

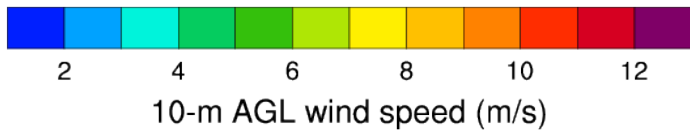
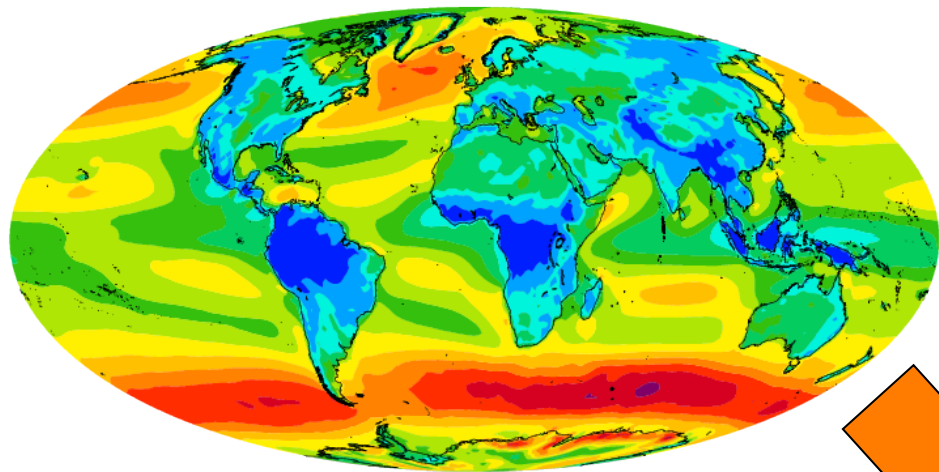
Mesoscale modeling ~~(in)~~ and the boundary layer

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With many thanks to Thomas T. Warner (1943-2011)

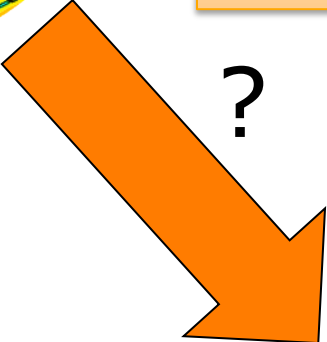
Outline

- What is the mesoscale? Why do we need mesoscale models?
- What processes are represented in mesoscale models? What are the sources of errors in these models?
- Why are parameterizations needed? Boundary-layer parameterizations
- Coupling between mesoscale and microscale models, some insights
- Numerical considerations (if we have time...)



Climate
(Atmospheric
reanalysis)
Models

Resource
prediction at
the wind
farm level



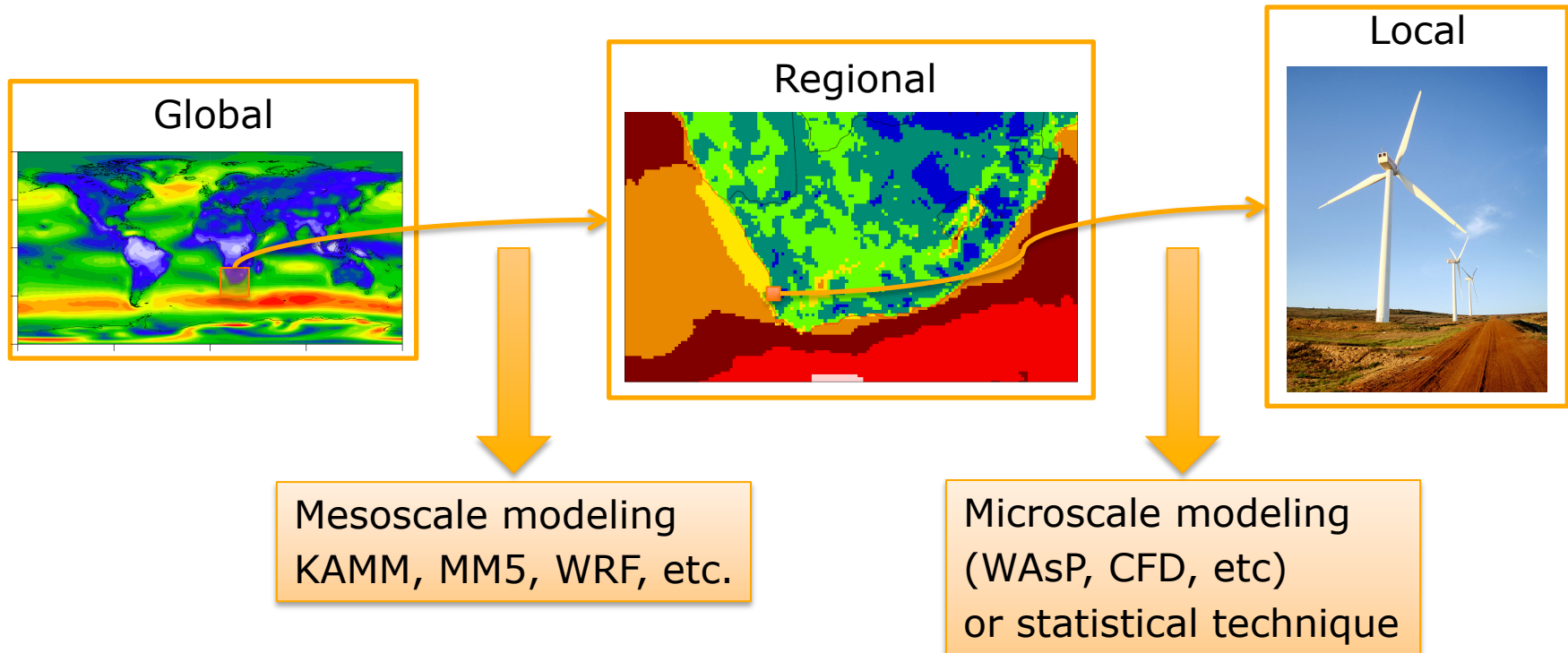
Weather
(Numerical
Weather
Prediction -
NWP) Models

Power
forecast at the
wind farm

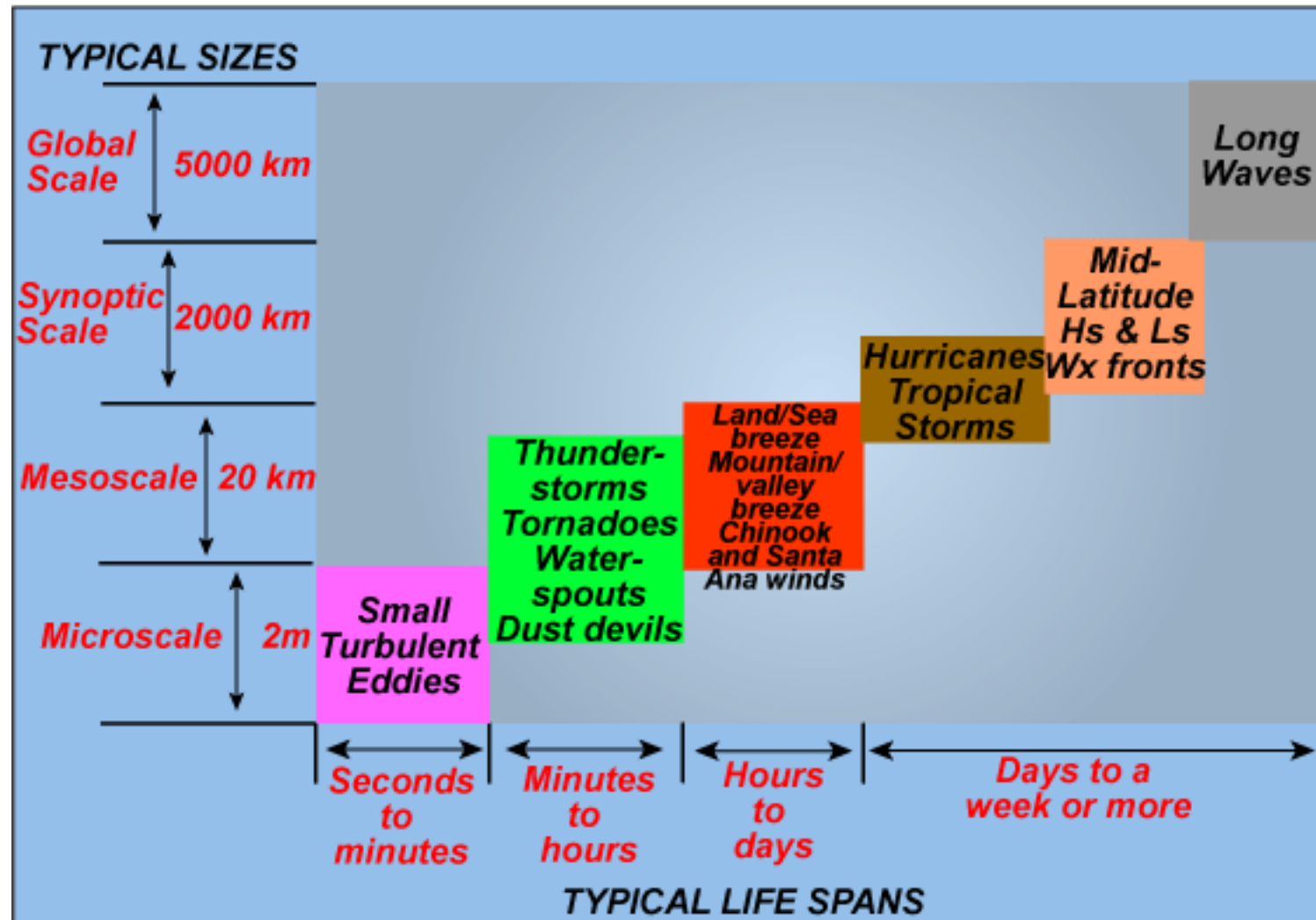


wind farm

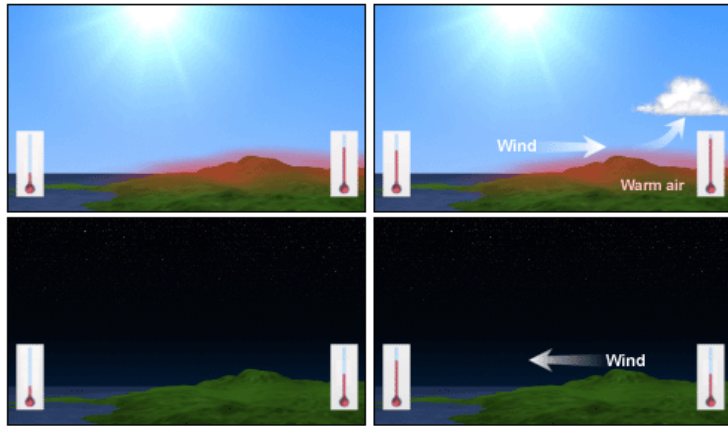
Typical downscaling steps



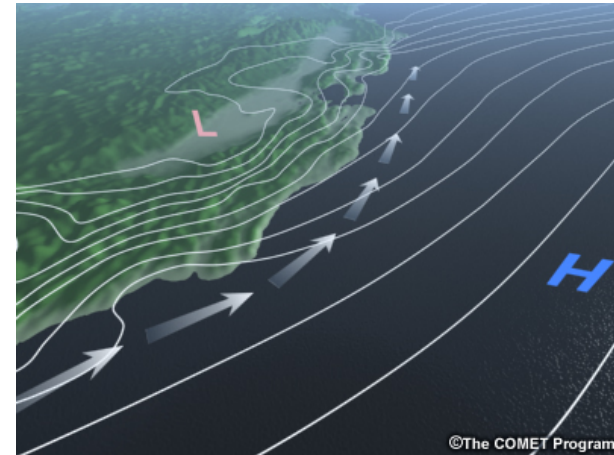
TIME AND SPACE SCALE OF ATMOSPHERIC MOTION



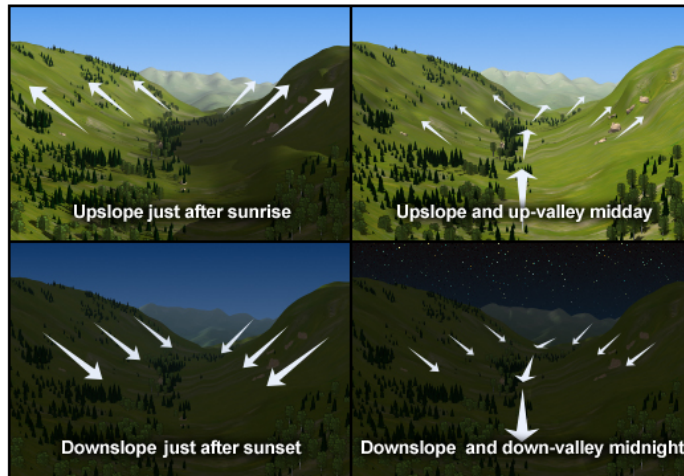
Mesoscale processes generate regional circulation systems and/or modify these general patterns



Coastal jet
sea-land breeze
©The COMET Program

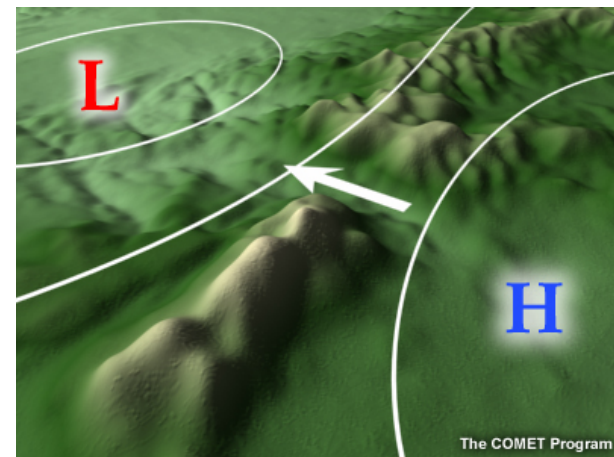


coastal jet



The COMET Program

mountain-valley breeze



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gap flow (not thermally)

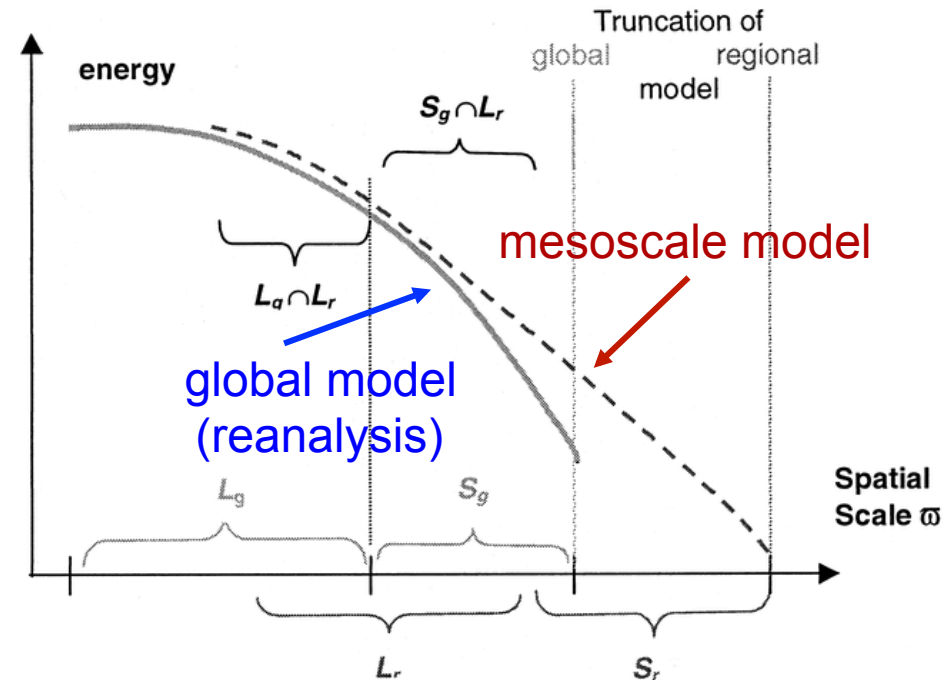
Dynamical downscaling for wind energy resource estimation

For estimating wind energy resources, mesoscale model simulations are:

- Not weather forecasting, spin-up may be an issue
- Not regional climate simulations, drift may be an issue

For this application:

- We “trust” the large-scale reanalysis that drives the downscaling
- We need to resolve smaller scales not present in the reanalysis



von Storch et al (2000)

The (primitive) equations that are the basis for models

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} + \frac{uv \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial x} - 2\Omega(w \cos \phi - v \sin \phi) + Fr_x$$

$$\frac{\partial v}{\partial t} = -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} - \frac{u^2 \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial y} - 2\Omega u \sin \phi - Fr_y$$

$$\frac{\partial w}{\partial t} = -u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} - \frac{u^2 + v^2}{a} - \frac{1}{\rho} \frac{\partial p}{\partial z} + 2\Omega u \cos \phi - g + Fr_z$$

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} + (\gamma - \gamma_d)w + \frac{1}{c_p} \frac{dH}{dt}$$

$$\frac{\partial \rho}{\partial t} = -u \frac{\partial \rho}{\partial x} - v \frac{\partial \rho}{\partial y} - w \frac{\partial \rho}{\partial z} - \rho \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)$$

$$\frac{\partial q_v}{\partial t} = -u \frac{\partial q_v}{\partial x} - v \frac{\partial q_v}{\partial y} - w \frac{\partial q_v}{\partial z} + Q_v$$

$$p = \rho RT$$

All equations have time-derivatives on the left...

$$\begin{aligned}
 \frac{\partial u}{\partial t} &= -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} + \frac{uv \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial x} - 2\Omega(w \cos \phi - v \sin \phi) + Fr_x \\
 \frac{\partial v}{\partial t} &= -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} - \frac{u^2 \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial y} - 2\Omega u \sin \phi - Fr_y \\
 \frac{\partial w}{\partial t} &= -u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} - \frac{u^2 + v^2}{a} - \frac{1}{\rho} \frac{\partial p}{\partial z} + 2\Omega u \cos \phi - g + Fr_z \\
 \frac{\partial T}{\partial t} &= -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} + (\gamma - \gamma_d)w + \frac{1}{c_p} \frac{dH}{dt} \\
 \frac{\partial \rho}{\partial t} &= -u \frac{\partial \rho}{\partial x} - v \frac{\partial \rho}{\partial y} - w \frac{\partial \rho}{\partial z} - \rho \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \\
 \frac{\partial q_v}{\partial t} &= -u \frac{\partial q_v}{\partial x} - v \frac{\partial q_v}{\partial y} - w \frac{\partial q_v}{\partial z} + Q_v \\
 p &= \rho RT
 \end{aligned}$$

+ equations for cloud water, rain, snow... etc

Other processes are treated with separate complex sets of equations

$$\begin{aligned}
 \frac{\partial u}{\partial t} &= -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} + \frac{uv \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial x} - 2\Omega(w \cos \phi - v \sin \phi) + Fr_x \\
 \frac{\partial v}{\partial t} &= -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} - \frac{u^2 \tan \phi}{a} - \frac{vw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial y} - 2\Omega u \sin \phi + Fr_y \\
 \frac{\partial w}{\partial t} &= -u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} - \frac{u^2 + v^2}{a} - \frac{1}{\rho} \frac{\partial p}{\partial z} + 2\Omega u \cos \phi - g + Fr_z \\
 \frac{\partial T}{\partial t} &= -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} + (\gamma - \gamma_d)w + \frac{1}{c_p} \frac{dH}{dt} \\
 \frac{\partial \rho}{\partial t} &= -u \frac{\partial \rho}{\partial x} - v \frac{\partial \rho}{\partial y} - w \frac{\partial \rho}{\partial z} - \rho \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \\
 \frac{\partial q_v}{\partial t} &= -u \frac{\partial q_v}{\partial x} - v \frac{\partial q_v}{\partial y} - w \frac{\partial q_v}{\partial z} + Q_v \\
 p &= \rho RT
 \end{aligned}$$

effect of friction, turbulence
 surface heating, change of phase, radiation
 cloud processes, surface evaporation

Boundary-layer processes affect all 5 terms.

These basic equations

- Are common to many different types of atmospheric models
 - operational weather prediction models
 - global climate models
 - building-scale urban (CFD) models
 - research atmospheric models
 - models of flow over an airfoil

The sources of model error

- Numerical approximations to the equations that allow us to solve them on a computer
- Initial conditions – the atmospheric state from which we begin the model forecast
- Lateral (+upper) boundary conditions, for limited-area models
- Lower boundary condition – land surface forcing
- Parameterizations of physical processes (e.g., turbulence, radiation, etc.)

Why do we need approximations to the equations?

- Nonlinear, nonhomogeneous partial-differential equations cannot be solved analytically. Therefore:
 - Convert the derivatives to algebraic expressions
 - Computers can solve algebraic equations

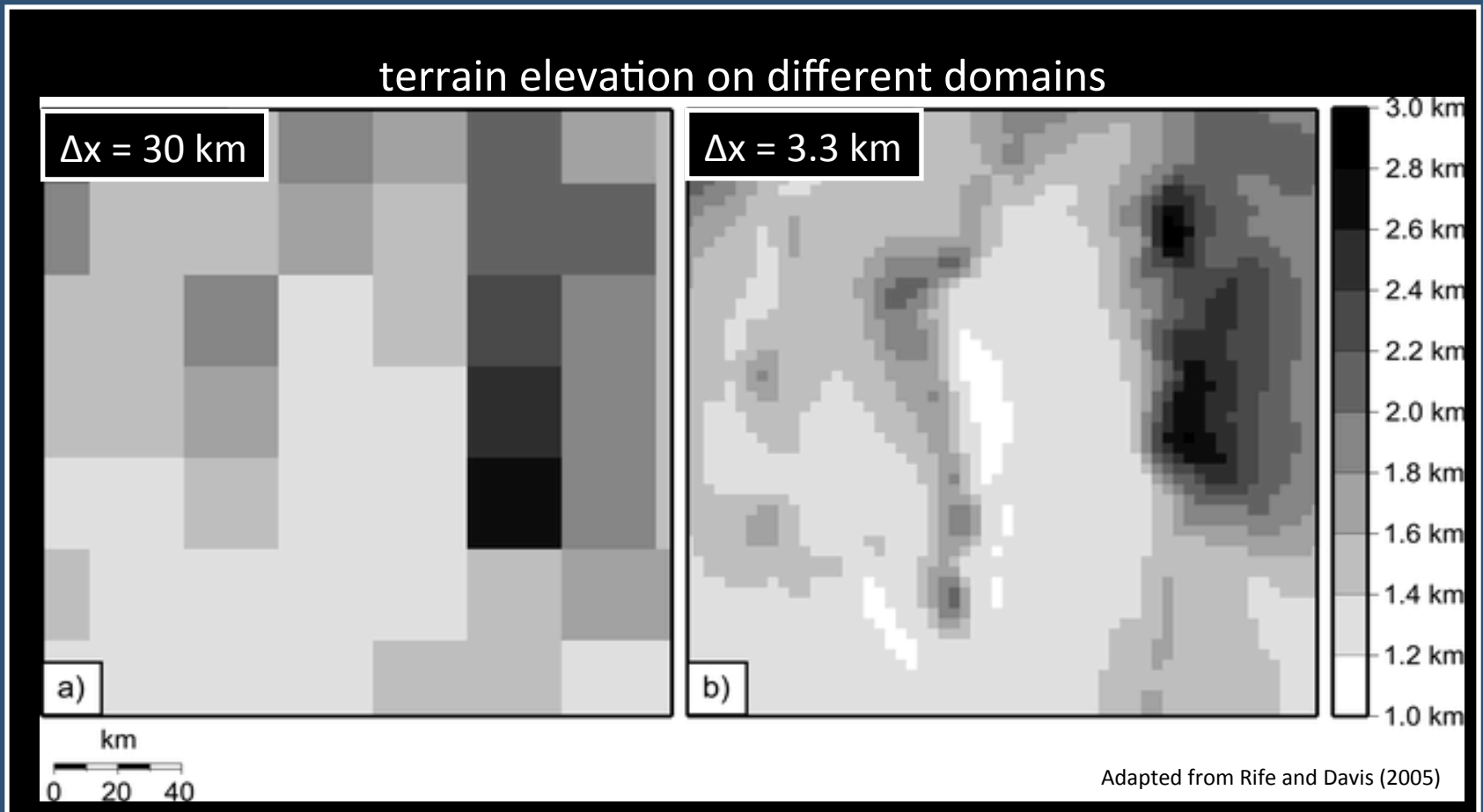
Space derivatives

- **Grid-point methods (most mesoscale models)** – equations are solved at points defined by a “quasi-regular”, 3D spatial grid
 - e.g., Cartesian or spherical (lat-lon) coordinates
 - Space derivatives estimated with finite-difference methods
- **Spectral methods (not as common in mesoscale models)** – estimate spatial variation of dependent variables with analytic functions
 - Space derivatives calculated analytically
 - Global or local functions may be used

The size of the grid increment

- Δx is chosen so that there is a sufficient number of grid points to represent the smallest meteorological feature of interest in the model solution. **A rule of thumb is that 10 grid points are needed in order to adequately resolve a wave.**
- The “truncation error” quantifies the error
- For synoptic-scale processes, $\Delta x = 100$ km may be adequate. For moist convection, $\Delta x = 1$ km would be more reasonable.

One advantage of higher resolution



Computational requirements for running a model

- The **total computer time involved in producing a forecast** of a given length, and over a specific area, will depend on
 - the number of grid points at which the equations must be solved at each time step, and
 - the number of time steps it takes to go from the start to the end of the integration.
- The number of grid points depends on the grid increment that is needed to resolve the important processes (the finer the mesh, the more points).
- The number of time steps needed depends on the time step itself, which is smaller for higher-resolution grids and when there are fast waves on the grid.

$$(U\Delta t/\Delta x \leq 1)$$

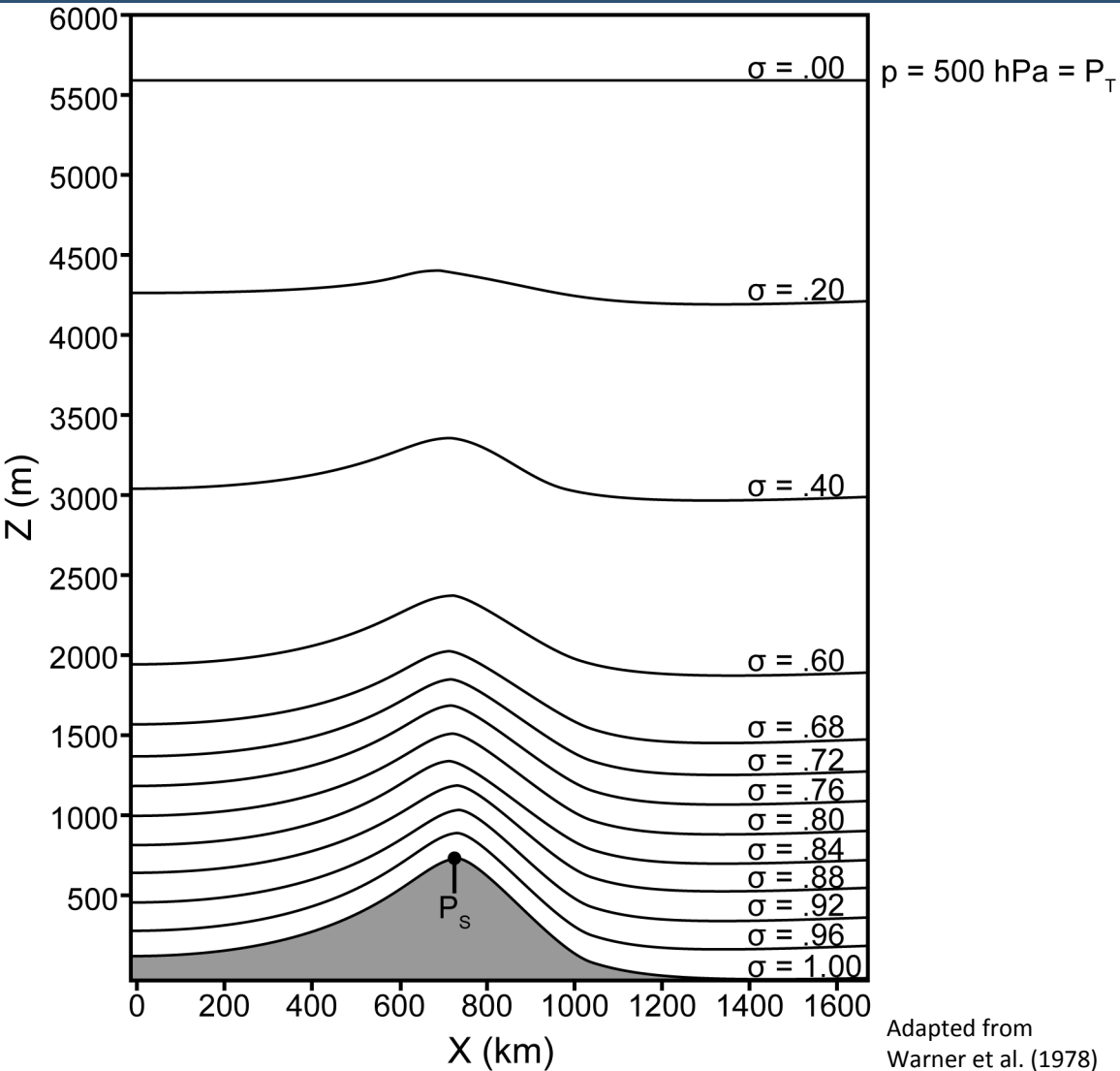
Desirable properties of a model vertical coordinate system?

- Single valued
- Does not intersect the ground
- Pressure-gradient force defined by one term

Vertical coordinate systems commonly used

- Height above sea level
- Pressure
- Potential temperature
- Sigma-p

Sigma-p



$$\sigma = \frac{p - p_t}{p_s - p_t}$$

$$\frac{\partial p^* u}{\partial t} \propto -m p^* \left(\frac{RT}{p^* + \frac{p_t}{\sigma}} \frac{\partial p^*}{\partial x} + \frac{\partial \phi}{\partial x} \right)$$

Sources of model error – a preview

- Numerical approximations to the equations that allow us to solve them on a computer
- Initial conditions – the atmospheric state from which we begin the model forecast
- Lateral (+upper) boundary conditions, for limited-area models
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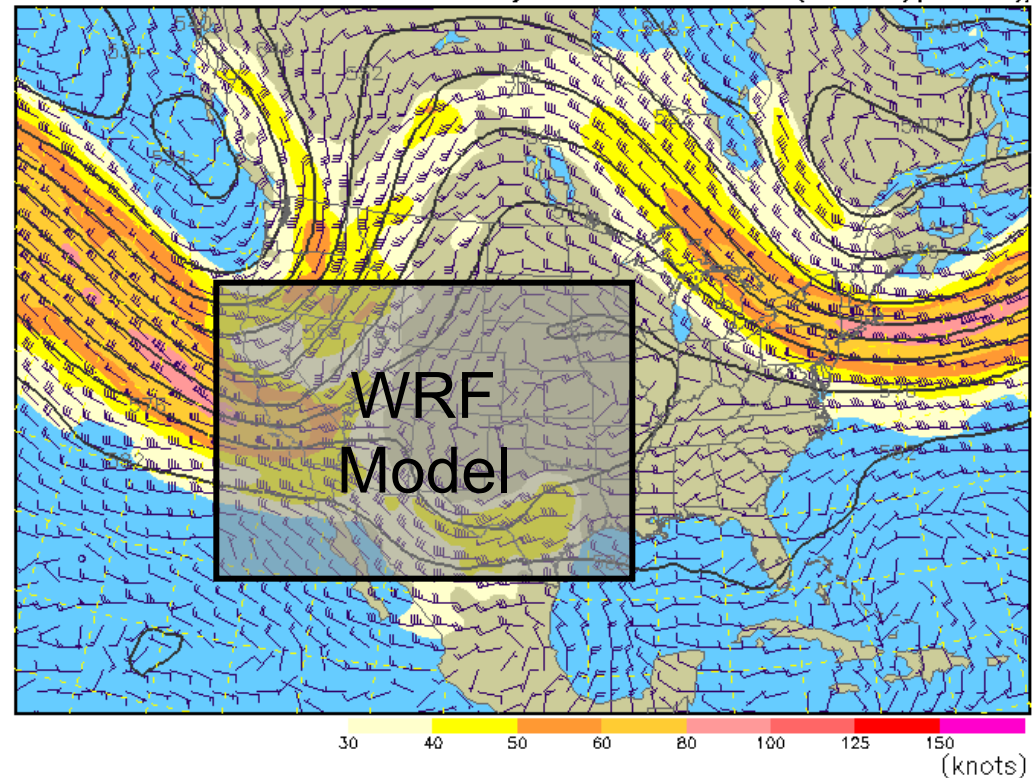
Initial conditions usually come from a large-scale (global) forecast or reanalysis

Interpolation
Assimilation of
observations
Interpolate to model
grid using balance
constraints

500 mb Heights (dm) / Isotachs (knots)

12-hour forecast valid 0000 UTC Thu 03 May 2007

NAM (WRF-NMM) (12z 02 May)



WRF – Weather, Research and Forecast model
Community mesoscale model²²– NCAR + other
USA laboratories

Analysis vs. Reanalysis

- **Analysis** is the set of initial conditions produced by an analysis system, i.e, defined on the global model grid (interpolation + data assimilation + model balance)
- **Reanalysis** is the retrospective analysis onto global grids using a multivariate physically consistent approach with a **constant** analysis system.
- Newer reanalysis products provide a consistent dataset with state of the art analysis system and horizontal resolution as fine as that of real-time operational analysis.

Operational
weather
centers

(❖ are
freely
available)

Reanalysis	Horiz.Res	Dates	Vintage	Status
NCEP/NCAR R1❖	T62	1948-present	1995	ongoing
NCEP-DOE R2❖	T62	1979-present	2001	ongoing
CFSR (NCEP)❖	T382	1979-present	2009	thru 2009, ongoing
C20r (NOAA)	T62	1875-2008	2009	Complete, in progress
ERA-40	T159 (0.8°)	1957-2002	2004	done
ERA-Interim	T255	1989-present	2009	ongoing
JRA-25	T106	1979-present	2006	ongoing
JRA-55	T319	1958-2012	2009	underway
MERRA (NASA)❖	0.5°	1979-present	2009	thru 2010, ongoing

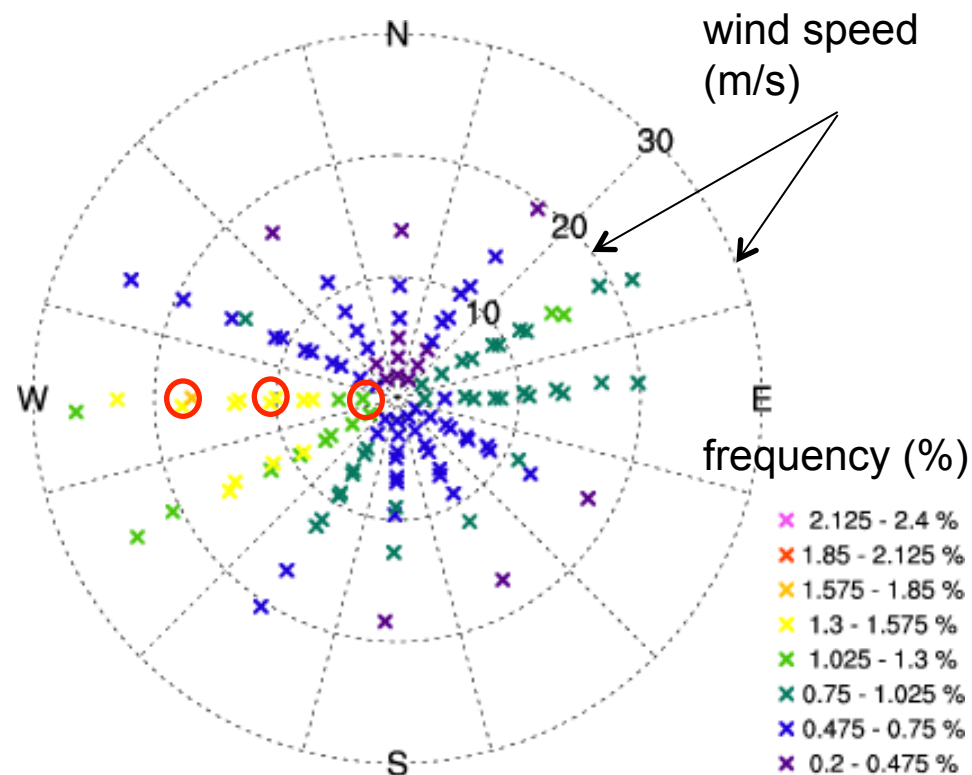
But mesoscale models can also be run
in idealized mode...

The Risø Wind Atlas method

The Wind Atlas Method

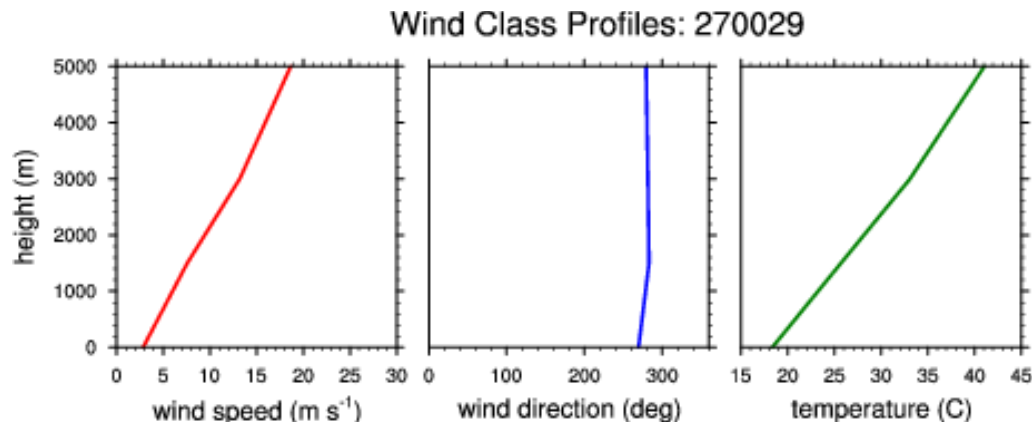
- Determine the large-scale wind forcing of a region based on long-term, but spatially coarse, dataset.
- Classify the geostrophic wind (and stability) time-series into wind classes
- Use a mesoscale model (KAMM) to determine how topography modifies the large-scale wind defined by each wind class.

125 wind classes for Southern S. Africa
– mean sea level geostrophic wind (NCEP/NCAR reanalysis)

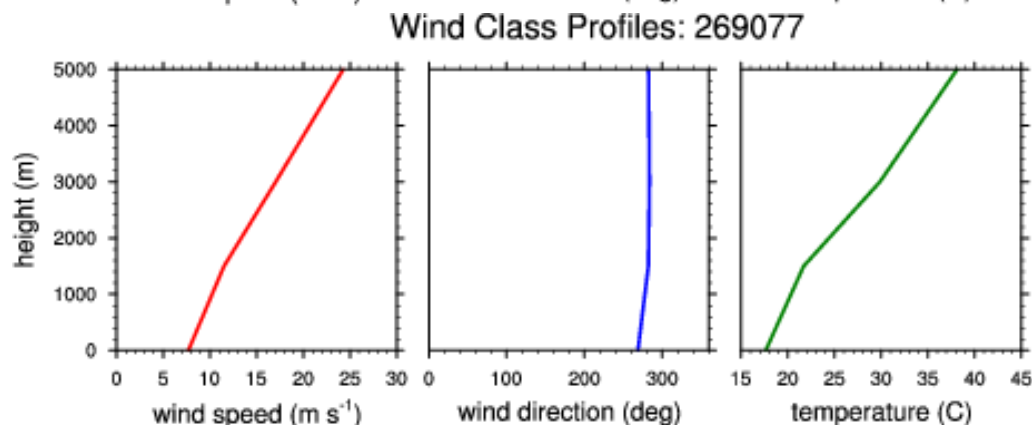


Example wind class profiles

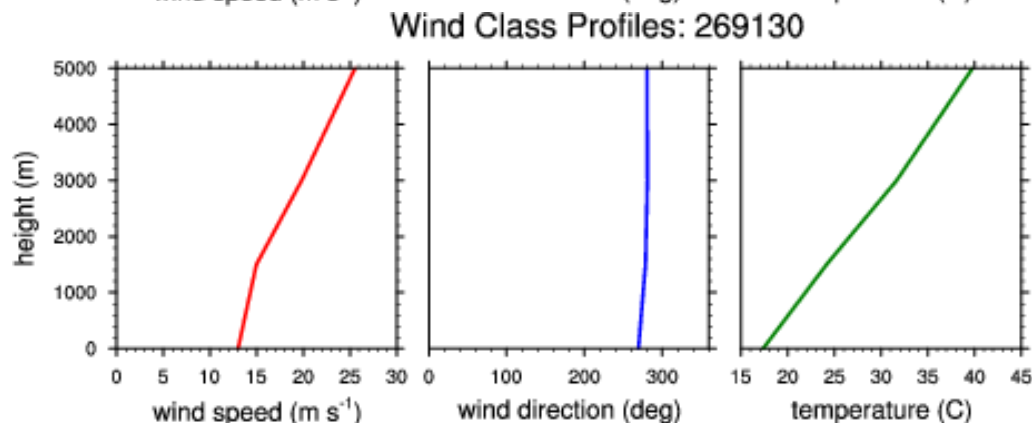
Wind Class: 095
Frequency: 1.17%
Wind speed 2.9 m/s
Wind direction: 270°



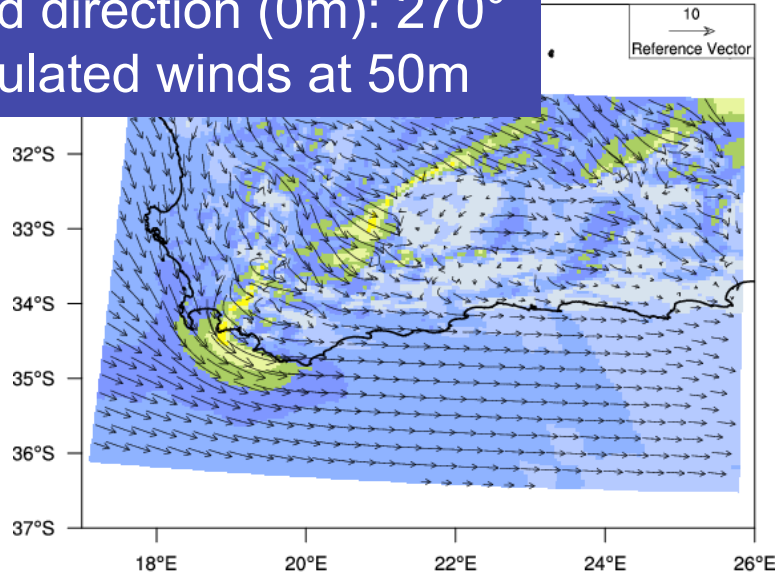
Wind Class: 098
Frequency: 1.33%
Wind speed 7.7 m/s
Wind direction: 269°



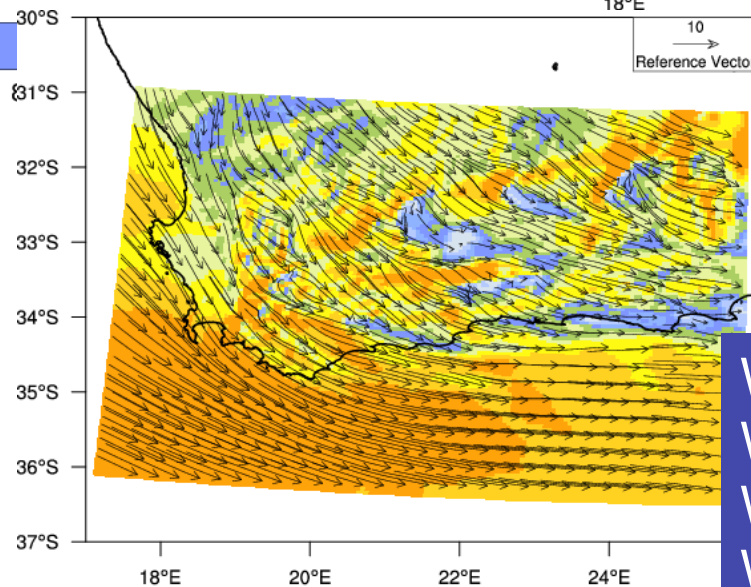
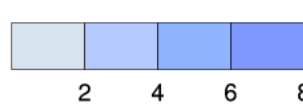
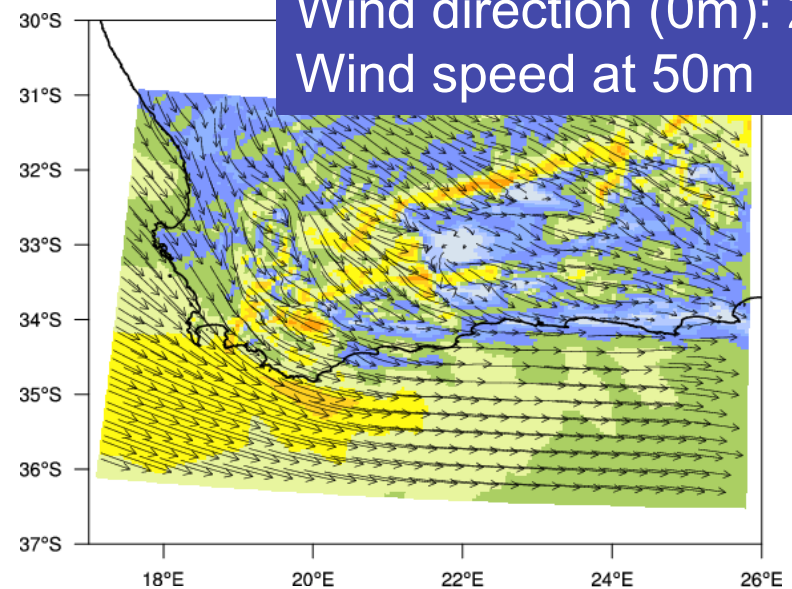
Wind Class: 101
Frequency: 1.51%
Wind speed 13.0 m/s
Wind direction: 269°



Wind Class Freq: 1.17%
 Wind speed (0m): 2.9 m/s
 Wind direction (0m): 270°
 Simulated winds at 50m



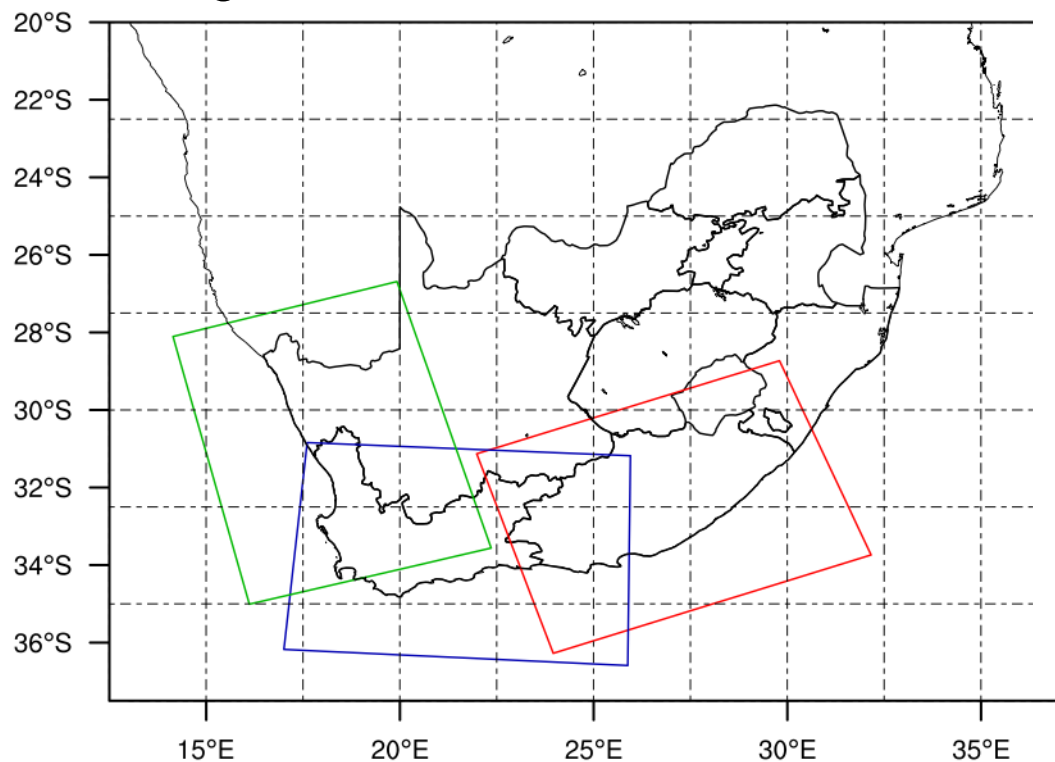
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 Wind speed at 50m



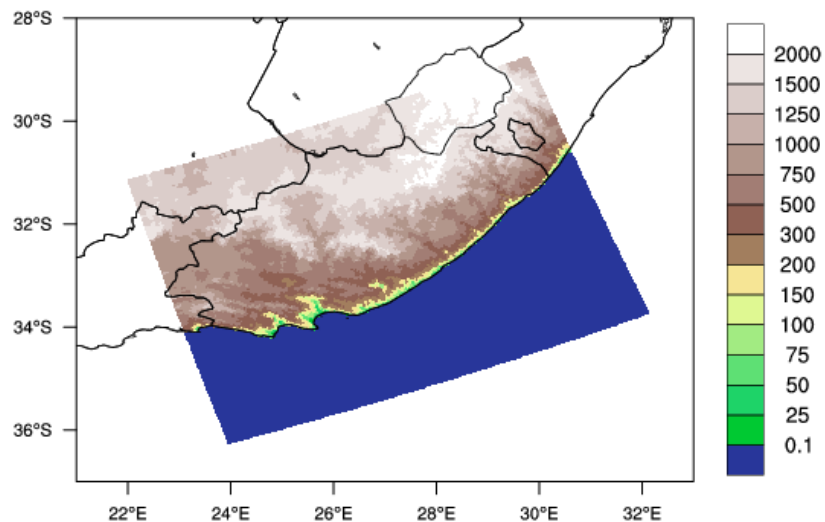
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 Wind direction (0m): 269°
 Wind speed at 50m

Original mesoscale model domains

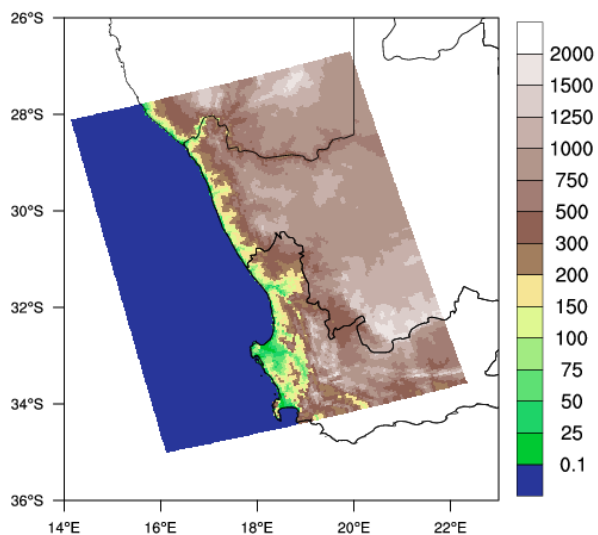
DTU



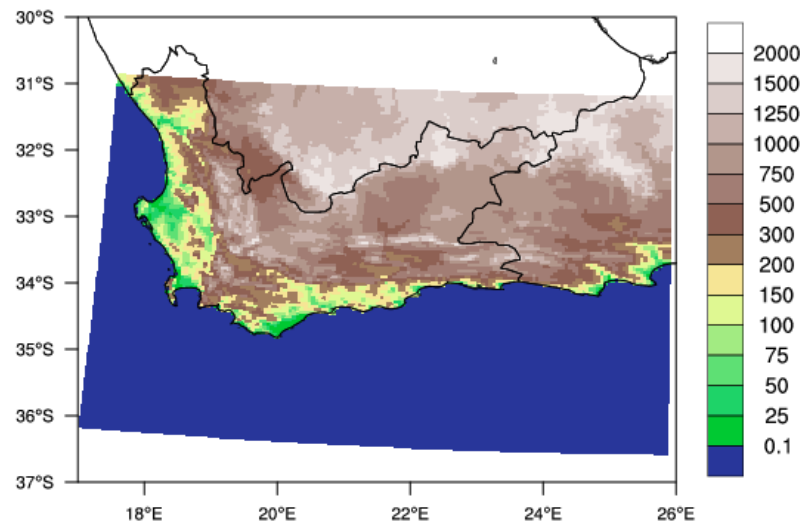
Grid resolution: 5 km



Grid resolution: 5 km



Grid resolution: 5 km



Sources of model error

- Numerical approximations to the equations that allow us to solve them on a computer
- Initial conditions – the atmospheric state from which we begin the model forecast
- Lateral boundary conditions, for limited-area models
- Lower and upper boundary condition (land surface forcing)
- Parameterizations of physical processes (e.g., turbulence, radiation, etc.)

Lateral Boundary Conditions

- Needed for LAMs because equations cannot be solved at the edge points – there are no points beyond the boundary to use in calculating derivatives perpendicular to it.
- The BCs need to be externally specified.
- Operational forecasting with LAMS: Define BCs based on previously run large-scale (global) forecast.
- Research simulations with LAMS: Define BCs based on global analysis of observations.
- Other modes exist in idealized simulations

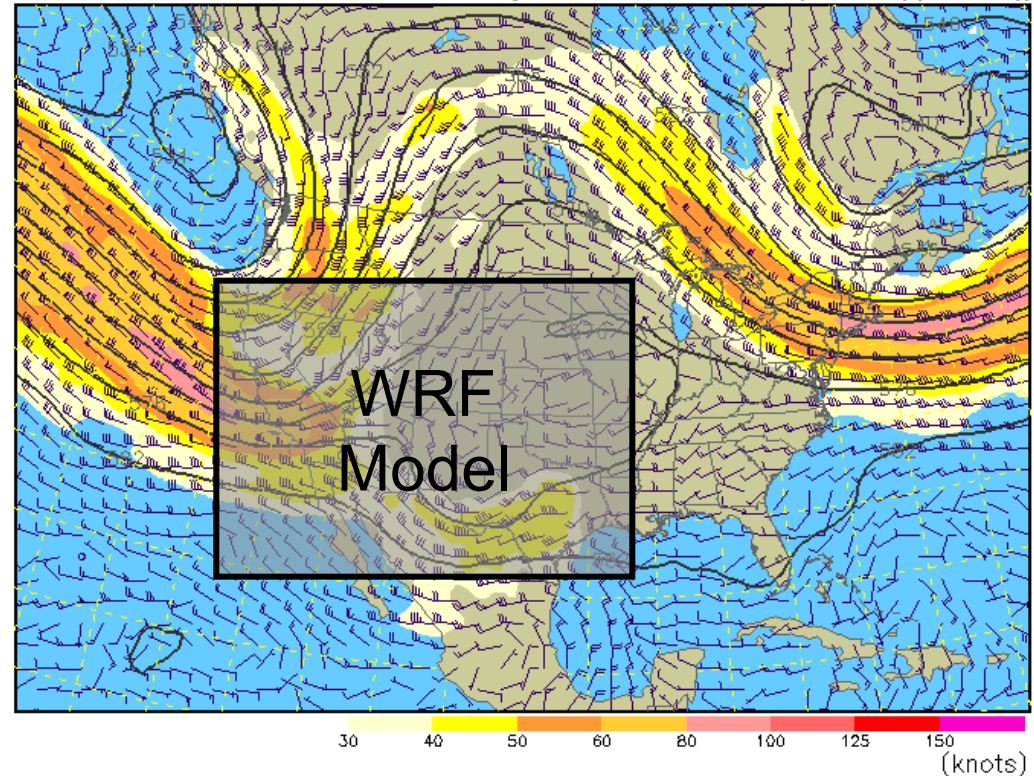
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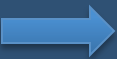
12-hour forecast valid 0000 UTC Thu 03 May 2007

NAM (WRF-NMM) (12z 02 May)

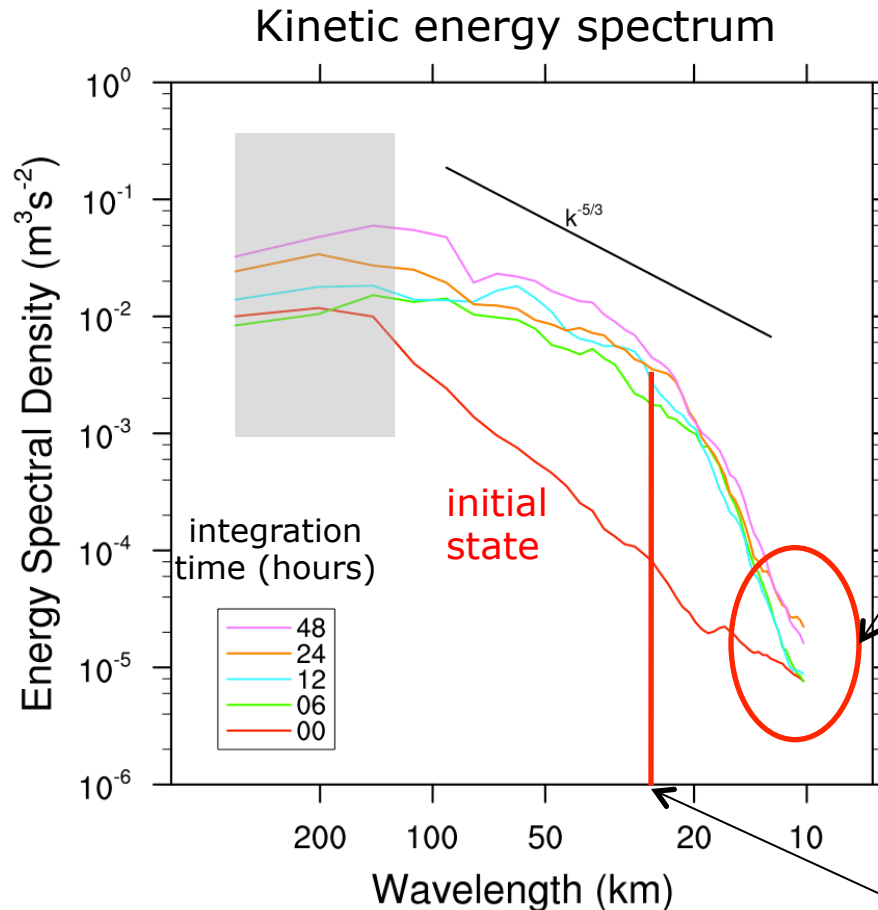


WRF – Weather, Research and Forecast model
Community mesoscale model – NCAR + other
USA laboratories

Upper and lower BCs

- Upper BCs: Model atmosphere cannot extend to infinity, as does the real atmosphere, so an artificial upper boundary needs to be defined. This must be formulated so that there is no artificial reflection of upward-propagating waves.
- Lower BCs: Specification of heat, moisture and momentum fluxes at the land and ocean surface.  Land surface model

Spin-up and resolution effects



Downscaling run 5 km horizontal resolution grid over Northern Europe

Time required to build up mesoscale structures: ~ 24 hours

This length depends on domain size, wind regime, orographic complexity and details of the model used.

Effective resolution $\sim 7 \times$ grid spacing, depends on model numerics

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Physical-process parameterizations

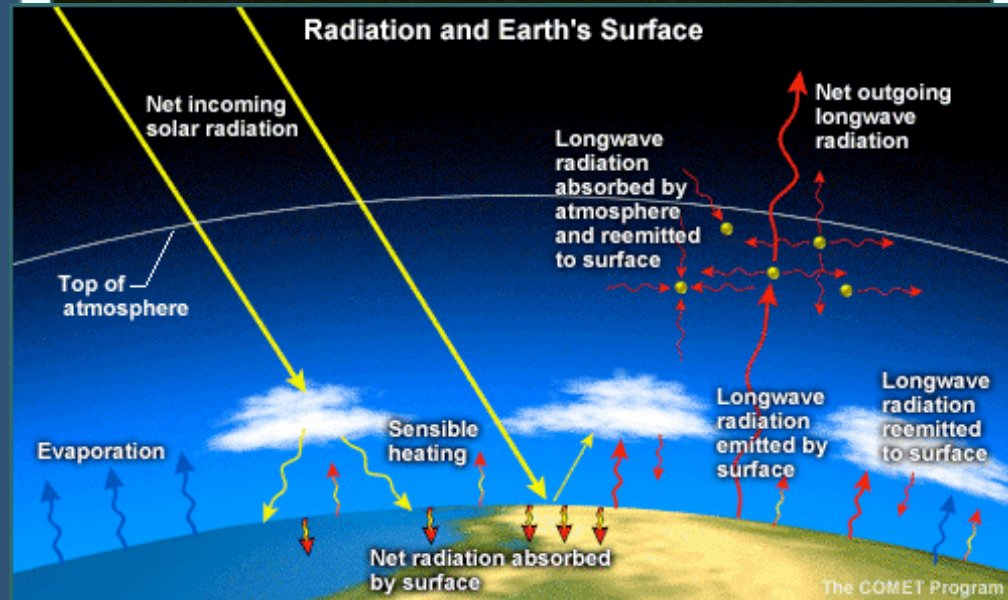
- What does “parameterize” mean?

Represent a process through a statistical or algorithmic relationship, rather than through a physical relationship

- Why do we parameterize some processes?
 - The complexity of a process makes it too computationally expensive to represent directly
 - There is insufficient knowledge about how a process operates, to allow it to be represented explicitly
 - The small scales involved in a process make it too computationally expensive to represent directly

Processes that are often parameterized

- Land-surface processes (surface fluxes, radiation, hydrology)
- Cloud microphysics
- Radiative transfer through the atmosphere – long and shortwave
- Turbulent fluxes - heat, moisture, momentum
- Cumulus convection (moist convection)

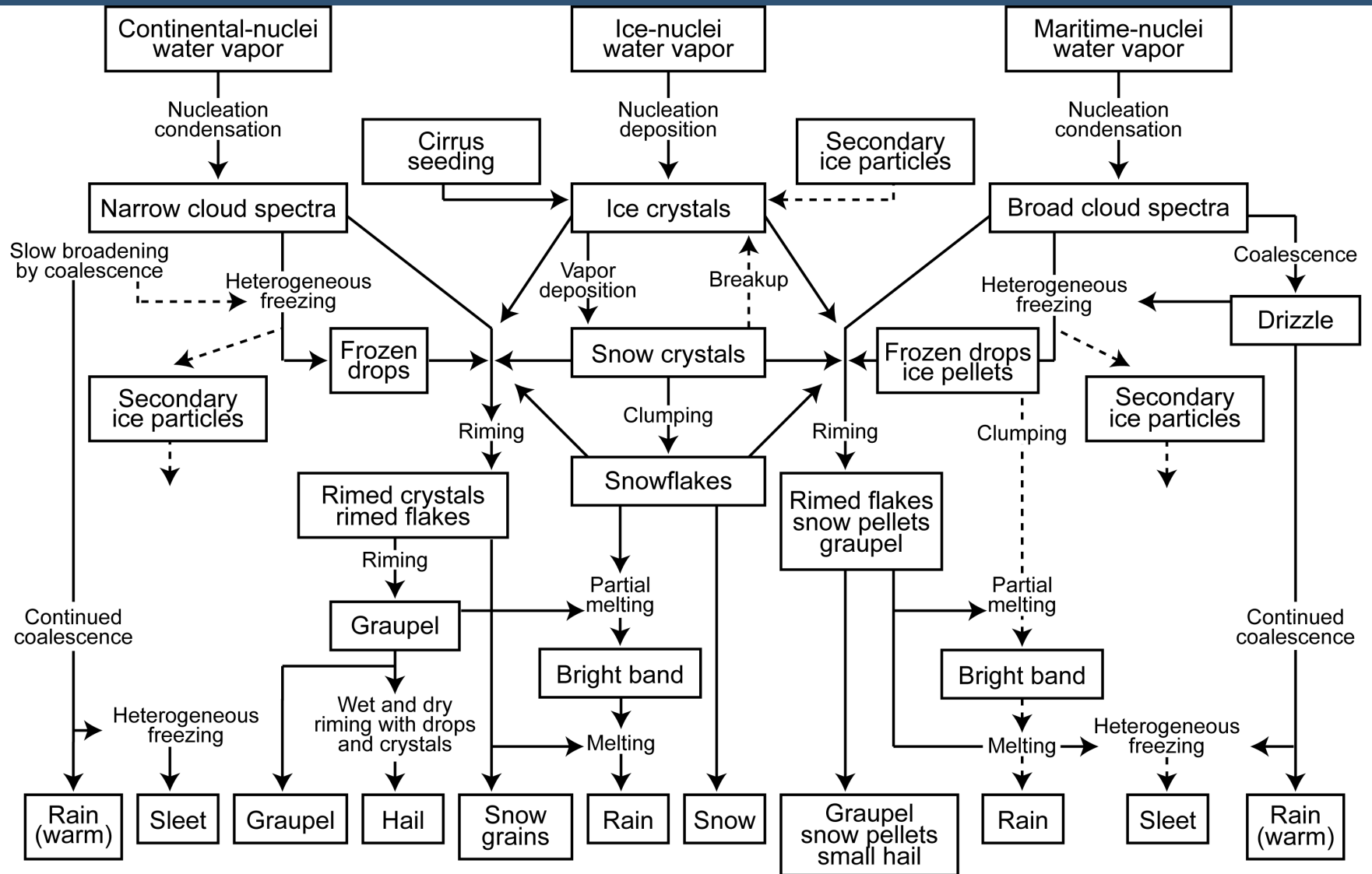


Grid increments and parameterizations

- Many parameterizations are designed for use with a certain range of horizontal grid increments – i.e., only those aspects of the physical system that are not resolved by the model need to be parameterized.
 - e.g., global models need to parameterize mesoscale and convective scale processes that lead to summer precipitation, but mesoscale models only need to parameterize the convective scale.
- For high resolutions, the model can begin to partially resolve processes that are being parameterized; there is thus a risk of “double counting”.

Cloud microphysics processes that may be parameterized

Adapted from
Braham and Squires
(1974)



Turbulence parameterizations

- Also known as boundary-layer parameterizations
- Infer turbulence intensity, to represent subgrid-scale vertical transport (mixing) of heat, moisture and momentum between the surface and the free atmosphere.
- The parameterization should also represent turbulent mixing anywhere in the atmosphere (for example, associated with wind shear near the jet stream)

Boundary-layer parameterization closures

The momentum equations in tensor notation:

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} - \delta_{i3}g + f\epsilon_{ij3}u_j - \frac{1}{\rho} \frac{\partial p}{\partial x_i}$$

Reynolds' stress term
Effects of turbulence on the mean flow.

$$u = \bar{u} + u', \bar{u}' = 0, \overline{a'b'} = 0.$$

$$\frac{\partial \bar{u}_i}{\partial t} = -\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} - \delta_{i3}g + f\epsilon_{ij3}\bar{u}_j - \frac{1}{\bar{\rho}} \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial}{\partial x_j} \overline{u'_i u'_j}$$

When the covariance terms $\overline{u'u'}, \overline{u'v'}, \overline{u'w'}, \overline{v'v'}, \overline{v'w'}, \overline{w'w'}$ are parameterized in terms of $\bar{u}, \bar{v}, \bar{w}$ It is called a **first-order** closure

$$\overline{\xi' u'_j} = -K \frac{\partial}{\partial x_j} \bar{\xi}$$

where ξ is u, v, w, θ, q , etc.

Only vertical components are retained.

Boundary-layer parameterization closures

In second order schemes

$$\frac{\partial \overline{u'_i u'_j}}{\partial t} = \dots - \frac{\partial}{\partial x_k} \overline{u'_i u'_j u'_k}$$

and so on.

A good advantage of second-order or higher method is that the second moments of the wind components can be used to quantify the total Turbulent Kinetic Energy (TKE)

There are also combinations of these approaches, parameterized versus predicted give rise to for example 1.5 order closure.

Different approaches

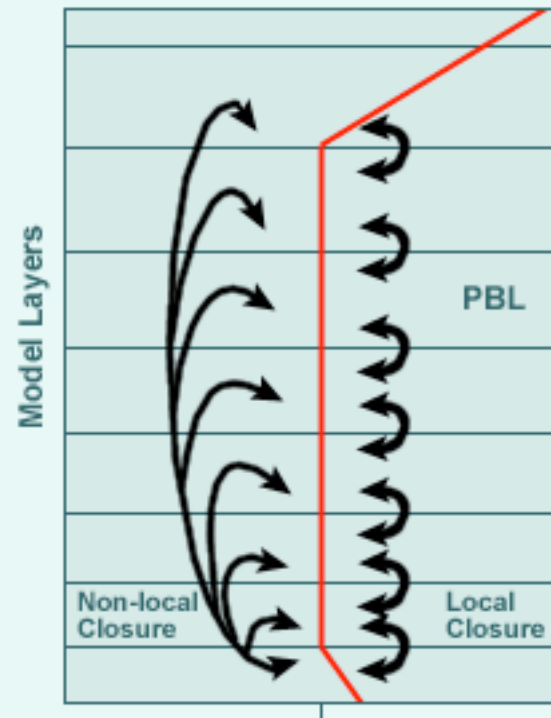
$$\overline{\xi' u'_j} = -K \frac{\partial}{\partial x_j} \bar{\xi}$$

Where the vertical derivatives are calculated

Adjacent grid point in the vertical -> **local closure**

Significantly farther away in the vertical -> **non-local closure**

Local Versus Non-local Closure Assumptions



Non-local closure:
properties of one layer
may mix with all the
other layers in the PBL,
thus simulating the mixing
done by large-scale eddies.

Local closure:
only properties
of adjacent layers
can mix

The COMET Program

Model Configuration – Real-time forecasting system

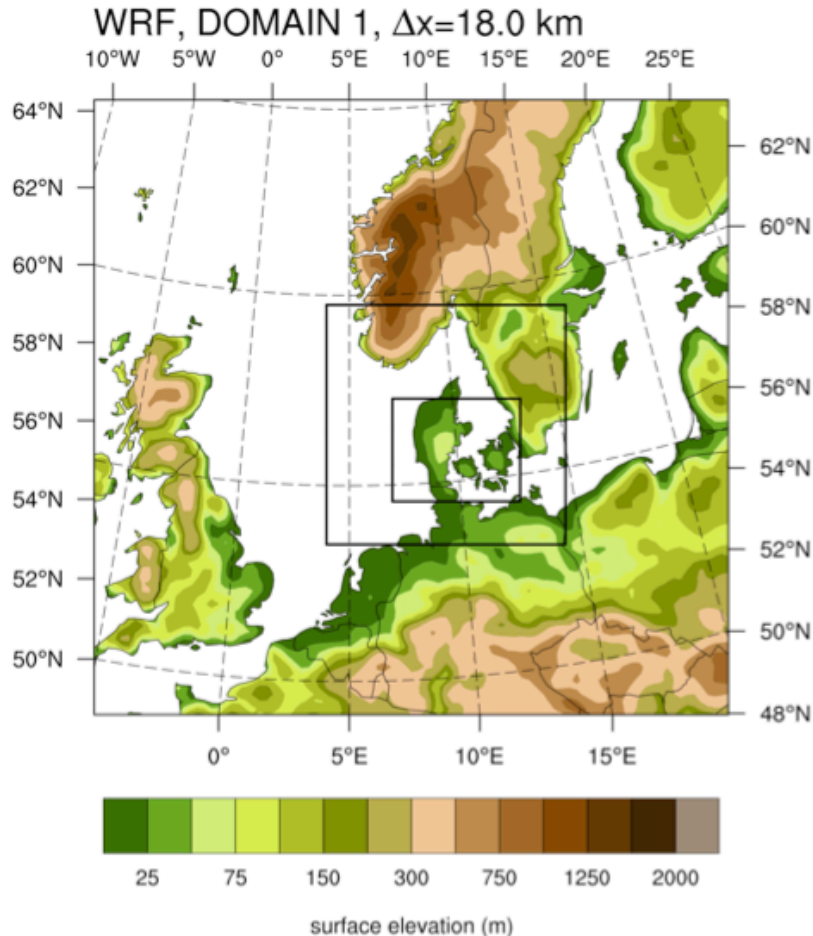


Table 1. WRF configuration

Daily runs at 12 GMT driven by GFS($1^\circ \times 1^\circ$) initial and boundary conditions for the period 1-30 October 2009;

SST from NCEP at $0.5^\circ \times 0.5^\circ$ horizontal resolution

Each simulation lasts 30 hours; hours 0-5 are not used in the analysis

Model domain: 18 km parent domain and two nests at 6 and 2 km

37 vertical levels; lowest 4 at 14, 52, 104, and 162 meters.

No data assimilation or nudging

Besides various PBL and surface layer schemes (see Table 1), the model uses: Thompson graupel scheme, Kain-Fritsch cumulus parameterization

One month long experiment: Same everything except for the PBL + surface layer scheme (ACM2 run with PX land surface model)

Description of PBL parameterizations in the WRF mesoscale model

Table I. Description of the seven experiments, PBL parameterizations, their closure type (Turbulence Kinetic Energy (TKE)) associated land surface models (LSM) and surface layer physics (SLS) schemes, as recommended in [16].

Experiment	PBL parameterization	Closure type	Land surface model	Surface layer scheme
ACM2	Asymmetric Convective Model version 2 [18]	First Order Closure	Pleim-Xu	Pleim-Xu
MRF	Medium Range Forecast Model [19]	Non-local-K mixing	Unified Noah LSM	Monin-Obukhov
MYJ	Mellor-Yamada-Janjic [20]	TKE 1.5-order	Unified Noah LSM	Eta similarity
MYNN2	Mellor-Yamada Nakanishi and Niino Level 2.5 [21]	TKE 1.5-order	Unified Noah LSM	MYNN
MYNN3	Mellor-Yamada Nakanishi and Niino Level 3 [22]	TKE 2nd-order	Unified Noah LSM	MYNN
QNSE	Quasi-Normal Scale Elimination [23]	TKE 1.5-order	Unified Noah LSM	QNSE
YSU	Yonsei University Scheme [24]	Non-local-K mixing	Unified Noah LSM	Monin-Obukhov

Diagnosis of the wind shear



Høvsøre test center, Denmark

Why focus on wind shear?

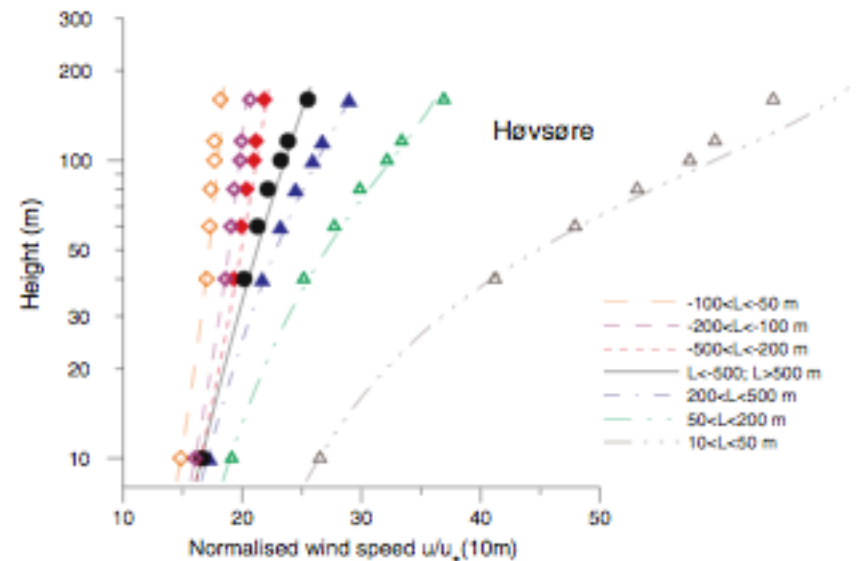
- Important to accurate power production estimates for modern large wind turbines
- Wake losses depend on atmospheric stability

Boundary-Layer Meteorol (2007) 124:251–268
DOI 10.1007/s10546-007-9166-9

ORIGINAL PAPER

On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer

Sven-Erik Gryning · Ekaterina Batchvarova ·
Burghard Brümmner · Hans Jørgensen · Søren Larsen

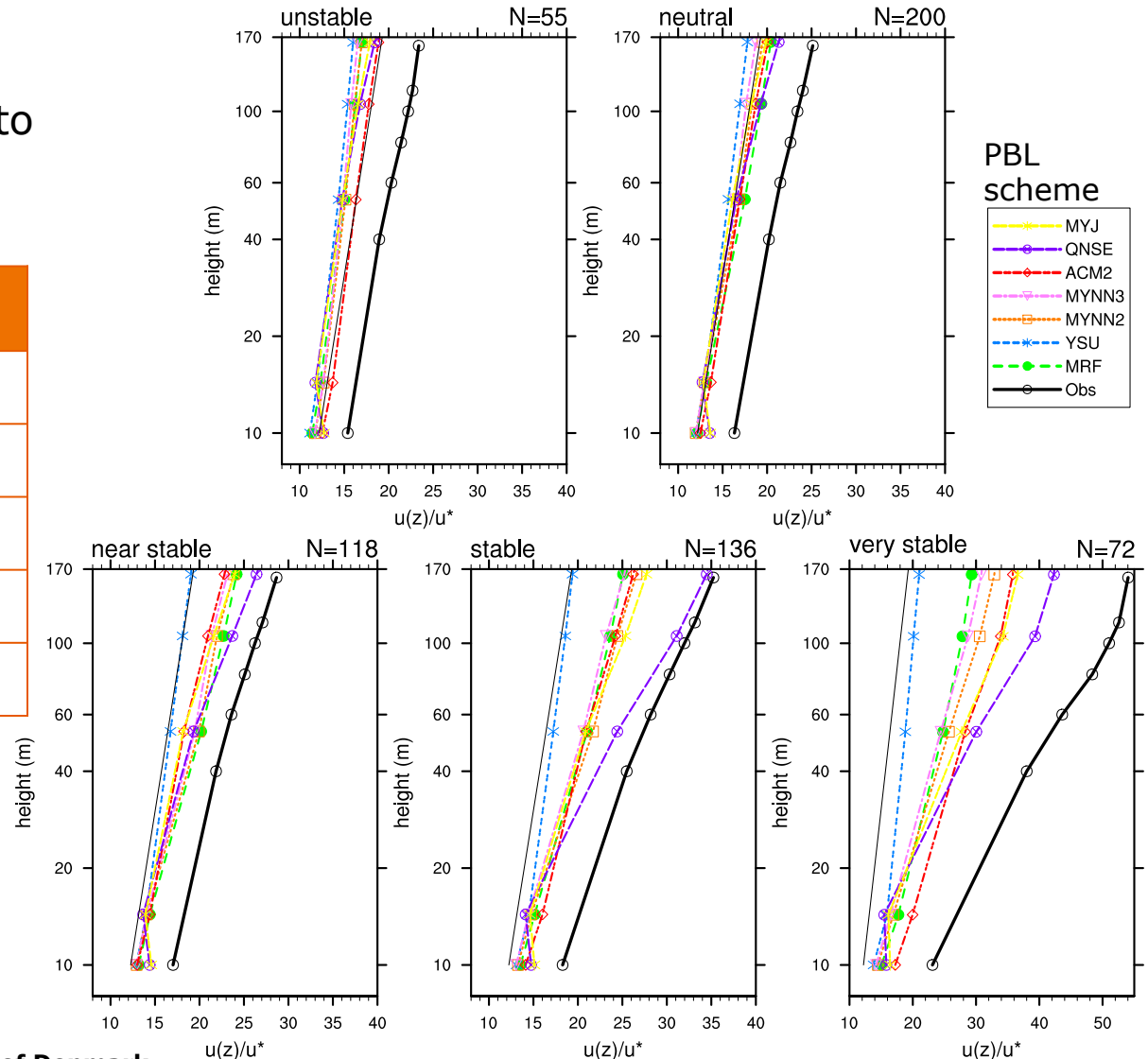


Wind profiles grouped according to observed stability at Høvsøre, Denmark, Oct. 2009

Stability classes according to the Obukhov length L (Gryning et al 2007)

Monin-Obukhov Length	stability class
$-500 < L < -50$	unstable
$L < -500$; $L > 500$	neutral
$200 < L < 500$	near-stable
$50 < L < 200$	stable
$10 < L < 50$	very stable

$$L = -(u_*^3 T_0) / (\kappa g \overline{w' T'}),$$

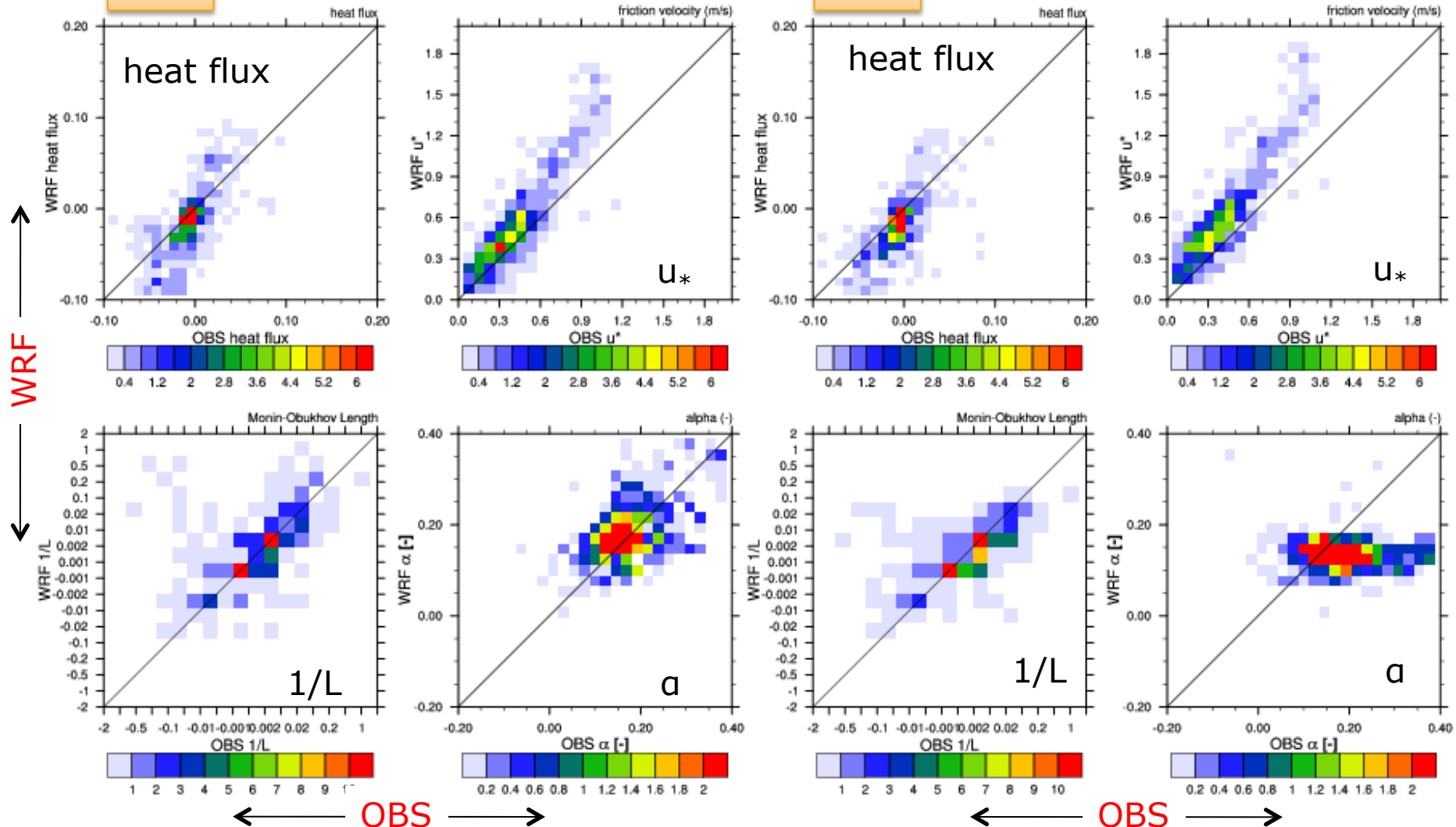


Choice of parameterizations is important

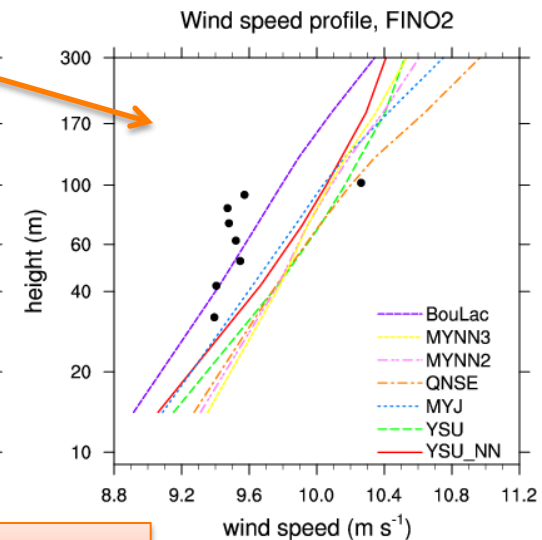
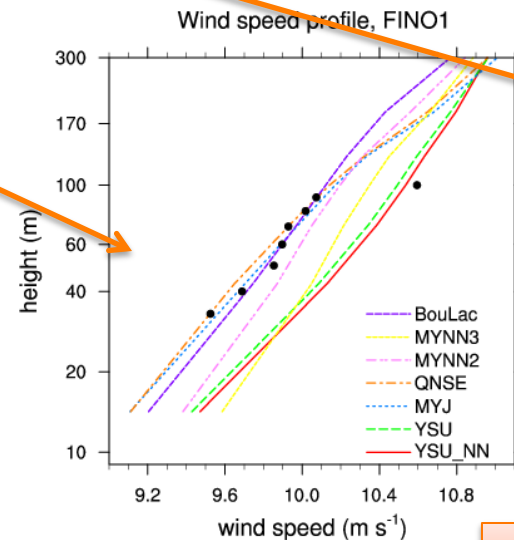
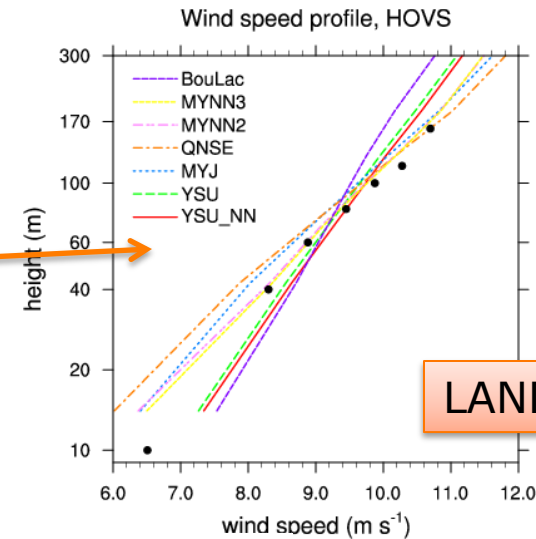
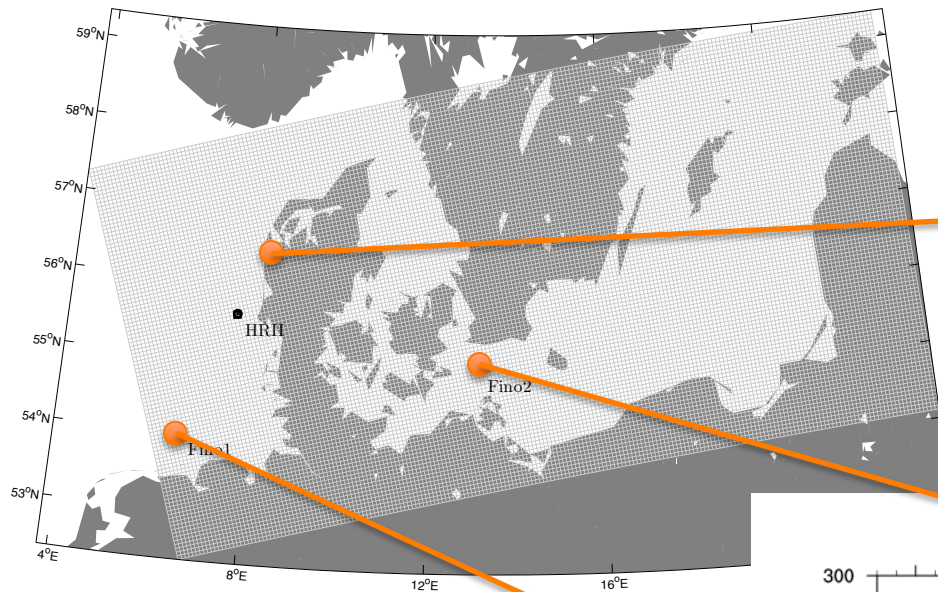
$$\frac{u_1}{u_2} = \left(\frac{z_1}{z_2} \right)^\alpha; \text{shear exponent; } 10\text{-}60 \text{ m}$$

MYJ Probability distributions MYJ

YSU Probability distributions YSU



Validation of downscaling wind profiles, October 2009



15, 5km dynamical downscaling
(WRF) – CFSR reanalysis

October 2009

6 boundary layer schemes
(MYNN2, MYNN3, MYJ, QNSE –
KTE schemes, BouLac, YSU –
Non-local schemes)

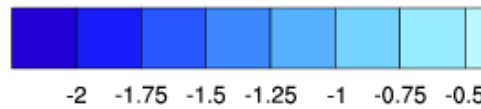
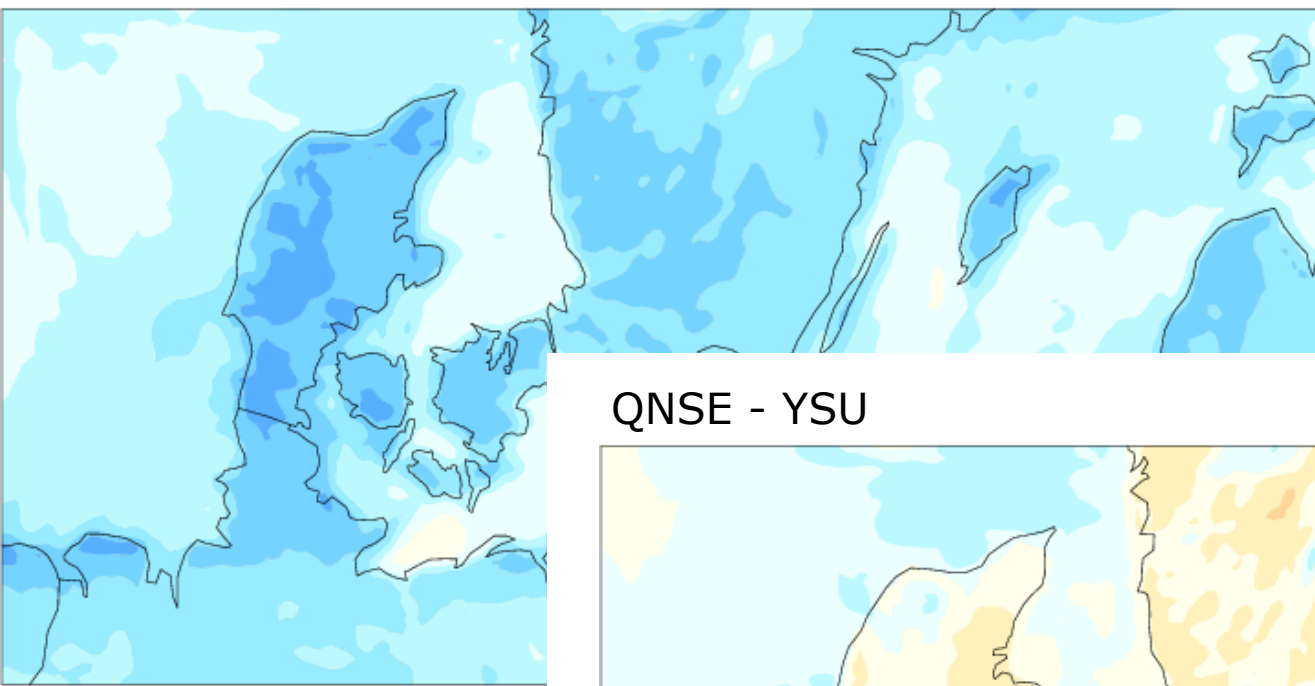
OCEAN

QNSE - YSU

height: 42m

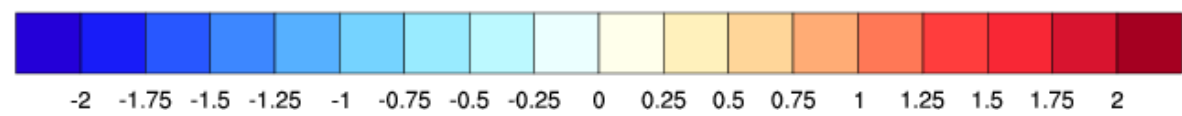
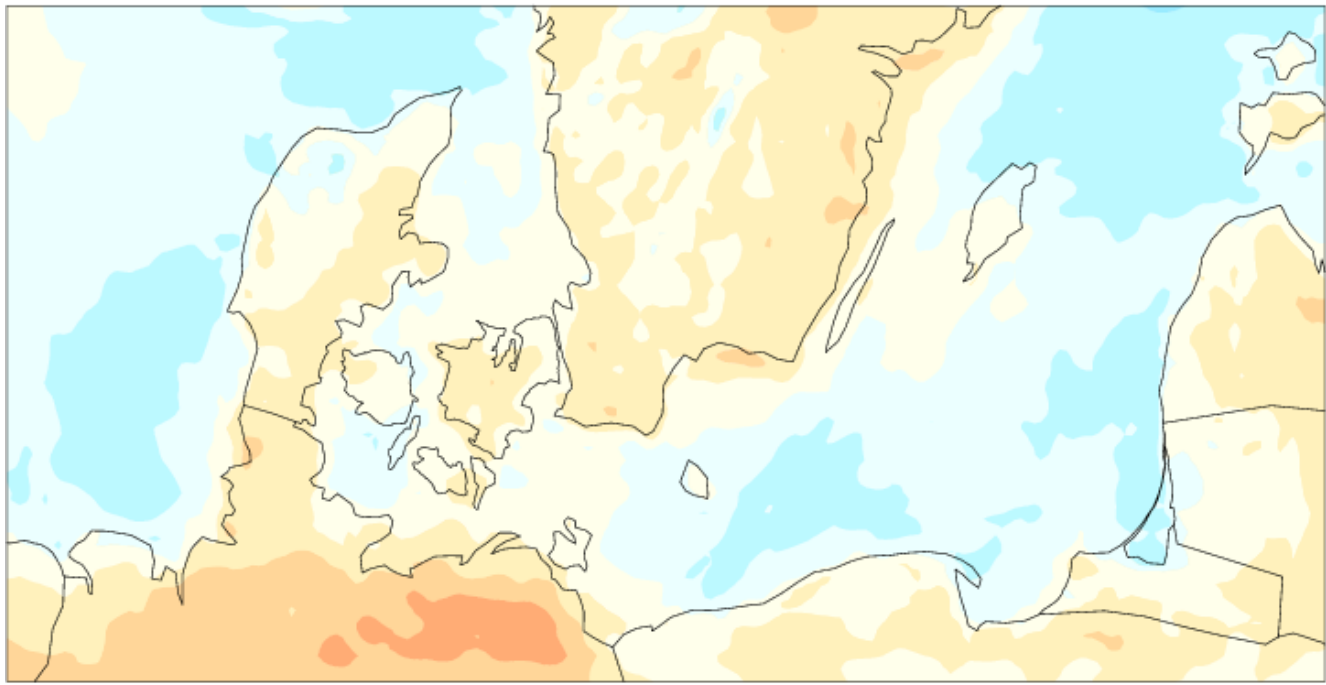


Monthly-mean (Oct 2009) differences in wind speed - 2 PBL schemes



QNSE - YSU

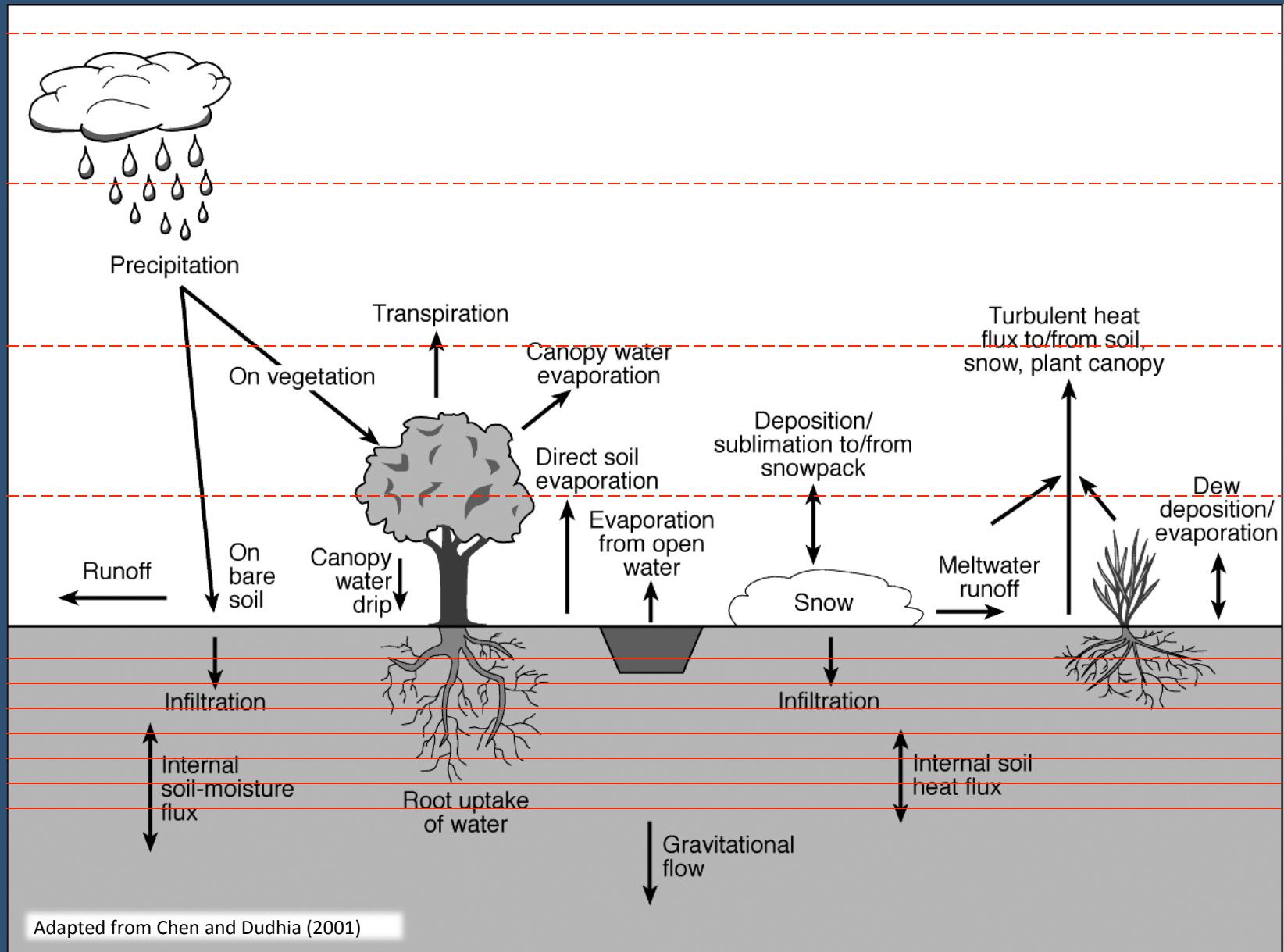
height: 127m



Land surface processes – background

- There has been an historical tendency for “atmospheric” models to become more-encompassing of the entire physical system:
 - Biosphere (vegetation)
 - Lithosphere (ice)
 - Hydrosphere (ocean and lake circulations)
 - Land surface/subsurface
 - Air chemistry
- More-encompassing models often called **Earth-system models**.
- Needs for non-atmospheric parts of the physical system?
 - e.g., sea-surface temperature may be specified if atmospheric simulations are sufficiently short (1-2 weeks) – instead of having an ocean model.
 - Longer simulations/forecasts (inter-seasonal, decadal) require that more processes be involved in the model dynamics.
- The land-atmosphere coupling operate on sub-diurnal time scales, so must be treated dynamically in all models.

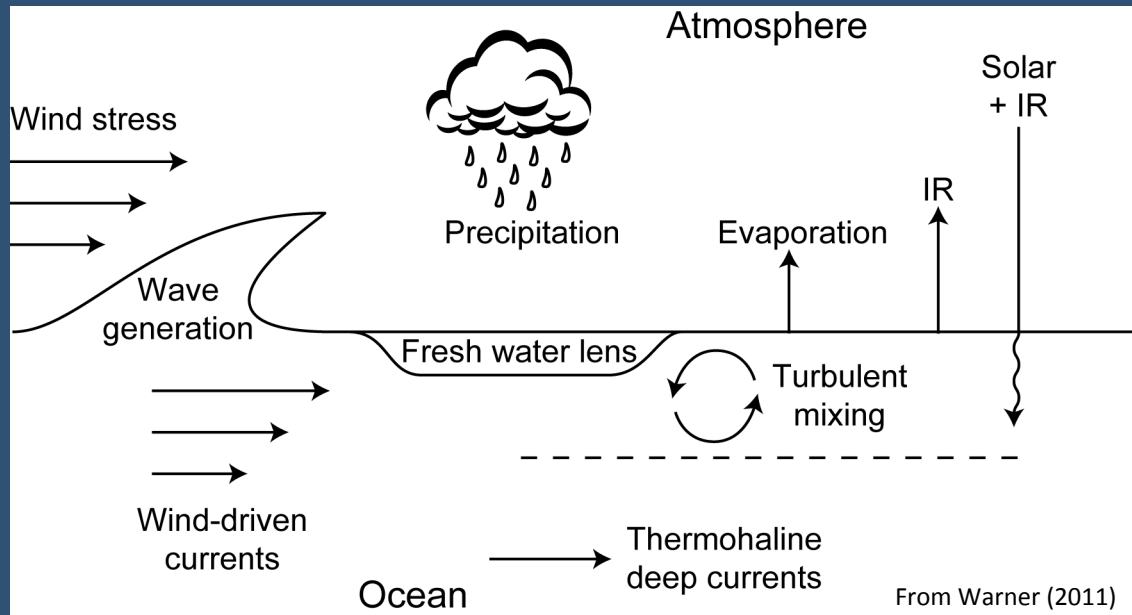
Processes that must be represented



Importance of properly modeling urban landscapes

- Climate change and human health
- Sea-level rise
- Indoor and outdoor air quality
- Human thermal stress
- Water resources and management
- Atmospheric transport of accidental or intentional releases of toxic material
- Severe weather, flood

Water Surfaces



NWP models usually treat these simply
Constant Sea-Surface Temperature
Wave roughness a function of wind speed

Coupling mesoscale and microscale models

Mesoscale to microscale coupling: Need for generalization

mesoscale view



$$h(x) = f(x)$$

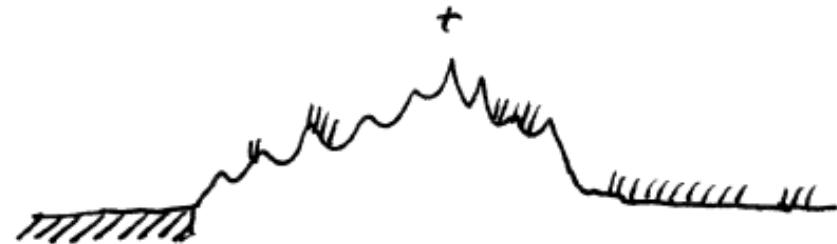
$$z_0(x) = r(x)$$

\neq

$$f(x) \neq g(x)$$

$$r(x) \neq s(x)$$

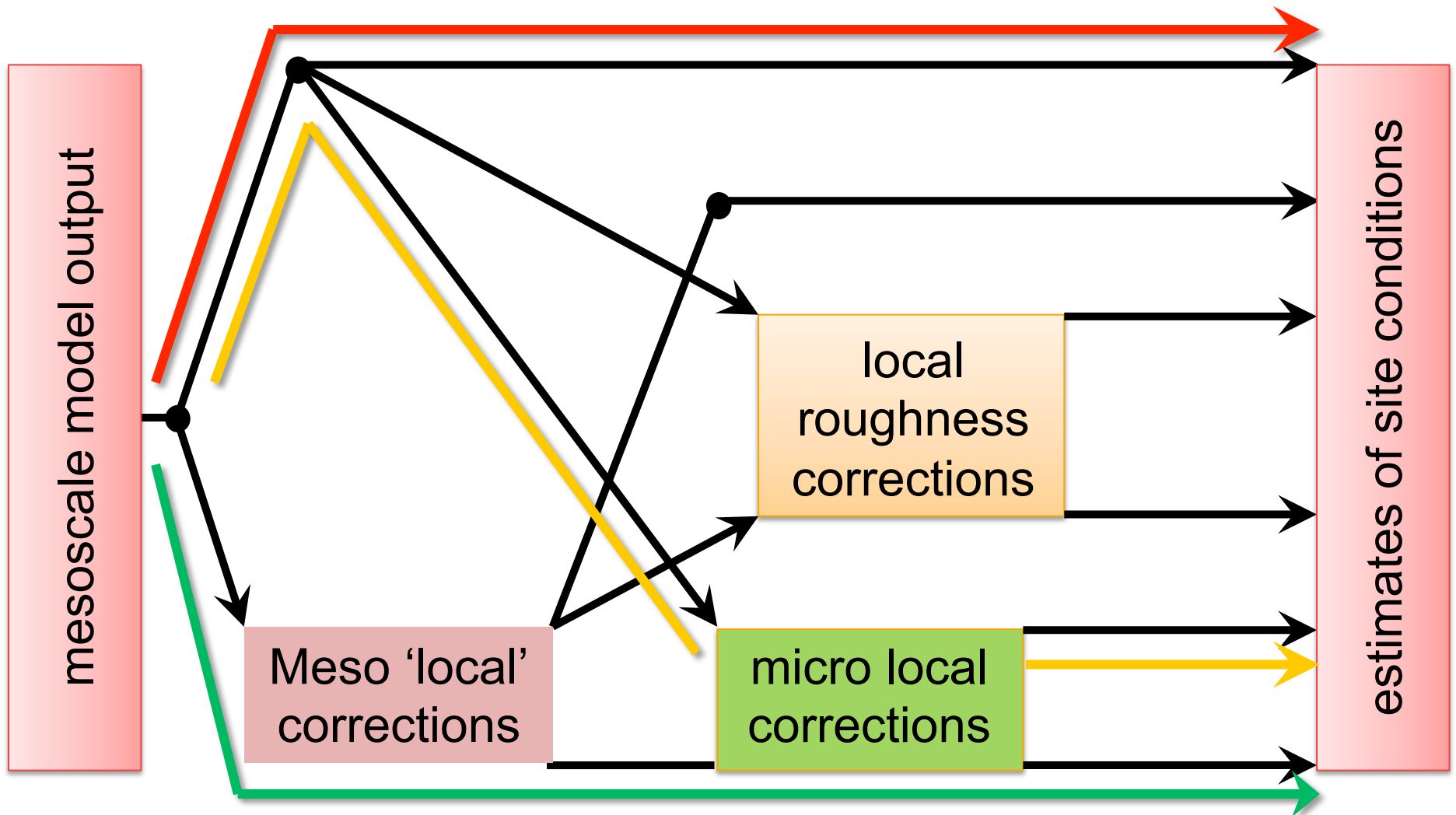
reality view



$$h(x) = g(x)$$

$$z_0(x) = s(x)$$

Routes from mesoscale model to site

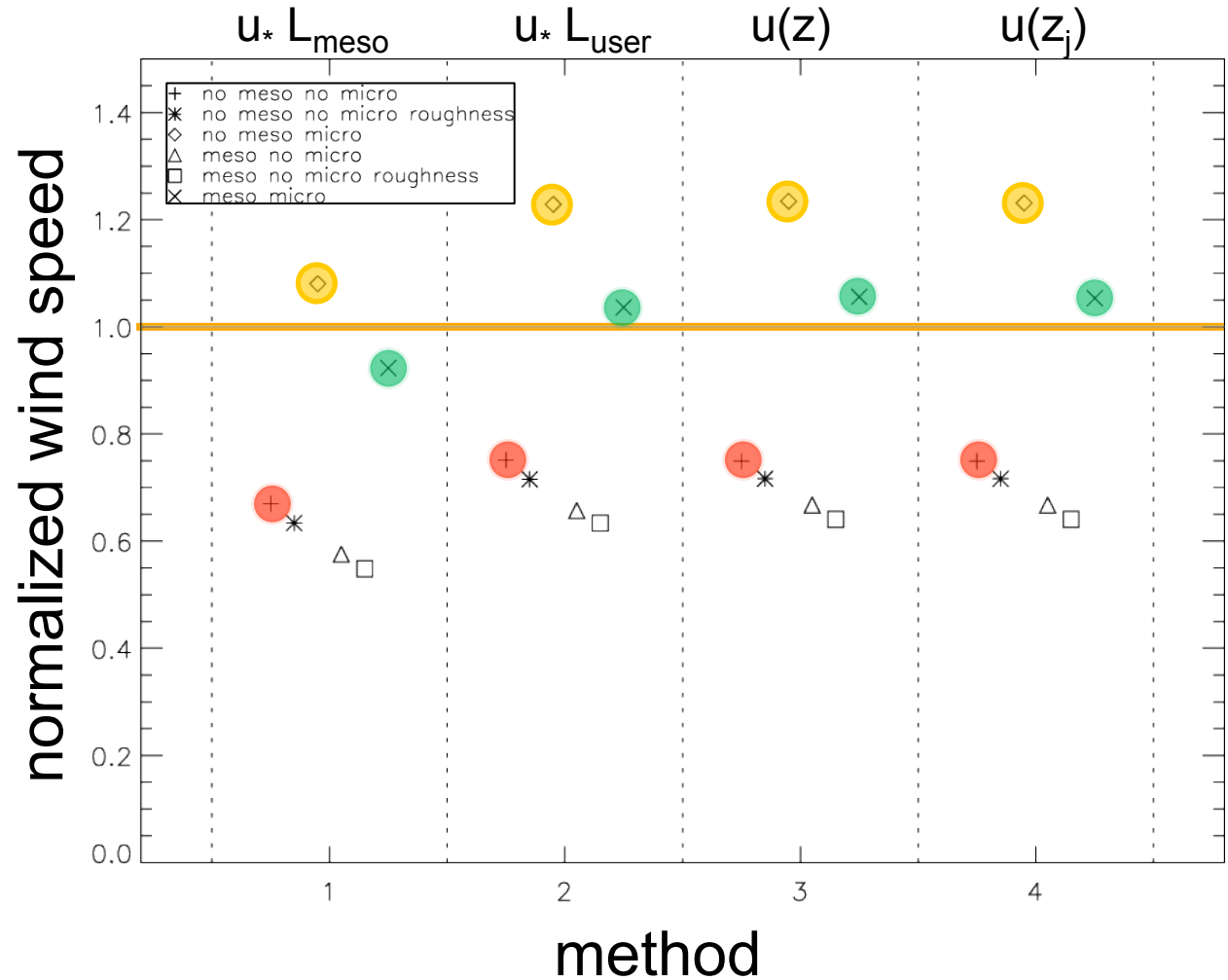


 direct
  micro corrections only
  meso & micro corrections

Verification of mean wind speed

Site in
northern
Spain

Mesoscale 'local'
corrections and
microscale local
corrections give best
agreement with
measurements

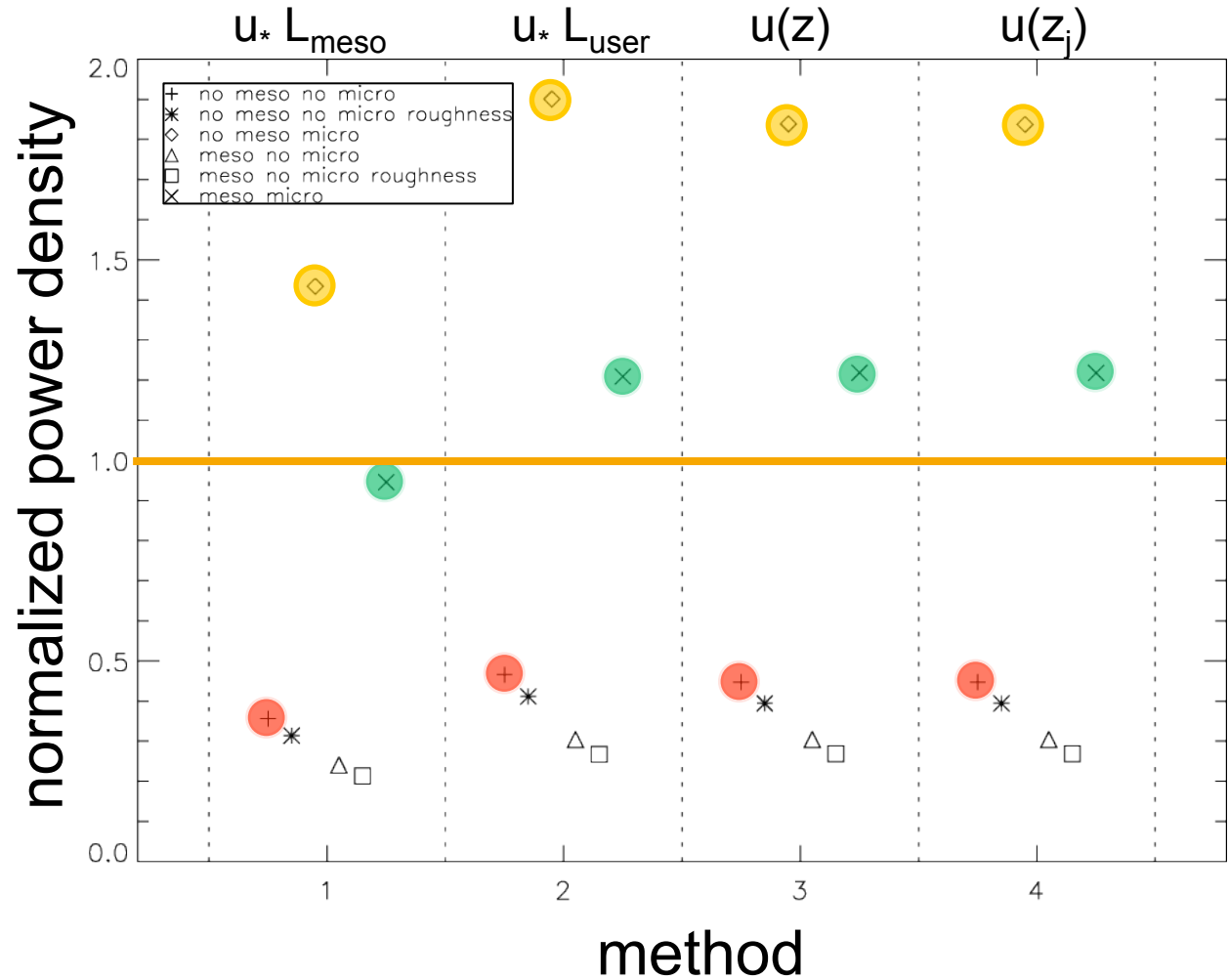


☹ direct ☺ micro corrections only 😊 meso & micro corrections

Verification of mean power density

Site in
northern
Spain

Mesoscale 'local'
corrections and
microscale local
corrections give best
agreement with
measurements



☹ direct ☹ micro corrections only 😊 meso & micro corrections

Importance of microscale... a motivation

Wind resource (power density) at 50 m calculated at different resolutions

