Priority Project $T^2RC^2$:

Towards a Single Precision Version of the Radiation Scheme

Single Precision vs. Double Precision

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Thanks to: A. Shtivelman$^1$, V. Clement$^2$ and P. Spoerri$^2$

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COSMO General Meeting, Jerusalem, September 2017
1. Overview

2. Method to evaluate the error growth

3. Analysis of 5 radiation scheme versions:
   - Entire Rad. Scheme in SP
   - Rad. Scheme in SP, but “fesft” in DP – “mixed 1”
   - Rad. Scheme in SP, but “fesft” in DP and SW and LW radiative fluxes in DP – “mixed 2”
   - Rad. Scheme in SP, but “fesft” in mixed pr. and SW and LW radiative fluxes in DP – “mixed 3”
   - Entire Rad. Scheme in DP

4. Summary
Overview

• Single vs. Double precision:

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Number of digits</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>$10^{38}$</td>
<td>$10^{-38}$</td>
<td>7.2</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Double</td>
<td>$10^{308}$</td>
<td>$10^{-308}$</td>
<td>16.0</td>
<td>$10^{-16}$</td>
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</tbody>
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Link to example

• DP→SP saves 20-40% run time for COSMO schemes.

• J. Despraz and O. Fuhrer (2012): COSMO physical schemes in SP ✓
  Radiation scheme in SP ✗

• Goals:

A. Find the hotspots in the radiation scheme which are sensitive to DP→SP
B. Check if possible to modify the code to allow running in SP
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   - Rad. Scheme in SP, but “fesft” in DP and SW and LW radiative fluxes in DP – “mixed 2”
   - Rad. Scheme in SP, but “fesft” in mixed pr. and SW and LW radiative fluxes in DP – “mixed 3”
   - Entire Rad. Scheme in DP

4. Summary
Example: \( C = 273.1722 \)  
There are 7 digits. How many are significant?

Add relative perturbation \( 10^{-7} \). Due to the SUBROUTINE, the output \( C \) changed to: \( D = 273.1256 \)

\[
ERR = 1.70588 \times 10^{-4} \quad \text{N}_\text{sig} = 4
\]

The SUBROUTINE causes loss of precision:

from 7 significant digits in the INPUT to 4 significant digits in the OUTPUT
Example 1

Histogram of $N_{sig,DP}(i,j,k)$ and $N_{sig,SP}(i,j,k)$ over all the grid points.

Ideal situation – same error growth in SP and DP.

- SP: 6.51
- DP: 6.72
- Delta: 0.2

Full-precision grid points (error is negligible)
Example 2

Bad situation – bigger error growth in SP

Histogram of $N_{\text{sig,DP}}(i, j, k)$ and $N_{\text{sig,SP}}(i, j, k)$ over all the grid points

Number of grid points (log scale)

Problematic grid points

Number of significant digits

SP: 4.73
DP: 6.74
delta: 2.01
Experiment

- Radiation **standalone** scheme was used for **one time step** runs

- **Configuration:**
  - 80X60X60 grid points
  - 0.02 deg resolution
  - Date: 16/6/2014 18UTC
  - Domain:

**total cloudiness “clct”**

16/6/2014 18UTC
Outline

1. Overview

2. Method to evaluate the error growth

3. Analysis of 5 radiation scheme versions:
   - Entire Rad. Scheme in SP
   - Rad. Scheme in SP, but “fesft” in DP – “mixed 1”
   - Rad. Scheme in SP, but “fesft” in DP and SW and LW radiative fluxes in DP – “mixed 2”
   - Rad. Scheme in SP, but “fesft” in mixed pr. and SW and LW radiative fluxes in DP – “mixed 3”
   - Entire Rad. Scheme in DP

4. Summary
Radiation Scheme in SP

SUBR. test_physics
(in src_physics.f90)

CALL init_test (which calls read_input
in src_read_write.f90)

DO ib=1,nblock
  ...
  CALL copy_to_block
  CALL radiation_organize
  CALL copy_from_block
  ...
END DO
...

CALL write_output (in src_readwrite.f90)

SUBR. radiation_organize
(in radiation_interface.f90)

... CALL fesft (in radiation_rg.f90) in SP

zfls, zflt, other output
    in SP

sohr(k) ~ zfls(k) - zfls(k+1)

thhr(k) ~ zflt(k) - zflt(k+1)

SUBR. radiation_rg_organize
(in radiation_rg_org.f90)
Radiation Scheme in DP

**SUBR. test_physics** (in src_physics.f90)

CALL init_test (which calls read_input in src_read_write.f90)

DO ib=1,nblock
  ...  
  CALL copy_to_block

  CALL radiation_organize

  CALL copy_from_block

  ...  
  END DO

  CALL write_output (in src_readwrite.f90)

**SUBR. radiation_organize** (in radiation_interface.f90)

CALL radiation_organize

CALL copy_to_block

CALL radiation_organize

CALL copy_from_block

...  

**SUBR. radiation_rg_organize** (in radiation_rg_org.f90)

CALL fesft (in radiation_rg.f90)  

zfls, zflt, other output

sohr(k) ~ zfls(k) - zfls(k+1)

thhr(k) ~ zflt(k) - zflt(k+1)
Solar heating rate

Effect of perturbation on error growth: histogram
Field=rad_sohr, levels: 41-60

- SP: 4.63
- DP: 5.92
- delta: 1.29

Effect of perturbation on error growth: domain view
SP, Field=rad_sohr, Mean over levels: 41-60 (valid grid points 100%)

Actual Field=rad_sohr [K/s], Mean over levels: 41-60
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
DP, Field=rad_sohr, Mean over levels: 41-60 (valid grid points 100%)
Solar heating rate

**SP vs. DP**

**Effect of perturbation on error growth: histogram**
- **Field=rad_sohr, levels: 21-40**
  - SP: 5.09
  - DP: 6.34
  - delta: 1.24

**Actual Field=rad_sohr [K/s], Mean over levels: 21-40**
- 16/6/2014 18UTC

**Effect of perturbation on error growth: domain view**
- **SP, Field=rad_sohr, Mean over levels: 21-40 (valid grid points, 100%)**
  - 12
- **DP, Field=rad_sohr, Mean over levels: 21-40 (valid grid points, 100%)**
  - 12
Solar heating rate

**SP vs. DP**

**Effect of perturbation on error growth: histogram**

Field=rad_sohr, levels: 1-20

- SP: 4.73
- DP: 6.74
- Delta: 2.01

**Actual Field=rad_sohr [K/s], Mean over levels: 1-20**
16/6/2014 18UTC

**Effect of perturbation on error growth: domain view**

SP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 100%)

**Effect of perturbation on error growth: domain view**

DP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 100%)
Thermal heating rate

**SP vs. DP**

**Effect of perturbation on error growth: histogram**
Field = rad_thhr, levels: 41-60

**Number of grid points (log scale)**

- Number of significant digits

- SP: 4.43
- DP: 4.78
- Delta: 0.35

**Effect of perturbation on error growth: domain view**
SP, Field = rad_thhr, Mean over levels: 41-60 (valid grid points 100%)

**Actual Field = rad_thhr [K/s], Mean over levels: 41-60**
16/6/2014 18UTC

**Effect of perturbation on error growth: domain view**
DP, Field = rad_thhr, Mean over levels: 41-60 (valid grid points 100%)
**Thermal heating rate**

**SP vs. DP**

**Effect of perturbation on error growth: histogram**

Field=rad_thhr, levels: 21-40

- **SP**: 4.97
- **DP**: 5.39
- **delta**: 0.42

![Histogram showing distribution of significant digits](image1)

**Actual Field=rad_thhr [K/s], Mean over levels: 21-40**

16/6/2014 18UTC

![Actual field distribution](image2)

**Effect of perturbation on error growth: domain view**

SP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points 100%)

![Domain view of SP](image3)

DP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points 100%)

![Domain view of DP](image4)
**Thermal heating rate**

**SP vs. DP**

### Effect of perturbation on error growth: histogram
- **Field=rad_thhr, levels: 1-20**
- **SP**: 4.86
- **DP**: 5.98
- **Delta**: 1.12

### Actual Field=rad_thhr [K/s], Mean over levels: 1-20
- **16/6/2014 18UTC**

### Effect of perturbation on error growth: domain view
- **SP, Field=rad_thhr, Mean over levels: 1-20 (valid grid points 100%)**
- **DP, Field=rad_thhr, Mean over levels: 1-20 (valid grid points 100%)**
1. Overview

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   - Entire Rad. Scheme in SP
   - Rad. Scheme in SP, but “fesft” in DP – “mixed 1”
   - Rad. Scheme in SP, but “fesft” in DP and SW and LW radiative fluxes in DP – “mixed 2”
   - Rad. Scheme in SP, but “fesft” in mixed pr. and SW and LW radiative fluxes in DP – “mixed 3”
   - Entire Rad. Scheme in DP

4. Summary
Mixed 1  Radiation Scheme in SP but “fesft” in DP

SUBR. test_physics  (in src_physics.f90)

CALL init_test (which calls read_input  
in src_read_write.f90)

DO ib=1,nblock  
  CALL copy_to_block
  CALL radiation_organize
  CALL copy_from_block
  ...
END DO  
...

CALL write_output (in src_readwrite.f90)

SUBR. radiation_organize  (in radiation_interface.f90)

...
  CALL radiation_organize
  CALL copy_to_block
  CALL radiation_organize
  CALL copy_from_block
  ...

SUBR. radiation_rg_organize  (in radiation_rg_org.f90)

CALL fesft  (in radiation_rg.f90)
  in DP

zfls, zflt, other output

sohr(k) ~ zfls(k) - zfls(k+1)

thhr(k) ~ zflt(k) - zflt(k+1)

Operational in MeteoSwiss
Mixed 2

Radiation Scheme in **SP**
but “fesft” in **DP**
and SW and LW radiative fluxes in **DP**

**SUBR.** test_physics
(in src_physics.f90)

```fortran
CALL init_test (which calls read_input
in src_read_write.f90)
... ib=1,nblock
    CALL copy_to_block
    CALL radiation_organize
    CALL copy_from_block
... END DO
CALL write_output (in src_readwrite.f90)
```

**SUBR.** radiation_organize
(in radiation_interface.f90)

```fortran
CALL radiation_organize
... CALL radiation_rg_organize
...```

**SUBR.** radiation_rg_organize
(in radiation_rg_org.f90)

```fortran
CALL fesft (in radiation_rg.f90)
...```

**Example:** Why keeping SW and LW radiative fluxes in **DP**?

\[
\begin{align*}
\text{zfls}(k) &= 1000.12345678 \\
\text{zfls}(k+1) &= 1000.11111111 \\
\text{sohr}(k) &= 0.01234567 \\
\end{align*}
\]

12 sig. digits $\Rightarrow$ 7 sig. digits

\[
\begin{align*}
\text{zfls}(k) &= 1000.12345678 \\
\text{zfls}(k+1) &= 1000.11111111 \\
\text{sohr}(k) &= 0.01234567 \\
\end{align*}
\]

7 sig. digits $\Rightarrow$ 2 sig. digits 😊
Solar heating rate

**SP vs. DP**

### Effect of perturbation on error growth: histogram

- **Field**: rad_sohr, levels: 41-60
- **SP**: 4.63
- **DP**: 5.92
- **delta**: 1.29

### Effect of perturbation on error growth: domain view

- **SP**, Field=rad_sohr, Mean over levels: 41-60 (valid grid points, 100%)
- **DP**, Field=rad_sohr, Mean over levels: 41-60 (valid grid points, 100%)

**Actual Field=rad_sohr [K/s], Mean over levels: 41-60**

- **16/6/2014 18UTC**

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Radiation
Solar heating rate

(SP + fesft in DP) vs. DP

**Effect of perturbation on error growth: histogram**

- **Field**: rad_sohr, **levels**: 41-60
- **SP**: 4.8
- **DP**: 5.79
- **delta**: 0.99

**Actual Field**: rad_sohr [K/s], **Mean over levels**: 41-60

- **16/6/2014 18UTC**

**Effect of perturbation on error growth: domain view**

- **SP, Field**: rad_sohr, **Mean over levels**: 41-60 (valid grid points 97%)
- **DP, Field**: rad_sohr, **Mean over levels**: 41-60 (valid grid points 100%)
Solar heating rate

(SP + fesft,zfls,zflt in DP) vs. DP
Solar heating rate

**SP VS. DP**

Effect of perturbation on error growth: histogram
Field=rad_sohr, levels: 21-40

SP: 5.09  
DP: 6.34  
delta: 1.24

Effect of perturbation on error growth: domain view
SP, Field=rad_sohr, Mean over levels: 21-40 (valid grid points 100%)

Actual Field=rad_sohr [K/s], Mean over levels: 21-40  
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
DP, Field=rad_sohr, Mean over levels: 21-40 (valid grid points 100%)
Solar heating rate

\((\text{SP} + \text{fesft in DP}) \text{ vs. DP})\)

**Effect of perturbation on error growth: histogram**

- **Field**: rad_sohr, levels: 21-40
- **SP**: 5.32
- **DP**: 6.2
- **delta**: 0.88

**Actual Field**: rad_sohr [K/s], Mean over levels: 21-40

- **16/6/2014 18UTC**

**Effect of perturbation on error growth: domain view**

- **Field**: rad_sohr, Mean over levels: 21-40 (valid grid points 96.8%)
- **DP**, Field=rad_sohr, Mean over levels: 21-40 (valid grid points 100%)
Solar heating rate

(SP + fesft, zfls, zflt in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_sohr, levels: 21-40

SP: 6.11
DP: 6.28
delta: 0.17

Effect of perturbation on error growth: domain view
SP, Field=rad_sohr, Mean over levels: 21-40 (valid grid points 100%)

Actual Field=rad_sohr [K/s], Mean over levels: 21-40
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
DP, Field=rad_sohr, Mean over levels: 21-40 (valid grid points 100%)
Solar heating rate

SP vs. DP

Effect of perturbation on error growth: histogram
Field=rad_sohr, levels: 1-20

- Number of grid points (log scale)
- Number of significant digits

SP: 4.73
DP: 6.74
delta: 2.01

Actual Field=rad_sohr [K/s], Mean over levels: 1-20
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
SP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 100%)

Effect of perturbation on error growth: domain view
DP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 100%)
Solar heating rate

(SP + fesft in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_sohr, levels: 1-20

SP: 4.99
DP: 6.74
delta: 1.75

Effect of perturbation on error growth: domain view
SP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 98.4%)

Actual Field=rad_sohr [K/s], Mean over levels: 1-20
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
DP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 100%)

x10^{-5}
Solar heating rate

(SP + fesft, zfls, zflt in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_sohr, levels: 1-20

SP: 6.51
DP: 6.72
delta: 0.2

Actual Field=rad_sohr [K/s], Mean over levels: 1-20
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
SP, Field=rad_sohr, Mean over levels: 1-20 (valid grid points 100%)

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Thermal heating rate

**SP vs. DP**

Effect of perturbation on error growth: histogram
Field = rad_thhr, levels: 41-60

- **SP:** 4.43
- **DP:** 4.78
- Delta: 0.35

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16/6/2014 18UTC

Effect of perturbation on error growth: domain view
SP, Field = rad_thhr, Mean over levels: 41-60 (valid grid points 100%)

Effect of perturbation on error growth: domain view
DP, Field = rad_thhr, Mean over levels: 41-60 (valid grid points 100%)
Thermal heating rate

(SP + fesft in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_thhr, levels: 41-60

- Number of grid points (log scale)

- Number of significant digits

SP: 4.45
DP: 4.77
delta: 0.33

Actual Field=rad_thhr [K/s], Mean over levels: 41-60
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
SP, Field=rad_thhr, Mean over levels: 41-60 (valid grid points 100%)

Effect of perturbation on error growth: domain view
DP, Field=rad_thhr, Mean over levels: 41-60 (valid grid points 100%)
Thermal heating rate \((SP + \text{fesft,zfis,zflt in DP})\) vs. DP

**Effect of perturbation on error growth: histogram**

Field=rad_thhr, levels: 41-60

- SP: 4.45
- DP: 4.77
- delta: 0.32

**Actual Field=rad_thhr [K/s], Mean over levels: 41-60**

16/6/2014 18UTC

**Effect of perturbation on error growth: domain view**

SP, Field=rad_thhr, Mean over levels: 41-60 (valid grid points 100%)

DP, Field=rad_thhr, Mean over levels: 41-60 (valid grid points 100%)
Thermal heating rate

**Effect of perturbation on error growth: histogram**
Field=rad_thhr, levels: 21-40

- SP: 4.97
- DP: 5.39
- Delta: 0.42

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**Effect of perturbation on error growth: domain view**
SP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points 100%)

**Effect of perturbation on error growth: domain view**
DP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points 100%)
Thermal heating rate

(SP + fesft in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_thhr, levels: 21-40

- Number of grid points (log scale)
- SP: 4.99
- DP: 5.35
- Delta: 0.36

Actual Field=rad_thhr [K/s], Mean over levels: 21-40
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
SP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points, 100%)

Effect of perturbation on error growth: domain view
DP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points, 100%)
Thermal heating rate (SP + fesft,zfls,zflt in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_thhr, levels: 21-40

Number of grid points (log scale)

<table>
<thead>
<tr>
<th>Number of significant digits</th>
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</tbody>
</table>

SP: 4.99
DP: 5.35
Delta: 0.36

Actual Field=rad_thhr [K/s], Mean over levels: 21-40
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
SP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points 100%)

Effect of perturbation on error growth: domain view
DP, Field=rad_thhr, Mean over levels: 21-40 (valid grid points 100%)
Thermal heating rate

SP VS. DP

Effect of perturbation on error growth: histogram
Field=rad_thhr, levels: 1-20

SP: 4.86
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Effect of perturbation on error growth: domain view
SP, Field=rad_thhr, Mean over levels: 1-20 (valid grid points 100%)

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16/6/2014 18UTC

Effect of perturbation on error growth: domain view
DP, Field=rad_thhr, Mean over levels: 1-20 (valid grid points 100%)
Thermal heating rate

(SP + fesft in DP) vs. DP

Effect of perturbation on error growth: histogram
Field=rad_thhr, levels: 1-20

SP: 5.05
DP: 5.98
delta: 0.93

Effect of perturbation on error growth: domain view
SP, Field=rad_thhr, Mean over levels: 1-20 (valid grid points 100%)

Actual Field=rad_thhr [K/s], Mean over levels: 1-20
16/6/2014 18UTC

Effect of perturbation on error growth: domain view
DP, Field=rad_thhr, Mean over levels: 1-20 (valid grid points 100%)
Thermal heating rate \((SP + \text{fesft, zfls, zflt in DP}) \text{ vs. DP}\)

**Effect of perturbation on error growth: histogram**
- Field = rad_thhr, levels: 1-20
- SP: 5.05
- DP: 5.98
- Delta: 0.93

**Actual Field = rad_thhr [K/s], Mean over levels: 1-20**
- 16/6/2014 18UTC

**Effect of perturbation on error growth: domain view**
- Field = rad_thhr, Mean over levels: 1-20 (valid grid points 100%)
Outline

1. Overview

2. Method to evaluate the error growth

3. Analysis of 5 radiation scheme versions:
   - Entire Rad. Scheme in SP
   - Rad. Scheme in SP, but “fesft” in DP – “mixed 1”
   - Rad. Scheme in SP, but “fesft” in DP and SW and LW radiative fluxes in DP – “mixed 2”
   - Rad. Scheme in SP, but “fesft” in mixed pr. and SW and LW radiative fluxes in DP – “mixed 3”
   - Entire Rad. Scheme in DP

4. Summary
Mixed 3

Radiation Scheme in SP
but “fesft” in **mixed precision** (14 fluxes in DP)
and SW and LW radiative fluxes in DP

SUBR. test_physics
(in src_physics.f90)

CALL init_test (which calls read_input
in src_read_write.f90)

DO ib=1,nblock
...
  CALL copy_to_block
  CALL radiation_organize
  CALL copy_from_block
...
END DO
...
CALL write_output (in src_readwrite.f90)

SUBR. radiation_organize
(in radiation_interface.f90)

SUBR. radiation_rg_organize
(in radiation_rg_org.f90)

CALL fesft (in radiation_rg.f90)

\[
\text{sohr}(k) \sim z\text{fls}(k) - z\text{fls}(k+1) \\
\text{thhr}(k) \sim z\text{flt}(k) - z\text{flt}(k+1)
\]

in mixed precision

zfls, zflt, other output

in DP
in SP

We skip the detailed results here ...
1. Overview

2. Method to evaluate the error growth

3. Analysis of 5 radiation scheme versions:
   - Entire Rad. Scheme in SP
   - Rad. Scheme in SP, but “fesft” in DP – “mixed 1”
   - Rad. Scheme in SP, but “fesft” in DP and SW and LW radiative fluxes in DP – “mixed 2”
   - Rad. Scheme in SP, but “fesft” in mixed pr. and SW and LW radiative fluxes in DP – “mixed 3”
   - Entire Rad. Scheme in DP

4. Summary
Summary

- **SOHR**
- **THHR**
- **Runtime benefit**

**Significant digits lost** vs **Runtime benefit (%)**

- **Mixed 3** (fesft in mixed precision and zfls, zflt in DP)
- **Mixed 1** (fesft in DP)
- **Mixed 2** (fesft in DP and zfls, zflt in DP)

---

**Mixed** 3
(fesft in DP)
and zfls, zflt in DP)
Summary

• Not worthwhile to run fesft in DP – it takes the same time as entire radiation scheme in DP

• Choose between 3 options:
  • Entire scheme in DP
  • “Mixed 3” version – save 15% runtime, lose 1.1 significant digits
  • Entire scheme in SP – save 20% runtime, lose 1.5 significant digits

Thank you!
Additional slides:

Synoptic situation
COSMO-2 ANALYSIS

Sea Surface Pressure and Tendency

Version: 943
Mon 16 Jun 2014 18UTC
16.06.2014 18UTC +00h

Air Pressure at Sea Level [hPa]
3h Sea Surface Pressure Tendency [hPa]

Mean: 1014.7 hPa
Mean: missing

© MeteoSwiss
Experiment domain
High Cloud Cover (p=28-400hPa or z=30-8km)

Cloud Area Fraction in High Troposphere (above ca 400hPa) [%]

Mean: 46.0 %

Experiment domain
Experiment domain
COSMO-2 ANALYSIS
500hPa Geopotential Height and Temperature

Mon 16 Jun 2014 18UTC
16.06.2014 18UTC +00h

Geopotential [gpm], level = 500 hPa
Air Temperature [deg C], level = 500 hPa

Mean: 5681.1 gpm
Mean: -17.1 deg C

Experiment domain
COSMO-2 ANALYSIS
3000m Windspeed and Wind Flags
Version: 943
Mon 16 Jun 2014 18UTC
16.06.2014 18UTC +00h

wind speed [knots], level = 3000 m
wind, level = 3000 m

Mean: 11.0 Max: 31.7 [knots]

Experiment domain
Additional slides:
<table>
<thead>
<tr>
<th>SP (fesft in DP)</th>
<th>fesft in DP+zfls,zflt in DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HR_{pe} = 1.123412 \times 10^{-5}$</td>
<td>$HR_{pe} = 1.12341278912 \times 10^{-5}$</td>
</tr>
<tr>
<td>$HR_{np} = 1.123401 \times 10^{-5}$</td>
<td>$HR_{np} = 1.12340167801 \times 10^{-5}$</td>
</tr>
<tr>
<td>Delta = $0.000 \times 10^{-5}$</td>
<td>Delta = $0.000011111 \times 10^{-5}$</td>
</tr>
<tr>
<td>SIG = ?</td>
<td>SIG = 5</td>
</tr>
</tbody>
</table>

**All in SP (also fesft)**

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$HR_{pe} = 1.123412 \times 10^{-5}$</td>
</tr>
<tr>
<td>$HR_{np} = 1.112401 \times 10^{-5}$</td>
</tr>
<tr>
<td>Delta = $0.011 \times 10^{-5}$</td>
</tr>
<tr>
<td>SIG = 2</td>
</tr>
</tbody>
</table>
COSMO spectral bands

<table>
<thead>
<tr>
<th>Interval number</th>
<th>Solar</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Limits (μm)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.53–4.64</td>
<td>8.33–9.01</td>
</tr>
<tr>
<td>2</td>
<td>0.70–1.53</td>
<td>10.31–12.5</td>
</tr>
<tr>
<td>3</td>
<td>0.25–0.70</td>
<td>9.01–10.31</td>
</tr>
<tr>
<td>4</td>
<td>20.0–104.5</td>
<td>H₂O, CO₂, N₂O, O₂</td>
</tr>
<tr>
<td>5</td>
<td>12.5–20.0</td>
<td>H₂O, O₃, CO₂, N₂O, O₂</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|                | Gaseous absorption, No. of kᵣ for H₂O, CO₂ and O₃ |                                   |
| Solar          | H₂O, CO₂, CH₄, N₂O (7, 6, 0)                     | H₂O, CO₂, CH₄, N₂O (7, 4, 0)      |
| Thermal        | H₂O, CO₂, N₂O (7, 3, 0)                         | H₂O, CO₂, N₂O (3, 3, 5)          |

<table>
<thead>
<tr>
<th>Droplet scattering absorption Rayleigh scattering Aerosol scattering absorption</th>
<th>Solar</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
<td>yes</td>
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<td>yes</td>
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<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

**TABLE 1. Spectral intervals and major optical constituents considered in the radiation scheme.**
SUBROUTINE test_physics (from src_physics.f90)

CALL init_test (which calls read_input from src_read_write.f90)
...
DO ib=1,nblock
...
CALL copy_to_block
CALL radiation_organize
CALL copy_from_block
...
END DO
...
CALL write_output (from src_readwrite.f90)

SUBROUTINE fesft (from radiation_rg.f90)

DO jspec=jpsol+1,jpspec (Thermal spectral loop)

CALL opt_th (from radiation_rg.f90)

Calculation of clouds/aerosols “grey” contribution to rad. fluxes:

CALL inv_th (from radiation_rg.f90)

Calculation of gases (h2o,co2,03) contribution to rad. fluxes:

DO jg = 3, 1, -1 (over gases)
  DO jc = icc,1,-1 (over absorption coefficients)
    CALL inv_th (from radiation_rg.f90)
  ENDDO
ENDDO
ENDDO

ENDDO

The module procedure inv_th solves a linear equation system for thermal fluxes using a Gaussian elimination-backsubstitution algorithm dedicated to the specific structure of the system matrix. Method: 1) setting of the RHS of the system using the layer boundary black body radiation and allowing for partial cloud cover in each layer. 2) solution of the equation system including the lower boundary condition. 3) matrix coefficients are calculated in the course of the elimination. 4) step for one layer at a time through a call to routine *coe_th*. 5) the final result, i.e. the so-called black body flux differences (cf. Ritter and Geleyn, 1992) are stored seperately for cloudy and cloud-free part of each layer boundary

DO jspec=1,jpsol (Solar spectral loop)
...
ENDDO

SUBROUTINE radiation_organize (from radiation_interface.f90)

CALL radiation_rg_organize

SUBROUTINE radiation_rg_organize (from radiation_org_org.f90)

...
### Example for 12.345:

<table>
<thead>
<tr>
<th>Precision</th>
<th>Rounded to significant figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>12.3450</td>
</tr>
<tr>
<td>5</td>
<td>12.345</td>
</tr>
<tr>
<td>4</td>
<td>12.35</td>
</tr>
<tr>
<td>3</td>
<td>12.3</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Another example for 0.012345:

<table>
<thead>
<tr>
<th>Precision</th>
<th>Rounded to significant figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.01234500</td>
</tr>
<tr>
<td>6</td>
<td>0.0123450</td>
</tr>
<tr>
<td>5</td>
<td>0.012345</td>
</tr>
<tr>
<td>4</td>
<td>0.01235</td>
</tr>
<tr>
<td>3</td>
<td>0.0123</td>
</tr>
<tr>
<td>2</td>
<td>0.012</td>
</tr>
<tr>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Method

- We have performed 4 simulations of radiation standalone:
  A. Double precision, unperturbed
  B. Double precision, with the input fields T,PP,QV,QC,QI,T_S,PS randomly perturbed to 1e-7
  C. Single precision, unperturbed
  D. Single precision, with the input fields T,PP,QV,QC,QI,T_S,PS randomly perturbed to 1e-7

- After one time step the radiation-related fields were retrieved (for the cases A,B,C,D)

- At any grid point the relative error is defined as:
  \( Er_{DP} = \frac{\text{abs}((A-B))}{\text{max}(\text{abs}(A),\text{abs}(B))} \)
  \( Er_{SP} = \frac{\text{abs}((C-D))}{\text{max}(\text{abs}(C),\text{abs}(D))} \)

- Number of significant digits is defined as:
  \( N_{sig_{DP}} = -\log_{10}(Er_{DP}) \)
  \( N_{sig_{SP}} = -\log_{10}(Er_{SP}) \)

- Lower number of significant digits means higher error growth.

- If for most of the radiation-related fields, \( N_{sig_{SP}} \) distribution (over all the grid points) is shifted towards lower values, compared to \( N_{sig_{DP}} \), one should not run the radiation scheme in SP

- We present error growth analysis for the following radiation-related fields:
  rad_alb_rad [1], rad_clch [1], rad_clcl [1], rad_clcm [1], rad_clc_sgs [1], rad_clct [1], rad_lwd_s [W/m2], rad_lwu_s [W/m2], rad_pabs [W/m2], rad_qc_rad [kg/kg], rad_qi_rad [kg/kg], rad_sobs [W/m2], rad_sobt [W/m2], rad_sod_t [W/m2], rad_sodwdmm [W/m2], rad_sohr [K/s], rad_sotr [1], rad_sotr_par [1], rad_sun_azi [deg], rad_sun_el [deg], rad_swdifd_s [W/m2], rad_swdifu_s [W/m2], rad_swdir_cor [1], rad_swdir_s [W/m2], rad_swtrdifd_s [W/m2], rad_swtrdifu_s [W/m2], rad_swtrdir_s [W/m2], rad_thbs [W/m2], rad_thbt [W/m2], rad_thhr [K/s]
Method cont.

• For every field, 4 subplots are presented:
  - **Right-hand side**: domain view of Nsig_SP (upper right) and Nsig_DP (lower right). For the 3D fields, we have first averaged the rel. errors over the levels ranges 1-20, 21-40, 41-60, and then calculated the numbers of significant digits.
  - **Upper left**: histograms of Nsig_SP (blue) and Nsig_DP (red) using all the grid points as sample (see explanation figure). For 2D fields the sample is 80X60. For 3D fields at specific levels range, all the relevant levels equally contributed to the sample, enlarging sample size to 80X60X20.
  - **Lower left**: domain view of the actual field. For 3D fields, the field values are averaged over the relevant levels ranges (1-20, 21-40, 41-60).

• Special cases:
  - Grid points with negligible fields values (max(abs(A),abs(B))<10^-12 or max(abs(C),abs(D))<10^-12) are ignored (rel. error is not calculated). These points appear as **white pixels** at the domain views (right-hand side), and counted to “-1” column at the histograms (see explanation figure).
  - “Full precision” grid points (rel. error below 10^-7.2 for SP and below 10^-16 for DP) are counted to “18” column at the histograms (see explanation figure). Grid points with rel. error=0 (exactly) are counted to “19” column at the histograms.