Symmetric 4th Order Horizontal Schemes In COSMO_5.0:

Computational Performance and Spectral Properties at Resolutions 50 km to 1 km

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Outline

1. Introduction
2. Advection schemes and implementation
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    2. Accuracy and stability for different RK schemes
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4. Atmosphere at rest: convergence and stability
5. Climate simulation: stability and precipitation
6. Effective resolution: theoretical and real case results
7. Implementation
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    2. New routines
    3. Implementation status and plans

1. The advection schemes

$$AdvW4 \quad := u(b_1\overline{\delta_\lambda q}^{\lambda} + b_2\overline{\delta_\lambda q}^{3\lambda}) + (b_1\overline{q}^{\lambda} + b_2\overline{q}^{3\lambda})\delta_\lambda u$$

$$AdvC4 \quad (\mathbf{v_h}\cdot\nabla_h u)^{On} := u\delta_\lambda^{On}u + \overline{\overline{v}^{O2,\phi}}^{O2,\lambda}\delta_\phi^{On}u$$

$$AdvN4 \quad (\mathbf{v_h}\cdot\nabla_h u)^{On} := u\delta_\lambda^{On}u + \overline{\overline{v}^{On,\phi}}^{On,\lambda}\delta_\phi^{On}u$$

$$AdvS4: \begin{cases} (\mathbf{v_h}\cdot\nabla_h u)_{i+\frac{1}{2},j} := \frac{9}{8}\overline{\overline{u}^{O4,\lambda}\delta_\lambda u}^{\lambda} - \frac{1}{8}\overline{\overline{u}^{O4,\lambda}\delta_{3\lambda}u}^{3\lambda} \\ \qquad + \frac{9}{8}\overline{\overline{v}^{O4,\lambda}\delta_\phi u}^{\phi} - \frac{1}{8}\overline{\overline{v}^{O4,\lambda}\delta_{3\phi}u}^{3\phi} \\ (\mathbf{v_h}\cdot\nabla_h v)_{i,j+\frac{1}{2}} := \frac{9}{8}\overline{\overline{u}^{O4,\phi}\delta_\lambda v}^{\lambda} - \frac{1}{8}\overline{\overline{u}^{O4,\phi}\delta_{3\lambda}v}^{3\lambda} \\ \qquad + \frac{9}{8}\overline{\overline{v}^{O4,\phi}\delta_\phi v}^{\phi} - \frac{1}{8}\overline{\overline{v}^{O4,\phi}\delta_{3\phi}v}^{3\phi} \end{cases}$$

, :

2. Implementation and Tests

2.1 New namelist parameters

l_higher_order_ss	logical	If .TRUE., 4th order interpolation is used for all schemes but advection
ladv_symmetric	logical	If .TRUE., symmetric formulation of advection is used.

2.2 Implementation and testing procedure

1. COSMO_4.24_hos : Implementation finished
   Europe // 0165 // ERAInt // 1979-1999:
   advC3p2d0.25, advS4p4d0.25, advS4p4d0.00, advN4p4d0.25
   Time to solution: HPSY(advS4p4)= 2x HPSY(advC3p2)
2. COSMO_5.0_hos : Implementation finished

Europe	0.44	NCEP, ERAInt	2000-2004
Europe	0.165, 0.11, 0.0625	0.44	2000-2001
COSMO-DE	0.044, 0.025	0.0625	2000-2001

   advC3p2d0.25, advS4p4d0.00, l_filter_oro=.TRUE./.FALSE.
   Time to solution: HPSY(advS4p4)= HPSY(advC3p2)

2. COSMO_5.3: Implementation ongoing
   Test simulations in weather and climate mode planned in 4-8 2017.

3. Optimization: COSMO_5.0_hos

Ad-hoc implementation in COSMO_4.24 (Ogaja & Will 2016)
100% longer time to solution with S4p4v2d0.00

- ➢ Code profiling and trace analysis

Additional time to solution increased due to additional boundary exchange

$$S4^* := \frac{9}{8}\overline{\overline{u}^{O4,\lambda}\delta_\lambda u}^{\lambda} - \frac{1}{8}\overline{\overline{u}^{O4,\lambda}\delta_{3\lambda} u}^{3\lambda} + \frac{9}{8}\overline{\overline{\hat{v}}^{O4,\phi}\delta_\phi u}^{\lambda} - \frac{1}{8}\overline{\overline{\hat{v}}^{O4,\phi}\delta_{3\phi} u}^{3\lambda}$$

- 4th order explicite interpolation and differencing require 2 neigbour points
- Symmetric advection discretisation requires an additional interpolation after advection computation. This interpolation requires the advection at neighbouring points
- A standard discretisation approach leads to an introduction of an **additional boundary exchange**.

3. Optimization: COSMO_5.0_hos

$$S4^* := \frac{9}{8}\overline{\overline{u}^{O4,\lambda}\delta_{\lambda}u}^{\lambda} - \frac{1}{8}\overline{\overline{u}^{O4,\lambda}\delta_{3\lambda}u}^{3\lambda} + \frac{9}{8}\overline{\hat{\overline{v}}^{O4,\phi}\delta_{\phi}u}^{\lambda} - \frac{1}{8}\overline{\hat{\overline{v}}^{O4,\phi}\delta_{3\phi}u}^{3\lambda}$$

- On staggered grid the target point is located between the source points. Thus, each discretisation requires the source variable at i-2, i-1, i and i+1 position.
- This assymetry opens the opportunity of optimisation of the discretisation.
- Theoretically, the computation of maximum number of points in first interpolation and differencing allows to compute the second interpolation without an additional boundary exchange

DO k=kstart_n, kend_n

```
DO k=kstart_n, kend_n

  ! a): calculate udu/dx, udv/dx, udp/dx, udt/dx at 'natural' grid-points
  !------------------------------------------------------------------------
  DO j=jstart_n, jend_n
    DO i=istart_n-2, iend_n+1
      cd_4order_1(i,j) =  dlam_dt(i,j,k) * eddlon * ( q(i+1,j,k) - q(i,j,k) )
      cd_4order_3(i,j) =  dlam_dt(i,j,k) * frac_1_3 * eddlon * ( q(i+2,j,k) - q(i-1,j,k) )
    END DO
  END DO

  ! b): interpolate udu/dx, udv/dx, udp/dx, udt/dx to 'prognostic' grid-points
```

3. Optimization: COSMO_5.0_hos

$$S4^* := \frac{9}{8}\overline{\overline{u}^{O4,\lambda}\delta_\lambda u}^{\lambda} - \frac{1}{8}\overline{\overline{u}^{O4,\lambda}\delta_{3\lambda} u}^{3\lambda} + \frac{9}{8}\overline{\hat{\overline{v}}^{O4,\phi}\delta_\phi u}^{\lambda} - \frac{1}{8}\overline{\hat{\overline{v}}^{O4,\phi}\delta_{3\phi} u}^{3\lambda}$$

- This is illustrated by the following example:

```
DO k=kstart_n, kend_n

  ! a): calculate udu/dx, udv/dx, udp/dx, udt/dx at 'natural' grid-points
  !-------------------------------------------------------------------------
  DO j=jstart_n, jend_n
    DO i=istart_n-2, iend_n+1
      cd_4order_1(i,j) =  dlam_dt(i,j,k) * eddlon * ( q(i+1,j,k) - q(i,j,k) )
      cd_4order_3(i,j) =  dlam_dt(i,j,k) * frac_1_3 * eddlon * ( q(i+2,j,k) - q(i-1,j,k) )
    END DO
  END DO

  ! b): interpolate udu/dx, udv/dx, udp/dx, udt/dx to 'prognostic' grid-points
  !---------------------------------------------------------------------------
  DO j=jstart_n, jend_n
    DO i=istart_n, iend_n
      advtend = - frac_1_16 * ( - ( cd_4order_3(i+1,j) + cd_4order_3(i-2,j) )    &
        &          + 9.0_ireals * ( cd_4order_1(i,j) + cd_4order_1(i-1,j) ) )
      tend(i,j,k) = tend(i,j,k) + advtend
    END DO
  END DO

END DO
```

- **Each term needs an appropriate definition of the subdomain boundaries !!!**

3. Optimization: COSMO_5.0_hos

Ad-hoc implementation in COSMO_4.24 (Ogaja & Will 2016)
100% longer time to solution with S4p4v2d0.00

- Code profiling and trace analysis

Additional time to solution increased due to additional boundary exchange

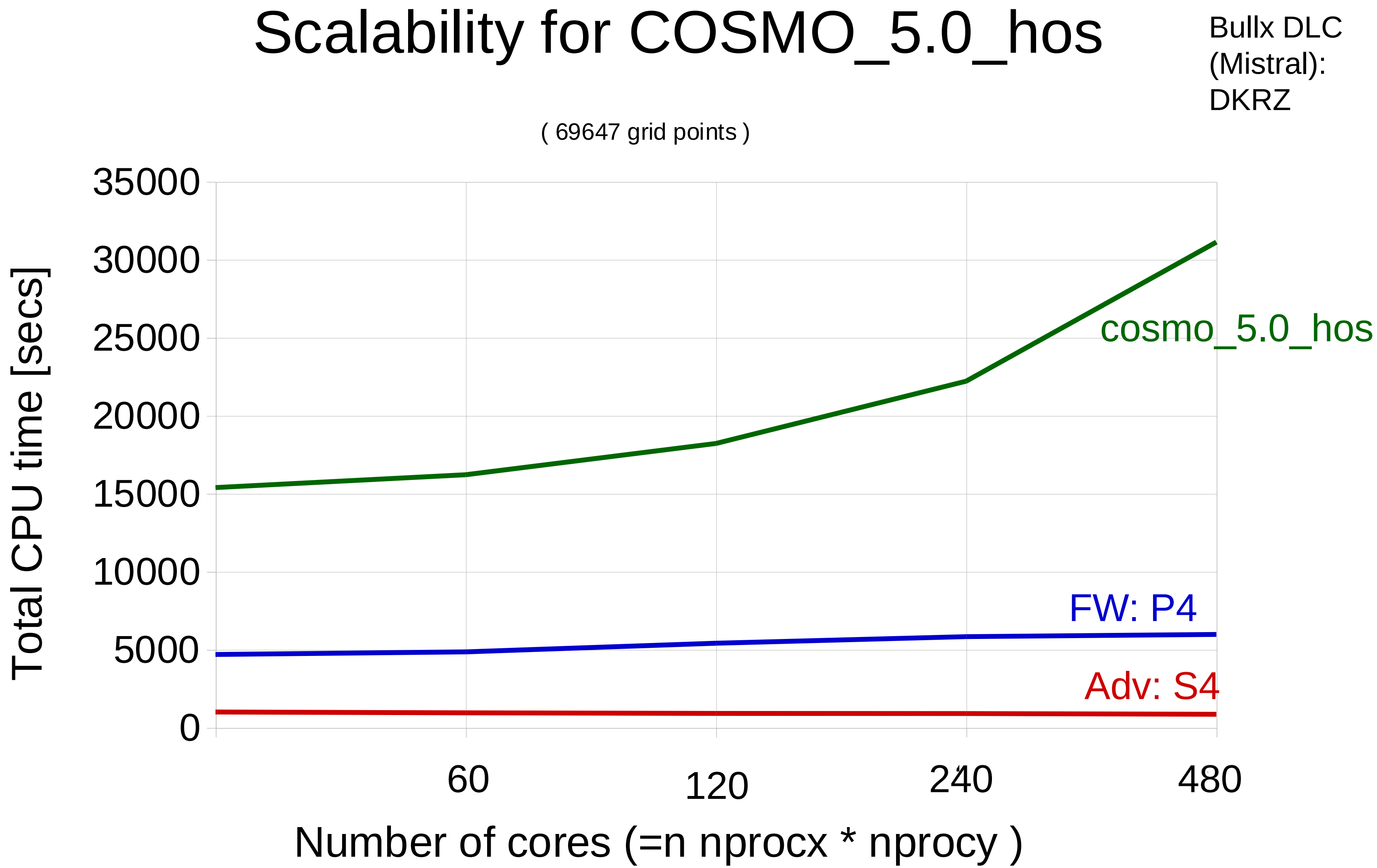
- Optimisation of AdvS4 implementation

Additional boundary exchange (in symmetric advection) removed
Number of variables allocated reduced.

- Final code profiling and trace analysis

Optimized COSMO_5.0_hos

3. Optimization: COSMO_5.0_hos



3. COSMO_5.0_hos: Computational cost
S4p4 versus C3p2

- 10% increase in computational time for Advection
- 3% increase in computational time for Fast-waves solver
- 1-2% increase in the total model run time

Full 4th order symmetric advection scheme without explicit horizontal diffusion reveals no difference in time to solution, cost and scalability

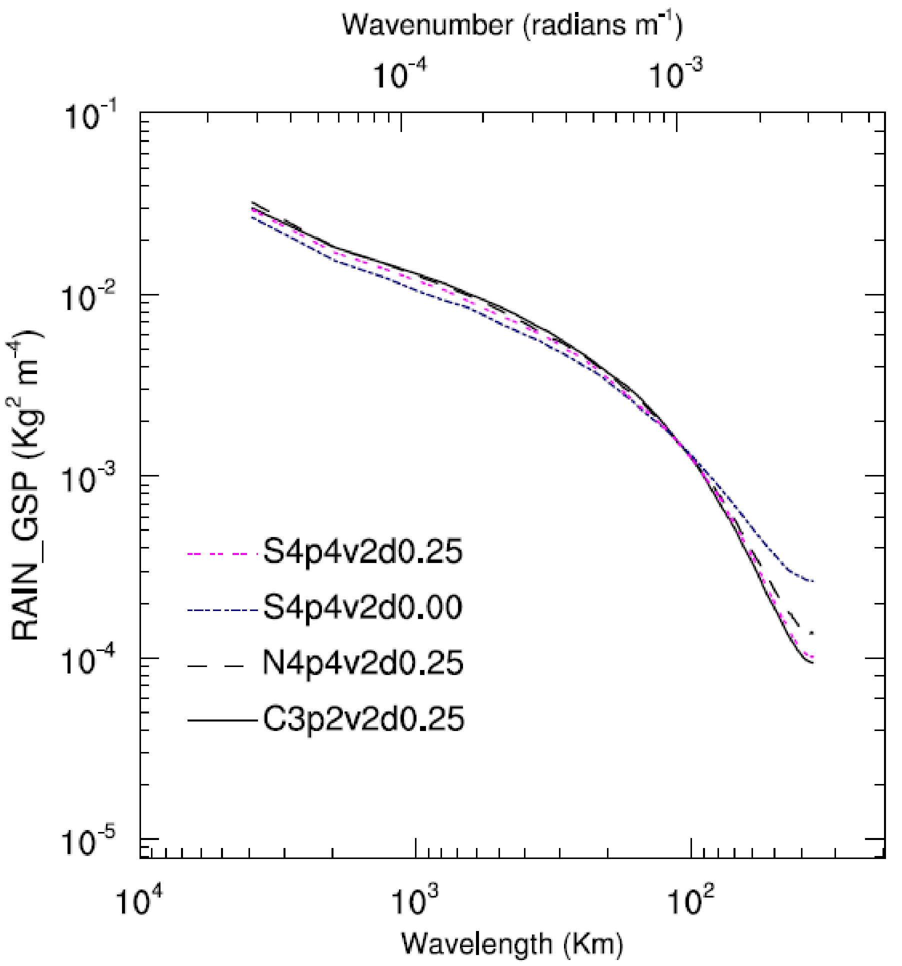
Higher order schmes (e.g.6) can be expected to bahave in a similar way.

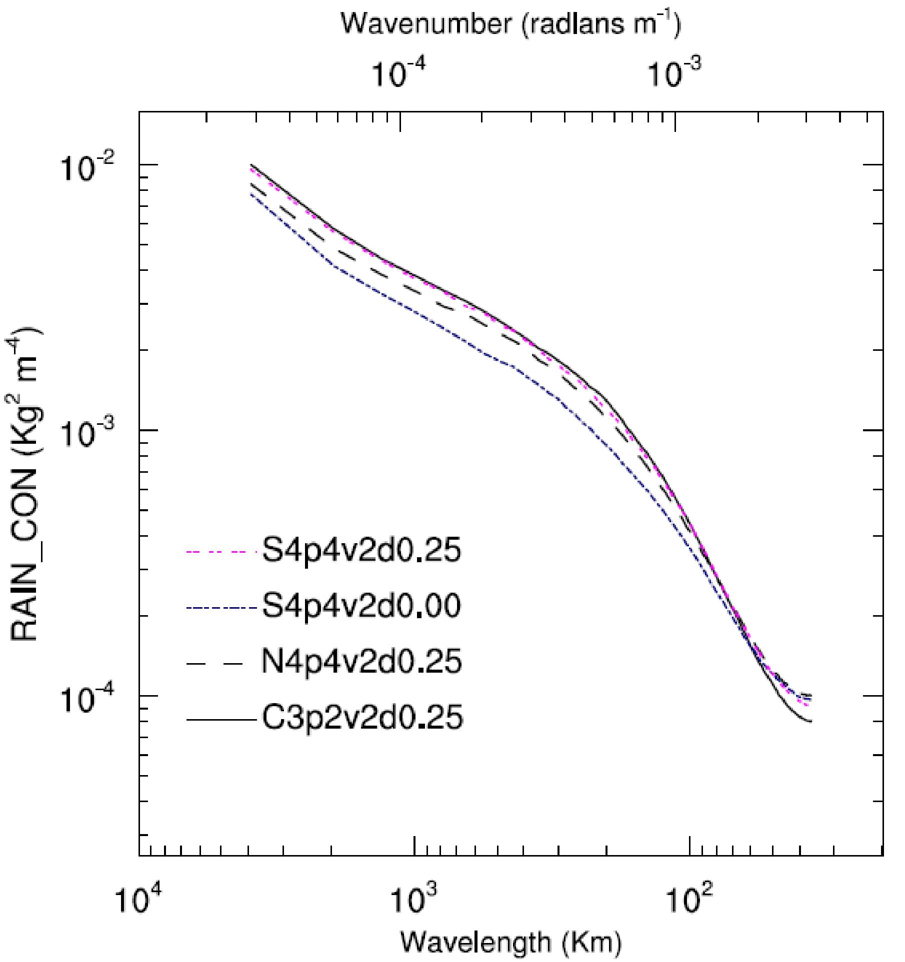
4. Real case climate simulation:

EU 50, C3p2,	NCEP	2000-2004
EU 50, S4p4	NCEP	
EU 50, C3p2	ERAINT	
EU 50, S4p4	ERAINT	
EU 18 S4p4,	EU	,
EU 18 S4p4,	ERA	
EU 18, S4p4,	NCEP	
EU 18, C3p2,	NCEP	

EU 7 S4p4,	EU50, ERA	2000-2001
EU 7 C3p2,	EU50, ERA	
EU 7S4p4,	EU50, NCEP	
EU 7 C3p2,	EU50, NCEP	
DE 5.0 S4p4	EU 7	
DE 2.8 S4p4	EU 7	
DE 2.8 C3p2	EU 7	

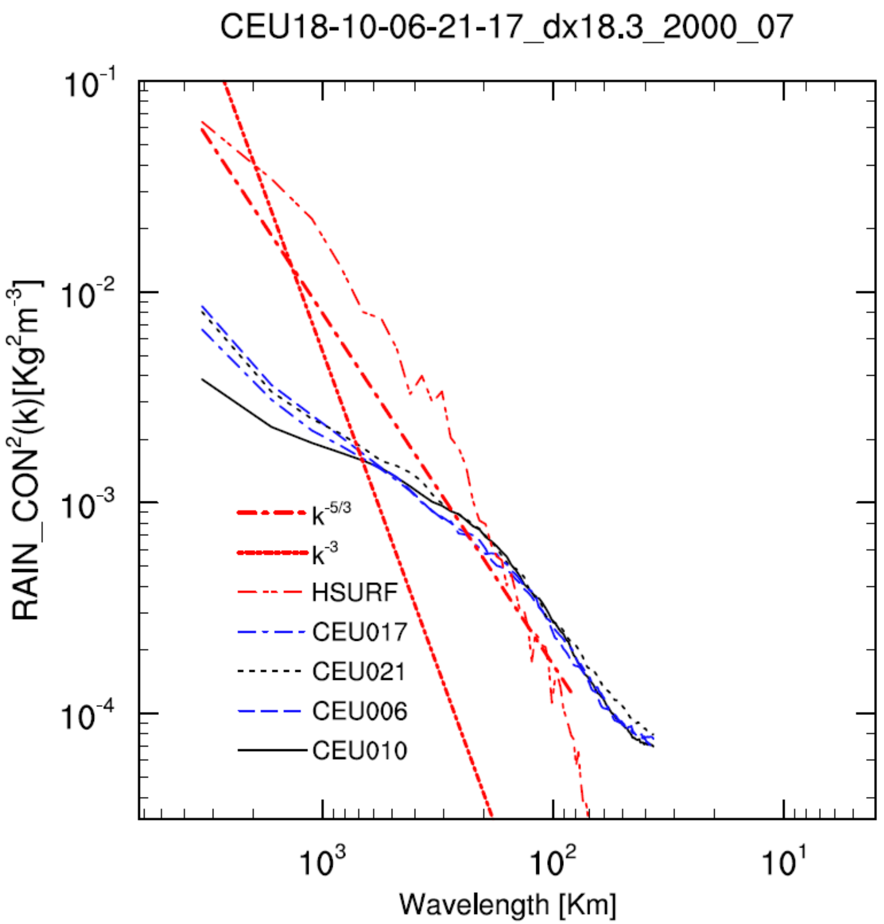
4. Real case climate simulation: Spectra of July precipitation, COSMO_4.24



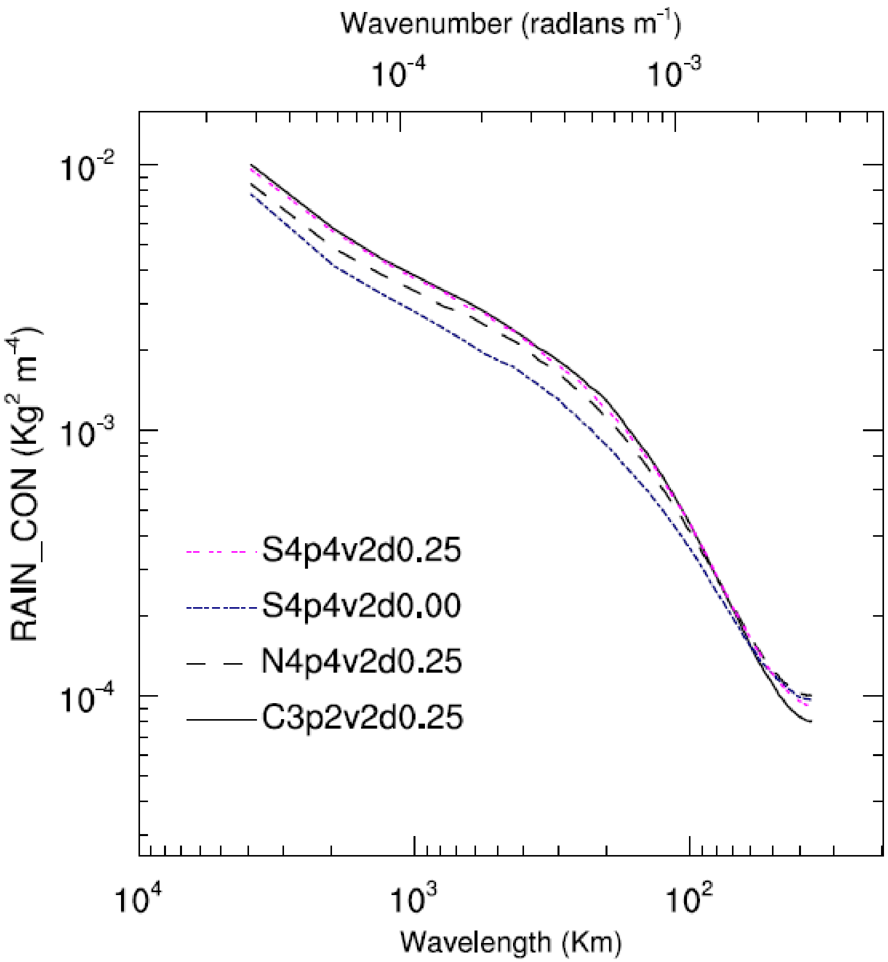


4. Real case climate simulation: Spectra of July precipitation,

COSMO_5.0

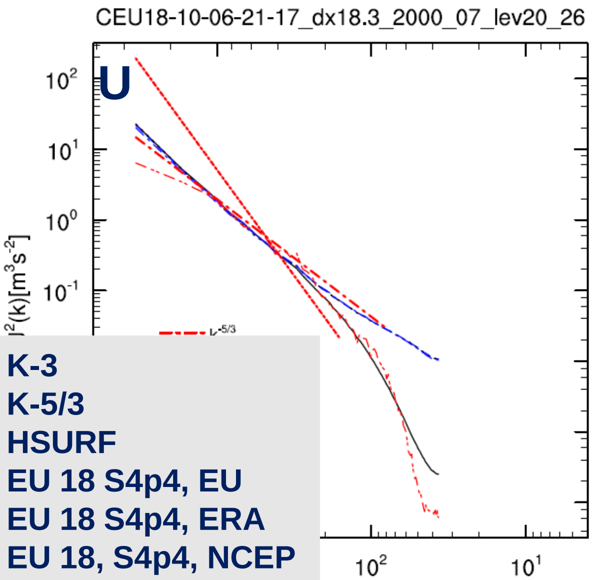


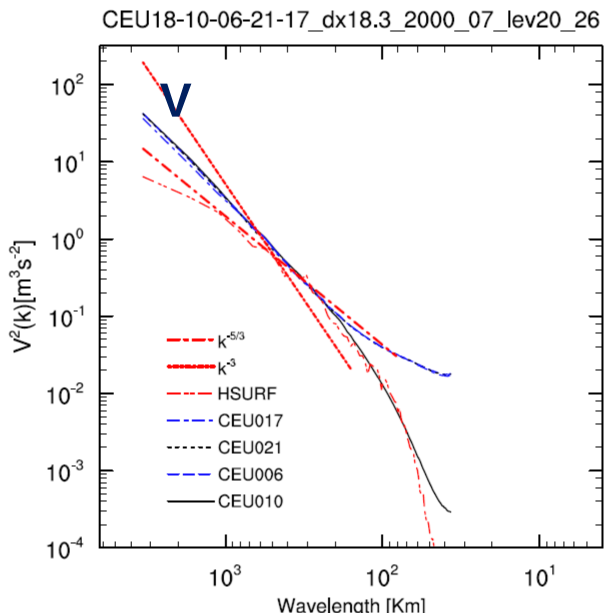
COSMO_4.24

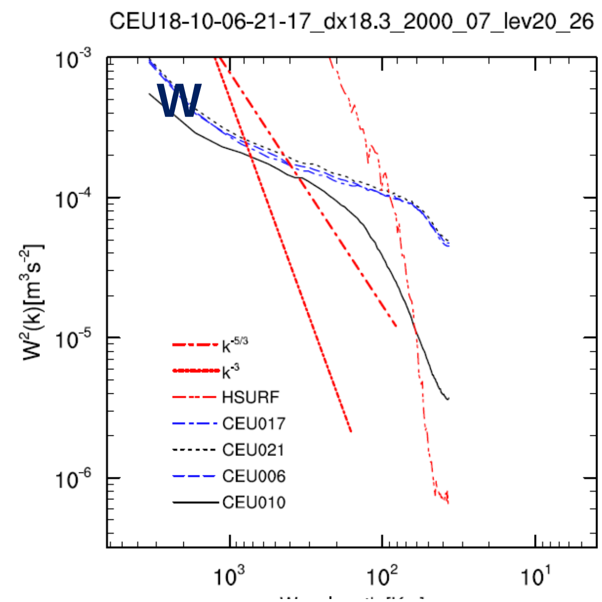


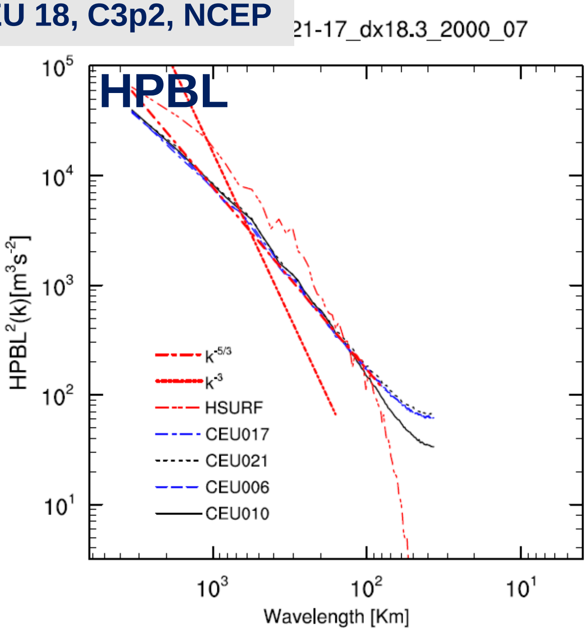
5. Effective model resolution: Real case zonal kinetic energy spectra, CCLM-EU 18km

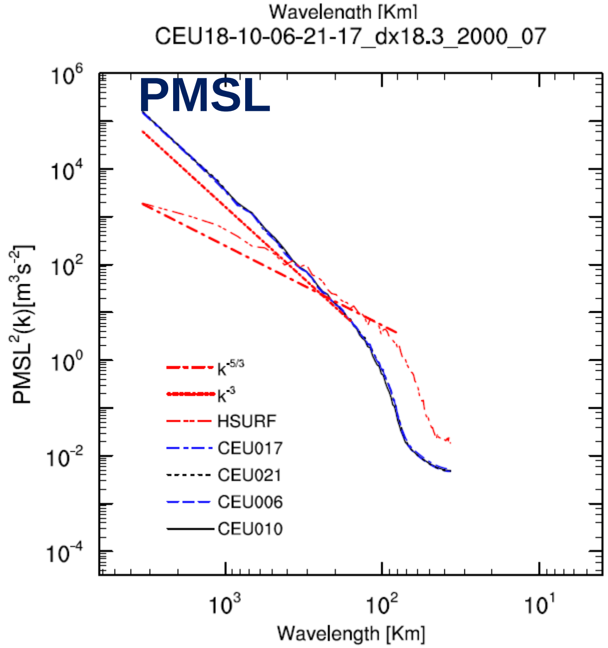
- K-3
- K-5/3
- HSURF
- EU 18 S4p4, EU
- EU 18 S4p4, ERA
- EU 18, S4p4, NCEP
- EU 18, C3p2, NCEP

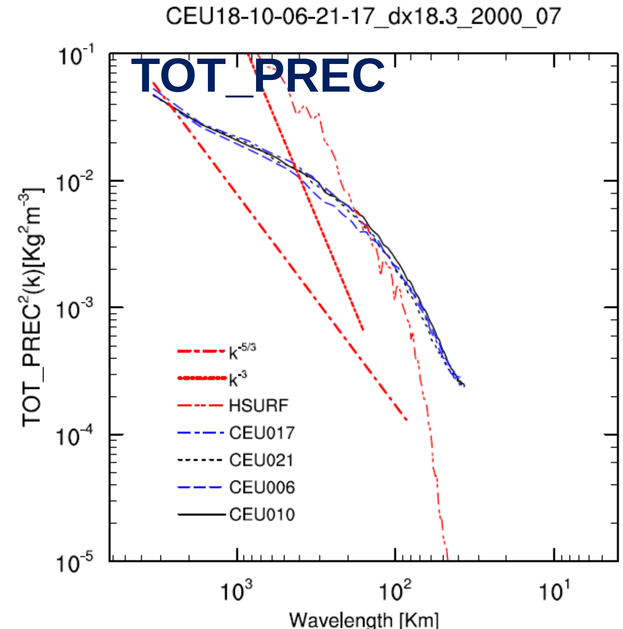




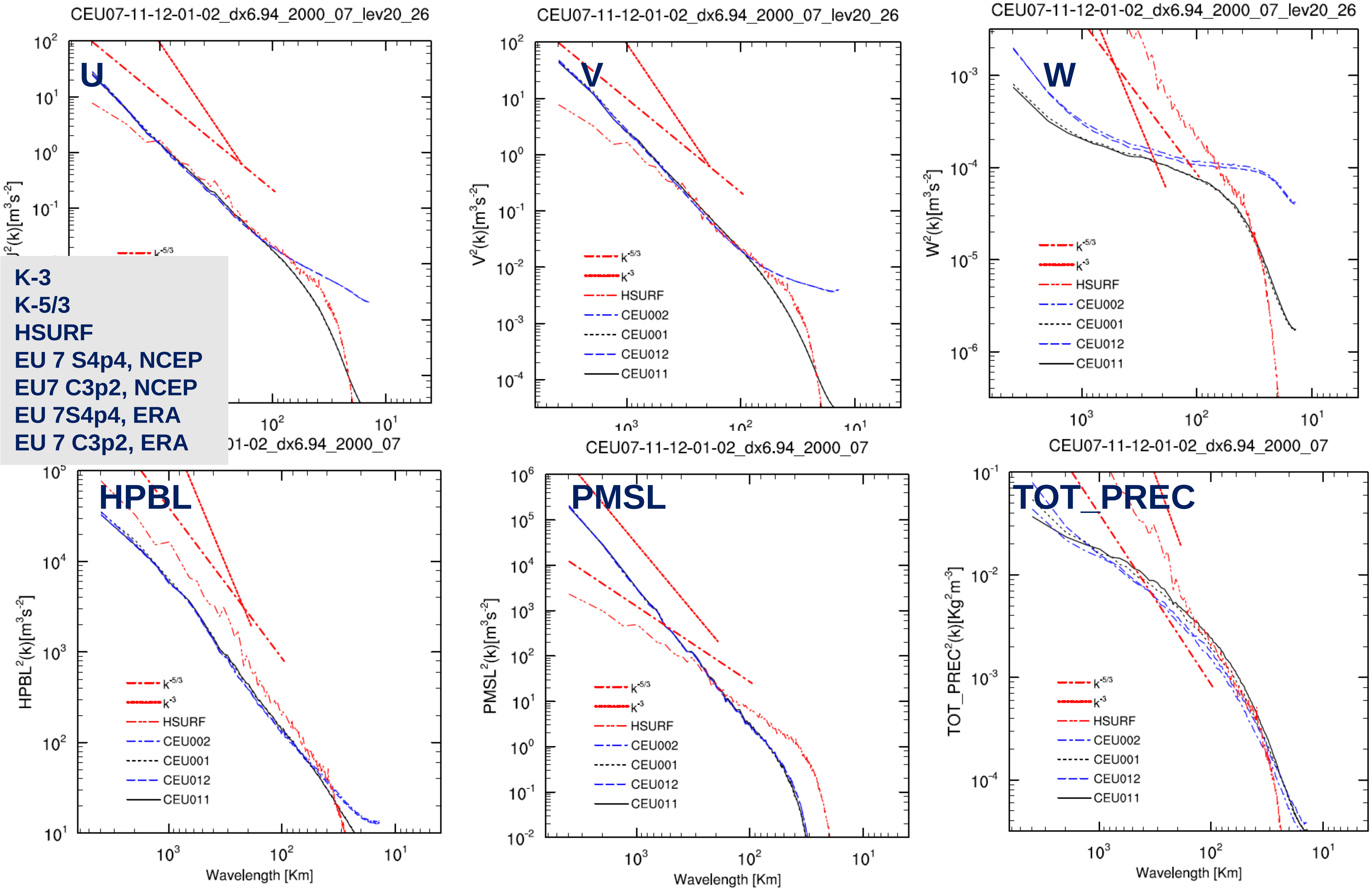




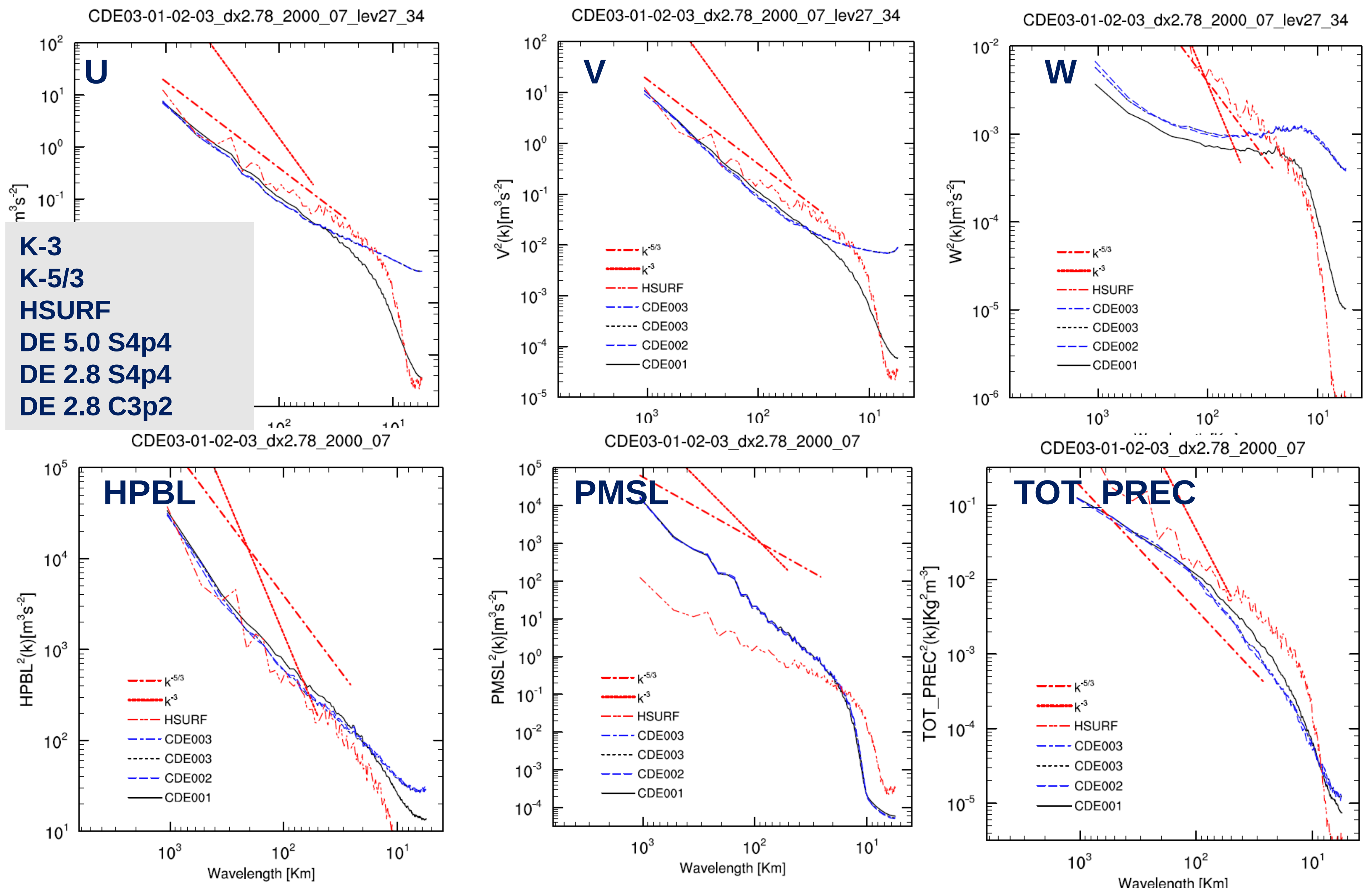




5. Effective model resolution: Real case zonal kinetic energy spectra, COSMO-EU



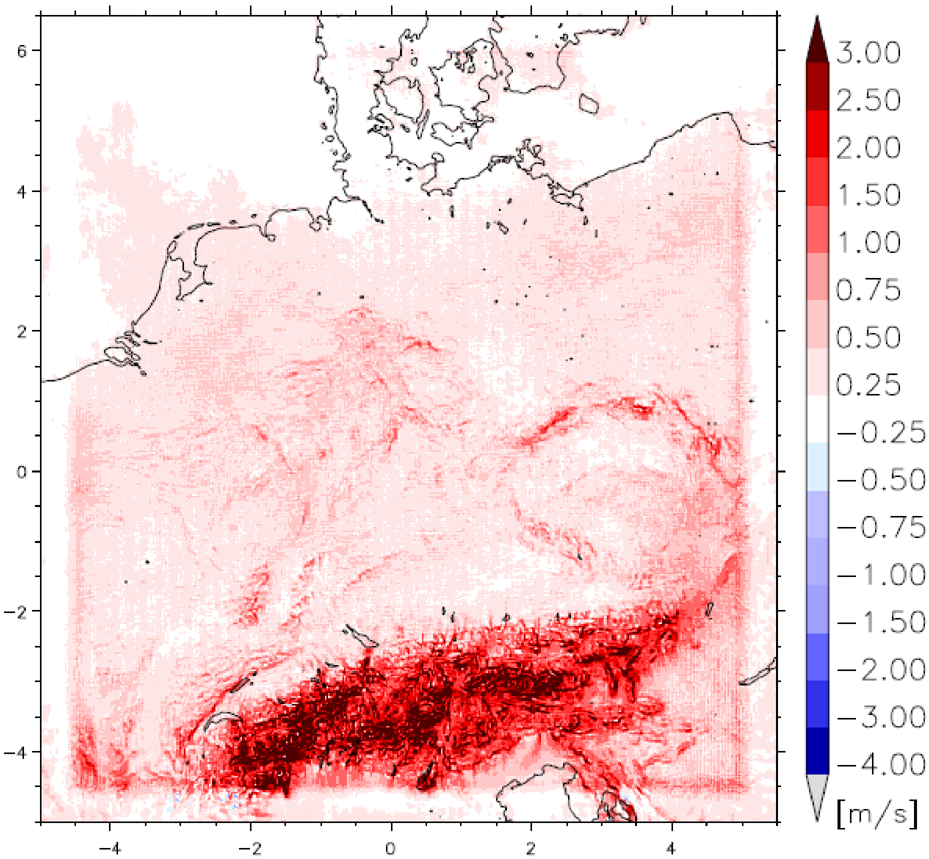
5. Effective model resolution: Real case zonal kinetic energy spectra COSMO-DE



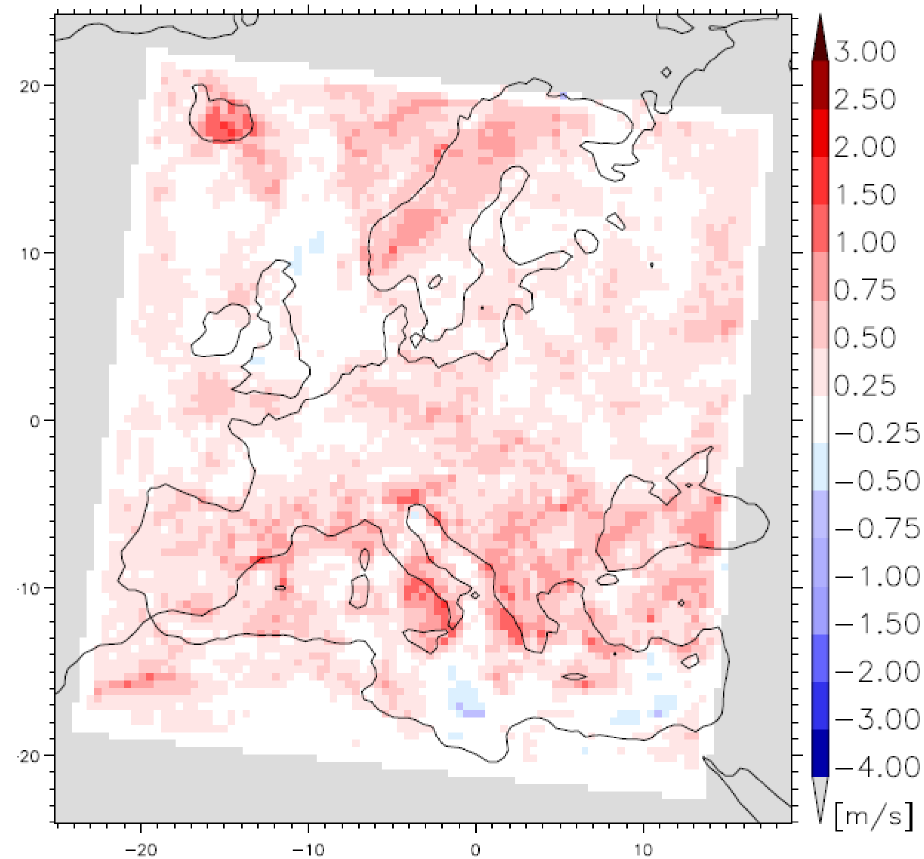
5. VMAX_10m 2000-2001

AdvS4p4v2d0.00 – C3p2v2d0.00

COSMO-DE **COSMO_EU**



(a) CDE002-CDE001



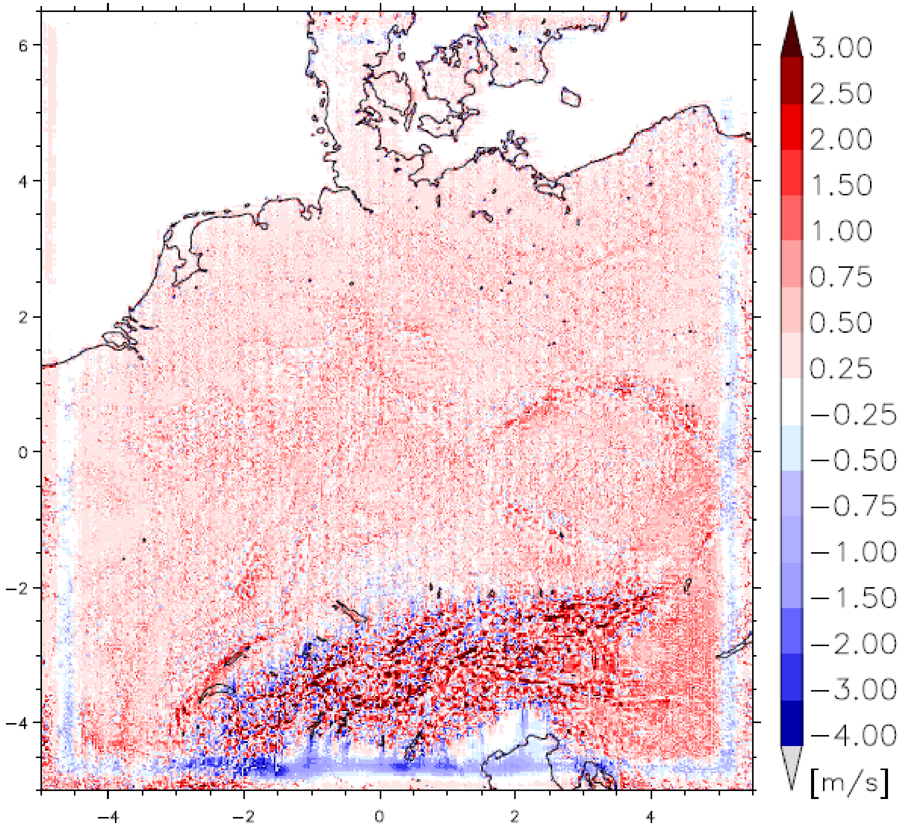
(a) CEU002-CEU001

5.Near surface climate

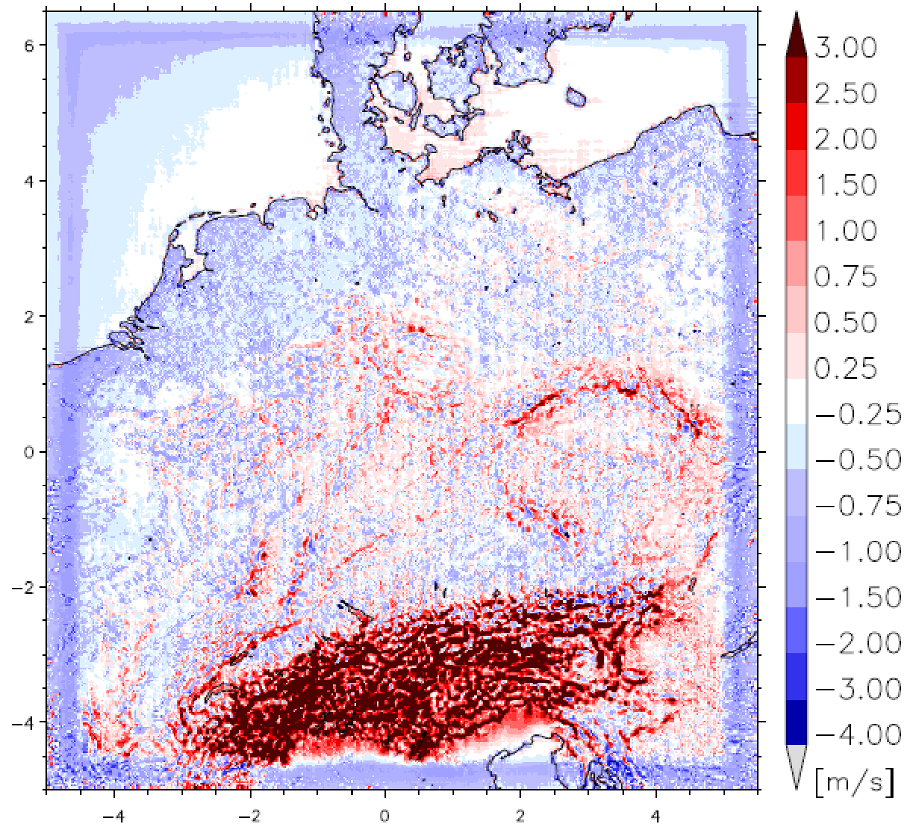
AdvS4p4v2d0.00

COSMO-DE — **COSMO-DE - COSMO_EU**

2.8km – 5km



(c) CDE002-CDE004

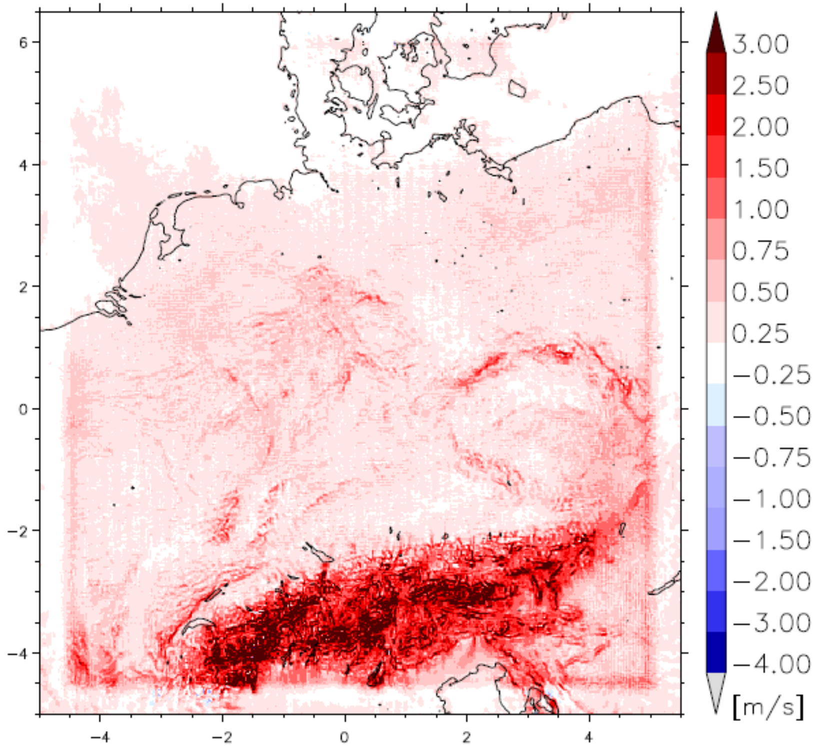


(d) CDE002-CEU002

5. VMAX_10m 2000-2001

AdvS4p4v2d0.00 – C3p2v2d0.00

COSMO-DE



(a) CDE002-CDE001

Interpretation:

- The deep convection parameterisation (DCP) has infinite speed. The grid scale dynamics has a finite speed.

- Horizontal diffusion prevents small scall dynamics by damping
- DCP prevents small scale dynamics by instantaneous vertical energy transport

- The quality of dynamics is visible if the spatial transport of conserved quantities by parameterisation is not much faster than the dynamical transport

6.Summary and Conclusions

•Horizontal diffusion prevents small scall dynamics by damping
• DCP prevents small scale dynamics by instantaneous vertical energy transport
• the horizontal spectra exhibit , that the orography is generating a substantial part of small scale dynamics in case of diffusive numerics

Non-dissipative 4th order dynamics:

• allows simulating weather and climate without numerical diffusion at same cost and similar quality of large scale climate as the reference scheme and exhibits substantial small scale differences
• in combination with appropriate orographic forcing it improves the effective resolution by approximately a factor of two (not shown)
• it has the potential to significantly improve the physical consistency of weather and climate simulations by direct simulation of the processes

*** Morinishi et al. JCP 1998, 2010; Ogaja & Will, MetZet 2016**