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]**

[1]Israel Meteorological Service, [2]MeteoSwiss

COSMO General Meeting, Jerusalem, September 2017

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**

Overview

- Single vs. Double precision:

  [Link to example]

	Max	Min	Number of digits	Precision
Single	10^{38}	10^{-38}	7.2	10^{-7}
Double	10^{308}	10^{-308}	16.0	10^{-16}

- 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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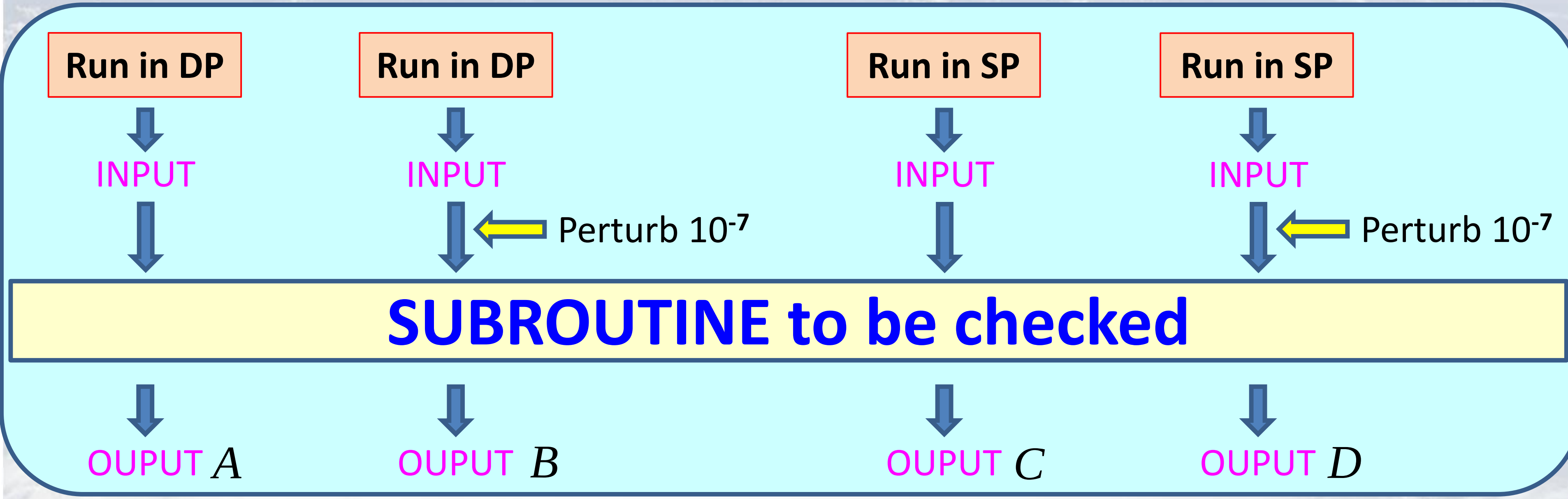
4. **Summary**

Method



$$ERR_{DP}(i,j,k) = \frac{|A(i,j,k) - B(i,j,k)|}{\max(|A|,|B|)} \qquad ERR_{SP}(i,j,k) = \frac{|C(i,j,k) - D(i,j,k)|}{\max(|C|,|D|)}$$

$$N_{sig,DP}(i,j,k) = -\log_{10}(ERR_{DP}) \qquad N_{sig,SP}(i,j,k) = -\log_{10}(ERR_{SP})$$

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**

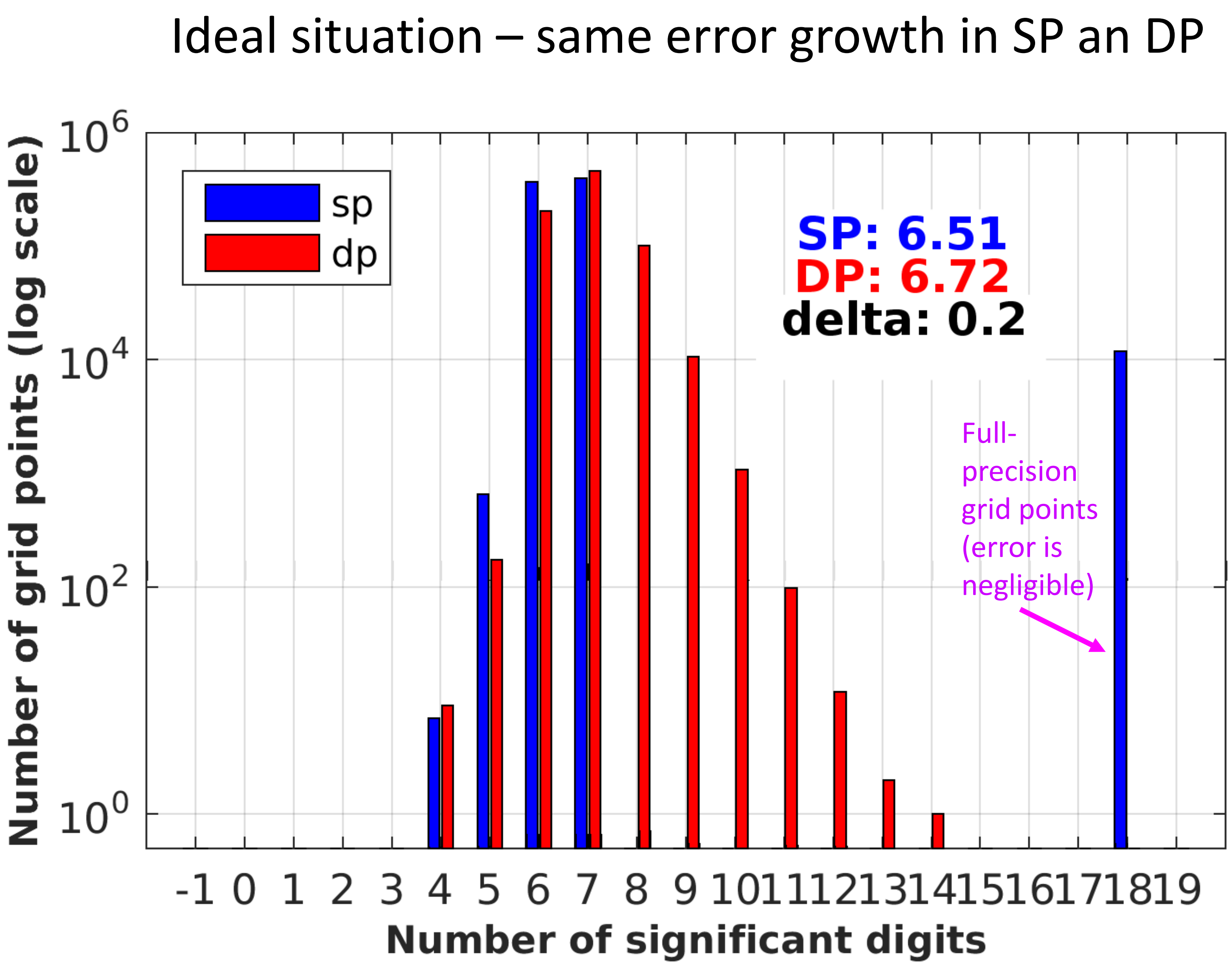
ERR=$1.70588 \cdot 10^{-4}$ $\boxed{N_{sig}=4}$ The SUBROUTINE causes loss of precision:

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



Example 2

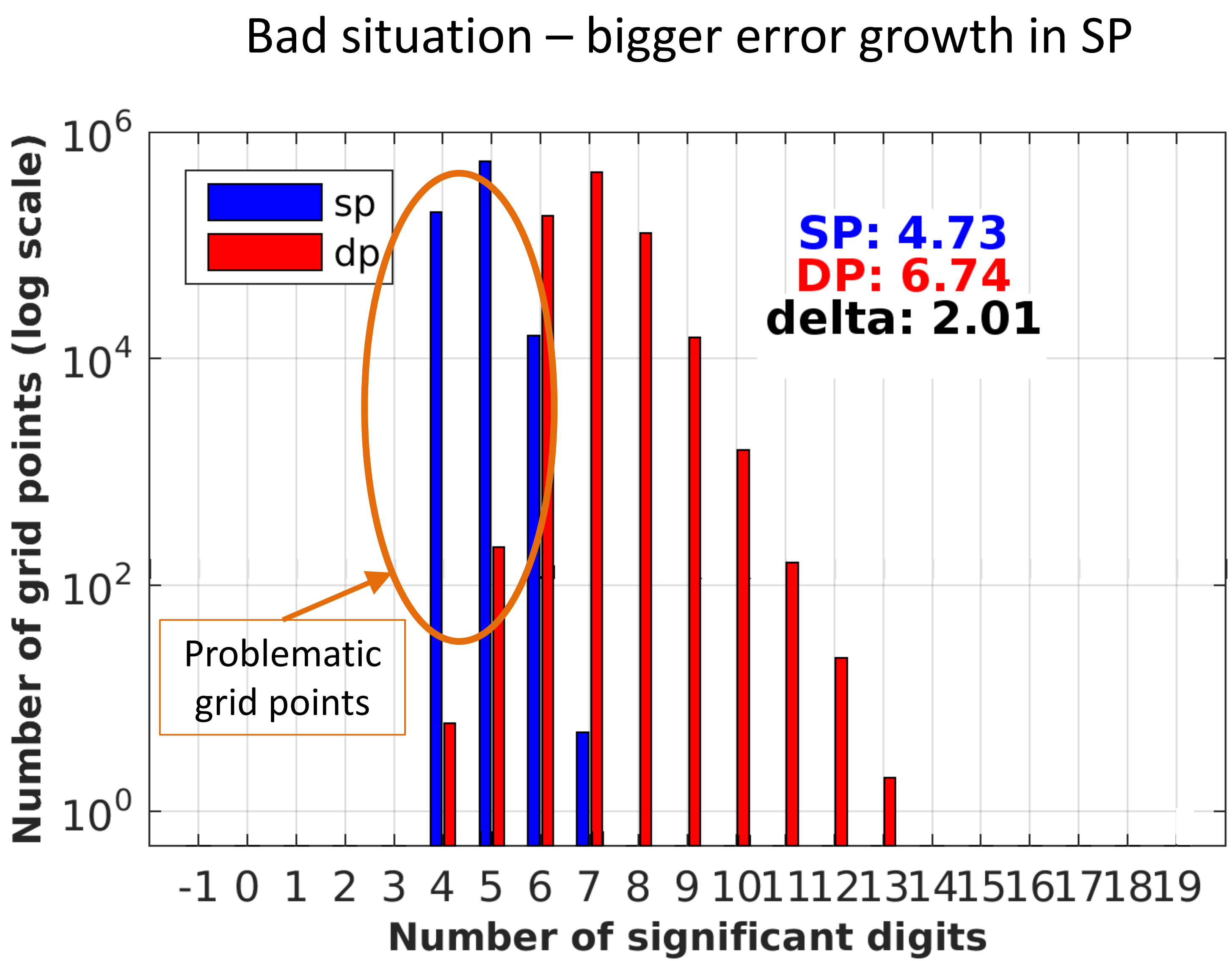
Histogram of

$N_{sig,DP}(i,j,k)$

and

$N_{sig,SP}(i,j,k)$

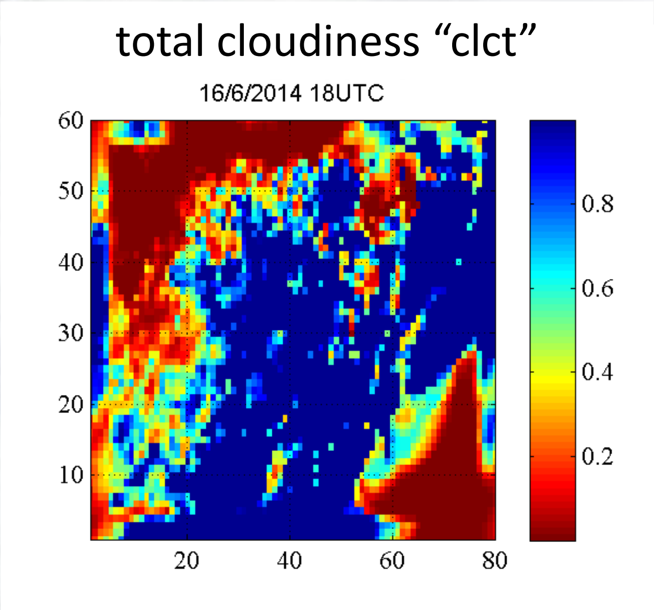
over all the grid points



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:



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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 radiation_rg_organize  →
...
```

SUBR. radiation_rg_organize
(in radiation_rg_org.f90

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

$\underbrace{\text{zfls , zflt}}_{\text{in SP}}\text{ , }\underbrace{\text{other output}}_{\text{in SP}}$

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

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

Radiation Scheme in DP

SUBR. test_physics
(in src_physics.f90)

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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_rg_organize
...
```

SUBR. radiation_rg_organize
(in radiation_rg_org.f90

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

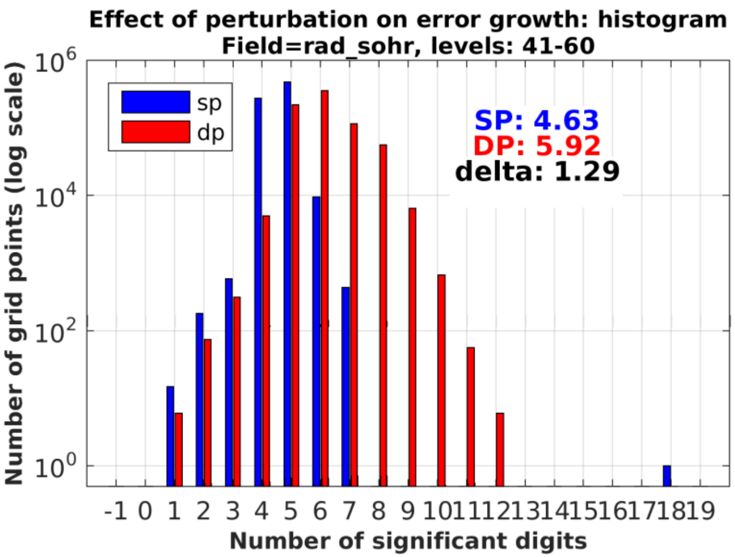
$\underbrace{\textbf{zfls , zflt}}_{\text{in DP}}$ **,** $\underbrace{\textbf{other output}}_{\text{in DP}}$

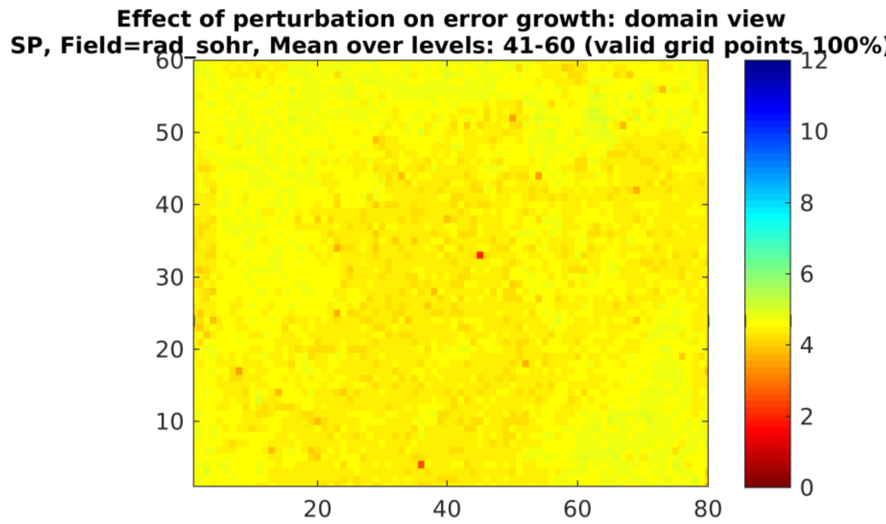
$$\mathbf{sohr}(k) \sim \mathbf{zfls}(k) - \mathbf{zfls}(k+1)$$

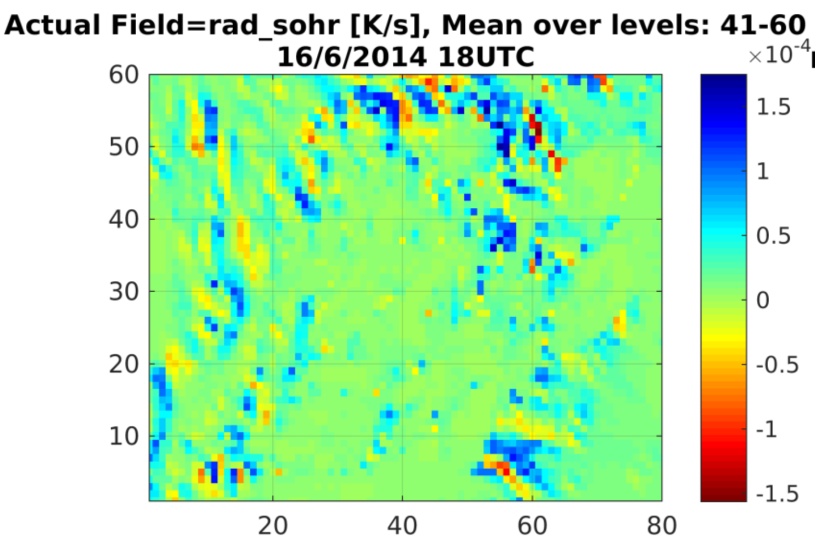
$$\mathbf{thhr}(k) \sim \mathbf{zflt}(k) - \mathbf{zflt}(k+1)$$

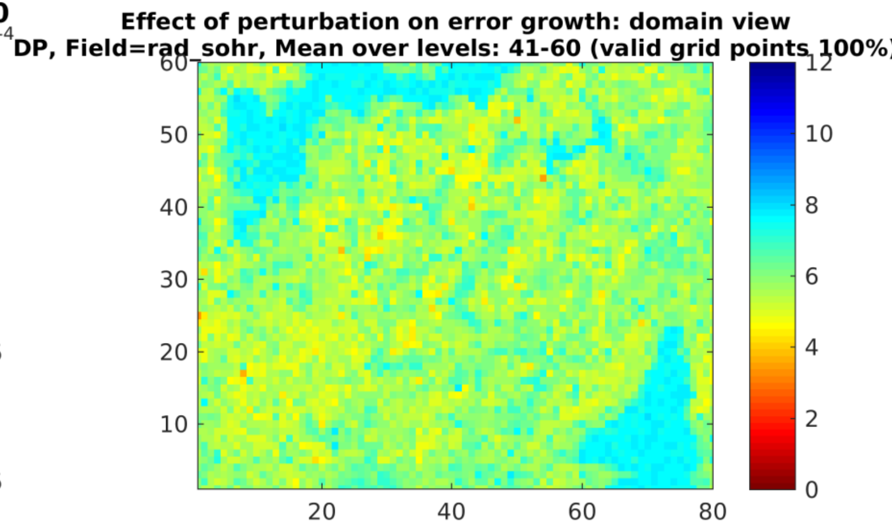
Solar heating rate

SP vs. DP



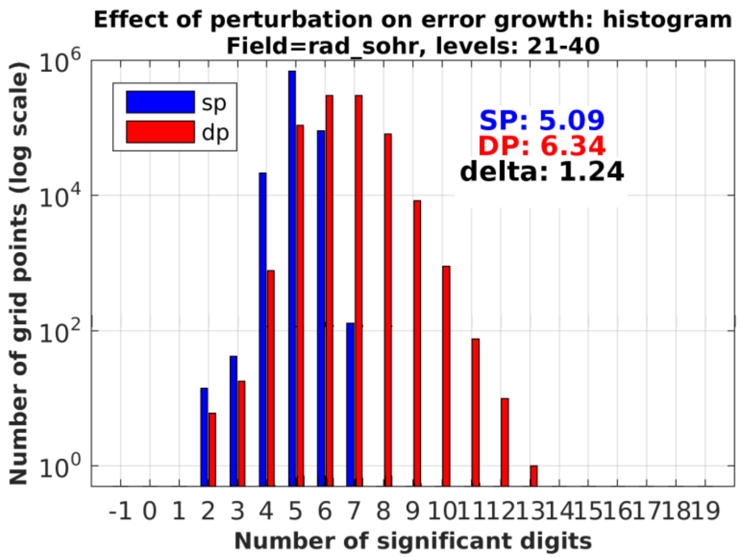


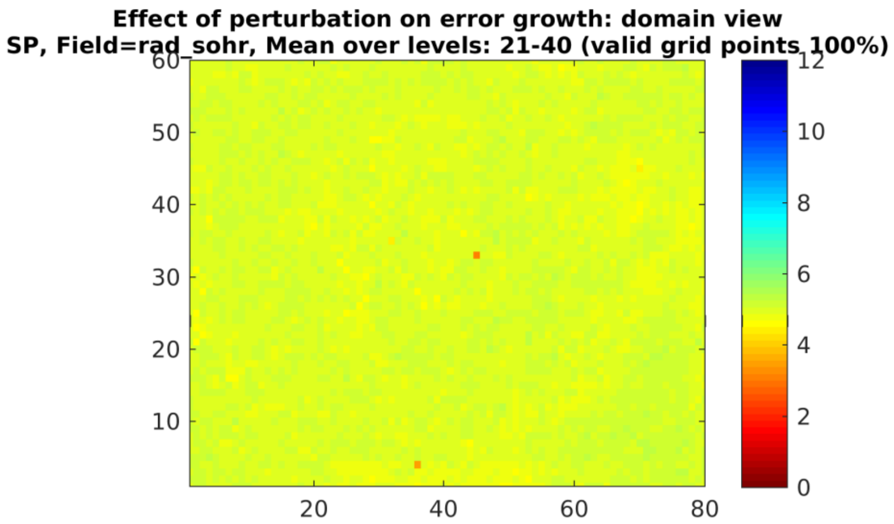


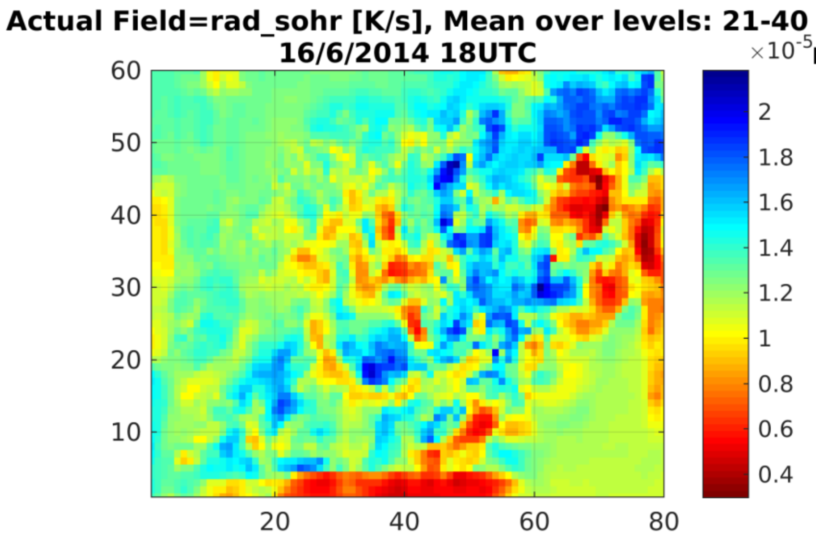


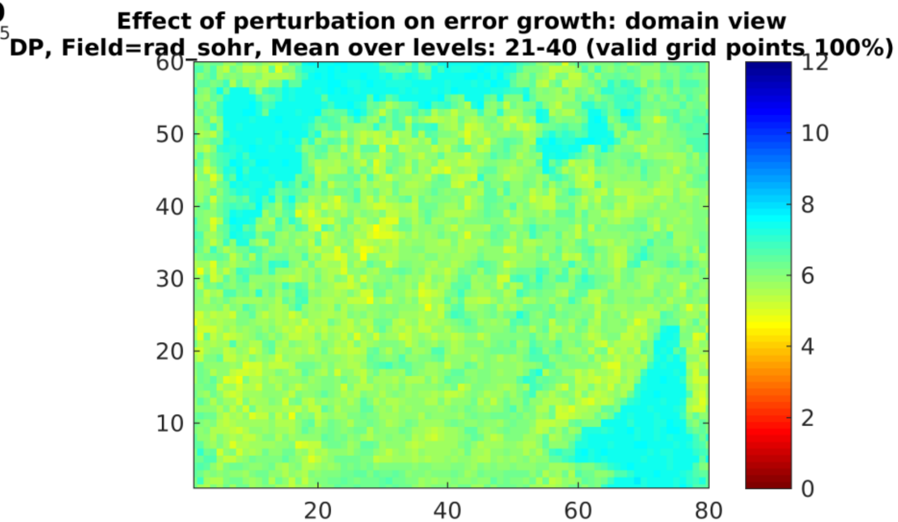
Solar heating rate

SP vs. DP



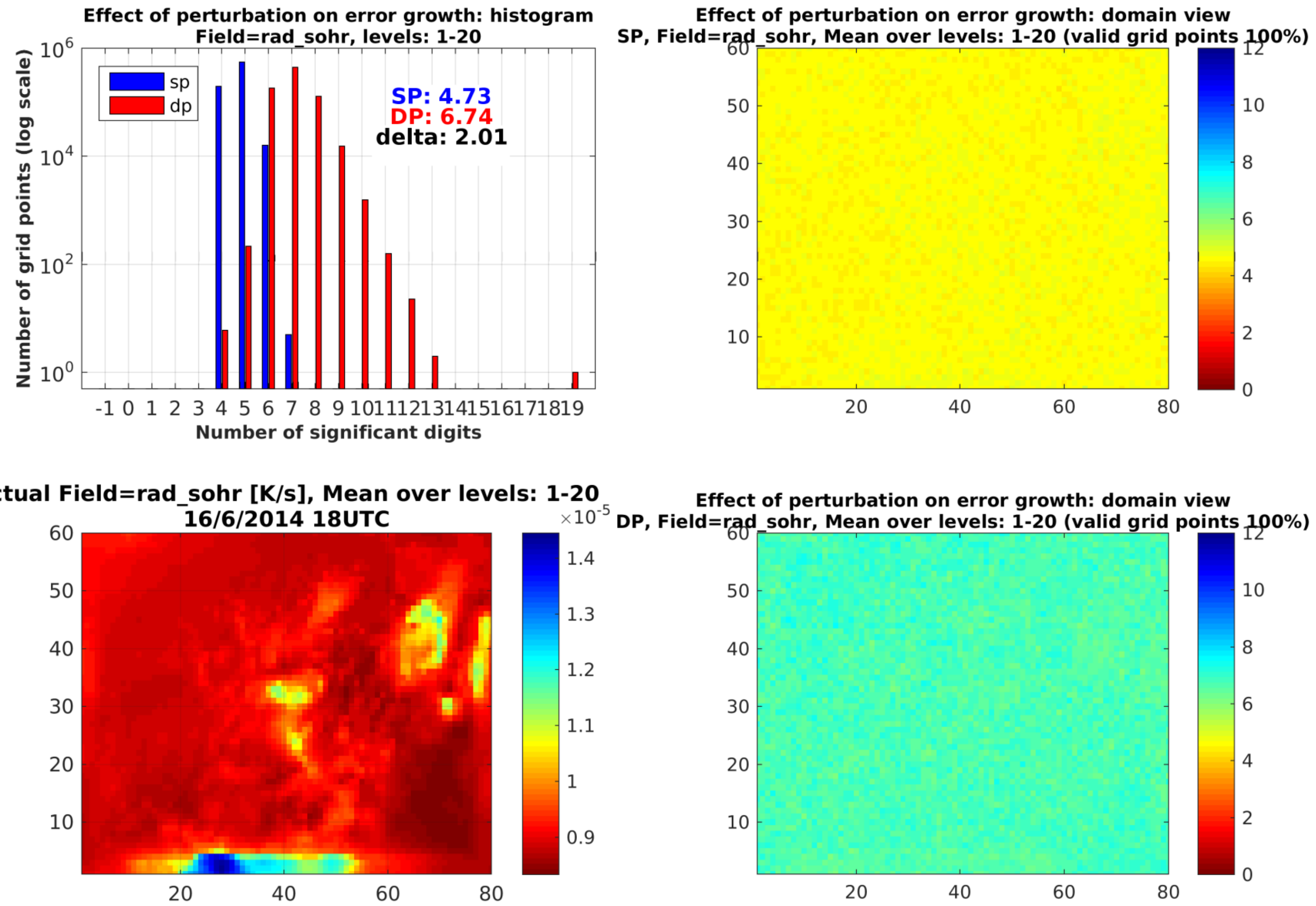






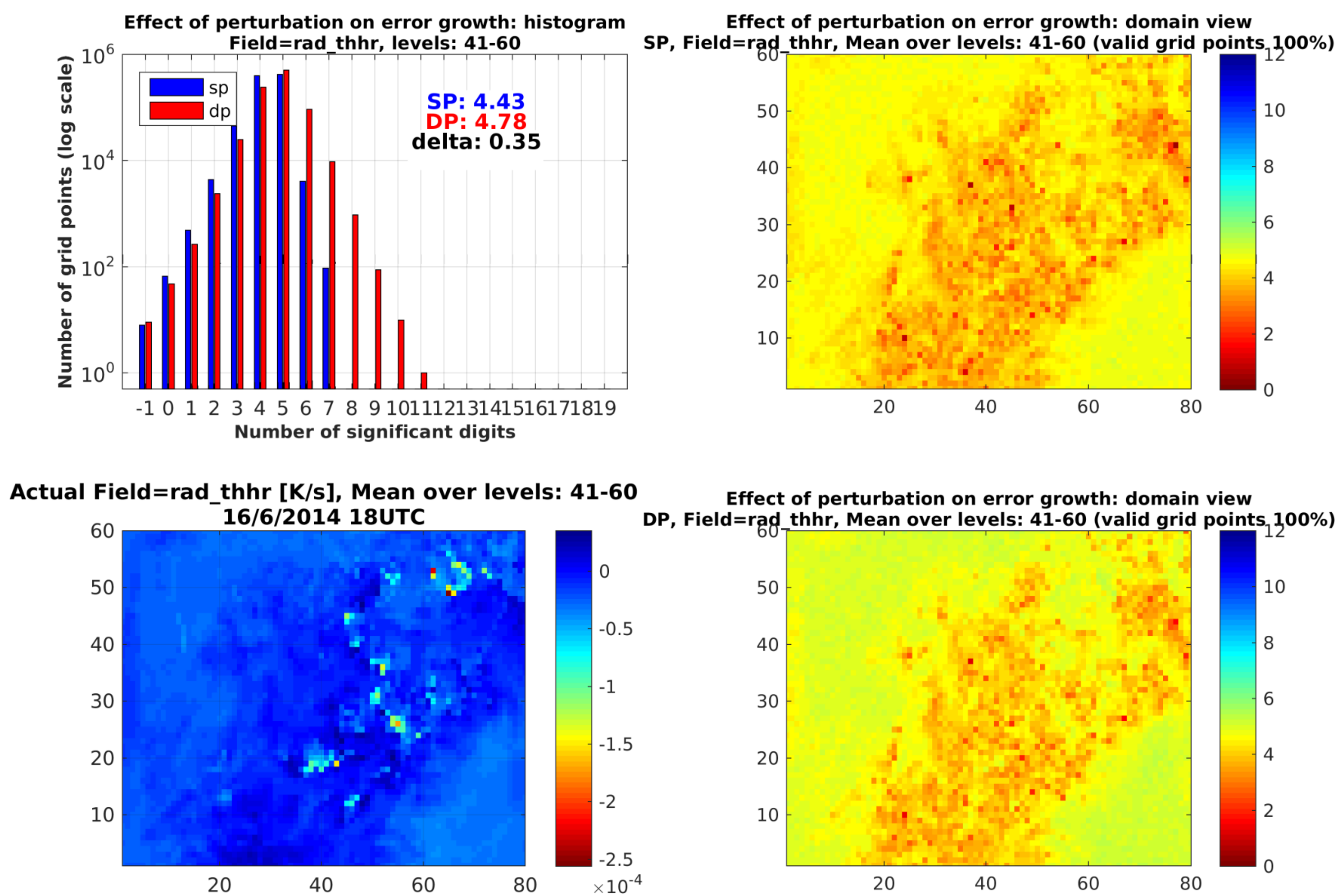
Solar heating rate

SP vs. DP



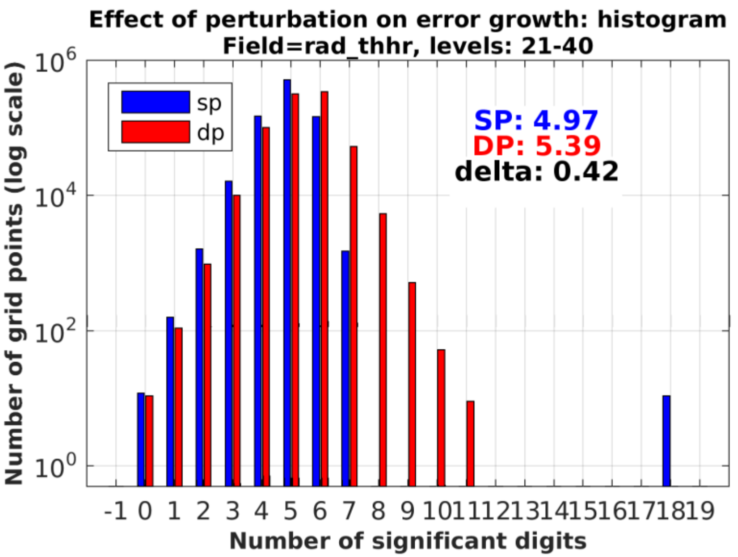
Thermal heating rate

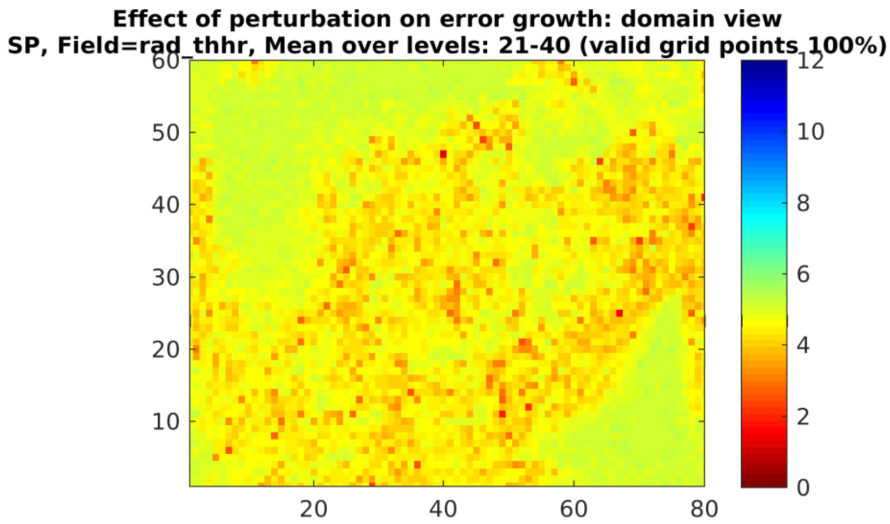
SP vs. DP

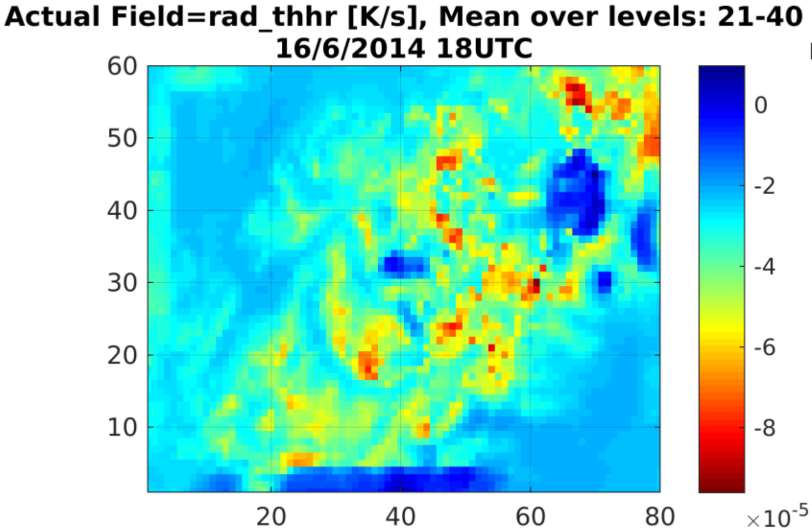


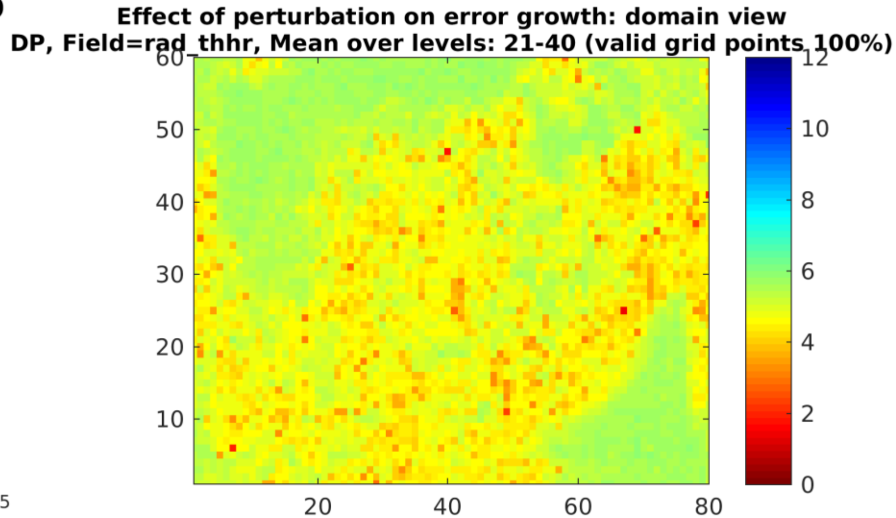
Thermal heating rate

SP vs. DP



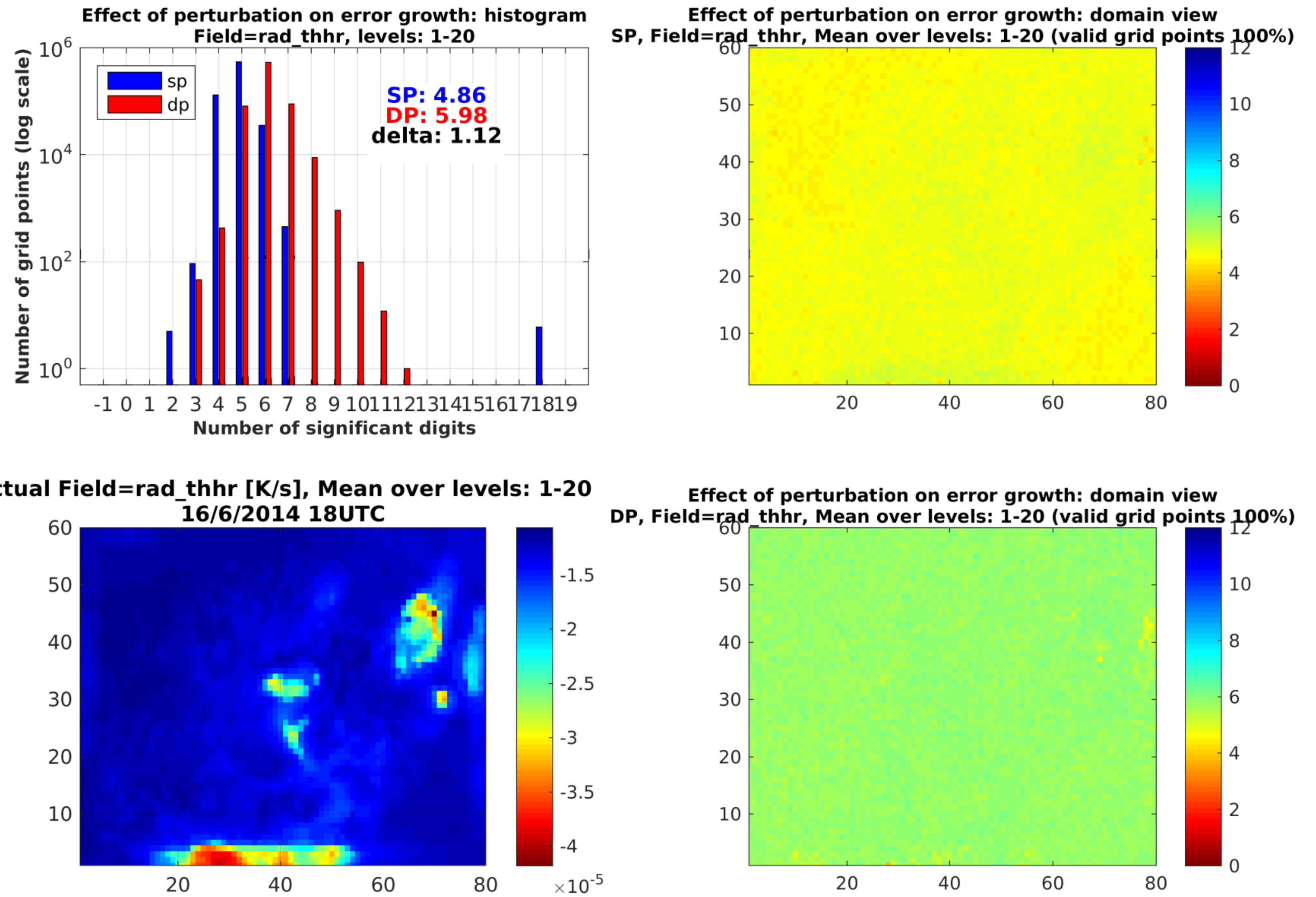






Thermal heating rate

SP vs. DP



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4. Summary

Mixed 1

Radiation Scheme in SP
but "fesft" in DP

Radiation
fesft

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(in src_physics.f90)

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    ...
    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_rg_organize
...
```

SUBR. radiation_rg_organize
(in radiation_rg_org.f90

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

zfls , zflt , other output
  in SP        in SP

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)

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_rg_organize
...

SUBR. radiation_rg_organize
(in radiation_rg_org.f90

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

$\underbrace{\text{zfls , zflt}}_{\text{in DP}}$, $\underbrace{\text{other output}}_{\text{in SP}}$

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

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

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

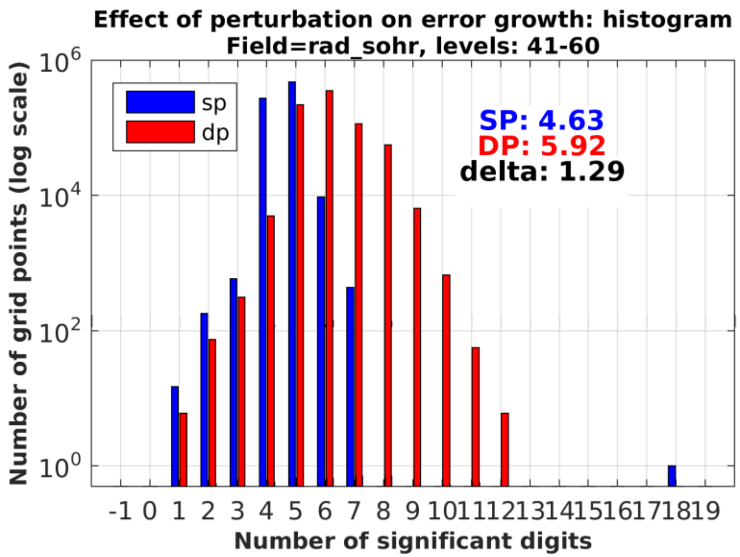
zfls(k)=1000.12345678	zfls(k)=1000.123~~45678~~
zfls(k+1)=1000.11111111	zfls(k+1)=1000.111~~11111~~
sohr(k)=0.01234567	sohr(k)=0.012~~34567~~
12 sig. digits → 7 sig. digits	**7 sig. digits → 2 sig. digits ☹**

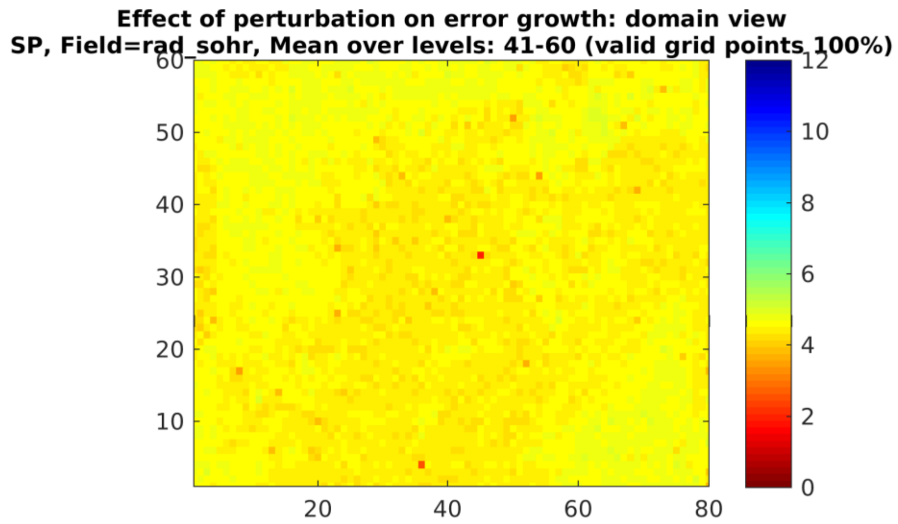
Solar heating rate

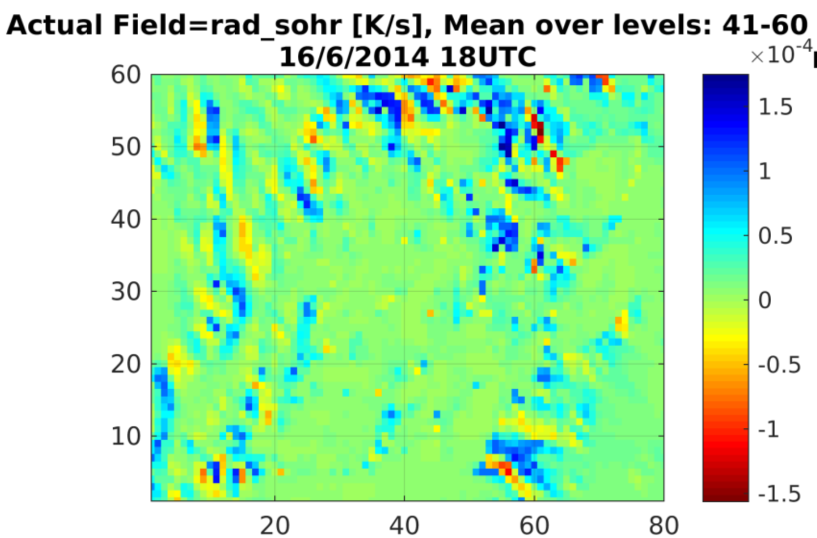
SP vs. DP

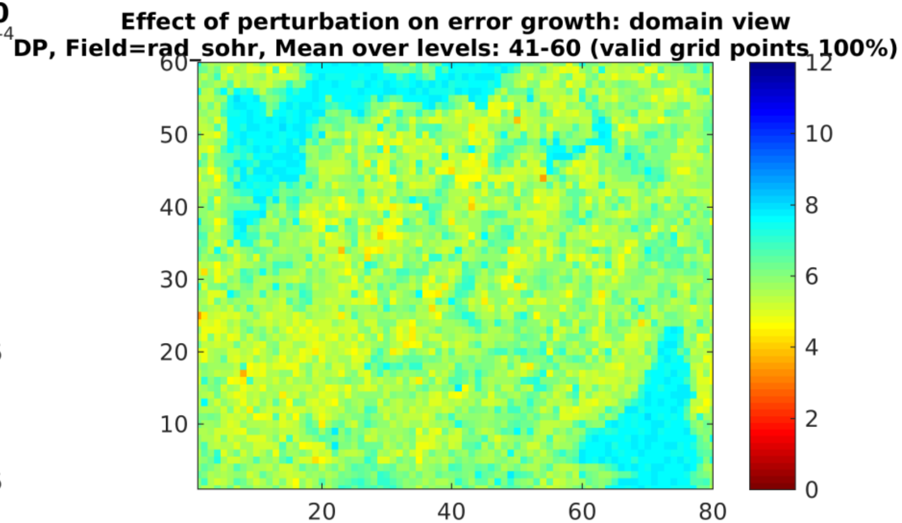
Radiation

SP



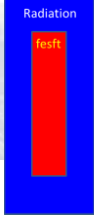


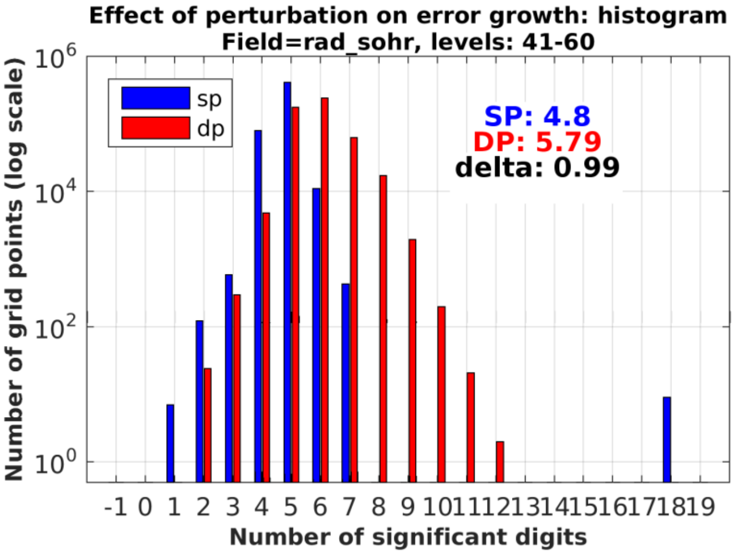


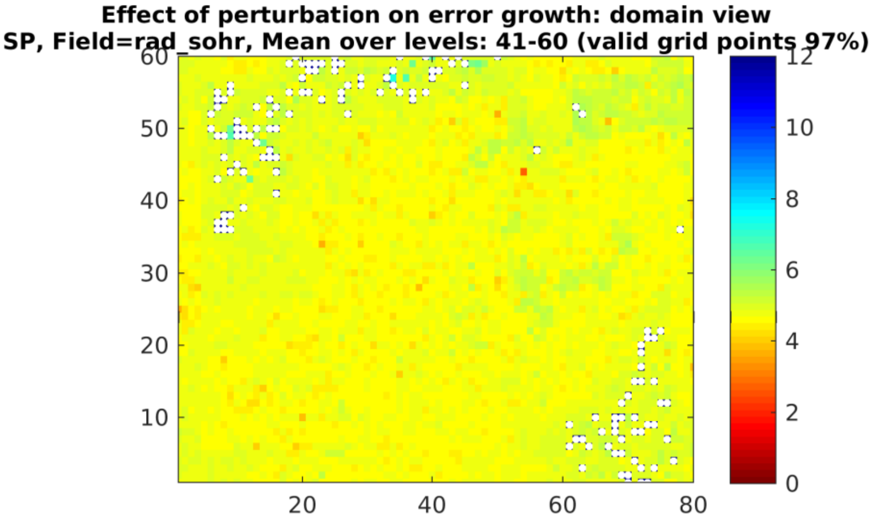


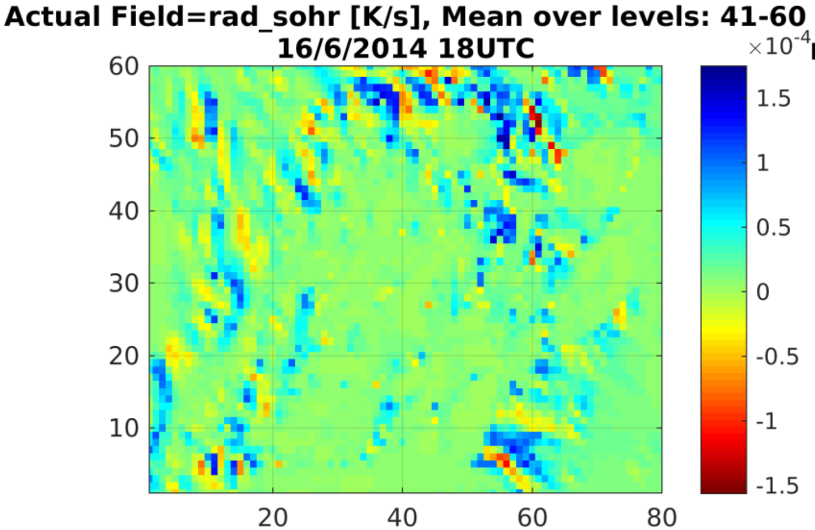
Solar heating rate

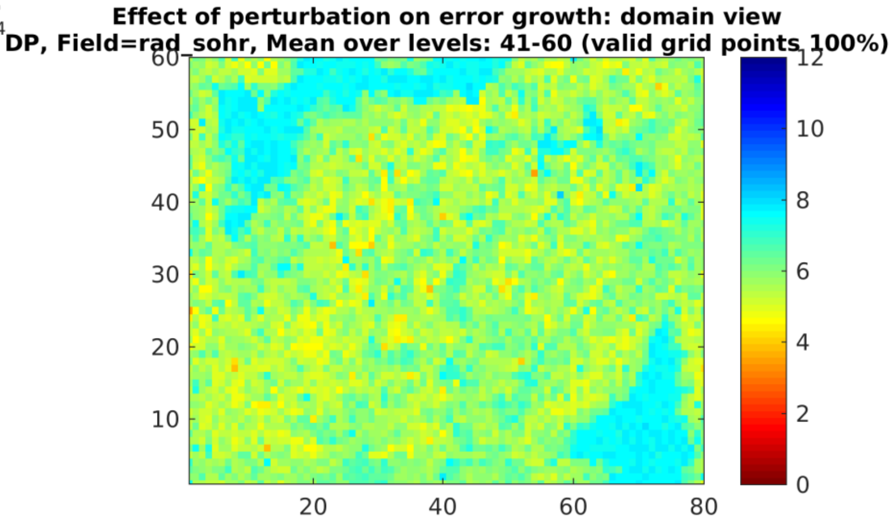
(SP + fesft in DP) vs. DP



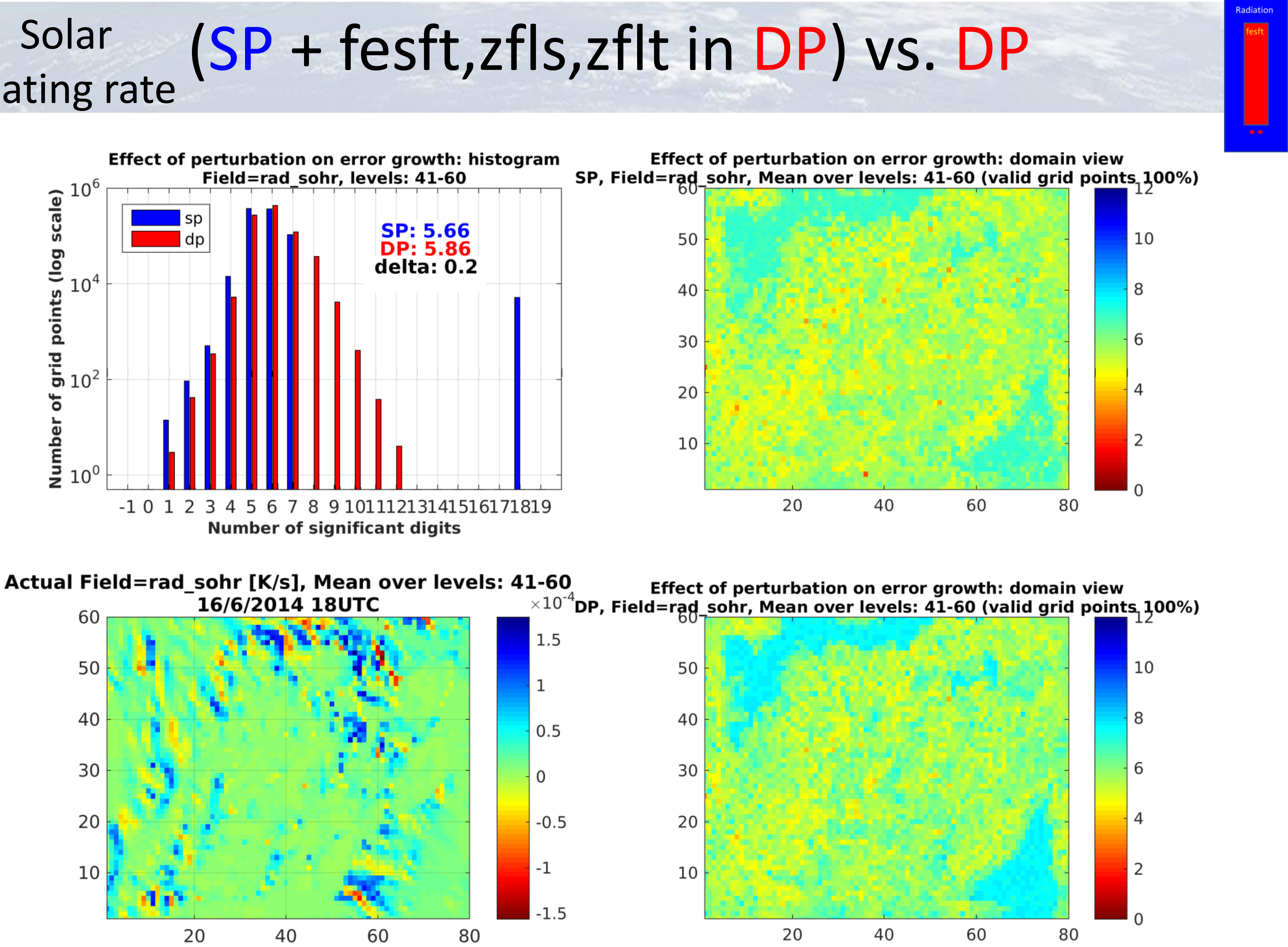






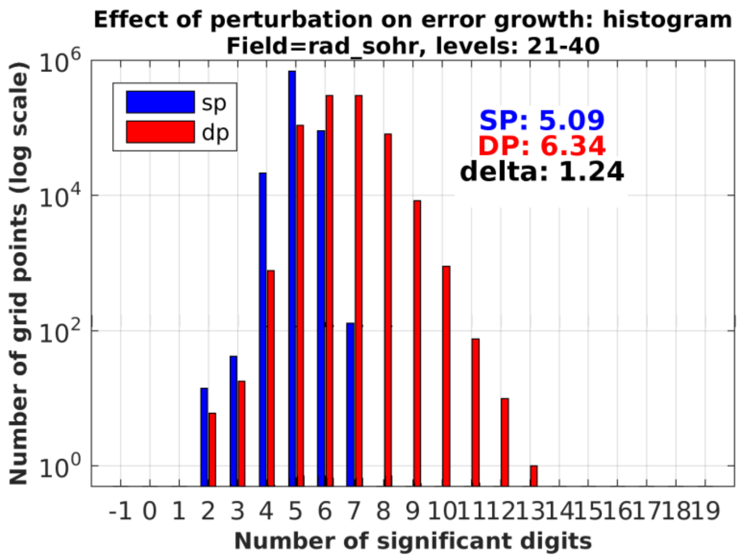


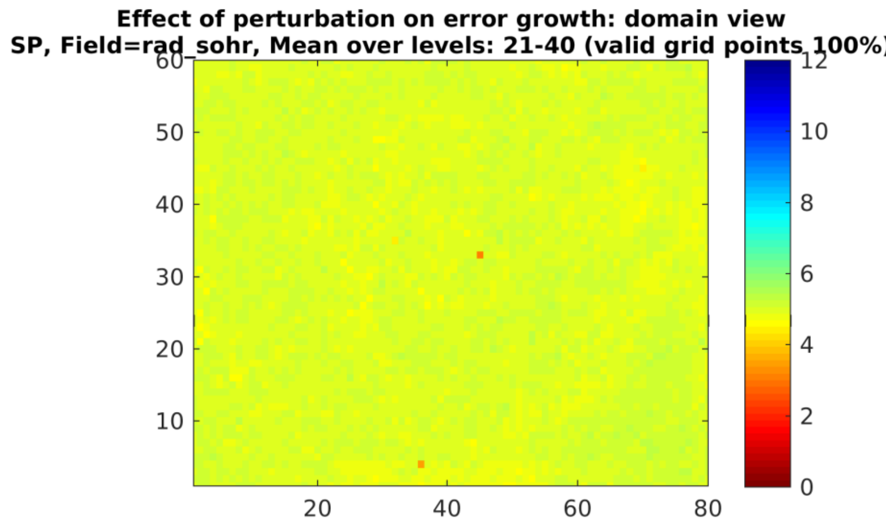
Solar heating rate (SP + fesft,zfls,zflt in DP) vs. DP

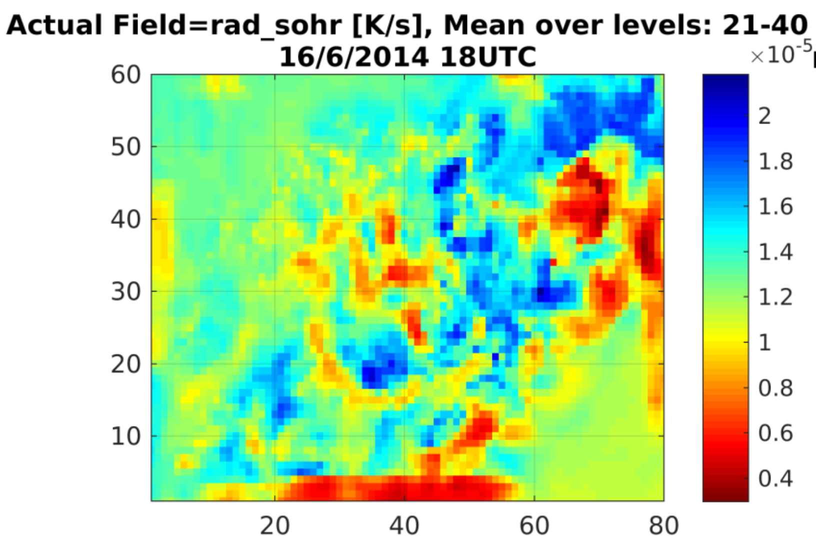


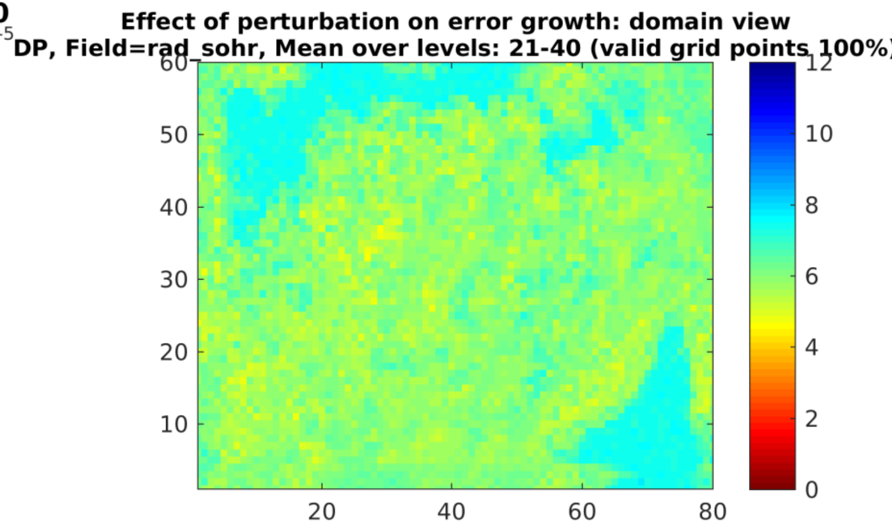
Solar heating rate

SP vs. DP



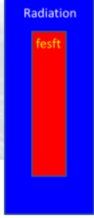


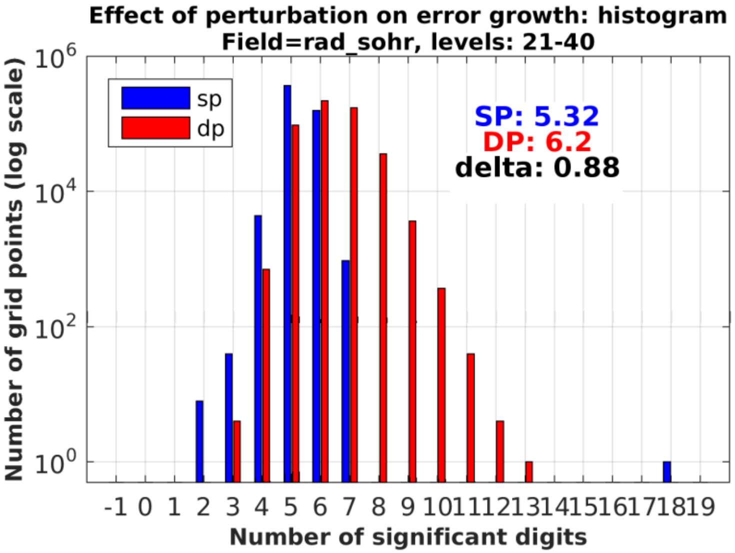


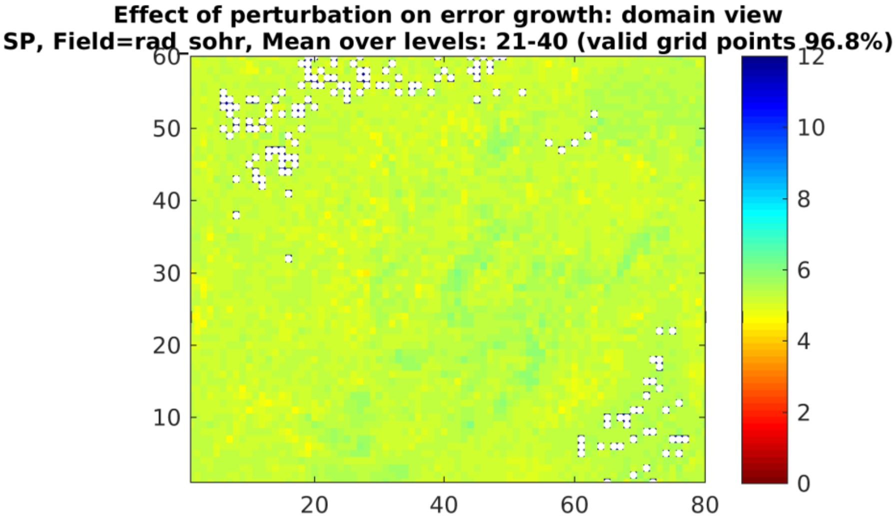


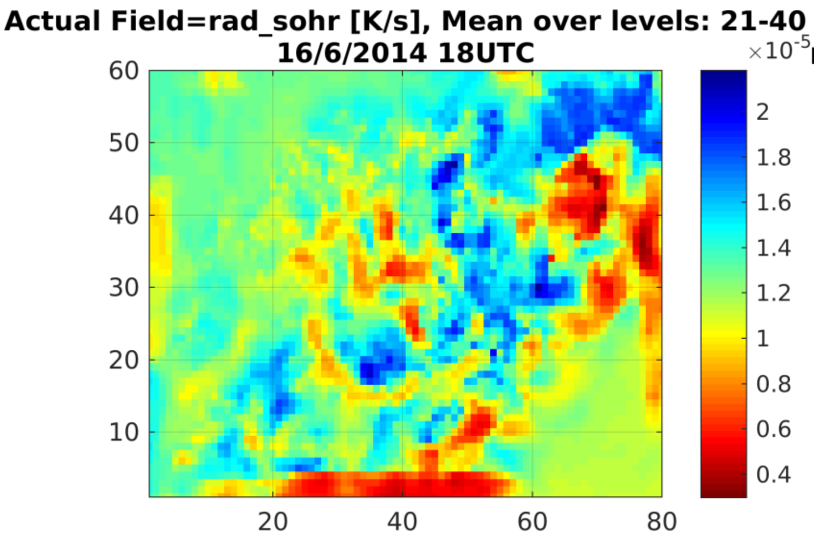
Solar heating rate

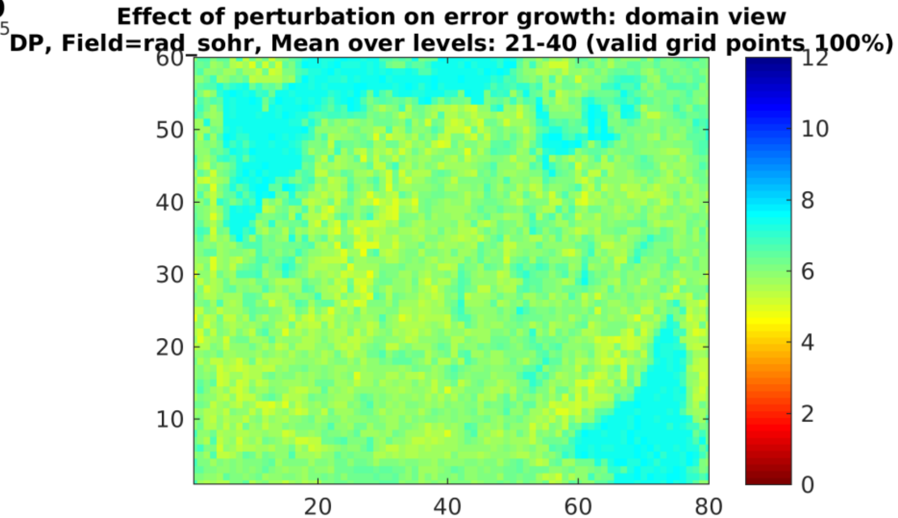
(SP + fesft in DP) vs. DP



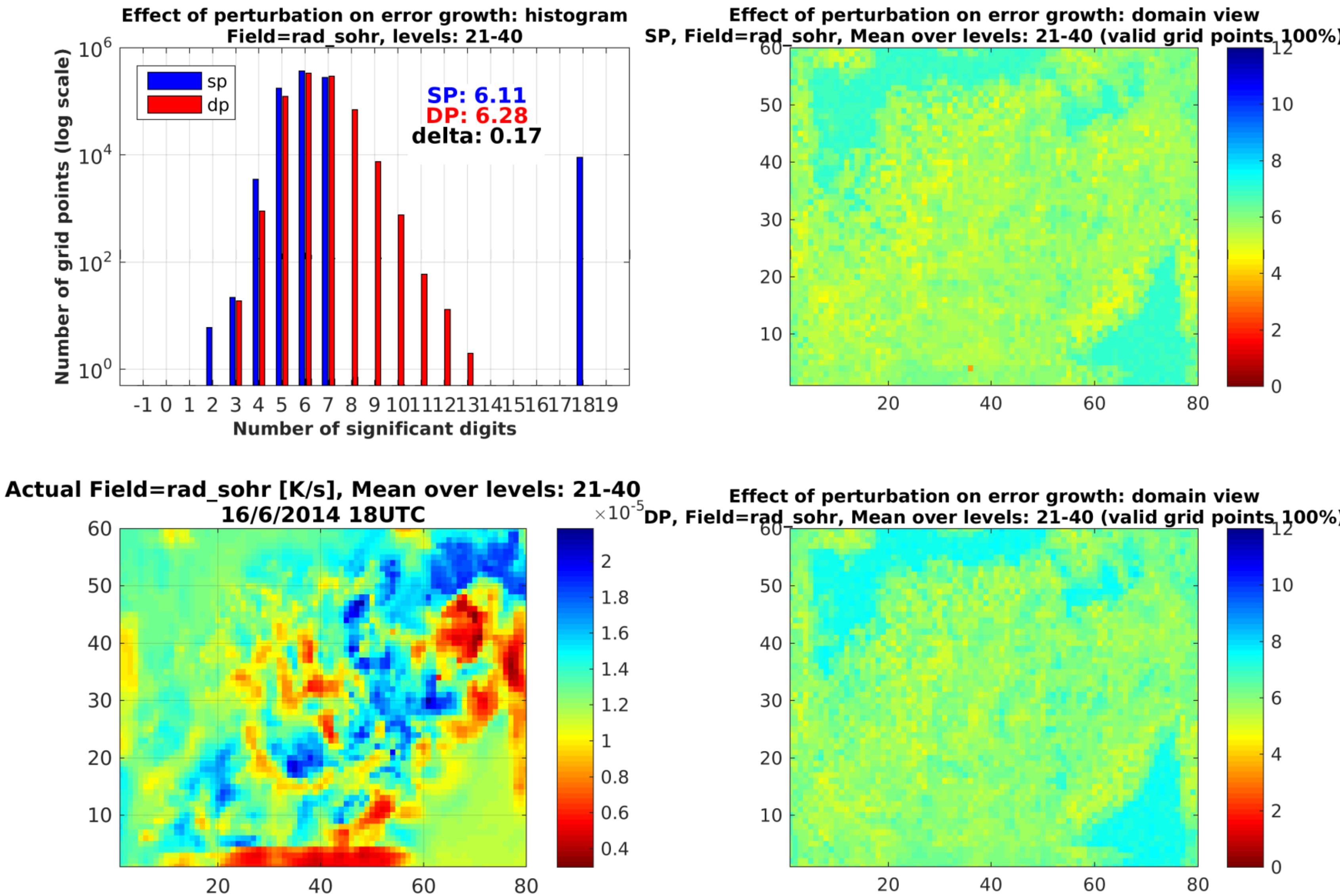






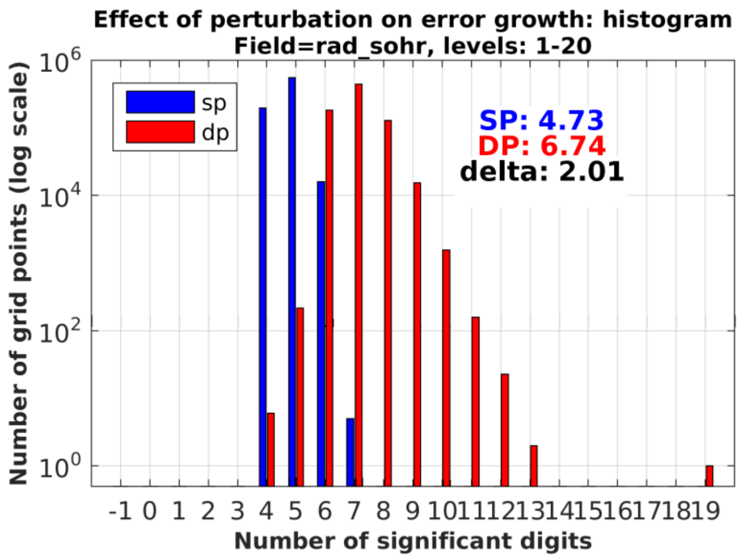


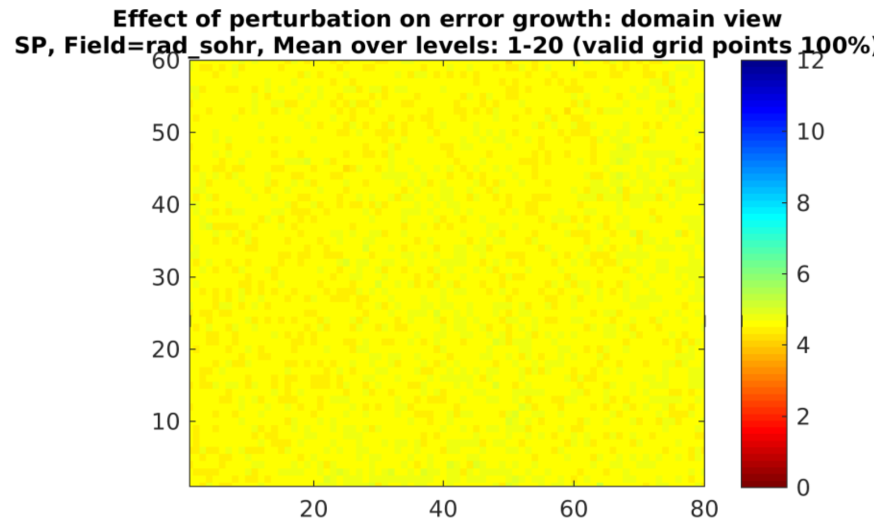
Solar heating rate (SP + fesft,zfls,zflt in DP) vs. DP

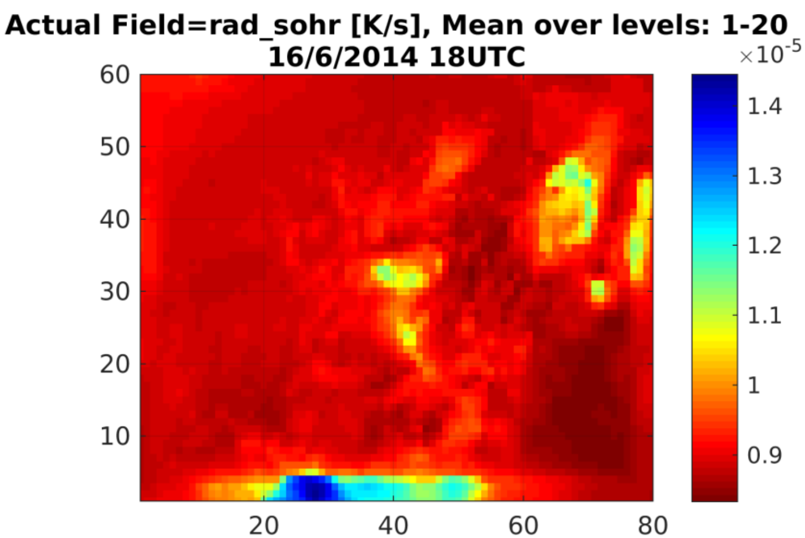


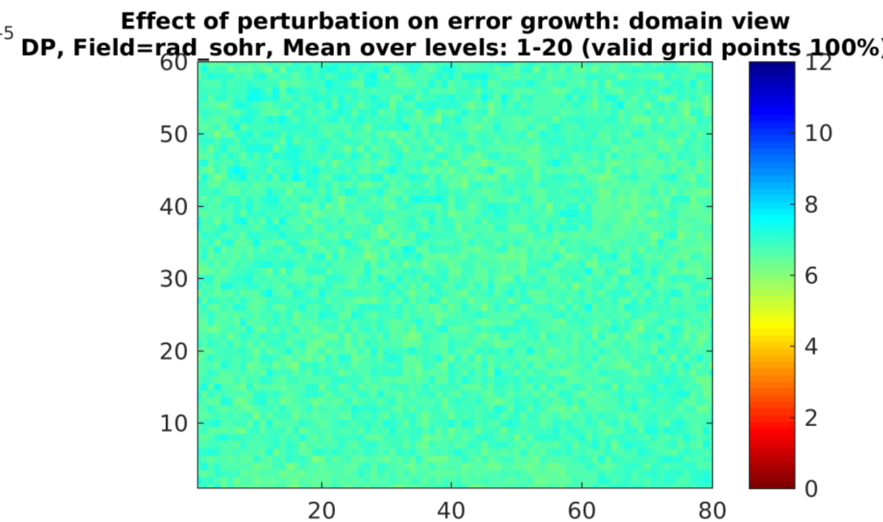
Solar heating rate

SP vs. DP





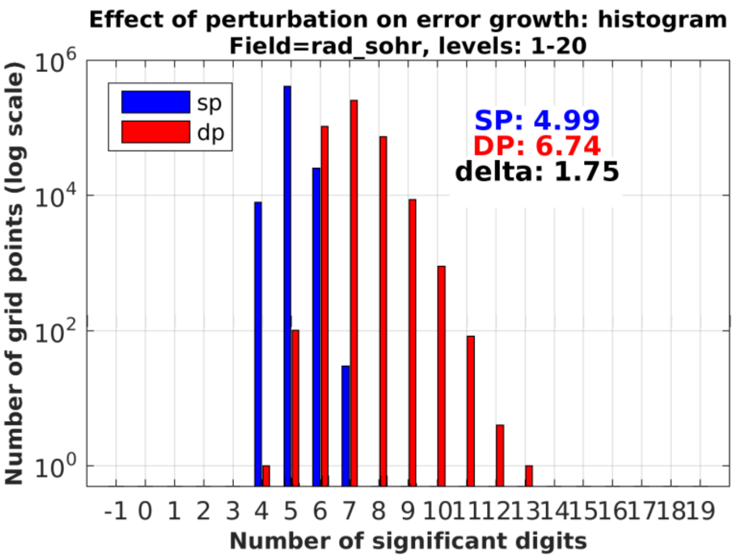


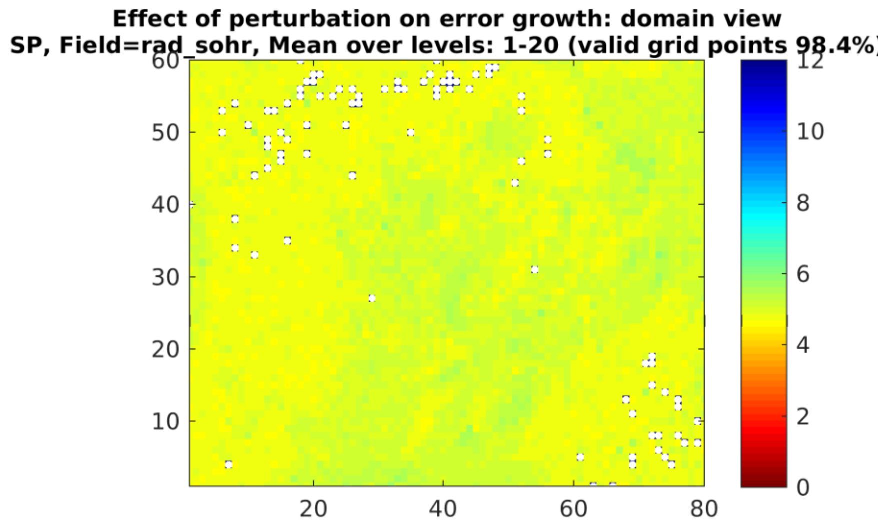


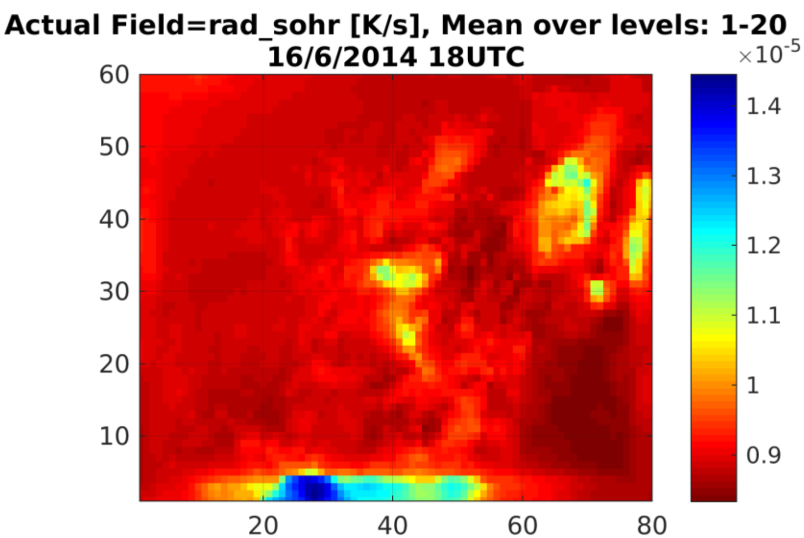
Solar heating rate

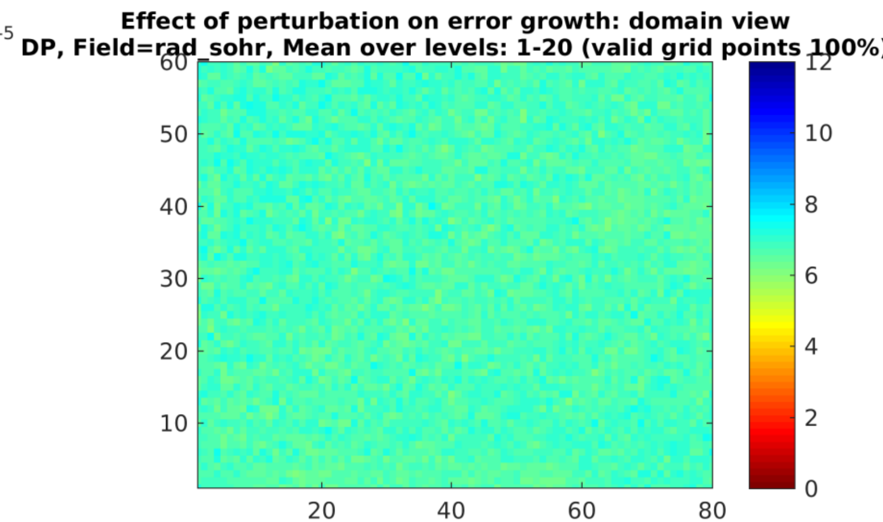
(SP + fesft in DP) vs. DP

Radiation
fesft









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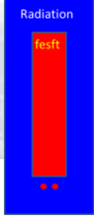
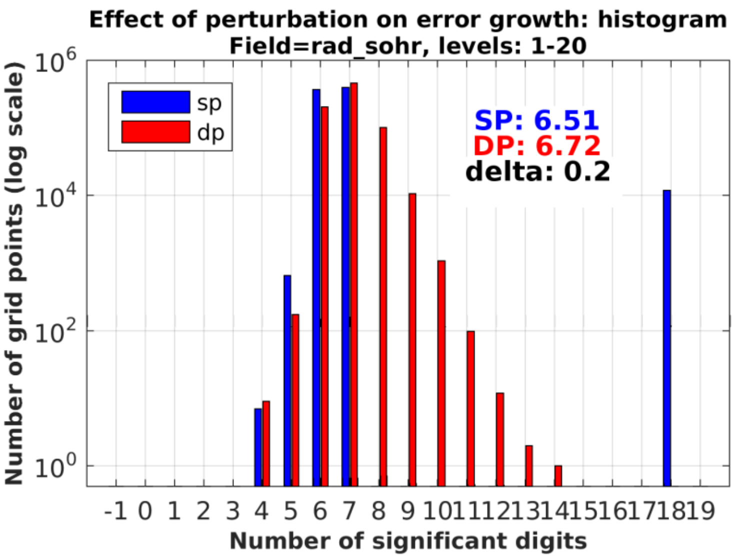
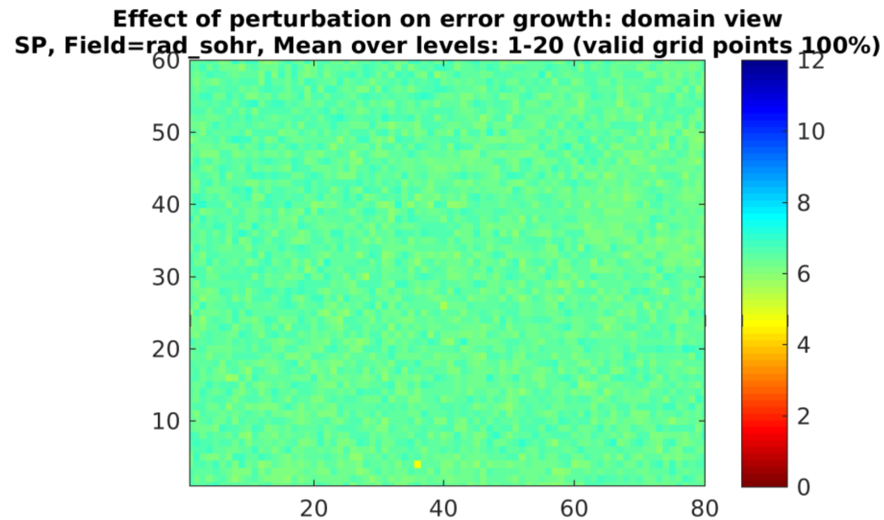
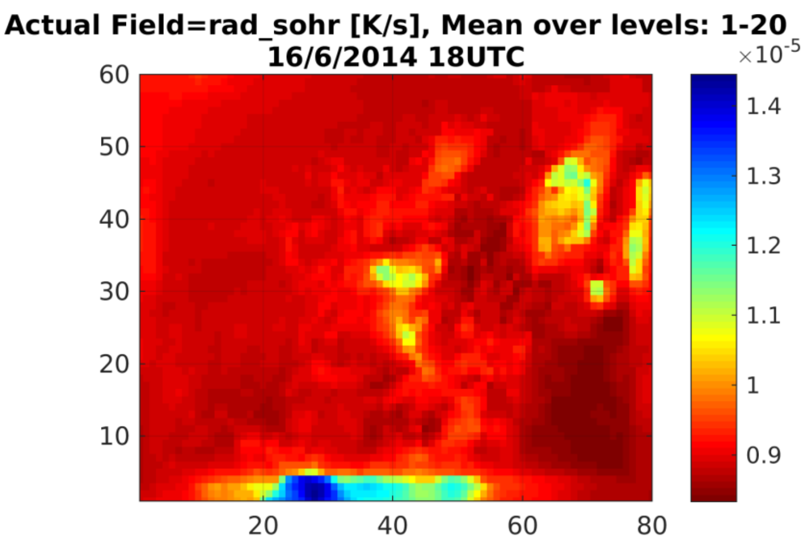
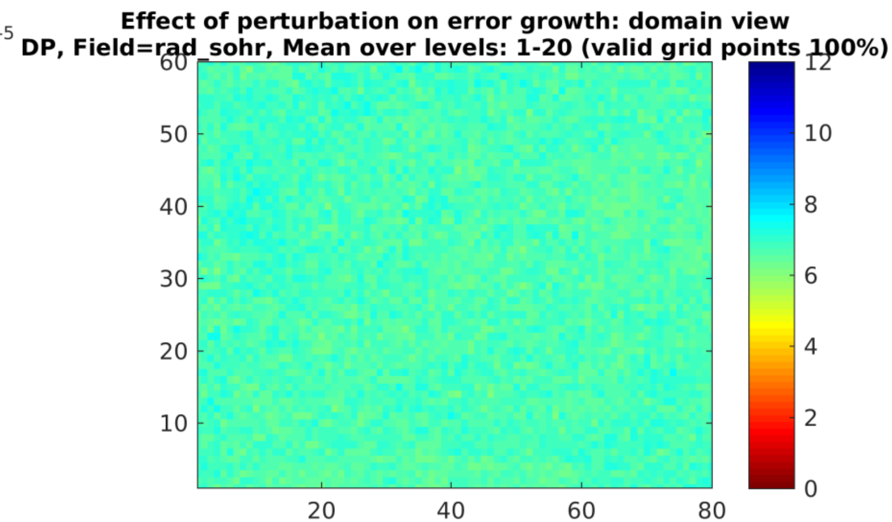








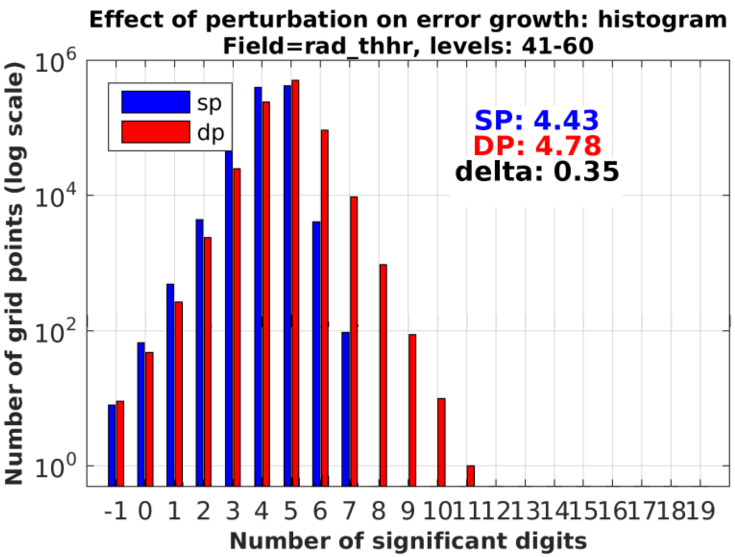


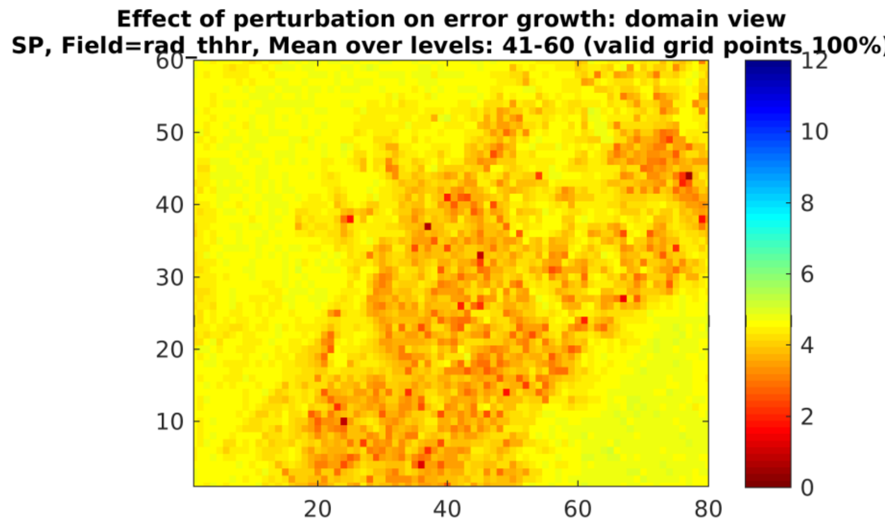
Thermal heating rate

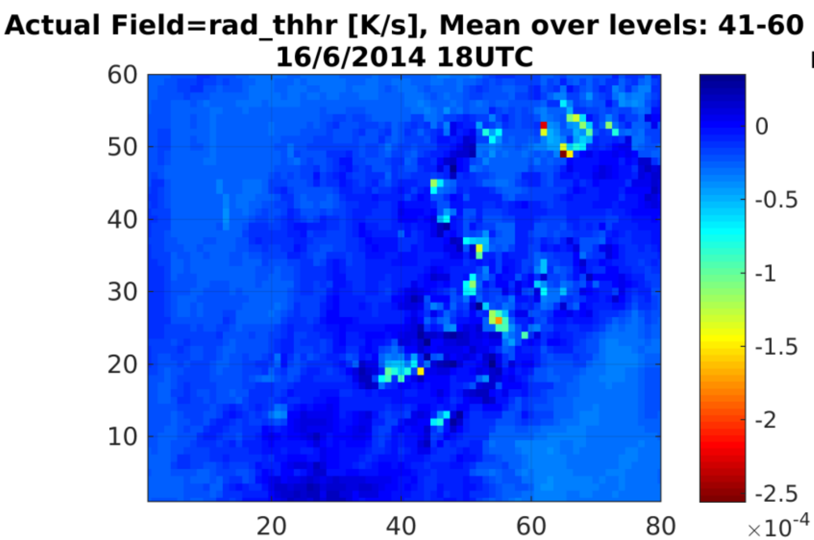
SP vs. DP

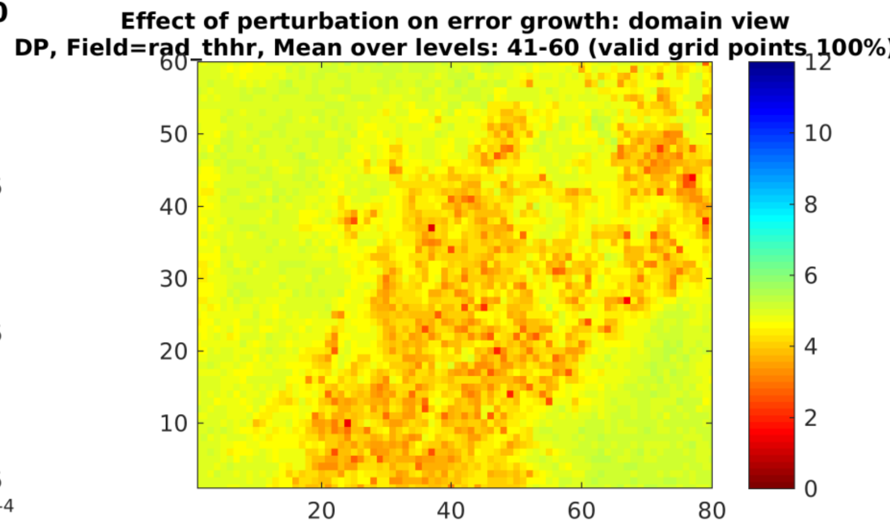
Radiation

SP



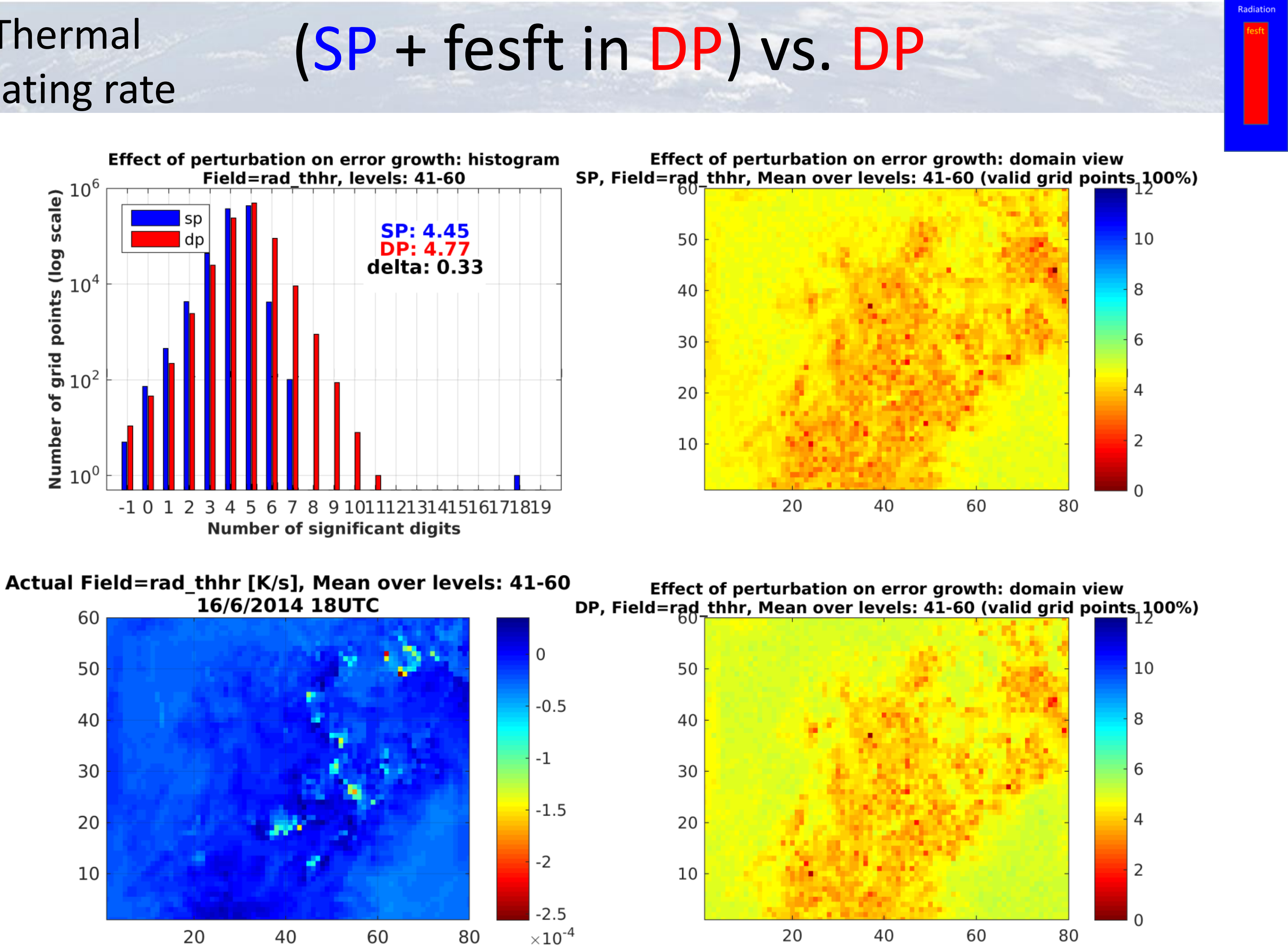




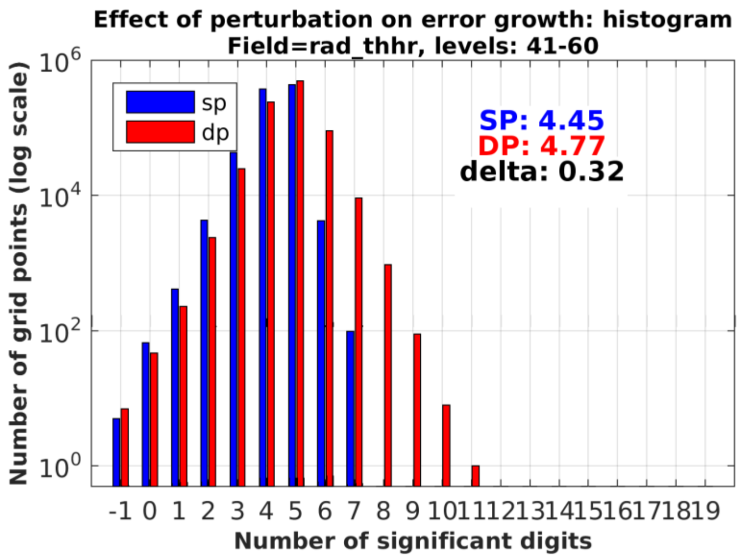


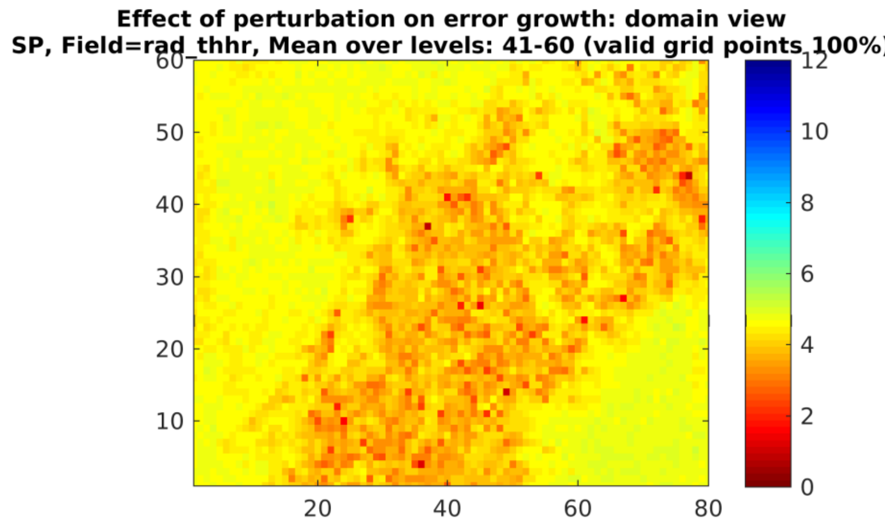
Thermal heating rate

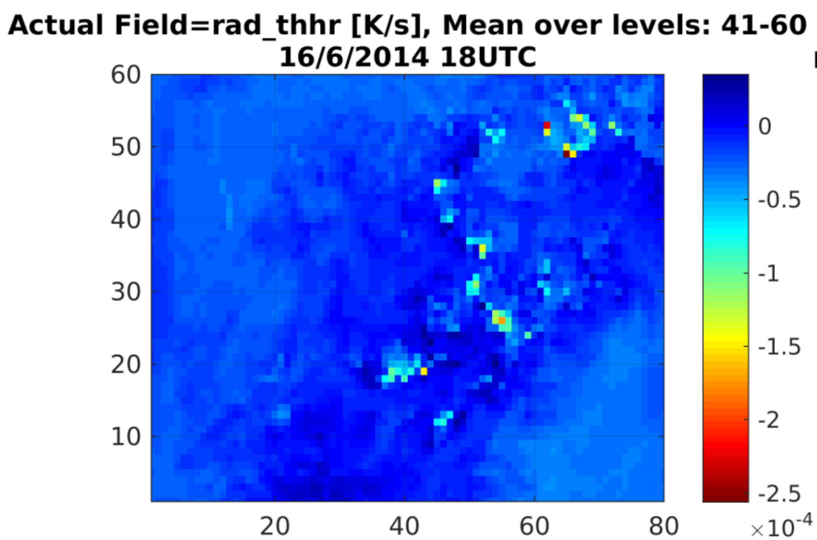
(SP + fesft in DP) vs. DP

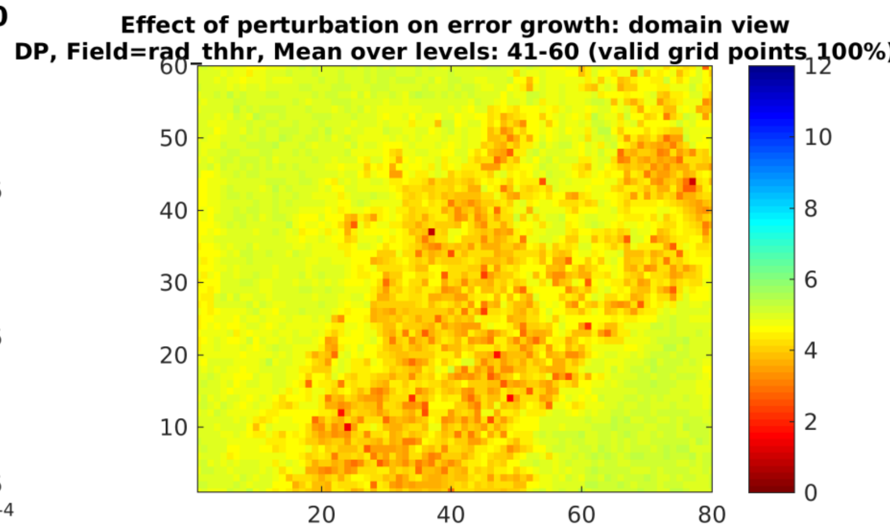


Thermal heating rate (SP + fesft,zfls,zflt in DP) vs. DP



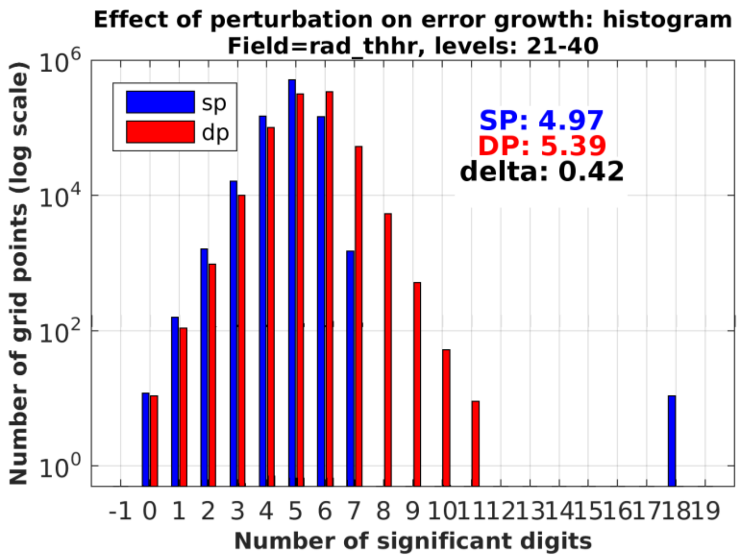


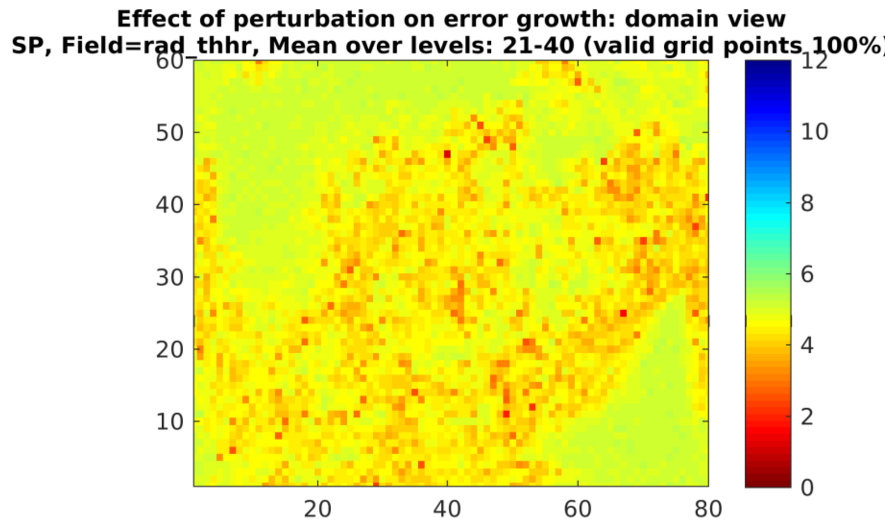


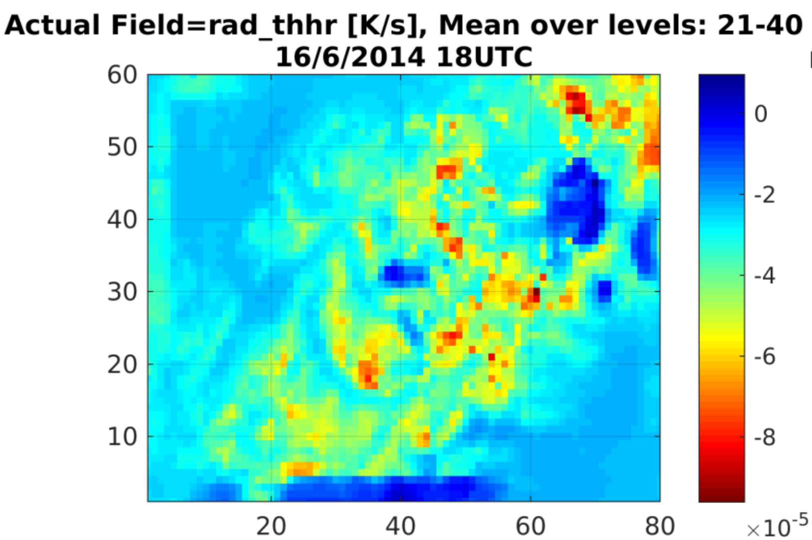


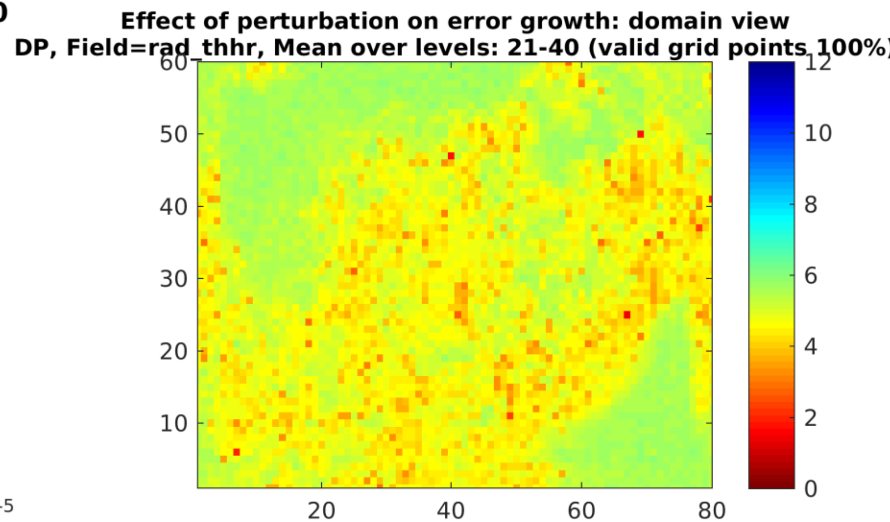
Thermal heating rate

SP vs. DP



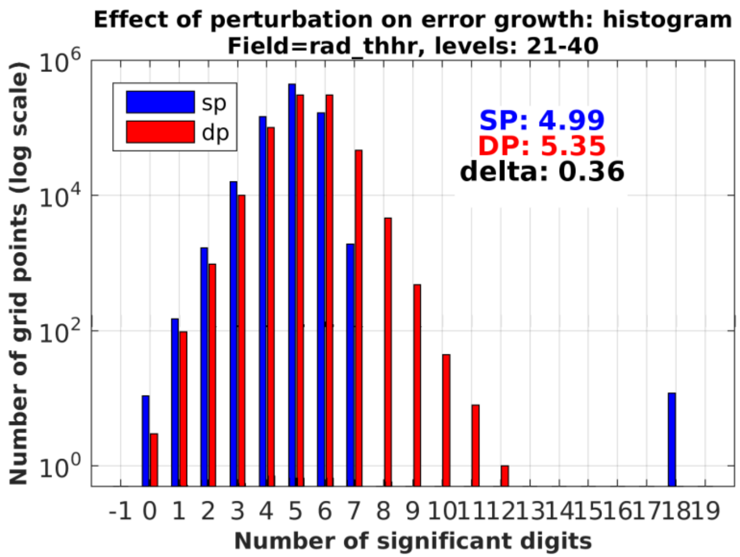


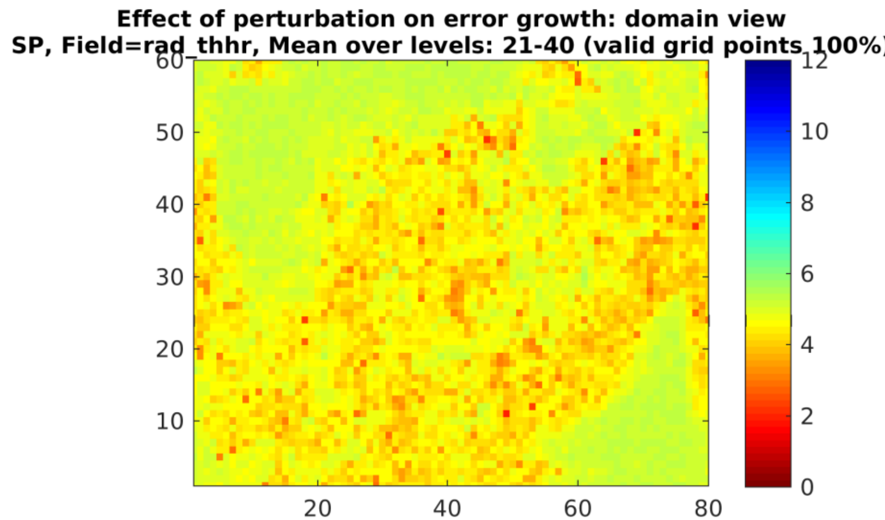


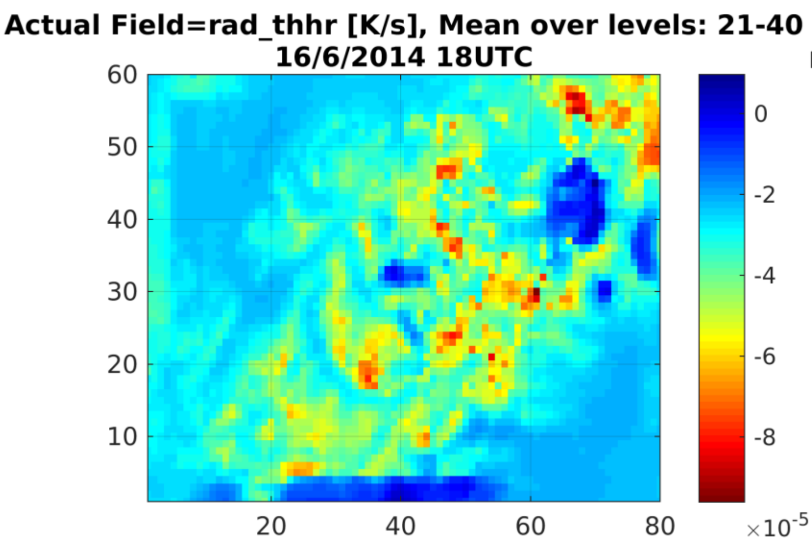


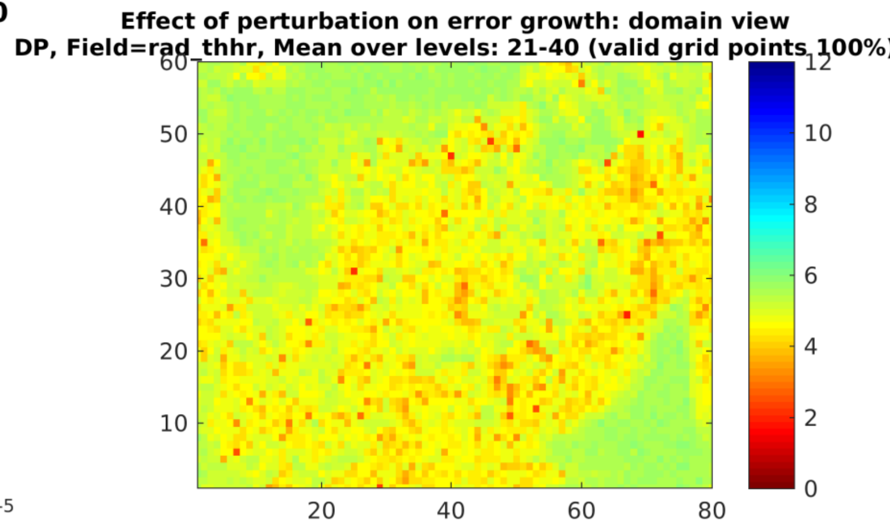
Thermal heating rate

(SP + fesft in DP) vs. DP

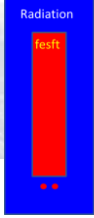


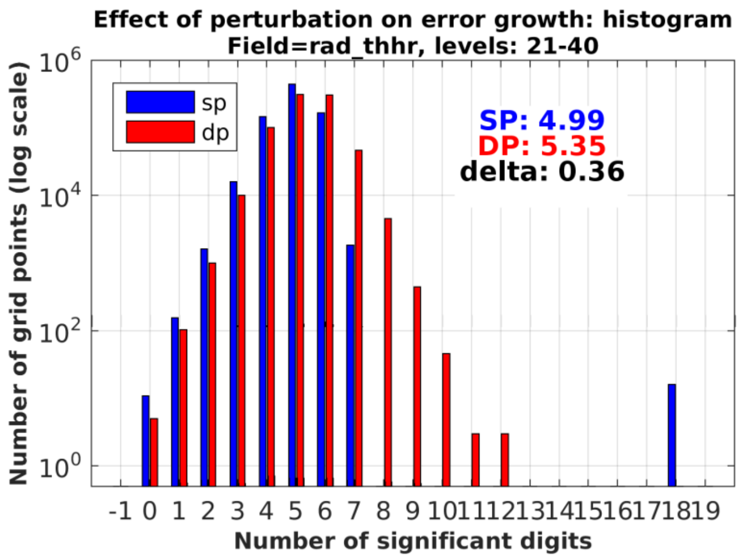


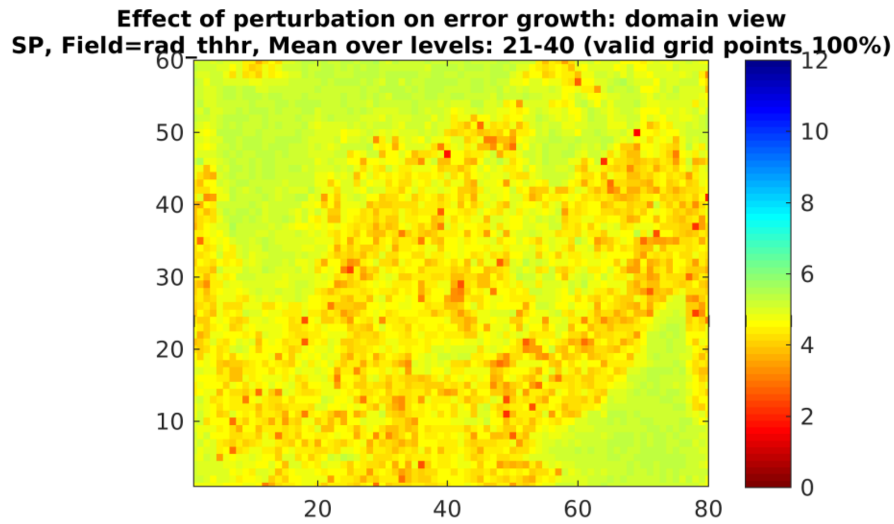


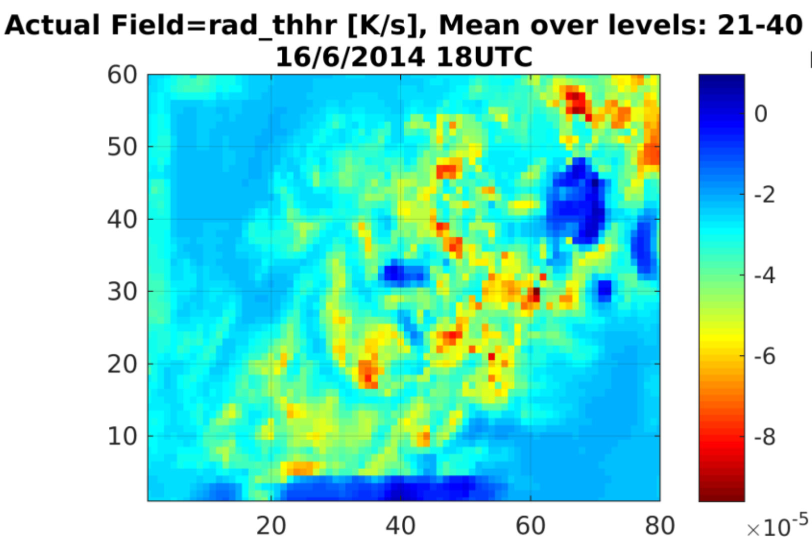


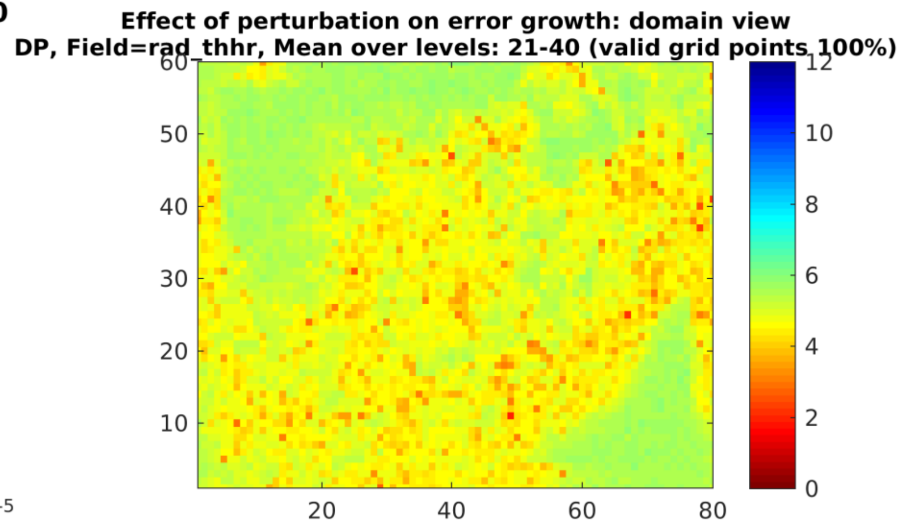
Thermal heating rate (SP + fesft,zfls,zflt in DP) vs. DP









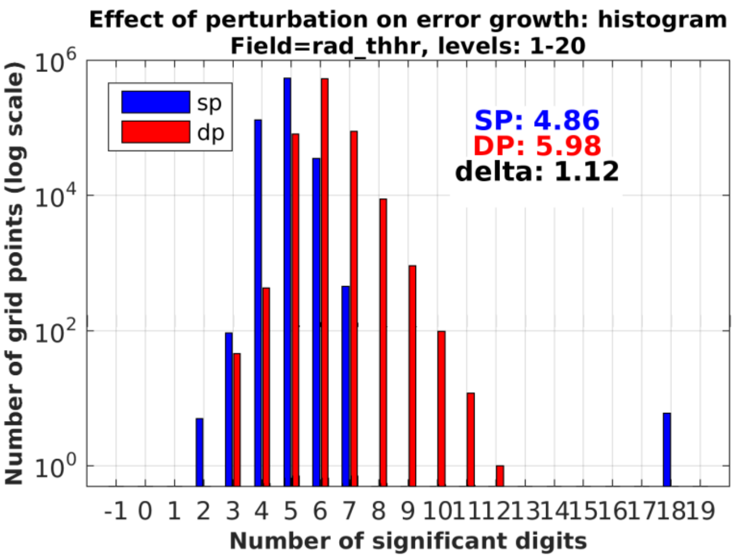


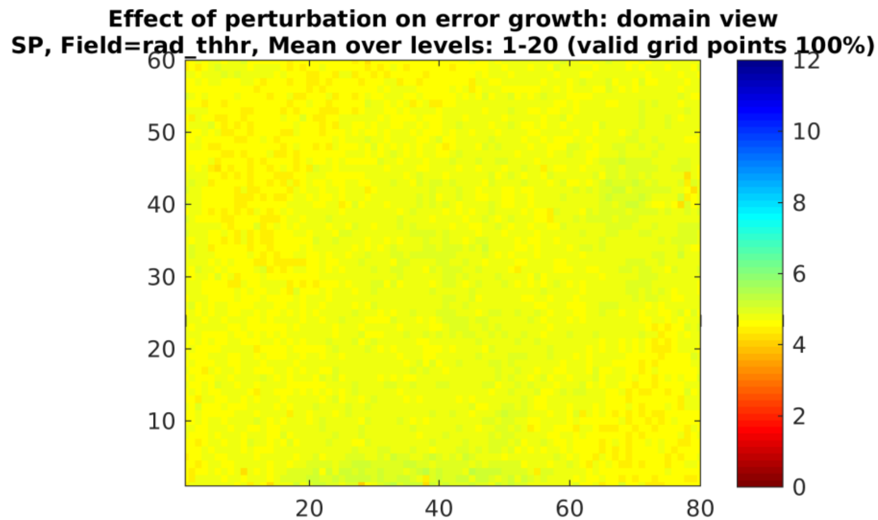
Thermal heating rate

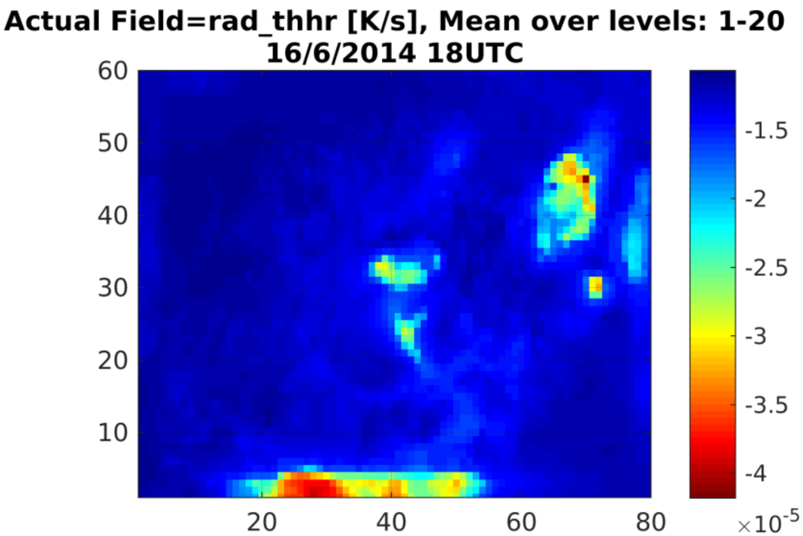
SP vs. DP

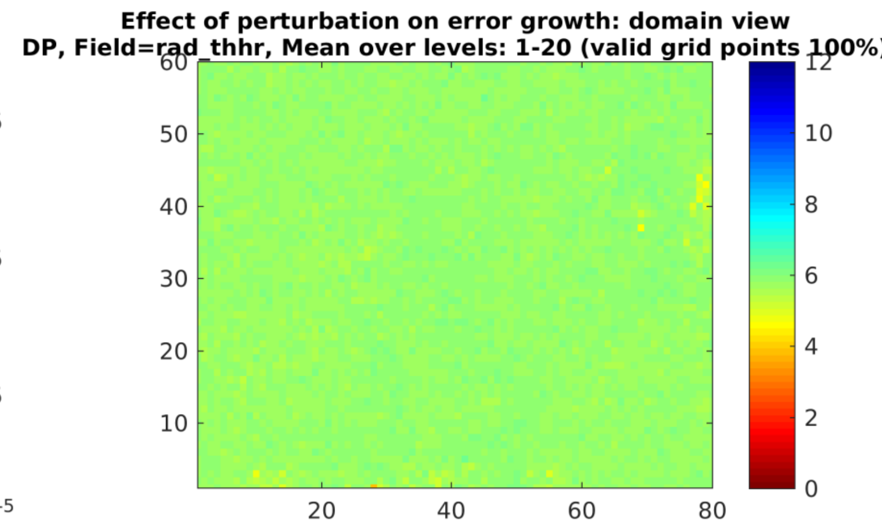
Radiation

SP





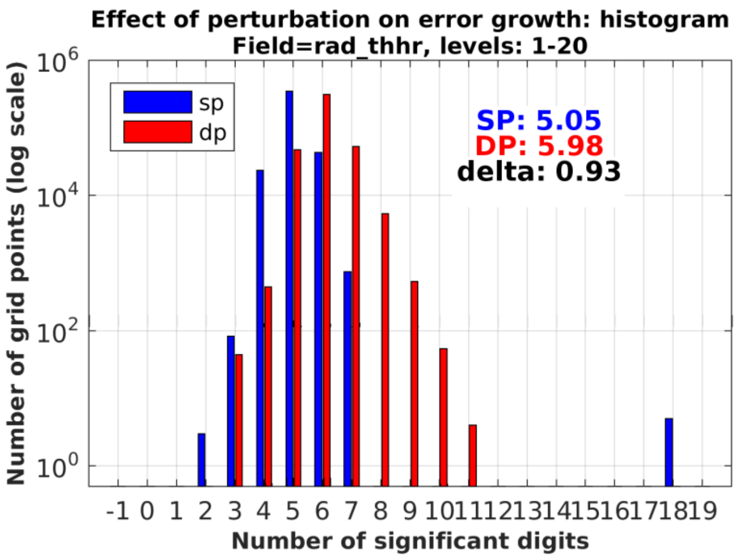


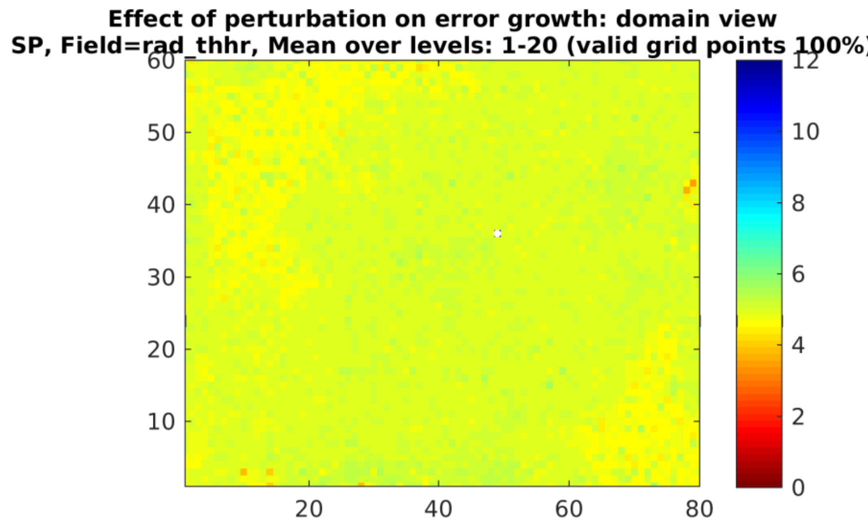


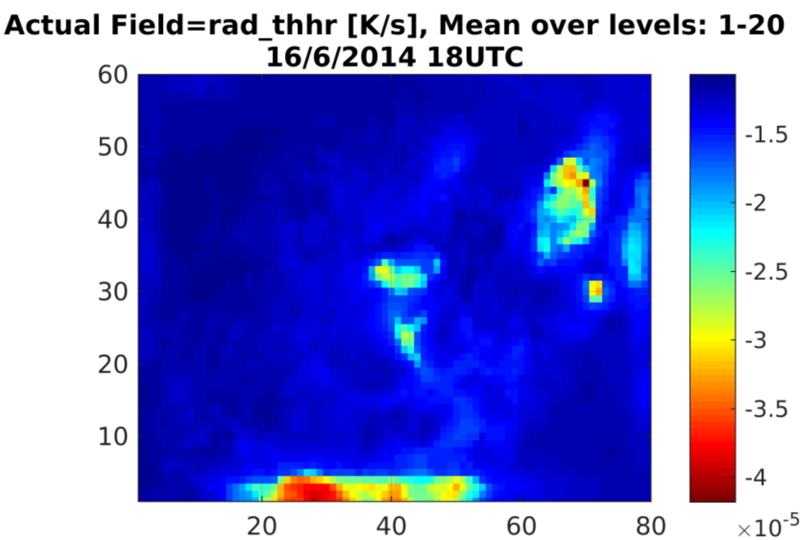
Thermal heating rate

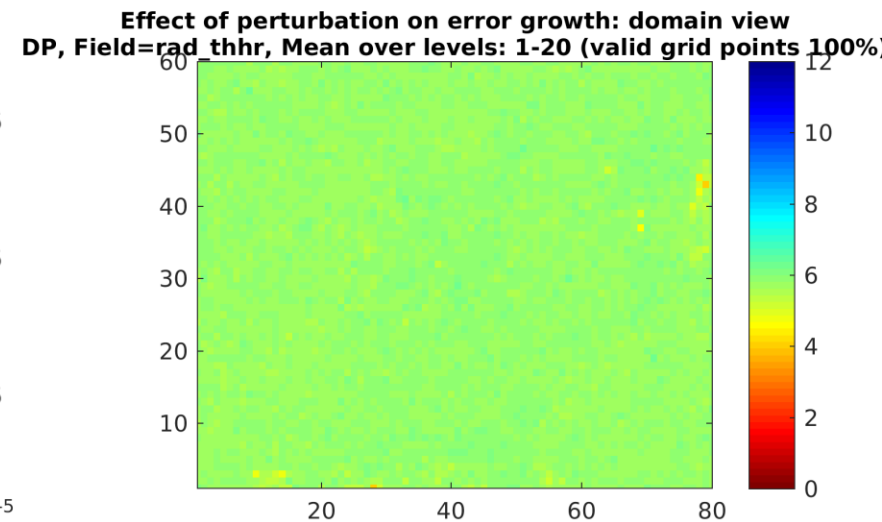
(SP + fesft in DP) vs. DP

Radiation
fesft

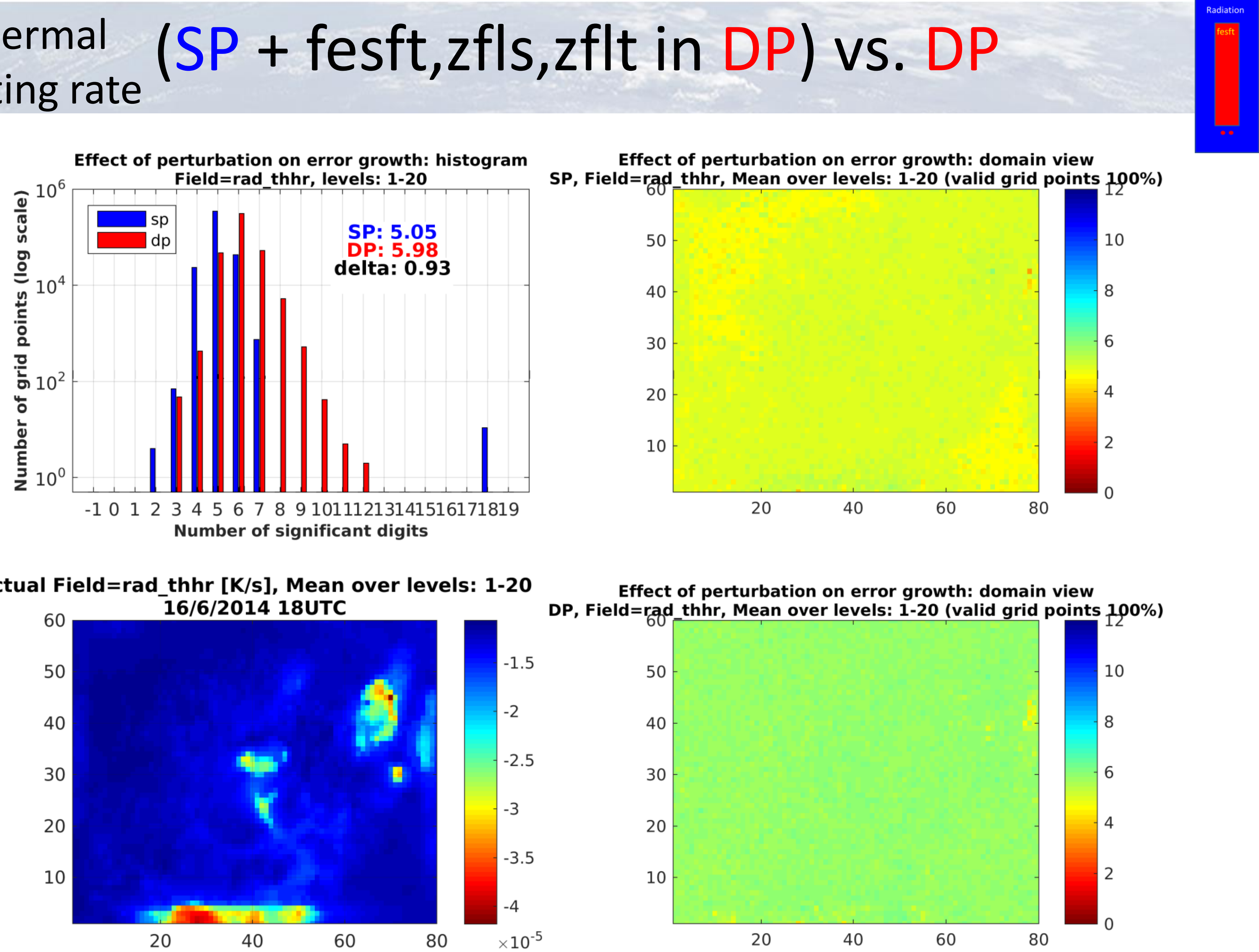








Thermal heating rate (SP + fesft,zfls,zflt in DP) vs. DP



Outline

1. **Overview**

2. **Method to evaluate the error growth**

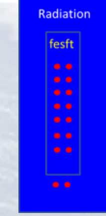
3. **Analysis of 5 radiation scheme versions:**

- 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)

```
...
CALL radiation_rg_organize
...
```

SUBR. radiation_rg_organize
(in radiation_rg_org.f90

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

in mixed precision

$\underbrace{\textbf{zfls , zflt}}_{\text{in DP}}$ **,** $\underbrace{\textbf{other output}}_{\text{in SP}}$

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

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

We skip the detailed results here …

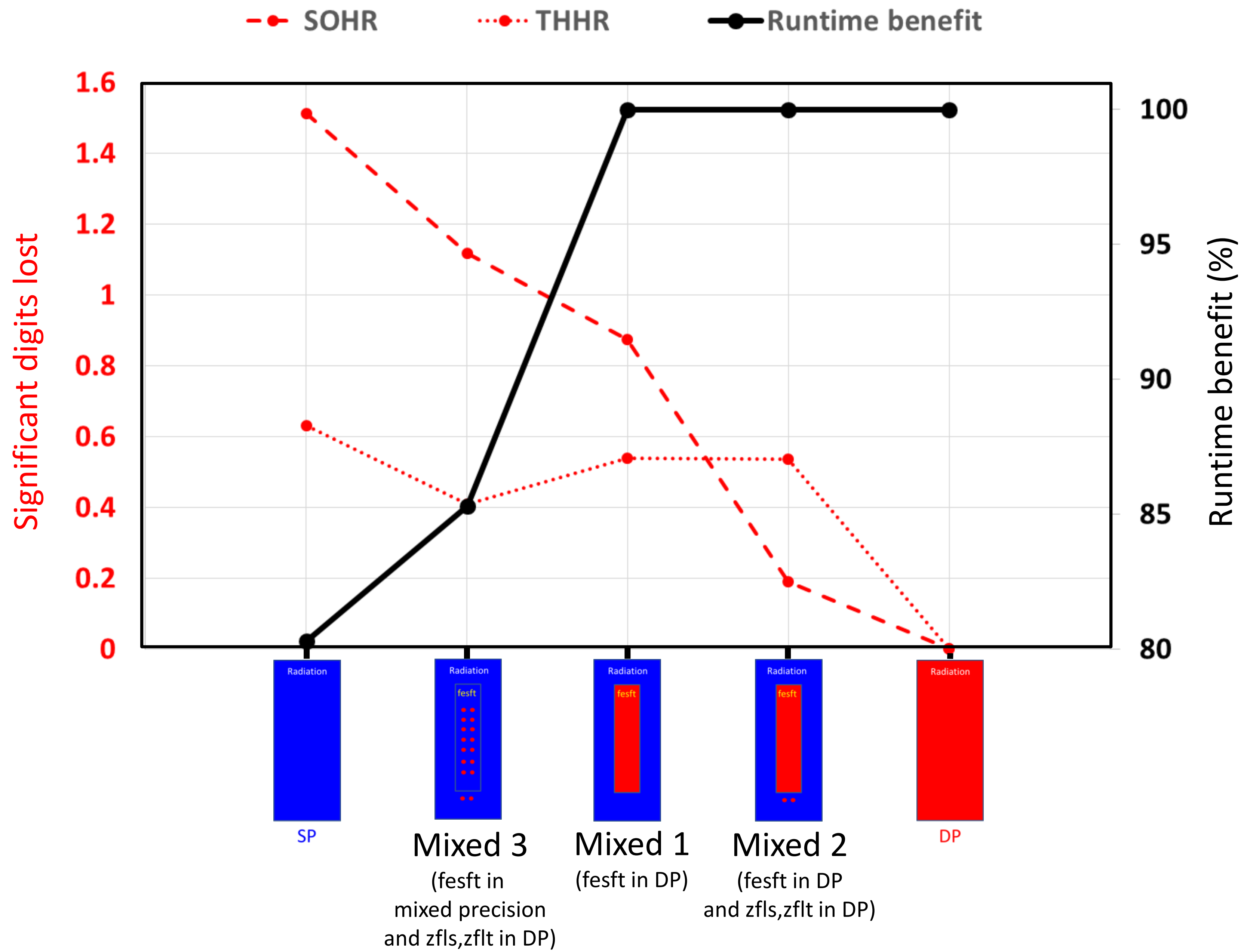
Outline

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**

Summary



SOHR
THHR
Runtime benefit
Significant digits lost
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Runtime benefit (%)
100
95
90
85
80
Radiation
fesft
SP
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)
DP

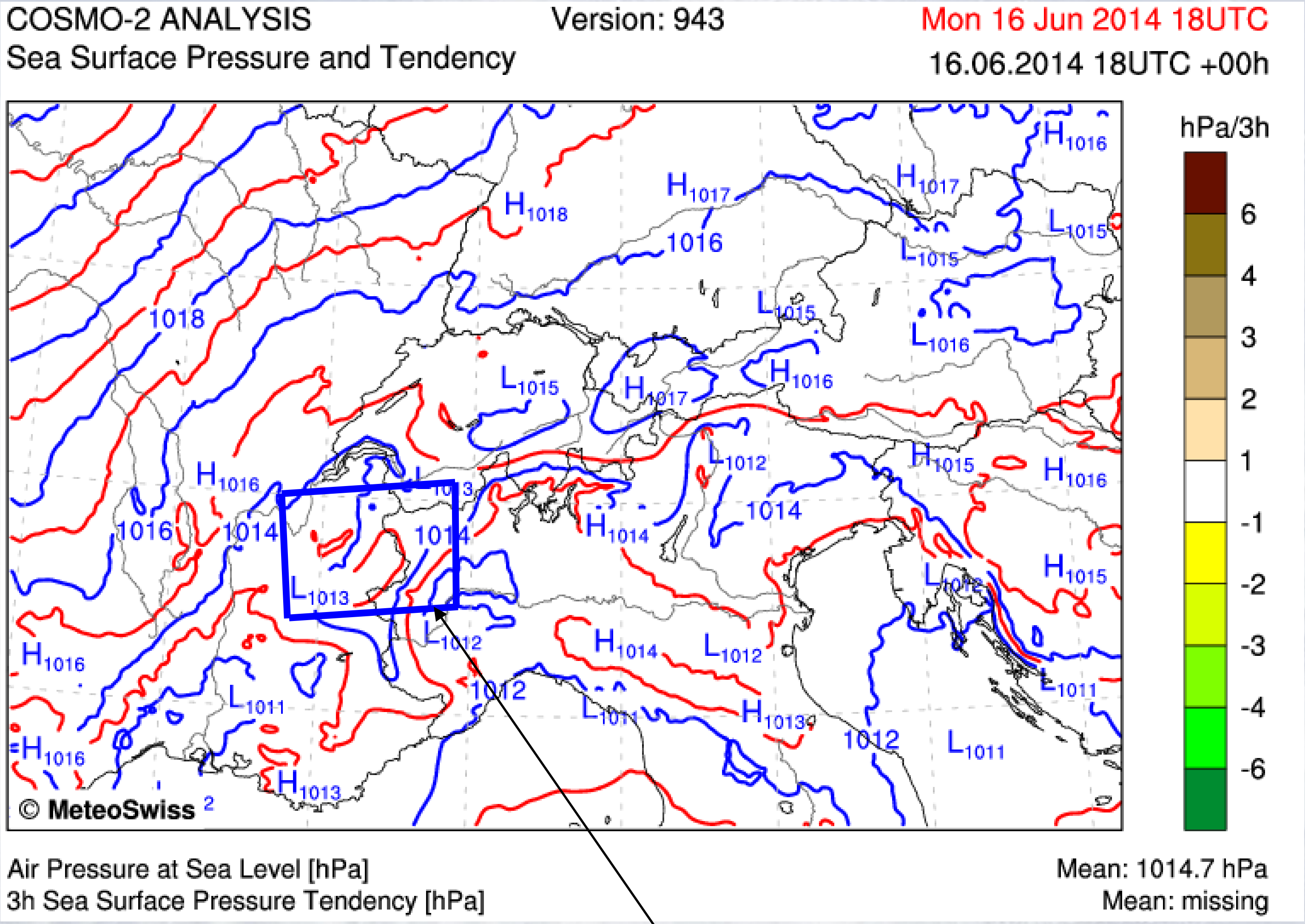
Summary

- 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**

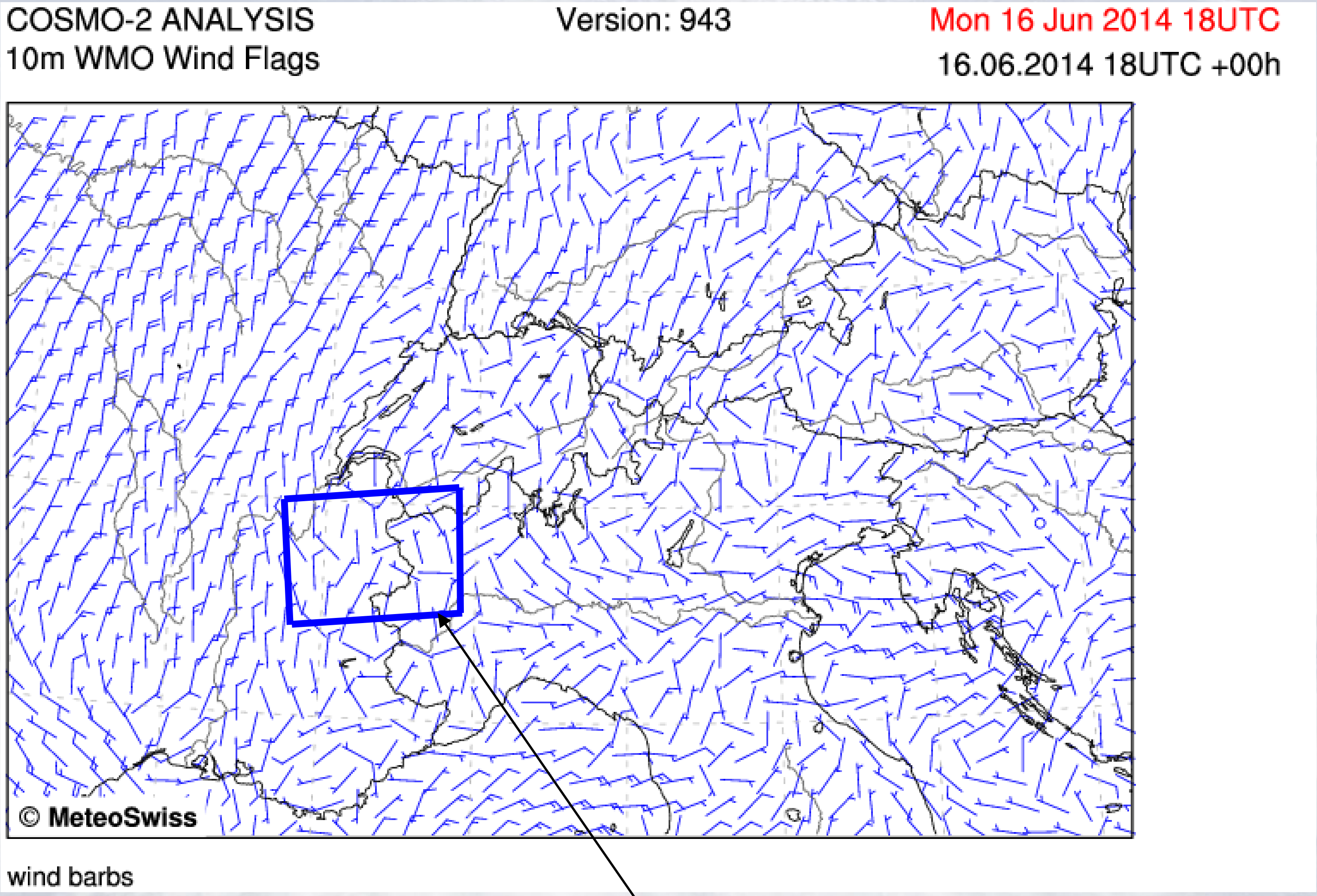
Thank you!

Additional slides:

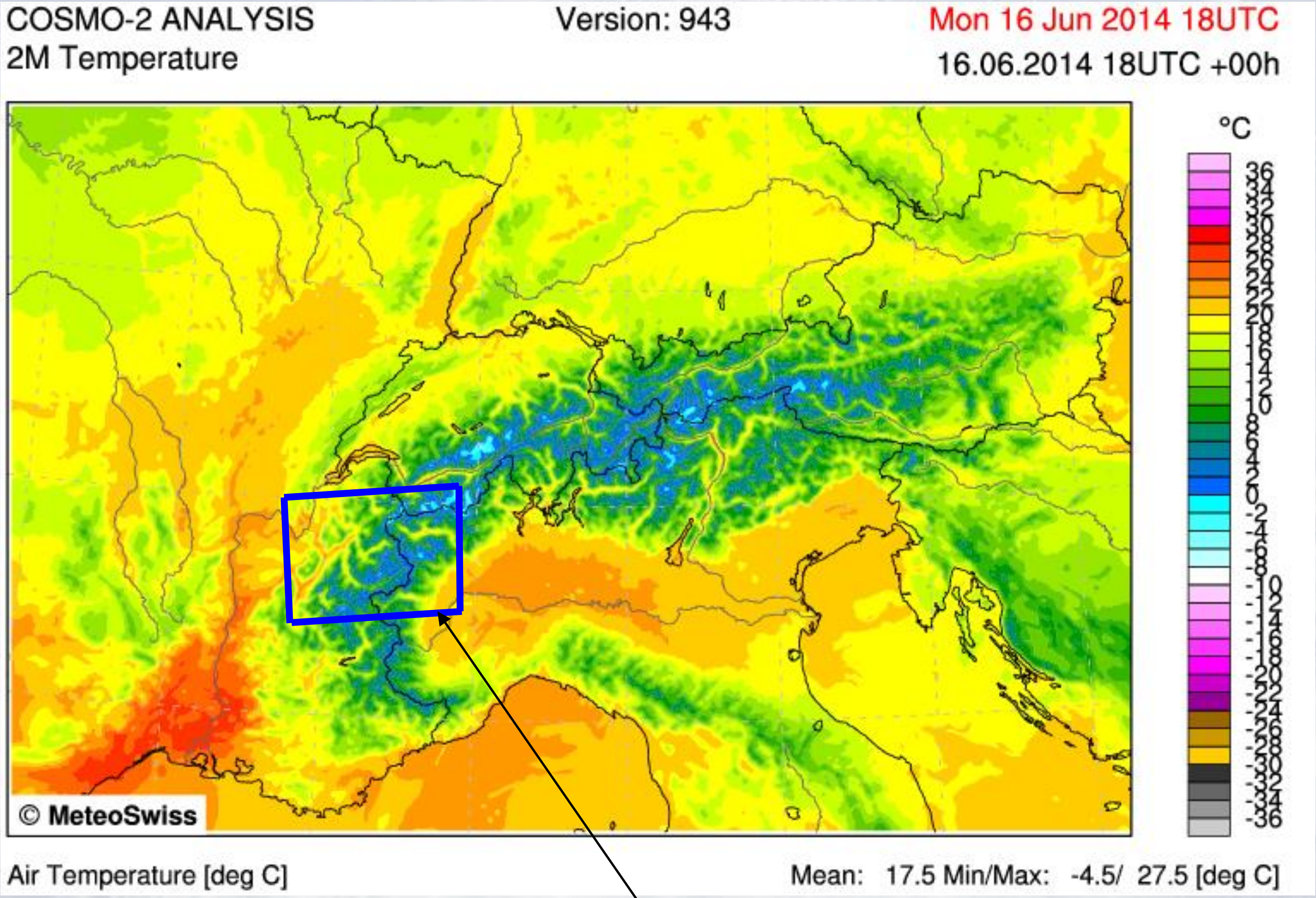
Synoptic situation



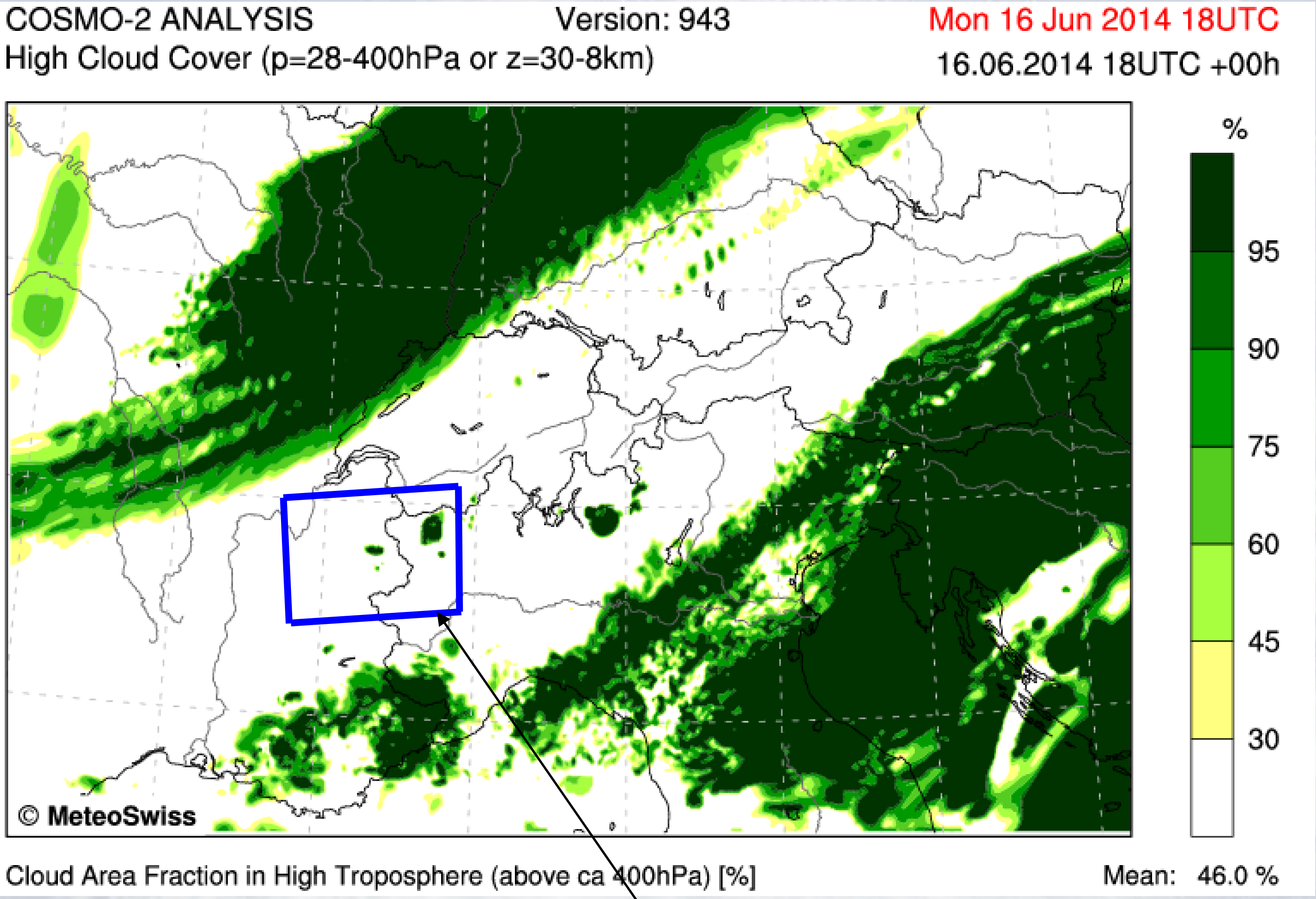
Experiment domain



Experiment domain

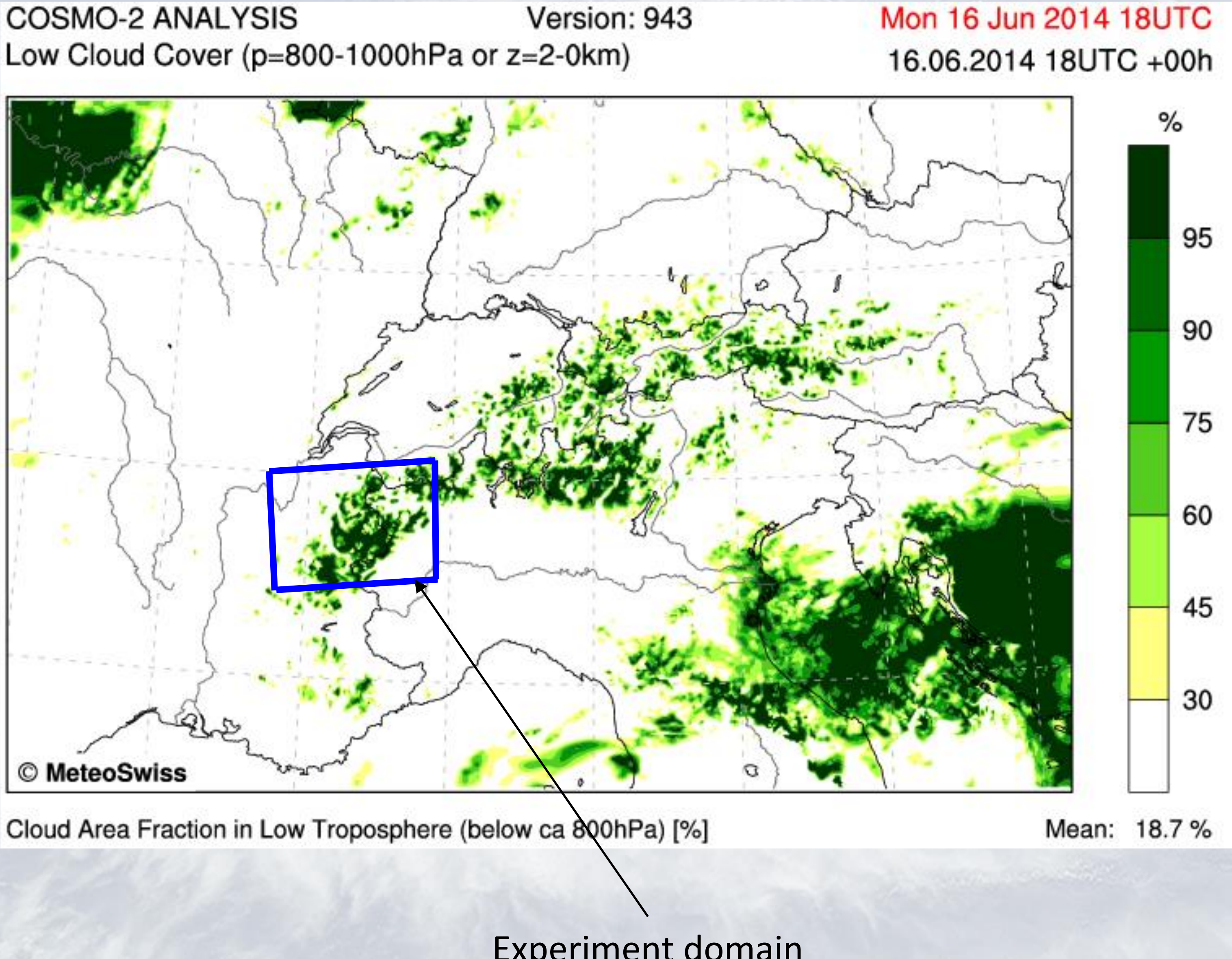


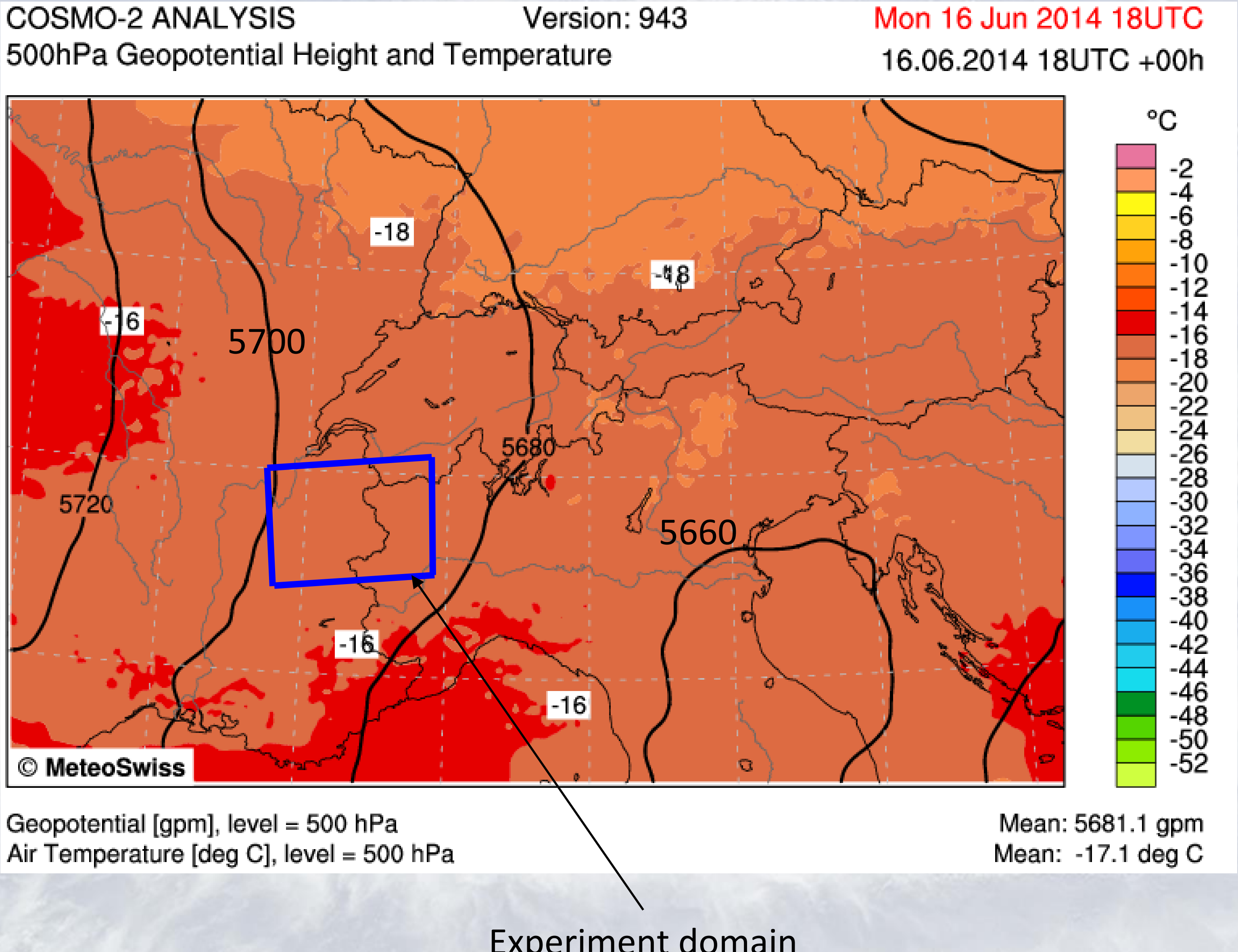
Experiment domain

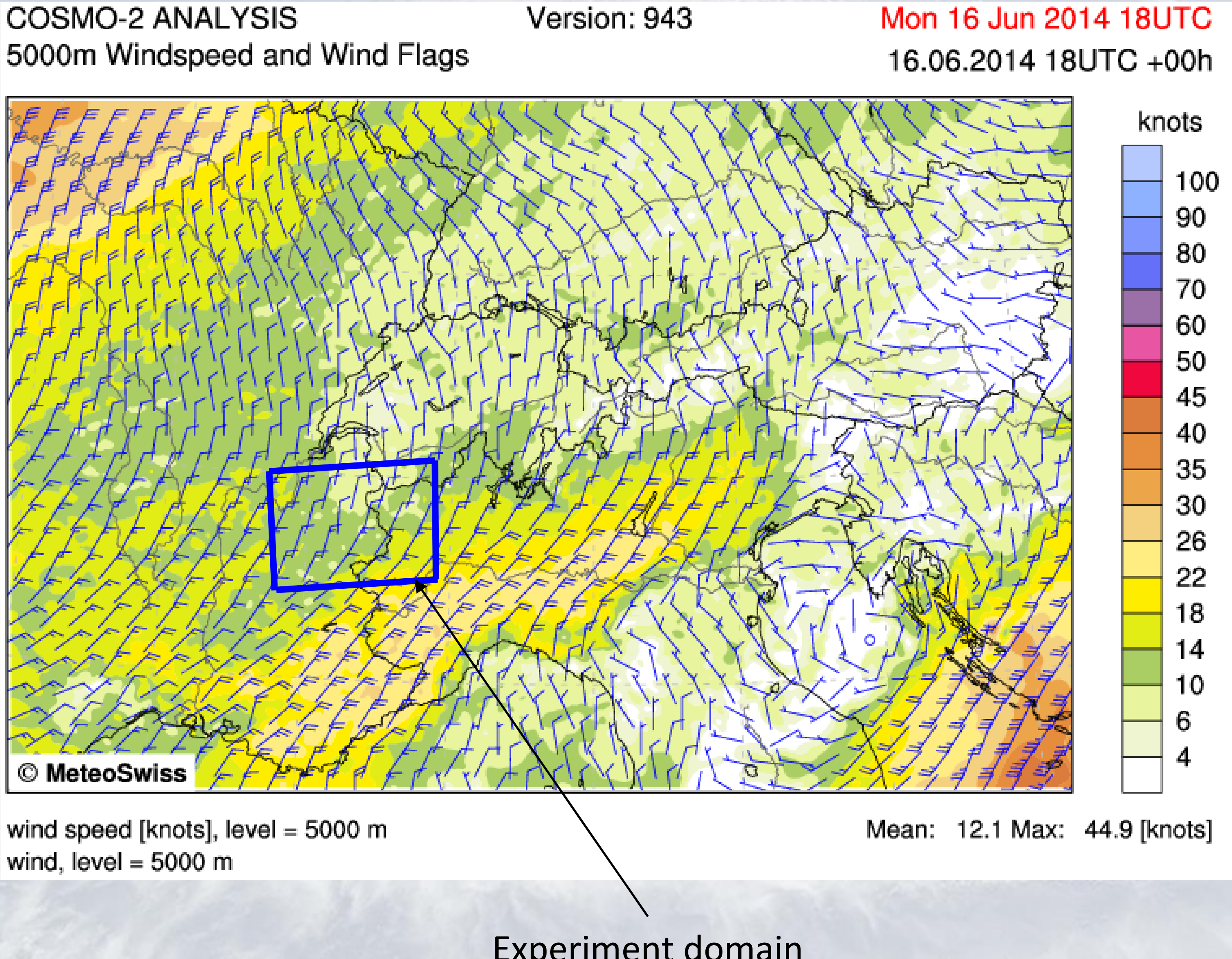


Experiment domain

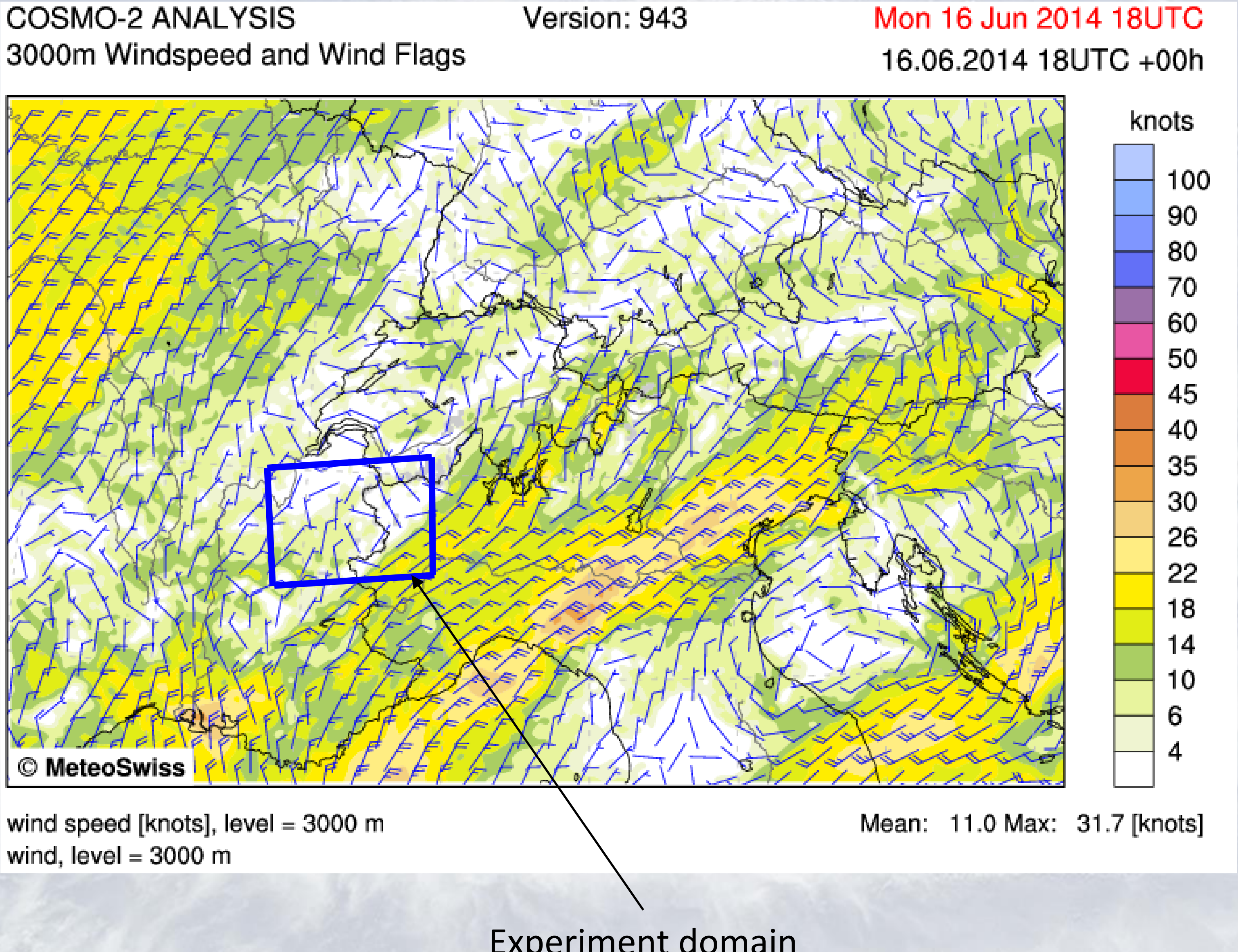

COSMO-2 ANALYSIS
Version: 943
Mon 16 Jun 2014 18UTC
Medium Cloud Cover (p=400-800hPa or z=8-2km)
16.06.2014 18UTC +00h
%
95
90
75
60
45
30
© MeteoSwiss
Cloud Area Fraction in Medium Troposphere (between ca 400hPa and 800hPa) [%]
Mean: 58.9 %
Experiment domain


COSMO-2 ANALYSIS
Version: 943
Mon 16 Jun 2014 18UTC
Low Cloud Cover (p=800-1000hPa or z=2-0km)
16.06.2014 18UTC +00h
%
95
90
75
60
45
30
© MeteoSwiss
Cloud Area Fraction in Low Troposphere (below ca 800hPa) [%]
Mean: 18.7 %
Experiment domain


COSMO-2 ANALYSIS
Version: 943
Mon 16 Jun 2014 18UTC
500hPa Geopotential Height and Temperature
16.06.2014 18UTC +00h
°C
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
-42
-44
-46
-48
-50
-52
-18
-16
5700
5720
5680
5660
-16
-16
© MeteoSwiss
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
5000m Windspeed and Wind Flags
Version: 943
Mon 16 Jun 2014 18UTC
16.06.2014 18UTC +00h
knots
100
90
80
70
60
50
45
40
35
30
26
22
18
14
10
6
4
© MeteoSwiss
wind speed [knots], level = 5000 m
wind, level = 5000 m
Mean: 12.1 Max: 44.9 [knots]
Experiment domain


COSMO-2 ANALYSIS
3000m Windspeed and Wind Flags
Version: 943
Mon 16 Jun 2014 18UTC
16.06.2014 18UTC +00h
knots
100
90
80
70
60
50
45
40
35
30
26
22
18
14
10
6
4
© MeteoSwiss
wind speed [knots], level = 3000 m
wind, level = 3000 m
Mean: 11.0 Max: 31.7 [knots]
Experiment domain

Additional slides:

SP (fesft in DP)

$HR_{pe}=1.1234\cancel{12}*10^{-5}$

$HR_{np}=1.1234\cancel{01}*10^{-5}$

$Delta=0.000*10^{-5}$

SIG=?

fesft in DP+zfls,zflt in DP

$HR_{pe}=1.12341278 9\cancel{12}*10^{-5}$

$HR_{np}=1.12340167 8\cancel{01}*10^{-5}$

$Delta=0.000011111*10^{-5}$

SIG=5

All in SP (also fesft)

$HR_{pe}=1.1\textcolor{red}{23}4\cancel{12}*10^{-5}$

$HR_{np}=1.1\textcolor{red}{12}4\cancel{01}*10^{-5}$

$Delta=0.011*10^{-5}$

SIG=2

COSMO spectral bands

TABLE 1. Spectral intervals and major optical constituents considered in the radiation scheme.

	Solar			Thermal				
Interval number	1	2	3	4	5	6	7	8
Limits (μm)	1.53–4.64	0.70–1.53	0.25–0.70	20.0–104.5	12.5–20.0	8.33–9.01 10.31–12.5	9.01–10.31	4.64–8.33
Gaseous absorption, No. of k_i for H_2O, CO_2 and O_3	H_2O, CO_2 CH_4, N_2O (7, 6, 0)	H_2O, CO_2, O_2 (7, 3, 0)	O_3, H_2O O_2 (3, 2, 5)	H_2O (7, 0, 0)	H_2O, CO_2, N_2O (7, 7, 0)	H_2O, CO_2, N_2O (4, 3, 0)	H_2O, O_3, CO_2, N_2O (3, 3, 5)	H_2O, CH_4, N_2O, CO_2 (7, 4, 0)
Droplet								
scattering	yes	yes	yes	yes	yes	yes	yes	yes
absorption	yes	yes	yes	yes	yes	yes	yes	yes
Rayleigh scattering	yes	yes	yes	no	no	no	no	no
Aeorsol								
scattering	yes	yes	yes	yes	yes	yes	yes	yes
absorption	yes	yes	yes	yes	yes	yes	yes	yes

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 radiation_organize
(from radiation_interface.f90)

```
CALL radiation_rg_organize
```

SUBROUTINE radiation_rg_organize : The module procedure forms the interface between the model and the radiation code adapted from the global model gm_e. Method: All variables that are required for the radiation code are provided or calculated from the model variables. The results are stored as solar and thermal heating rates on the corresponding global arrays sohr and thhr.

SUBROUTINE radiation_rg_organize
(from radiation_org_org.f90)

```
...
CALL fesft
...
```

fesft organizes the radiative transfer calculations by calling routines for the calculation of basic optical properties (opt_th/opt_so), the derivation of layer coefficients (coe_th/coe_so) for an implicit delta-two-stream scheme and the inversion (inv_th/inv_so) of the corresponding system matrix. These operations are performed separately for thermal and solar parts of the spectrum and are embedded in loops over the various spectral intervals. Within each interval, a data-controlled decision is taken, whether the so-called ESFT or FESFT approach is used for the handling of gaseous absorption. Before the actual flux calculation starts, some preliminary steps provide utility arrays which are applicable to all spectral intervals (e.g. cloud geometry factors, integrated layer water content, etc.)

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,o3) 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
```

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
```

Example

back

example for **12.345** :

Precision	Rounded to significant figures
6	12.3450
5	12.345
4	12.35
3	12.3
2	12
1	10
0	N/A

Another example for **0.012345**:

Precision	Rounded to significant figures
7	0.01234500
6	0.0123450
5	0.012345
4	0.01235
3	0.0123
2	0.012
1	0.01
0	N/A

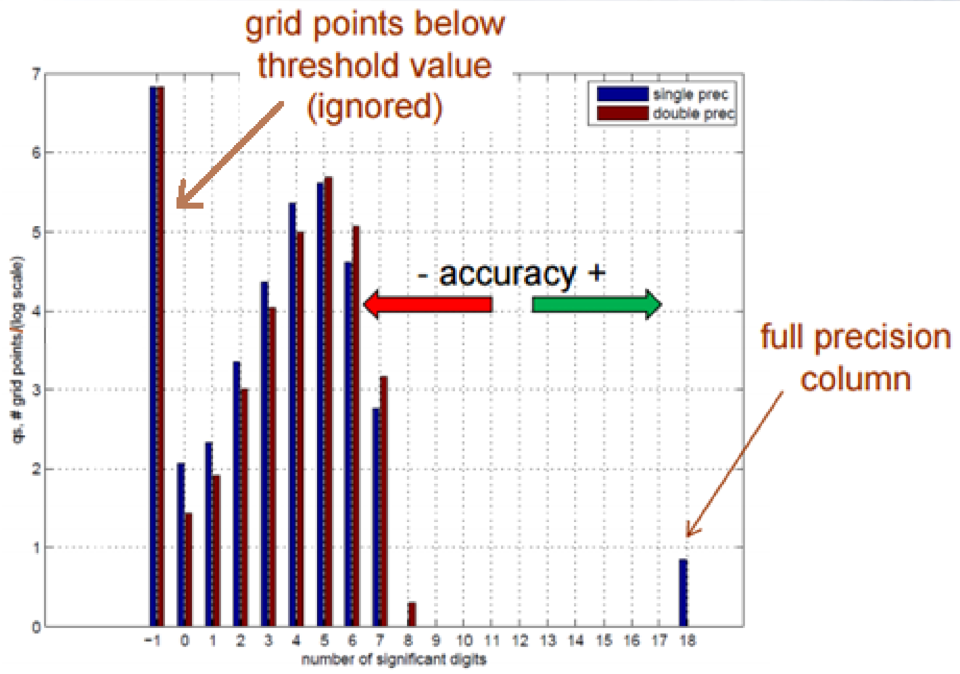
Method

- 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=abs((A-B)/max(abs(A),abs(B))
  Er_SP=abs((C-D)/max(abs(C),abs(D))
- Number of significant digits is defined as:
  Nsig_DP=-$\log_{10}$(Er_DP)
  Nsig_SP=-$\log_{10}$(Er_SP)
- Lower number of significant digits means higher error growth.
- If for most of the radiation-related fields, Nsig_SP distribution (over all the grid points) is shifted towards lower values, compared to Nsig_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_sodwddm [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 than 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.



Explanation figure (J. Despraz)