Examination of the impact of mixing-length formulation on mesoscale simulation results

A Lokal-Modell case study

Jürgen Helmert

Leibniz-Institute for Tropospheric Research, Leipzig

Fifth International SRNWP-Workshop on Non-Hydrostatic Modelling
Bad Orb, 27-29 October 2003

Overview

- Introduction

- Turbulence length-scales derived from large-eddy simulation

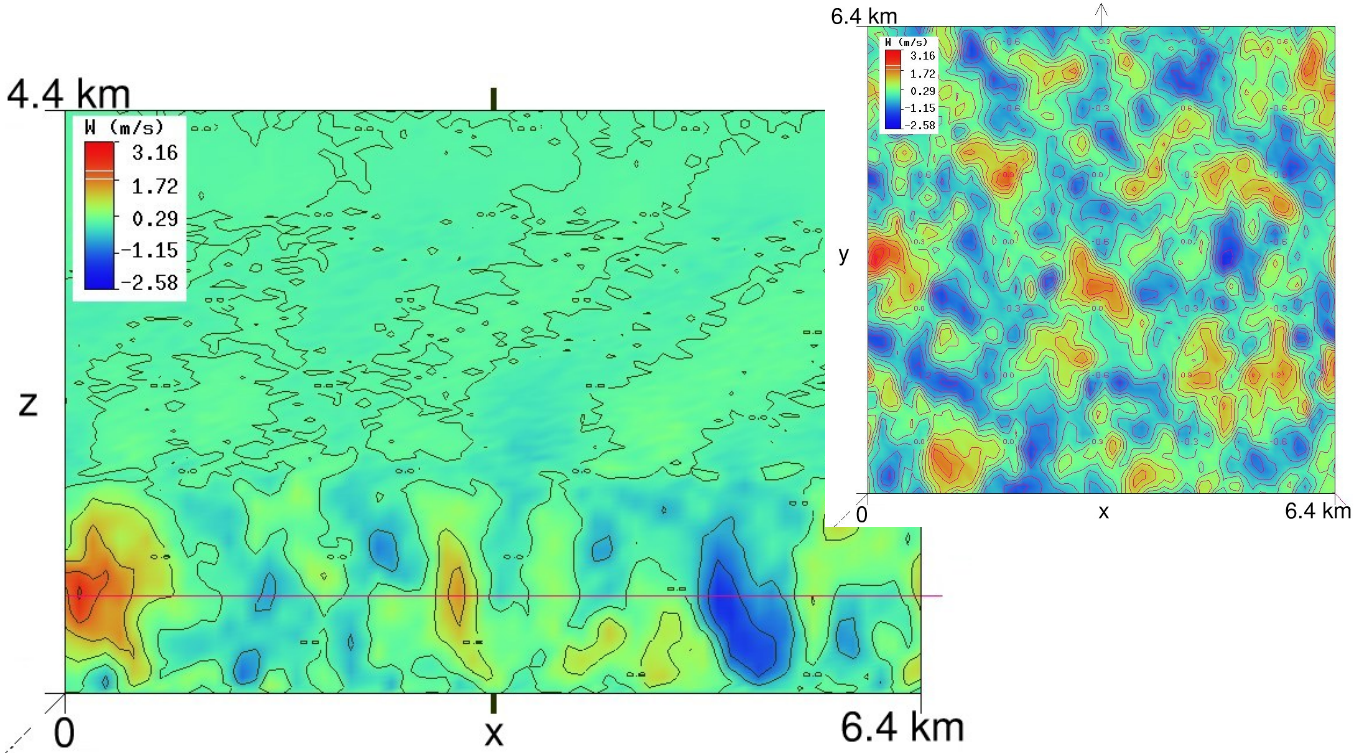
- Mesoscale response to mixing-length formulation

- Conclusions and outlook

Introduction

Boundary layer turbulence

Coherent structures in convective boundary layers

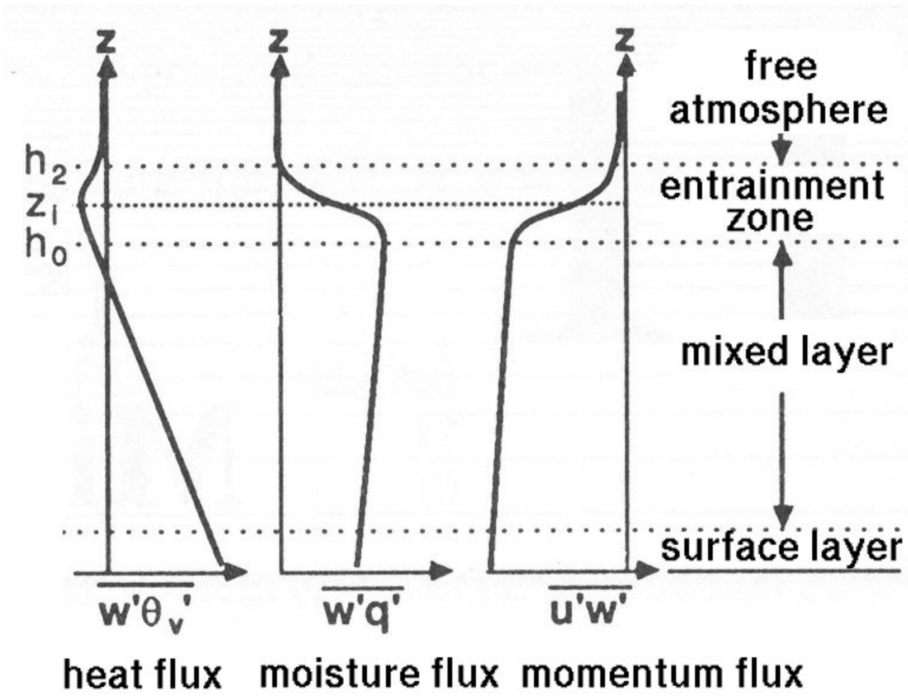


Introduction

Turbulence closure

Parameterisation of turbulent fluxes

local – eddy diffusivity approach: $\overline{w'\phi'} = -K_{\phi}(z,t)\frac{\partial\overline{\phi}}{\partial z}$



Introduction

Turbulence closure – Mellor-Yamada approach

- Aim: K-Parameterisation in dependence on atmospheric stability state[1]
- Requirements:
  - Specification of a characteristic velocity scale $e^{1/2}$
  - Specification of a characteristic mixing length scale l

$$K \sim l e^{1/2}$$

[1] *Mellor and Yamada, 1974; Mellor and Yamada, 1982*

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Turbulence closure – Mellor-Yamada approach

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$$K \sim l e^{1/2}$$

- Specification of the characteristic velocity scale by a prognostic TKE-equation:

$$\frac{\partial \overline{e}}{\partial t} = \ldots$$

- Specification of the characteristic mixing length scale by a prognostic equation is difficult!

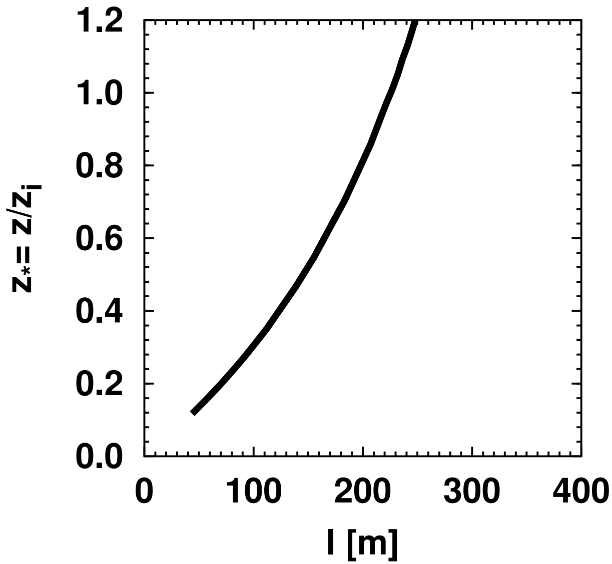
[1] *Mellor and Yamada, 1974; Mellor and Yamada, 1982*

Introduction

Turbulence closure – Specification of the mixing length

- Master length scale approach[1]: neutral boundary layer[2]

$$l = \left(\frac{1}{\kappa z} + \frac{1}{l_0} \right)^{-1}$$

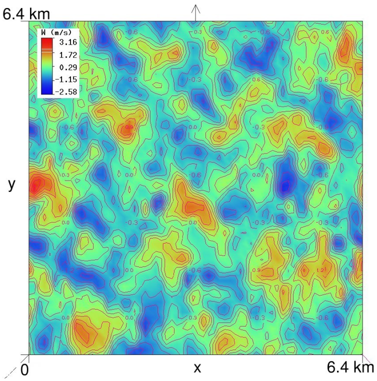


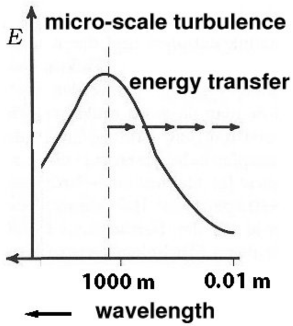
[1] *Mellor and Yamada, 1974,1982*

[2] *Blackadar, 1962*

Introduction

Characteristic turbulence length scales





spectral peak wavelength

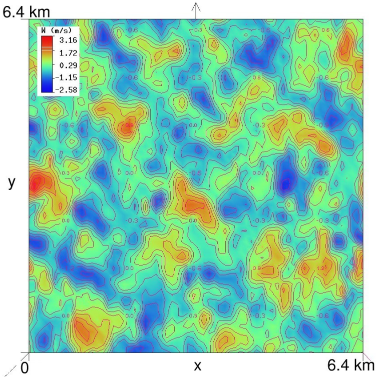
$$\Phi_w(\lambda) = \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} e^{-i\lambda\cdot\mathbf{r}} w(\mathbf{r}) \mathrm{d}\mathbf{r}$$

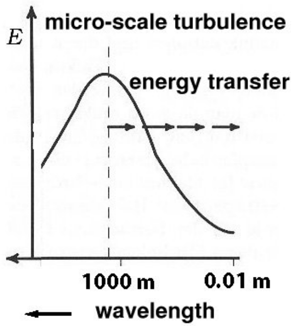
$$E_w(\lambda) = \int_{-\infty}^{\infty} \frac{1}{2} \left\| \Phi_w(\lambda) \right\|^2 \mathrm{d}\lambda$$

$$(\lambda_m)_w = \max \left\{ E_w(\lambda) \right\}$$

Introduction

Characteristic turbulence length scales





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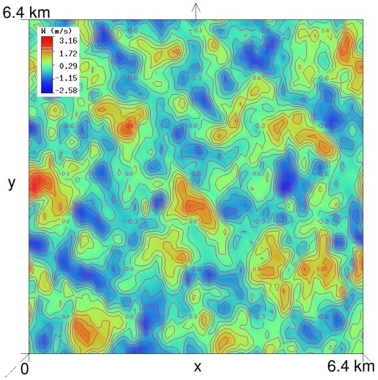
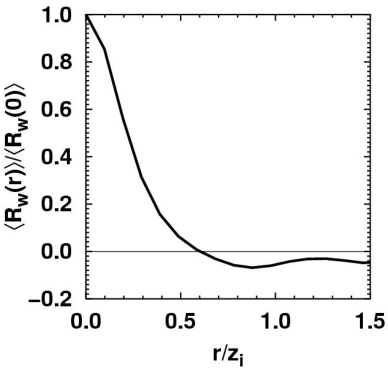




integral length scale

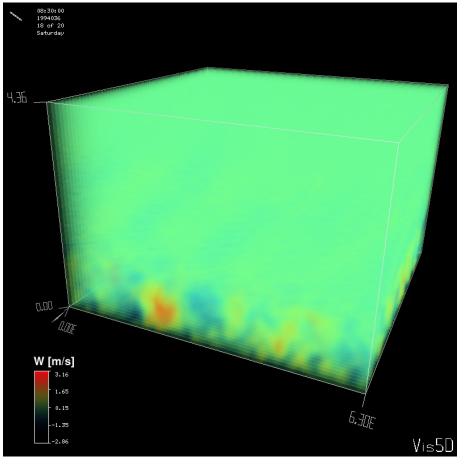
$$R_w(\mathbf{r}) = \int_{-\infty}^{\infty} w(\mathbf{x}) w(\mathbf{x}+\mathbf{r}) \mathrm{d}\mathbf{x}$$

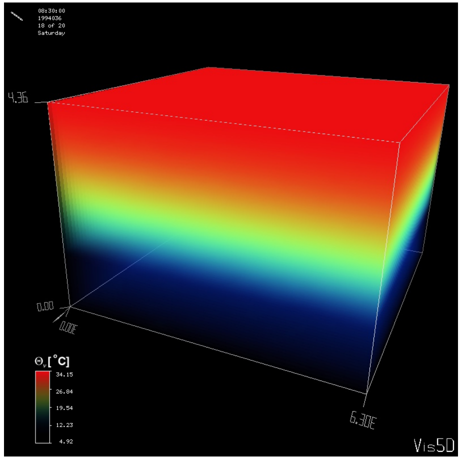
$$\Lambda_w = \frac{1}{R_w(0)} \int_{0}^{\infty} R_w(r) \mathrm{d}r$$

Introduction

Determination of characteristic turbulence length scales

- Large-eddy simulation[1]
  - High-resolution numerical simulation of convective boundary layers
  - Grid space $\Delta x \sim 0.1$ km $\longrightarrow$ coherent structures are resolved
  - Modification of boundary layer parameters (wind, temperature, heat flux)
  - Supplement to laboratory experiments and field measurements

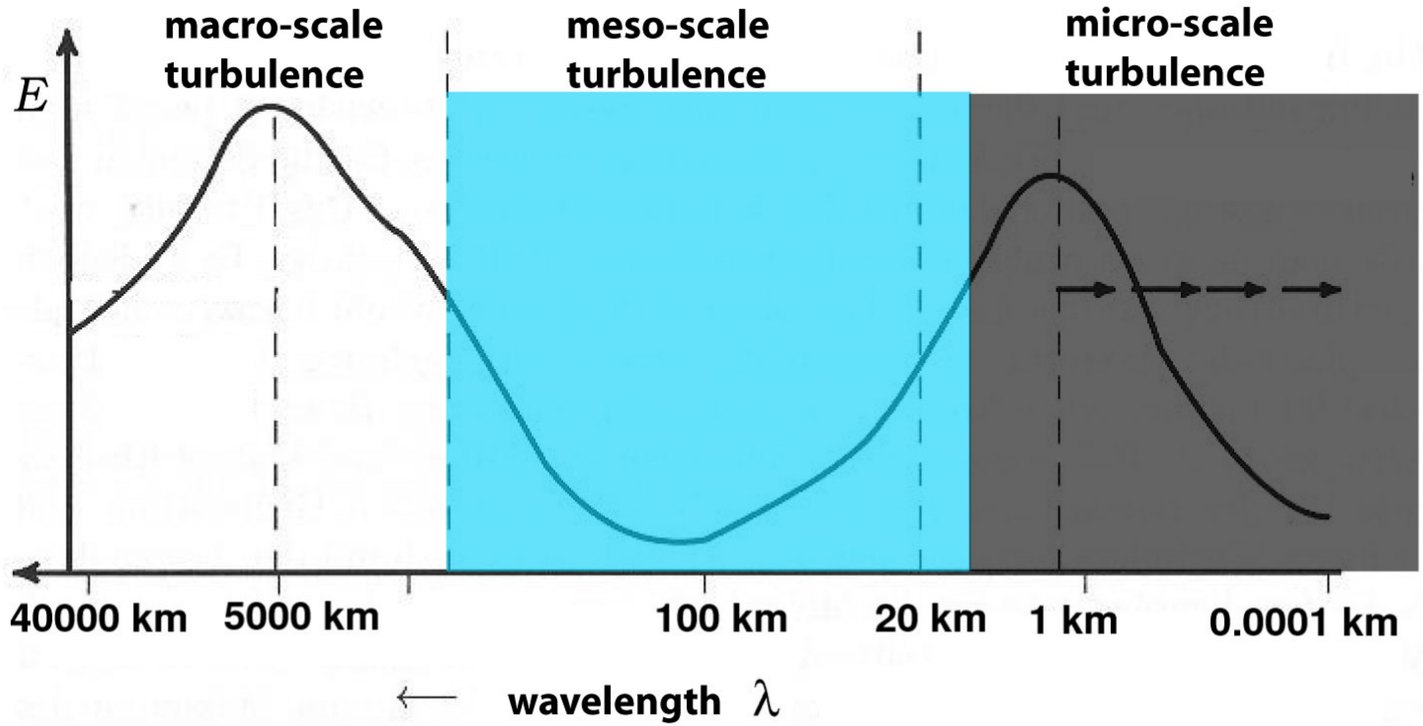




[1] *e.g. Graf and Schumann, 1991; Khanna and Brasseur, 1998)*

Introduction

Energy spectrum of atmospheric flows



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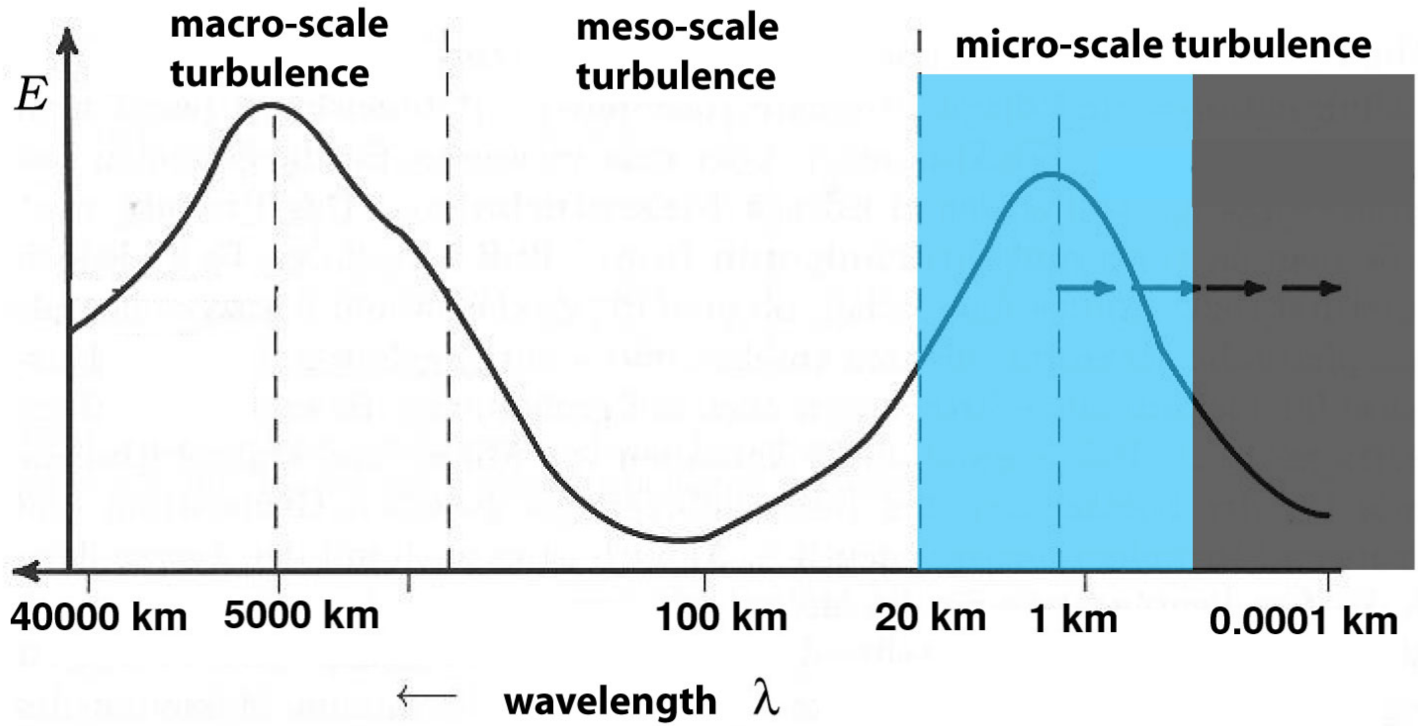

Large-Eddy Simulation

LES cases

Lauf	$-z_i/L$	u_* [m s^{-1}]	w_* [m s^{-1}]	z_i [m]	$-L$ [m]	$\overline{u}_g$ [m s^{-1}]	$\overline{q}_t$ [g kg^{-1}]	$\overline{(w'\theta'_v)_s}$ [K m s^{-1}]
A	2.12	0.82	1.43	1593.30	751.00	20	24	0.058
B	5.91	0.50	1.23	1026.00	173.60	10	24	0.058
C	7.09	0.86	2.73	1600.00	225.80	20	12	0.231
D	9.16	0.73	2.06	1400.00	152.80	15	0	0.200
E	10.94	0.75	2.25	1586.70	145.00	15	12	0.231
F	11.41	0.74	2.27	1620.00	142.00	15	15	0.231
G	11.78	0.53	1.65	1246.70	105.80	10	24	0.115
H	17.29	0.56	1.98	1426.70	82.50	10	24	0.173
I	18.69	0.57	2.07	1400.00	74.90	10	0	0.200
J	23.22	0.57	2.21	1506.70	64.90	10	6	0.231
K	23.65	0.58	2.25	1586.70	67.10	10	24	0.231
L	24.89	0.57	2.24	1573.30	63.20	10	12	0.231
M	25.29	0.58	2.30	1686.70	66.70	10	18	0.231
N	48.25	0.46	2.26	1606.70	33.30	5	24	0.231

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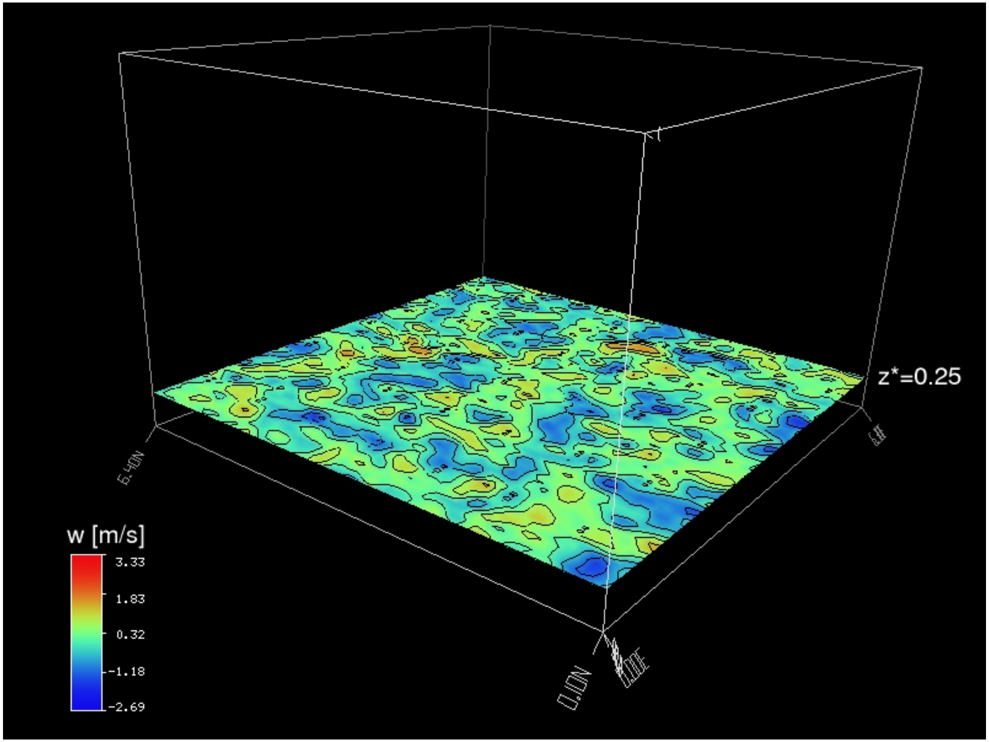
Large-Eddy Simulation

Determination of characteristic turbulence length scales

- 1D sampling of turbulent fluctuations at horizontal LES model levels
- Computation of 1D- spectra and auto-covariances for x- and y-pathways



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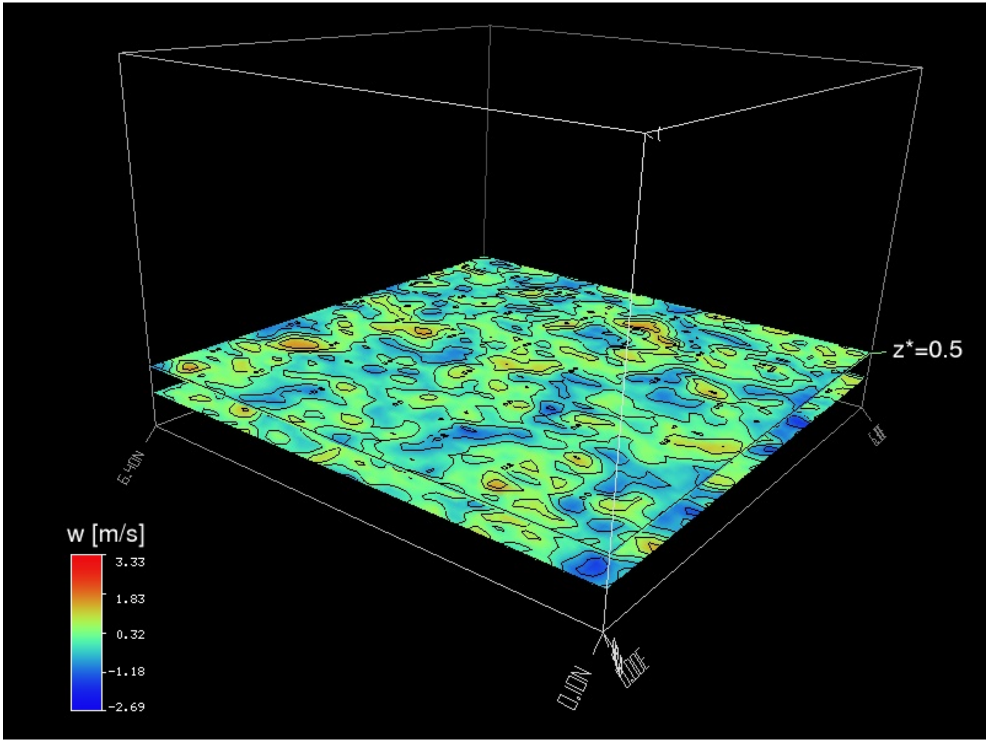

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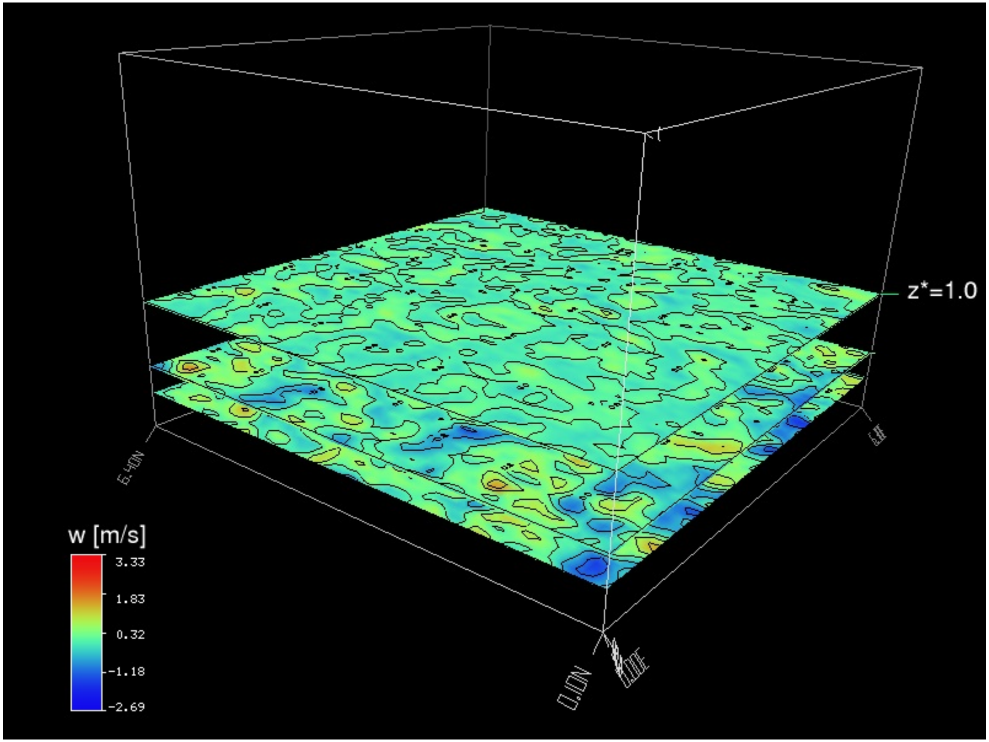
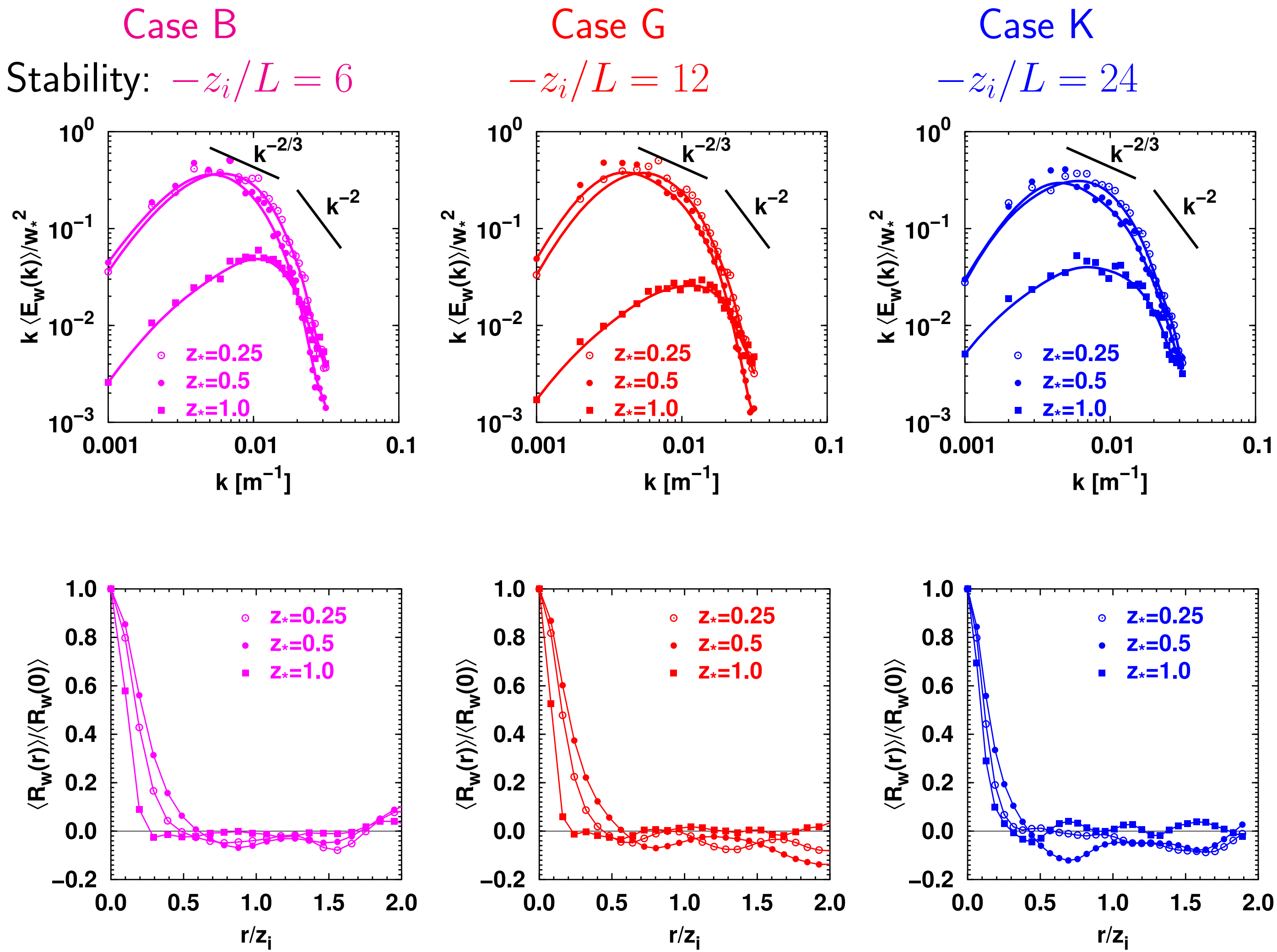
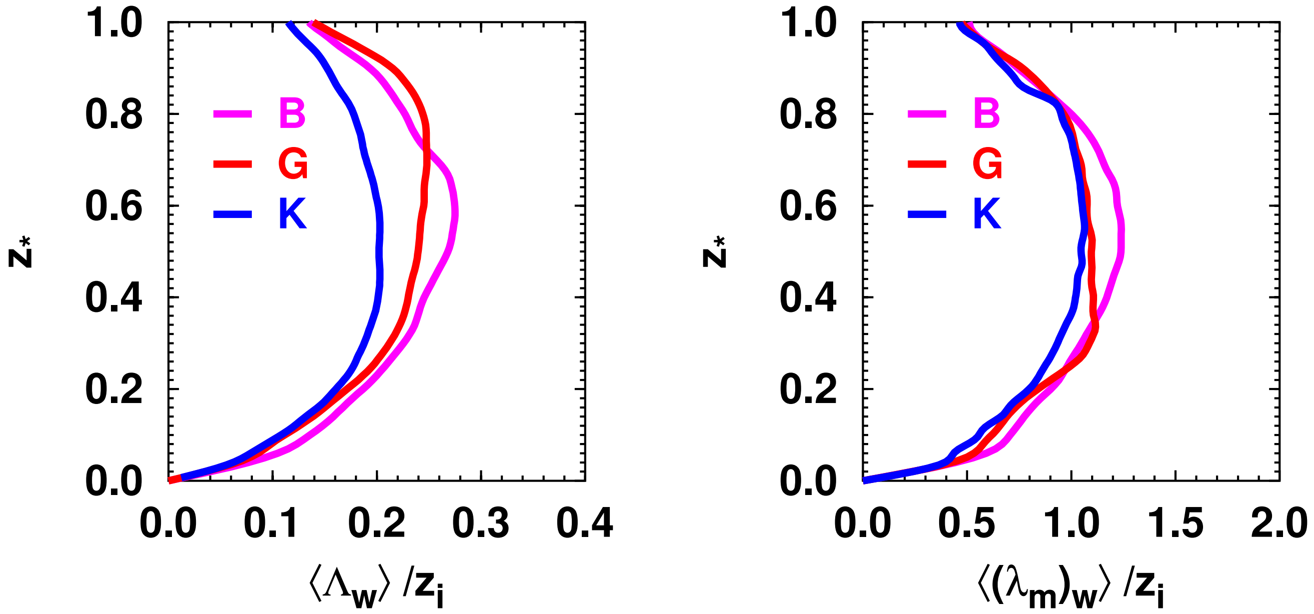


Large-Eddy Simulation



Large-Eddy Simulation

- Stability-dependent turbulence length scales
- Agreement with laboatory experiments[1], atmospheric measurements[2], and further numerical simulations[3]



[1]Wind tunnel exp.: *Kaiser and Fedorovich, 1998*

[2] SEMAPHORE: *Durand et al., 2000*

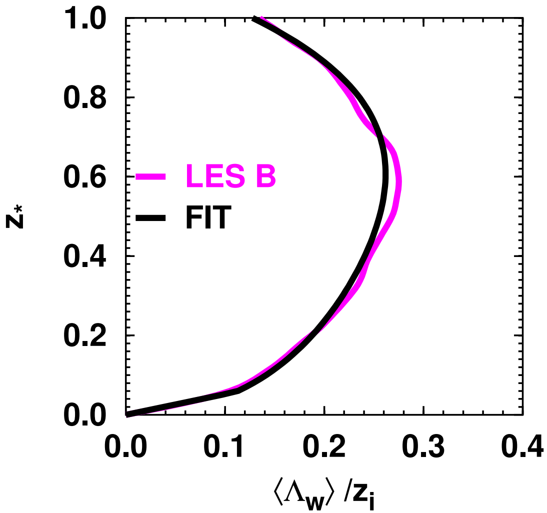
[3] LES: *Graf and Schumann, 1991, Khanna and Brasseur, 1998*

Large-Eddy Simulation

Parameterisation of turbulence length scales

Integral length scale

$$\frac{\langle \Lambda_w \rangle}{z_i} = \begin{cases} a_0 z_*, & z_* < z_{*0} \\ a_1 (z_*)^{1/2} (1 - a_2 z_*)(1 + a_3 z_*)^2, & z_* \geq z_{*0} \geq 1 \end{cases}$$



Case	a_0	Δa_0	a_1	Δa_1	a_2	Δa_2	a_3	Δa_3
B	1.992	0.025	0.4773	0.0033	0.8910	0.0026	1.444	0.047

Large-Eddy Simulation

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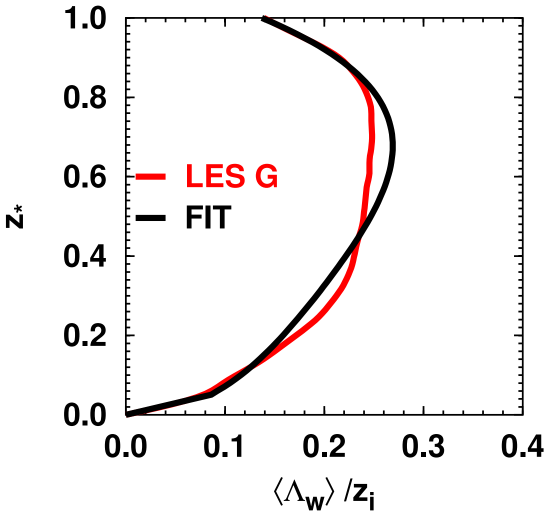

Case	a_0	Δa_0	a_1	Δa_1	a_2	Δa_2	a_3	Δa_3
G	1.704	0.015	0.3930	0.0041	0.8991	0.0046	2.457	0.140

Large-Eddy Simulation

Parameterisation of turbulence length scales

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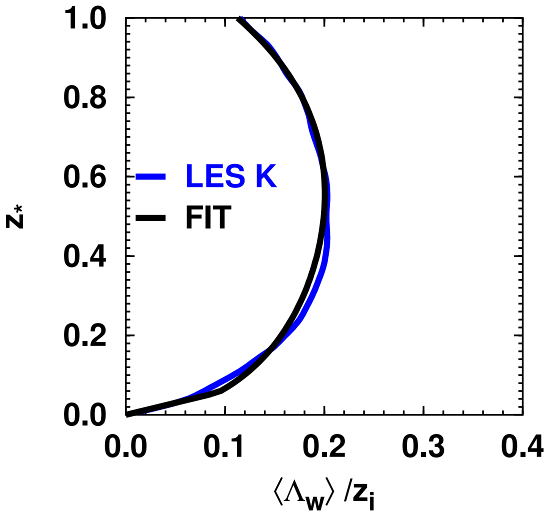
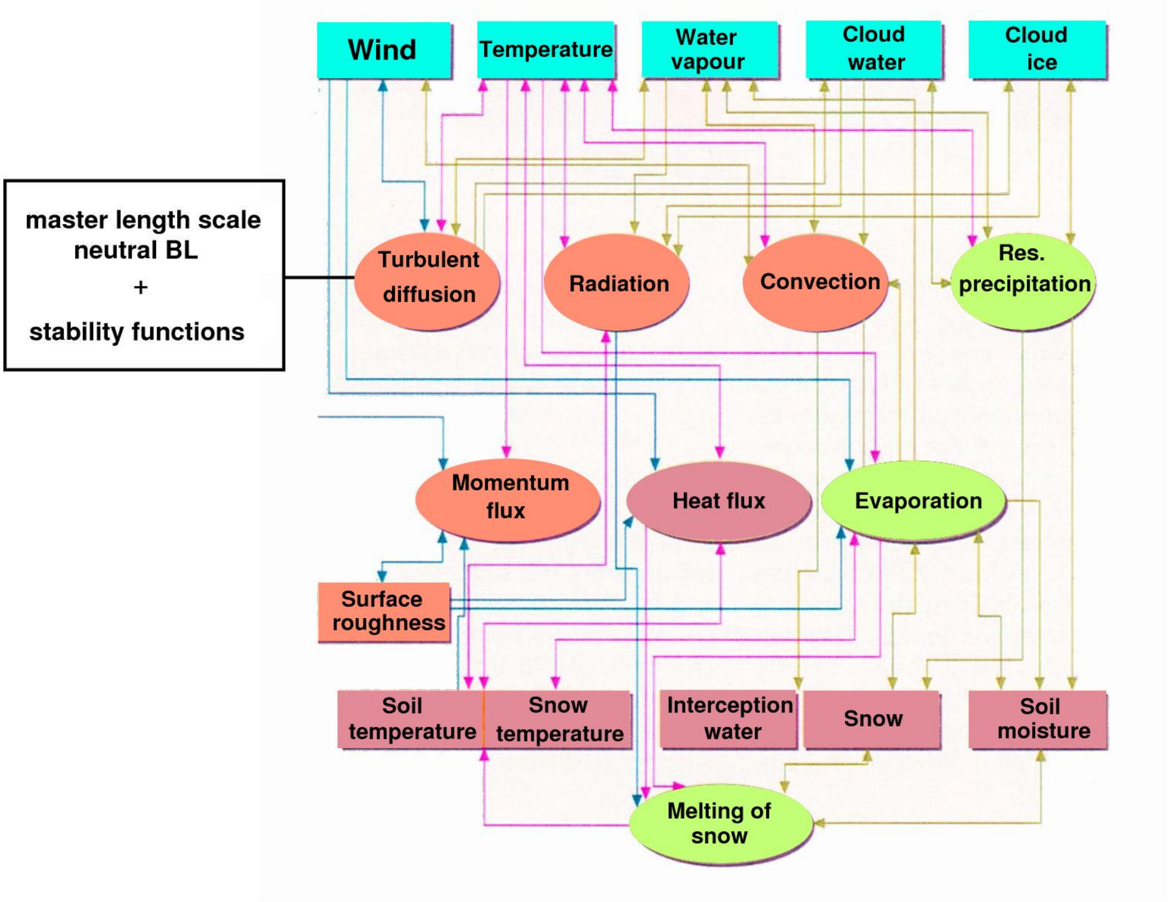


Case	a_0	Δa_0	a_1	Δa_1	a_2	Δa_2	a_3	Δa_3
K	1.659	0.012	0.4087	0.0038	0.8452	0.0086	0.780	0.068

Lokal-Modell Case Study

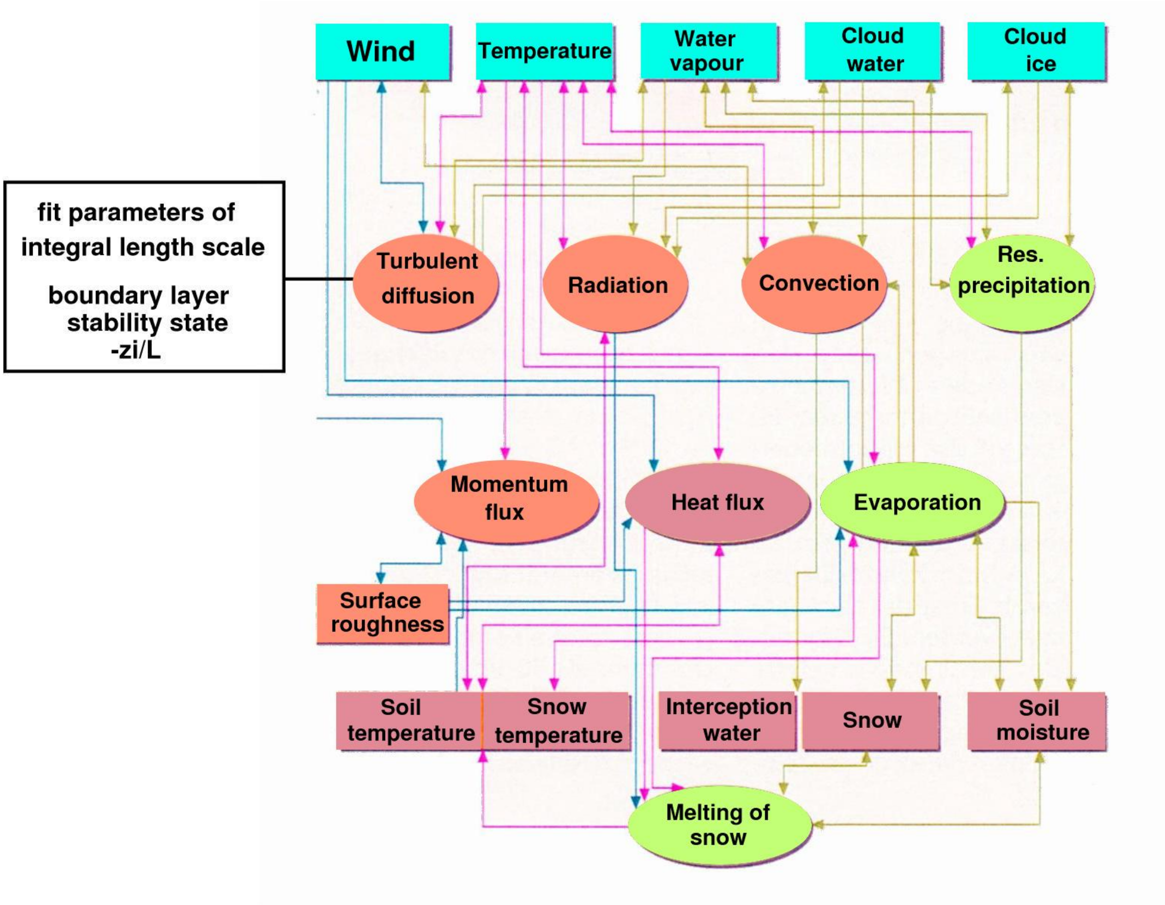
Implementation of the modified mixing length



[1] *Deutscher Wetterdienst (DWD)*

Lokal-Modell Case Study

Implementation of the modified mixing length



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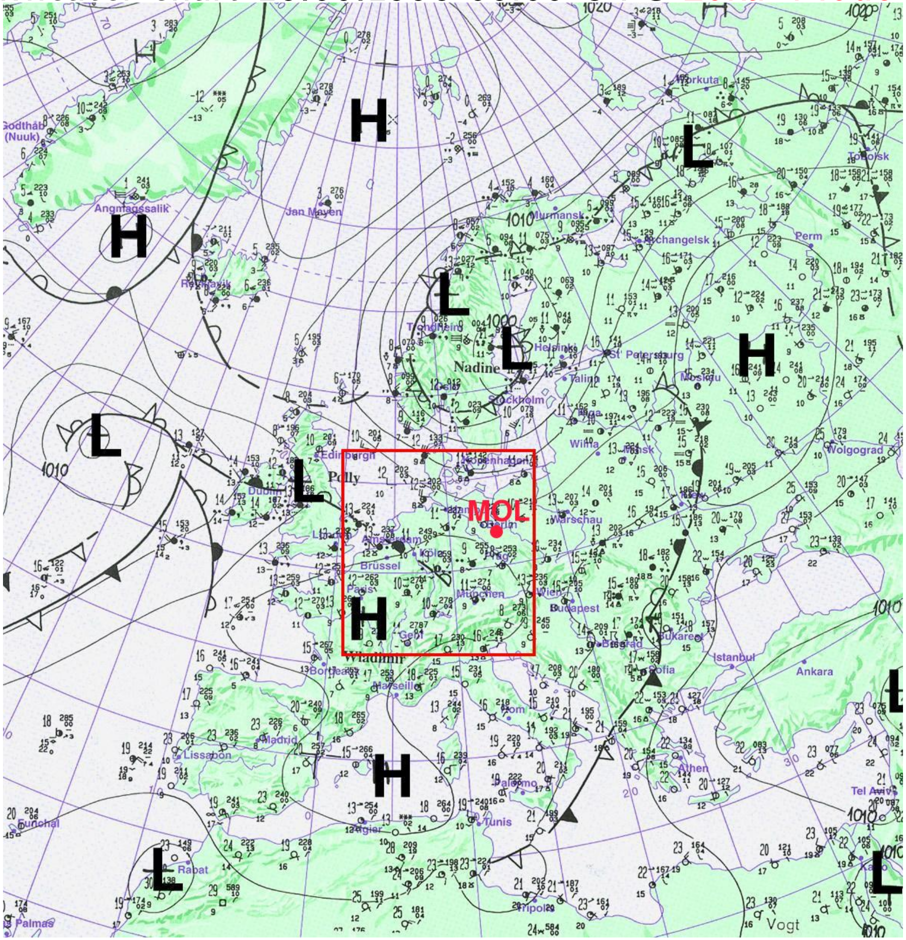
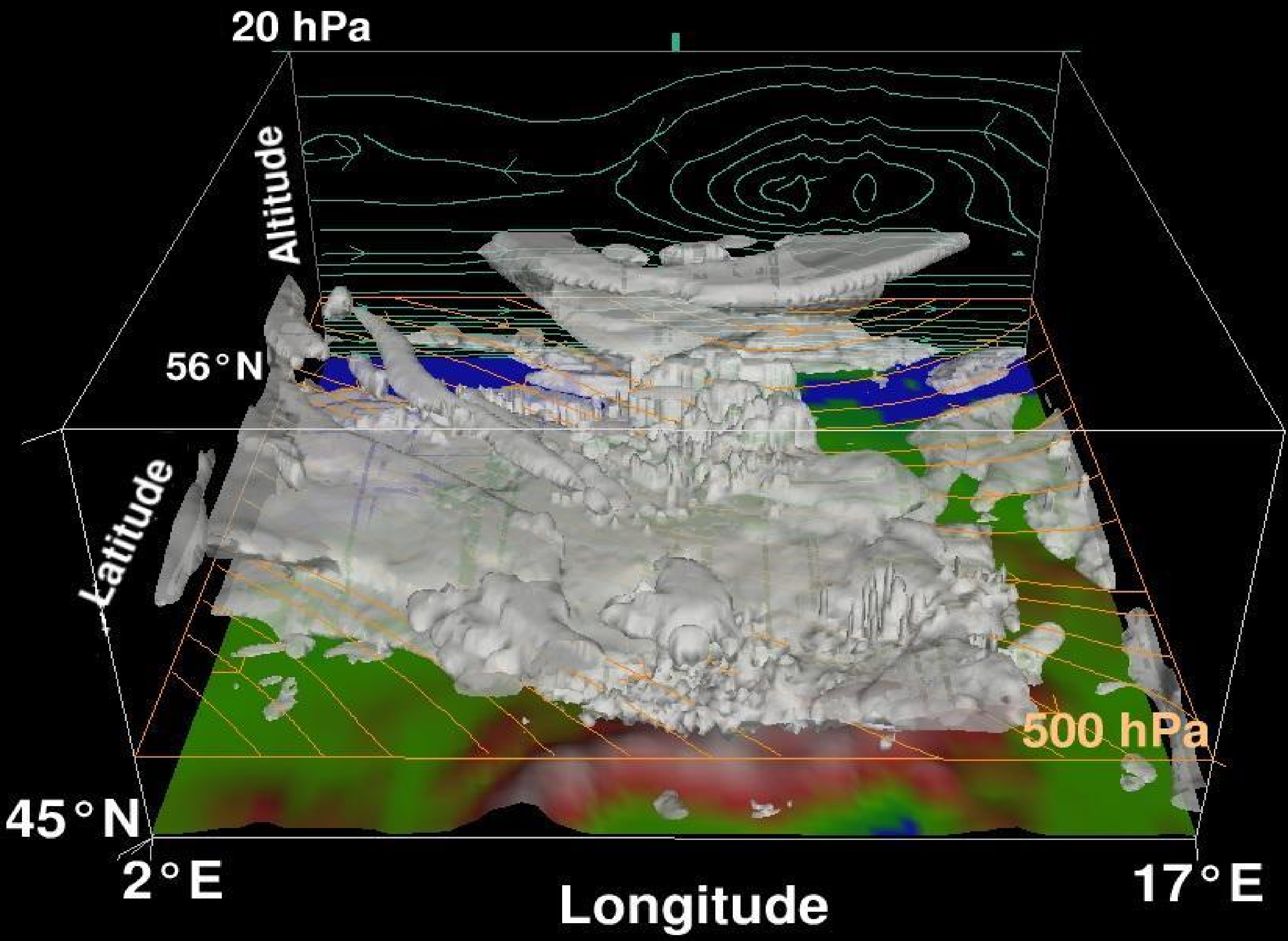
[1] *Deutscher Wetterdienst (DWD)*

Lokal-Modell Case Study

Simulation scenario LITFASS

Surface wheater chart 18.06.1998 00:00 UTC Lokal-Modell domain



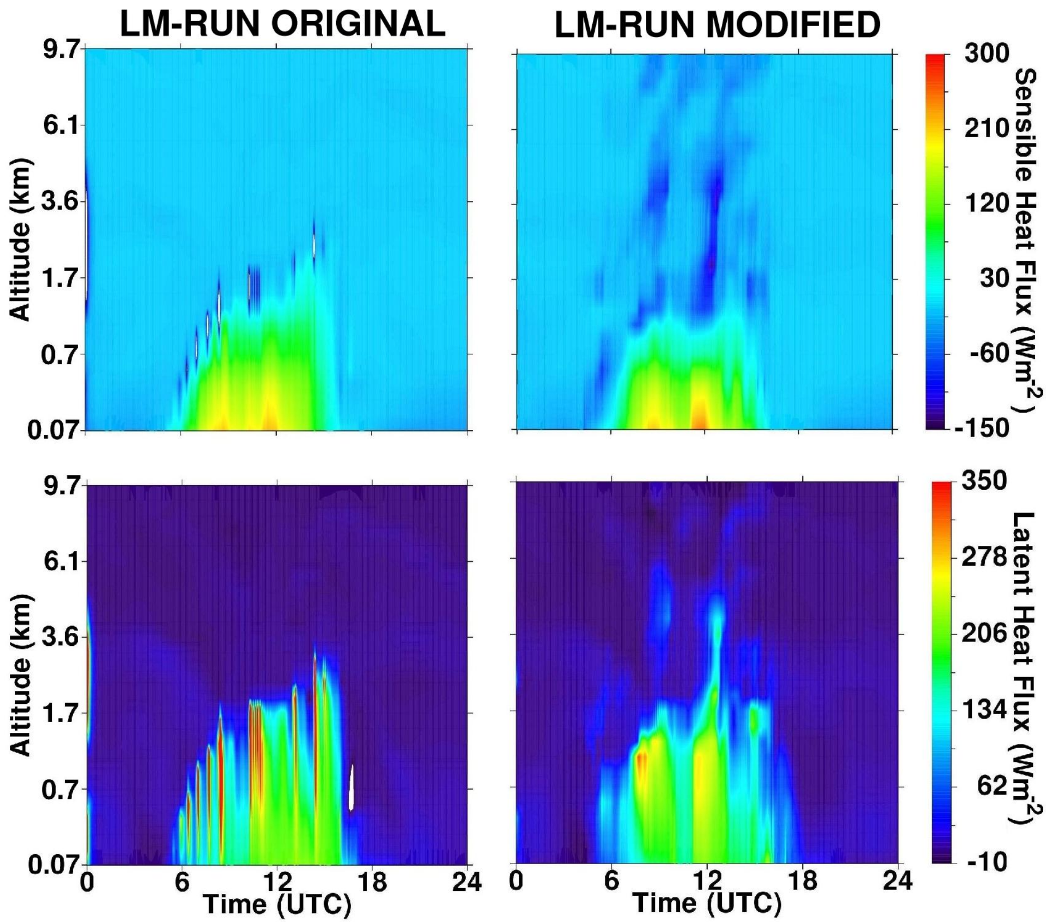


20 hPa
Altitude
56° N
Latitude
500 hPa
45° N
2° E
Longitude
17° E

Lokal-Modell Case Study

Direct Comparison of Simulation Results

Turbulent Fluxes at grid point MOL



Lokal-Modell Case Study

Direct Comparison of Simulation Results

Statistical Analysis

- Correlation coefficient

$$\varrho_{A,B} = \frac{\frac{1}{N_x N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \left(A_{i,j} - \overline{A}\right) \left(B_{i,j} - \overline{B}\right)}{\left\{\frac{1}{N_x N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \left(A_{i,j} - \overline{A}\right)^2\right\}^{1/2} \left\{\frac{1}{N_x N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \left(B_{i,j} - \overline{B}\right)^2\right\}^{1/2}}$$

- Centered pattern RMS difference (CP-RMS difference)[1]

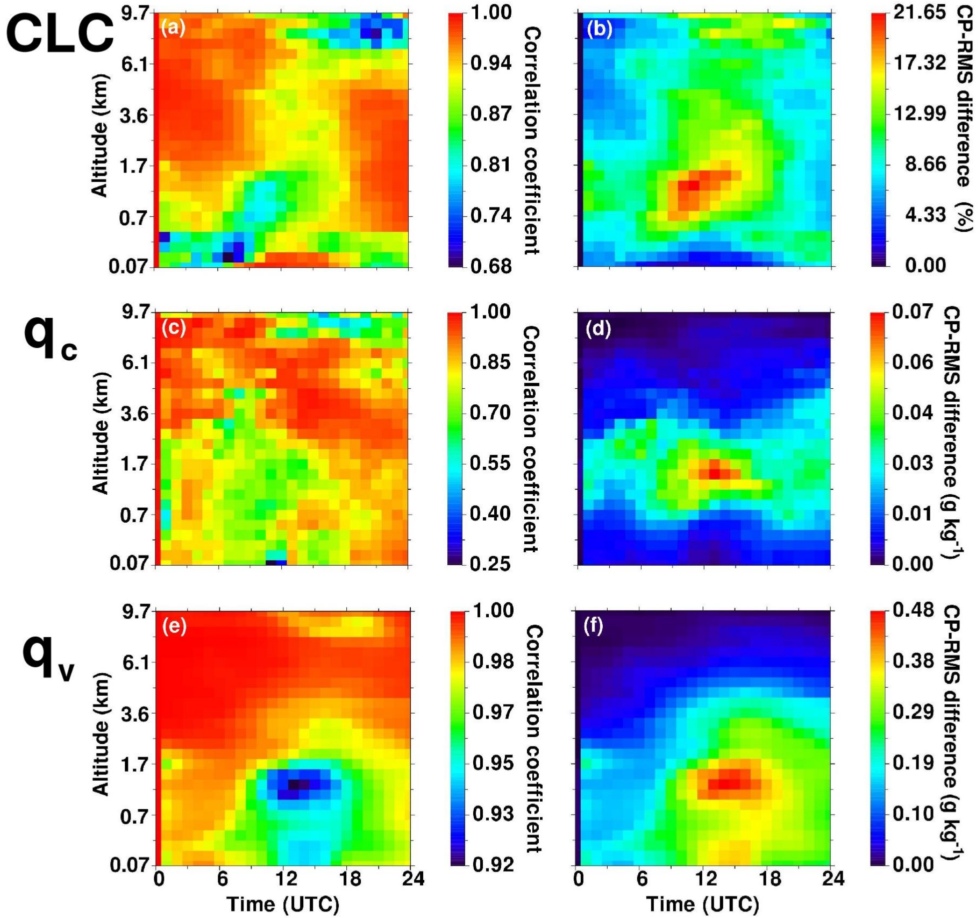
$$\delta_{A,B}^{\mathsf{CP}} = \left[\frac{1}{N_x N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \left\{(A_{i,j} - \overline{A}) - (B_{i,j} - \overline{B})\right\}^2\right]^{1/2}$$

[1] *Taylor, 2001*

Lokal-Modell Case Study

Direct Comparison of Simulation Results

Statistical Analysis – 3D fields

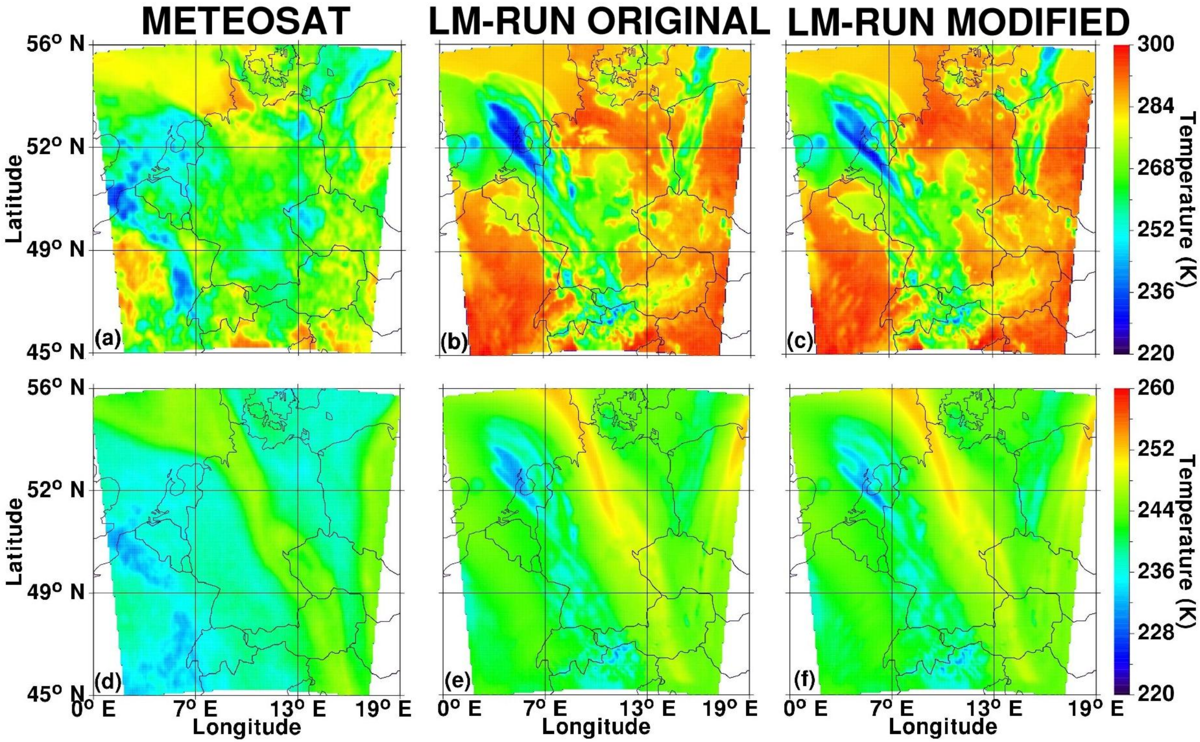


Lokal-Modell Case Study

Verification of Simulation Results

Brightness temperatures from METEOSAT satellite observations[1]

2 channels: T_{IR} 10.5 μm-12.5 μm and T_{WV} 5.7 μm-7.1 μm



[1] *Morcrette, 1991*

Lokal-Modell Case Study

Verification of Simulation Results

Comparison with 4dVar-analysis data – statistical analysis

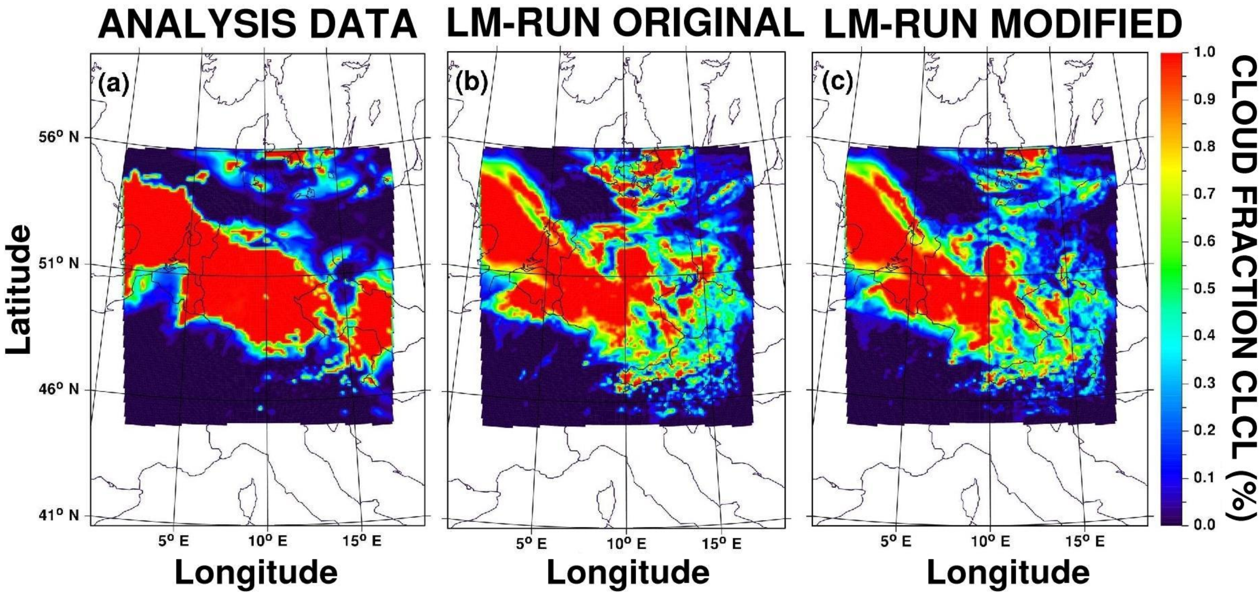
Parameter	Time [UTC]	$\varrho_{A,I}$	$\varrho_{A,II}$	$\frac{\Delta\varrho}{\varrho_{A,I}}$ [$\cdot 100$ %]	$\delta^{CP}_{A,I}$ [Unit of the	$\delta^{CP}_{A,II}$ parameter]	$\frac{\Delta\delta^{CP}}{\delta^{CP}_{A,I}}$ [$\cdot 100$ %]
$T_{2\ m}$	06:00	0.95	0.951	0.1	0.84	0.835	-0.616
	12:00	0.913	0.91	-0.343	1.637	1.714	4.7
	18:00	0.955	0.954	-0.158	1.088	1.106	1.646
$U_{10\ m}$	06:00	0.955	0.944	-1.127	0.864	0.921	6.598
	12:00	0.857	0.829	-3.363	1.284	1.376	7.175
	18:00	0.781	0.774	-0.883	1.367	1.352	-1.068
CLCH	06:00	0.595	0.601	1.006	0.372	0.37	-0.6
	12:00	0.443	0.423	-4.479	0.446	0.455	2.012
	18:00	0.333	0.353	6.12	0.418	0.41	-1.89
CLCM	06:00	0.822	0.823	0.148	0.245	0.245	-0.32
	12:00	0.705	0.7	-0.82	0.318	0.319	0.392
	18:00	0.653	0.651	-0.348	0.342	0.341	-0.235
CLCL	06:00	0.749	0.746	-0.42	0.289	0.291	0.491
	12:00	0.629	0.698	10.88	0.358	0.319	-10.959
	18:00	0.711	0.707	-0.592	0.315	0.314	-0.455

Lokal-Modell Case Study

Verification of Simulation Results

Comparison with 4dVar-analysis data – 2D fields

Example: cloud fraction of low clouds 18.06.98 12:00 UTC



Conclusions

- Problems in parameterisation of turbulent transports
- Characteristic turbulence length scales as turbulent mixing length in turbulence closure models
- Three-dimensional large-eddy simulations of convective boundary layers for a wide range of stability states
- Development of an approximation for the vertical profile of integral length scale
- Case study with the Lokal-Modell of the DWD
- Sensitivity of cloud fraction of low clouds on turbulent mixing length

Outlook

- Large-eddy simulations
  - Further investigations of the moisture – and cloud impact on characteristic turbulence length scales
  - Two-dimensional spectra and auto-covariances $\longrightarrow$ reduced sampling complexity
- Mesoscale Simulations
  - Larger number of synoptic situations
  - Use of further assimilated data in analysis data for verification purposes

Acknowledgment

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Barbara Heide

Examination of the impact of mixing-length formulation on mesoscale simulation results

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Jürgen Helmert

Leibniz-Institute for Tropospheric Research, Leipzig

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