

Running COSMO–WRF on very high resolution over complex terrain

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Abstract This is a technical documentation of the procedure to run the Weather Research and Forecasting (WRF) Model over complex alpine terrain using Consortium for Small-Scale Modeling (COSMO) reanalysis by the Federal Office of Meteorology and Climatology (MeteoSwiss) as initial and boundary conditions (COMSO-WRF). The setup is adapted for very-high resolution simulations based on COSMO-2 (2.2 km resolution) reanalysis. This document gives an overview over steps to setup COSMO-WRF and adaptations needed to run COSMO-WRF. Additionally, the calculation of precipitation rate at a horizontal plane and remapping of COSMO–WRF output on Swiss Coordinates are documented.

1 Introduction

To run the atmospheric model Weather Research and Forecasting (WRF) model version 3.7.1 (Skamarock et al., 2008) over complex alpine terrain using Consortium for Small-Scale Modeling (COSMO-2) reanalysis (2.2 km resolution) by the Federal Office of Meteorology and Climatology (MeteoSwiss) as initial and boundary conditions, numerous adaptations are needed. Several pre-preprocessing steps are required to get the data ready for standard WRF pre-processing. Here, we provide a description of these steps and illustrate the WRF setup presented in Gerber et al. (2018). Information in boxes is additional information, which may be specifically for a certain software or system or is not necessarily needed to run a WRF simulation, but may be of interest. Some parts of the description are specifically for retrieving COSMO-2 reanalysis and the setup of WRF on Piz Daint on the Swiss National Supercomputing Center (CSCS) and are likely different for different computing systems. COSMO-2 reanalysis data is available on Piz Daint. MeteoSwiss has to be contacted for permission and access. A list of software, scripts, files and data, needed to get through the whole procedure, is given in Appendix A.1. Users who have not worked with WRF before are strongly encouraged to work through the WRF online tutorial (<http://www2.mmm.ucar.edu/wrf/OnLineTutorial/index.htm>, accessed 20 November 2017) to familiarize themselves with the WRF model. Prior to performing the standard WRF procedure, several additional steps are needed to run COSMO-WRF over complex terrain, which will be described in Sections 2 and 3, commenting on pre-preprocessing steps for meteorological data and static data, respectively. Section 4 gives information about installing WRF and the WRF pre-processing system (WPS). Information about adaptations and recommended settings for WPS and WRF are given in Sections 5 and 6, while Section 7 gives some information on post-processing procedures.

Note

This document is intended as a guideline. It does not claim to be complete. No responsibility will be taken in case of damage or loss of any kind.

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2 Meteorological data

COSMO-2 reanalysis are given on a rotated coordinate system, which is not readable by the WRF pre-processing system (WPS). Therefore, COSMO-2 data needs to be regridded to regular latitude-longitude coordinates. Additionally, several grib parameters need to be changed to make COSMO-2 input readable by WPS. The rotation is performed using the program `fieldextra` by MeteoSwiss, which is available on the CSCS computing system.

Location `fieldextra`: `/users/oprusers/osm/opr/abs/fieldextra` (location may change)

Location COSMO-2 files: `/store/archive/mch/msopr/owm/COSMO/LA<YEAR>/<DATE>.tar`

Note

Fieldextra is a licensed software which belongs to MeteoSwiss and is the official COSMO post-processing software. Free license may be granted to R&D institutions, but without support; if you are interested contact MeteoSwiss. Additionally, COSMO-2 reanalysis belong to MeteoSwiss and to access and use the data MeteoSwiss must be asked for permission.

2.1 Get COSMO-2 files

Download `.tar` files for chosen dates.

Run `./cosmo_untar.sh`

Note

All COSMO output is given in UTC (Daniel Leuenberger, MeteoSwiss, 21 August 2017, per email).

2.2 Run `fieldextra`

Basic instruction about the use of `fieldextra` was provided by A. Iriza and R. Dumitrache from Meteo Romania (personal communication), who previously implemented a COSMO-WRF version to assess the accuracy of high resolution WRF simulations (Iriza et al., 2016). Advice about namelist setting was further provided by G. de Morsier from MeteoSwiss (personal communication). In `fieldextra` surface (2-dimensional) and atmospheric (3-dimensional) data need to be processed separately. The domain, variables, vertical levels, format, in- and output folder for the transformation are specified in the namelists `2Ddata.nl` and `3Ddata.nl`.

In `2Ddata.nl` and `3Ddata.nl`:

- `in_file = '<path_to_input_files>'`
- `out_file = '<path_for_output_files>'`
- `out_regrid_target = 'getlatlon, 4000000, 43000000, 12000000, 49000000, 20000, 20000'`, specifies the domain, which is processed 'getlatlon, llon, llat, rlon, ulat, gridx, gridy', with llon and rlon the left and right longitude, llat and ulat the lower and upper latitude, and gridx and gridy the cellsize in x- and y-direction, respectively.
- Specify variables to be read and vertical levels, to which they should be interpolated (see example in `2Ddata.nl` and `3Ddata.nl`).

For a single day:

```
> /users/oprusers/osm/opr/abs/fieldextra 3Ddata.nl # for 3D data
> /users/oprusers/osm/opr/abs/fieldextra 2Ddata.nl # for surface data
```

Note

When paths change, all paths and lines 45-48 in `3Ddata.nl` need to be adapted (analogously for `2Ddata.nl`).

For a series of days:

- Adapt `create_list.sh` and `rot_vel_from_raw_for_WRFinput.py` (runs over 24h for all given dates)
- run the script


```
> python rot_vel_from_raw_for_WRFinput.py
```

 or submit batch job (on CSCS):


```
> sbatch rot_vel_from_raw_for_WRFinput.job
```
- Additionally adapt and run `2Ddata.nl` for surface data:


```
> /users/oprusers/osm/opr/abs/fieldextra 2Ddata.nl
```

Create netcdf from COSMO grib

Adapt output format in `3Ddata.nl` and `2Ddata.nl` and run `fieldextra`.

```
out_type = 'NETCDF'
out_file = '<outfile_path_and_name>.nc'
```

2.3 Change grib parameters

The following grib parameters (`indicatorOfParameter`) have to be changed for WPS, as COSMO and WRF use different conventions for grib codes.

Mixing ratio

- Ice mixing ratio (QI): 33 → 178 (because U has also GRIB code 33)

Calling

```
> ./change_vals_day.bash <DATE>
```

changes mixing ratio values for each hour of the specified `<DATE>`, which has the format `YYYYMMDD`.

Soil parameters The following soil parameters need to be adapted:

- Soil temperature (T_SO): 197 → 85
- Soil moisture (W_SO): 198 → 86

Additionally, `indicatorOfTypeOfLevel` and the levels of the soil parameters need to be adapted (Table 1). Calling

```
./change_vals_day_soil.bash <DATE>
```

changes soil values for each hour of the specified day, where `<DATE>` has the format `YYYYMMDD`.

3 Geographical/static data

To run WRF on very-high resolutions (up to 50 meters) over very steep and complex terrain, high-resolution static data (topography, landuse, soiltype) is necessary. The WRF package provides only static data up to a resolution of 2 arc min. Here, we use topographic data with a resolution of 1 arc sec (~30 m). Additionally, landuse data and soil type data are pre-processed for the same resolution. Before the data can be used by WPS it needs to be translated to the binary format readable by WPS.

Table 1: Transformation of soil levels from COSMO to WRF.

COSMO		→	WRF	
top	bottom		top	bottom
1	1	→	0	1
2	2	→	1	3
6	6	→	3	9
18	18	→	9	27
54	54	→	27	81
162	162	→	81	243
486	486	→	243	729
1458	1458	→	729	2187

3.1 Topography

The topography is retrieved from the Aster 1 s digital elevation model (METI/NASA, 2009). To get a smooth transition between the COSMO topography and the WRF topography, a transitional topography is generated at the edges of the WRF domain. This is important to prevent strong boundary effects, which eventually cause instabilities in the simulations.

Note

There are even higher resolution digital elevation models available for Switzerland. However, they do not cover the whole domain of the parent domain of our simulation setup. We did not use the higher quality topography for the inner domains, to avoid inconsistencies of topography at the boundaries of the nests. However, as strong smoothing (see Section 5.1) is applied during the WRF preprocessing, we would most likely not benefit much from the higher quality digital elevation model.

- Download 1s resolution topography: <https://gdex.cr.usgs.gov/gdex/> (accessed: 18 August 2017). Dataset: ASTER Global DEM V2 (<https://lpdaac.usgs.gov/node/1079>, accessed: 15 November 2017, METI/NASA, 2009)
- Extract a slightly larger domain than the parent domain in ArcGIS and save it as ascii-file. The domain extracted from the digital elevation model should be slightly larger to make sure the whole domain, which will be simulated, is inside the extracted digital elevation model. The domain extracted for the simulations in Gerber et al. (2018) was about 0.1° larger in each direction. As the coordinates of COSMO-2 all end with an equal number at the second decimal place, the domain has to be chosen such that its boundaries are at coordinates ending with an equal number at the second decimal place (e.g. 46.00, 64.02, 64.04, etc., and 9.86, 9.88, 9.90, etc.).

Note

When smoothing the boundaries (see next step) the outermost grid points are set to COSMO topography. This range should approximately cover the excess part of the extracted digital elevation model (e.g. $\sim 0.1^\circ$).

Steps for extraction of topographic data in ESRI ArcGIS

In ArcCatalogue:

- Create new polygon (specify coordinates, e.g. WGS84 coordinates for Aster topography)

In ArcMap:

- Open Map
- Add digital elevation model (e.g. Aster 1 s resolution)
- Add polygon
- Draw polygon: Start editing → choose polygon → draw the approximate polygon → save

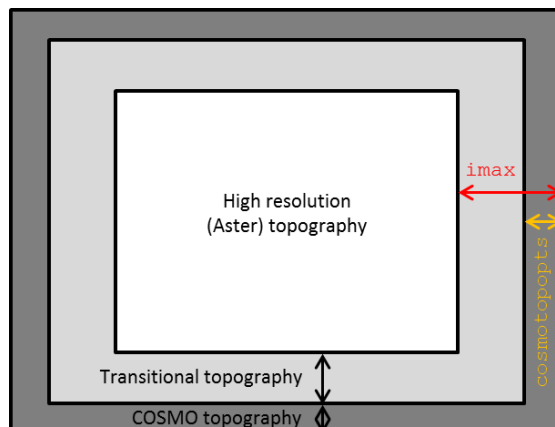


Figure 1: Illustration of boundary smoothing. Dark grey shows the boundary, which is changed to COSMO topography. Light grey shows the transitional zone, which changes by a linear interpolation from COSMO to the high resolution topography. *imax* and *cosmotopopts* are the variables in *toposmoothtest_wgs_84_cosmound.nc1* specifying the boundaries.

- Move edges to chosen position/coordinates:
 - use 'Edit Tool'
 - double click on polygon → right click on edge → Move to . . .
 - specify coordinate → Enter
 - Save & stop editing
 - Extract domain from digital elevation model:
 - Arc Toolbox → Spatial Analyst Tools → Extraction → Extract by mask
 - Save as Ascii:
 - Arc Toolbox → Conversion Tools → From Raster → Raster to Ascii
- Run boundary smoothing to adapt topography boundaries of the extracted e.g. Aster topography to COSMO topography.
- To run the boundary smoothing (*toposmoothtest_wgs_84_cosmound.nc1*), one COSMO file in .nc format is required (see box in Section 2.2). The date does not matter, as only the static (topographic) information is needed. *toposmoothtest_wgs_84_cosmound.nc1* is converting topography at the boundary of the domain to COSMO topography. A transitional topography zone between COSMO and Aster topography is additionally added (Figure 1). The width of the two zones can be chosen by the user. For the domain used in Gerber et al. (2018) (using Aster topography with a resolution of 1 arc second) a COSMO topography boundary of 0.1° (360 grid points) and a transitional boundary of 0.3° (~30 km, 1080 grid points) are used. Depending on the domain and the complexity of the topography these boundaries may need to be adapted.
- Adapt the file *toposmoothtest_wgs84_cosmound.nc1*:
- Choose input and output directories
 - Choose the domain: $y_1, y_2 = \text{min./max. latitude}$, $x_1, x_2 = \text{min./max. longitude}$
 - Choose number of grid points for COSMO-topography: *cosmotopopts* (row 17). This should approximately cover the area, which will be outside of the model domain.
 - Choose number of grid point for the COSMO-topography and transitional topography: *imax* (row 18)
- Output will be written to: `outputdirectory+'WRFmatrix_0.txt'`
- Create binary file and adapt index file.
- Run `ascii_to_bin_topo_wgs84_ws2sf1.f90` to create the binary file needed by WPS (adapt folder and file name in row 23):

```
> gfortran -o ascii_to_bin_topo_wgs84_ws2sf1.exe
  ascii_to_bin_topo_wgs84_ws2sf1.f90 write_geogrid.o
> ./ascii_to_bin_topo_wgs84_ws2sf1.exe
```

This generates the binary file 00001-XXXXX.00001-YYYYY, where XXXXX is the number of grid points in x-direction and YYYYY is the number of grid points in y-direction. Copy the binary file to topo_RES (RES gives the resolution of the data) folder in your geog folder.

Adapt the index file (see example file index_topo) in /geog/topo_RES/ folder. When choosing topography from Aster with 1 s resolution the values known_lat, known_lon, tile_x and tile_y have to be adapted. For the known_lat, known_lon, tile_x, and tile_y the total contained domain has to be specified, i.e. the domain including the extra 0.1°.

3.2 Landuse

High resolution landuse data is retrieved from the Coordination of Information on the Environment (Corine) dataset (European Environmental Agency, 2006). Corine landuse categories cannot be read by WPS directly. Thus, we did a transformation of Corine landuse categories to United States Geological Survey (USGS) landuse categories. Furthermore, Corine landuse is projected to the Aster grid.

- Download Corine landuse data: <https://www.eea.europa.eu/data-and-maps/data/clc-2006-raster> (downloaded: 15 June 2016, accessed: 18 August 2016, new version available)
- Reclassify Corine categories to USGS categories and remap on chosen resolution and project on WGS84.

For this step, we follow the description by Arnold et al. (2010) provided on <http://forum.wrfforum.com/viewtopic.php?f=22&t=2266> (accessed: 18.8.2017), which is based on the reclassification from Corine to USGS landuse categories by Pineda et al. (2004). As Pineda et al. (2004) defines USGS landuse categories between 101 and 124 an additional conversion (subtraction of 100) is needed for landuse categories to fit WRF requirements, which defines USGS landuse categories between 1 and 24. Furthermore, the data needs to be remapped on the chosen resolution if the resolution of the digital elevation model is different from the resolution of the Corine landuse data (additional step to description by Arnold et al., 2010) and finally needs to be projected to WGS84 coordinates.

Steps for transformation and extraction of Corine data (adapted from Arnold et al., 2010), ESRI ArcGIS

In ArcMap:

- Open Map (document, which was produced while processing the digital elevation model)
- Add landuse data
- Remap:
 - ArcToolbox → Spatial Analyst Tools → Reclass → Reclassify (or any of the other Reclass tools, based on Pineda et al. (2004), subtracting 100 for each category.)
- Resample:
 - ArcToolbox → Data Management Tools → Raster → Raster Processing → Resample: Choose cell size of digital elevation model; choose nearest neighbor interpolation
- Reproject to WGS84 coordinates:
 - ArcToolbox → Data Management Tools → Projections and Transformations → Raster → Project Raster
- Extract domain (same as for digital elevation model) from landuse data:
 - Arc Toolbox → Spatial Analyst Tools → Extraction → Extract by mask
- Save as Ascii:
 - Arc Toolbox → Conversion Tools → From Raster → Raster to ASCII

- Create binary file and adapt index file.
Run `ascii_to_bin_landuse.f90` to create the binary file needed by WPS (adapt folder and file name in row 23):

```
> gfortran -o ascii_to_bin_landuse.exe ascii_to_bin_landuse.f90
  write_geogrid.o
> ./ascii_to_bin_landuse.exe
```

This generates the binary file `00001-XXXXX.00001-YYYYY`, where `XXXXX` is the number of grid points in x-direction and `YYYYY` is the number of grid points in y-direction. Copy the binary file to `landuse_RES` (`RES` gives the resolution of the data) folder in your `geog` folder.

Adapt the index file (see example file `index_landuse`) in `/geog/landuse_RES/` folder. When choosing topography from Aster with 1s resolution the values `known_lat`, `known_lon`, `tile_x` and `tile_y` have to be adapted. For the `known_lat`, `known_lon`, `tile_x` and `tile_y` the total contained domain has to be specified, i.e. the domain including the extra 0.1°.

3.3 Soil type

Keeping the model simple, we only use one soil type (*silty clay loam*) for the whole domain. This is not exactly accurate but as we are mainly simulating over a snow cover, the soil type should not make a strong difference for our simulations. The same file is used for the top and bottom layer soil, which are distinguished in WRF (`SOIL_TOP` and `SOIL_BOT`).

- Create soil type file for whole domain.
Run the script `soiltype_writing.py` to create a soiltype file consisting of *silty clay loam* (category 8) or any other chosen category (to be changed in row 42) for the whole domain on the resolution of the topography data. Adapt the input and output file names and folders (rows 12 and 29).
- Create binary file and adapt index file.
Run `ascii_to_bin_soiltype.f90` to create the binary file needed by WPS (adapt folder and file name in row 23):

```
> gfortran -o ascii_to_bin_soiltype.exe ascii_to_bin_soiltype.f90
  write_geogrid.o
> ./ascii_to_bin_soiltype.exe
```

This generates the binary file `00001-XXXXX.00001-YYYYY`, where `XXXXX` is the number of grid points in x-direction and `YYYYY` is the number of grid points in y-direction. Copy the binary file to `soiltype_bot_RES` and `soiltype_top_RES` (`RES` gives the resolution of the data) folder in your `geog` folder.

Adapt the index file (see example file `index_soiltype`) in `/geog/soiltype_bot_RES/` and `/geog/soiltype_top_RES/` folders. When choosing topography from Aster with 1s resolution the values `known_lat`, `known_lon`, `tile_x` and `tile_y` have to be adapted. For the `known_lat`, `known_lon`, `tile_x` and `tile_y` the total contained domain has to be specified, i.e. the domain including the extra 0.1°.

4 Installation of WRF and WPS

Generally, WRF and WPS are installed following the instruction given by the WRF tutorial: <http://www2.mmm.ucar.edu/wrf/OnLineTutorial/> (accessed: 18 August 2017). However, to make WPS run with COSMO input some adaptations are necessary.

Compiling WRF:

1. `./configure` – choose the distributed memory (dmpar) option for INTEL compiler: INTEL (ftn/icc): CRAY XC option (the exact option number varies with WRF version)
2. `./compile -j 8 em_real`

Note

WPS is compiled *after* compilation of WRF. Before compiling WPS, it is critical that the changes suggested in Section 4.1 are implemented. Compile WPS using the INTEL compiler - *but only in serial mode!*

Setup environment to install WRF and WPS on Piz Daint CSCS

WRF and WPS were compiled using INTEL compilers provided by the CSCS Programming Environment

The following steps were carried out by modifying the `~/ .bashrc` script:

1. Change the programming environment from Cray to Intel (`module switch PrgEnv-cray /6.0.4 PrgEnv-intel`)
2. Load the netcdf module (`module load cray-netcdf`)
3. Set path for the netcdf library specific for the compiler (INTEL) used: (`export NETCDF=/opt/cray/pe/netcdf/4.4.1.1.3/INTEL/16.0/`)

4.1 Adaptations for WPS

`./ungrib/src/rrpr.f90`

- Add lines to specify soil moisture and soil temperature variables
- Convert soil moisture values to the unit of WRF (m^{-1} to $\text{m}^3 \text{m}^{-3}$).
- Change all lake temperatures $>300 \text{ K}$ to 285 K as lake temperatures in COSMO are unrealistically high.

`./ungrid/src/rd_grib1.f90`

- line 397 was edited and the variables `map%dx` and `map%dy` were hard-coded to be equal to the resolution of the incoming COSMO data in the units of degrees.
- The resolution of the incoming COSMO data is set in the field extra script - in the present case it is 0.02° and thus `map%dx = 0.02` and `map%dy = 0.02`.

4.2 Problem with Morrison microphysics in WRF version 3.7.1

Running the Morrison microphysics scheme without cumulus scheme in WRF version 3.7.1 requires some adaptation, as described in <http://www2.mmm.ucar.edu/wrf/users/wrfv3.7/known-prob-3.7.1.html> (accessed 18 August 2017).

Problem with Morrison Scheme (posted January 15, 2016, <http://www2.mmm.ucar.edu/wrf/users/wrfv3.7/known-prob-3.7.1.html>)

Problem: When using the Morrison scheme without any cumulus turned on in any of the domains (for example, running a single domain with Morrison scheme only), problems exist because the Morrison scheme uses some tendency arrays from output with a cumulus scheme. However, these arrays were not allocated when no cumulus scheme is used.

Solution: If you wish to use this scheme without any cumulus, you must edit Registry.EM_COMMON, and update this line, from:

```
package morr_two_moment mp_physics==10 - moist:qv,qc,qr,qi,qs,qg;
  scalar:qni,qns,qnr,qng
```

to

```
package morr_two_moment mp_physics==10 - moist:qv,qc,qr,qi,qs,qg;
  scalar:qni,qns,qnr,qng;state:rqruten,rqscuten,rqicuten
```

Once you update the file, save the file, and then you will need to go back to the WRFV3/ directory, issue a `clean -a`, then reconfigure, and recompile the code.”

5 Running WPS

To create meteorological and geographic input on a user defined grid, three pre-processing steps need to be performed prior to running WRF. `geogrid` interpolates the geographic (static) data, i.e. topography, landuse, soil type etc. to the chosen horizontal grid for the parent domain and all nests. `ungrib` reads meteorological data given in `grib1` or `grib2` format. Finally, `metgrid` horizontally interpolates the meteorological data to the horizontal grid produced by `geogrid`. Vertical interpolation will be done by the program `real`, which is the last pre-processing step but part of WRF (see Section 6). General information about WPS and WRF namelist settings are based on Wang et al. (2016).

5.1 Geogrid

To run `geogrid.exe` static data must be available in the `/geog/` folder (Section 3) and the `index` file in the `/geog/` folder must be adapted for the desired domain. In the `namelist.wps` the `&share` and `&geogrid` section must be specified. An example of `namelist.wps` is given in Appendix A.3. Suggestions and information about some namelist options are listed in Table 2.

GEOGRID.TBL (in `/WPS/geogrid/`) For `geogrid.exe` to be able to read the static data provided in the newly created folders for topo, landuse and soiltype, in `/geog/` the `GEOGRID.TBL` file needs to be adapted.

- Add `interp_option` and `rel_path` for all static data (`HGT_M`, `HGT_U`, `HGT_V`, `LANDUSEF`, `SOILCTOP`, and `SOILCBOT`).
- Change the default path to the new folder.
- For `LANDUSEF` additionally add line `land_mask_water`.

Terrain smoothing For complex topography and very high resolution simulations maximum slope angles are likely very high. Large slope angles are critical for simulations with eta-coordinates, as too steep slopes may cause problems when calculating the pressure gradient, as height differences between neighboring grid points may become up to an order of magnitude larger than the elevation difference between neighboring eta levels (Doyle et al., 2013). Therefore, it is recommended to apply a terrain smoothing to keep all slope angles below 45° . For the simulations in Gerber et al. (2018) a minimum number of four smoothing cycles with WPS 1-2-1 smoothing is needed. WPS 1-2-1 smoothing applies a moving window filter with a window length of 3. Grid points $i-1$, i , and $i+1$ are weighted with a ratio of 1:2:1. However, a very small simulation timestep is needed for a simulation with maximum slope angles of 45° (see Section 6). To speed up simulations a stronger smoothing may be applied. To check maximum slopes in the `geo_em.d*.nc` files

see_slopes.nc1 may be used. The smoothing type and the number of smoothing cycles need to be chosen in GEOGRID.TBL:

- Chose smoothing type (smooth_option) and number of smoothing cycles (smooth_passes) in GEOGRID.TBL.

Table 2: Description and suggestions for some options in namelist.wps. An example of namelist.wps can be found in Appendix A.3.

Section	Option	Description
&geogrid	Parent_grid_ratio	An odd parent grid ratio is recommended because the WRF grids are Arakawa C-staggered and therefore mass and velocity points of the parent and nest will be coincident. A ratio of 1:3 is recommended as it is most tested (Skamarock et al., 2008; Gill and Pyle, 2010).
	e_we/e_sn	For nested domains the ending point of the domain in west-east (we) and south-north (sn) direction must be chosen "one greater than some integer multiple of the nesting ratio" (Wang et al., 2016), to make sure that the upper right corner coincides with a grid point of the parent domain. e_we and e_sn must be chosen such that they are inside the domain available for topography, landuse and soiltype, but not too far from the boundary, such that the smooth transition between COSMO and the high resolution topography is inside the domain (Figure 1).
	geog_data_res	Give the name of your newly created folder in /geog/, which contains your topography binaries.
	dx, dy	dx and dy are given in meters except when using 'lat-lon' projection, where dx and dy are given in degrees.
	map_proj	For mid-latitude domains 'lambert' projection is most accurate. However, the output will not be on regular output coordinates. For some applications 'mercator' projection may thus be preferred.
	ref_lat/ref_lon	Specifies the lower left corner (ref_x = 1, ref_y = 1) of the parent domain and must be chosen such that it is inside the domain provided by static data but not too far from the edge such that the transitional topography is inside the domain.
	geog_data_path	Path of the /geog/ folder.
&metgrid	fg_name	Should correspond to the prefix in &ungrib, except if the intermediate files from ungrib were moved to a different directory.
	%opt_output_from_metgrid_path	A path for met_em.d*.nc files may be specified.
&share	Opt_output_from_geogrid_path	A path for the output files geo_emd0*.nc can be specified.

Run geogrid: > ./geogrid.exe

5.2 Ungrib

To run ungrib on COSMO-2 data all the steps described in Section 2 need to be performed in advance. As COSMO-2 is not a standard input for WRF, a variable table translating COSMO-2 grib codes is required and needs to be linked to WPS/Vtable (Vtable.COSMO.mixing.landuse, see Appendix A.2).

Run ungrib:

```
> ./link_grib.csh <path_to_COSMO_files>/laf # (no * to add all files)
> ./ungrib.exe
```

5.3 Metgrid

Once geogrid.exe and ungrib.exe were run successfully, metgrid.exe can be run. Sections &geogrid and &ungrib should be left unchanged. Section &share should stay unchanged except for start_date and end_date for the nested domains, for which the start and the end date can be set to the start date and time for the nests. For the nests only the start date and time needs to be processed, because the nests are only initialized with COSMO input but boundary conditions will always be taken from the parent domain.

METGRID.TBL (in /WPS/metgrid/) When running a simulation with a land surface model, METGRID.TBL needs to be adapted such that metgrid is able to read soil temperatures and soil moisture. For name=ST and name=SM the new soil levels need to be added as conditional statement:

```
=====
name=ST
...
# ELSE IF
    fill_lev = 1 : T_S00001(200100)
    fill_lev = 3 : T_S00002(200100)
    fill_lev = 9 : T_S00006(200100)
    fill_lev = 27 : T_S00018(200100)
    fill_lev = 81 : T_S00054(200100)
    fill_lev = 243 : T_S00162(200100)
=====
name=SM
...
# ELSE IF
    fill_lev = 1 : W_S00001(200100)
    fill_lev = 3 : W_S00002(200100)
    fill_lev = 9 : W_S00006(200100)
    fill_lev = 27 : W_S00018(200100)
    fill_lev = 81 : W_S00054(200100)
    fill_lev = 243 : W_S00162(200100)
=====
```

Additionally, for each soil level a block specifying soil temperature and soil moisture properties needs to be added:

```
=====
name=T_S00000
    interp_option=sixteen_pt+four_pt+wt_average_4pt+wt_average_16pt
    +search
    masked=water
    interp_mask=LANDSEA(0)
    missing_value=-1.E30
    fill_missing=285.
    flag_in_output=FLAG_T_S00000
=====
```

```

name=W_S00001
  interp_option=sixteen_pt+four_pt+wt_average_4pt+wt_average_16pt
  +search
  masked=water
  interp_mask=LANDSEA(0)
  missing_value=-1.E30
  fill_missing=1.
  flag_in_output=FLAG_W_S00001
=====

```

Run metgrid:

```
> ./metgrid.exe
```

Semi-idealized simulations for sensitivity studies

Option 1 To perform simulation over real complex topography but with constant meteorological input, one possibility is to use a certain meteorological field from COSMO-2 and repeatedly feed it to WRF as boundary condition. A test has been run but no thorough analysis has been performed. To make a certain meteorological condition available for every boundary input timestep, `met_em.d*.nc` files can be multiplied and the timestamp of the files may be adapted. To adapt the timestamp in the multiplied `.nc`-files `change_Times_netcdf.nc1` is available. However, before using this approach the following short-comings should be addressed:

- Are the chosen atmospheric conditions representative?
- Are the chosen nighttime/daytime conditions problematic when repeated for day/night times?

Option 2 Another option to address the sensitivity of precipitation to different wind speeds has been performed in Gerber et al. ([in prep.](#)). For this analysis wind speeds have been reduced to one third or two thirds of the original wind speeds, while all other variables were left unchanged for a given event. To adapt wind speeds in the `met_em*.nc` files `change_wind_netcdf.nc1` is available.

6 Running WRF

Setting up a very-high resolution simulation over complex terrain for snow covered conditions is challenging. Different settings and changes to standard settings are needed to run COSMO-WRF simulations. Below, the settings used for simulations presented in Gerber et al. (2018) are mentioned and described. An example of `namelist.input` is given in Appendix A.4.

Vertical nesting in version 3.7.1 As vertical nesting (Daniels et al., 2016) is not fully implemented in version 3.7.1, the `eta_levels` have to be determined manually. The simplest procedure to do this is to run a very short simulation for each number of vertical levels on a single domain.

Note

This issue has been fixed in newer versions of WRF (Megan Daniels, personal communication).

- Choose vertical levels
- For each domain, i.e. for all different numbers of vertical levels:
 - Run a very short simulation (2 s, setting `history_interval_s = 1`) on only one domain with the chosen number of vertical levels.
 - Use `ncdump -v ZNW wrfout_d01_<DATE> > dumpETA.txt`
 - Copy and paste the ZNW (eta levels) into the `namelist.input`

Additional refinement of vertical levels on 50 meter resolution A refinement of vertical levels in the boundary layer was performed to get a higher resolution of close-ground processes in very-high resolution simulations. The refinement is performed as suggested in a WRF tutorial about `real` by Gill (2015). For the refinement 10 additional eta-levels are added to the boundary layer.

Large Eddy Simulations (LES) To run WRF simulation in the LES mode different settings are required. Generally, the LES mode of WRF is based on choosing no boundary layer parametrization (`bl_pbl_physics = 0`). Depending if the simulation is run with or without a land surface model, different additional settings need to be chosen (Dudhia, 2012). The use of the LES mode is basically recommended for simulation with $dx \ll 1$ km. Recommended namelist settings for complex topography and high resolution simulations are given in (Dudhia, 2012).

Settings chosen for simulations in Gerber et al. (2018) are based on Dudhia (2012):

```
diff_opt = 2

isfflx = 1 # drag and heat flux from physics
sf_sfclay_physics = 1
sf_surface_physics ≠ 0

km_opt = 2 # or 3
mix_isotropic = 0 # set to 1 for dx ≈ dz
gwd_opt = 0
```

Alternatively, the following may be chosen:

```
isfflx = 2 # drag from physics, heat flux from tke_heat_flux
sf_sfclay_physics = 1
```

Note

`mix_isotropic` has been set to 0 for all simulation domains for the simulation in Gerber et al. (2018). It might be valuable to change `mix_isotropic` to 1 for the two innermost domains with resolutions of 150 m and 50 m, respectively.

Mesoscale setting Given the setup with resolutions of 1350 m, 450 m, 150 m, and 50 m in the parent domain and the three nests, a mesoscale setting is appropriate for the parent domain with a grid size of 1350 m. For mesoscale simulations a planetary boundary layer (PBL) scheme (`bl_pbl_physics`) has to be chosen. For complex terrain the Yonsei University (YSU) PBL scheme (Hong et al., 2006) was found to be one of the best schemes for simulations over complex terrain (Gómez-Navarro et al., 2015). A more sophisticated version of YSU PBL is available, which takes into account subgrid scale orography (Jiménez and Dudhia, 2012). This is claimed to correct for negative (positive) wind speed biases over mountainous (flat) terrain (Jiménez and Dudhia, 2012; Lee et al., 2015). Comparing the influence of a parent domain with and without corrections for subgrid scale orography would be very interesting. To keep the simulation setup simple, simulations in Gerber et al. (2018) were run with the uncorrected YSU PBL scheme for the parent domain.

Note on model resolutions

In numerical modeling different zones are distinguished. Large-scale and mesoscale simulations are commonly used for simulations with horizontal resolutions of >10 km. For these coarse resolutions no turbulence is resolved and a boundary layer parameterization is needed. At small scales ($< \text{few } 100$ m) large eddy simulations (LES) are used, which allow to resolve all major eddies. The zone in between is usually referred to as the “grey zone” or “terra incognita” (Wyngaard, 2004). This is the zone where a certain part of turbulent kinetic energy is resolved but not all. The “grey zone” is most challenging in numerical simulations. Approaches have been proposed to skip the “grey zone” by choosing the grid ratio accordingly (Rai et al., 2017).

Roughness length of snow in complex terrain Snow cover is often assumed to have a very low roughness length, which is good for relatively flat and gentle terrain. However, snow cover in alpine terrain is likely rough due to large rocks and the complex topography, which is only partially smoothed out by the snow cover. Therefore, for simulations over snow in complex terrain, we suggest to increase the roughness length of snow to 0.2 m instead of the default value of 0.002 m, as the size of roughness elements of 2 m seems to be reasonable to account for missing terrain features and roughness due to large rocks in snow covered complex terrain. Roughness was determined by the comparison of a 2 m digital terrain model (DTM-AV © 2018 swisstopo (5704 000 000)) with a 25 m digital elevation model (dhm25 © 2018 swisstopo (5740 000 000)). To evaluate the roughness of complex alpine terrain, the average of the absolute difference of the two terrain models for a domain covering the upper Dischma valley (Davos, Switzerland, innermost domain in simulations by Gerber et al. (2018) between 2200 and 2700 meter above sea level has been taken. The average difference is 2.5 m. To account for smoothing due to snow coverage, we estimate the size of roughness elements to 2 m.

Depending on the chosen surface model, different tables need to be adjusted to change the roughness length properties. When using `sf_surface_physics = 4` (see next paragraph) the file `MPTABLE.TBL` is used. In `MPTABLE.TBL` the roughness length of snow is specified as `Z0SNO`. We suggest changing `Z0SNO` from 0.002 m to 0.2 m.

Land-surface model The most common land surface model in WRF is the Noah land surface model (Tewari et al., 2004). However, this model has been further developed and a more recent version Noah with multiple parametrization (Noah-MP Niu et al., 2011; Yang et al., 2011) is available. Noah-MP has a more sophisticated treatment of snow. Therefore, COSMO-WRF in Gerber et al. (2018) is run with Noah-MP surface physics (`sf_surface_physics = 4`). When running a simulation with a surface model, the number of input soil layers (`num_metgrid_soil_levels`), the input source (`surface_input_source`), the number of soil levels in WRF (`num_soil_layers`), and the number of land categories (`num_land_cat`) have to be specified. For `sf_surface_physics = 4` the parameter `ifsnow` is irrelevant as it is only used for `sf_surface_physics = 1` (Wang et al., 2016).

Simulation timestep The simulation timestep is strongly dependent on the steepness and complexity of the topography and may therefore differ for different domains. Based on the timestep requirements of simulations over complex terrain in the surroundings of Davos (Switzerland, Gerber et al., 2018), with maximum slope angles of 45° at a 50 m resolution (simulation set up with parent domain and three nest with horizontal resolutions of 1350 m, 450 m, 150 m, and 50 m and 40, 40, 60, and 90 vertical levels and a model top at 150 mbar) we recommend to start with:

```
timestep = 1 # second
parent_time_step_ratio = 1,3,3,3,
```

For a simulation with the same simulation setup but stronger terrain smoothing (maximum slope angles for 50 m resolution of 37.4°), the following setup is recommended to start with:

```
timestep = 6 # seconds
parent_time_step_ratio = 1,3,4,2,
```

Note

Time steps should always be chosen such that they end up to round numbers to avoid stability problems in the model (M. Daniels, personal communication).

Horizontal resolution and domain The specifications for horizontal resolution and the domain have to be set corresponding to the settings chosen in WPS (Section 5).

Radiation The simplest schemes are chosen for radiation. `slope_radiation` and `topo_shading` make sure shadows due to topography in complex terrain are properly simulated. The radiative time step `radt` is 5 min. Based on the WRF User Guide it is recommended to choose `radt` as “1 min per km of dx” (Wang et al., 2016). However, calculating radiation more frequently than every 5 min to 15 min is not necessary as radiation is not a quickly changing process. The parameter `icloud` allows for cloud effects on radiation.

Precipitation The microphysics scheme (`mp_physics`) is set to the Morrison 2-moment scheme (Morrison et al., 2005; Morrison et al., 2009). The Morrison 2-moment scheme (option 10) and the Thompson graupel scheme (option 8) have been found to most properly simulate solid precipitation in complex terrain (Liu et al., 2011). The cumulus parameterization (`cu_physics`) is set to zero, as it is recommended to run simulations without a cumulus parameterization for grid sizes <4 km (e.g. Wang, 2015).

Run a simulation Prior to running `wrf.exe`, the input data has to be interpolated to the chosen vertical levels by `real.exe`. Namelist setting in `namelist.input` for `real.exe` and `wrf.exe` are identical (Appendix A.3 and Appendix A.4). Once all settings in the `namelist.input` are chosen, `real.exe` can be run and if successful, `wrf.exe` can be run.

To restart a simulation the `namelist.input` has to be adapted:

- Change `run_days`, `run_hours`, `run_minutes` and `run_seconds` to the remaining time.
- Change `start_year`, `start_month`, `start_day`, `start_hour`, `start_minute` and `start_second` to the date and time of the last available restart file. The frequency of restart files can be determined by `restart_interval`.
- Change `restart` to `.true.` if it is the first restart.
- Restart the simulation.

Running a simulation on Piz Daint at CSCS

To run a simulation a batch job needs to be submitted. Therefore, batch scripts are required for both, to run `real` and `wrf` (`real.job` and `wrf.job`). On Piz Daint, any simulation can run over a maximum of 24 h. Therefore, longer WRF simulations need to be restarted every 24 h. To run the simulation, the batch script has to be submitted:

```
> sbatch WRF_real.job
```

To check the status of the simulation:

```
> squeue -u $USER
```

Output from the simulation is written to `rs1.out.0000`. When `real.exe` was successful `SUCCESS COMPLETE REAL_EM INIT` will be written at the end of `rs1.out.0000`. Note: `rs1.out.*` and `rs1.error.*` files are written for each cpu.

When `real` is successful, `wrf.exe` can be run:

```
> sbatch WRF_wrf.job
```

To restart the simulation, the `namelist.input` needs to be adapted and another batch job needs to be submitted.

7 Post processing

Different post-processing methods will be described. The list does not cover all aspects of post-processing that may be valuable for any kind of analysis. However, we provide some post-processing information for more complex analysis.

7.1 Map WRF output on Swiss Coordinates

For comparison to e.g. operational radar data by MeteoSwiss, it is helpful to display the same domain as the radar. However, radar data comes in Swiss Coordinates (CH1903LV03). This requires mapping of WRF output on the Swiss Coordinate system and plot it in the Swiss Coordinate reference frame.

- create the required lat/lon coordinate grid in swiss coordinates (CH1903LV03)
→ `create_CH1903LV03_vector.py`

- remap the created ascii-file into global coordinates (ETRF93/CHTRF95 (ETRS89/CHTRS95/ WGS84) using the REFRAME tool by swisstopo (<https://www.swisstopo.admin.ch/de/karten-daten-online/calculation-services/reframe.html>, accessed: 22 August 2017)
- interpolate the WRF data onto the new global coordinates, which correspond to the swiss coordinates and plot them in the reference frame of swiss coordinates
→ `plane_2dfield_snowacc24h_everyoutputtime_raddom.py`

7.2 Precipitation rate at horizontal level

Precipitation rate (RAINNC: total precipitation, SNOWNC: solid precipitation without graupel and GRAUPELNC: graupel only) in WRF is only given as a ground level output. To analyze precipitation fields with respect to radar precipitation fields, WRF precipitation needs to be extracted at the radar elevation level. Given the particle size distribution $N(D)$

$$N(D) = N_0 D^\mu e^{-\lambda D}, \quad (1)$$

where D is the particle diameter, N_0 is the intercept, λ the slope and μ the shape parameter of the size distribution, precipitation rate (R_i) can be calculated from the predicted mixing ratios (q_i) and the predicted number concentration (N_i) of hydrometeors (i) as:

$$R_i = \int_0^\infty v_i(D) m_i(D) N_i(D) dD \quad (2)$$

with terminal fall velocity $v(D) = \alpha D^\beta$ and mass $m(D) = a D^b$, where D is the particle diameter and α , β , a , and b are constants (Table 3). Integration of R_i results in:

$$R_i = N_{0,i} a_i \alpha_i \frac{\Gamma(b_i + \beta_i + 1 + \mu_i)}{\lambda_i^{(b_i + \beta_i + 1 + \mu_i)}} \quad (3)$$

with

$$\lambda_i = \left[\frac{a_i \Gamma(\mu_i + b_i + 1)}{q_i \Gamma(\mu_i + 1)} \right] \quad (4)$$

and

$$N_{0,i} = \frac{N_i \lambda_i^{(\mu_i + 1)}}{\Gamma(\mu_i + 1)} \quad (5)$$

Due to the terrain-following vertical coordinates all WRF parameters need to be interpolated to the radar elevation, which is done by inverse-weighted interpolation between the two closest eta-levels to the required elevation.

Note

The precision of the output fields strongly depends on the output-timestep. Strong differences between e.g. SNOWNC and calculated precipitation at the ground level may arise with an output timestep of 30 minutes, as WRF updates summed precipitation every simulation timestep.

Table 3: Constants for precipitation rate calculation for the ice, snow and graupel hydrometeors. ρ is the density of the different hydrometers. a and b are the constants for the mass and α and β are the constants for the terminal fall velocity equation. μ is the shape parameter of the particle size distribution. Values for graupel are given for simulations run without hail (i.e. option `IHAIL = 0`).

Hydrometeor	ρ	a	b	α	β	μ
Ice	500	$\rho_{\text{ice}} \frac{\pi}{6}$	3	700.00	1.00	0
Snow	100	$\rho_{\text{snow}} \frac{\pi}{6}$	3	11.72	0.41	0
Graupel	400	$\rho_{\text{graupel}} \frac{\pi}{6}$	3	19.30	0.37	0

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A.1 Requirements

Software

- fieldextra (available on CSCS, owned by MeteoSwiss: /users/oprusers/osm/opr/abs/fieldextra, location may change)
- WRF version 3.7.1 (including WPS, http://www2.mmm.ucar.edu/wrf/users/download/get_source.html, accessed: 14 March 2018)
- python
- gfortran
- NCL
- GIS software (e.g. ArcGIS)

Data

- COSMO-2 reanalysis (available on CSCS, owned by MeteoSwiss: /store/archive/mch/msopr/own/COSMO/LA<YEAR>/<DATE>.tar)
- Aster topography: <https://gdex.cr.usgs.gov/gdex/> (accessed: 18 August 2017)
- Corine landuse: <https://www.eea.europa.eu/data-and-maps/data/clc-2006-raster> (downloaded: 15 June 2016, accessed: 18 August 2017, new version available)

Pre-preprocessing scripts

Meteorological data (MeteorologicalData.zip)

- cosmo_untar.sh
- create_list.sh
- 2Ddata.nl
- 3Ddata.nl
- rot_vel_from_raw_for_WRFinput.py
- rot_vel_from_raw_for_WRFinput.job (if running as batch job)
- change_vals_day.bash
- change_vals_day_soil.bash
- change_Times_netcdf.ncl
- change_wind_netcdf.ncl

Static data (StaticData.zip)

- toposmoothtest_wgs84_cosmobound.ncl
- soiltype_writing.py
- write_geogrid.o
- ascii_to_bin_topo_wgs84_ws2sf1.f90
- ascii_to_bin_topo_wgs84_ws2sf1.exe
- ascii_to_bin_landuse.f90
- ascii_to_bin_landuse.exe
- ascii_to_bin_soiltype.f90
- ascii_to_bin_soiltype.exe
- see_slopes.ncl

Adapted Files to compile WPS/WRF

WPS (WPSSetup.zip)

- rrpr.f90-soilmoistandtempadapted
- rd_grib1.f90-COSMO
- Corrections for WRF3.7.1 when using Morrison microphysics: <http://www2.mmm.ucar.edu/wrf/users/wrfv3.7/known-prob-3.7.1.html> (accessed 18 August 2017)

Files to run WPS/WRF

WPS (WPSrun.zip)

- index_topo
- index_landuse
- index_soiltype
- GEOGRID.TBL-aster-121_4 (example with four smoothing cycles of 1-2-1 smoothing)
- METGRID.TBL-T_SOfill1285-W_SOfill11
- namelist.wps
- Vtable.COSMO.mixing.soil

Note

index files need to be named *index* in their respective folder (Section 3).

WRF (WRFRun.zip)

- MPTABLE.TBL_Z0SN00.2
- namelist.input
- WRF_real.job
- WRF_wrf.job

Postprocessing

Map WRF output on Swiss Coordinates (Postprocessing.zip)

- Coordinate transformation swiss coordinates to global coordinates for whole grid: <https://www.swisstopo.admin.ch/de/karten-daten-online/calculation-services/reframe.html> (accessed: 22 August 2017)
- create_CH1903LV03_vector.py
- create_arcgis_ascii.py
- read_wrffields.py

Precipitation rate at horizontal level Python scripts may be made available upon request.

A.2 Vtable for COSMO-2 data

GRIB Code	Level Code	Level 1	Level 2	metgrid Name	metgrid Units	METGRID Description
6	100	*		GEOPT	m2 s-2	
	100	*		HGT	m	Height
11	100	*		TT	K	Temperature
33	100	*		UU	m s-1	U
34	100	*		VV	m s-1	V
52	100	*		RH	%	Relative Humidity
11	1	0		SKINTEMP	K	Skin temperature (can use for SST also)
11	105	2		TT	K	Temperature at 2 m
52	105	2		RH	%	Relative Humidity at 2 m
33	105	10		UU	m s-1	U at 10 m
34	105	10		VV	m s-1	V at 10 m
1	1	0		PSFC	Pa	Surface Pressure
2	102	0		PMSL	Pa	Sea-level Pressure
66	1	0		SNOWH	m	Physical Snow Depth
31	100	*		QC	kg kg-1	Cloud water mixing ratio
36	100	*		QS	kg kg-1	Snow water mixing ratio
39	100	*		QG	kg kg-1	Graupel water mixing ratio
35	100	*		QR	kg kg-1	Rain water mixing ratio
178	100	*		QI	kg kg-1	Ice mixing ratio
85	112	0	1	T_SO0001	K	Soil temperature 1 cm below ground
85	112	1	3	T_SO0002	K	Soil temperature 2 cm below ground
85	112	3	9	T_SO0006	K	Soil temperature 6 cm below ground
85	112	9	27	T_SO0018	K	Soil temperature 18 cm below ground
85	112	27	81	T_SO0054	K	Soil temperature 54 cm below ground
85	112	81	243	T_SO0162	K	Soil temperature 162 cm below ground
86	112	0	1	W_SO0001	m	Soil moisture 1 cm below ground
86	112	1	3	W_SO0002	m	Soil moisture 2 cm below ground
86	112	3	9	W_SO0006	m	Soil moisture 6 cm below ground
86	112	9	27	W_SO0018	m	Soil moisture 18 cm below ground
86	112	27	81	W_SO0054	m	Soil moisture 54 cm below ground
86	112	81	243	W_SO0162	m	Soil moisture 162 cm below ground

A.3 namelist.wps

```

&share
wrf_core           = 'ARW',
max_dom            = 1,
start_date        = '2016-01-29_05:00:00', '2016-01-30_05:00:00', '2016-01-30
  _17:00:00', '2016-01-30_23:00:00',
end_date          = '2016-02-01_00:00:00', '2016-01-30_05:00:00', '2016-01-30
  _17:00:00', '2016-01-30_23:00:00',
interval_seconds  = 3600,
io_form_geogrid   = 2,
opt_output_from_geogrid_path = '/project/s569/gerberf/input_WPS/GEO_EM/'
/

&geogrid
parent_id         = 1, 1, 2, 3,
parent_grid_ratio = 1, 3, 3, 3,
i_parent_start    = 1, 105, 83, 88,
j_parent_start    = 1, 82, 54, 55,
e_we             = 184, 202, 199, 199,
e_sn             = 237, 199, 199, 199,
geog_data_res    = 'topo_1s', 'topo_1s', 'topo_1s', 'topo_1s',
dx               = 1350,
dy               = 1350,
map_proj         = 'lambert',
ref_lat          = 45.4,
ref_lon          = 7.4,
ref_x            = 1,
ref_y            = 1,
truelat1         = 46.4,
truelat2         = 47.2,
stand_lon        = 9.0,
geog_data_path   = '/project/s569/gerberf/geog_origWRF'
/

&ungrib
out_format       = 'WPS',
prefix           = '/project/s569/gerberf/input_WPS/FILES/COSMO_Jan-
  Mar_landsurf_ptop100/FILE',
/

&metgrid
fg_name          = '/project/s569/gerberf/input_WPS/FILES/COSMO_Jan-
  Mar_landsurf_ptop100/FILE'
io_form_metgrid  = 2,
opt_output_from_metgrid_path = '/project/s569/gerberf/input_WRF/METFILES/
  COSMO_Jan-Mar_smoothboundaries1440_cosmo-le-360
  _mixing_1350_lambert_landuse_wrfsmooth14_ptop100/'
/

```

A.4 namelist.input

```

&time_control
  run_days           = 2,
  run_hours          = 19,
  run_minutes        = 0,
  run_seconds        = 0,
  start_year         = 2016, 2016, 2016, 2016,
  start_month        = 01, 01, 01, 01,
  start_day          = 29, 30, 30, 30,
  start_hour         = 05, 05, 17, 23,
  start_minute       = 00, 00, 00, 00,
  start_second       = 00, 00, 00, 00,
  end_year           = 2016, 2016, 2016, 2016,
  end_month          = 02, 02, 02, 02,
  end_day            = 01, 01, 01, 01,
  end_hour           = 00, 00, 00, 00,
  end_minute         = 00, 00, 00, 00,
  end_second         = 00, 00, 00, 00,
  interval_seconds   = 3600,
  input_from_file    = .true., .true., .true., .true.,
  fine_input_stream  = 0, 2, 2, 2,
  history_interval   = 30, 30, 30, 30,
  frames_per_outfile = 48, 48, 48, 48,
  restart            = .false.,
  restart_interval   = 60,
  write_hist_at_0h_rst = .true.,
  io_form_history    = 2,
  io_form_restart    = 2,
  io_form_input      = 2,
  io_form_boundary   = 2,
  io_form_auxinput2  = 2,
  debug_level        = 0,
/

&domains
  time_step          = 1,
  time_step_fract_num = 0,
  time_step_fract_den = 1,
  max_dom            = 4,
  e_we               = 184, 202, 199, 199,
  e_sn               = 237, 199, 199, 199,
  e_vert             = 40, 40, 60, 90,
  vert_refine_method = 0, 2, 2, 2,
  eta_levels         = 1, 0.993, 0.983, 0.97, 0.954, 0.934, 0.909,
    0.88, 0.8600174, 0.840035, 0.8200524, 0.8000699, 0.761449, 0.7237018,
    0.6868118, 0.6507629, 0.615539, 0.5811244, 0.5475038, 0.5146619,
    0.4825837, 0.4512546, 0.42066, 0.3907857, 0.3616177, 0.3331423, 0.3053457,
    0.2782149, 0.2517365, 0.2258978, 0.200686, 0.1760886, 0.1520934,
    0.1286884, 0.1058616, 0.08360139, 0.06189632, 0.0407351, 0.02010664, 0,
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p_top_requested          = 15000,
num_metgrid_levels      = 39,
num_metgrid_soil_levels = 6,
dx                      = 1350, 450, 150, 50,
dy                      = 1350, 450, 150, 50,
grid_id                 = 1, 2, 3, 4,
parent_id               = 1, 1, 2, 3,
i_parent_start          = 1, 105, 83, 88,
j_parent_start          = 1, 82, 54, 55,
parent_grid_ratio       = 1, 3, 3, 3,
parent_time_step_ratio  = 1, 3, 3, 3,
feedback                = 0,
smooth_option           = 0,
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&physics
mp_physics              = 10, 10, 10, 10,
ra_lw_physics           = 1, 1, 1, 1,
ra_sw_physics           = 1, 1, 1, 1,
slope_rad               = 1, 1, 1, 1,
topo_shading            = 1, 1, 1, 1,
radt                    = 5., 5., 5., 5.,
sf_sfclay_physics      = 1, 1, 1, 1,
sf_surface_physics     = 4, 4, 4, 4,
bl_pbl_physics         = 1, 0, 0, 0,
bldt                    = 0, 0, 0, 0,
cu_physics              = 0, 0, 0, 0,
cudt                    = 0, 0, 0, 0,
isfflx                  = 1,
ifsnow                  = 1,
icloud                  = 1,
surface_input_source    = 1,
num_soil_layers         = 4,
num_land_cat            = 24,
sf_urban_physics       = 0, 0, 0, 0,
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&fdda
/

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&dynamics
rk_ord                  = 3,
diff_opt                = 2, 2, 2, 2,
km_opt                  = 2, 2, 2, 2,

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diff_6th_opt      = 0, 0, 0, 0,
damp_opt          = 3,
zdamp             = 5000., 5000., 5000., 5000.,
dampcoef         = 0.2, 0.2, 0.2, 0.2,
w_damping        = 0,
khdif            = 0, 0, 0, 0,
kvdif            = 0, 0, 0, 0,
non_hydrostatic  = .true., .true., .true., .true.,
moist_adv_opt    = 1, 1, 1, 1,
scalar_adv_opt   = 1, 1, 1, 1,
epssm            = 1, 1, 1, 1,
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&bdy_control
specified         = .true., .false., .false., .false.,
spec_bdy_width   = 5,
spec_zone        = 1,
relax_zone       = 4,
nested           = .false., .true., .true., .true.,
/

&grib2
/

&namelist_quilt
nio_tasks_per_group = 0,
nio_groups          = 1,
/
```


References

- Arnold, D., I. Schicker, and P. Seibert (2010). *High-Resolution Atmospheric Modelling in Complex Terrain for Future Climate Simulations(HiRmod), Report 2010*. Tech. rep. Institute of Meteorology (BOKU-Met), University of Natural Resources and Life Sciences, Vienna, Austria (cited on p. 6).
- Daniels, M. H., K. A. Lundquist, J. D. Mirocha, D. J. Wiersema, and F. K. Chow (2016). “A New Vertical Grid Nesting Capability in the Weather Research and Forecasting (WRF) Model”. *Monthly Weather Review*, 144, 3725–3747. doi: [10.1175/MWR-D-16-0049.1](https://doi.org/10.1175/MWR-D-16-0049.1) (cited on p. 12).
- Doyle, J. D., C. C. Epifanio, A. Persson, P. A. Reinecke, and G. Zängl (2013). “Mountain Weather Research and Forecasting: Recent Progress and Current Challenges”. Ed. by K. F. Chow, F. S. De Wekker, and J. B. Snyder. Springer Netherlands. Chap. Mesoscale Modeling over Complex Terrain: Numerical and Predictability Perspectives, 531–589. doi: [10.1007/978-94-007-4098-3_9](https://doi.org/10.1007/978-94-007-4098-3_9) (cited on p. 9).
- Dudhia, J. (2012). *Overview of WRF physics*. accessed: 22 December 2017. URL: http://www2.mmm.ucar.edu/wrf/users/tutorial/201207/Physics_full.pdf (cited on p. 13).
- European Environmental Agency (2006). *CORINE Land Cover (CLC) 2006 raster data, Version 13* (cited on p. 6).
- Gerber, F., N. Besic, V. Sharma, R. Mott, M. Daniels, M. Gabella, A. Berne, U. Germann, and M. Lehning (2018). “Spatial variability of snow precipitation and accumulation in COSMO-WRF simulations and radar estimations over complex terrain”. *The Cryosphere*, submitted, 1–20 (cited on pp. 1, 4, 5, 9, 12–14).
- Gerber, F., R. Mott, and M. Lehning (in prep.). “The importance near-surface winter precipitation processes in complex alpine terrain” (cited on p. 12).
- Gill, D. (2015). *Real – Description of General Functions*. accessed: 21 December 2017. URL: http://www2.mmm.ucar.edu/wrf/users/tutorial/china_2015/real.pdf (cited on p. 13).
- Gill, D. and M. Pyle (2010). *Nesting in WRF*. accessed: 21 December 2017. URL: http://222.195.136.24/lecture/study_wrfv3/tutorial/201007/WRFNesting.pdf (cited on p. 10).
- Gómez-Navarro, J. J., C. C. Raible, and S. Dierer (2015). “Sensitivity of the WRF model to PBL parametrizations and nesting techniques: evaluation of wind storms over complex terrain”. *Geoscientific Model Development*, 8, 3349–3363. doi: [10.5194/gmd-8-3349-2015](https://doi.org/10.5194/gmd-8-3349-2015) (cited on p. 13).
- Hong, S.-Y., Y. Noh, and J. Dudhia (2006). “A New Diffusion Package with an Explicit Treatment of Entrainment Processes”. *Monthly Weather Review*, 134, 2318–2341. doi: [10.1175/MWR3199.1](https://doi.org/10.1175/MWR3199.1) (cited on p. 13).
- Iriza, A., R. C. Dumitrache, A. Lupascu, and S. Stefan (2016). “Studies regarding the quality of numerical weather forecasts of the WRF model integrated at high-resolutions for the Romanian territory”. *Atmosfera*, 29, 11–21. doi: [10.20937/ATM.2016.29.01.02](https://doi.org/10.20937/ATM.2016.29.01.02) (cited on p. 2).
- Jiménez, P. A. and J. Dudhia (2012). “Improving the Representation of Resolved and Unresolved Topographic Effects on Surface Wind in the WRF Model”. *Journal of Applied Meteorology and Climatology*, 51, 300–316. doi: [10.1175/JAMC-D-11-084.1](https://doi.org/10.1175/JAMC-D-11-084.1) (cited on p. 13).
- Lee, J., H. H. Shin, S.-Y. Hong, P. A. Jiménez, J. Dudhia, and J. Hong (2015). “Impacts of subgrid-scale orography parameterization on simulated surface layer wind and monsoonal precipitation in the high-resolution WRF model”. *Journal of Geophysical Research - Atmospheres*, 120, 644–653. doi: [10.1002/2014JD022747](https://doi.org/10.1002/2014JD022747) (cited on p. 13).
- Liu, C., K. Ikeda, G. Thompson, R. Rasmussen, and J. Dudhia (2011). “High-Resolution Simulations of Wintertime Precipitation in the Colorado Headwaters Region: Sensitivity to Physics Parameterizations”. *Monthly Weather Review*, 139, 3533–3553. doi: [10.1175/MWR-D-11-00009.1](https://doi.org/10.1175/MWR-D-11-00009.1) (cited on p. 15).
- METI/NASA (2009). *2009, ASTER Global Digital Elevation Model V002, NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov), accessed 01 24, 2018, at http://dx.doi.org/10.5067/ASTER/ASTGTM.002. Aster GDEM is a product of NASA and METI*. (Cited on p. 4).

- Morrison, H., J. A. Curry, and V. I. Khvorostyanov (2005). “A New Double-Moment Microphysics Parameterization for Application in Cloud and Climate Models. Part I: Description”. *Journal of Atmospheric Sciences*, 62, 1665–1677. doi: [10.1175/JAS3446.1](https://doi.org/10.1175/JAS3446.1) (cited on p. 15).
- Morrison, H., G. Thompson, and V. Tatarskii (Mar. 2009). “Impact of Cloud Microphysics on the Development of Trailing Stratiform Precipitation in a Simulated Squall Line: Comparison of One- and Two-Moment Schemes”. *Mon. Wea. Rev.*, 137.3, 991–1007. doi: [10.1175/2008MWR2556.1](https://doi.org/10.1175/2008MWR2556.1) (cited on p. 15).
- Niu, G.-Y., Z.-L. Yang, K. E. Mitchell, F. Chen, M. B. Ek, M. Barlage, A. Kumar, K. Manning, D. Niyogi, E. Rosero, M. Tewari, and Y. Xia (2011). “The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements”. *Journal of Geophysical Research*, 116, D12109. doi: [10.1029/2010JD015139](https://doi.org/10.1029/2010JD015139) (cited on p. 14).
- Pineda, N., O. Jorba, J. Jorge, and J. M. Baldasano (2004). “Using NOAA AVHRR and SPOT VGT data to estimate surface parameters: application to a mesoscale meteorological model”. *International Journal of Remote Sensing*, 25, 129–143. doi: [10.1080/0143116031000115201](https://doi.org/10.1080/0143116031000115201) (cited on p. 6).
- Rai, R. K., L. K. Berg, B. Kosović, J. D. Mirocha, M. S. Pekour, and W. J. Shaw (2017). “Comparison of Measured and Numerically Simulated Turbulence Statistics in a Convective Boundary Layer Over Complex Terrain”. *Boundary-Layer Meteorology*, 163, 69–89. doi: [10.1007/s10546-016-0217-y](https://doi.org/10.1007/s10546-016-0217-y) (cited on p. 13).
- Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X.-Y. Huang, W. Wang, and J. G. Powers (2008). *A Description of the Advanced Research WRF Version 3*. Tech. rep. Boulder, Colorado, USA: Mesoscale and Microscale Meteorological Division, National Center for Atmospheric Research (cited on pp. 1, 10).
- Tewari, M., F. Chen, W. Wang, J. Dudhia, M. A. LeMone, K. Mitchell, M. Ek, G. Gayno, J. Wegiel, and R. H. Cuenca (2004). “Implementation and verification of the unified Noah land surface model in the WRF model”. *20th conference on weather analysis and forecasting/16th conference on numerical weather prediction*, 11–15 (cited on p. 14).
- Wang, W. (2015). *Considerations for Designing an Numerical Experiment*. accessed: 22 December 2017. URL: http://www2.mmm.ucar.edu/wrf/users/tutorial/201501/BEST_PRACTICES.pdf (cited on p. 15).
- Wang, W., C. Bruyère, M. Duda, J. Dudhia, D. Gill, M. Kavulich, K. Keene, H.-C. Lin, J. Michalakes, S. Rizvi, X. Zhang, J. Berner, and K. Fossell (2016). *Weather Research & Forecasting ARW Version 3 Modeling System User’s Guide*. Tech. rep. Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research (cited on pp. 9, 10, 14).
- Wyngaard, J. C. (2004). “Toward Numerical Modeling in the “Terra Incognita””. *Journal of Atmospheric Sciences*, 61, 1816–1826. doi: [10.1175/1520-0469\(2004\)061<1816:TNMITT>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<1816:TNMITT>2.0.CO;2) (cited on p. 13).
- Yang, Z.-L., G.-Y. Niu, K. E. Mitchell, F. Chen, M. B. Ek, M. Barlage, L. Longuevergne, K. Manning, D. Niyogi, M. Tewari, and Y. Xia (2011). “The community Noah land surface model with multiparameterization options (Noah-MP): 2. Evaluation over global river basins”. *Journal of Geophysical Research*, 116, D12110. doi: [10.1029/2010JD015140](https://doi.org/10.1029/2010JD015140) (cited on p. 14).