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Monte-Carlo Spectral Integration in COSMO Radiation Scheme

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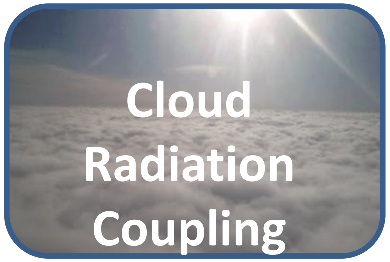
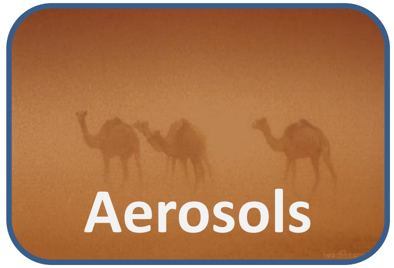
Outline

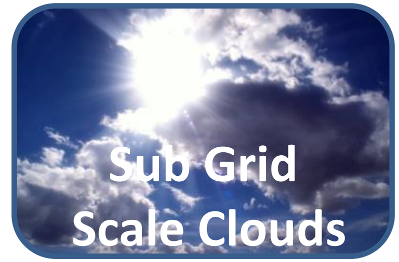
- General description of radiative transfer calculation methods
- COSMO radiation scheme RG92
- What is Monte-Carlo Spectral Integration?
- The COSMO-MCSI setup
- Run time and errors comparisons
- Model performance verifications against observational data
- Conclusions

Testing & Tuning of Revised Cloud Radiation Coupling - $T^2(RC)^2$

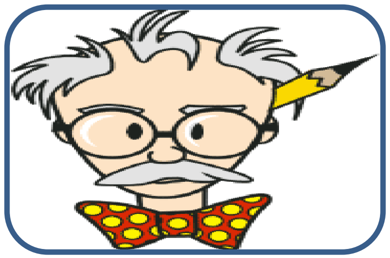
Revised Cloud/aerosols Radiation Coupling

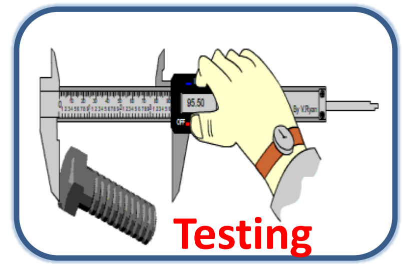






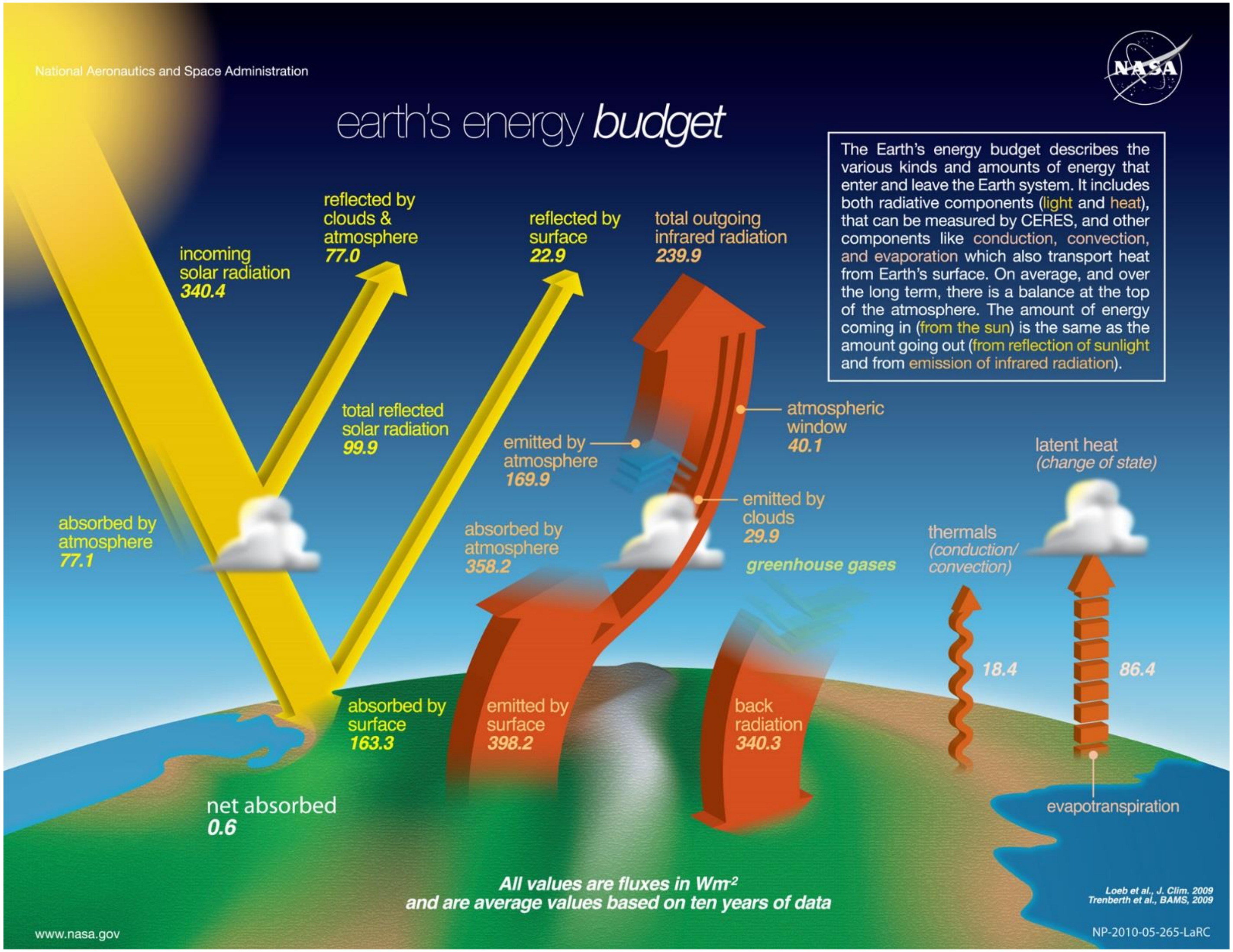
Testing & Tuning



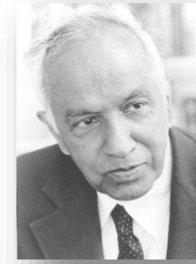


Run Time Optimization

Earth’s Energy Budget



Chandrasekhar's General Radiative Transfer Equation (RTE)



$$\mu \frac{dI_\nu(\tau_\nu,\mu,\phi)}{d\tau_\nu} = I_\nu(\tau_\nu,\mu,\phi) - \varpi_\nu(\tau_\nu)\frac{j_\nu^{sca}(\tau_\nu,\mu,\phi)}{\sigma_{sca}(\nu)} - (1-\varpi_\nu(\tau_\nu))\frac{j_\nu^{thermal\ \ emi}(\tau_\nu)}{\sigma_{abs}(\nu)}$$

I_ν - radiance

τ_ν - extinction optical thickness (abs. + sca.) – here treated as vertical coordinate

μ - cos(Solar zenith angle)

ϕ - azimuth angle

ϖ_ν- single scattering albedo, (ϖ_ν=0 "pure abs", ϖ_ν=1 "pure sca"))

$$\varpi_\nu = \frac{n_{sca}\sigma_{sca}}{n_{sca}\sigma_{sca} + n_{abs}\sigma_{abs}}$$

$\sigma_{sca/abs}(\nu)$- scattering/absorption cross section $j_\nu^{sca/emi}(\tau_\nu,\mu,\phi)$- sca./emission ability

$$\mu \frac{dI_\nu(\tau_\nu,\mu,\phi)}{d\tau_\nu} = I_\nu(\tau_\nu,\mu,\phi) - \varpi_\nu(\tau_\nu) \oint_{4\pi} d\Omega' \frac{1}{4\pi} P_\nu(\mu',\phi',\mu,\phi) I_\nu(\tau_\nu,\mu,\phi) - (1-\varpi_\nu(\tau_\nu)) B_\nu(T(\tau_\nu))$$

$P_\nu(\mu',\phi',\mu,\phi)$- scattering phase function (probability that ray from μ',ϕ' will scatter to μ,ϕ)

 $B_\nu(T(\tau_\nu))$- Planck's Function

Assumptions we make for simplicity

- Plane parallel atmosphere
- Local thermal equilibrium (LTE) – only thermal emissions considered
- Two-stream approximation (1D problem) ↓↑
  - Isotropic scattering for half sphere (many scatterings)
  - Rayleigh/Henyey-Greenstein phase functions

$$P_{Ray}(\theta) = \frac{3}{4}(1 + cos^2\theta)$$

$$g = \frac{1}{2}\int_{-1}^{1} P(cos\theta)cos\theta dcos\theta$$

$$P_{HG}(\theta) = \frac{1 - g^2}{(1 + g^2 - 2gcos\theta)^{3/2}}$$

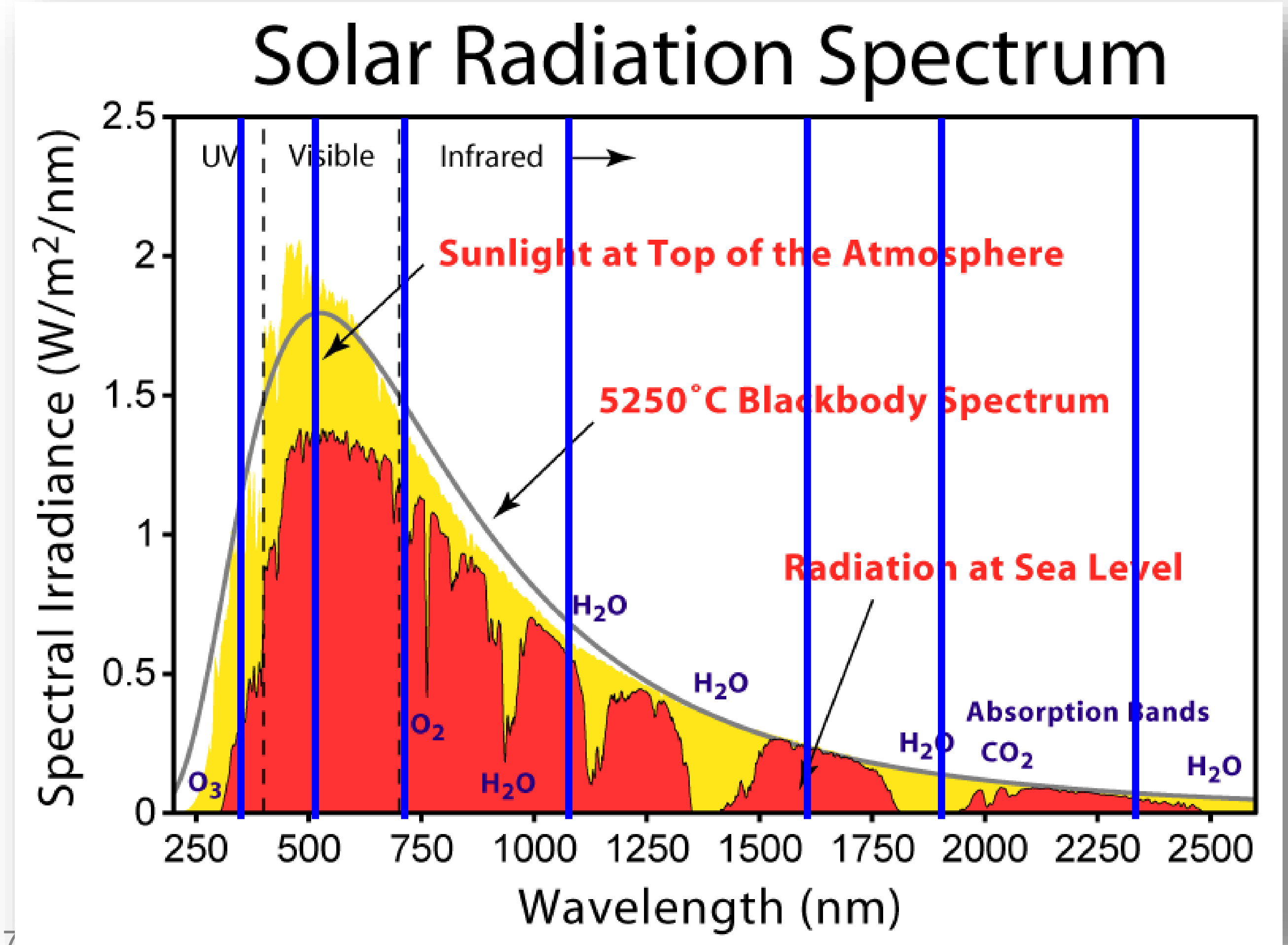
0°: $$\frac{1+g}{(1-g)^2}$$

180°: $$\frac{1-g}{(1+g)^2}$$

$$g = \begin{cases} 1 & forward \\ 0 & \\ -1 & backwards \end{cases}$$

And that's not all…

The RTE needs to be computed for each (x, y, z, ν) and separately for each of the gases, aerosols, hydrometeors



COSMO radiation:

3 Visible bands

5 Thermal bands

The k-distribution Method

- For gases (H_2O, CO_2, O_3...) the absorption is rapidly changing as a function wavelength. Line by line (LBL) methods are too expensive for NWP
- In the k-distribution method gases absorption spectra for each band is transformed from wavelength to cumulative probability space

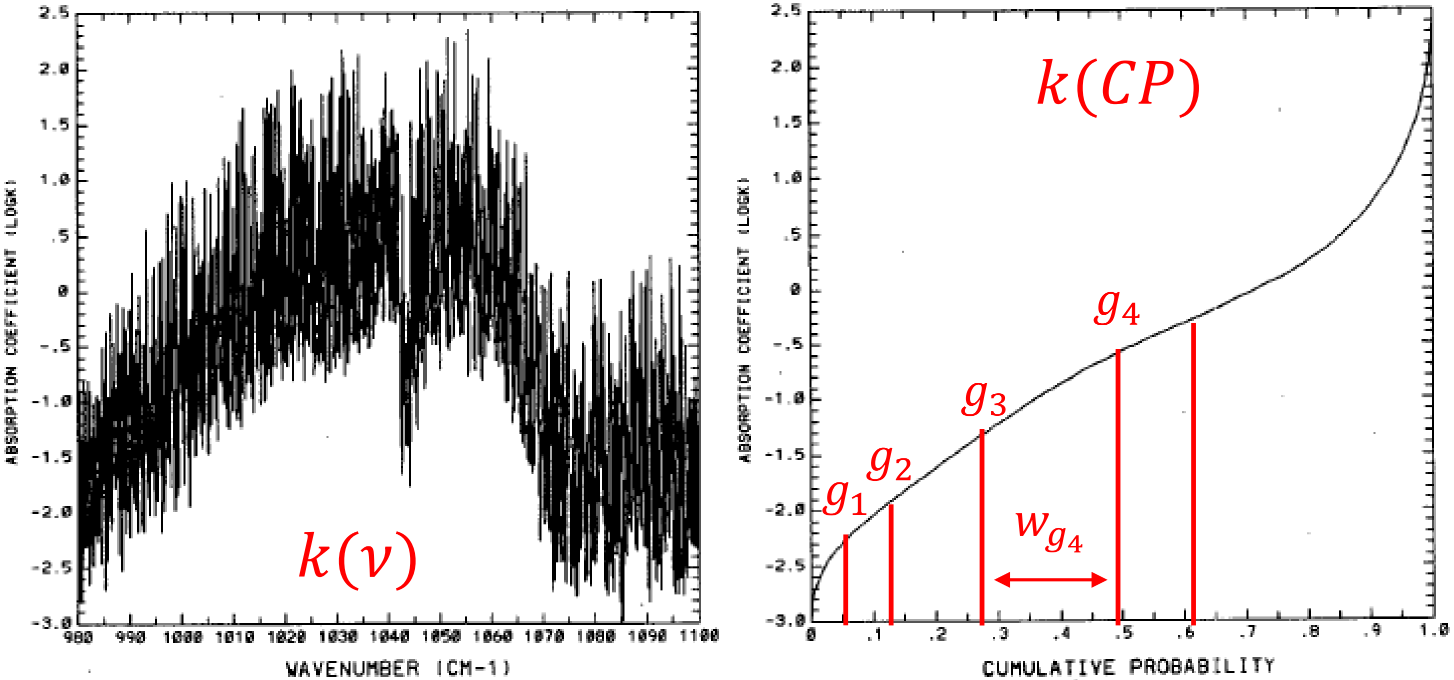


FIG. 1. Absorption coefficient k in (cm atm)$^{-1}$ as a function of (a) wavenumber and (b) cumulative probability for the O_3 9.6-μm band for a pressure of 25 mb and a temperature of 220 K.

Fu & Liou 1992

Exponential Sum Fitting Technique - ESFT

- One simple application of KDM is calculating the transmission function for a wide spectral interval and to fit it to series of exponentials as function of path length u :

$$T_{\bar{\lambda}}(u) \approx \frac{1}{\Delta\lambda} \int_{\Delta\lambda} e^{-k_\lambda u} d\lambda \approx \int_0^1 e^{-k(g)u} dg \approx \sum_g w_g e^{-k_g u}, \quad \sum_g w_g = 1$$

- The total flux is a some of pseudo-monochromatic fluxes for all three gasses, in all spectral intervals b and for all g-points

$$F(x,y,z,t) \approx \sum_b w_b \sum_{g_{b,1}} \sum_{g_{b,2}} \sum_{g_{b,3}} w_{g,b,1} w_{g,b,2} w_{g,b,3} F(\delta_0 + \delta_{g,b,1} + \delta_{g,b,2} + \delta_{g,b,3})$$

δ_0- optical thickness of gray constituents only (clouds, aerosols)

- But still - computationally very expensive!

Fast ESFT - FESFT

- First guess would be neglecting overlapping absorption bands of different gases in other words considering only the dominant gas in each band – causes systematic errors we cannot afford
- FESFT - Calculate each gas + gray constituents separately and then combine:

$$\bar{T}_{1,\lambda} = \frac{F^1}{F^0} = \frac{\sum_g w_g \, F(\delta_0 + \delta_1)}{F^0}$$

$$F \approx \prod_{i=1}^{N_{gas}} \bar{T}_{i,\lambda} F^0$$

- CPU run time gain is factor of ~**3**
- Reasonable accuracy
- COSMO's default scheme

Still not fast enough →
compromise on spatial/temporal resolution

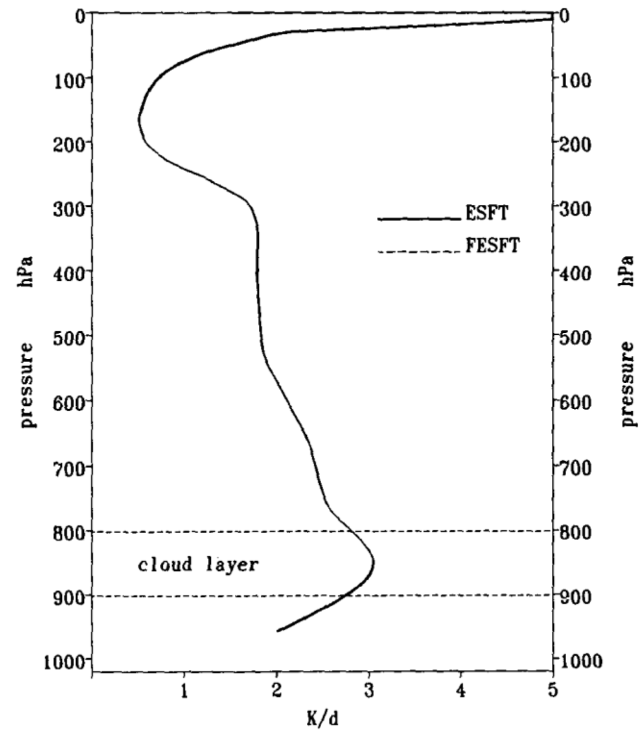
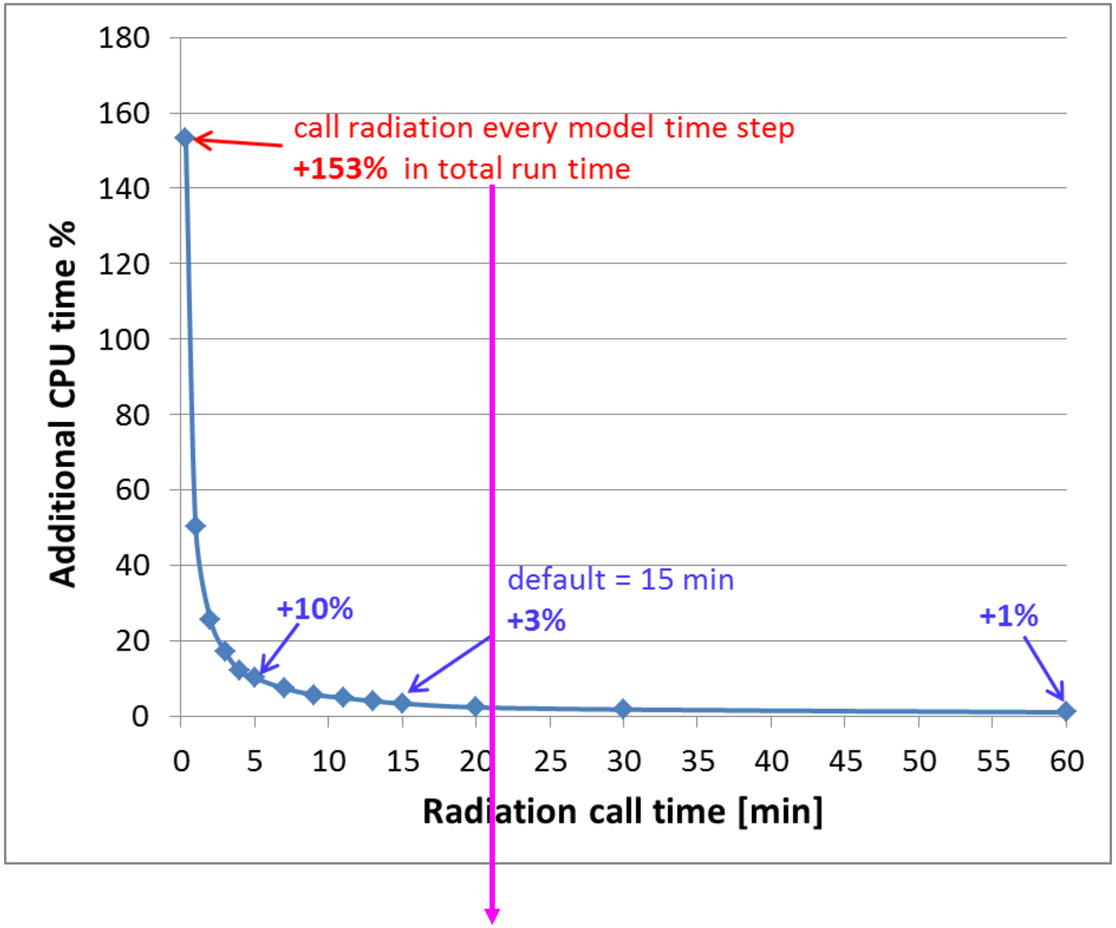


FIG. 1. Comparison of solar heating rates in a midlatitude summer atmosphere using the exponential sum-fitting technique in its original (ESFT) and its approximate fast (FESFT) version. A cloud with 10 g m^{-2} liquid water content is located between the 1000- and 2000-m heights. Solar zenith angle is 30° and a surface albedo of 0.20 is assumed.

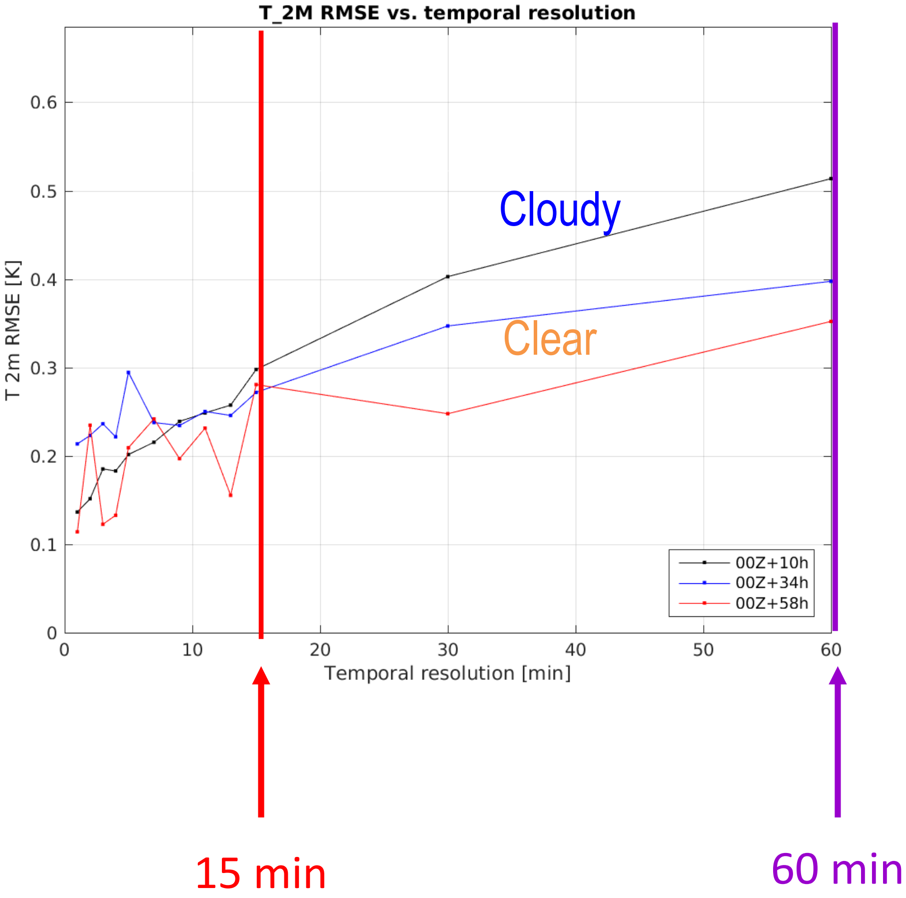
Radiation Temporal Resolution

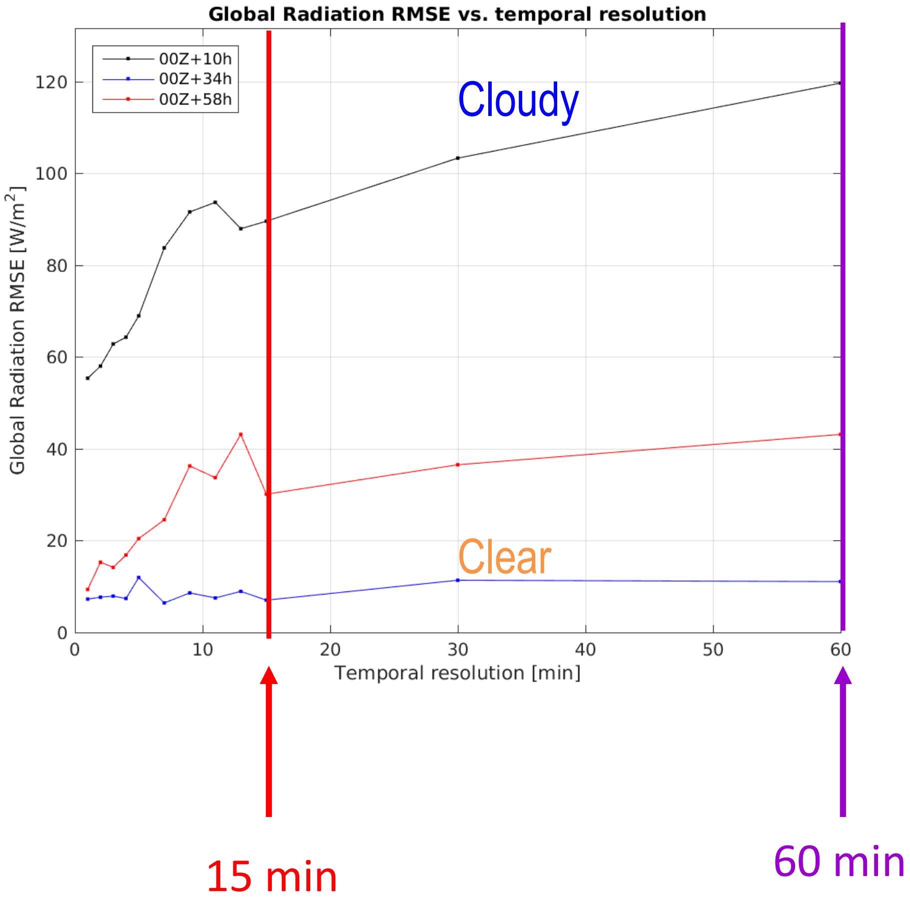


COSMO 2.8
operational setup
using FESFT

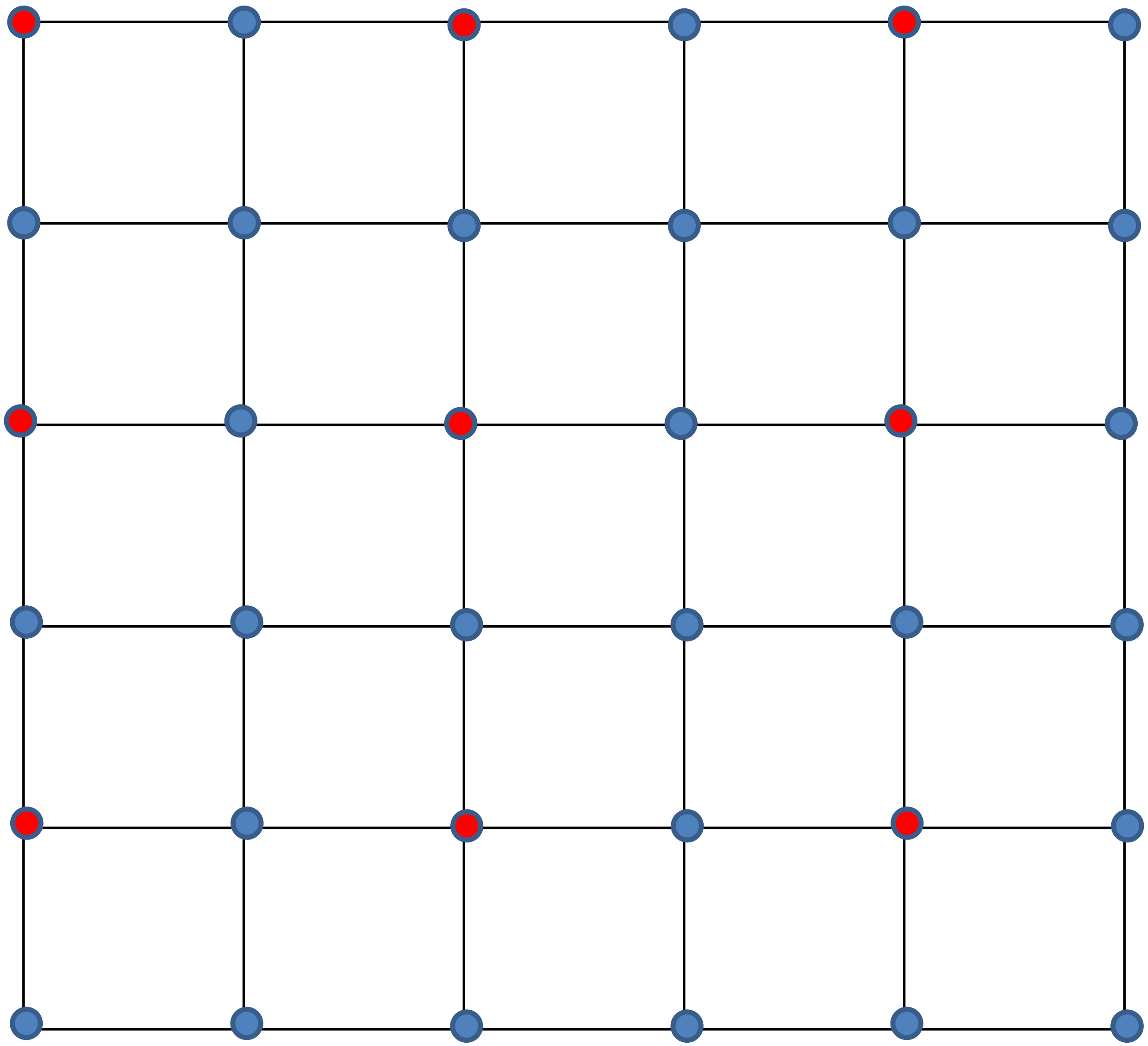
COSMO_radiation = 1.5 X COSMO model

Radiation Temporal Resolution





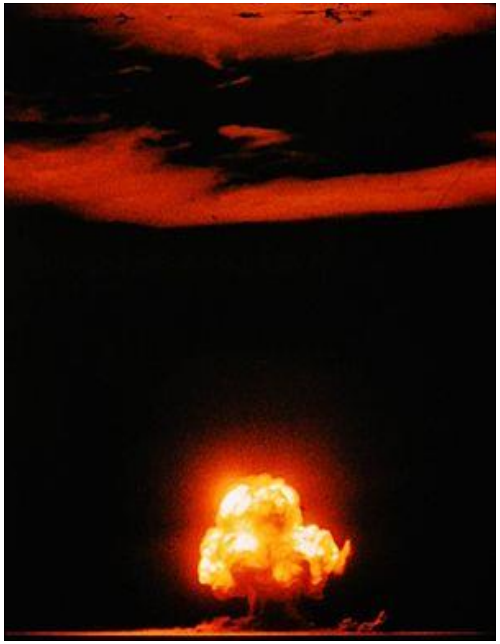
Radiation Spatial Resolution



nradcoarse = 2

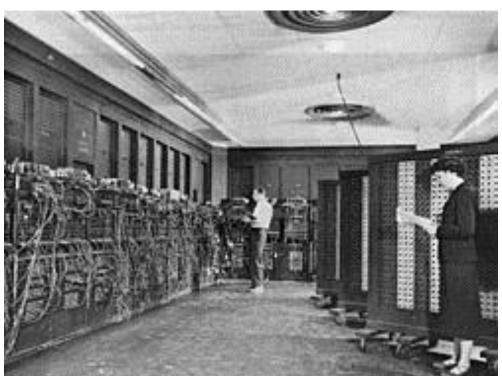
Monte-Carlo Method

Manhattan Project



Stanislaw Ulam

John von Neumann



ENIAC

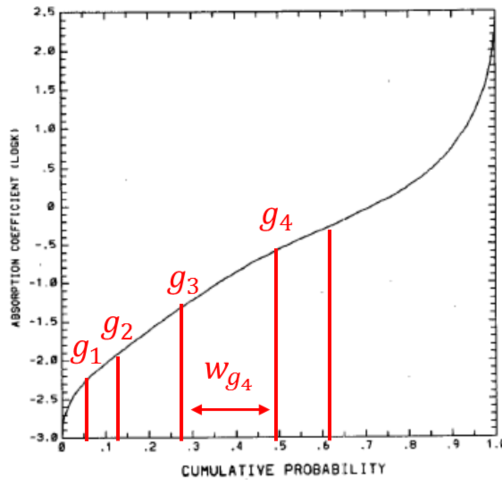
Charney, J. G.; Fjörtoft, R.; Neumann, J. (1950). "Numerical Integration of the Barotropic Vorticity Equation". Tellus. ***2*** *(4): 237–254. doi:10.1111/j.2153-3490.1950.tb00336.x.*

Monte-Carlo Spectral Integration - MCSI

J. Adv. Model. Earth Syst., Vol. 1, Art. #1, 9 pp.

Monte Carlo Spectral Integration: a Consistent Approximation for Radiative Transfer in Large Eddy Simulations

Robert Pincus[1] and Bjorn Stevens[2]



$$P(g) = \frac{1}{w_{g(b)}}$$

Back to ESFT **but** instead of doing this every 15 min (45 time steps):

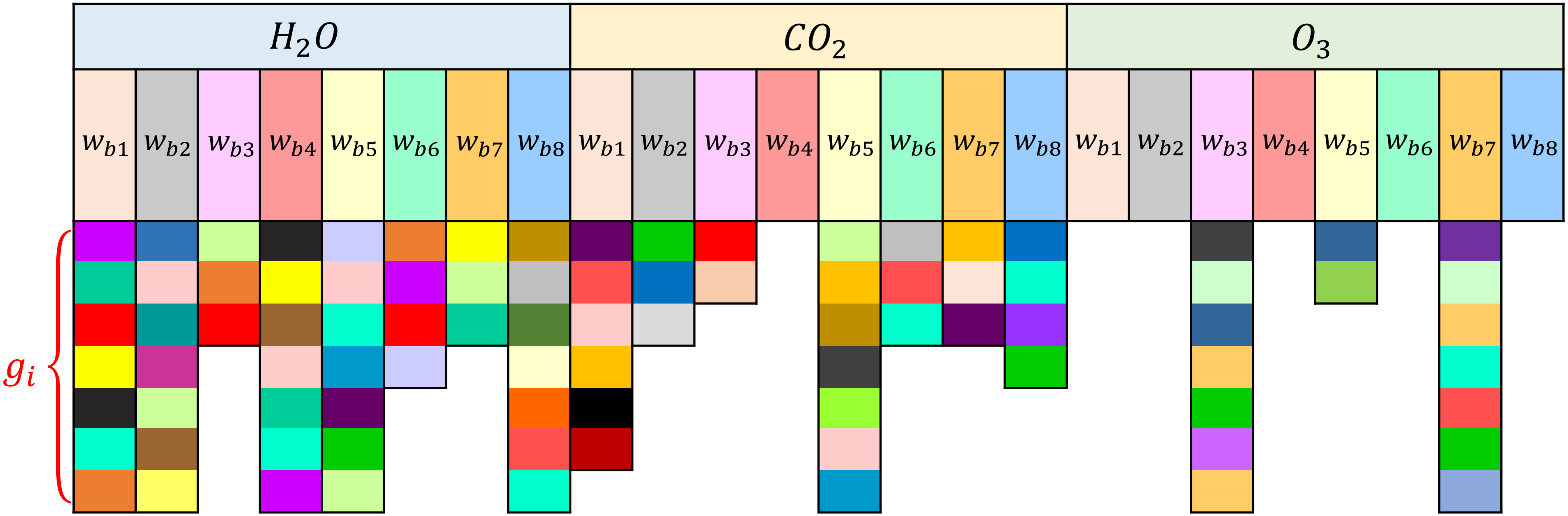
$$F(x,y,z,t) \approx \sum_b w_b \sum_{g_{b,1}} \sum_{g_{b,2}} \sum_{g_{b,3}} w_{g,b,1} w_{g,b,2} w_{g,b,3} F(\delta_0 + \delta_{g,b,1} + \delta_{g,b,2} + \delta_{g,b,3})$$

Pick only one g point according to its probability weight for each gas & band more frequently (i.e. every time step):

$$F(x,y,z,t) \approx \sum_b w_b F(\delta_0 + \delta_{g',b,1} + \delta_{g',b,2} + \delta_{g',b,3})$$

Locally temporal big errors that averages fast to an accurate solution!

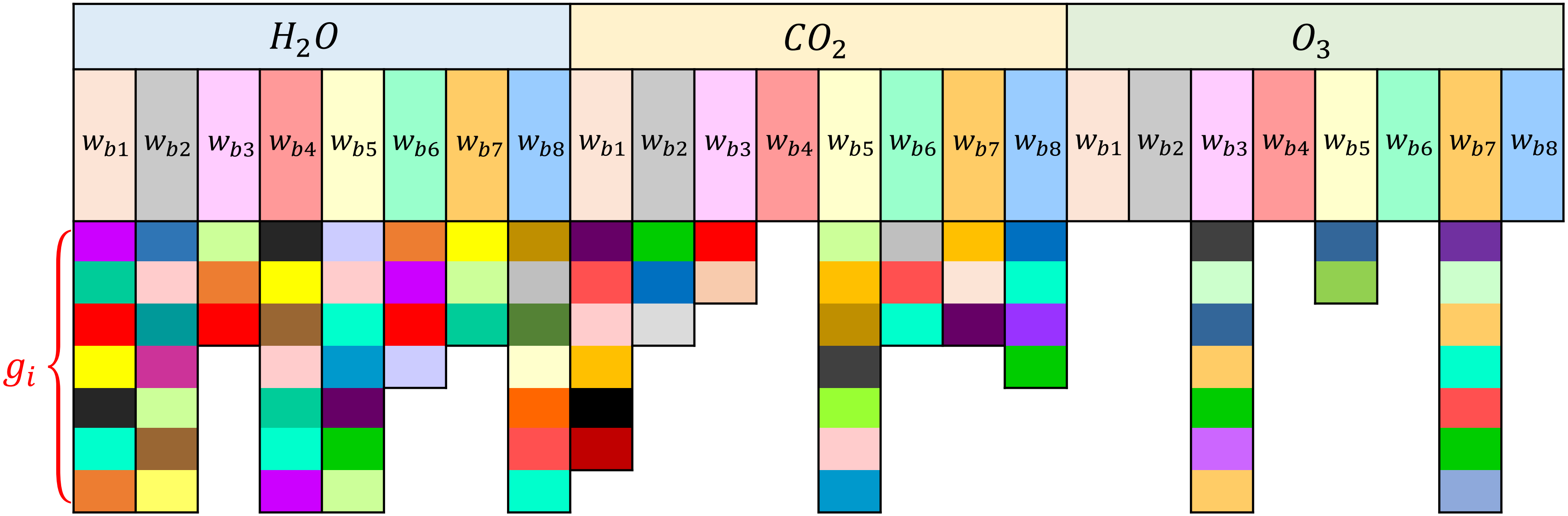
COSMO ESFT Diagram



Example: for spectral interval b=7 we have 3x3x7 = 63 calls inv_th/inv_so subrutines which calculate the fluxes

→ Total of 301 calls to inv_th/inv_so subrutines

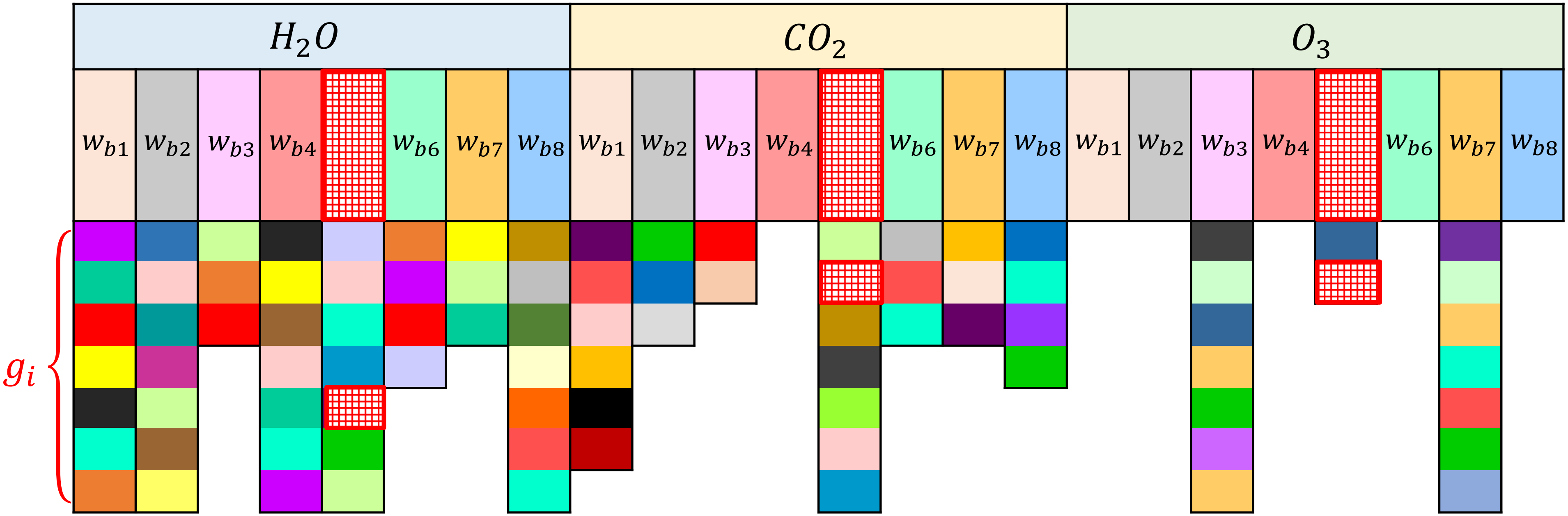
COSMO FESFT Diagram



→ Here we calculate each b, g only once (all small boxes)
total of 87 calls to inv_th/inv_so subrutines

$$\text{CPU gain} \approx \frac{calls\ decreas}{frequency\ increase} = \frac{301/87}{1} = 3.46$$

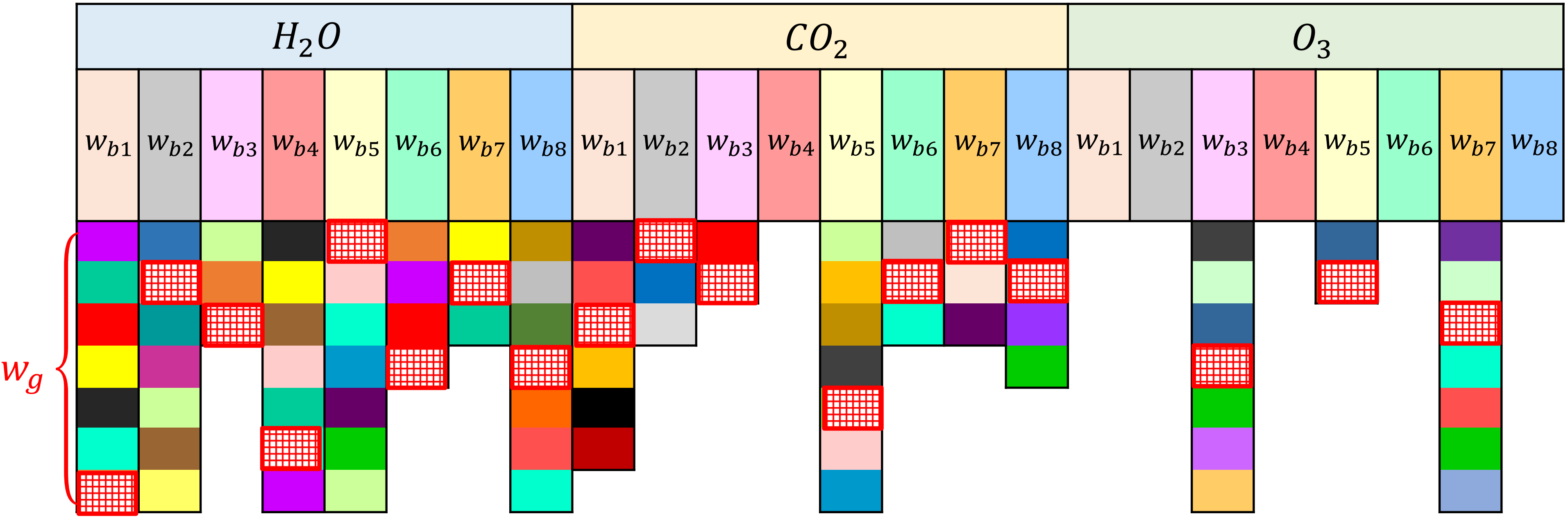
COSMO MCSI Diagram – Classic Version



→ Only 1 call to inv_th/inv_so subrutines instead of 301 calls in ESFT

$$\text{CPU gain} \approx \frac{calls\ decreas}{frequency\ increase} = \frac{301/1}{45} = \mathbf{6.7}$$

COSOMO MCSI Diagram – Soft Version



→ Only 8 calls to inv_th/inv_so subrutines instead of 301 calls in ESFT!

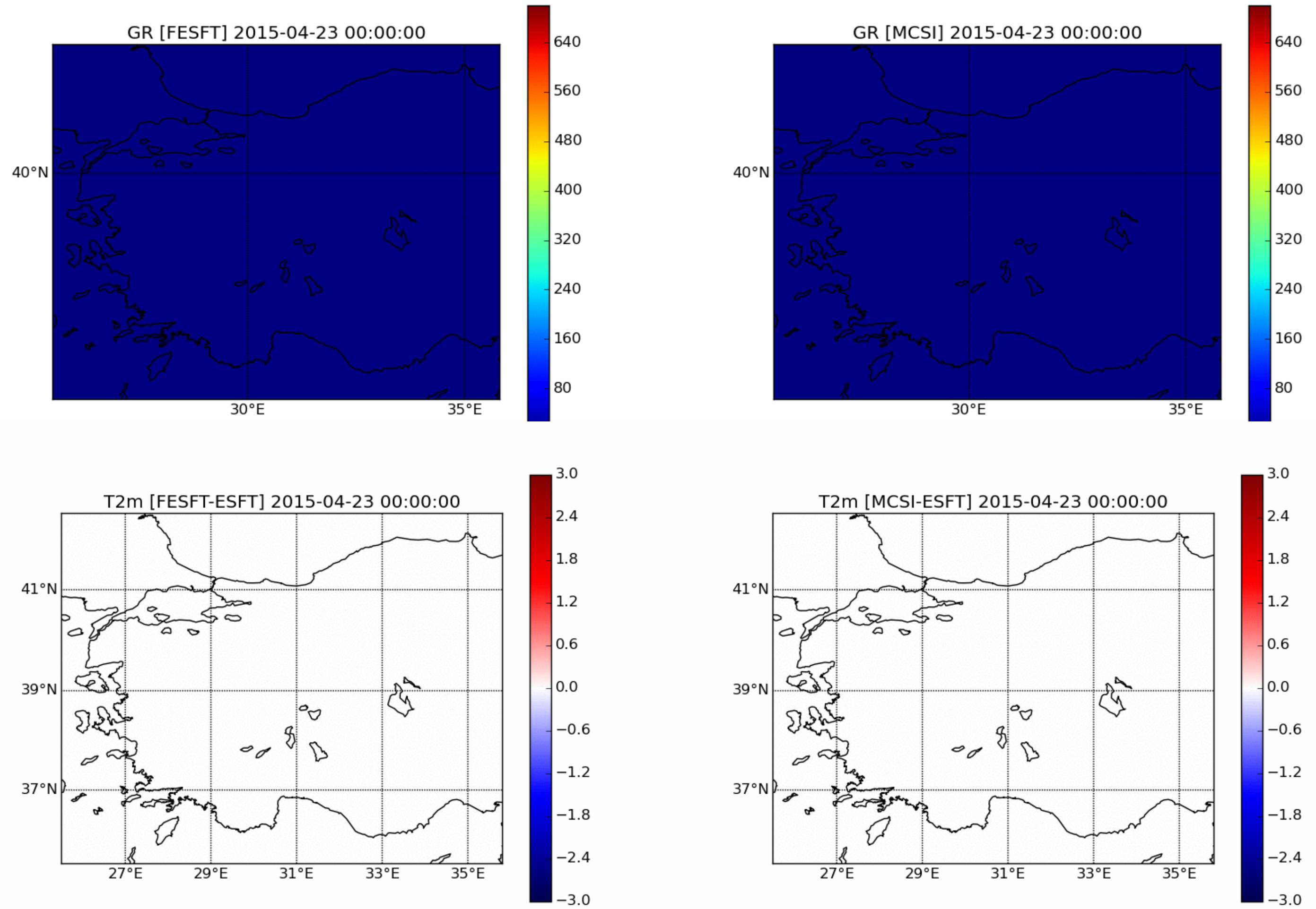
$$\text{CPU gain} \approx \frac{calls\ decreas}{frequency\ increase} = \frac{301/8}{45} = \mathbf{0.83}$$

COSMO Radiation Module

```
MODULE src_radiation
…
SUBROUTINE organize_radiation
…
SUBROUTINE fesft          ! ESFT & FESFT
….
    DO jspec= 1, nspec     ! Spectral loop
      …
      DO jh2o = 1, ih2o    ! Loop over H2O coefficients
        DO jco2 = 1, ico2  ! Loop over CO2 coefficients
          DO jo3  = 1, io3 ! Loop over O3  coefficients
            …
            CALL     inv_th/so
            …
…
…
```

Run Time & Errors Comparisons

- COSMO-2.8km
- Test case: 23-25/04/2015 – Turkey
- Partial cloudiness + High wind speeds
- Stand alone computer 1-node 4 CPUs

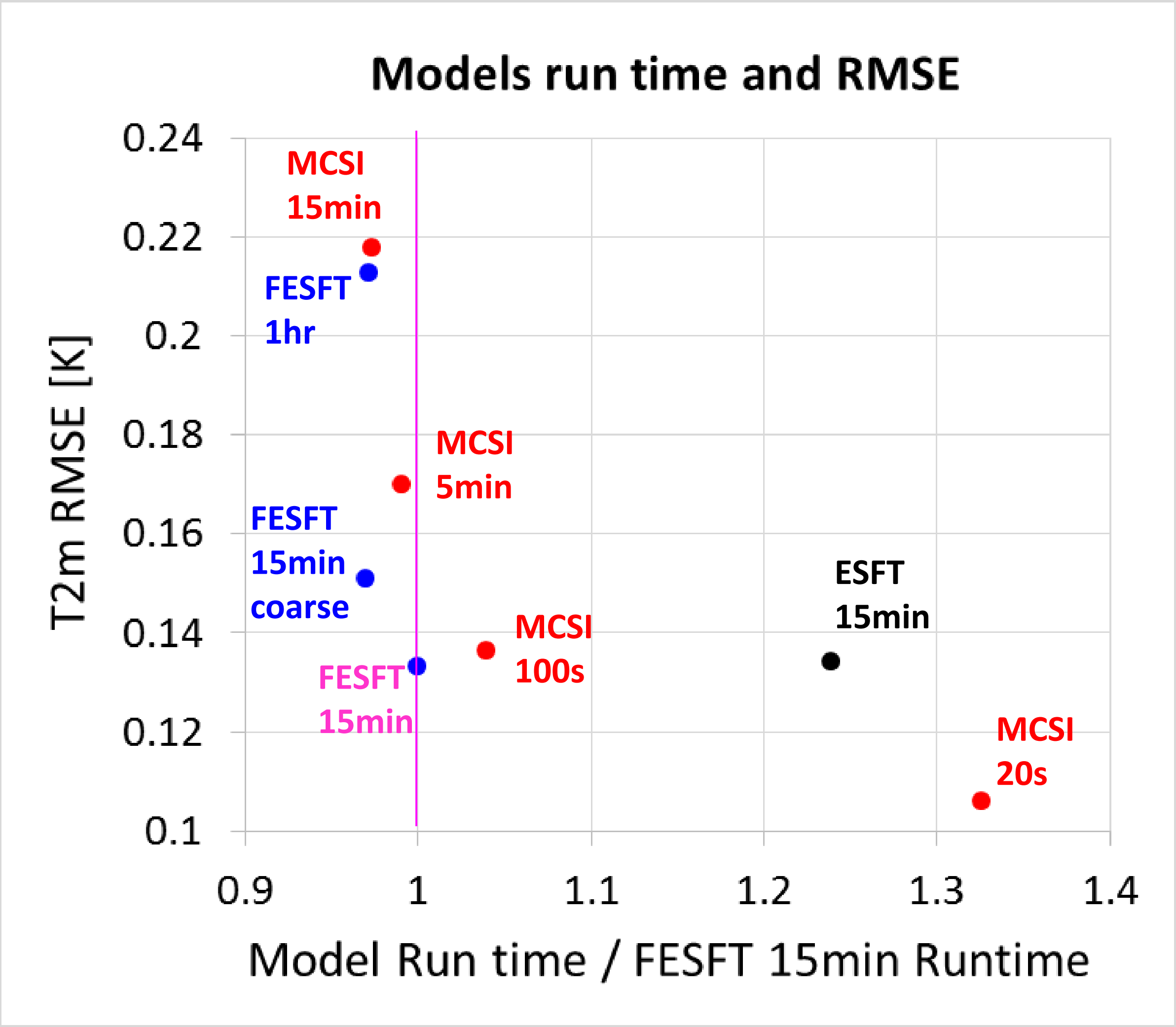


Run Time & Errors Comparisons

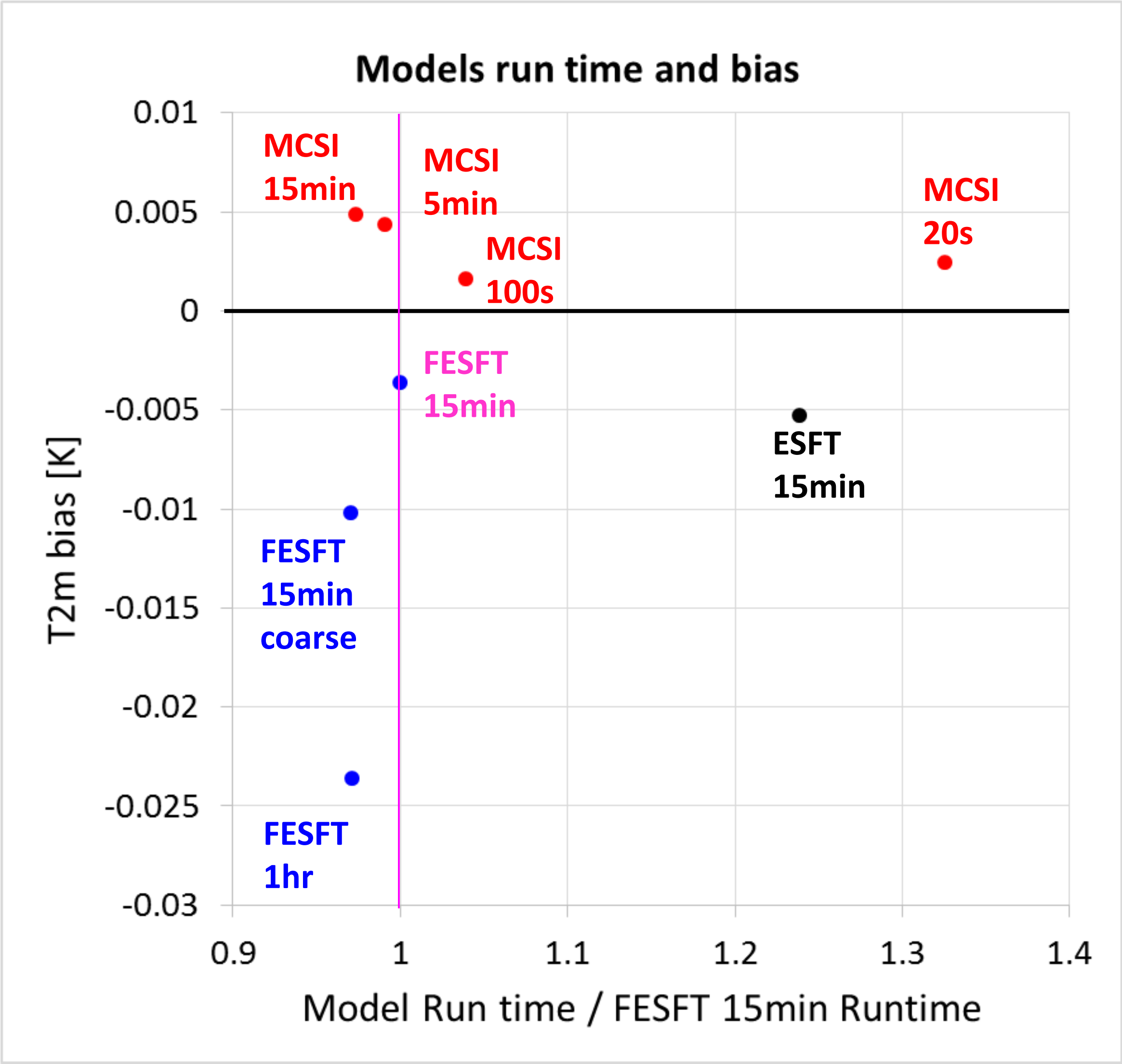
1^{st} day	ESFT		FESFT				MCSI			
Temporal Resolution	20s	15min	20s	15min (default)	15min coarse	1hr	20s	100s	5min	15min
Radiation cost [%]	730	28.93	156.69	4.09	1.00	1.15	38.02	8.20	3.14	1.34
Radiation cost compared to default	178	7.07	38.30	1	0.25	0.28	9.29	2.00	0.77	0.33
Total model runtime compared to default	7.97	1.24	2.47	1	0.97	0.97	1.33	1.04	0.99	0.97
T_{2m} RMSE [K]	0	0.134	0.067	0.133	0.151	0.213	0.106	0.136	0.170	0.218
T_{2m} Bias [K]	0	-0.005	0.001	-0.004	-0.010	-0.024	0.002	0.002	0.004	0.005
GR RMSE [W/m^2]	0	43.3	14.8	43.5	44.0	66.2	104.9	108.2	111.5	116.6
GR Bias [W/m^2]	0	-0.02	0.10	-0.14	-2.48	-3.71	0.11	0.05	0.39	0.89

* Averaged over 116,053 grid points and over 24h

Run Time & Errors Comparisons

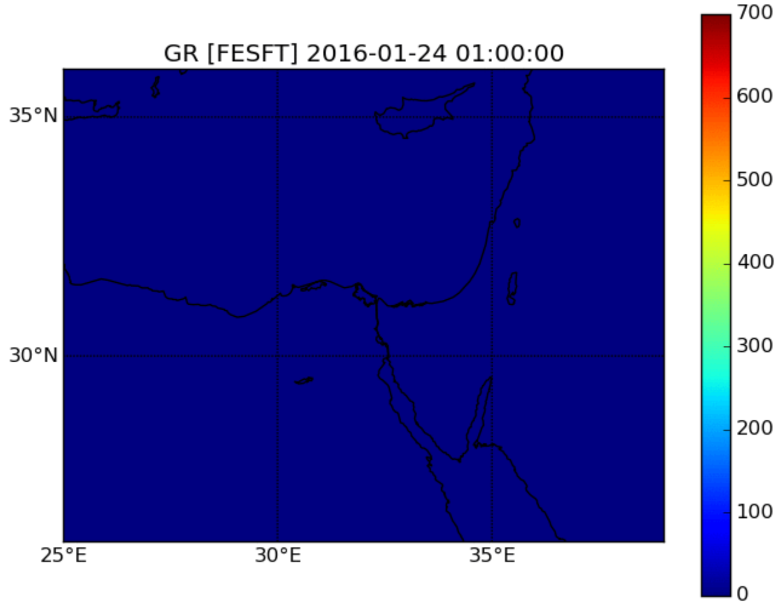


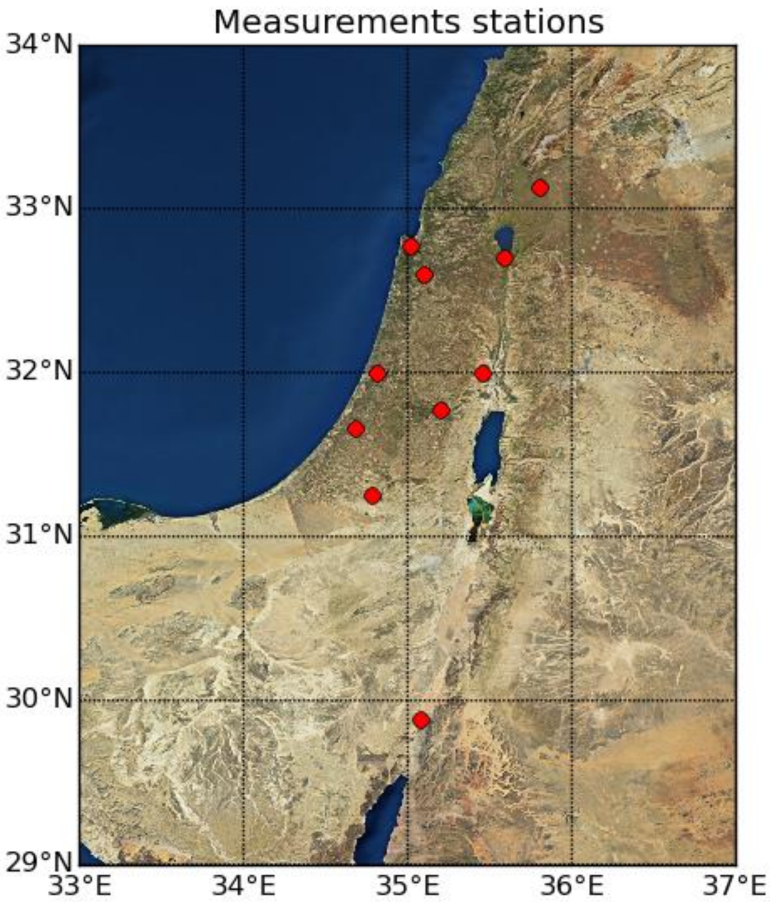
Run Time & Errors Comparisons



Testing MCSI Scheme vs. Ground Based Measurements

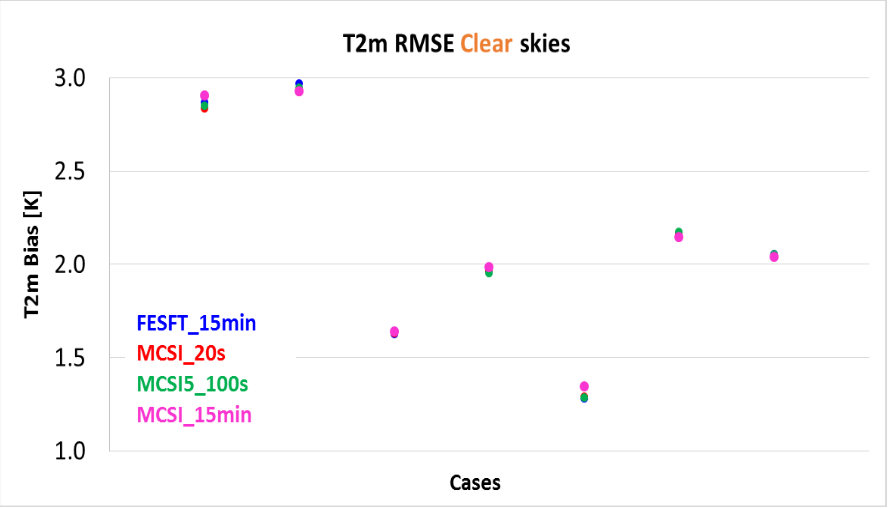
- **29 test cases** in different weather situations, lead time of 30h/42h
- **10** measurement stations – T2m validation
- Compare 3 models:
  - FESFT – 15 min / 45 steps
  - MCSI – 20 s / 1 step
  - MCSI – 100 s / 5 step
  - MCSI – 15 min / 45 steps

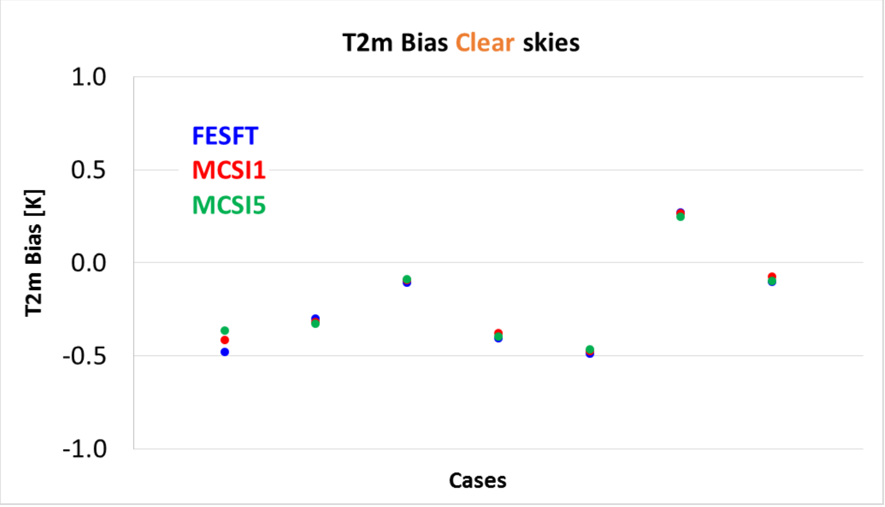




Testing vs. Ground Based Measurements

Clear skies





<u>T2m RMSE</u>:

FESFT_15min 2.13 [K]

MCSI_20s 2.12 [K]

MCSI_100s 2.13 [K]

MCSI_15min 2.14 [K]

<u>T2m bias</u>:

FESFT_15min -0.23 [K]

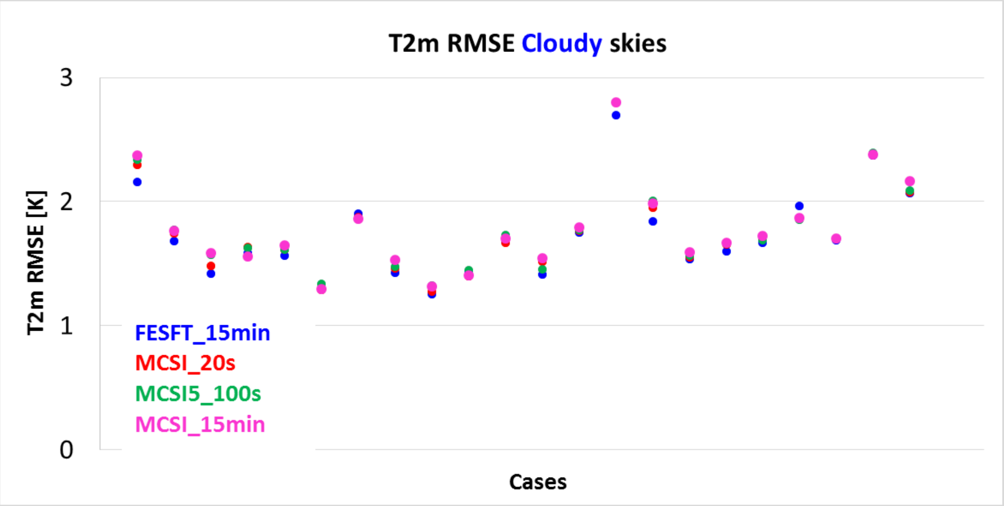
MCSI_20s -0.21 [K]

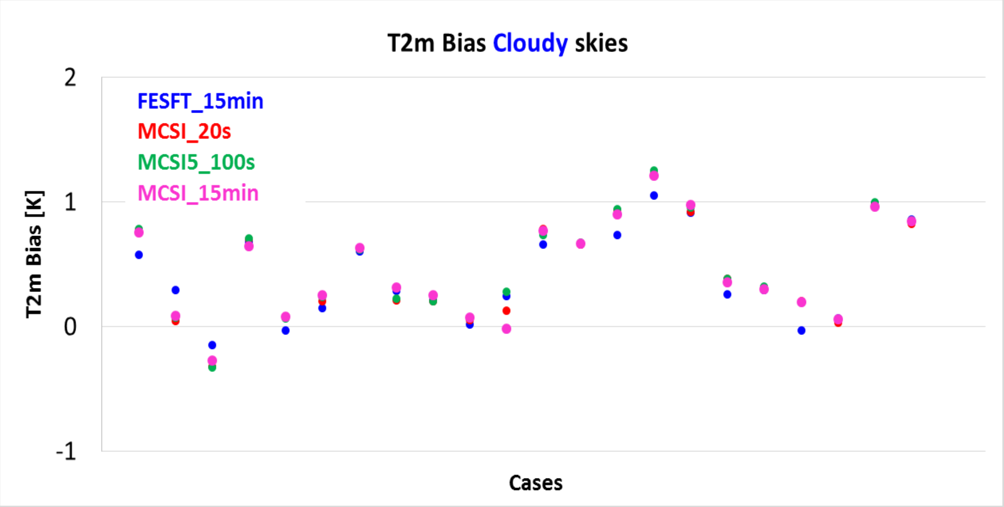
MCSI_100s -0.21 [K]

MCSI_15min -0.21 [K]

Testing vs. Ground Based Measurements

Cloudy skies





T2m RMSE:

FESFT_15min 1.73 [K]
MCSI_20s 1.76 [K]
MCSI_100s 1.78 [K]
MCSI_15min 1.79 [K]

T2m bias:

FESFT_15min 0.42 [K]
MCSI_20s 0.45 [K]
MCSI_100s 0.47 [K]
MCSI_15min 0.46 [K]

Summary

- “Full” radiation scheme calculations is impractical in NWP applications
- We can compromise on the : spatial, temporal or spectral resolutions
- Each has it own advantages and disadvantages. The MCSI greatest strength is that the “dilution” of computations is wise and based on statistical reasoning
- The MCSI is now implemented in COSMO (itype_mcsi = 1) gives a reasonable and comparable results in both CPU and performance to the default FESFT scheme
- MCSI did not show a significant advantage to the FESFT which deserves a change in the default scheme choice
- Nevertheless, the tests shown here were done on 2.8 km / 20 seconds model resolution. It is possible that MCSI can be preferable when using different model uses (climate, LES) and model resolutions.