Development of fine-scale structures in large-eddy simulations over complex terrain

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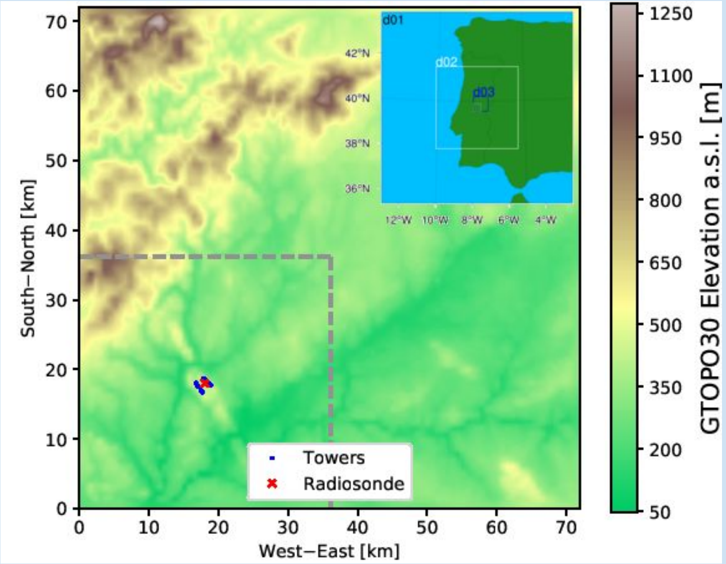
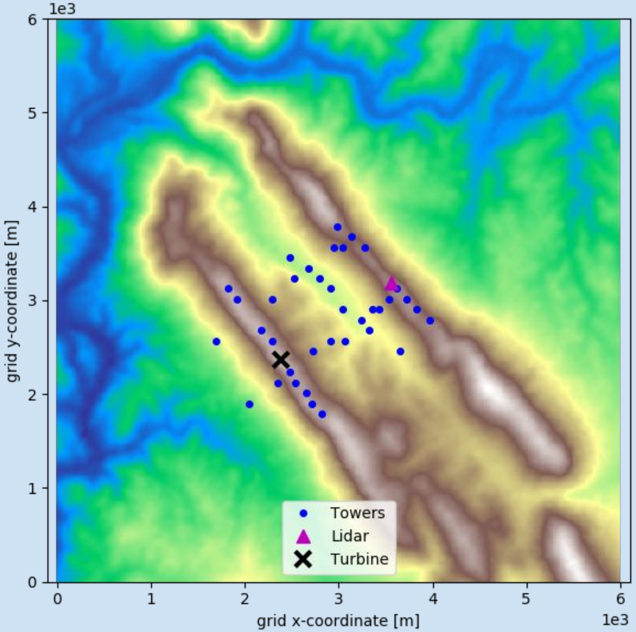
Motivation

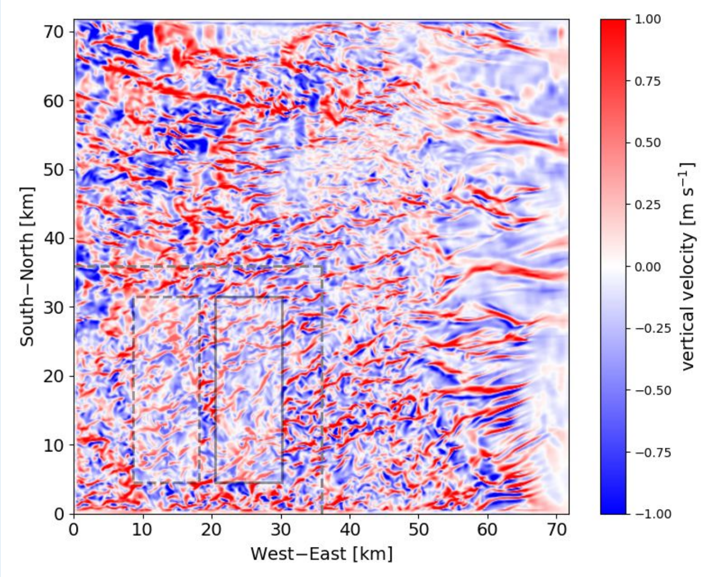
Grid nesting for numerical weather prediction
- Development of fine scale turbulence in large-eddy simulation

Reduce computational cost
- Smaller domains

Wind energy forecast
- The Perdigão field campaign (Fernando, et al. 2019)







Overview

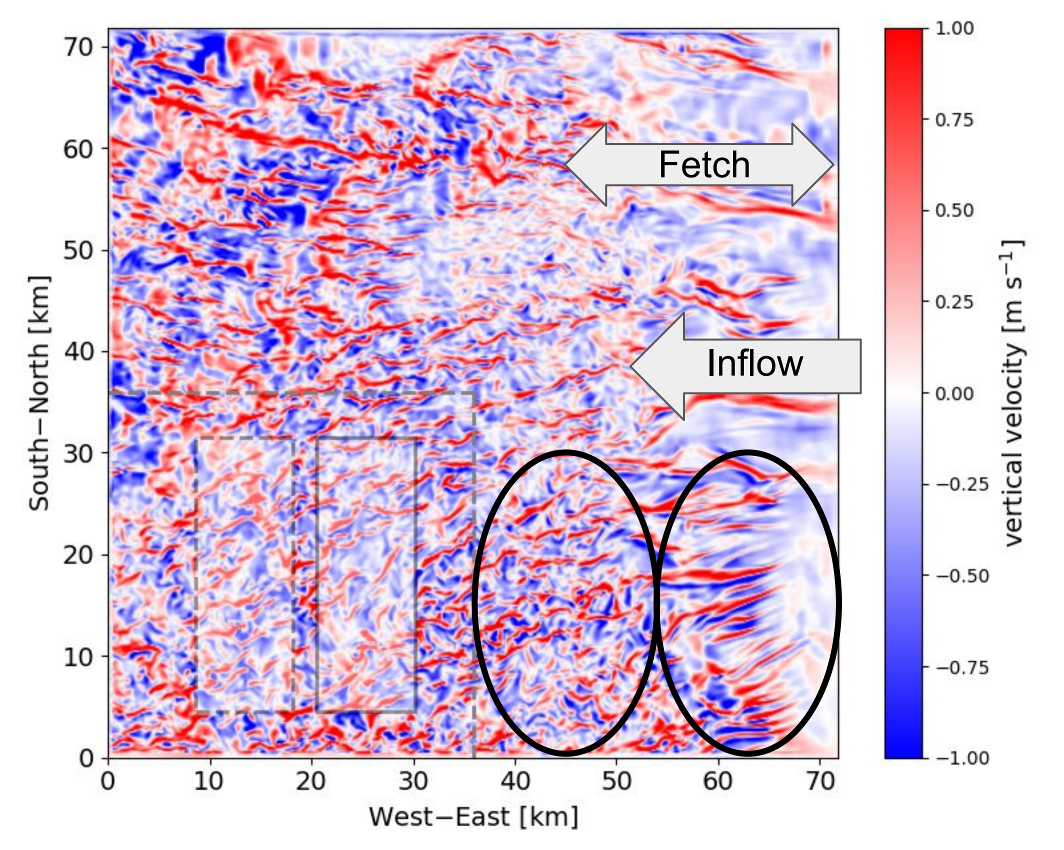
Developing turbulence in large-eddy simulation (LES)

Cell Perturbation Method (CPM)

Diurnal variations
- Strongly convective
- Weakly convective
- Stably stratified

Topography resolution sensitivity
- 30 arcsec ~ 1 km USGS (GTOPO30)
- 3 arcsec ~ 90 m Shuttle Radar Topography Mission (SRTM)

Fetch to develop turbulence



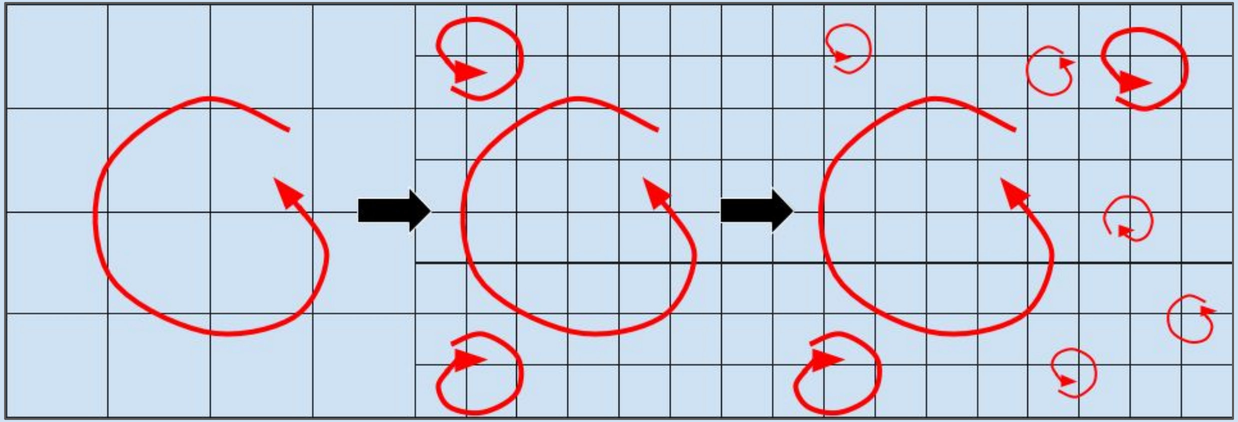
Fetch: Distance from inflow boundary

Fine scale, turbulent structures

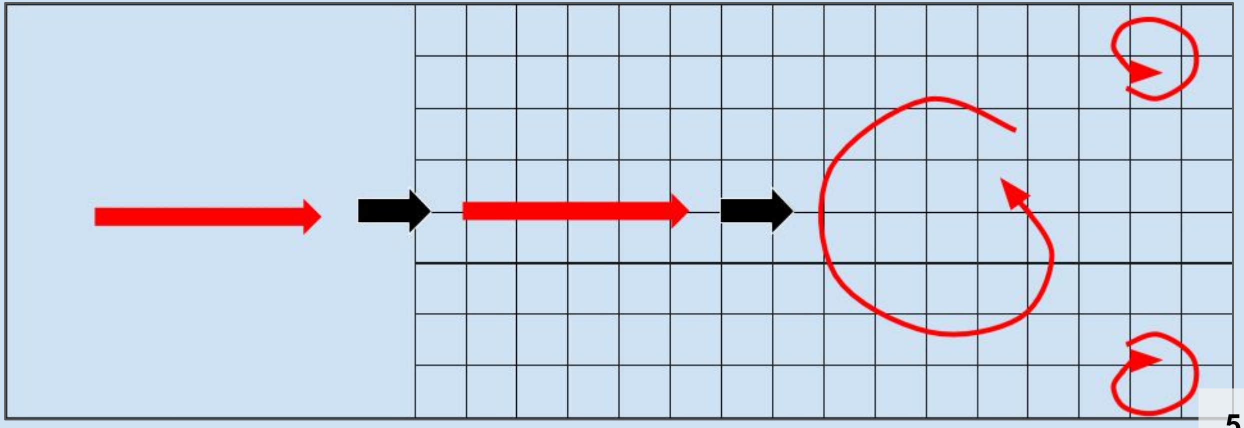
Un- and under-resolved turbulence
- ‘Streaks’
- Large scale structures

Fetch to develop turbulence

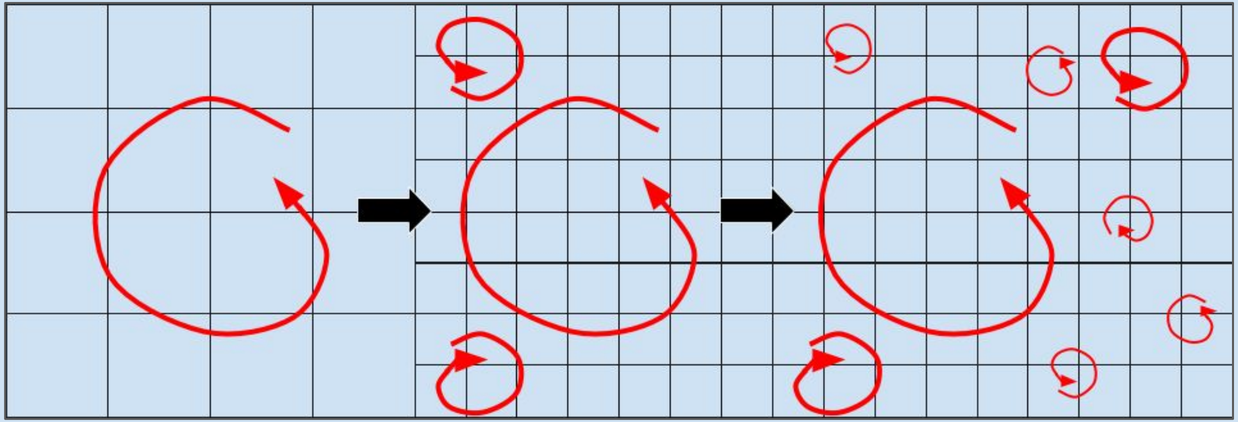
Ideal nest



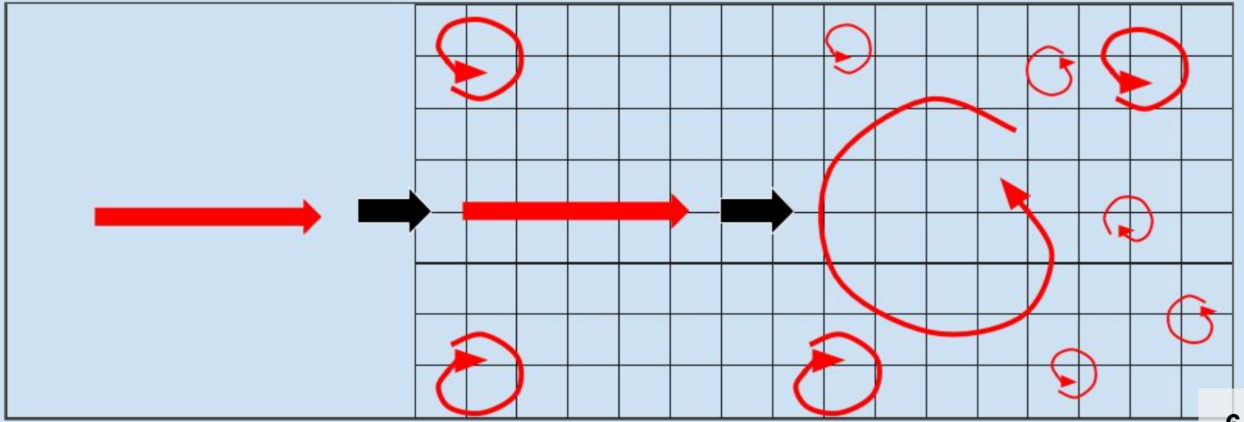
Typical practice



Fetch to develop turbulence

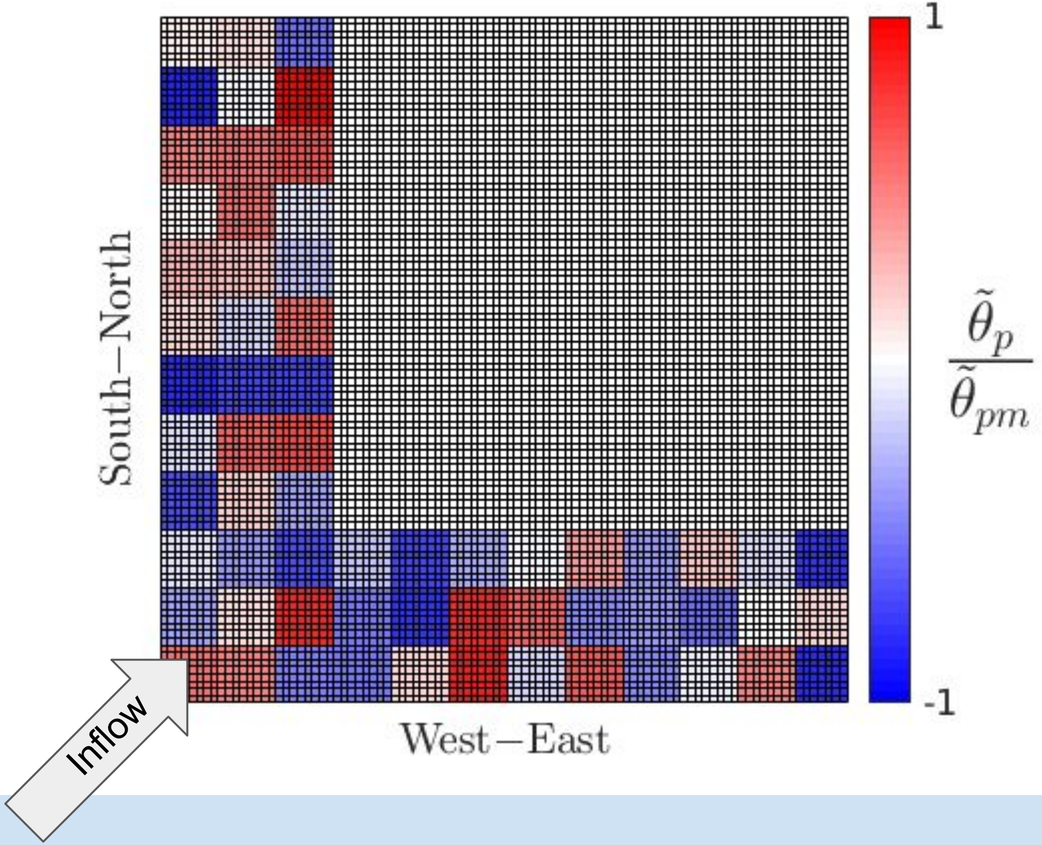


Ideal nest



Typical practice
Cell Perturbation Method applied

Cell Perturbation Method (CPM)



Perturbations applied to potential temperature field

Three, 8x8 grid point 'cells' along inflow boundaries

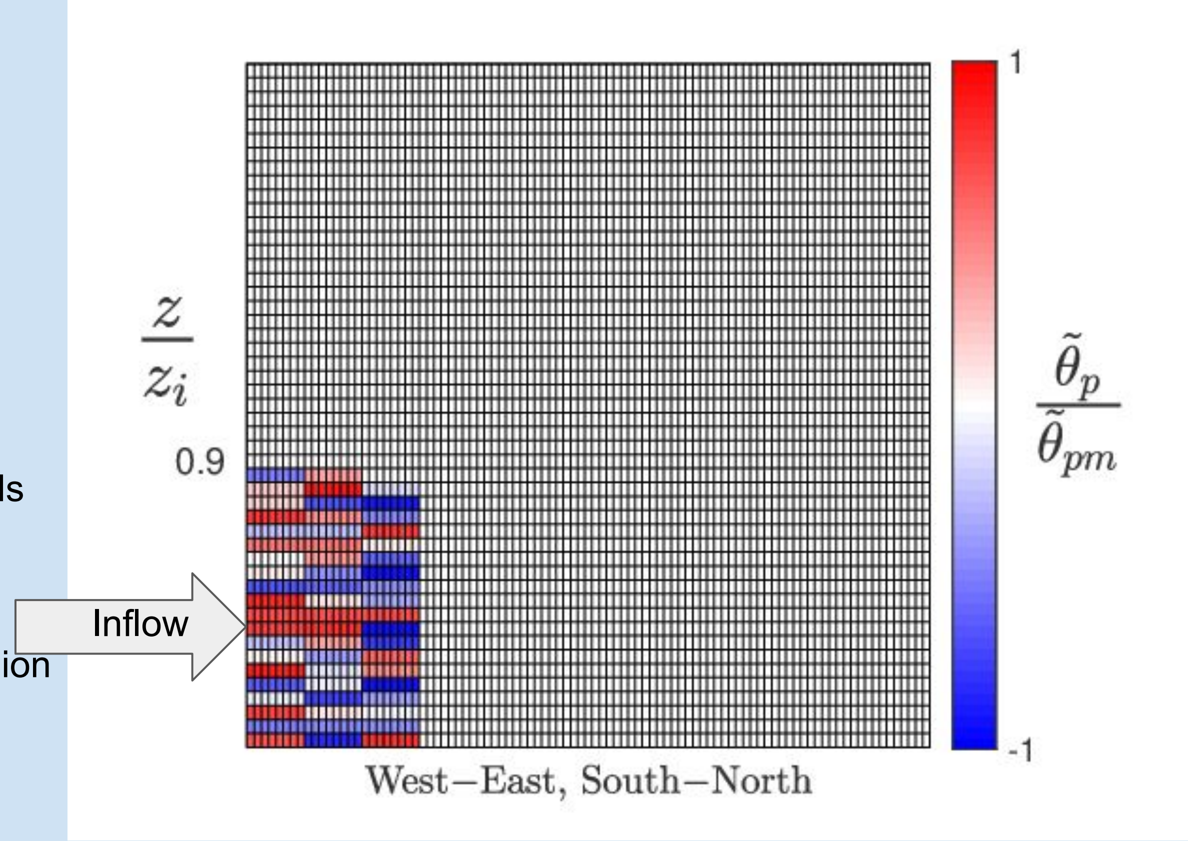
Momentum affected by buoyancy

Cell Perturbation Method (CPM)

Perturbations applied for most of the boundary layer depth, $0.9z_i$

Magnitude determined by wind speeds just above boundary layer, $1.1z_i$

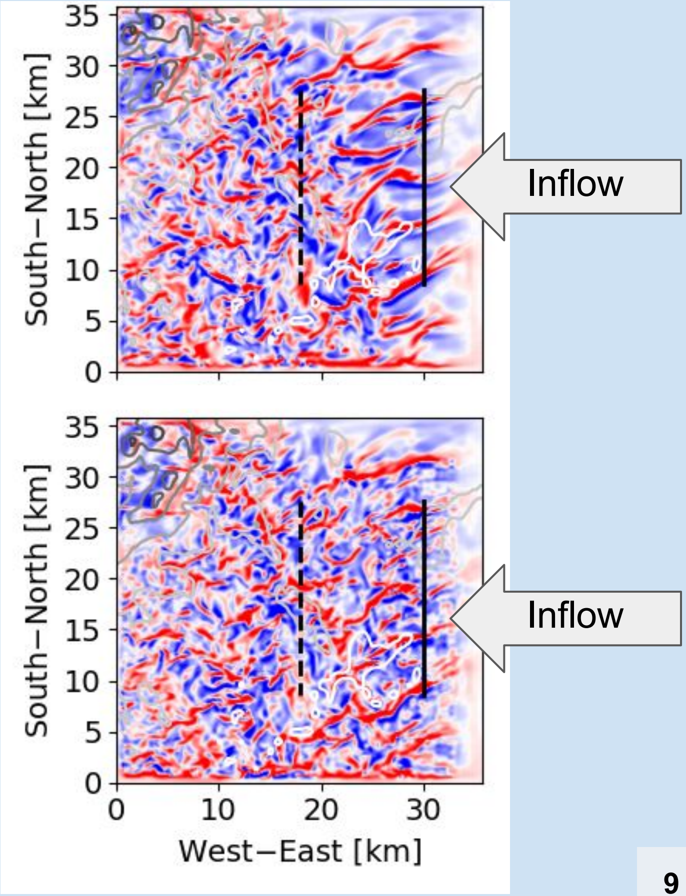
New perturbations applied after advection across the perturbation region



Cell Perturbation Method (CPM)

No CPM

CPM applied



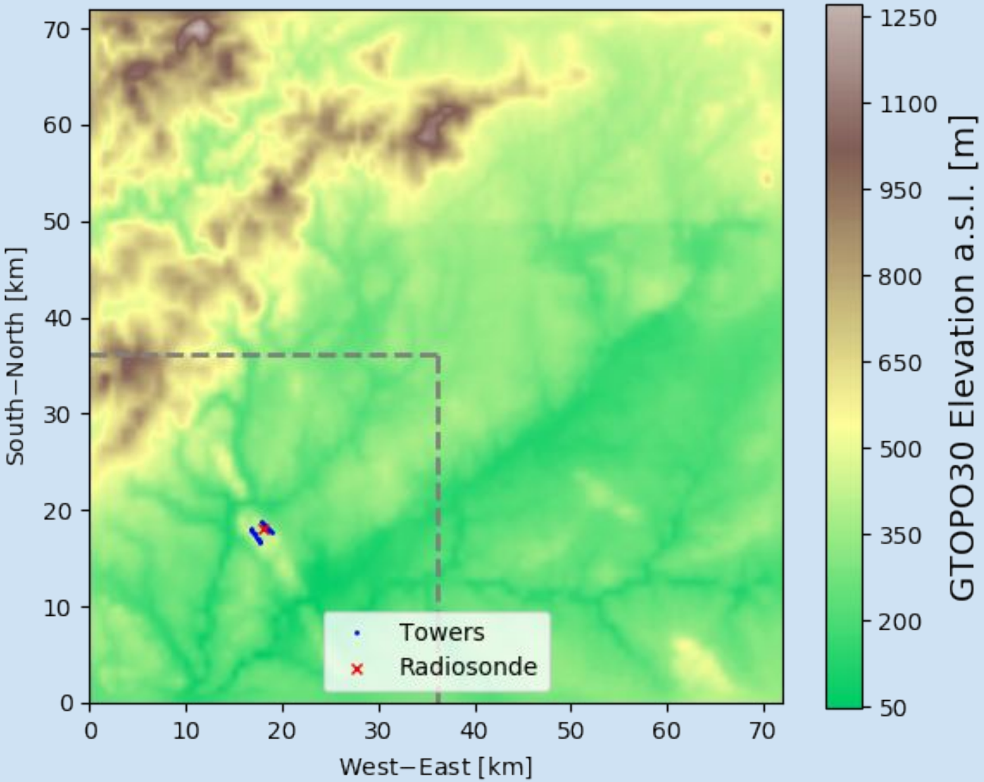
Goal is to reduce fetch, distance from inflow, before fine scale structures develop

Visually, seems to work

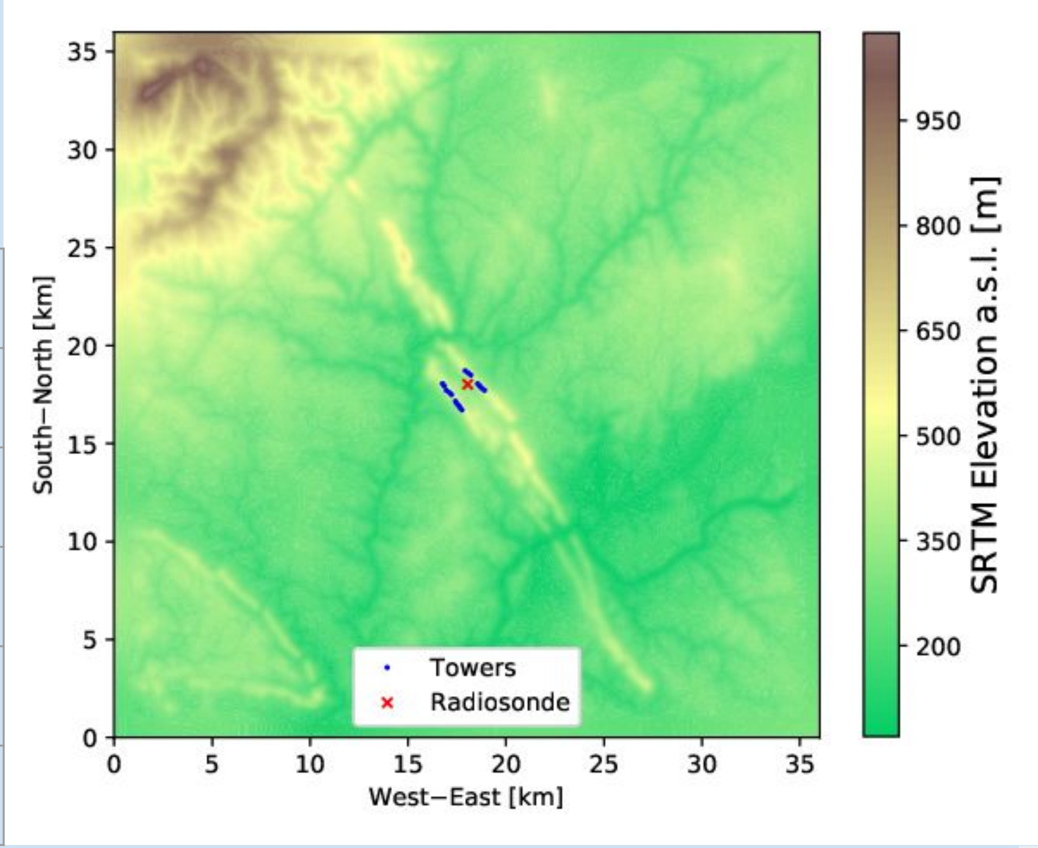
How to measure? What is expected?

Nested large-eddy simulation

	Δx,Δy	nx*ny*nz	CPM	Topo.
d03_30s	150 m	241*241	off	30s
d03_30s_cpm	150 m	241*241	on	30s
d03_ref	150 m	481*481	off	30s



Nested large-eddy simulation



	Δx,Δy	nx*ny*nz	CPM	Topo.
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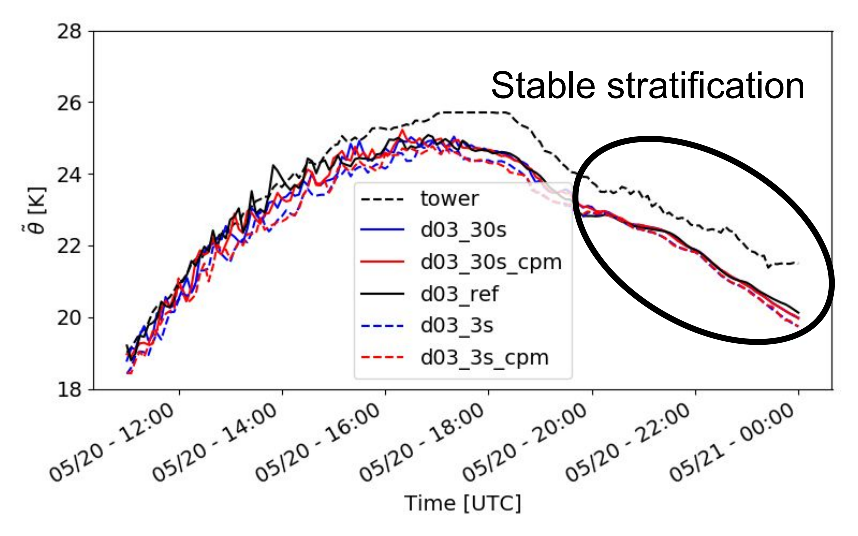
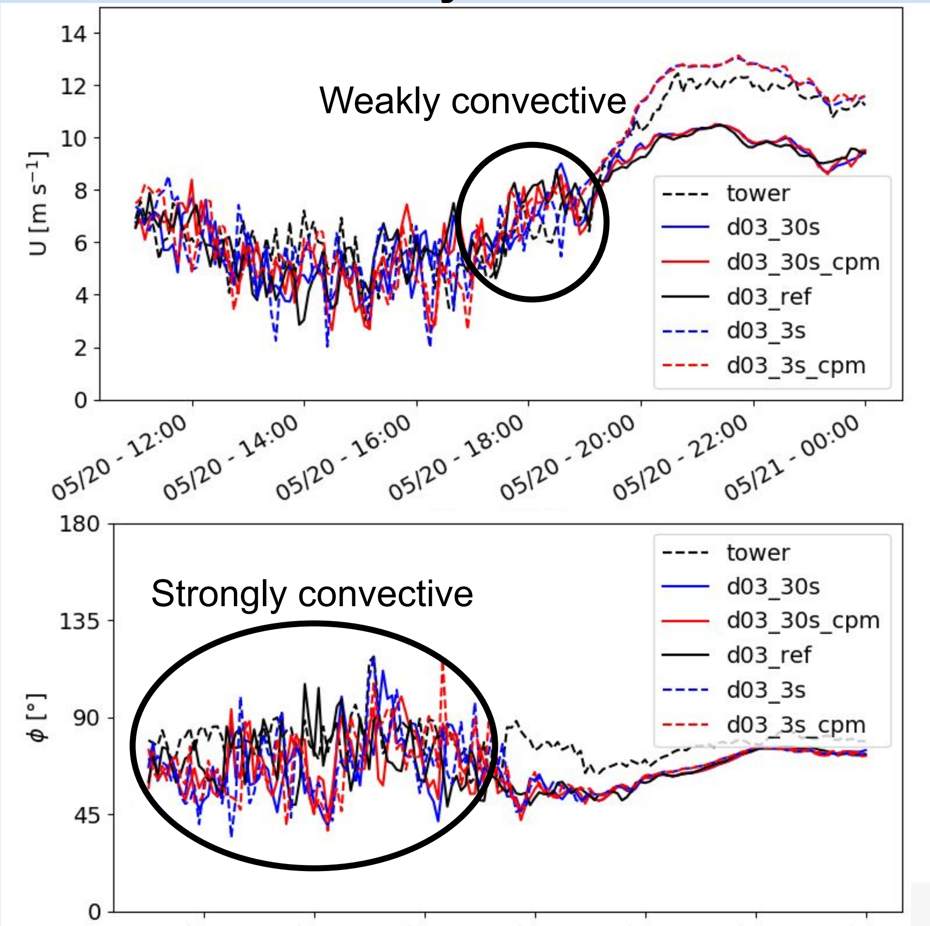
d03_30s_cpm	150 m	241*241	on	30s
d03_ref	150 m	481*481	off	30s
d03_3s	150 m	241*241	off	3s
d03_3s_cpm	150 m	241*241	on	3s

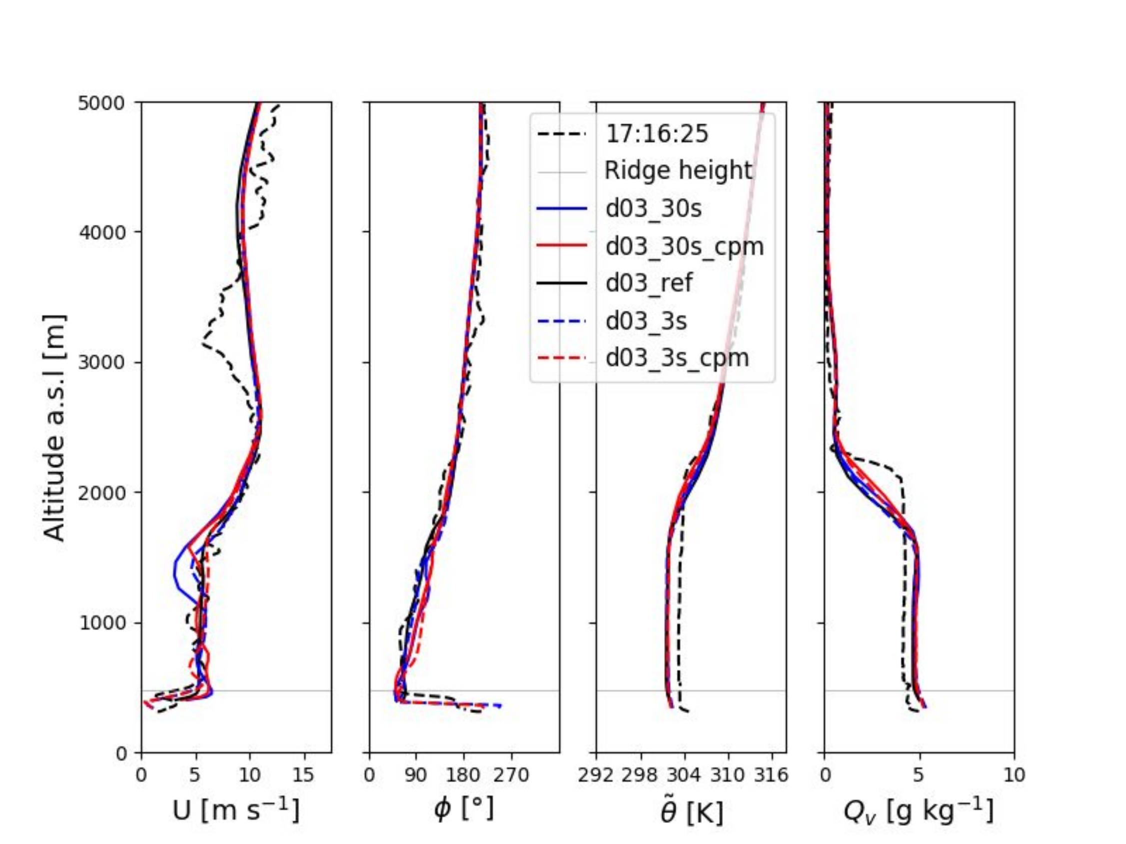
Diurnal Cycle

Tower tSE04 time series from 100 m a.g.l.





Weakly convective, 1715 UTC



Well mixed layer

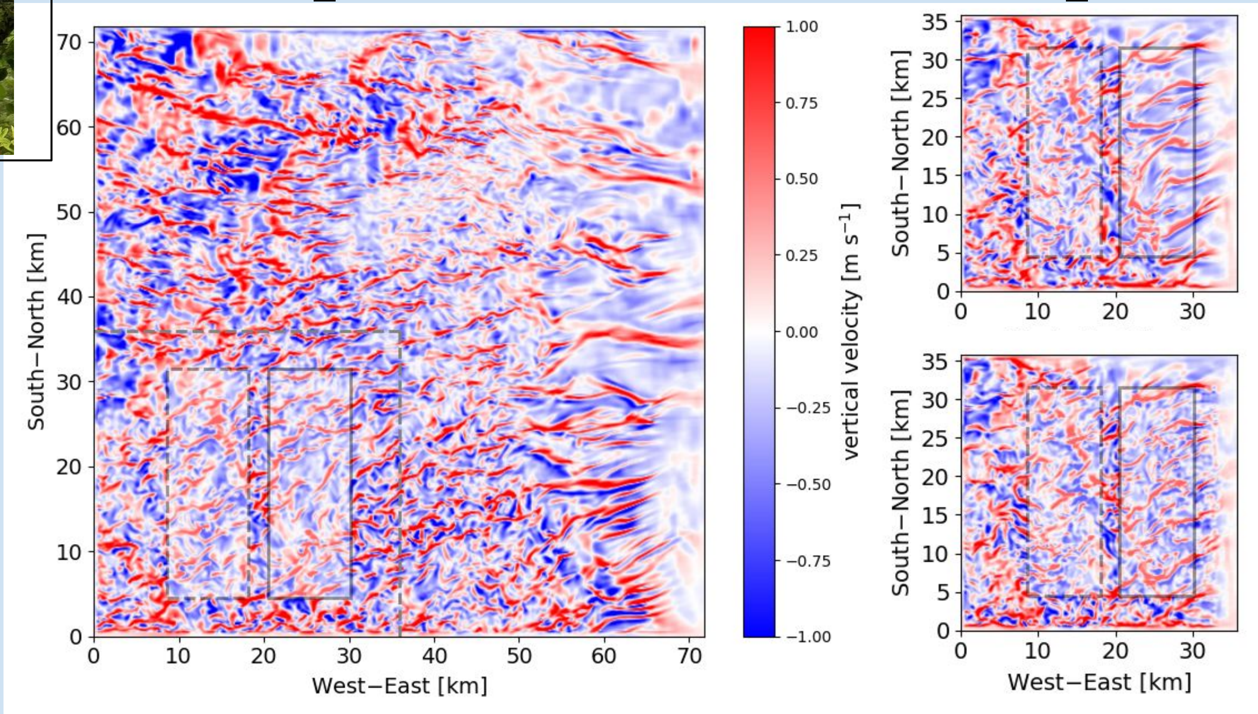
East by North-Easterly boundary layer flow, above ridge height

Note, only *3s* simulations have solutions defined in valley

Weakly convective, 1715 UTC

d03_ref

d03_30s



d03_30s_cpm

Two patches:

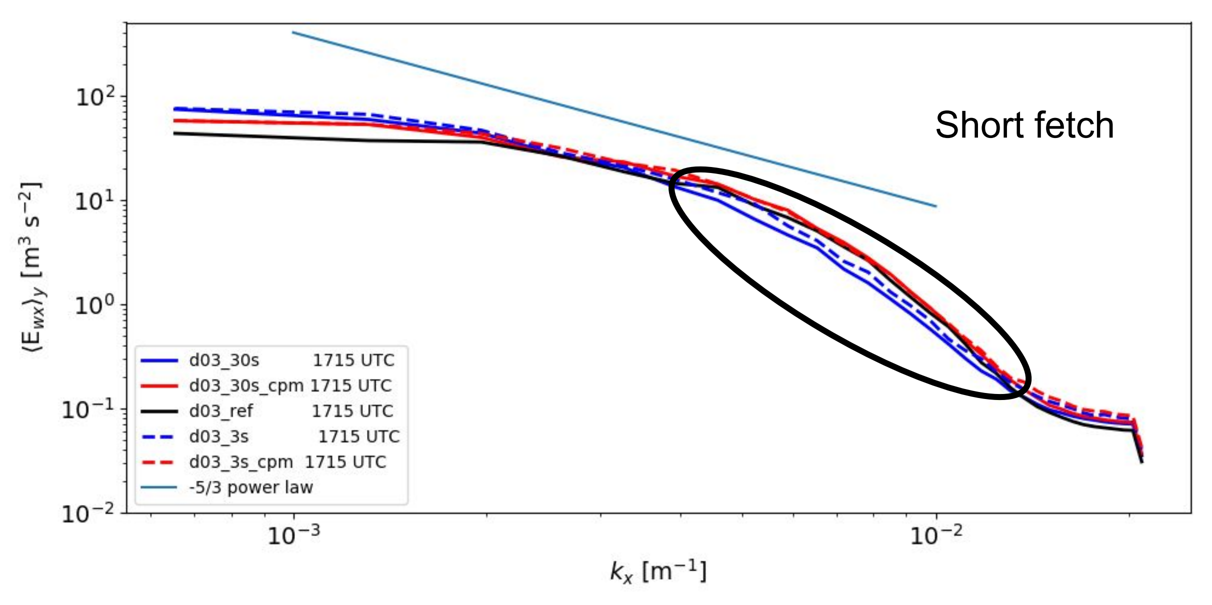
Short fetch

Long fetch

Reference simulation always has +240 points (36 km) more fetch than other LES

Spectra computed in x direction, then averaged in y and time

Weakly convective, 1715 UTC



Without CPM, LES underestimate energy spectral density for wavenumbers just greater than the resolved inertial subrange

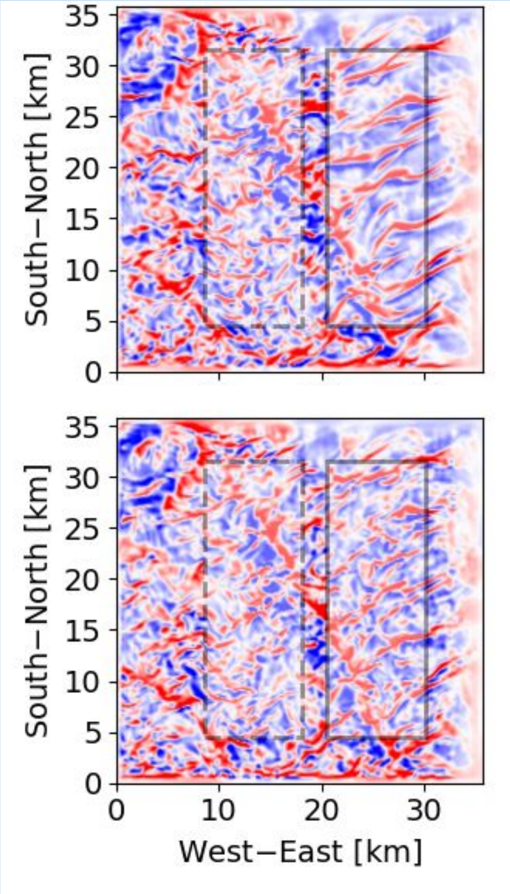
Simulations with CPM agree with the reference simulation

Without CPM, high res topography adds energy but spectra are still underestimated compared to d03_ref

Weakly convective, 1715 UTC

d03_3s

d03_3s_cpm



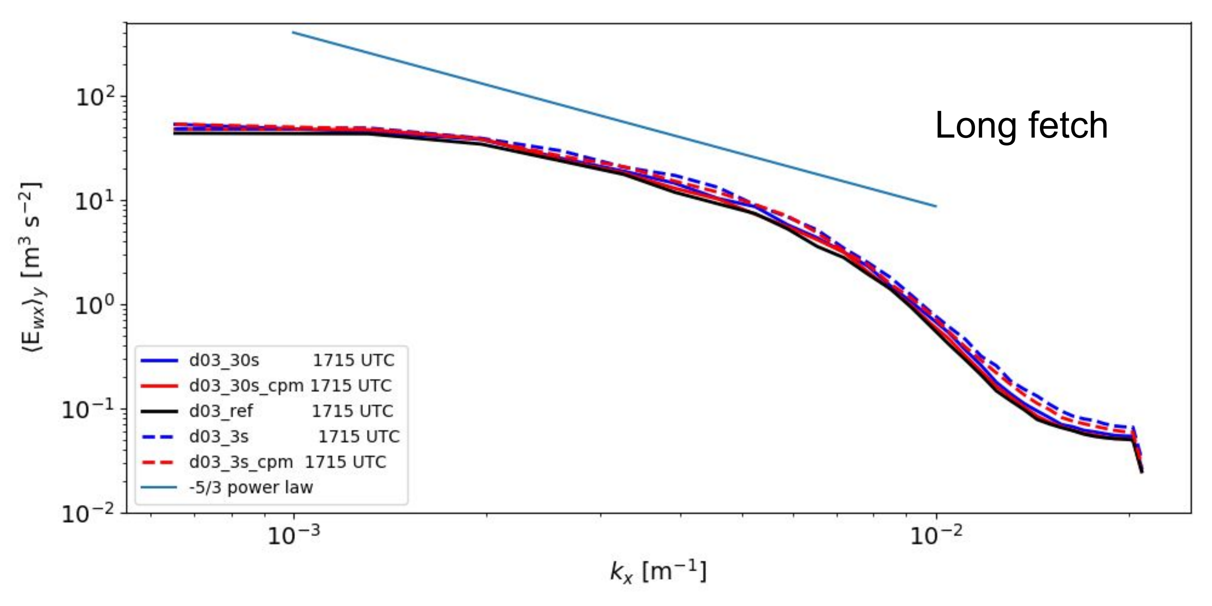
Without CPM, LES underestimate energy spectral density for wavenumbers just greater than the resolved inertial subrange

Simulations with CPM agree with the reference simulation

Without CPM, high res topography adds energy but spectra are still underestimated compared to d03_ref

‘Streaks’ persits in high resolution topography LES without CPM

Weakly convective, 1715 UTC

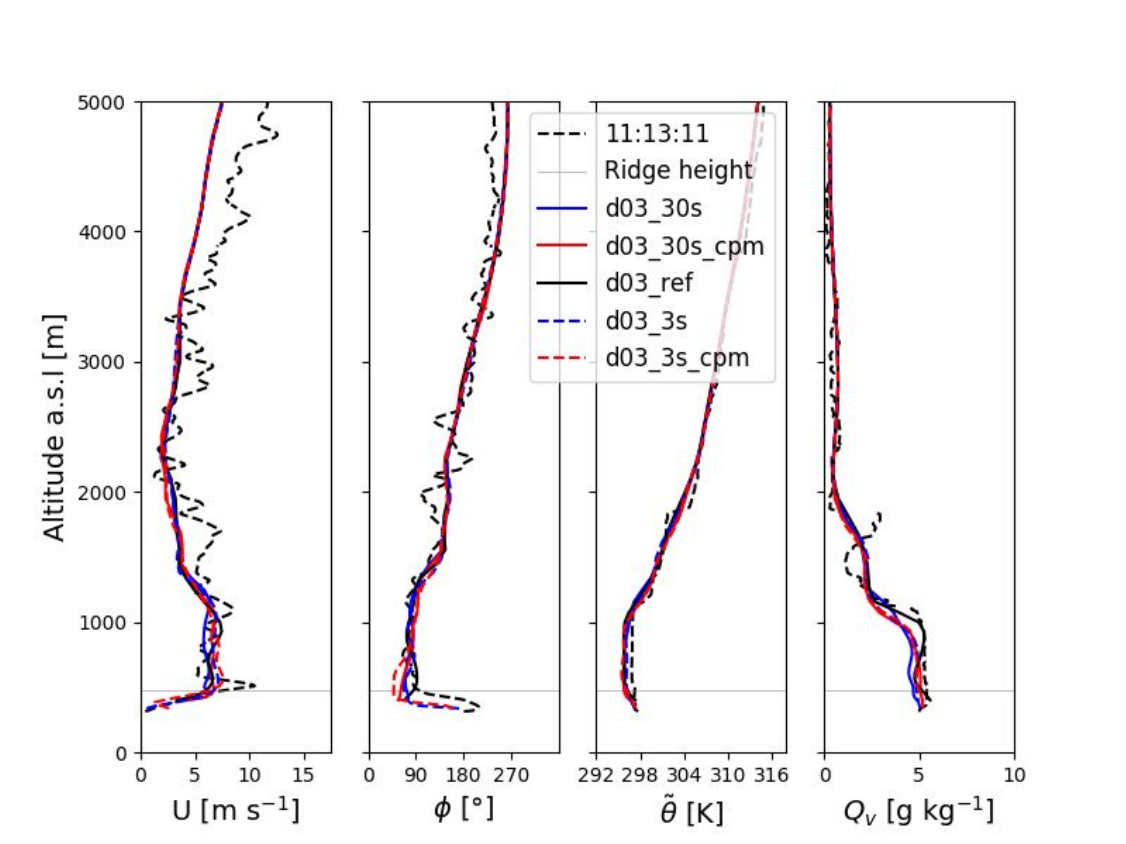


Spectra eventually collapse

Some increased energy due to topography, most notable at highest wavenumbers

Conclusion:
CPM accelerates development of turbulence, in ways high resolution topography cannot, without contaminating the long term development of turbulence.

Strongly convective, 1115 UTC

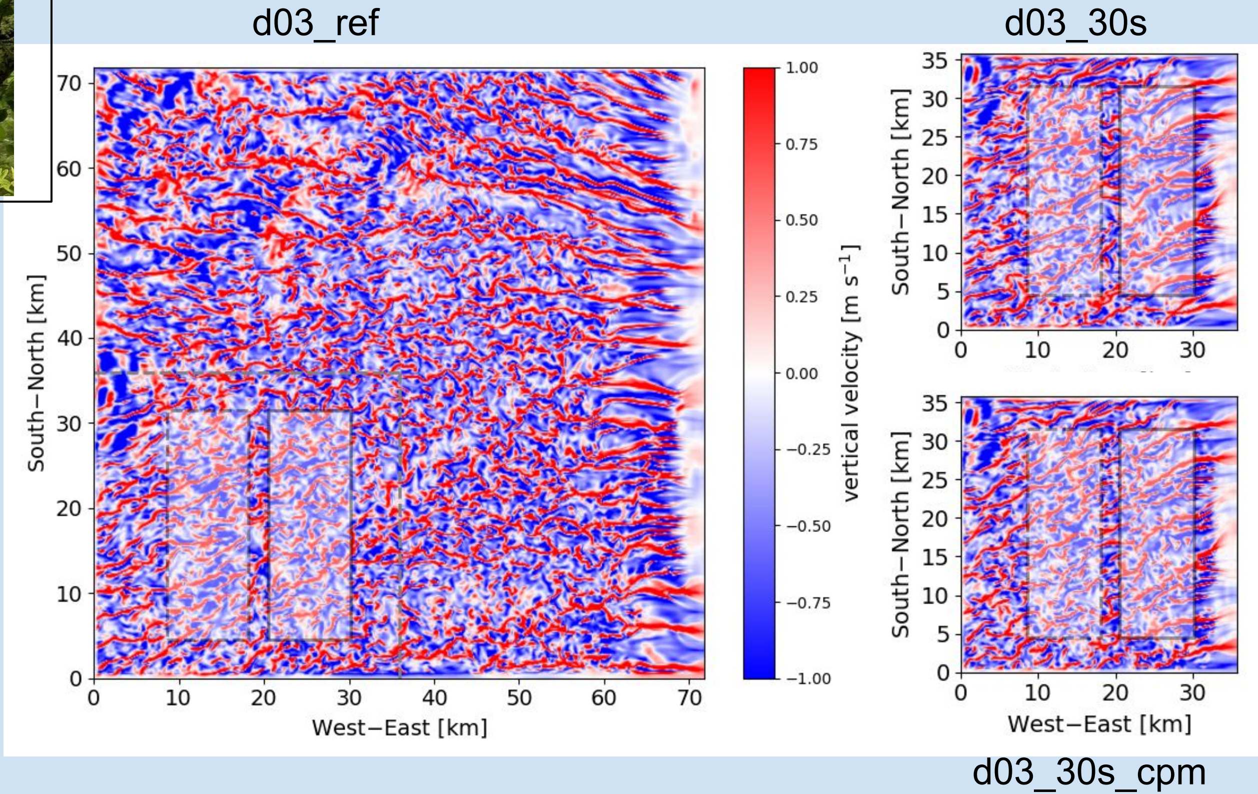


Well mixed layer

Easterly boundary layer flow, above ridge height

Note, only *3s* simulations have solutions defined in valley

Strongly convective, 1115 UTC

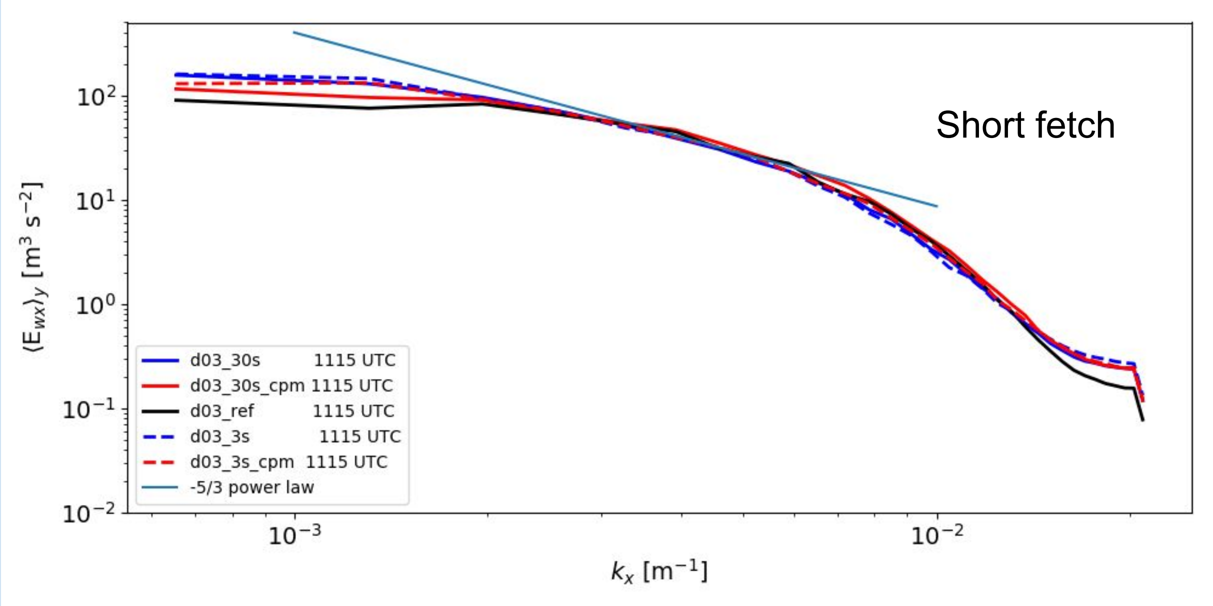


Finer scale features than weakly convective time

‘Streaks’ break up soon after inflow

CPM does not significantly change the turbulence

Strongly convective, 1115 UTC



Finer scale features than weakly convective time

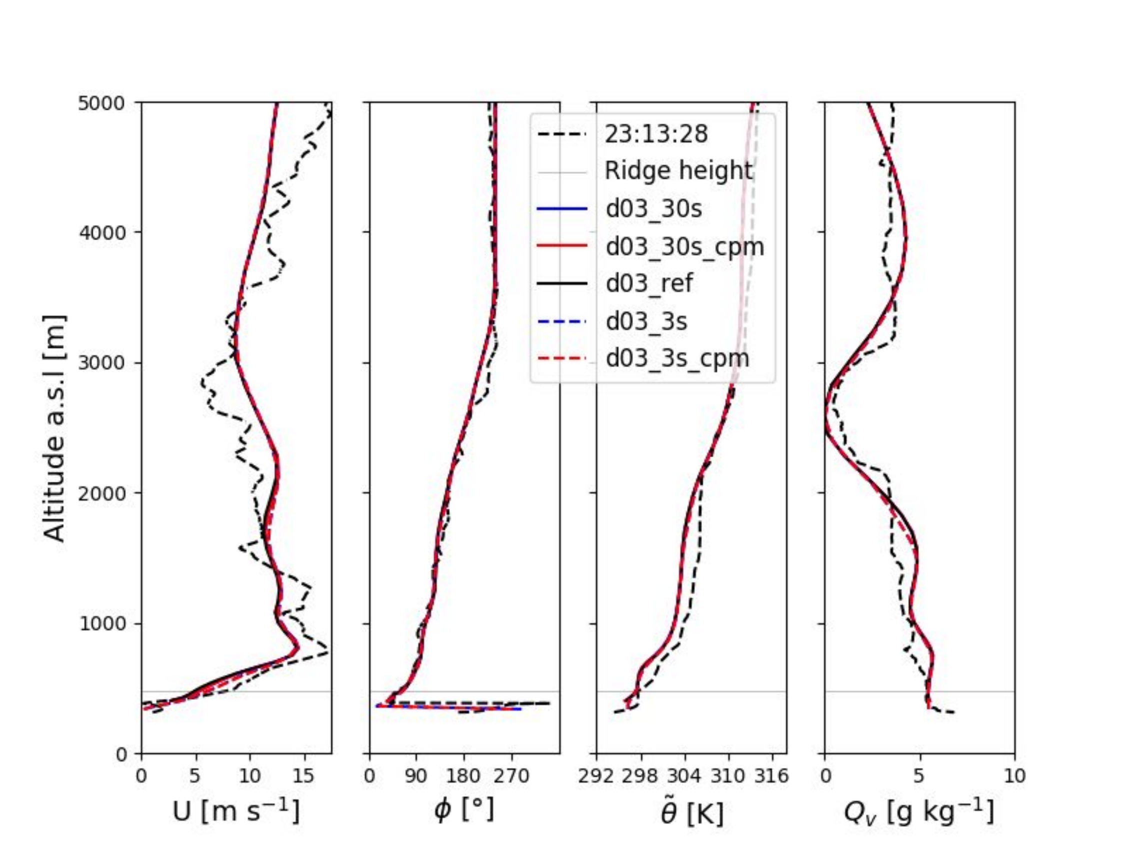
‘Streaks’ break up soon after inflow

CPM does not significantly change the turbulence

Topography resolution does not significantly change turbulence

Resolved inertial subrange

Stably stratified, 2315 UTC



Wind speeds higher, peak at bottom of residual layer

Bulk stability below 1 km a.s.l.

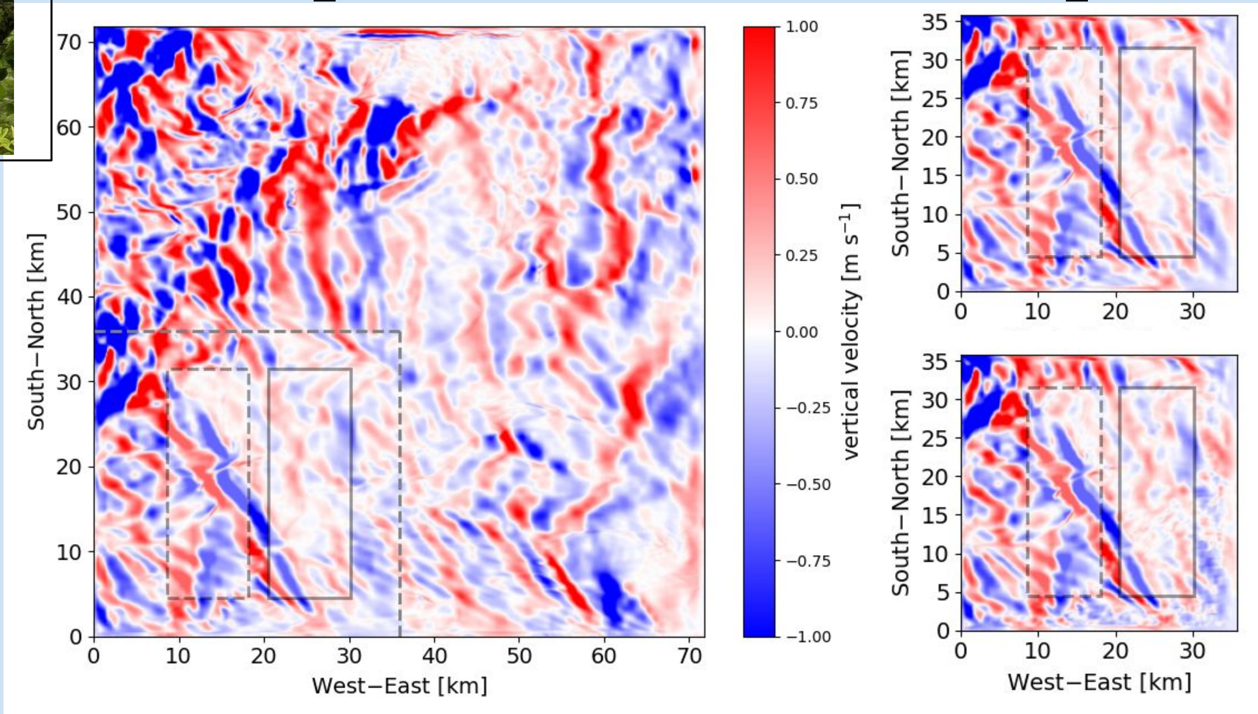
Easterly boundary layer flow, above ridge height

Note, only *3s* simulations have solutions defined in valley

Stably stratified, 2315 UTC

d03_ref

d03_30s



d03_30s_cpm

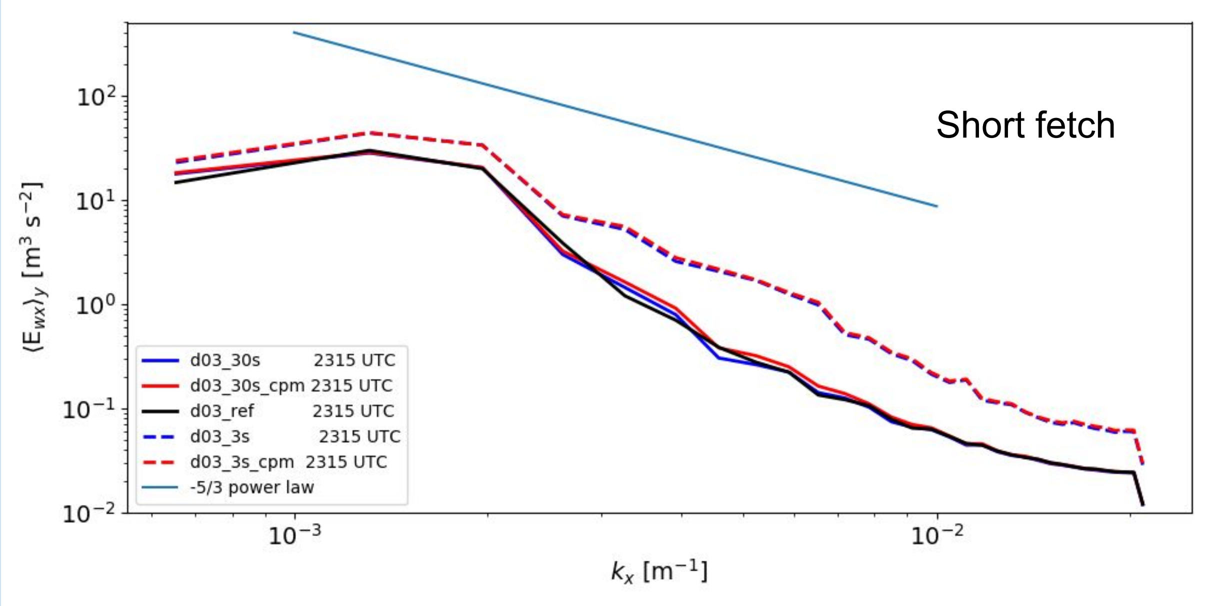
No apparent finer scale structures

No ‘streaks’ aligned with direction of flow

Wave structures, aligned in the spanwise direction

CPM does not significantly change the turbulence

Stably stratified, 2315 UTC



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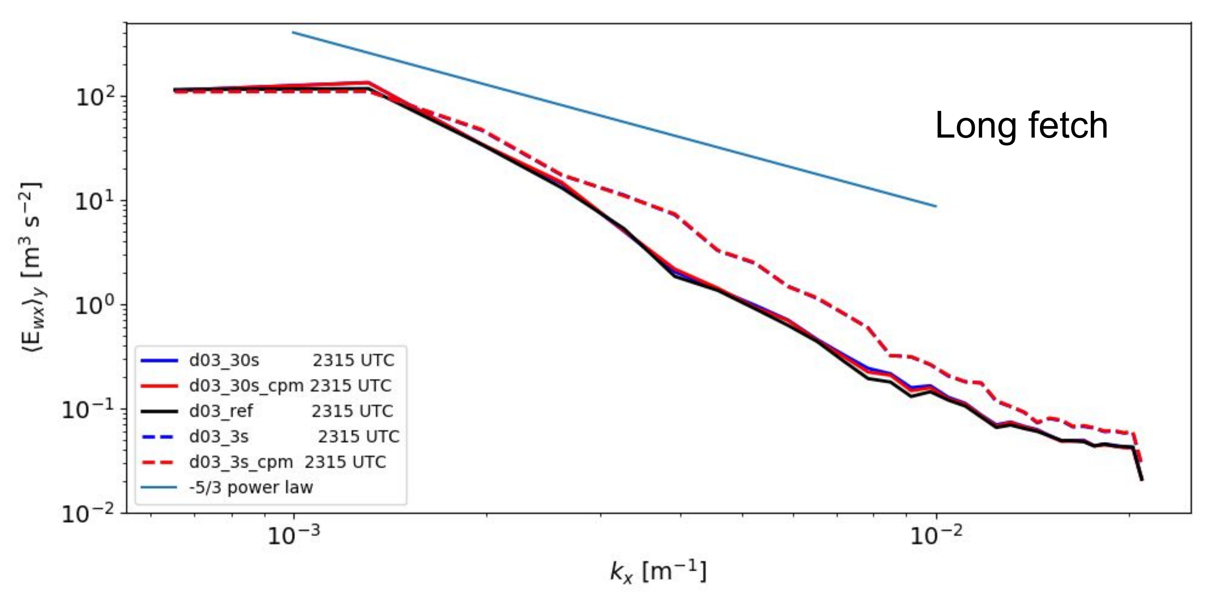

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Wave structures, aligned in the spanwise direction

CPM does not significantly change the turbulence

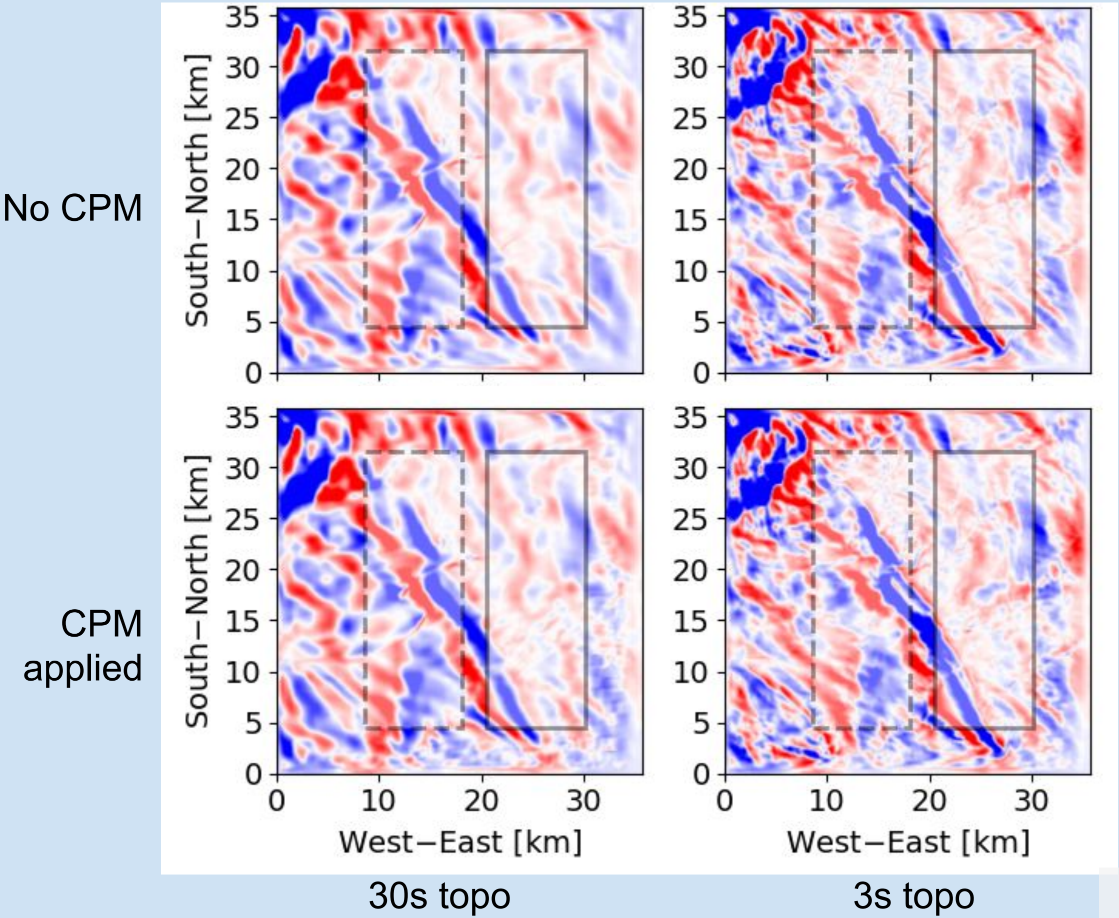
Only 3 arcsec topography LES have resolved inertial subrange

Stably stratified, 2315 UTC

Fine scale structures apparent in the 3 arcsec topography LES

None in 30 arcsec topography, even with CPM

Requires new formulation of CPM for stable conditions



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Weakly Convective:
The cell perturbation method (CPM) - accelerates the development of turbulence in large-eddy simulation
High resolution topography - does not accelerate turbulence as effectively as CPM

Stable conditions:
CPM - Current formulation does not improve resolved turbulence. Other formulation available, untested.
High resolution topography - Increase turbulent energy, possibly resolves inertial subrange.

Strongly convective:
Large-eddy simulations develop turbulence after limited fetch, regardless of CPM or topography.