LAM systems in ACCORD at hectometric scales :

- Temporal and Spatial aspects of physics-dynamics coupling -

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Hectometric resolution NWP in ACCORD: Why ?

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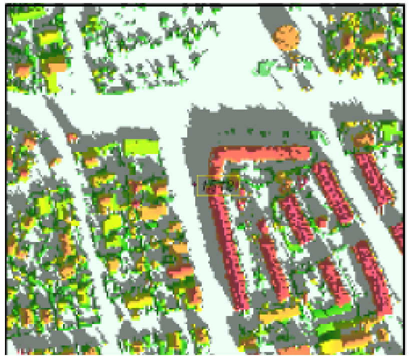
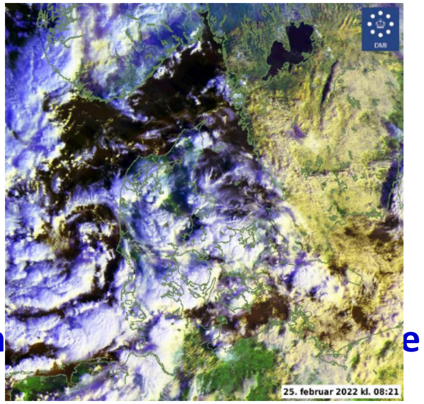
* More detailed lower boundary conditions from very high resolution data bases give better surface geo-potential, roughness, albedo, etc.



Different and very detailed surface physiographic data bases are available, e.g. shadows from buildings and trees can be resolved from national data bases
Figure from Mahura et al., DMI Sci- Rep- No. 10 -05

* Fine scale cloud- and precipitation systems varying over a fraction of an hour can potentially be resolved if sub-km models are executed with an appropriate NWP setup



MSG satellite picture 25 February 2025 showing details of clouds over southern Scandinavia (DMI home page , 25 February 2022)

[Potential benefits of LAM systems at sub-km grids in ACCORD are bein e collaboration (March 2022)]

➢ Potential benefits of LAM systems in ACCORD at sub-km resolution are being analyzed (March 2022),

Hectometric resolution NWP in ACCORD: Requirements (1)

Achieving

Accuracy, Numerical Stability and Computational speed

is inherently connected to the *numerics* of the model setup including the *physics-dynamics coupling*

Key characteristics of methods used in NWP :

a) Eulerian versus path based (e.g. semi-Lagrangian methods)
b) Parallel versus sequential processes
c) Degree of implicitness / expliciteness in the numerical schemes
d) Iterative / non-iteratives methods

Overview references :

Davies, T. 2018: Physics-dynamics coupling and task parallelism. *3rd Workshop on Physics Dynamics Coupling PDC18, ECMWF July 2018*

Mahura, A., Petersen ,C., Sattler, K. , Sass, B. .H., Petersen , T., 2010: High resolution physiographic data for Fine-Scale Road Weather Forecasting. *DMI Scientific Report. 10-05, 30 pp*

Martinez, I., 2004 : `Final version of the physics-dynamics coupling´. Pp 37 -47 in Hirlam Newsletter No. 46, available at http://hirlam.knmi.nkl

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Ubilai, S., Schär, C., Schlemmer, L., Schulthess, T.C. (2021): A numerical analysis of six physics-dynamics coupling schemes for atmospheric models *Journal of Advances in Modeling Earth Systems* , 13, e2020MS002377. https://doi.org/10.1029/2020MS002377

Hectometric resolution NWP in ACCORD: Requirements (2)

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Some considerations and necessary requirements for successful LAMs at hectometric grids:

(1) Accuracy :

- **The potential increase of accuracy due to increased resolution must not be \`sacrificed´ , e.g. by introducing poor numerical schemes.**
- **The independent vertical column approach (ICA) in physics show some weaknesses at high spatial resolution, e.g. in the context of radiation…**

(2) Numerical Stability :

Parts of the numerical schemes used are claimed to be unconditionally stable. In practice time step limitations imply shorter time steps , e.g. below 10 seconds at sub-km model resolution, perhaps due to

- **steep orography,**
- **on/off switches in the numerical schemes**
- **potentially strong interaction between physics and dynamics at the shortest spatial scales.**

(3) Computational speed :

- **The current need for very small time steps is potentially problematic for operational models at hectometric scale since <u>results need to be produced with short execution time</u> !**
- **Attention should be paid to code optimization and numerics allowing longer time steps e.g. in the model physics. Code structure should be adapted to modern computers, e.g. using GPUs.**

Computational efficiency of physics-dynamics coupling :

We may consider the potential for model speed up as a consequence of an efficient physics- dynamics coupling focusing on the impact of longer physics time steps : A speedup factor S of execution time of dynamics + physics over a given forecast period may be estimated to a first approximation according to (1) :

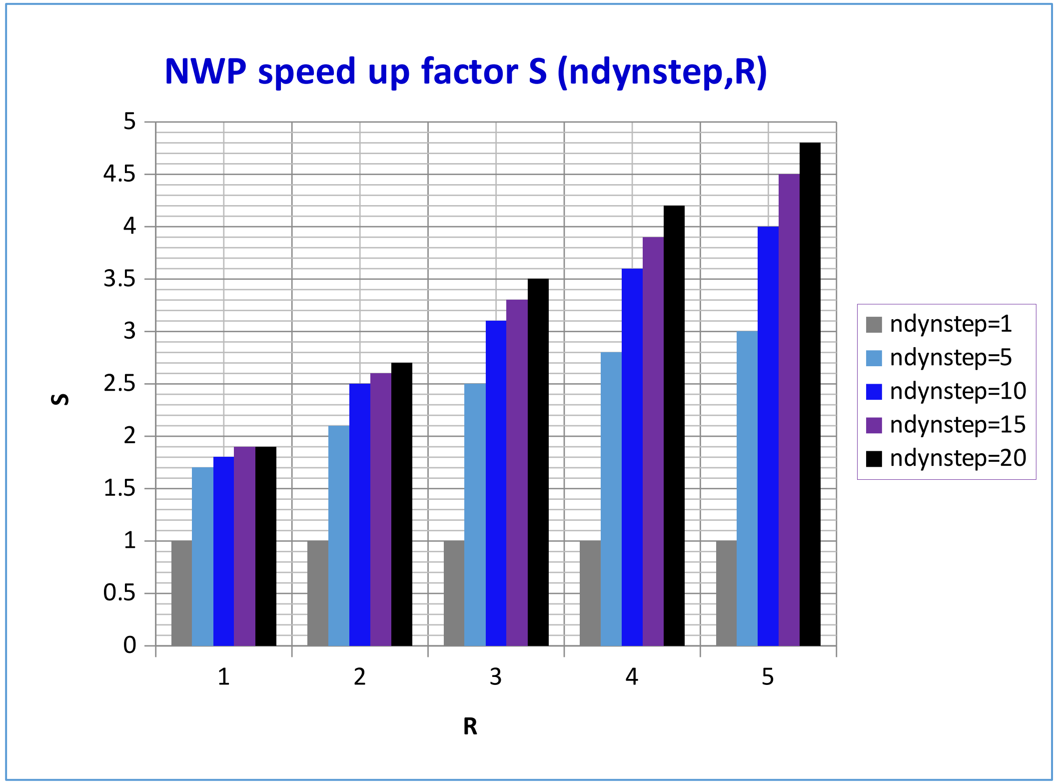
$$(1) \qquad S = N_{dynstep} * (1 + 1/R) / [1 + N_{dynstep} /R]$$

$N_{dynstep}$ means the number of dynamics time steps per physics time step. **$R = C_{physstep} / C_{dynstep}$** , with $C_{dynstep}$ and $C_{physstep}$ meaning the cost(s) of a dynamics and physics time step respectively.
This formula is based on the simple principle that one
estimates the cost of a model run based on the number of dynamics and physics time steps under the different possible choices
of less frequent physics time steps and the relative cost of a physics time step compared to a dynamics time step.

One may use (1) to display the speed up factor for a given choice of cost ratio R between physics and dynamics time step, as a function of $N_{dynstep}$. <u>For simplicity It is assumed that all physics processes are computed with the same frequency. The results are illustrated in Figure 1</u>

The range of $N_{dynstep}$ between 5 and 20 seems to be realistic choices to be tested for sub-km model setups in the future. As a consequence

this methodology seems potentially powerful to speed up high resolution runs, if the physics computations imply equal or higher costs than the dynamics (cost ratio **R** ≥ 1)



Speed up factor S for different numbers of dynamic time steps per physics time step

using different fixed values (1,2,3,4,5) of cost ratio **R** between physics and dynamics. The results are based on equation (1).

Towards hectometric resolution NWP in ACCORD:

Potential savings with efficient physics setups in ACCORD ,

Exemplified by timings from HARMONIE –AROME setup in DMI

Model = CY43

Relative TIMING of PHYSICS versus timing of total forecast step
[physics time step equal to dynamics time step, except for radiation running with 15 min. fixed time step]

Forecast model	\`NEA 2500 m grid´ Δt = 75 s	\` Zealand-500 m grid´ Δ t = 15 s	\`Zealand-200 m grid ´ Δ t = 8 s
relative timing MF_PHYS/ MASTER	35 % - 58 %	26 % - 47 %	39 % - 49 %

Relative timing of physics indicate only a modest sensitivity to model resolution

For radiation processes it is already possible to run with longer time steps. If radiation is run every time step of the model dynamics –consistent with use of (1) for model speedup - the model physics will be even larger fraction of a time step.

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Physics – Dynamics coupling: Overview of possible setups (1)

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OPTION-1 :

Parallel independent coupling of dynamics and physics executed every time step.

PROPERTIES:

a) Prone to `numerical noise' , e.g. in the case of `on-off' switched in physical processes at local time steps
b) Expensive option especially in the case of expensive physics, e.g. aerosol- and chemistry options
c) The combined effect of physics processes are less well balanced compared with sequential physics implementation because one process does not know about the results of other processes, e.g.

two parallel processes each reducing humidity by more than 50 % lead to an update with negative humidity. Sequential updates of the two processes, lead to non-negative humidity.

Step / process	Step 1	Step 2	Step 3	....	Step k
Dynamics D	$\delta D(1)$	$\delta D(2)$	$\delta D(3)$	....	$\delta D(k)$
Physics P_1 (parallel)	$\delta P_1(1)$	$\delta P_1(2)$	$\delta P_1(3)$	....	$\delta P_1(k)$
Physics P_2 (parallel)	$\delta P_2(1)$	$\delta P_2(2)$	$\delta P_2(3)$	....	$\delta P_2(k)$
....				....	$\delta P_j(k)$
Physics P_M (parallel)		$\delta P_M(2)$	$\delta P_M(3)$	....	$\delta P_M(k)$

Updating the model state from previous known state $\Phi(k-1)$ to a new model state $\Phi(k)$ where the dynamics and physics increments, $\delta D(k)$ and $\delta P_m(k)$ respectively are described by functions $F_D[\Phi(k-1)]$ and $F_{Pm}[\Phi(k-1)]$ multiplied by the time step Δt.

$$\Phi(k) = \Phi(k-1) + \delta D(k) + \sum_{m=1}^{M} (\delta P_m(k))$$

$$\delta D(k) = F_D[\Phi(k-1)] \cdot \Delta t$$

$$\delta P_m(k) = F_{Pm}[\Phi(k-1)] \cdot \Delta t$$

Physics – Dynamics coupling: Overview of possible setups (2)

OPTION-2:

Sequential coupling of dynamics and physics executed every time step.

PROPERTIES:

a) Expensive option especially in the case of expensive physics, e.g. aerosol- and chemistry options
b) The combined effect of physics processes are better balanced compared with parallel physics implementation because each physics process `knows´ about the effect of previous physics processes

Step / process	Step 1	Step 2	Step 3	………	Step k
Dynamics D	$\delta D(1)$	$\delta D(2)$	$\delta D(3)$	………	$\delta D(k)$
Physics P_1 (sequential)	$\delta P_1^*(1)$	$\delta P_1^*(2)$	$\delta P_1^*(3)$	………	$\delta P_1^*(k)$
Physics P_2 (sequential)	$\delta P_2^*(1)$	$\delta P_2^*(2)$	$\delta P_2^*(3)$	………	$\delta P_2^*(k)$
………				………	$\delta P_{m*}(k)$
Physics P_M (sequential)	$\delta P_M^*(1)$	$\delta P_M^*(2)$	$\delta P_M^*(3)$	………	$\delta P_M^*(k)$

Updating the model state from previous known state $\Phi(k-1)$ to a new model state $\Phi(k)$ where the dynamics and physics increments, $\delta D(k)$ and $\delta P_j(k)$, $1 \le j \le M$ respectively are described by functions $F_D[\Phi(k-1)]$ and $F_{Pj}[\Phi_j^*(k)]$ multiplied by the time step Δt.

$\Phi(k) = \Phi(k-1) + \delta D(k) + \delta P_M^*(k)$, $\delta D(k) = F_d[\Phi(k-1)] \cdot \Delta t$

$\delta P_m^*(k) = F_{Pm}[\Phi_{m-1}^*(k)] \cdot \Delta t$

$\Phi_{m-1}^*(k) = \Phi(k-1) + \delta D(k) + \sum_{j=1}^{m-1} \delta P_j^*(k)$,

$\Phi_j^*(k) = \Phi_{j-1}^*(k) + \delta P_j^*(k)$ are sequential updates as a consequence of calling different physics processes.

Physics – Dynamics coupling: Overview of possible setups (3)

OPTION-3 :

Sequential coupling of dynamics and physics with physics updates every $N_{dynstep}$ time steps.

PROPERTIES:

a) Cheap option since physics process tendencies are kept constant in $N_{dynstep}$ time steps
b) Processes are expected in better balance than in the case of parallel physics because each physics process `knows´ about the effect of previous physics processes.

Step / process	Step 1	Step 2	Step 3		Step $N_{dynstep}$
Dynamics D	$\delta D(1)$	$\delta D(2)$	$\delta D(3)$	....	$\delta D(N_{dynstep})$
Physics P_1 (sequential)	$\delta P_1^*(1)$	$\delta P_1^*(1)$	$\delta P_1^*(1)$	....	$\delta P_1^*(1)$
Physics P_2 (sequential)	$\delta P_2^*(1)$	$\delta P_2^*(1)$	$\delta P_2^*(1)$	....	$\delta P_2^*(1)$
....				....	$\delta P_{m*}(1)$
Physics P_M (sequential)	$\delta P_M^*(1)$	$\delta P_M^*(1)$	$\delta P_M^*(1)$	....	$\delta P_M^*(1)$

Updating the model state from previous known state $\boldsymbol{\Phi}(k-1)$ to a new model state $\boldsymbol{\Phi}(k)$ where the dynamics and physics increments $\boldsymbol{\delta D}(k)$ and $\boldsymbol{\delta P}_j(k)$, $1 \le j \le M$ respectively are described by functions $F_D[\boldsymbol{\Phi}(k-1)]$ and $F_{Pj}[\boldsymbol{\Phi}_j^*(k)]$ multiplied by the time step Δt.

$\boldsymbol{\Phi}(k) = \boldsymbol{\Phi}(k-1) + \boldsymbol{\delta D}(k) + \boldsymbol{\delta P}_M^*(k)$, $\boldsymbol{\delta D}(k) = F_d[\boldsymbol{\Phi}(k-1)] \cdot \Delta t$.

Symbol (*) means that updates are based on the accumulated previous processes

$\boldsymbol{\delta P}_m^*(k) = F_{Pm}[\boldsymbol{\Phi}_{m-1}^*(k)] \cdot \Delta t$, $\boldsymbol{\Phi}_{m-1}^*(k) = \boldsymbol{\Phi}(k-1) + \boldsymbol{\delta D}(k) + \sum_{j=1}^{m-1} \boldsymbol{\delta P}_j^*(1)$,

$\boldsymbol{\Phi}_j^*(k) = \boldsymbol{\Phi}_{j-1}^*(k) + \boldsymbol{\delta P}_j^*(1)$ are sequential updates as a consequence of calling different physics processes that were estimated at the first of $N_{dynstep}$ steps.

Physics – Dynamics coupling: Overview of possible setups (4)

OPTION-4 :

Incremental coupling of Dynamics and Physics with long physics time steps after preceeding $N_{dynstep}$ dynamical \`sub-steps´.

PROPERTIES:

a) Less prone to \`numerical noise', since dynamics is <u>an averaged input</u> to physics over the number of \`$N_{dynstep}$´ time steps.
b) Cheap option especially in the case of expensive physics, e.g. aerosol- and chemistry options
c) Potentially more numerically stable in view of time averaged dynamics input

Step / process	Step 1	Step 2	Step 3	………	Step $N_{dynstep}$
Dynamics D	$\delta D(1)$	$\delta D(2)$	$\delta D(3)$	……….	$\delta D(N_{dynstep})$
Physics P_1 incremental LONG					$\delta P_1(N_{dynstep})$
Physics P_2 Incremental LONG				………	$\delta P_2(N_{dynstep})$
………				………	$\delta P_1(N_{dynstep})$
Physics P_M Incremental LONG				……….	$\delta P_M(N_{dynstep})$

Updating the model state from initial state $\boldsymbol{\Phi}(0)$ to a new model state $\boldsymbol{\Phi}(N_{dynstep})$ after $\mathbf{N}_{dynstep}$ time steps

$$\boldsymbol{\Phi}(N_{dynstep}) = \boldsymbol{\Phi}(0) + \sum_{k=1}^{Ndynstep} \boldsymbol{\delta D}(k) \quad + \quad \boldsymbol{\delta P}_M{}^*(N_{dynstep})$$

$$\boldsymbol{\delta D}(k) = F_d[\boldsymbol{\Phi}(k-1)] \cdot \Delta t \quad ,$$

$$\boldsymbol{\delta P}_m{}^*(N_{dynstep}) = F_{Pm}[\boldsymbol{\Phi}_{m-1}{}^*(N_{dynstep})] \cdot \Delta t \cdot N_{dynstep} \, , \quad \text{for all } m \le M$$

$$\boldsymbol{\Phi}_{m-1}{}^*(N_{dynstep}) = \sum_{j=1}^{m-1} \boldsymbol{\delta P}_j^* \, (Ndynstep),$$

$$\boldsymbol{\Phi}_j{}^*(N_{dynstep}) = \boldsymbol{\Phi}_{j-1}{}^*(N_{dynstep}) + \boldsymbol{\delta P}_j{}^*(N_{dynstep})$$

$\boldsymbol{\delta P}_j{}^*(N_{dynstep})$ are sequential updates as a consequence of calling different physics processes.

Long physics time steps :

Example from a DMI-HIRLAM Eulerian setup used in the past

[Sass, B. H., Nielsen, N.W., Jørgensen, J.U., Amstrup, B., Kmit, M., Mogensen, K.S. , 2002:

The Operational DMI-HIRLAM system DMI Tech. Rep. 02-05 [Available from https://www.dmi.dk]

Example from DMI with OPTION-4 based on HIRLAM Eulerian model (2002)

(100 s time step in dynamics, physics every 6th time step) :

P_1 : **Turbulence**, with forcing with time averaged tendencies from dynamics over $N_{dynstep}$

P_2 .... P_N : **Parameterizations other than turbulence**

P_{N+1} : **Final turbulence step**, with forcing from dynamics + physics – **excluding turbulence**

Experience : Significant model speed up and increased numerical stability due to time averaging of the dynamics tendencies over the $N_{dynstep}$ time steps.

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Temporal aspects of physics-dynamics coupling

SUMMARY:

- ACCORD LAM setups tested at sub-km grid scale, require small dynamical time steps of < 10 sec. due to numerical stability constraints. This makes sub-km model setups expensive, considering fixed forecast range. It is then desirable to run the model physics with longer time steps.

- Timings of studied model setups indicate that model physics require up to about 50 % of a model time step. The timings do NOT appear to be very sensitive to model resolution.

- Model speedup due to implementing less frequent physics could amount up to 50 % (factor S=1.5), or even more, depending on the cost of physics compared with dynamics and the frequency of the call to physics.

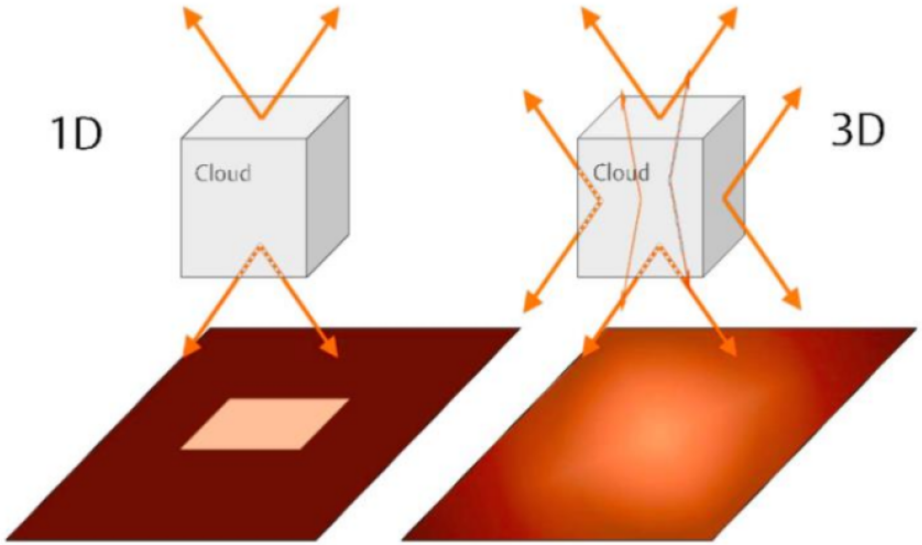
Physics –Dynamics coupling : Include also spatial aspects

- **Radiation processes may become very expensive. This calls for code optimizations and ways to treat 3-dimensional effects of radiation at different model resolutions .**

The SPARTACUS solver (ecRad)

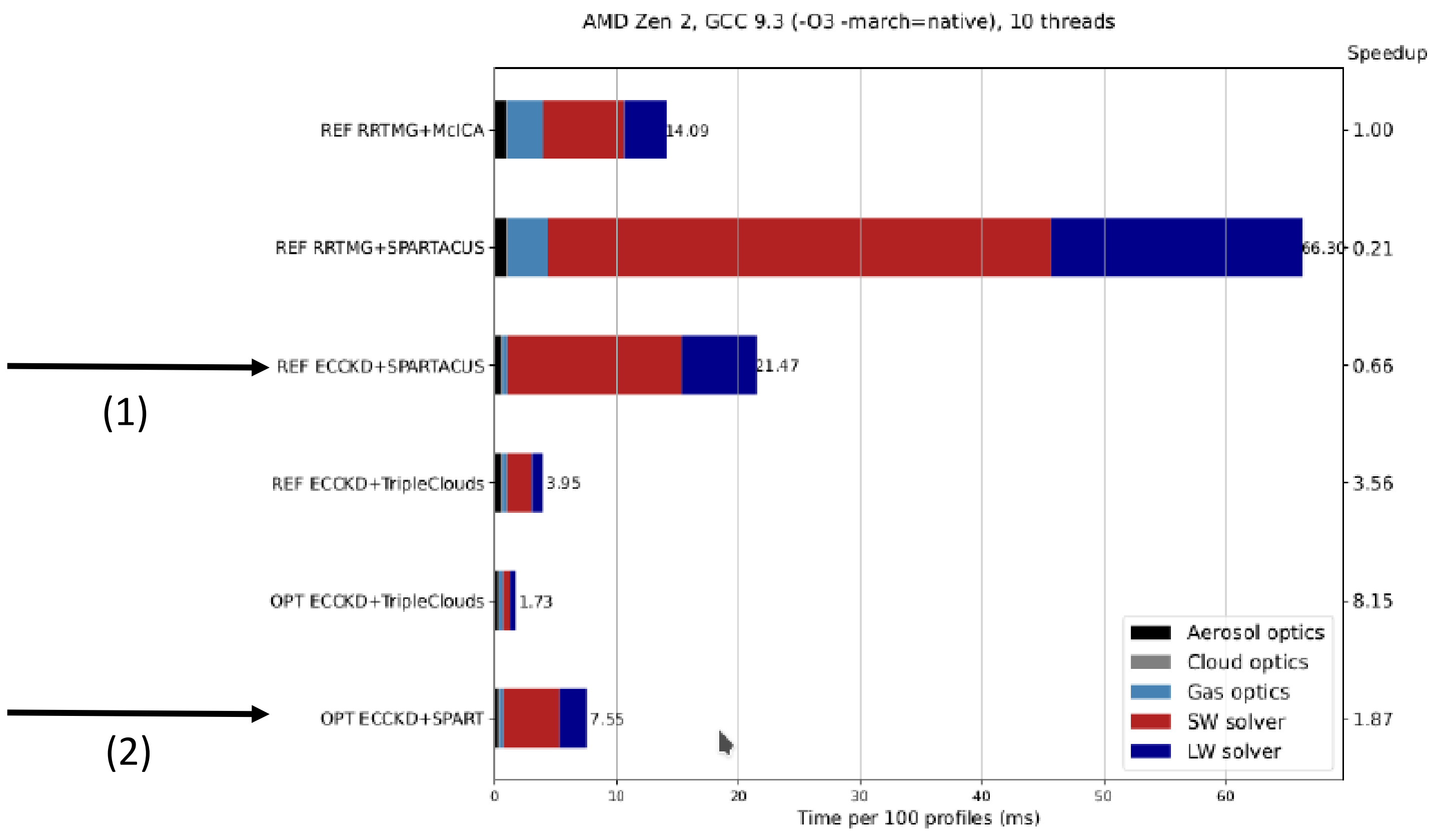
1: Schemes designed for multi-km scale :

- The scheme ecRAD has been developed in ECMWF and valid in particular for grid sizes above 1 km. The SPARTACUS sub-grid solver has been developed (Hogan et al. 2016) .



Schematic of outgoing fluxes and their contributions to total downwelling flux in 1-D and 3-D schemes for a cubic cloud. Because of symmetry, the total outward flux G through every cloud face is the same, as discussed in section 2. Every arrow symbolizes a flux of $G/2$ through the respective face. At cloud sides, half of the outgoing radiation is at an upward angle, the other half at a downward angle. The distribution of downwelling flux at the surface is shown below: in a 1-D scheme, we only see downwelling flux directly underneath the cloud, while in a 3-D scheme, cloud side fluxes result in a more spread-out distribution as well as in higher total downwelling flux.

Physics –Dynamics coupling : Spatial aspects in radiation



Schemes developed for multi-km scale :

A recent code (1) has become available (REF ECCKD + SPARTACUS) and optimized by Ukkonen (2021-22) in DMI ,(2). [further discussion in ACCORD side meeting on 3D effects]

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Why consider to run some model physics such as radiation both at coarser spatial resolution and less frequently than model dynamics ?

2: Schemes valid at sub-km grids :

- **Processes such as radiation become progressively less accurate using an independent vertical column approach (ICA), due to 3D radiation effects involving radiation from neighboring grid columns** (discussed below)

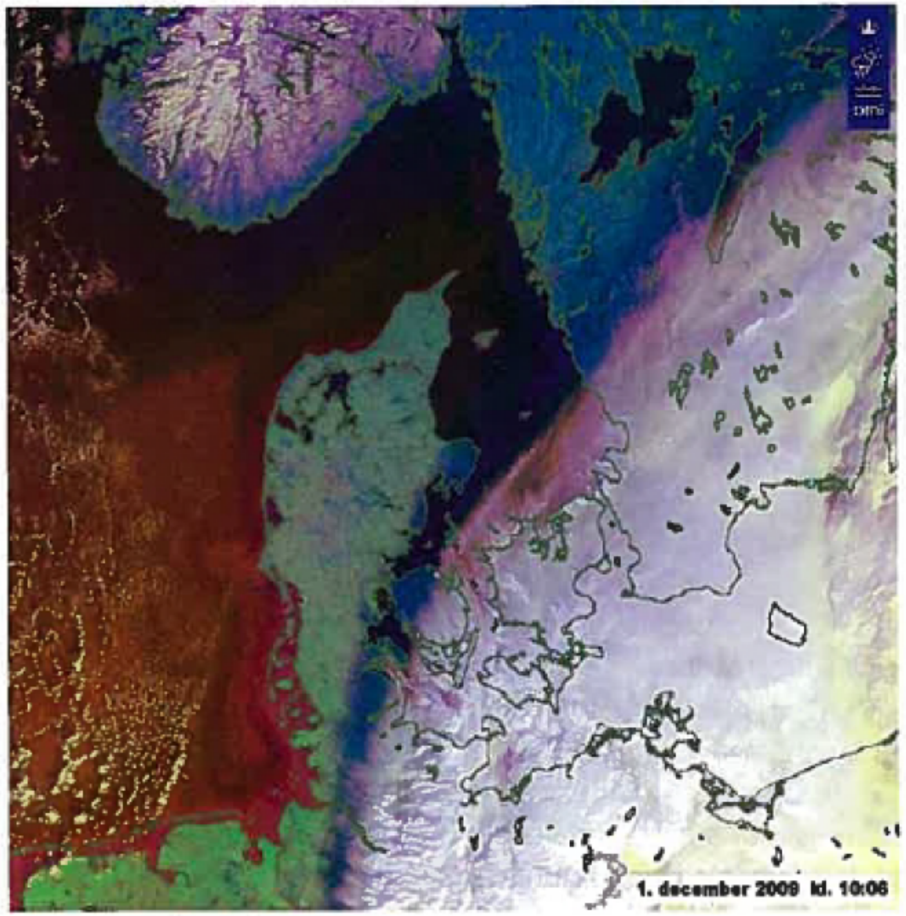
- **A strategy for computations of some processes such as radiation in a coarser horizontal grid could potentially give very significant additional computational savings without model degradation in general (less points considered in call to radiation).**

- **The time frequency of full radiation computations should not follow the very short dynamics time step that is e.g. below 10 s, since radiation only needs to resolve longer time scales. Full resolution surface temperature variations and solar zenith angle changes could be accounted for with existing intermittent radiation (e.g. RADHEAT)**

Physics –Dynamics coupling : Spatial aspects

The picture illustrates the impact of `shadow effects ´ from clouds , reducing incoming solar radiation in some areas with no clouds aloft in the vertical direction.

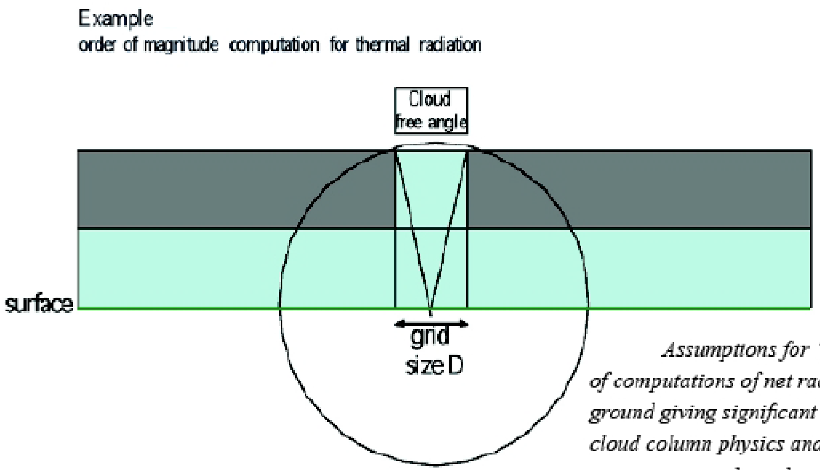
3D effects of solar radiation



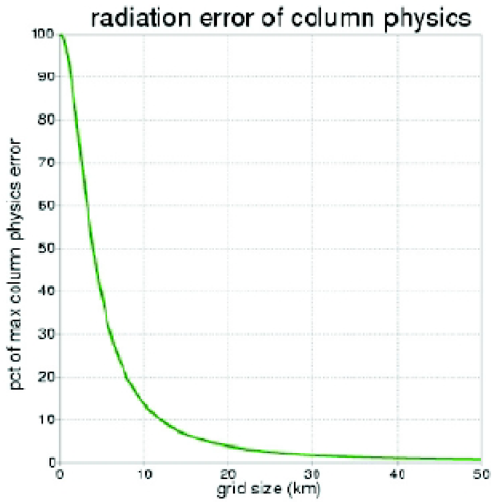
Visuelt NOAA-billede fra dmi.dk.

Physics –Dynamics coupling : Spatial aspects

Thermal 3D radiation aspects



Assumptions for 'worst case' type of computations of net radiation at the ground giving significant differences between cloud column physics and more realistic computations where the actual sky view (cloud free cone) is taken into account, integrating radiance over the half sphere above the ground – cloud layers of big horizontal extent exist outside the vertical 'column' (cylinder) !

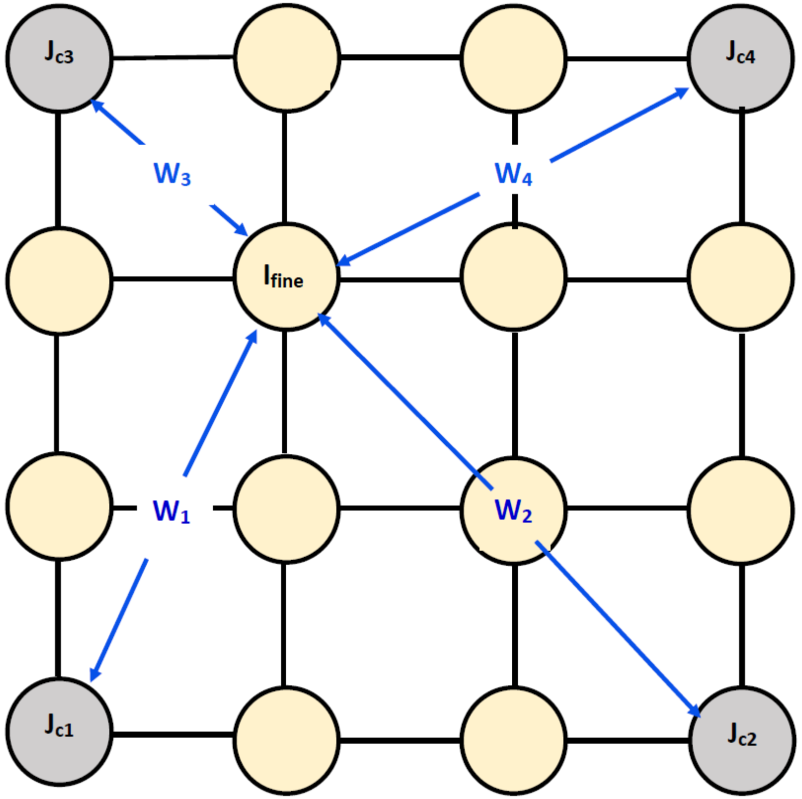


: Results for thermal radiation in stratifom cloud conditions.
Maximum error occurs when the grid size goes to very small values considering a cloud free column while in reality the surroundings are covered by a large cloud sheet radiating like a black body towards the ground. The figure shows the percentage of the maximum error (~98 W/m²) as a function of grid size, arising from executing column physics under the specified conditions.

Physics –Dynamics coupling : Spatial aspects

Conversion of results between grids to save computing time

and introduce 3D-aspects in simplified form (combine with AI ?)



1) Define N_c as the number of grid points with full physics computations in a horizontal grid. The corresponding number of points in a full grid resolution is N_{fine}. The points J_c make a true regular subset of the full set of points I_{fine}, with $1 \le I_{fine}(J_c) \le N_{fine}$

2) Define integer array references $I_{fine}(J_c)$ [$J_c \in 1: N_c$] to the fine grid , I_{fine} , with $1 \le I_{fine}(J_c) \le N_{fine}$ pointing to corresponding values of the fine grid at the same physical location as that of the coarse grid point.

3) Make a call to the physics scheme , e.g. radiation scheme with loop length of 1: N_c and let the call reference the selected values of the fine mesh.

4) Having called the physics scheme at coarse mesh : Select a computational method to define corresponding values of the full resolution fine-mesh by some sort of interpolation, e.g. using weight factors $W(J_c)$ of neighbouring coarse mesh points J_c to the fine mesh point I_{fine} considered. The weight factors could depend on e.g. differences in latitude, longitude, cloud cover, and on solar zenith/azimuth angles.

NB : Code considerations: should ACCORD code be based on ECMWF routine suerad.F90 ? or alternative code developed, e.g. in the context of mf_phys.F90 ?

Physics – Dynamics coupling in ACCORD

Suggested future work in ACCORD applicable to very high model resolution :

1) Establish a framework that allows more flexibility in the way physics and dynamics are coupled

2) Less frequent physics calls : One way is to compute physics less frequently than dynamics in view of the very short time steps of the dynamics. The frequency of physics calls could be process dependent , e.g. depending on the character of the physics (`fast´ versus `slow´ processes) . Some storage of the given process is expected at intermediate time steps.

3) Another way is to possibly realize dynamical sub-stepping during longer physics time steps (option -4 mentioned)

4) Use MUSC, later full 3D model setup to develop and validate new approaches for dynamics-physics coupling: Diagnose computational speed further , the accuracy and numerical stability in MUSC case studies and full 3D setups.

5) For sub-km resolution find alternatives to a traditional independent column approach, e.g. do full radiation physics computations at a coarser mesh only, gaining potentially both speed and accuracy

Physics – Dynamics coupling schemes :

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