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The Influence of Transport Model Resolution on the Inverse Modelling of Synthetic Greenhouse Gas Emissions in Switzerland

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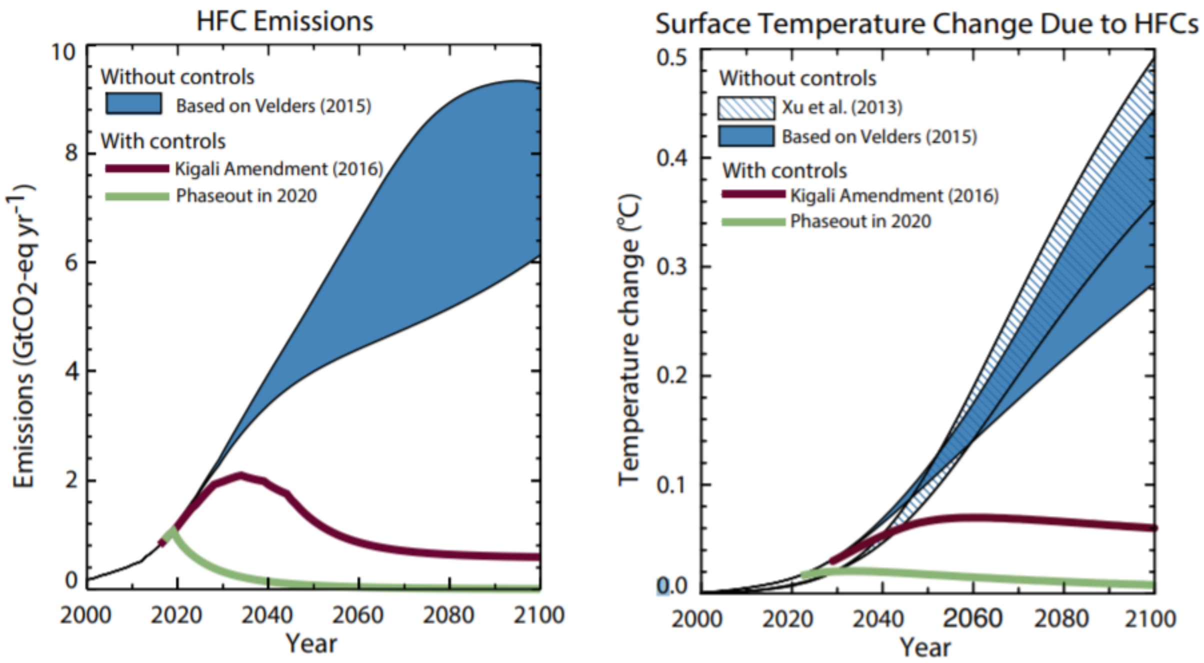
Motivation



Scenarios of HFC emissions and global average surface-temperature response (Source: Global Ozone Research and Monitoring Project—Report No. 58).

Halocarbons

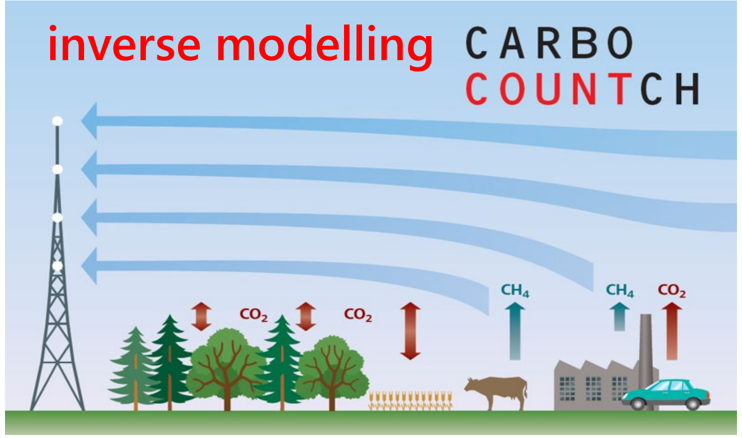
- Large contributors to current anthropogenic forcing (~14%)
- Chlorine and bromine-containing halocarbons are the main drivers of the destruction of the stratospheric ozone layer
- Therefore, emissions and spatial distribution needs to be monitored

Inverse modelling

- Provides observation-based estimates of greenhouse gas emissions
- Makes valuable information available to policy makers when reviewing emission mitigation strategies and confirming the countries' pledges for emission reduction.

Atmospheric transport models

- Source sensitivities derived from atmospheric transport models are the drivers of inverse models
- Any performance advances directly affect the performance of inverse models



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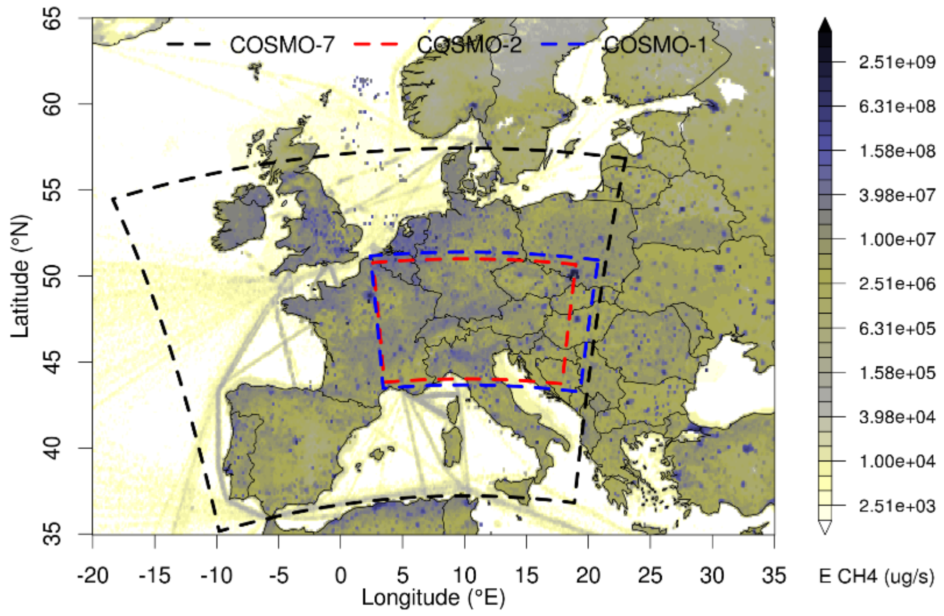
Atmospheric Transport Model Applied for Estimation of Swiss GHG Emissions

- FLEXPART-COSMO (V8C2.0)
  - Langrangian Particle Dispersion Model (LPDM)
  - Driven by COSMO meteorology
- Input: COSMO-7 (MeteoSwiss analysis)
  - 7 km x 7 km resolution, 60 levels
  - Hourly fields
- Simulation set-up for individual receptors
  - 3-hourly release of 50’000 particles per site
  - 4 day backward or until out of domain
  - Different release heights to account for smoothed model topography

(Henne et al., 2016)

Moving to higher resolution

- COSMO-1 (MeteoSwiss analysis)
  - 1km x 1km resolution, 80 levels
  - Hourly fields



Model domains and CH_4 emission distribution (EDGAR+Swiss)

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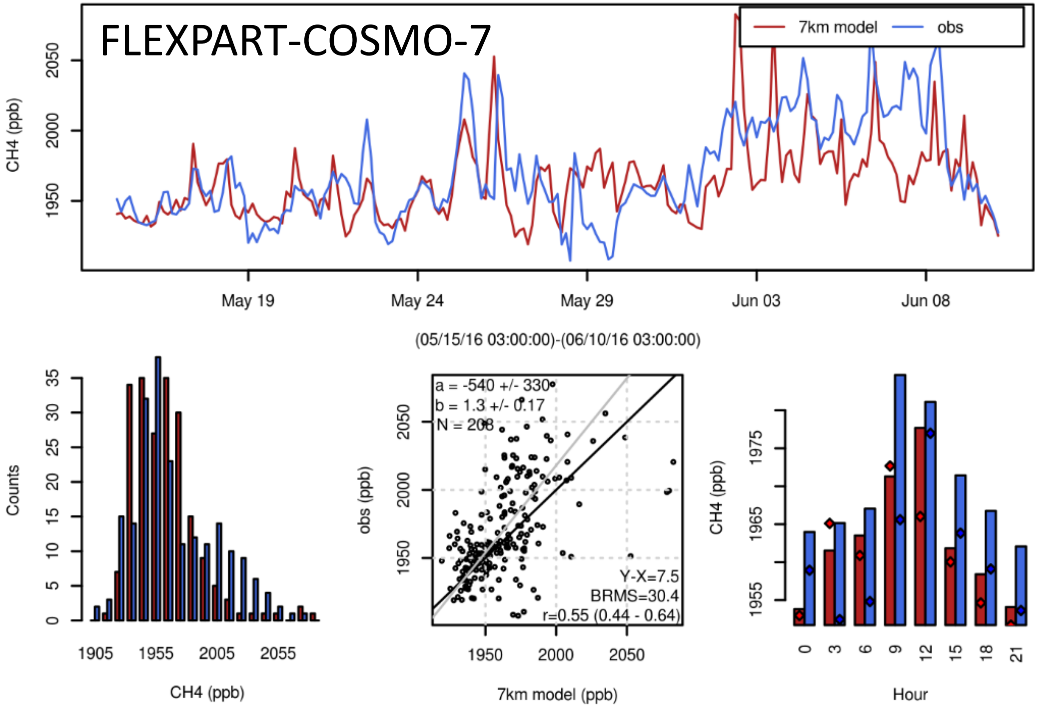
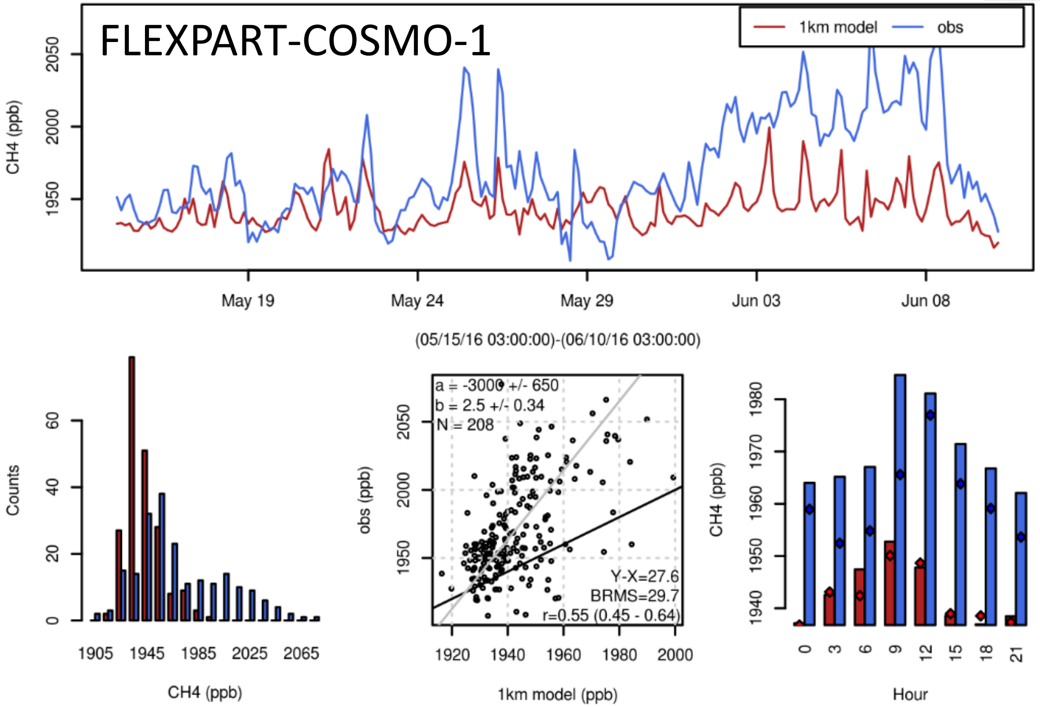
Influence of model resolution on CH_4 simulations at Swiss Tall Tower Site Beromünster





Upper figure: Time series of CH_4 concentration for May-June 2016 at the receptor site in Beromünster Switzerland evaluating model (red line) vs. observations (blue line).
Bottom left figure: Distribution of the concentrations for the model and the observations.
Bottom middle figure: Scatter plot of observations (Y axis) vs model (x axis) concentration values.
Bottom right figure: Diurnal cycle of CH_4 concentrations for the model and observations.

CH_4 at Beromünster, a site on the Swiss Plateau, is used as a validation target, since previous work had shown good performance of FLEXPART-COSMO-7 for this site and compound.

Variability seen in the observations not well described by FLEXPART-COSMO-1!

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Possible Reasons for Increased Dispersion in Higher Resolution Simulations

- Wind fields: Unrealistic wind speeds and wind gradients in high resolution model?
- Bugs in the code of the model: Do potential model bugs/simplifications in the transport description manifest stronger at high resolution (e.g., due to larger topographic gradients)?
- Domain size: Is the COSMO-1 domain to small to account for significant fraction of observed concentrations?
- Turbulence Scheme: Is current FLEXPART turbulence scheme inadequate for high resolution? Duplication of turbulence that is already grid-resolved by COSMO?

The most likely causes have been addressed and/or ruled out the only remaining seems to be the possible duplication of part of the turbulence spectrum by the COSMO itself and the turbulence scheme in FLEXPART.

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Transport Description in Lagrangian Particle Dispersion Models

Describe pollution dispersion by transport of **air parcels** in atmosphere.

Use of thousands of parcels to treat **turbulence** as a **stochastic** process.

Transport equation

$$\frac{d\boldsymbol{X}}{dt} = \boldsymbol{u}[\boldsymbol{X}(t)]$$

$$x(t) = x(t=0) + \int_0^t u(t')dt'$$

$$x(t+\Delta t) = x(t) + u(t)\Delta t$$

Mean Turbulence

$$u(t) = \overline{u}(t) + u'(t)$$

Turbulence Term (Langevin equation)

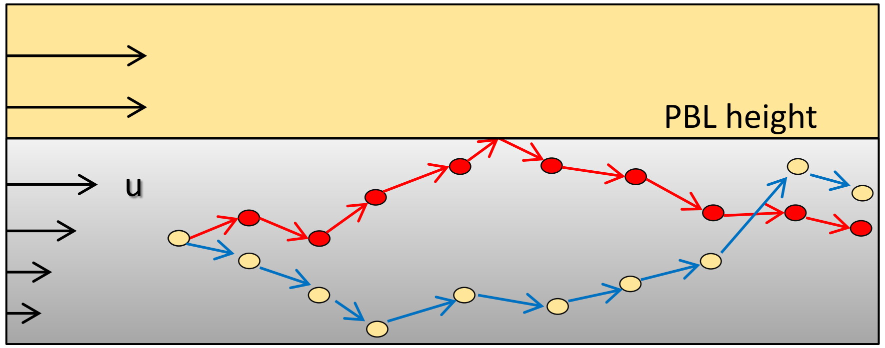
$$dv_{t_i} = a_i(\boldsymbol{x}, \boldsymbol{v_t}, t)dt + b_{ij}(\boldsymbol{x}, \boldsymbol{v_t}, t)d\boldsymbol{W_j}$$

$$d\left(\frac{w}{\sigma_w}\right) = -\frac{w}{\sigma_w}\frac{dt}{\tau_{L_w}} + \frac{\partial \sigma_w}{\partial z}dt + \frac{\sigma_w}{\rho}\frac{\partial \rho}{\partial z}dt + \left(\frac{2}{\tau_{L_w}}\right)^{1/2}dW$$

Hanna Scheme

Parameterization scheme provides approximations for the variations of the wind ($\sigma_{u,v,w}$) and Langrangian timescale (τ_L) as functions of,

- ABL height (h)
- Obhukov Length (L)
- Friction velocity (u_*)
- Convective velocity scale (w_*)



Comparison of the turbulence scheme parameters between high and low resolution models should shed light on the problem

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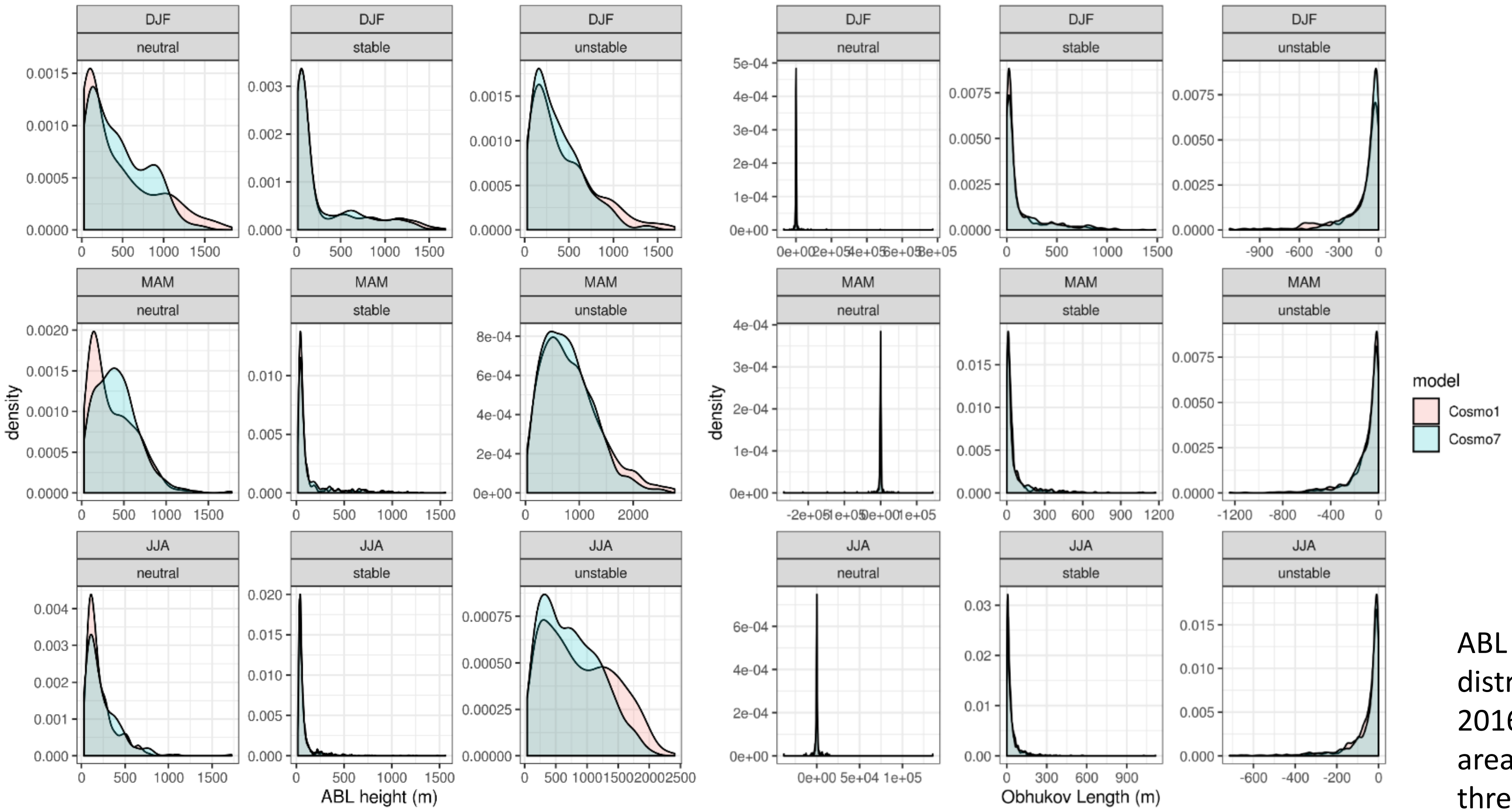
Comparison of Parameters Driving FLEXPART Turbulence Scheme: ABL Heights, Obhukov Length

ABL heights

Obhukov length



- Obhukov lengths have similar distributions for both models for all different stability classes and seasons
- ABL Heights are higher during unstable condition in FLEXPART-COSMO-1

ABL heights (left) and Obhukov length (right) distribution comparison for the first 9 months of 2016. Red area corresponds to COSMO-1 while blue area to COSMO-7. Comparison is done according to three different stability classes and seasons.

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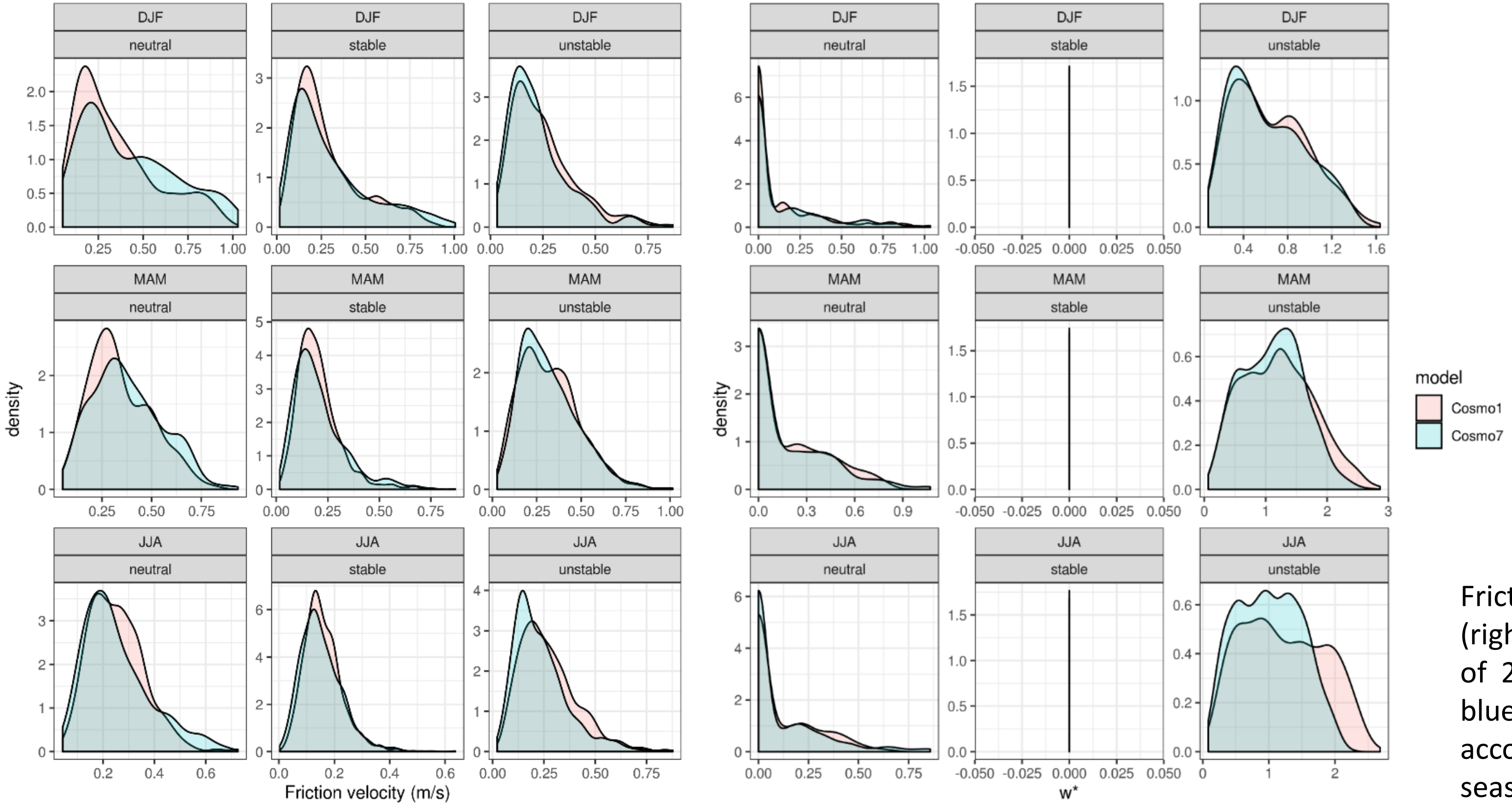
Comparison of Parameters Driving FLEXPART Turbulence Scheme: Friction Velocity, Convective Velocity Scale

Friction velocity

Convective velocity scale



- Friction velocity has higher values during neutral conditions in FLEXPART-COSMO7 and lower values during unstable conditions.
- Convective velocity scale is larger in unstable cases in FLEXPART-COSMO1. The behavior seems to be more prominent during summer months

Friction velocity (left) and Convective velocity sscale (right) distribution comparison for the first 9 months of 2016. Red area corresponds to COSMO-1 while blue area to COSMO-7. Comparison is done according to three different stability classes and seasons.

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How can we quantify the difference between turbulence scheme parameters? Turbulence Kinetic Energy (TKE)

Kinetic energy of the flow

$$\mathrm{KE} = \frac{1}{2}\boldsymbol{u}^2$$

Deviation Mean

$$\boldsymbol{u} = \boldsymbol{u}' + \overline{\boldsymbol{u}}$$

By substituting the latter into KE formula and average according to Reynolds we end up:

$$MKE = \frac{1}{2}(\overline{u^2} + \overline{v^2} + \overline{w^2})$$

$$TKE = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

Wind variances

$$\overline{u'}^2 = \frac{1}{T}\int_0^T (u(t) - \overline{u})^2\,dt = \sigma_{\mathrm{u,v,w}}$$

By the assumption of homogeneous and stationary turbulence temporal average and spatial average are equal according to ergodic theorem

Analogue to TKE, we calculate grid-resolved turbulence ($\mathrm{TKE_G}$) by summation of the wind variances in a small area (20 km x 20 km) around the validation site, representing 3x3 grid cells in COSMO-7 and 19x19 grid cells in COSMO-1

TKE part which is unresolved by the model and needs to be parameterized

$\mathrm{TKE_g}$ which is the resolved share of TKE by the model itself

Hanna Scheme

In Hanna Turbulence parameterization scheme wind variances are functions of Obhukov Length, ABL Height, Friction velocity and convective velocity scale. Hence, TKE is a quantitative measure of the difference of these parameters between FLEXPART-COSMO-1 and FLEXPART-COSMO-7

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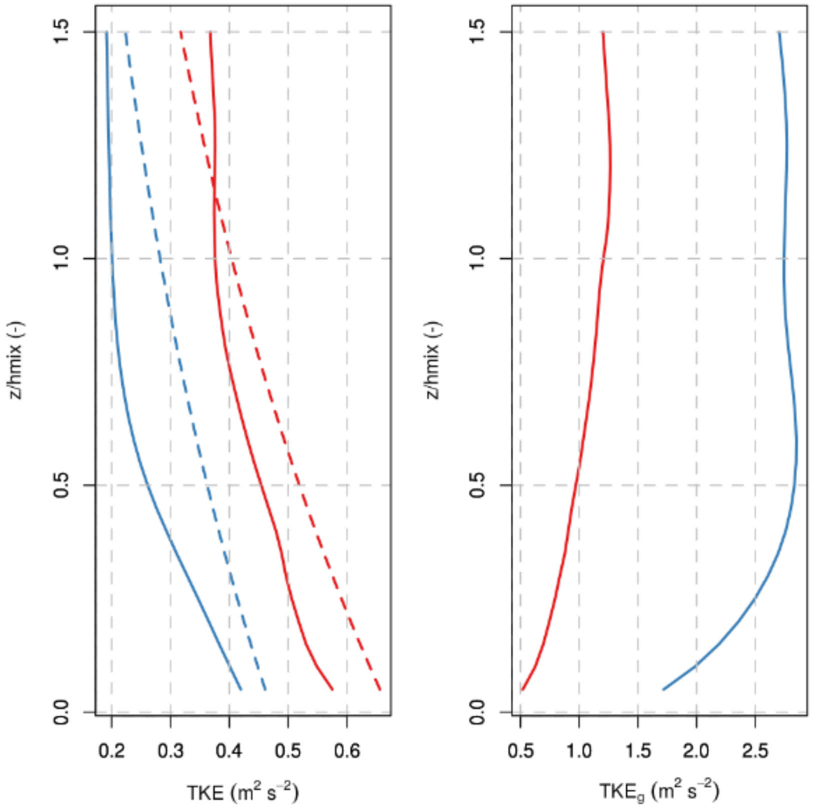
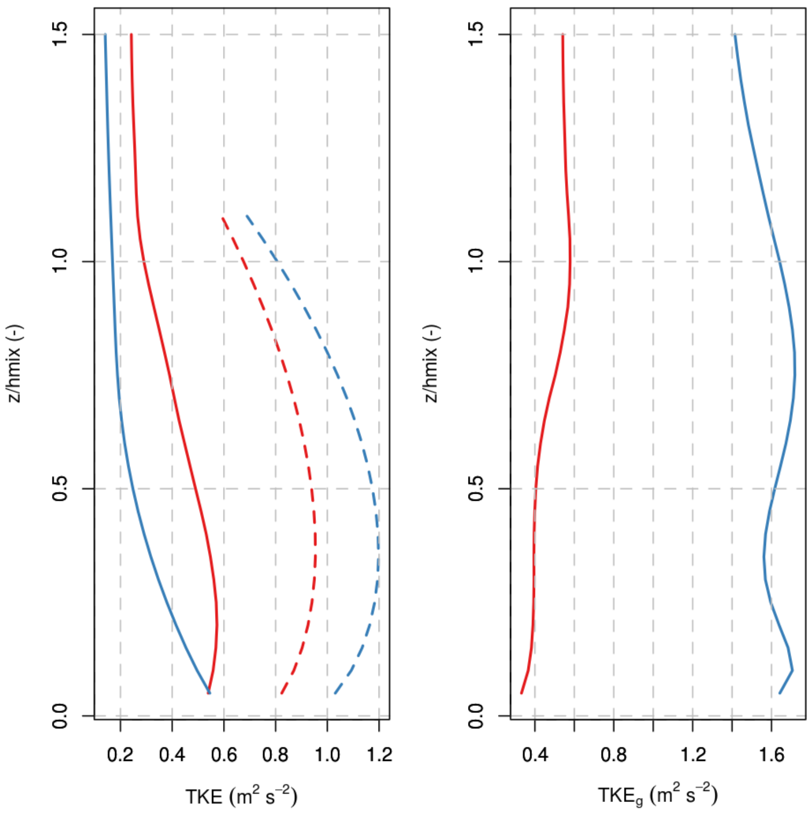
Analysis of TKE Profiles: COSMO vs. FLEXPART

Neutral stability



Unstable stability



- TKE in COSMO-1 is lower in comparison to COSMO-7.
- Larger grid-resolved turbulence in COSMO-1
- Amount of turbulence, resolved by the turbulence scheme is lower in COSMO-1.
- Similar results were obtained for stable boundary layers.

Comparisons of vertical profiles between COSMO-1 and COSMO-7 for TKE (continuous lines correspond to COSMO, dashed lines to FLEXPART-COSMO) and grid resolved turbulence (TKEg).
The vertical axis is normalized by ABL height.

The analysis was carried out for an area of 20x20 km centered on the validation site, Beromünster, corresponding to 3x3 and 19x19 grid cells in COSMO-7 and COSMO-1, respectively.

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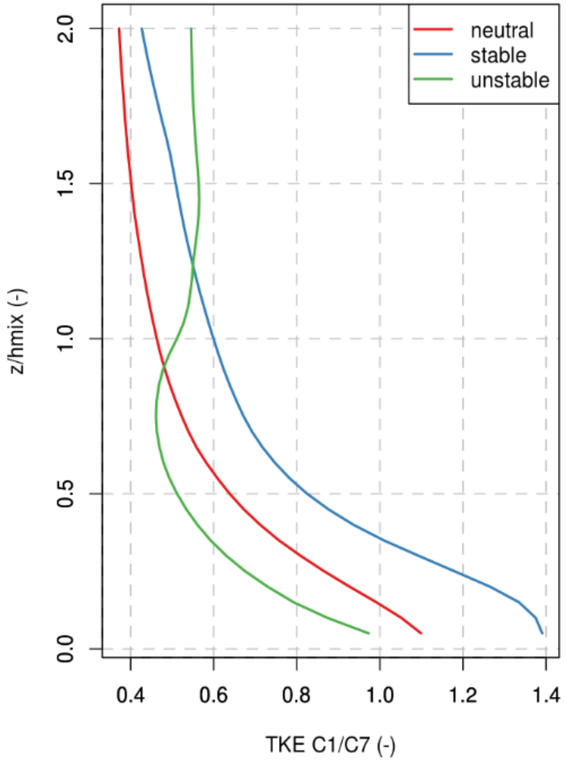
Turbulence Kinetic Energy Profiles According to Different Stability Classes



TKE ratios between COSMO1 and COSMO7 for different stability classes. Y axis is scaled by ABL Height while X axis by friction velocity

- Hanna turbulence scheme needs to be scaled to exclude the turbulence already resolved by the grid of the high resolution model
- Scaling of the turbulence scheme according to TKE ratios between COSMO1 and COSMO7 looks a promising solution
- Polynomial fitting of the profiles seen in the figure can be used as a simple first approach to scale turbulence

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Final Remarks, how can we fix the dispersion problem?

- FLEXPART-COSMO 1 is much more dispersive than FLEXPART- COSMO 7
- Offline nesting with FLEXPART-ECMWF improved high resolution model, but did not solve the problem.
- Only realistic driver of dispersion seems to be the duplication of grid resolved turbulence by FLEXPART's turbulence scheme.
- TKE as a quantitative measure of the difference of turbulence parameterization parameters provides an insight on that.
- TKE in COSMO1 much lower than in COSMO7. "Grid-resolved" higher in FLEXPART-COSMO1 in comparison to FLEXPART-COSMO7.
- How can we tune turbulence?
- Scaling turbulence according to TKE ratios between the models
- Derivation of a new set of constants/parameters in the original Hanna scheme

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