Non-Cyclic Boundary Conditions

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Cyclic horizontal boundary conditions are used in many LES applications.

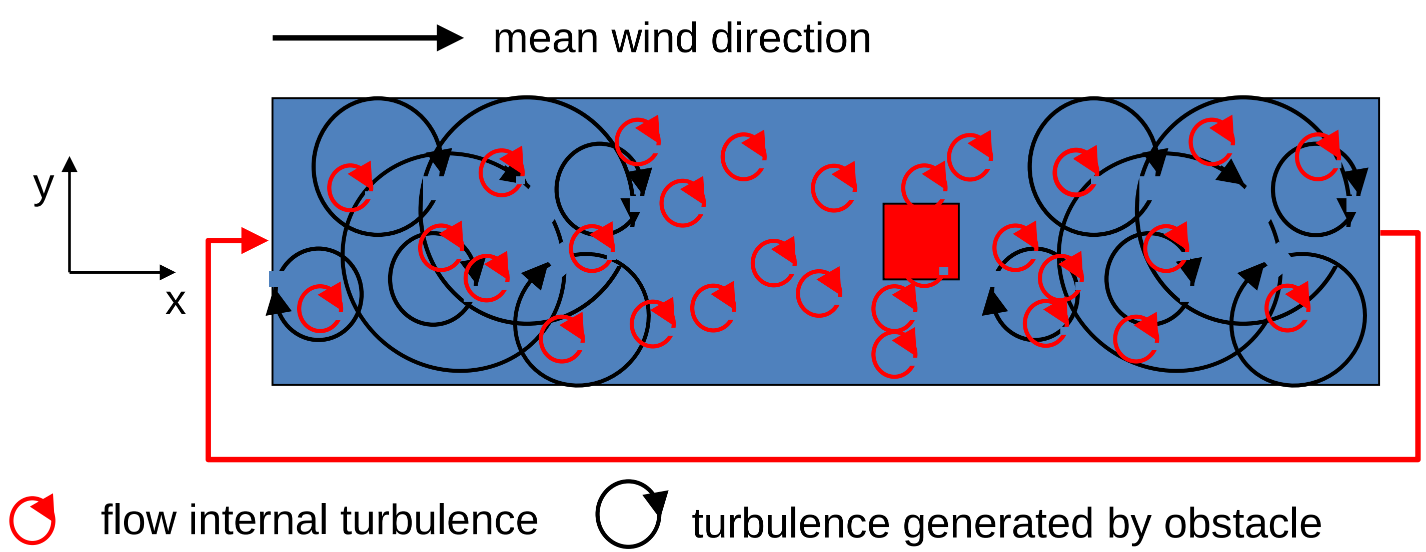
Why?

- LES requires that the main energy containing eddies are resolved by the model.
- With cyclic boundary conditions, the turbulence does not experience any horizontal boundaries and hence it can freely develop.
- Disadvantages of cyclic boundary conditions:
  - They cannot be used to study isolated phenomena (e.g. a single building).
  - Only non-cyclic boundary conditions can solve this problem.
- Disadvantages of non-cyclic boundary conditions:
  - If simple Dirichlet conditions (fixed vertical profiles) are used at the inflow, the inflow is laminar and some (significant) domain space may be required in order to allow turbulence to develop.
  - At the outflow, a boundary condition is required which allows the eddies to freely leave the domain.

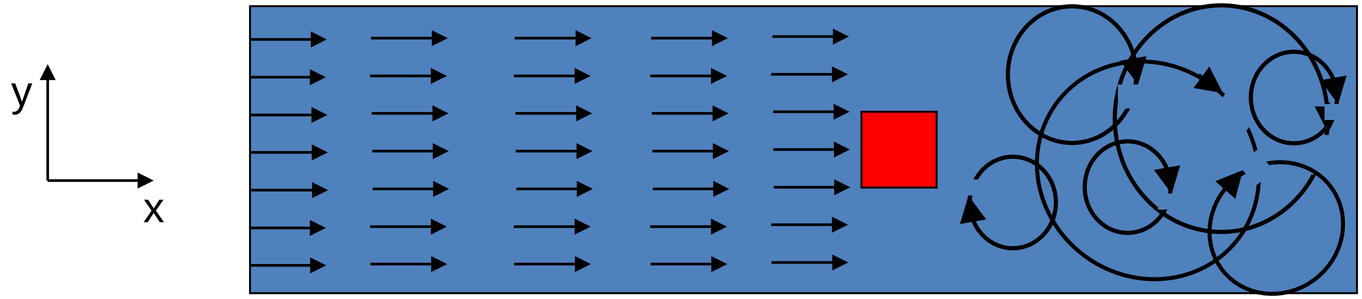
Example: Turbulence generated by a single obstacle.

Cyclic boundary conditions along x would allow the generated turbulence to enter the domain again, and so finally to modify the turbulence on the leeward side of the building.

This would not be a simulation of a single building, but of an infinite row of buildings!

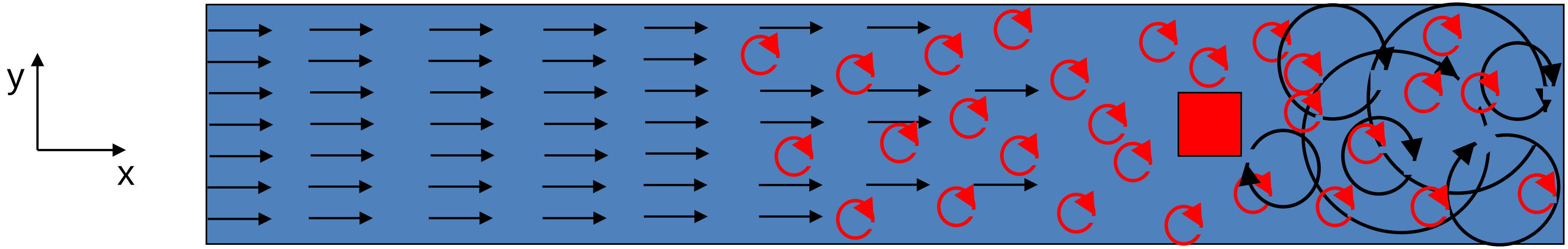


Using Dirichlet-conditions (e.g u(z) = const.), there is no turbulence at the inflow.



the flow is laminar -> LES approach fails!

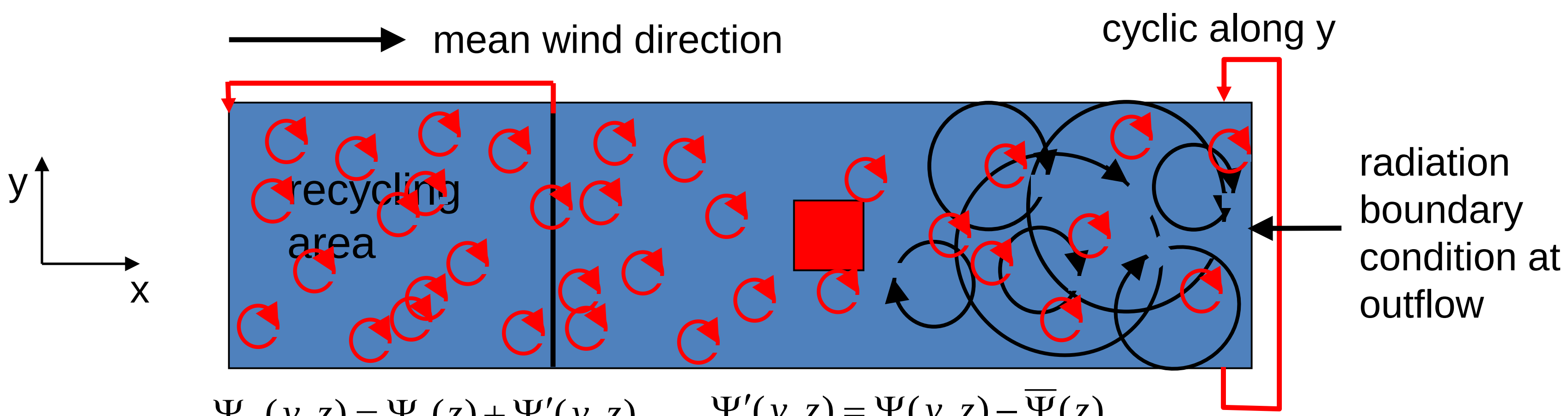
For very long model domain internal turbulence may develop upstream of area of interest.



There is a need to supply turbulence information at the inflow.

Three methods are available in PALM:

- by a statistical model (Xie and Castro, 2008)
- by reading from file boundary conditions generated by a precursor run
- by a recycling-method (Lund et al., 1998; Kataoka and Mizuno, 2002) -> see in the following

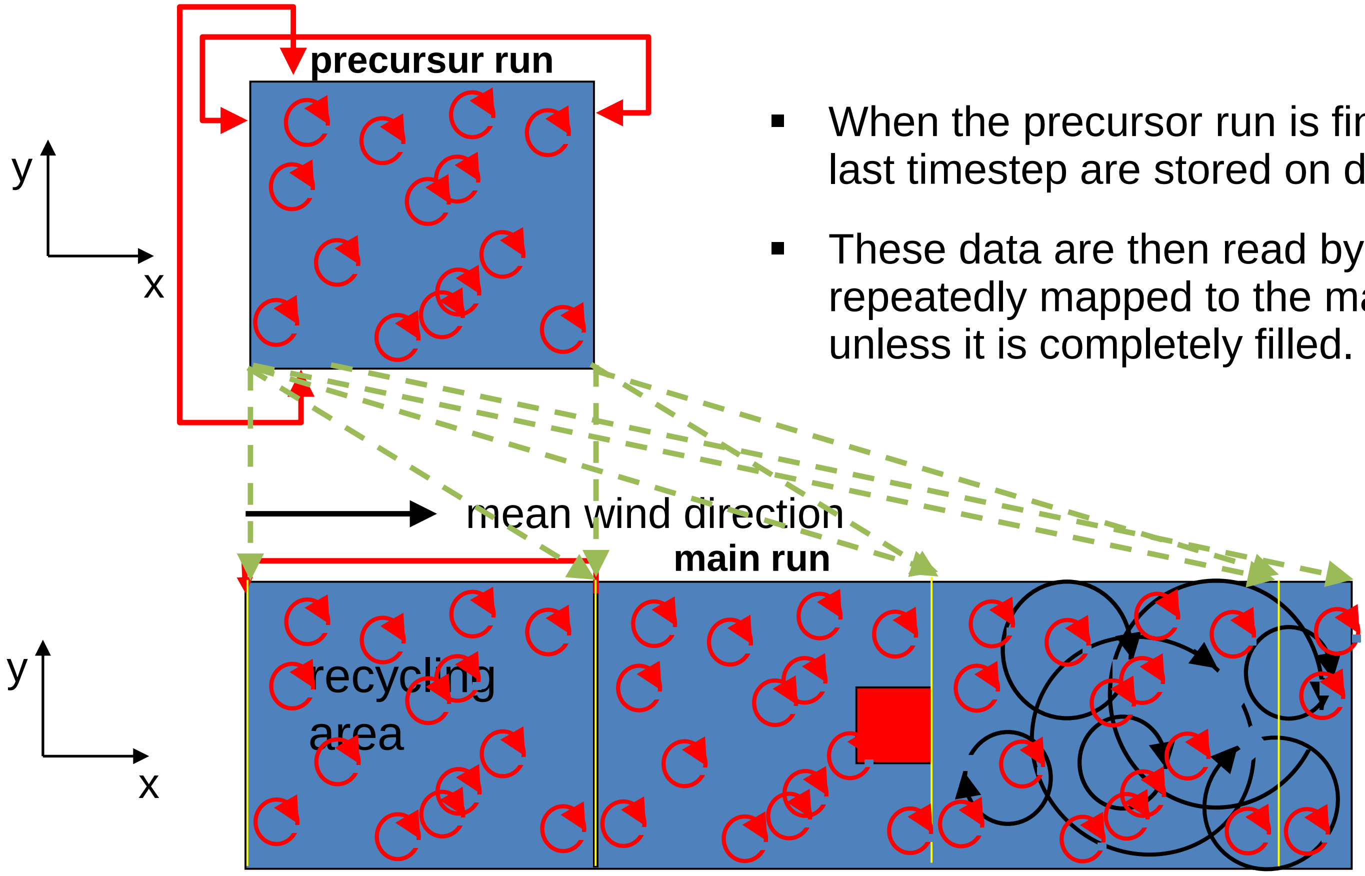


$$\Psi_{in}(y,z) = \Psi_0(z) + \Psi'(y,z) \qquad \Psi'(y,z) = \Psi(y,z) - \overline{\Psi}(z)$$

$\overline{}$ denotes an average along y

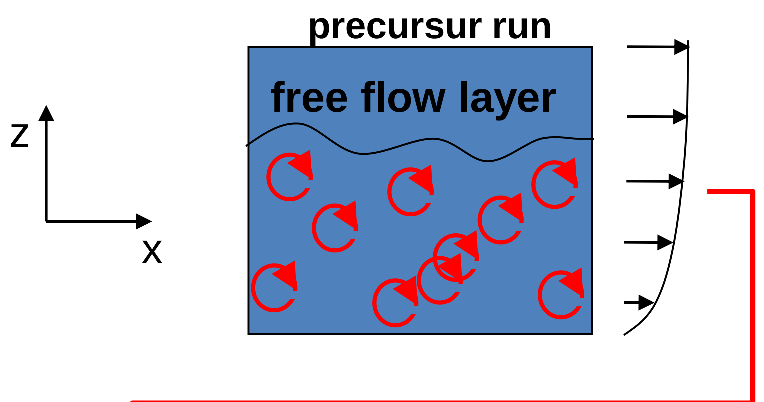
How do we get the initial turbulence in the recycling area?
If there is no turbulence, there is nothing to recycle!

Initial turbulence is created by a precursor run with cyclic boundary conditions and much smaller domain size than used for the main run.

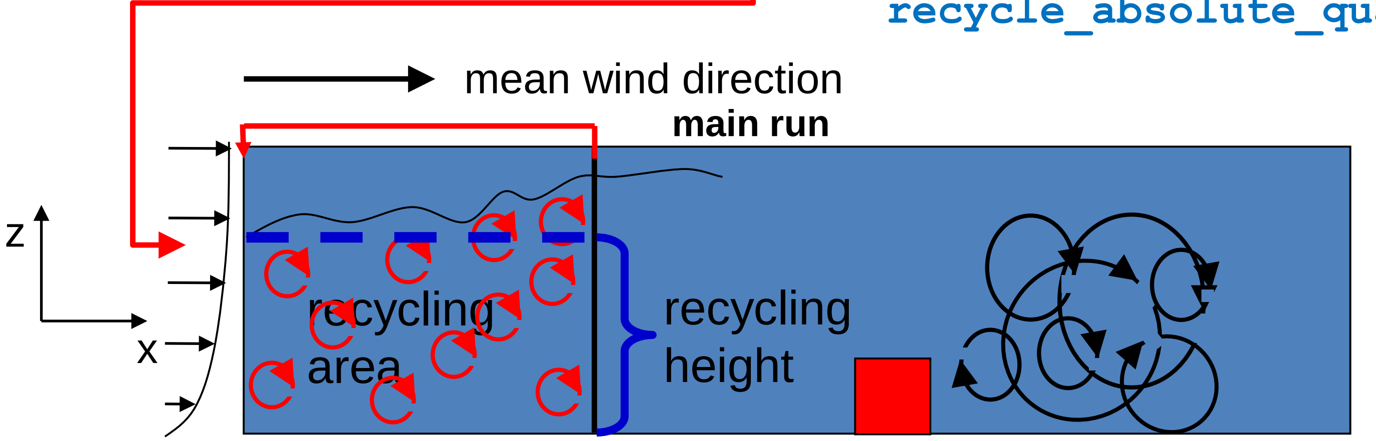


- When the precursor run is finished, data of the last timestep are stored on disc.
- These data are then read by the main run and repeatedly mapped to the main run domain, unless it is completely filled.

- Inflow profiles for the main run have to be taken from the precursor run. It is recommended to use the horizontally averaged profiles from the last time step of the precursor run.
- Alternatively, u-, v-profiles can be prescribed by parameters **`u_profile`**, **`v_profile`**. They should match the turbulence state of the flow.

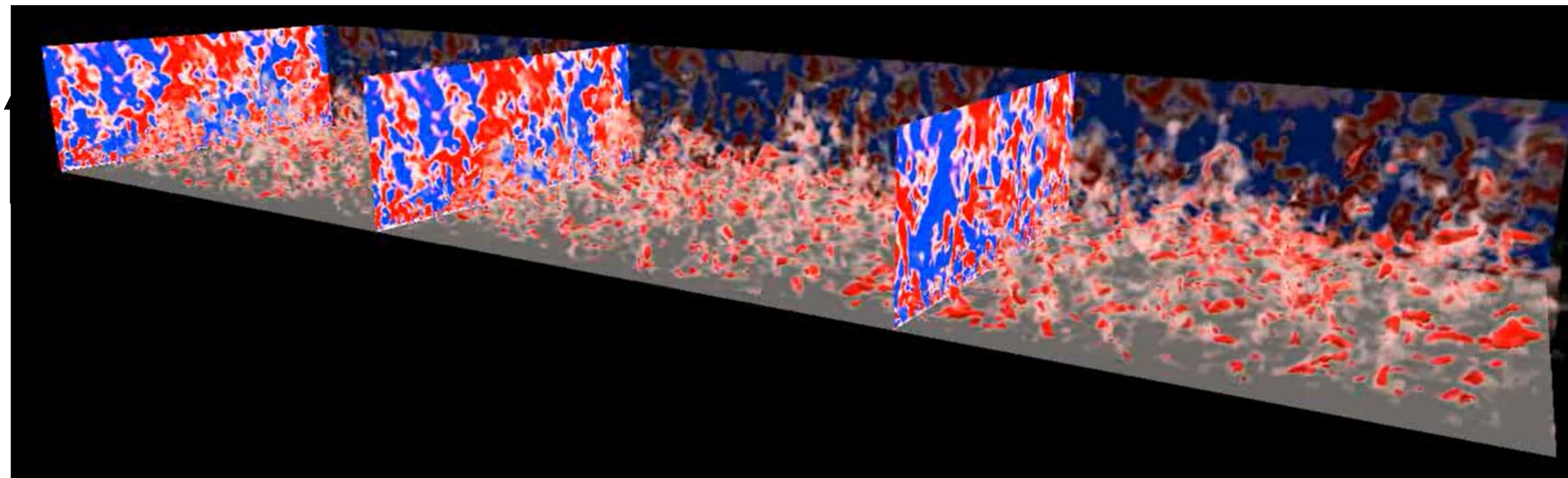


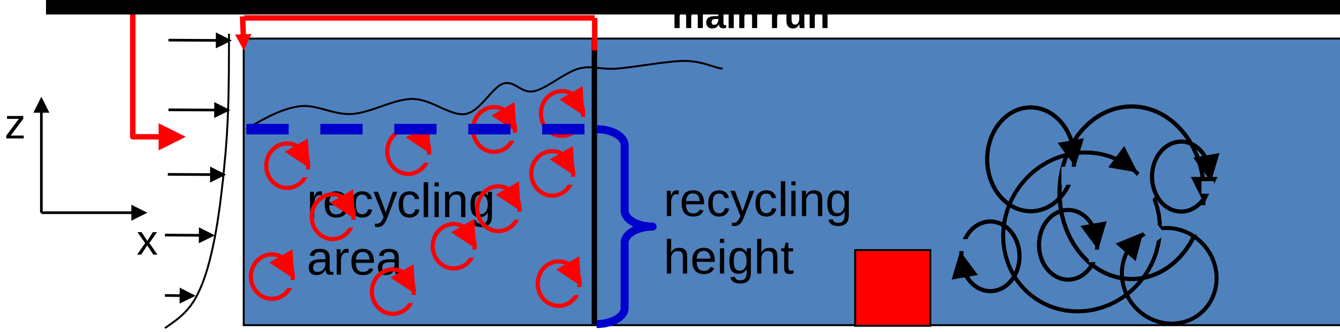
- Since the height of the turbulent boundary layer may increase with increasing distance from the inflow boundary, recycling has to be limited to the height of the turbulent boundary layer at the inflow. Otherwise, the boundary layer height will continuously increase with time.
- Limitation can be switched off with parameter **`recycle_absolute_quantities`**



How to Create a Turbulent Inflow (III)

- Inflow profiles for the main run have to be taken from the precursor run. It is recommended to use the horizontally averaged profiles from the last time step of the precursor run.
- Alternatively, u-, v-profiles can be prescribed by parameters `u_profile`, `v_profile`. They should match the turbulence state of the flow.





- At the outflow boundary a radiation boundary condition is used for calculating the velocities u_i,

$$\frac{\partial u_i}{\partial t} + c_i \frac{\partial u_i}{\partial n} = 0$$

  n being the direction normal to the outflow boundary.

- The transport velocity c_i is calculated and constrained as follows:

$$c_i = \frac{\Delta n}{\Delta t} \frac{u_{i,b-1}^{t} - u_{i,b-1}^{t-1}}{u_{i,b-1}^{t-1} - u_{i,b-2}^{t-1}} \quad \text{with} \quad 0 \leq c_i \leq \frac{\Delta n}{\Delta t}$$

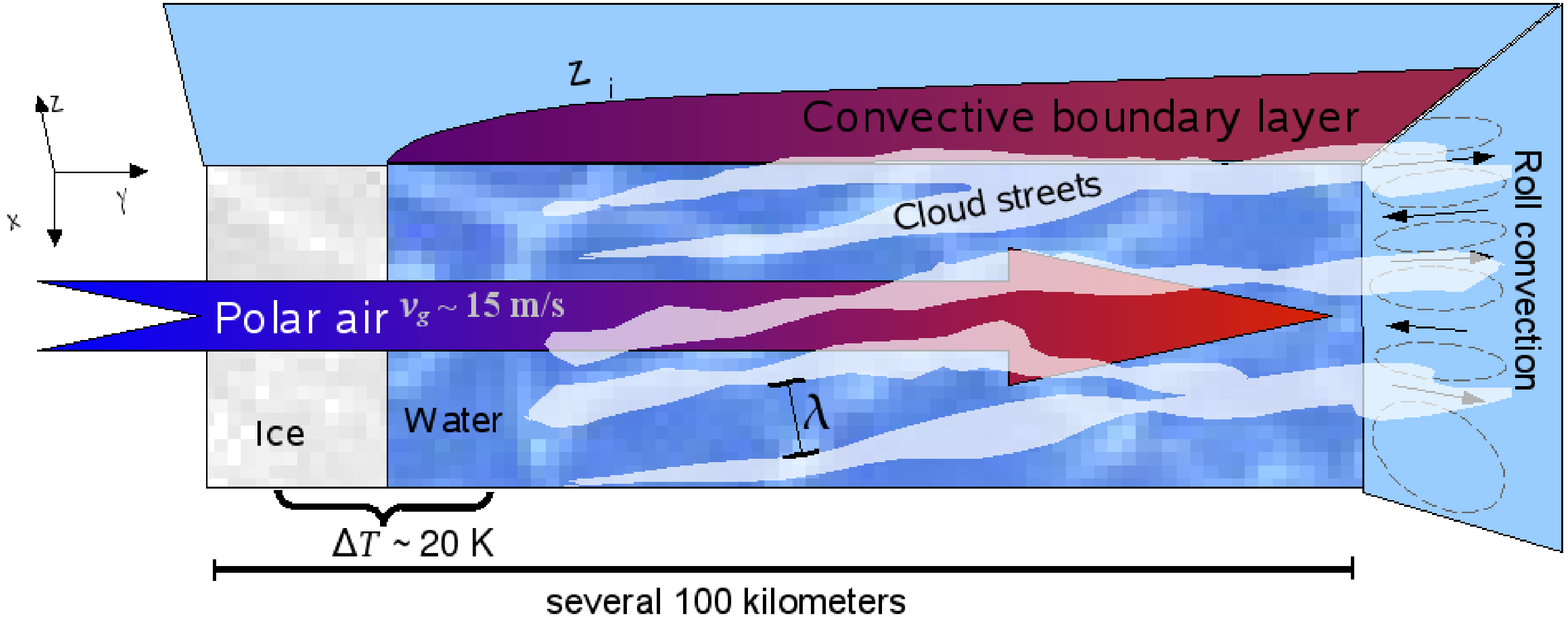
  with b being the index at the boundary.

- The radiation boundary condition requires that the outflow boundary normal velocity component always points outside the domain. Normal velocities pointing inside the domain can produce strong unphysical jets. This may happen under convective conditions with weak background wind or because of recirculation zones behind buildings.
- In such cases you may use a turbulent outflow conditions (technically similar to the recycling method at the inflow). See parameter **`turbulent_outflow`**.

- **Status of availability:**
  - Non-cyclic boundary conditions along one of the horizontal directions (x or y).
    - Dirichlet conditions at inflow (stationary vertical profiles: u, v, pt, q, w=0).
    - Radiation condition at outflow.
  - Turbulence recycling method for inflow from left.
  - Turbulent outflow condition for outflow to the right.
  - Synthetic generator for inflow from left.
  - Read boundary data from file for inflow from left.
  - PALM allows for nesting in larger scale models (so-called offline-nesting). In such a case, boundary values for all boundaries (left/right, north/south, top) are provided by the larger scale model in the so-called dynamic driver (file in NetCDF format, see https://palm-model.org/trac/wiki/doc/app/iofiles/pids/dynamic). This feature is described in lecture “Grid nesting”. The respective driver files can be created with the utility program **`inifor`**.
  - PALM can be offline-nested with the COSMO model from the German Weather Service (DWD). Offline-nesting with WRF is available too. Currently, a new utility program **`promet`** is developed to create driver files both from ICON (the new DWD model) and WRF data.

- **Further requirements for PALM runs using non-cyclic boundary conditions:**
  - The multigrid-method has to be used for solving the Poisson-equation.
  - A damping zone might need to be activated in the vicinity of the inflow in order to avoid reflection of gravity waves at the domain boundary (only if stably stratified layers exist).
  - Very strong gravity waves may be triggered, if the prescribed inflow velocity profile (Dirichlet condition) does not match the profile that PALM tries to generate due to the given conditions (e.g. geostrophic wind, surface roughness, stratification, etc.). In such cases, a strong divergence/convergence of the horizontal wind field appears at the inflow, that trigger strong vertical velocities, which in turn trigger gravity waves. Damping often does not help to remove these waves.
  - If turbulence recycling is **not** used, it may be necessary to continuously impose perturbations on the horizontal velocity field to allow the development of turbulence with increasing fetch from inflow.

Cold air outbreaks



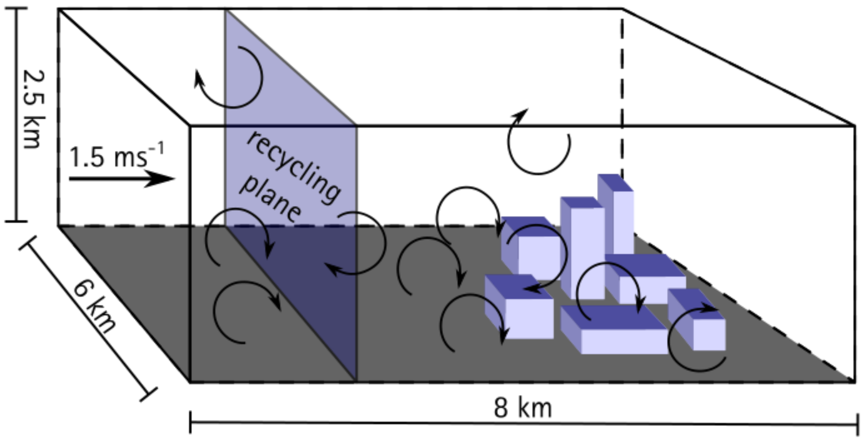
Gryschka, M., C. Drüe, D. Etling and S. Raasch. 2008: On the influence of sea-ice inhomogeneities onto roll convection in cold-air outbreaks. *Geophys. Res. Lett.*, **35**, L23804, doi:10.1029/2008GL035845.

Gryschka, M. and S. Raasch, 2005: Roll Convection During a Cold Air Outbreak: A Large Eddy Simulation with Stationary Model Domain. *Geophys. Res. Lett.*, **32**, L14805, doi:10.1029/2005GL022872.

Turbulence recycling has not been used!

City ventilation

Gronemeier, T., S. Raasch, E. Ng. 2017: Effects of Unstable Stratification on Ventilation in Hong Kong. *Atmosphere.*, **8** (9), doi:10.3390/atmos8090168.



This study used the turbulence recycling method at the inflow and the turbulent outflow method.

Non-cyclic boundary conditions

How to set up non-cyclic runs with PALM

- required / recommended parameter settings:

```
&initialization_parameters
      ...
      bc_lr = 'dirichlet/radiation', !left in / right out
      ! or
      bc_ns = 'dirichlet/radiation', !north in / south out
      psolver = 'multigrid',
      initializing_actions = 'set_1d-model_profiles',
      conserve_volume_flow = .T.,
      ...

/
```

Non-cyclic boundary conditions

How to set up turbulence recycling with PALM (I)

- First, a prerun has to be carried out. The domain size of the prerun has to be large enough to capture all relevant scales of turbulence.
- Restart data have to be output and output of instantaneous, horizontally averaged profiles has to be switched on and performed at the end of the run. This enables writing of profiles to the restart file, which can then be used by the main run.
- Instead of using averaged profiles from the prerun, inflow profiles for the main run can also be prescribed using parameters **u_profile**, **v_profile**, and **uv_heights**.
- Ensure data output of profiles at the end of the simulation:

```
&runtime_parameters

     end_time = 3600.0,
     dt_dopr = 3600.0, data_output_pr = 'u',
     ...

/
```

Non-cyclic boundary conditions

How to set up turbulence recycling with PALM (II)

- The main run has to read the restart data from the precursor run (although it is not a restart run!).
- Both the precursor run and the main run are using the same run-identifier!
- The namelist file of the precursor run is named **`<run-identifier>_pcr`** , the namelist file of the main run is named **`<run-identifier>_p3d`** (as usual).
- The palmrun command to start the precursor run is

```
palmrun ... -r "<run-identifier>" –a "pcr restart"
```

- The palmrun command to start the main run is

```
palmrun ... -r "<run-identifier>" –a "d3# cyclic"
```

- The number of processors and the domain decomposition are allowed to differ between the prerun and the main run.

How to set up turbulence recycling with PALM (III)

- required / recommended parameter settings for the main run:

```
&initialization_parameters
    ...
    bc_lr = 'dirichlet/radiation',
    psolver = 'multigrid',
    initializing_actions = 'cyclic_fill',
    conserve_volume_flow = .T.,
    ...
/
```

```
&turbulent_inflow_parameters

    turbulent_inflow_method = 'recycle_turbulent_fluctuation',
    recycling_width = ...,
    inflow_damping_height = ...,

/
```

recycling_width: Horizontal width of the recycling domain.

inflow_damping_height: Vertical extent of the recycling domain. If the precursor run simulated a convective boundary layer, information is automatically taken from the precursor data.

Non-cyclic boundary conditions

Final remarks

- Non-cyclic boundary conditions and turbulence recycling method require extreme care with setting of the respective parameters.
- Known difficulties:
  - Gravity waves can cause problems in capping inversions.
  - Simulations with convective motions and slow background wind will violate the requirements of the radiation boundary condition.
  - Homogeneous surface heating may produce a horizontal temperature gradient, which in turn results in thermal wind effects. This is of course physical, but should be taken into account and it might cause further problems together with the boundary conditions.
  - Simulations with pure neutral stratification cause less problems.
- See exercise E3 “Flow around building with non-cyclic boundary condition” for further hints and a step-by-step guide how to use non-cyclic boundary conditions.