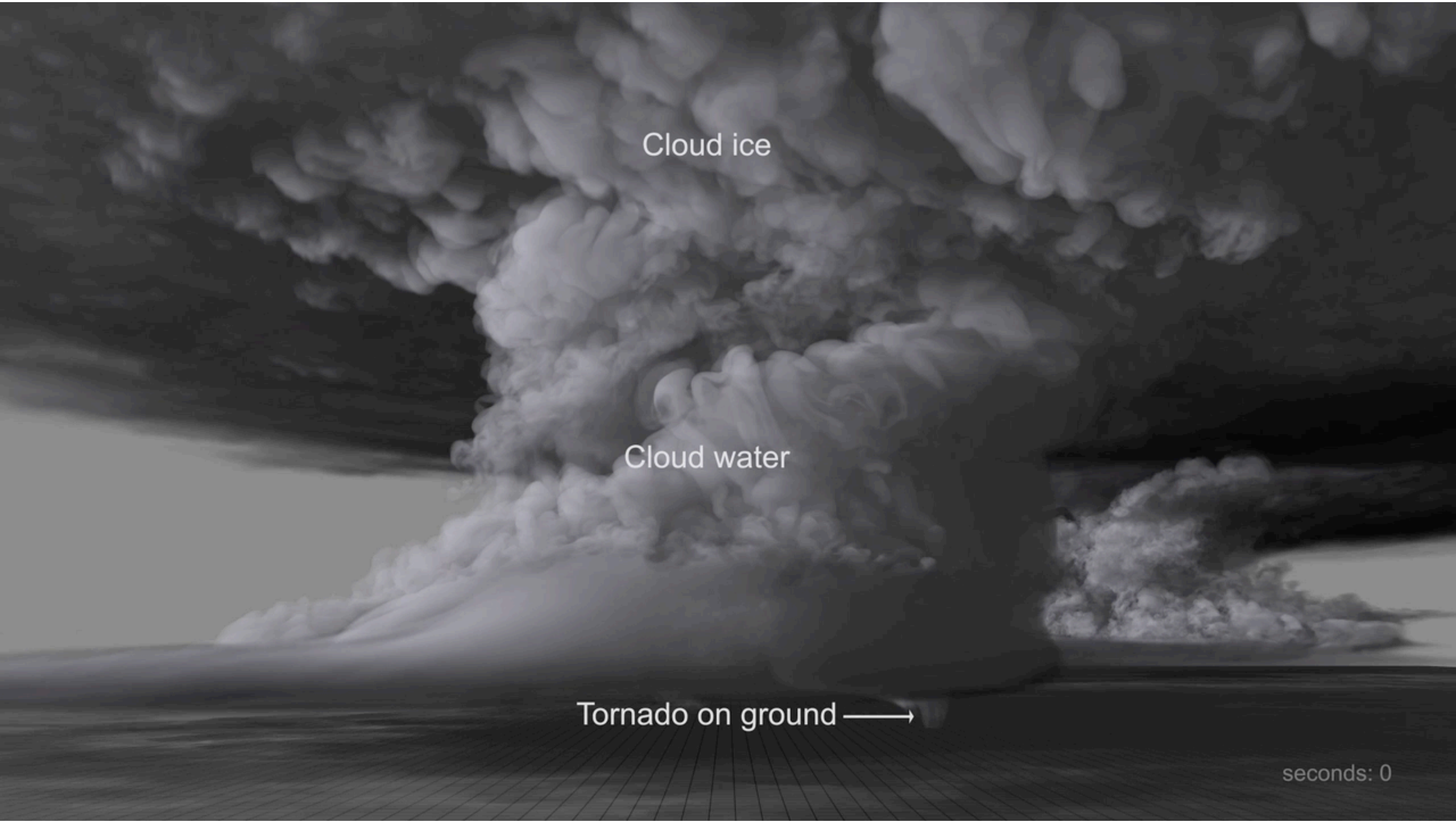
CM1 model: 3-D, non-hydrostatic, non-linear, time-dependent.
Run on "Blue Waters" Cray XE/XK hybrid machine at Nat'l Ctr for Supercomputing Applications, UIUC using over 20,000 cores.

$\Delta x = \Delta y = \Delta z = 15$ m isotropic inner domain
imbedded in larger domain 120x120x20 km.
18.4×10^9 grid points total

For more, see http://orf.media

Tornadic Thunderstorm Simulation

Visualization by David Bock, NCSA. See http://lantern.ncsa.illinois.edu/Vis/XSEDE/XSEDE15/Bock_Leigh.mov



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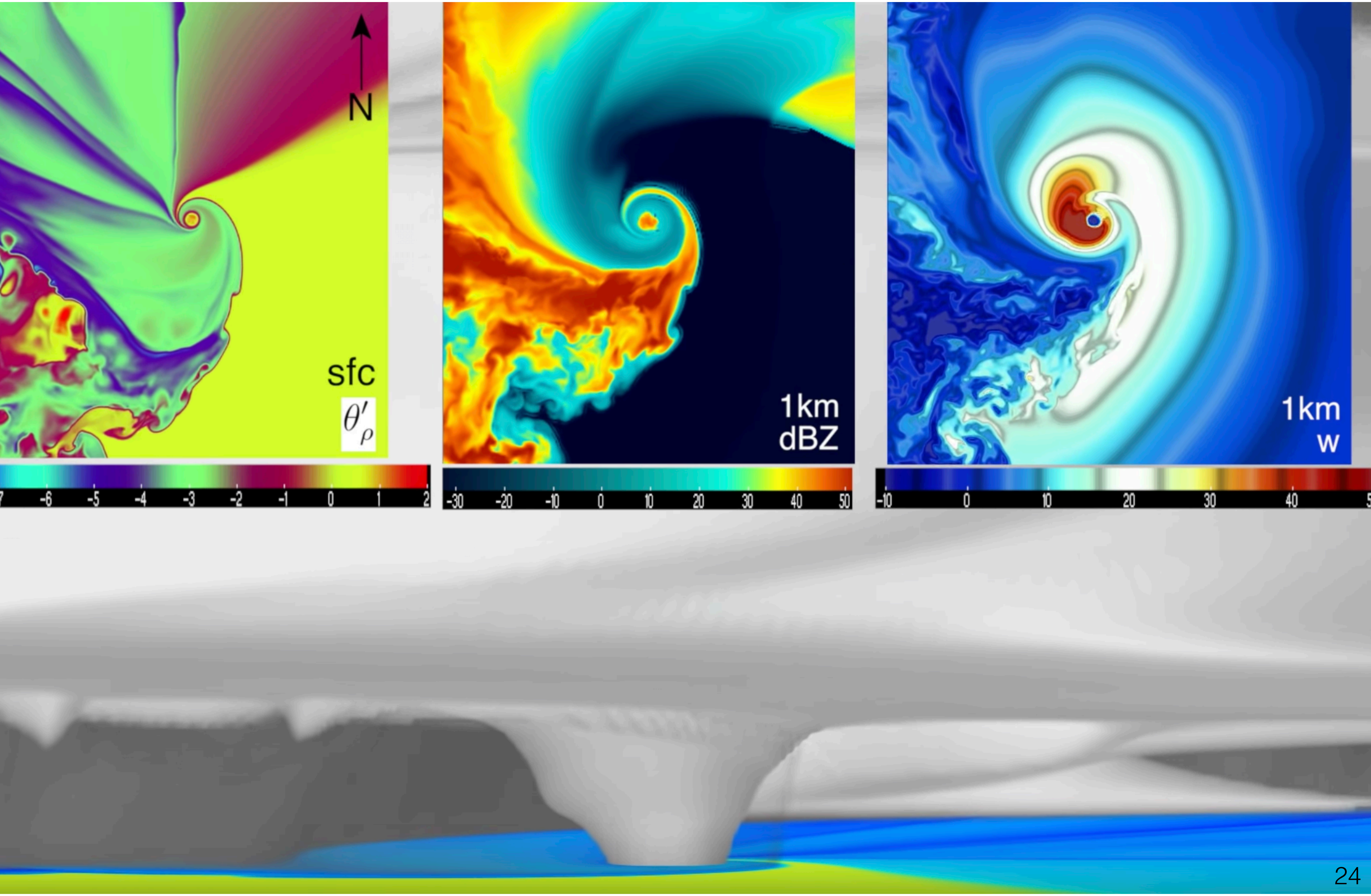

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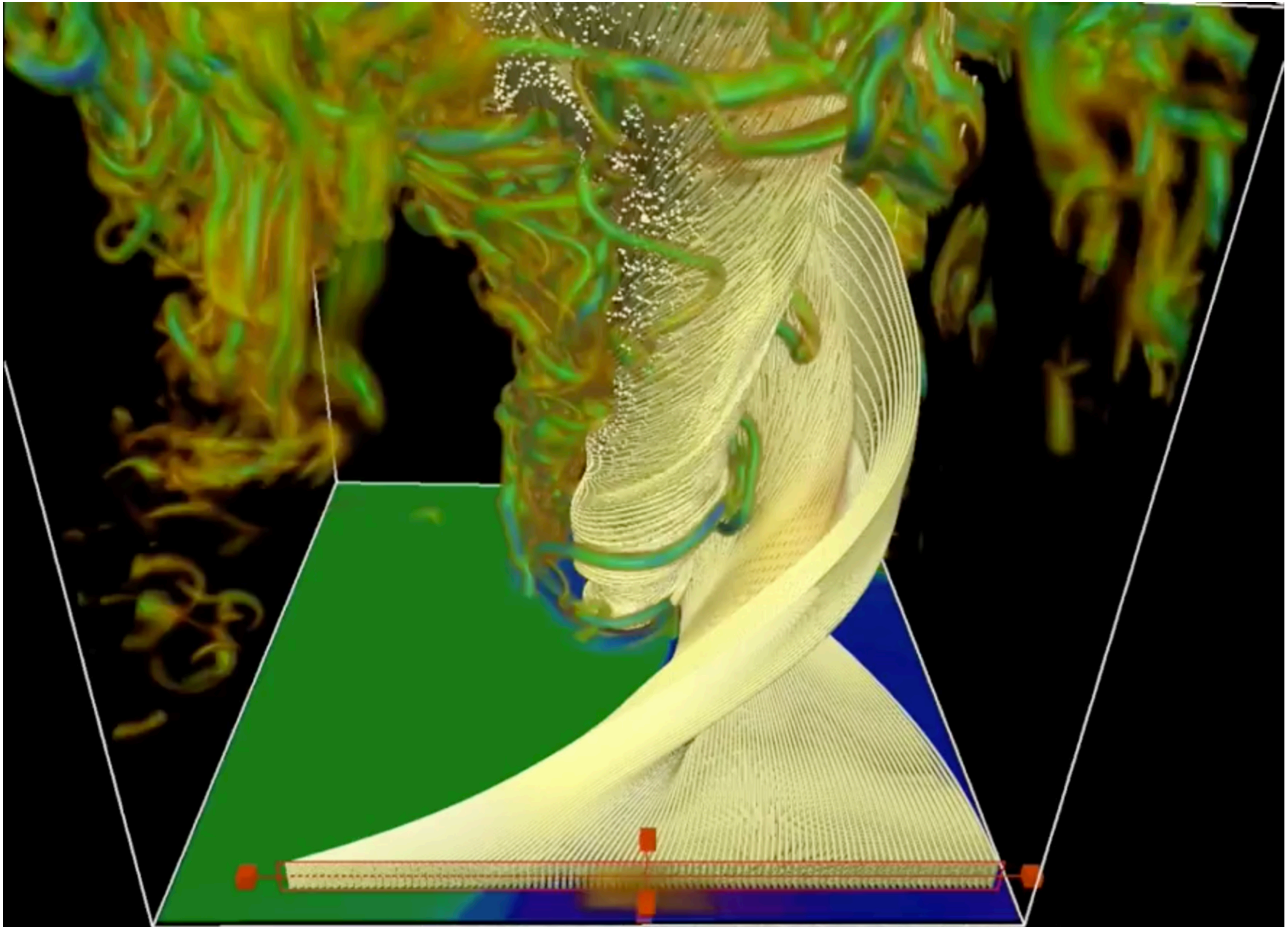

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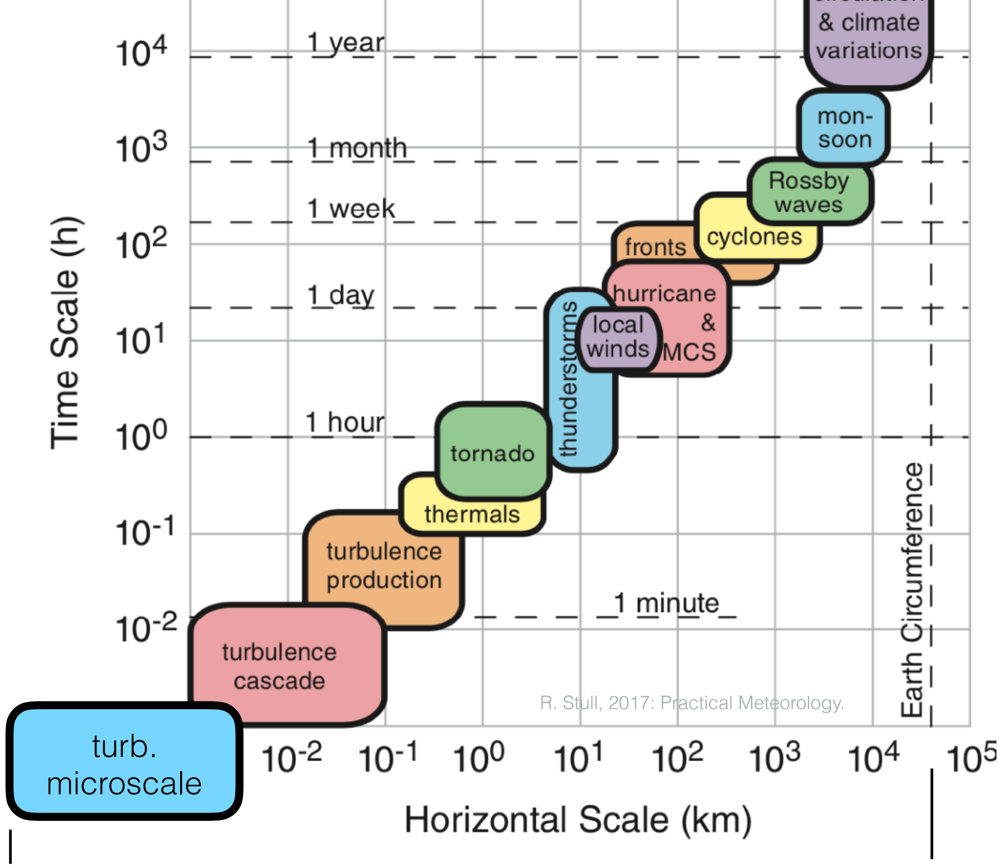
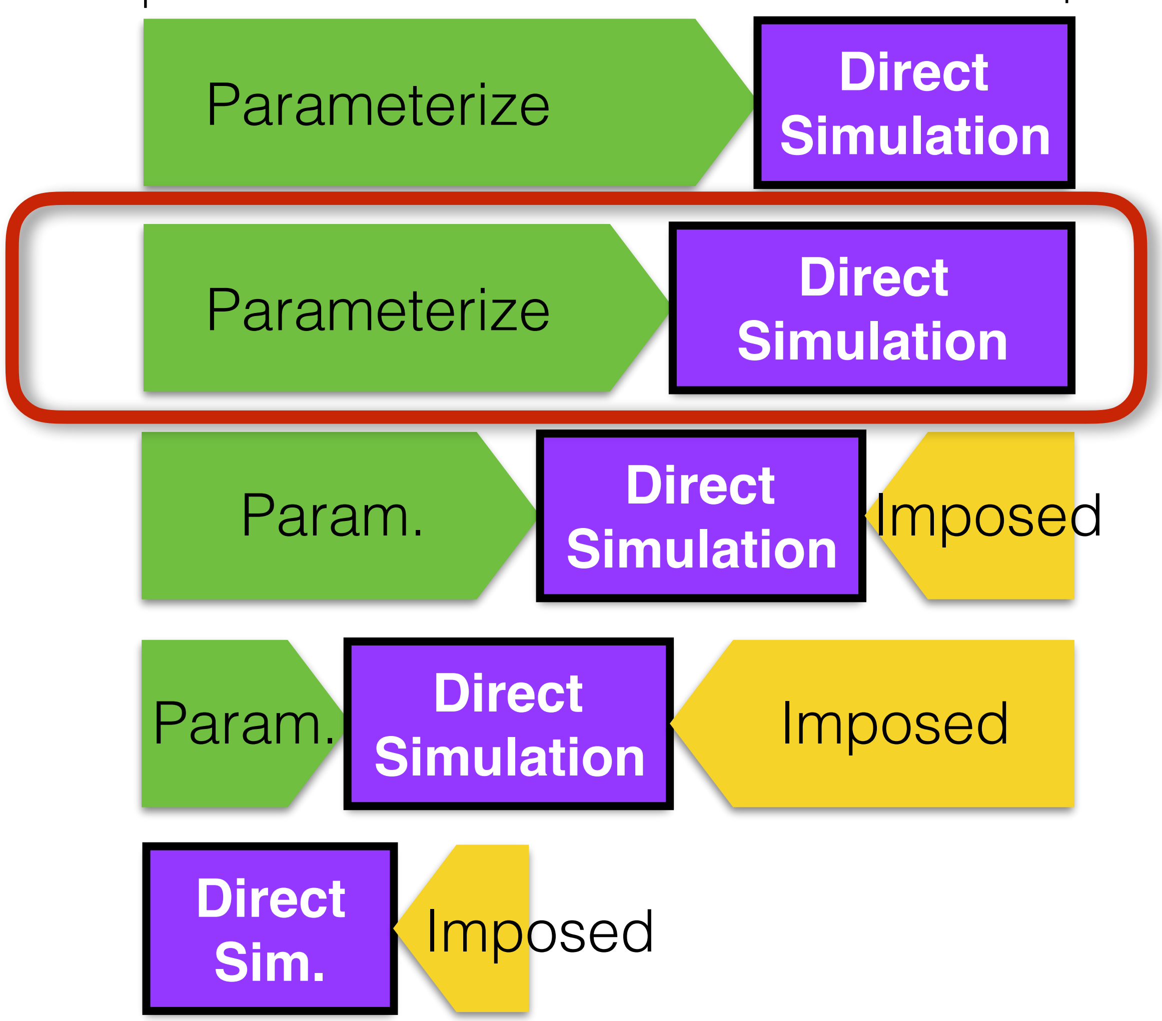


Real-time Weather Forecasts



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... but for Operational Weather Prediction

- The need for speed
    - ✳ Must finish the CFD calculations (i.e., the weather forecast) before the weather happens...
- The need for ICs
    - ✳ ... but cannot start the CFD until we have the ICs (called the "analysis" or the "initialization")...
- The need for weather observations
    - ✳ ... but cannot create the ICs until worldwide weather observations have been made & communicated.

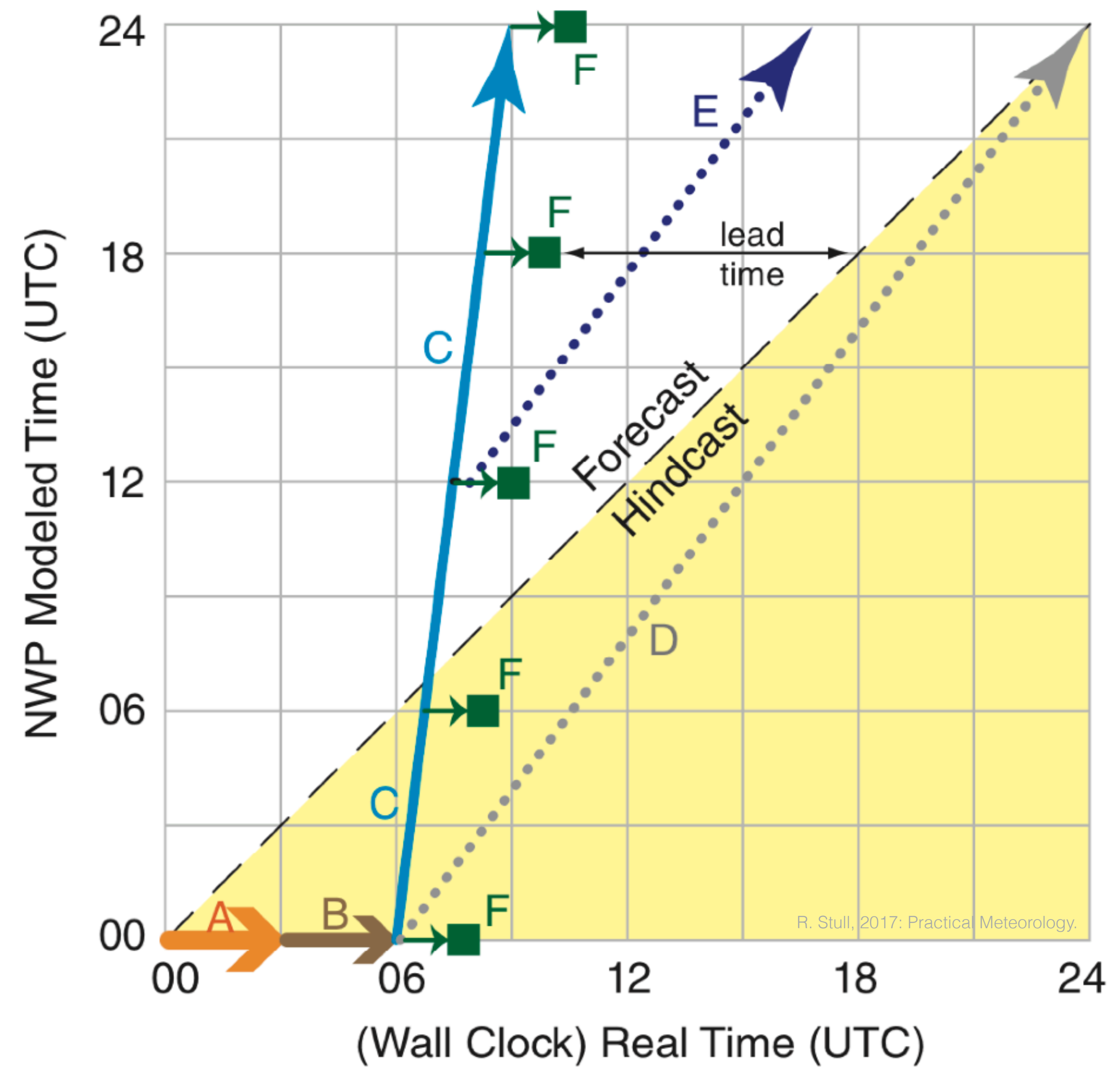
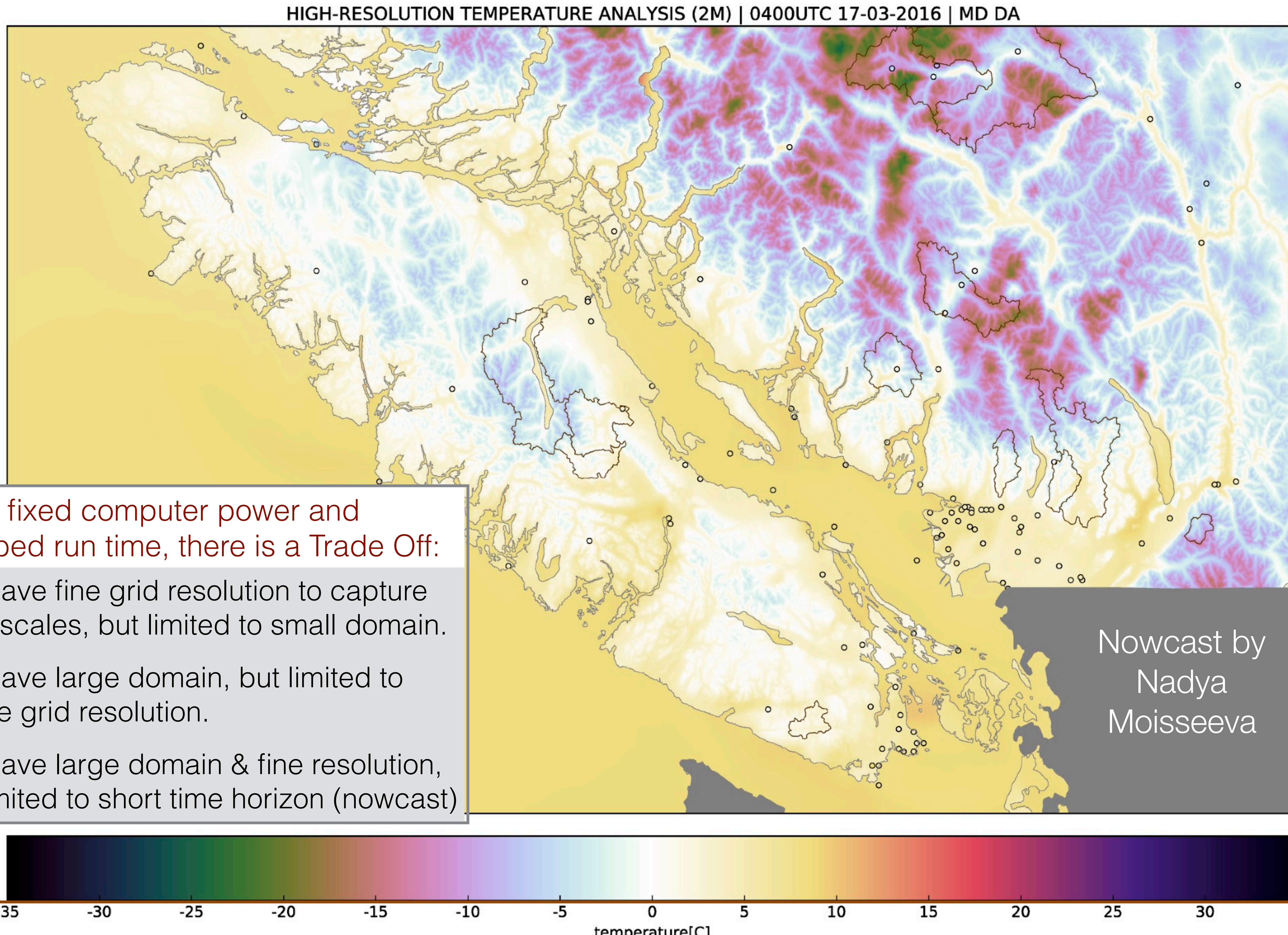


Figure 20.12
Hypothetical forecast schedule, for a 00 UTC initialization.
A: wait for weather observations to arrive.
B: data assimilation to produce the analysis (ICs).
C: coarse-mesh forecast.
D: fine-mesh forecast, initialized from 00 UTC.
E: fine-mesh forecast initialized from coarse forecast at 12 h.
F: post-processing and creation of products (e.g., weather maps).

Trade-off: Accuracy, Resolution, Timeliness, Domain Size, Fcst. Horizon



For any fixed computer power and prescribed run time, there is a Trade Off:

- Can have fine grid resolution to capture small scales, but limited to small domain.
- Can have large domain, but limited to coarse grid resolution.
- Can have large domain & fine resolution, but limited to short time horizon (nowcast)

Compromise Solutions: Nested or Variable Grids

NCAR WRF model:

Nested grids, as run operationally at UBC.

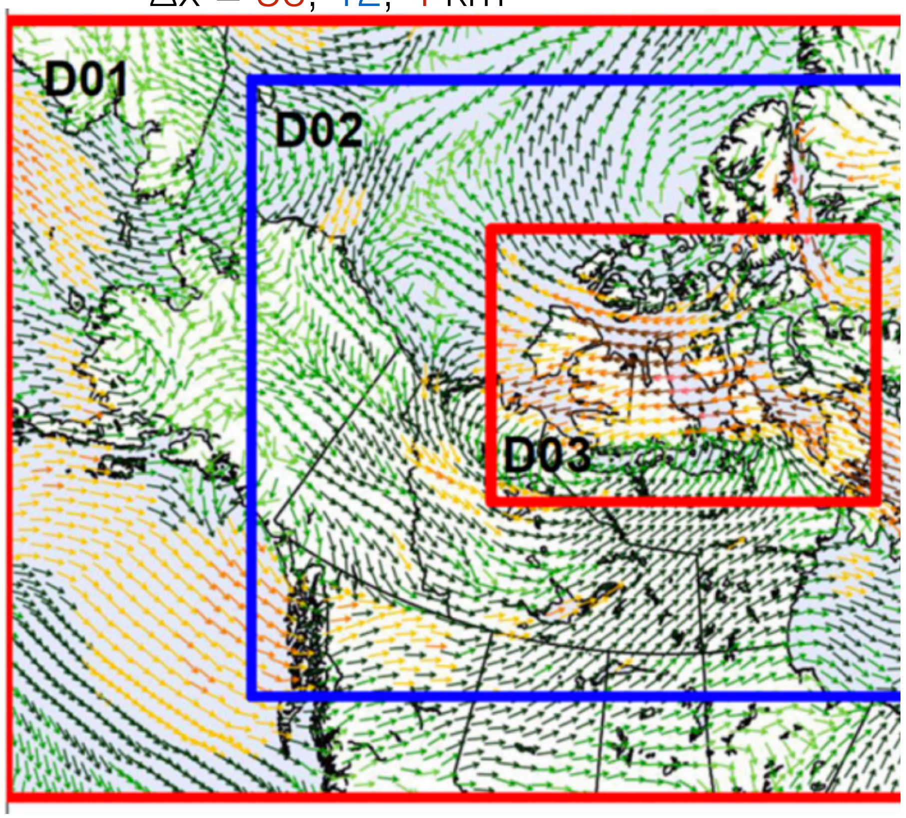
NCAR MPAS model:

Unstructured centroidal Voronoi tessellation.

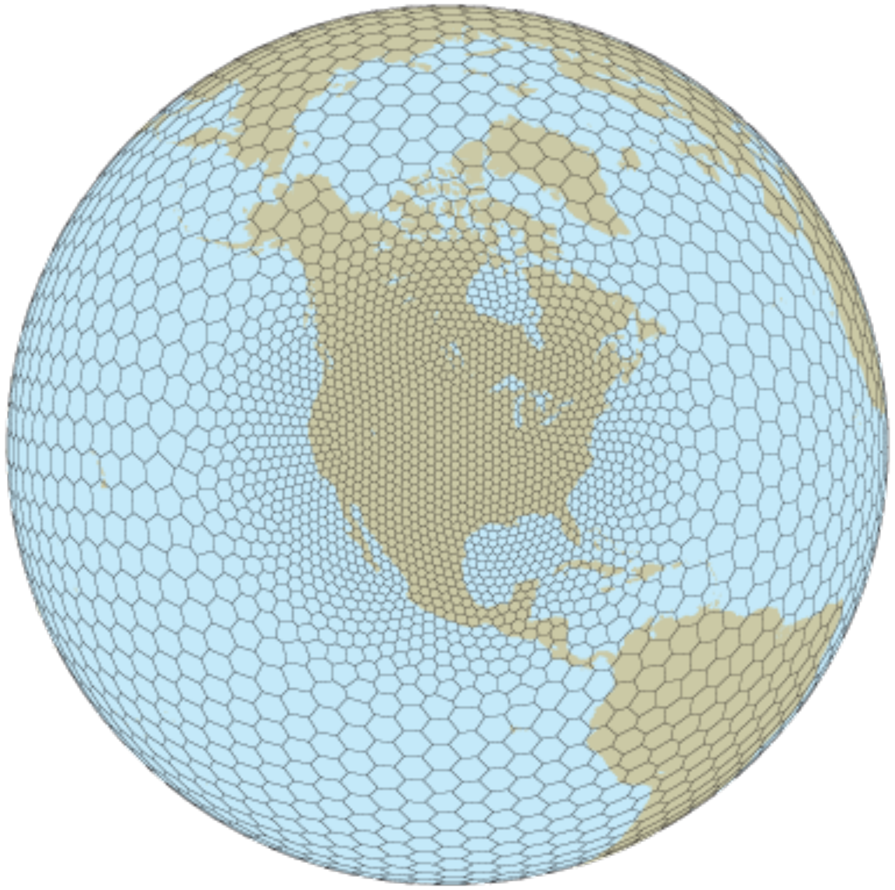
NOAA/Princeton FV3 model:

Cubed sphere with an analytic Schmidt (1977) transformation

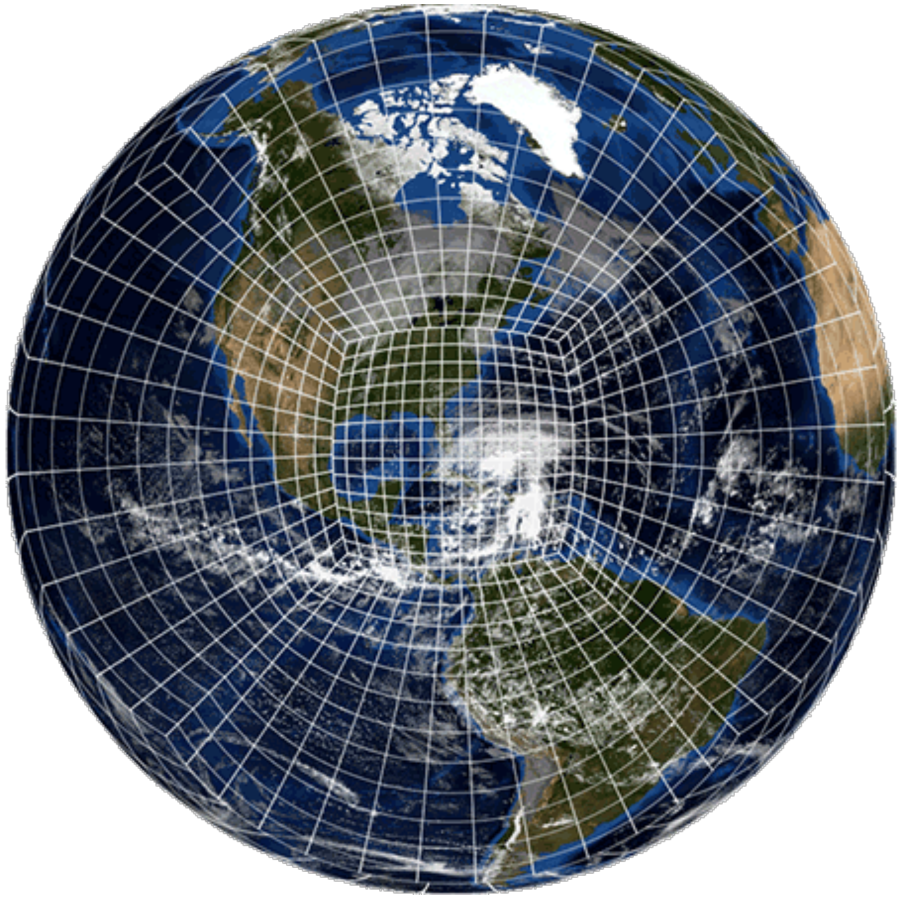
Δx = 36, 12, 4 km



WRF = NCAR Weather Research & Forecast model



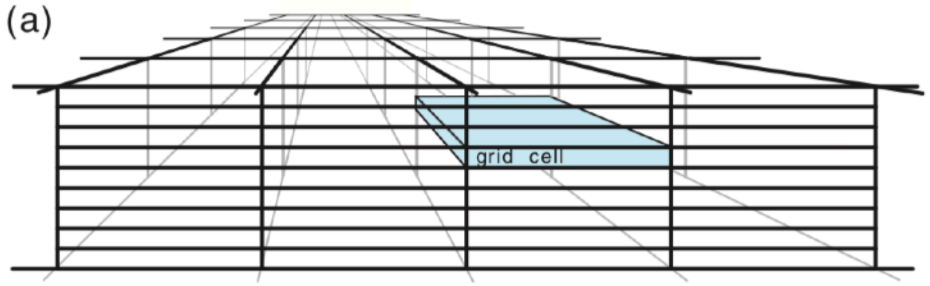
https://mpas-dev.github.io/atmosphere/atmosphere.html



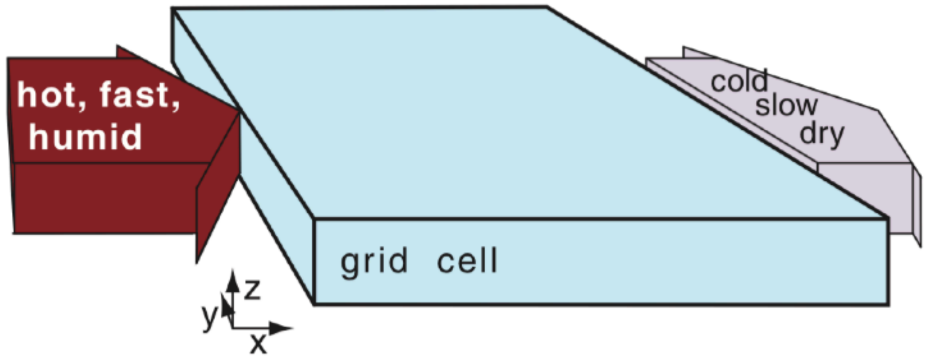
https://www.gfdl.noaa.gov/fv3/fv3-grids/

NCAR = Nat'l Center for Atmospheric Research; MPAS = Model for Prediction Across Scales; FV3 = Finite Volume vers.3

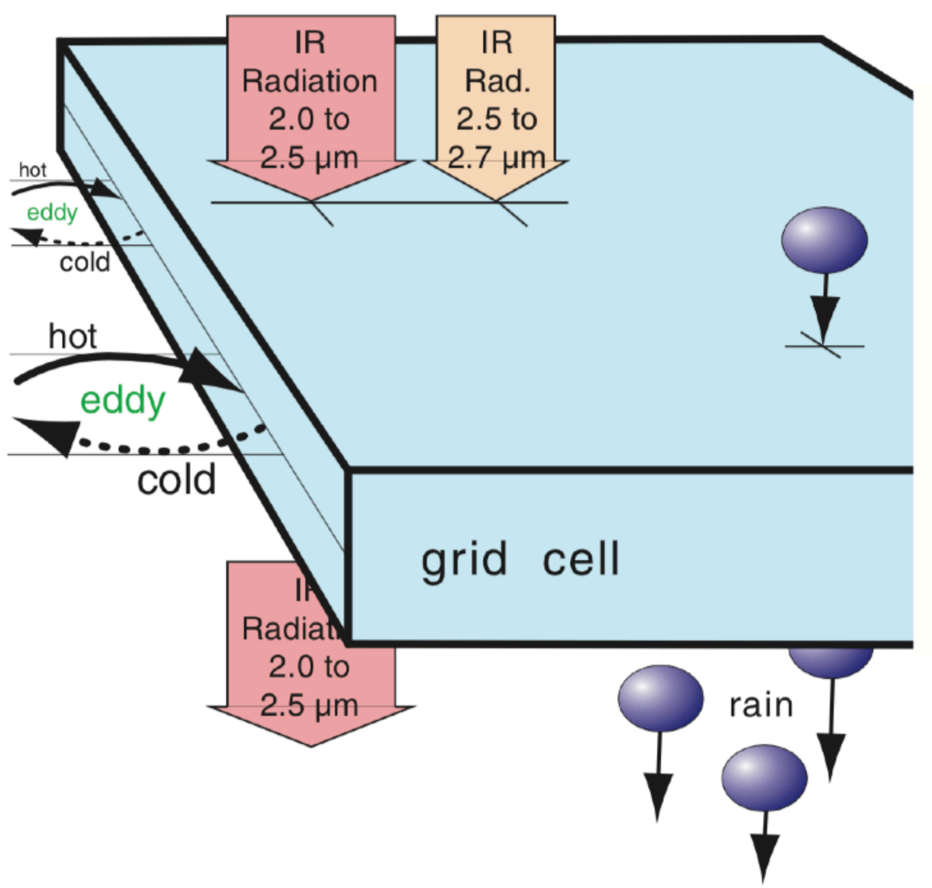
Resolved vs. Subgrid Scales



(b) Resolved: advection (convection)



(c) Subgrid: parameterized



R. Stull, 2017: Practical Meteorology.

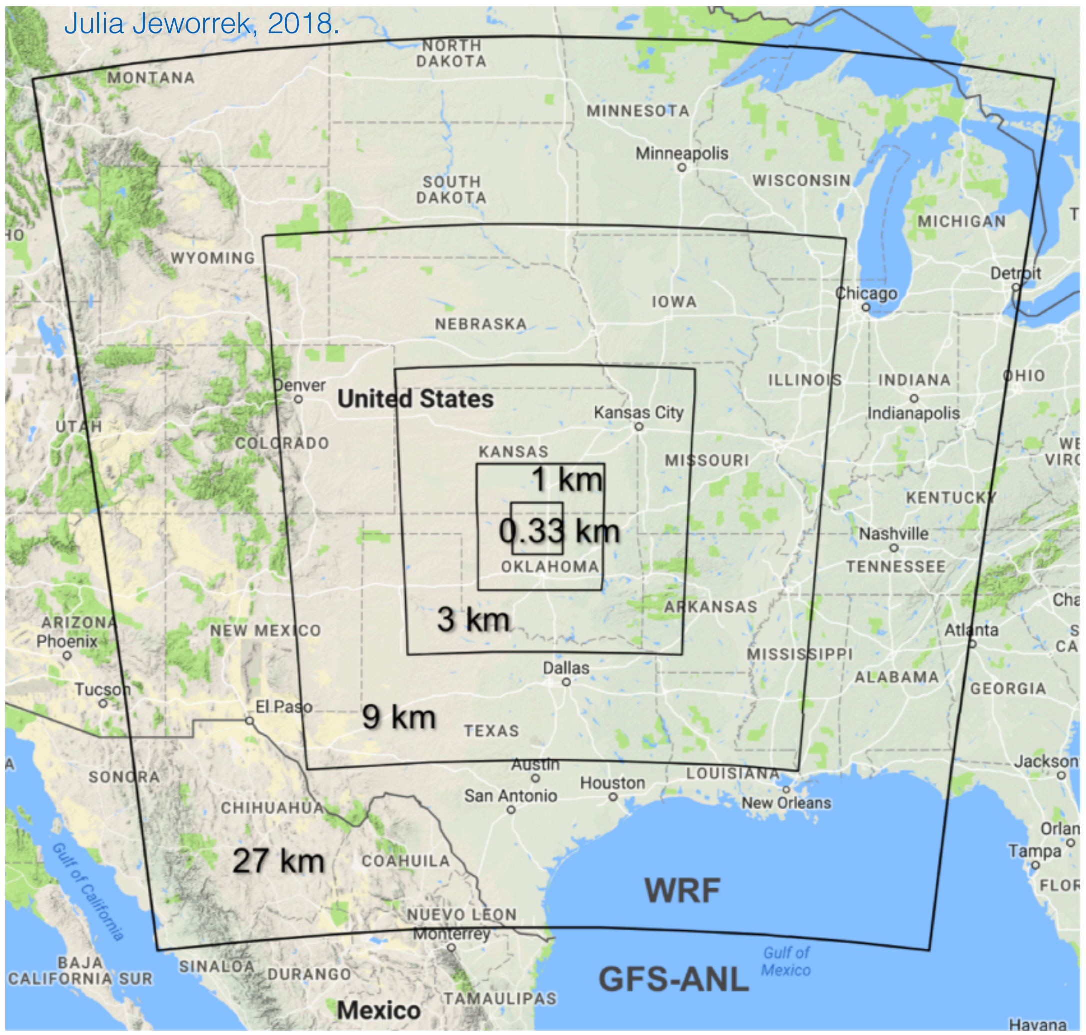
Unresolved (parameterized) microphysics (cloud & precip. droplet evolution) in resolved temperature & humidity environments

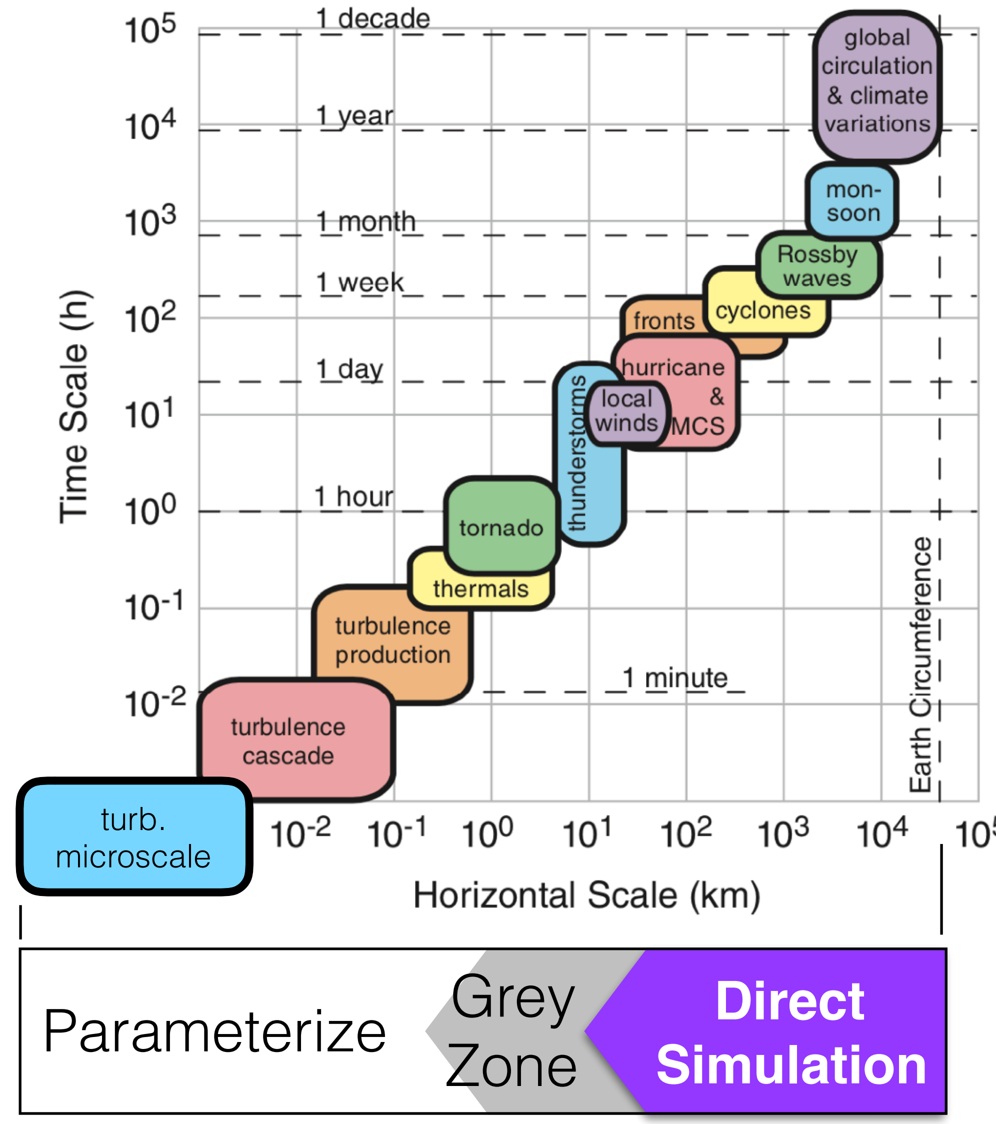
Unresolved in horizontal, but spanning multiple vertical layers. Causes resolvable effects:

- Subgrid convective clouds
- Subgrid turbulent fluxes in atm.boundary layer

Scale-Aware Params. vs. Grey Zone

Experiments by Julia Jeworrek, 2018.





Multi-scale operational forecast models being developed:
NCAR MPAS model & NOAA/Princeton FV3:

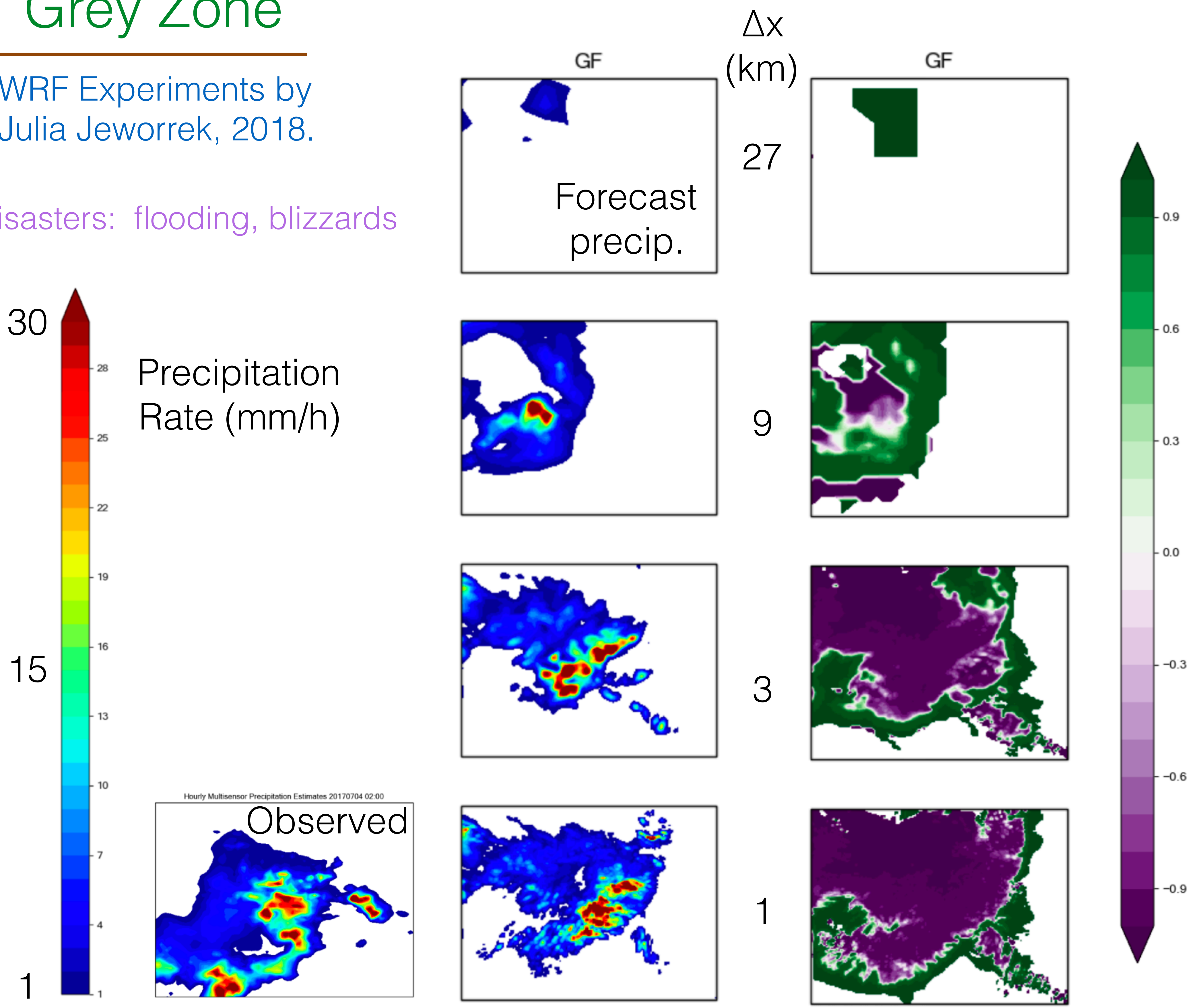
- Designed to utilize scale-aware parameterizations.

NOAA = Nat'l Oceanic & Atmos. Admin.; MPAS = Model for Prediction Across Scales; FV3 = Finite Volume vers.3

Grey Zone

WRF Experiments by
Julia Jeworrek, 2018.

Disasters: flooding, blizzards

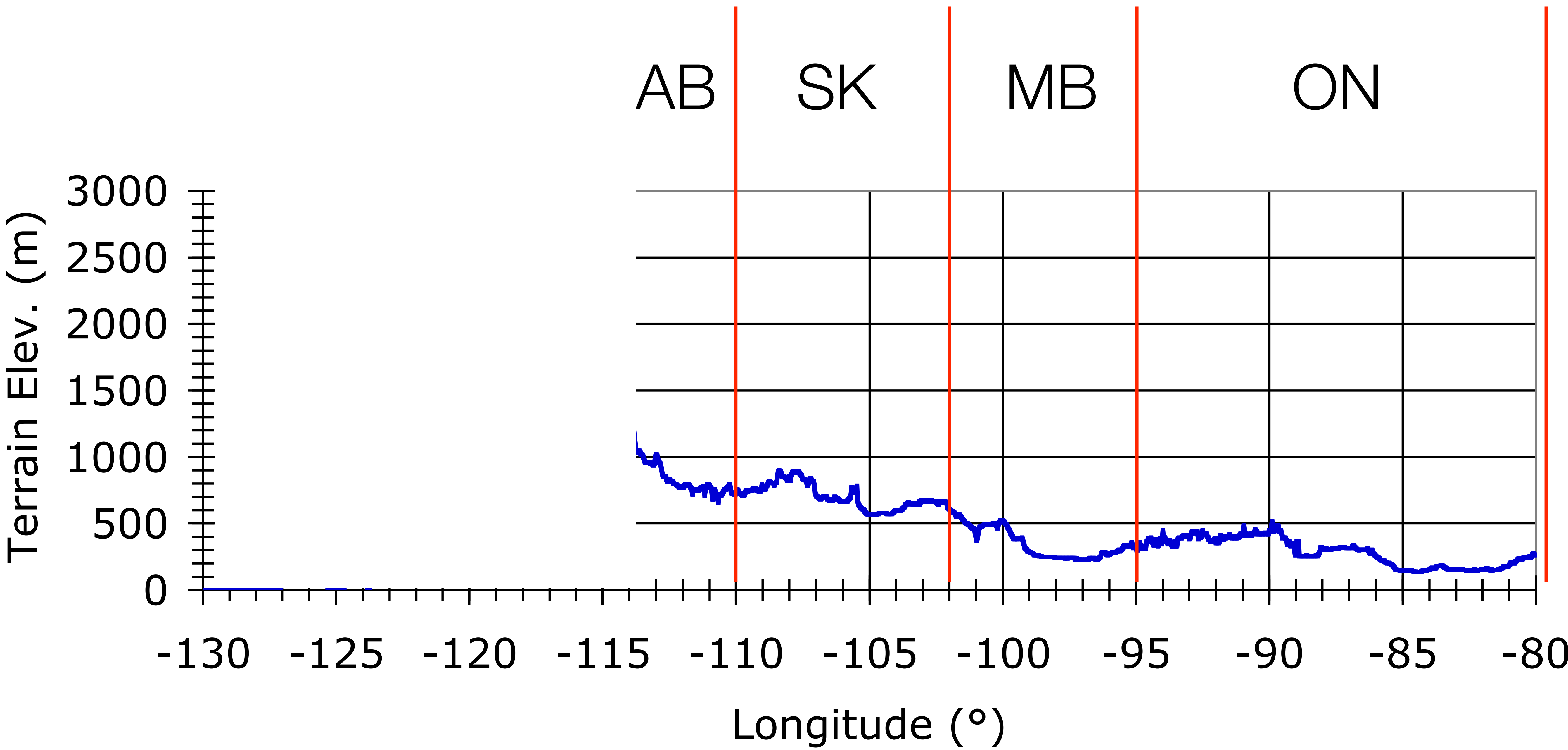


Mostly
parameterized
by subgrid
cumulus
param.

Mostly
resolved on
grid scale by
microphysics
(rain, snow,
etc.) param.

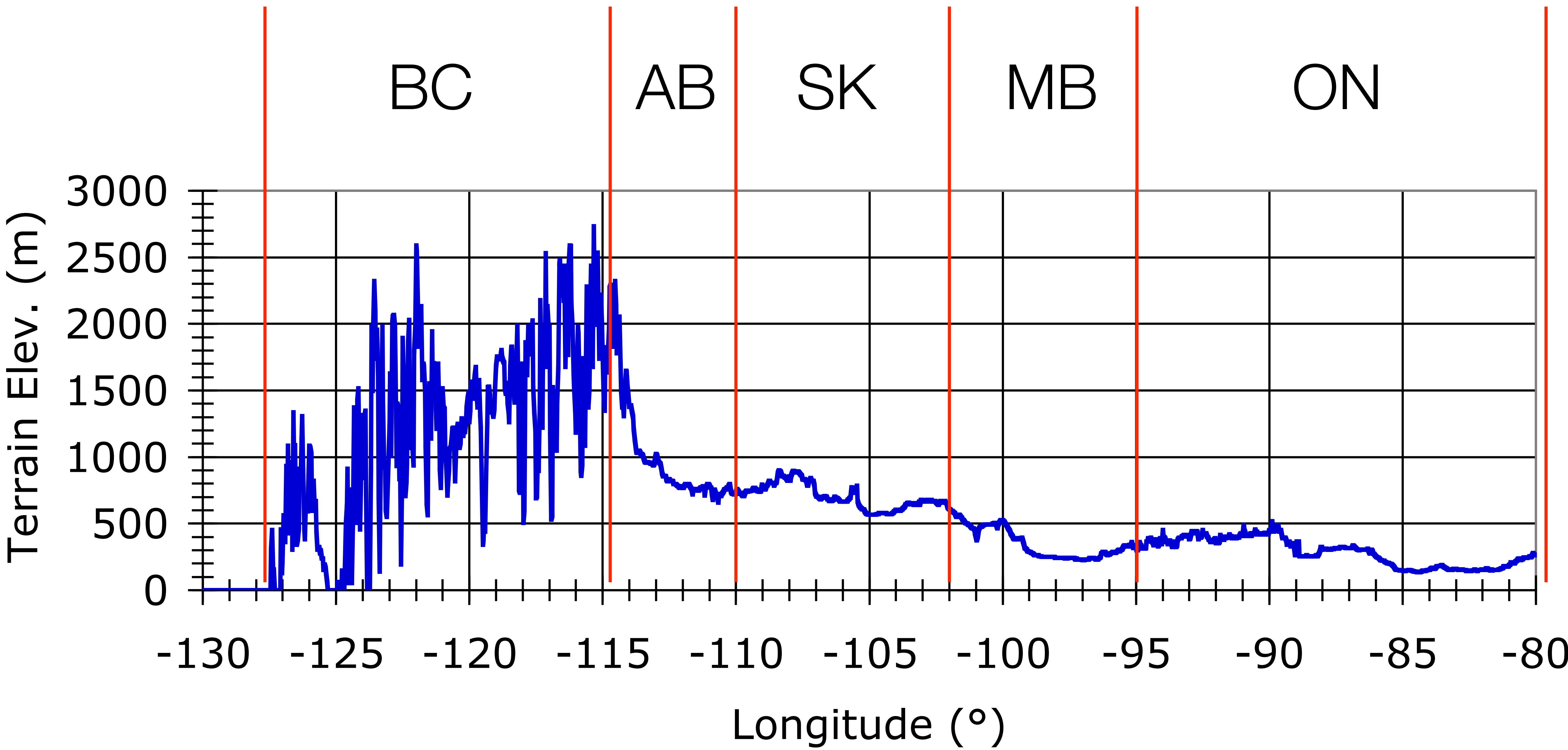
GF = Grell-Freitas cumulus parameterization. Julia Jeworrek & Stull, 2018: Mon. Weather Rev. (submitted)

Model Bottom Boundary Issues -> Terrain



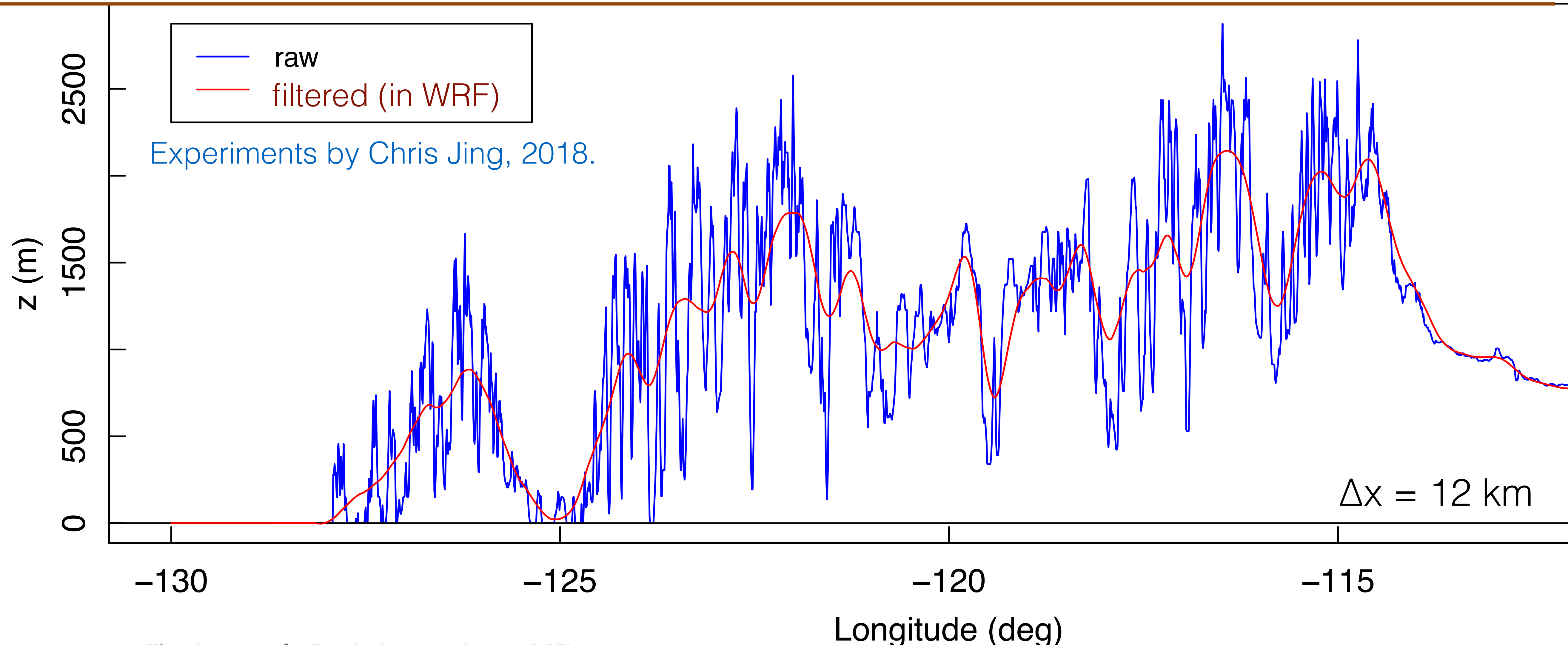
- West-East terrain cross section through Whistler (50.12°N)

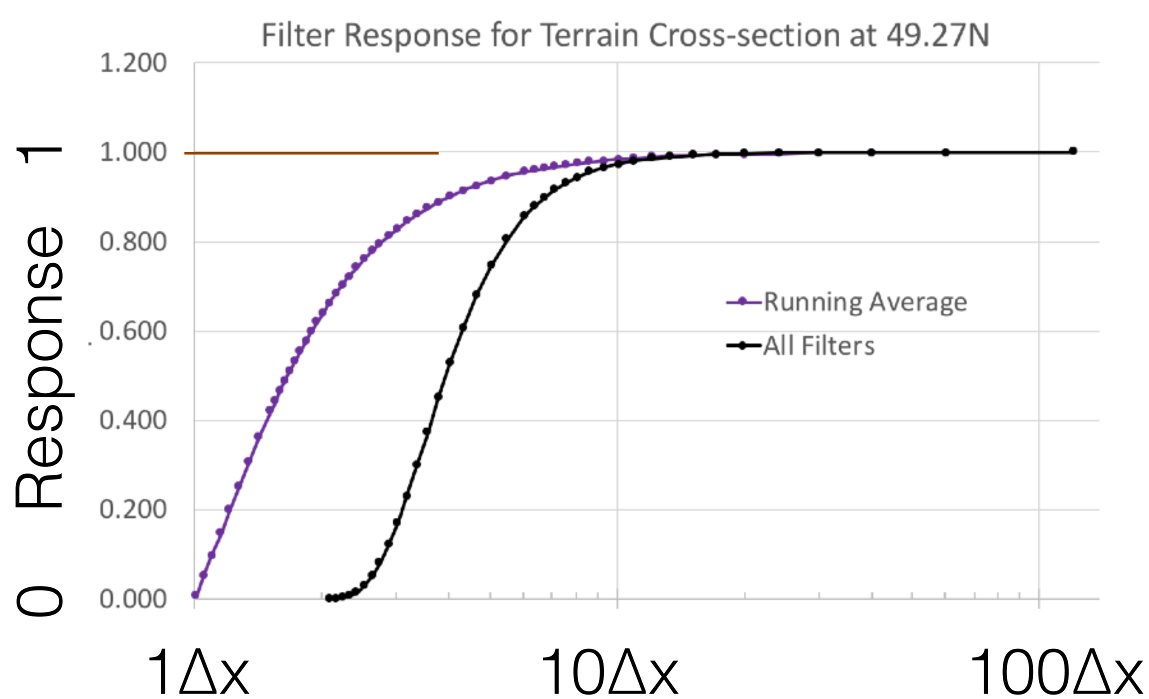
Model Bottom Boundary Issues -> Terrain



- West-East terrain cross section through Whistler (50.12°N)

Terrain Elevation, zoomed on British Columbia



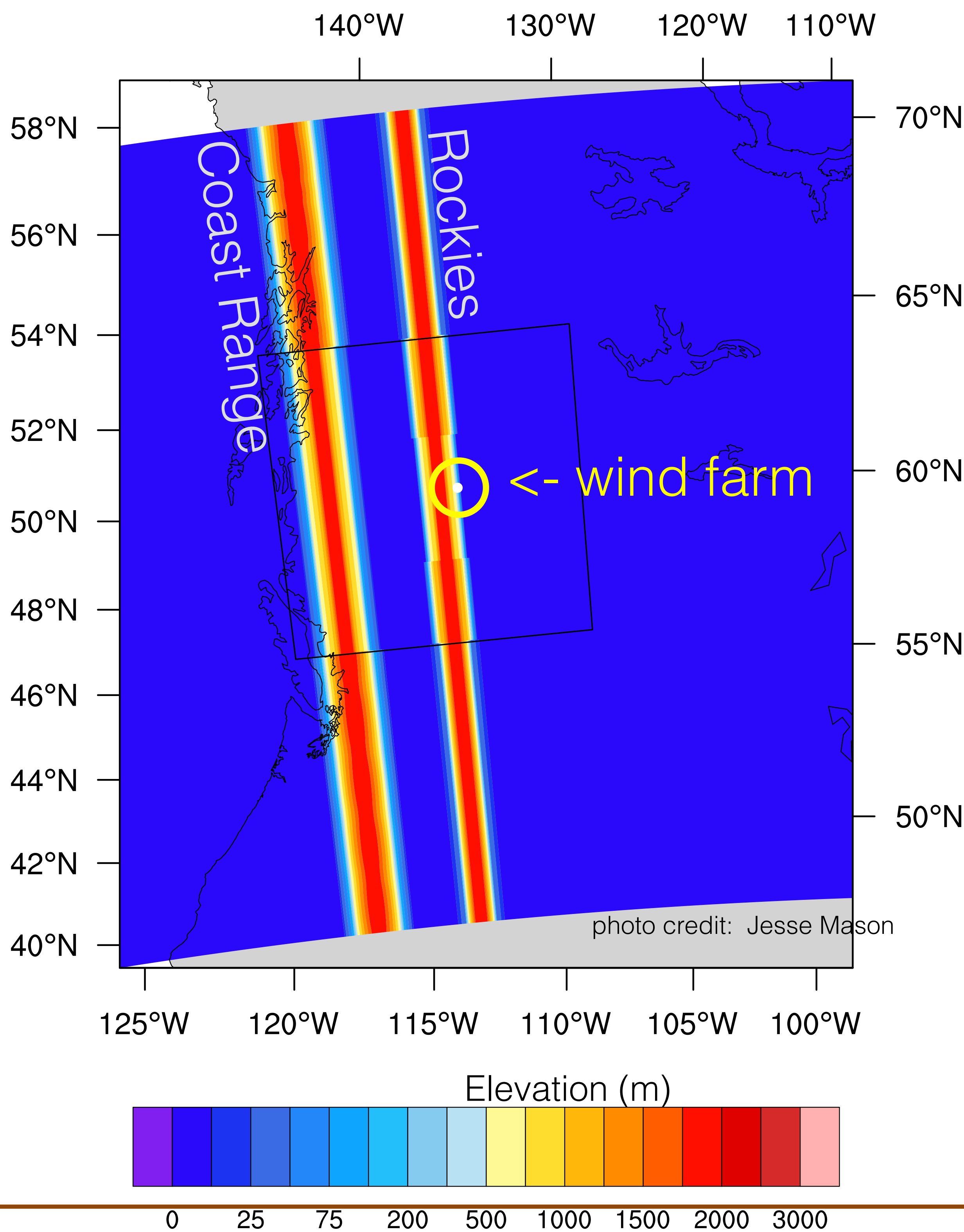


- Desired: removed short wavelength
- Undesired: Chopped off mountain tops

Disasters: Cold-air damming, outflow windstorms, mountain waves & turb., downslope windstorms...

Nonlocal Flow Effects

Simulations by Jesse Mason



Numerical Simulations of Idealized Terrain

for a wind-ramp event at a wind farm:

- Rocky Mountains (add / remove)
- Coast Range (add / remove)

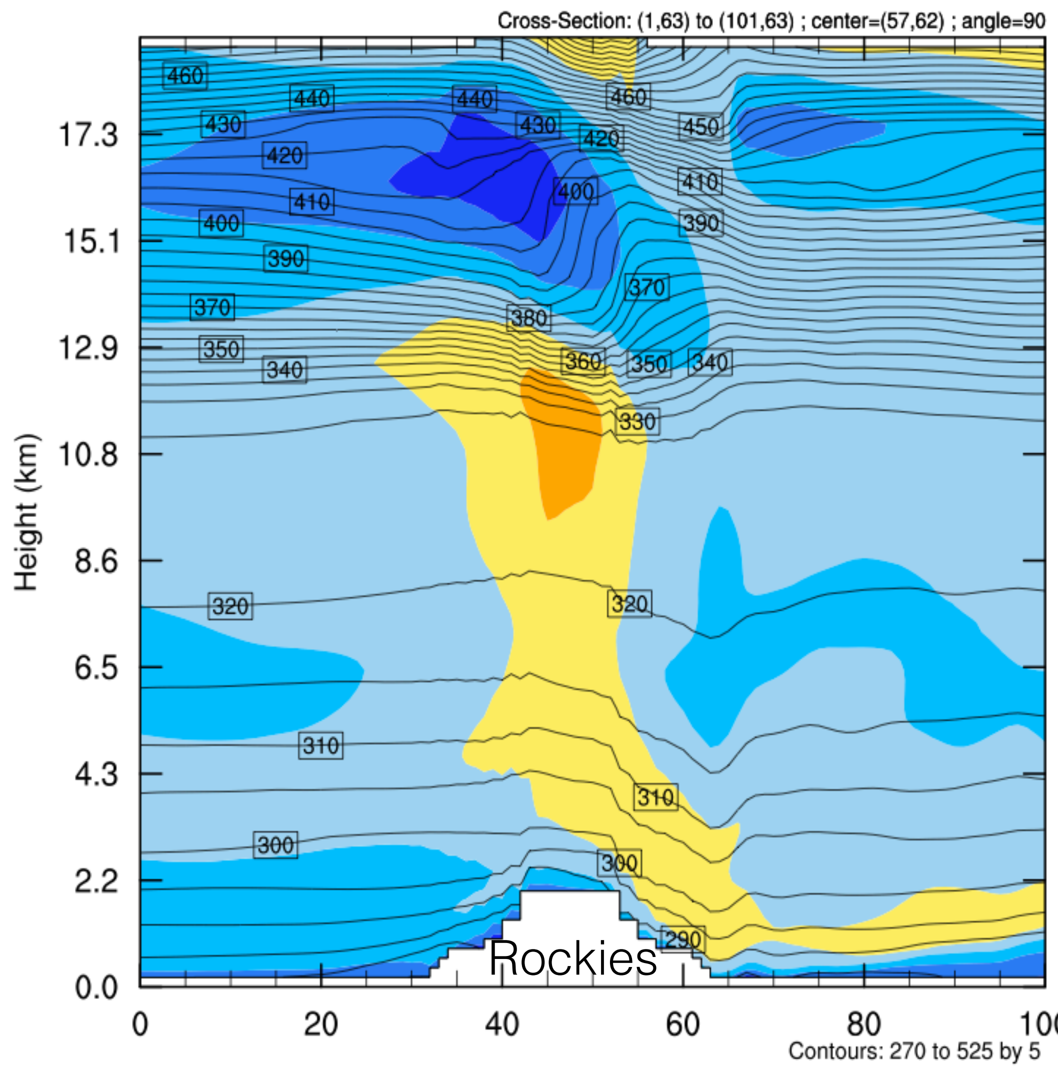
Enables discovery of alternative / better forecast methods

Nonlocal Flow Effects

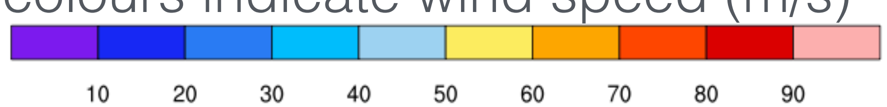
Simulations by Jesse Mason

Enables discovery of alternative / better forecast methods

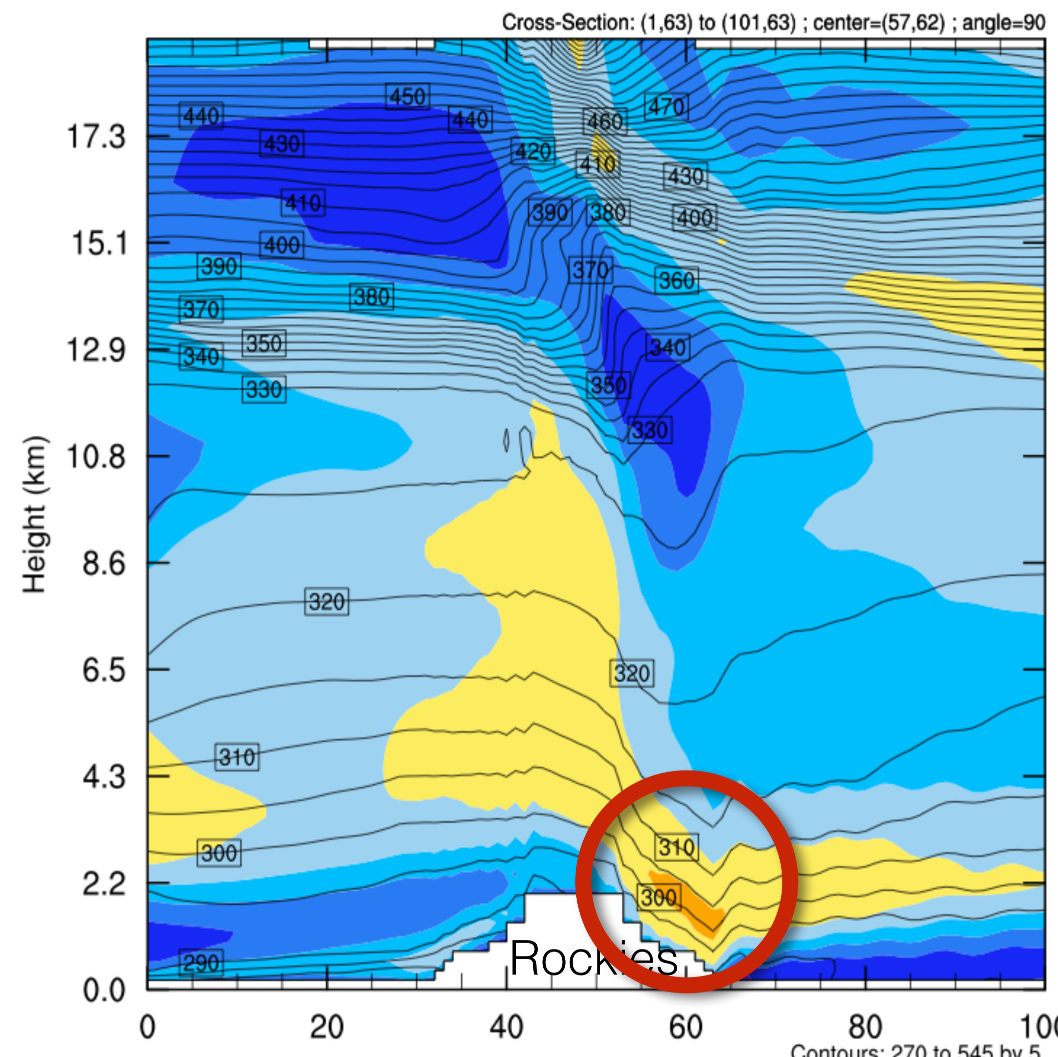
Idealized Rockies Only



colours indicate wind speed (m/s)



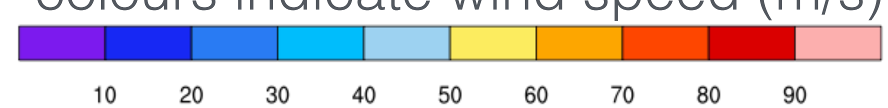
Both Idealized Ranges



Is more accurate for this wind-ramp event

photo credit: Jesse Mason

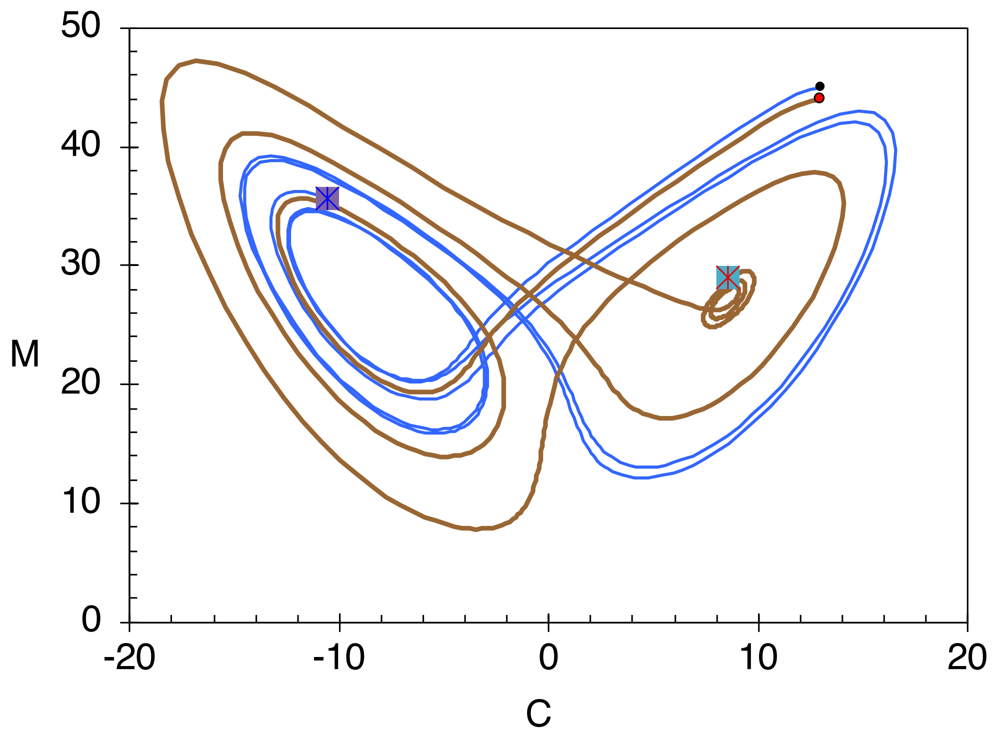
colours indicate wind speed (m/s)



Inference: need sufficiently <u>large</u> NWP forecast domain to capture upwind effects.

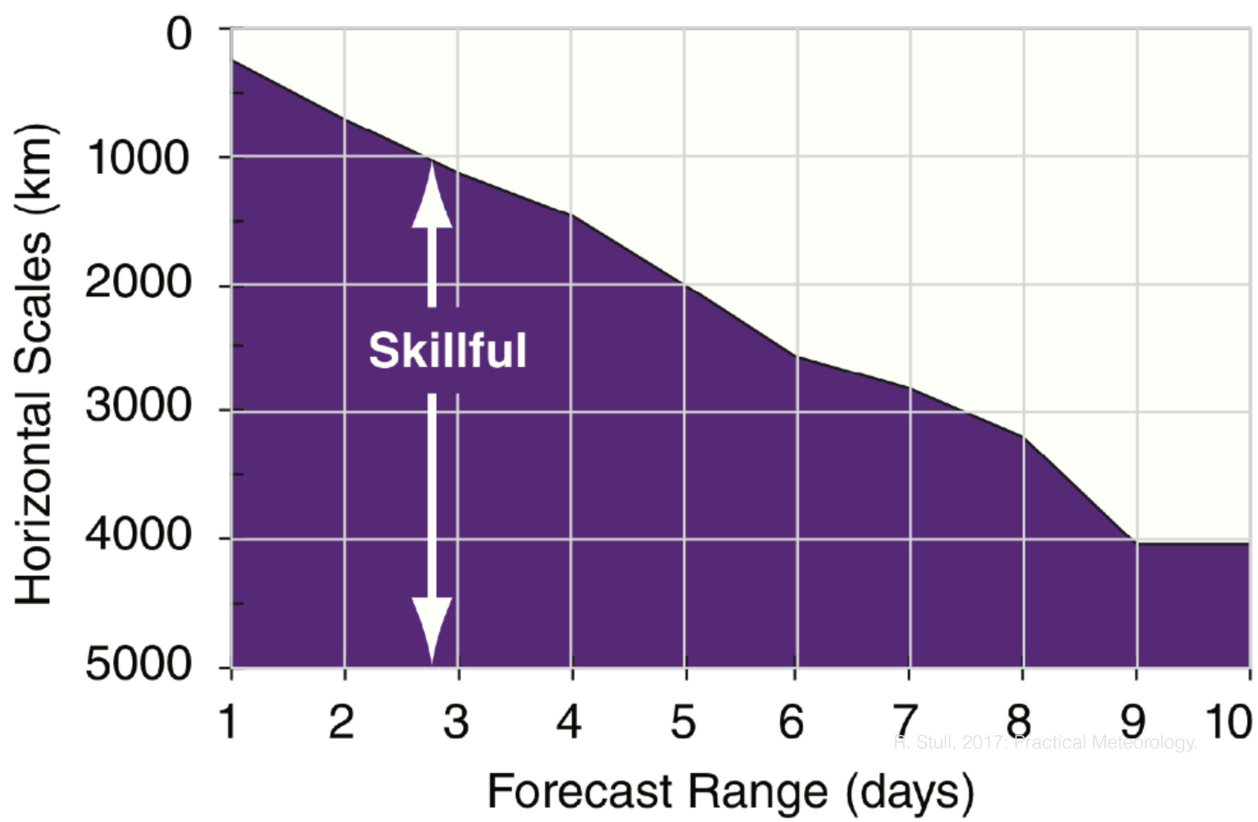
Chaos: Predictability vs. Scale

Ed Lorenz: Deterministic non-periodic motions. ==> Chaos. Sensitive dependence on ICs.



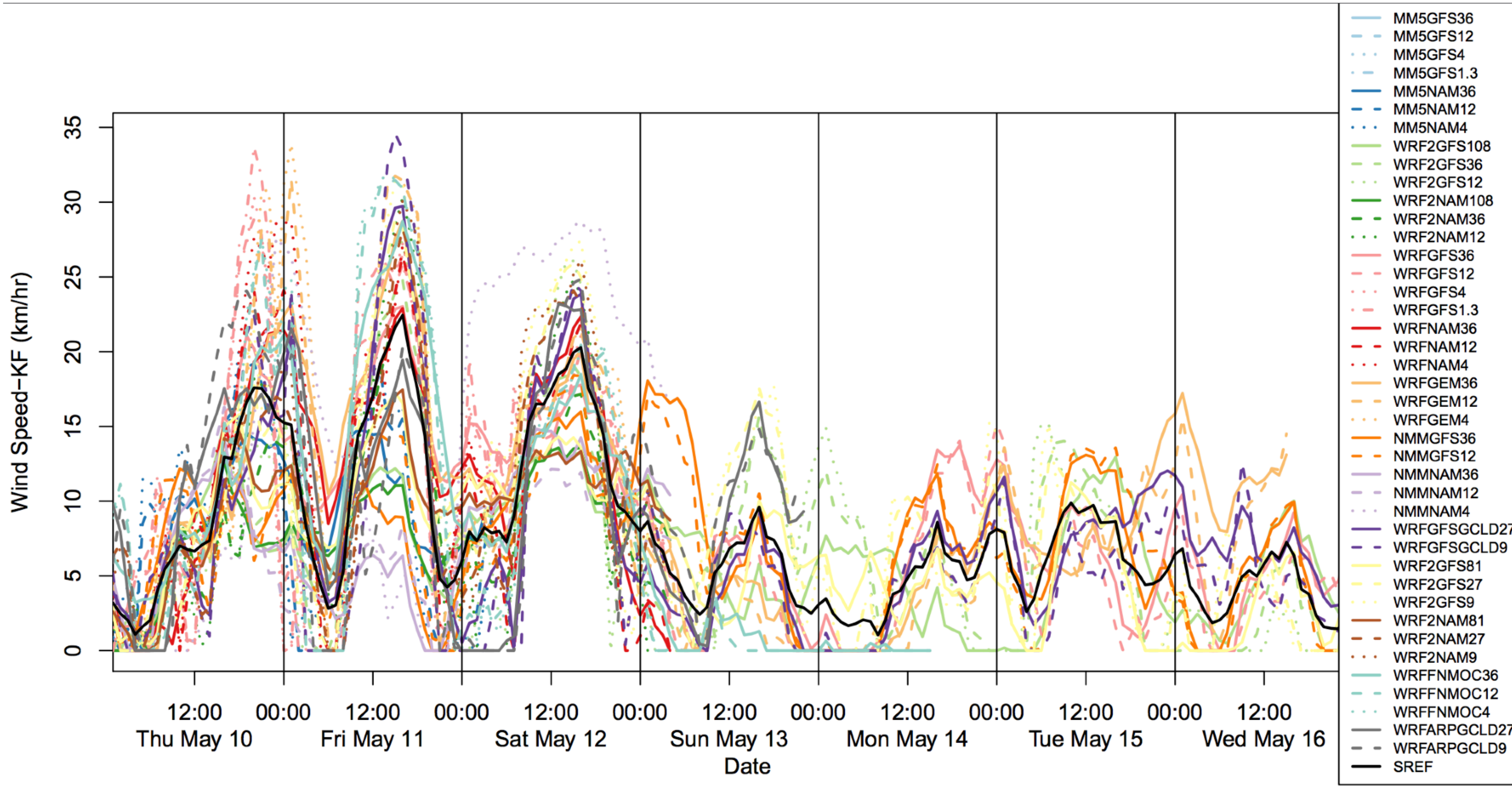
- Atmos. has more degrees of freedom than the Lorenz system. More chaotic.
- CFD models only approximate atmos. physics, thus forecast evolves incorrectly.
- To create the ICs, assimilate weather observations (have big gaps) into a previous forecast (has errors).
- Thus, ICs are guaranteed to be off.
- Thus, forecasts diverge from reality; namely, skill decreases with fcst. horizon.

Prediction of smaller-scale weather phenomena loses skill sooner.



Superposition of all scales still appears in the forecast, but the smaller-scale phenomena are bad.

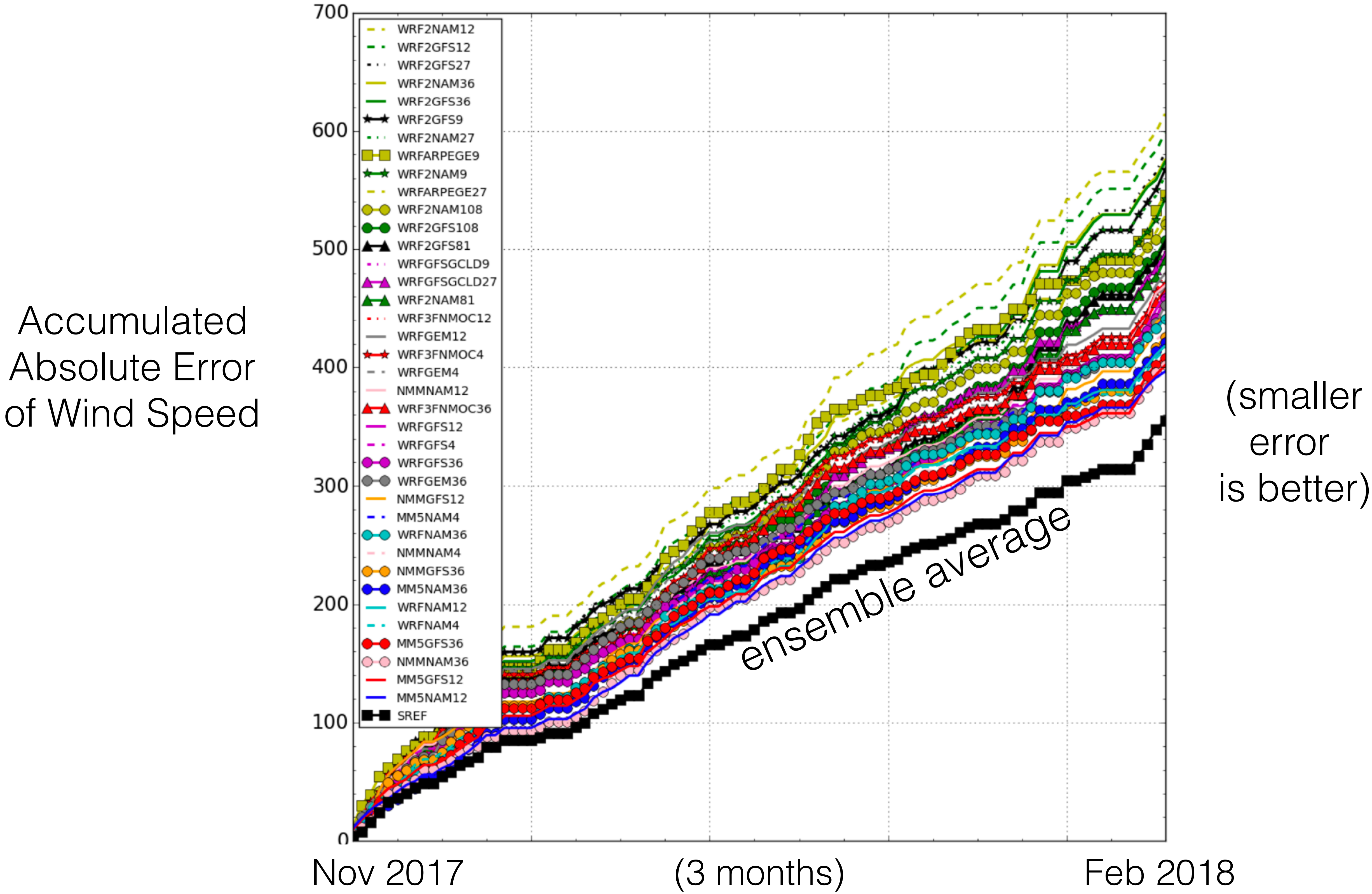
Use ensembles to mitigate chaos



— black line shows ensemble average

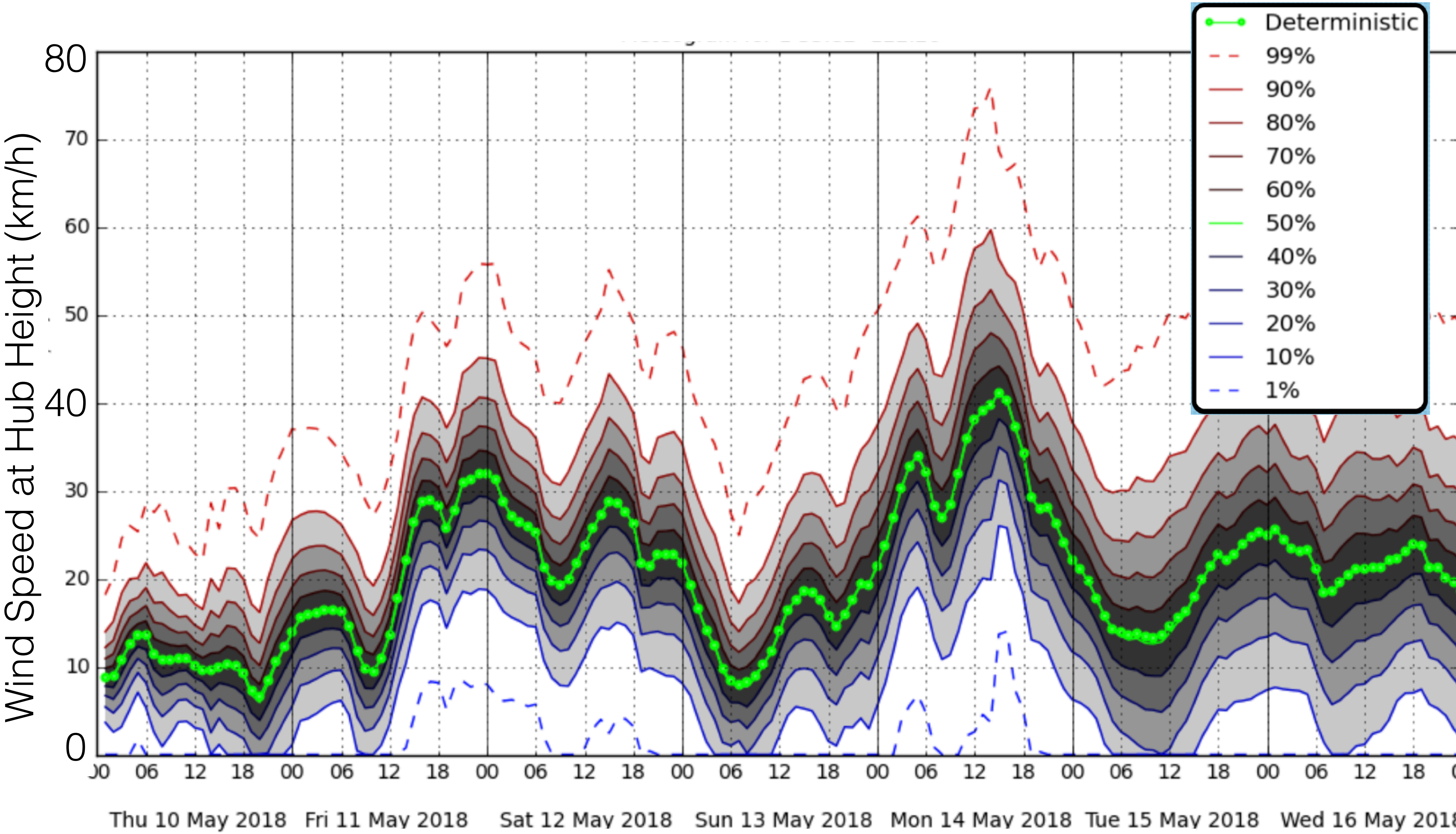
Ensemble = many CFD forecasts of the same location and event, with different models, parameterizations, ICs, etc.

Ensemble Average is Usually Best



Day-2 Wind-speed forecast at hub height

Ensemble Spread -> Calibrate into Probability Fcsts.



1 week forecast: 10 - 16 May 2018

Simplified cost / loss **example** for blade-replacement maintenance decision:

Issue: Should you schedule the blade replacement for 18 local time today when 4 m/s winds are predicted deterministically?
Next slow winds in 2 days.

Assumptions: Max wind speed for crane safety ~ 5 m/s. 2 MW turbine costs \$4M installed. Blades = 18% of cost. Crane rental = \$80,000/day. If selling at 5¢/kWh, then downtime cost = \$2,400/day.

http://www.windustry.org/community_wind_toolbox_8_costs

photo credit: Mark Stull

Simplified cost / loss **example** for blade-replacement maintenance decision:

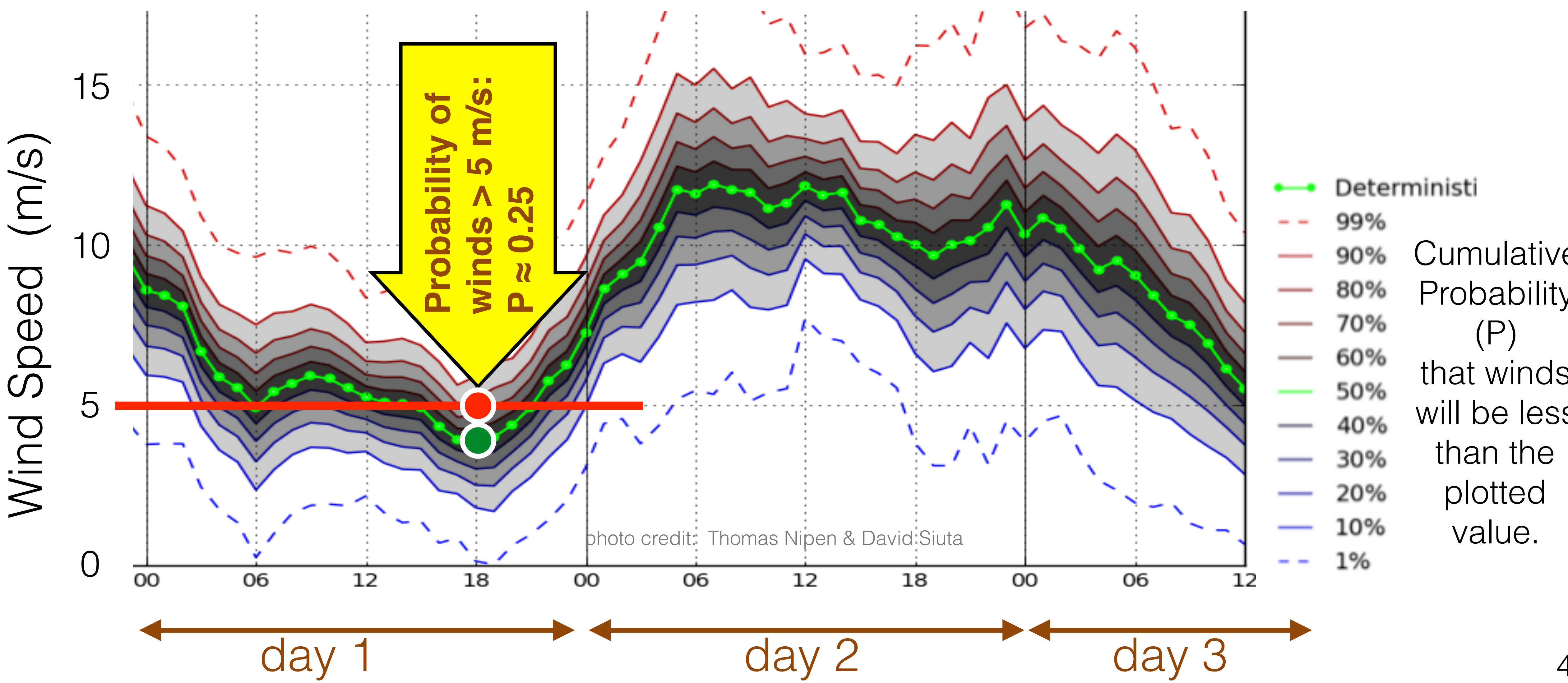
Solution:

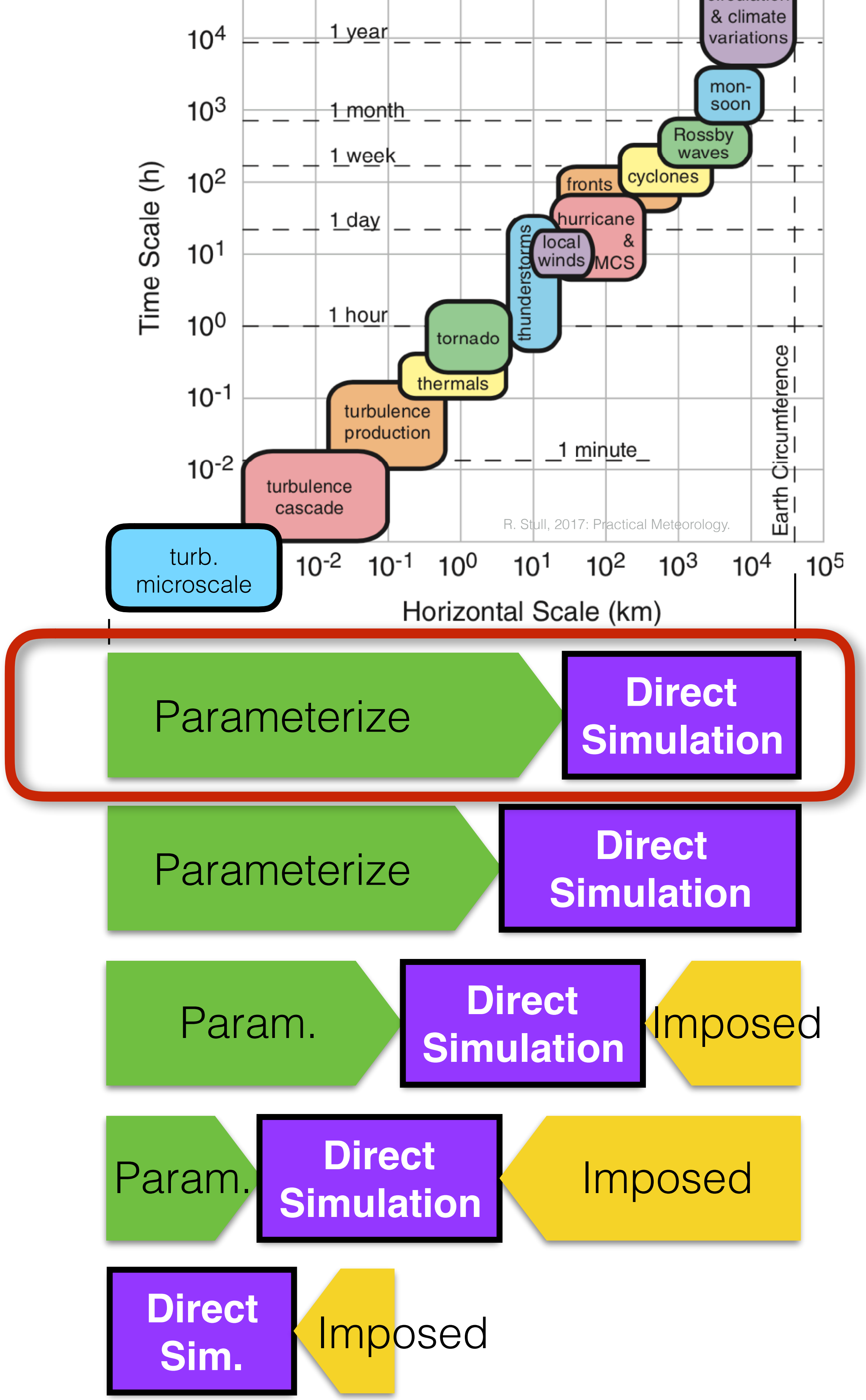
Cost to protect the blades (postpone the replacement) ≈ $165k.

Loss if blades damaged during attempt ≈ $970k.

Cost/Loss ratio R ≈ 0.17

P > R,   Therefore do not replace blades today.





Climate Simulations

Weather phenomena for all simulated scales are realistic, but none are real

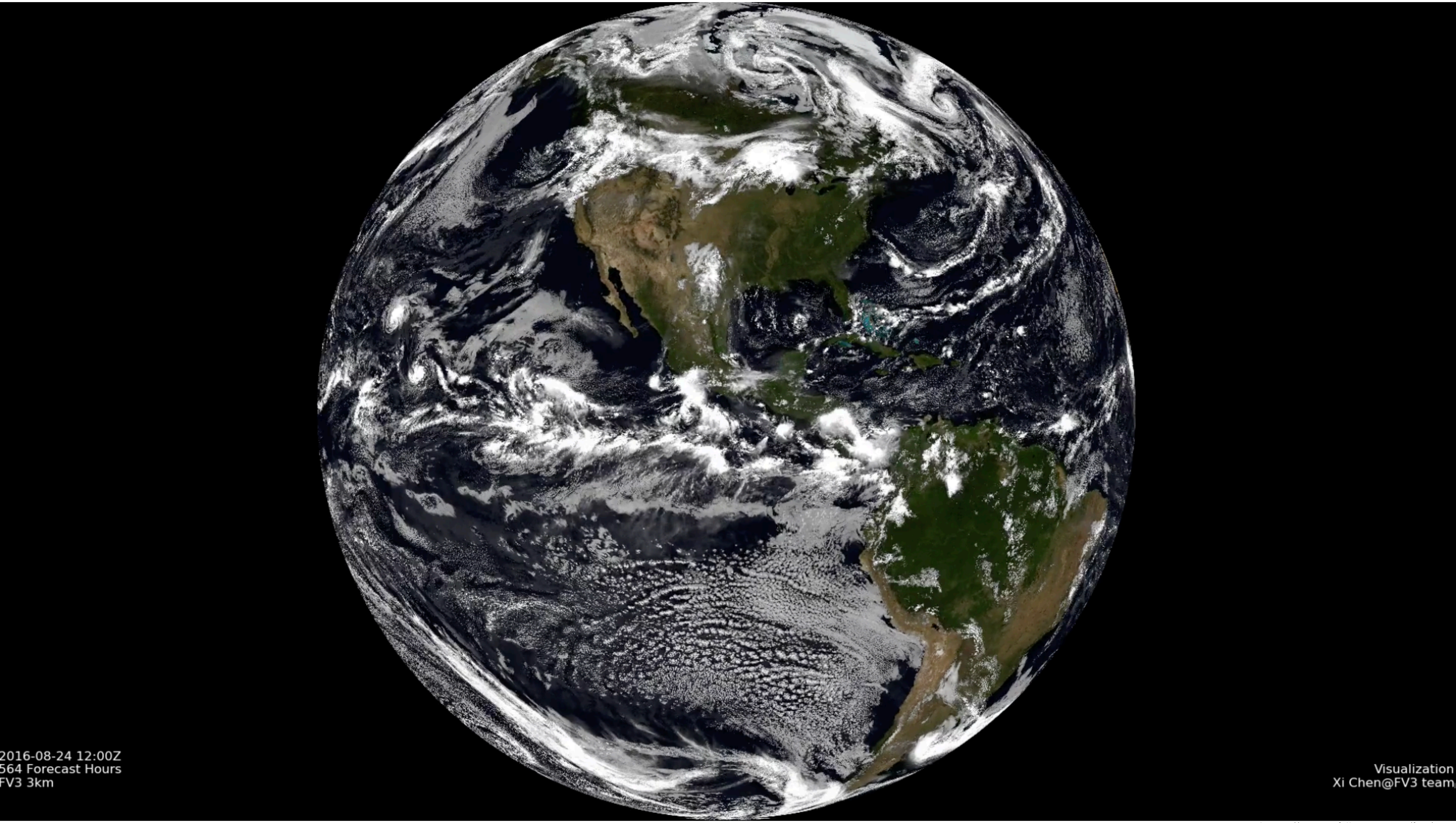
(except for global scales that are driven by persistent boundary conditions).

- Climate Projections. BCs important
  (simulates net effect of many scales)
- Weather Forecasts. ICs important
  (real-time operational forecasts)
- Storm Simulations. Not real time
  (but getting closer to real-time)
- Atmos.Boundary Layer Simulations
  (bottom 2 km of atmosphere)
- Engineering Simulations

BCs = boundary conditions, ICs = initial conditions. Atmos. Boundary Layer (ABL) = bottom 2 km of atmosphere

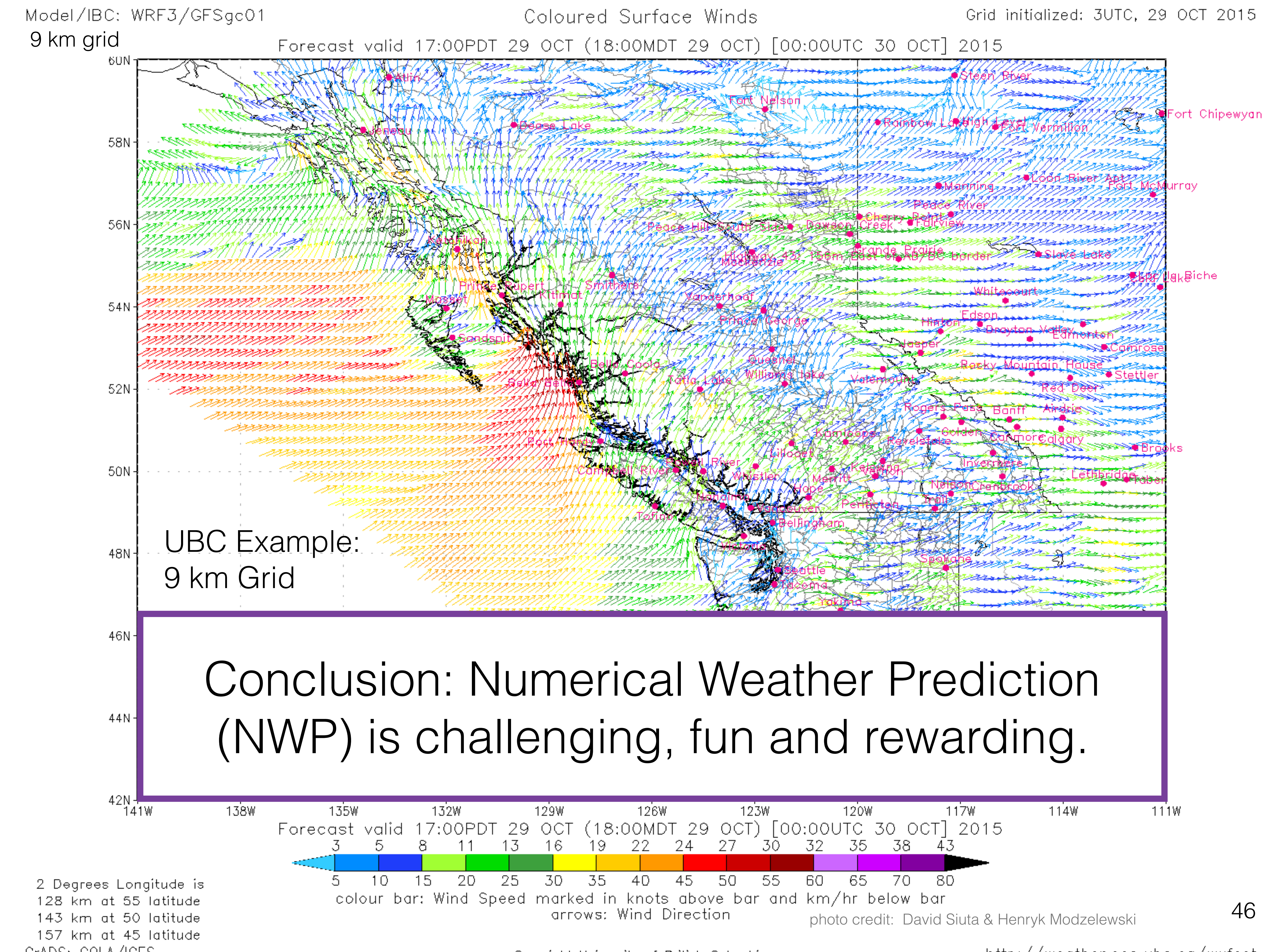
Coupled atmos-, cryo-, hydro-, anthro-spheres

NOAA/Princeton GFDL - FV3 Simulation at 3 km, by Shian-Jiann Lin & colleagues.



https://www.gfdl.noaa.gov/fv3/

NOAA = Nat'l Oceanic & Atmos. Admin.; GFDL = Princeton Geophysical Fluid Dynamics Lab.; FV3 = Finite Volume model version 3.



UBC Example:
9 km Grid

Conclusion: Numerical Weather Prediction (NWP) is challenging, fun and rewarding.

photo credit: David Siuta & Henryk Modzelewski

Peculiarities & Disasters in Weather CFD

CFD2018 - 26th Annual Conference of the Canadian CFD Society
10 - 12 June 2018

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Any Questions?

Topics:

1. Peculiarities of Meteorological vs. Engineering CFD
2. Some weather Disasters:
   - thunderstorms
   - tornadoes
   - forest-fire smoke
   - floods
   - hurricanes
   - climate change
   - blizzards
   - hazards to wind turbines

Colleagues:
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James Campbell
Tim Chui
Dominique Cook
Alison Deere
Anthony DiStefano
Rosie Howard
Bryan Jansens
Julia Jeworrek
Chris Jing
Frans Liqui Lung
Jesse Mason
Henryk Modzelewski
Nadya Moisseeva
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Marjolein Ribberink
Kyle Sha
Roland Schigas
Greg West
Eve Wicksteed
Tatjana Zenker