Refractivity fluctuations as a systematic error source in radio occultations

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Negative N-bias

COSMIC/OCC–ECMWF differences: 2007, 2008, 2009

Change in ECMWF cycle 32r3, 2008:
- i) COSMIC RO assimilated to surface
- ii) updated convection and entrainment physics

<u>Sources of negative N-bias:</u>

-Super refraction

-Deep occultations

-Horizontal gradients (inversion with Wigner distribution function; TFMs)

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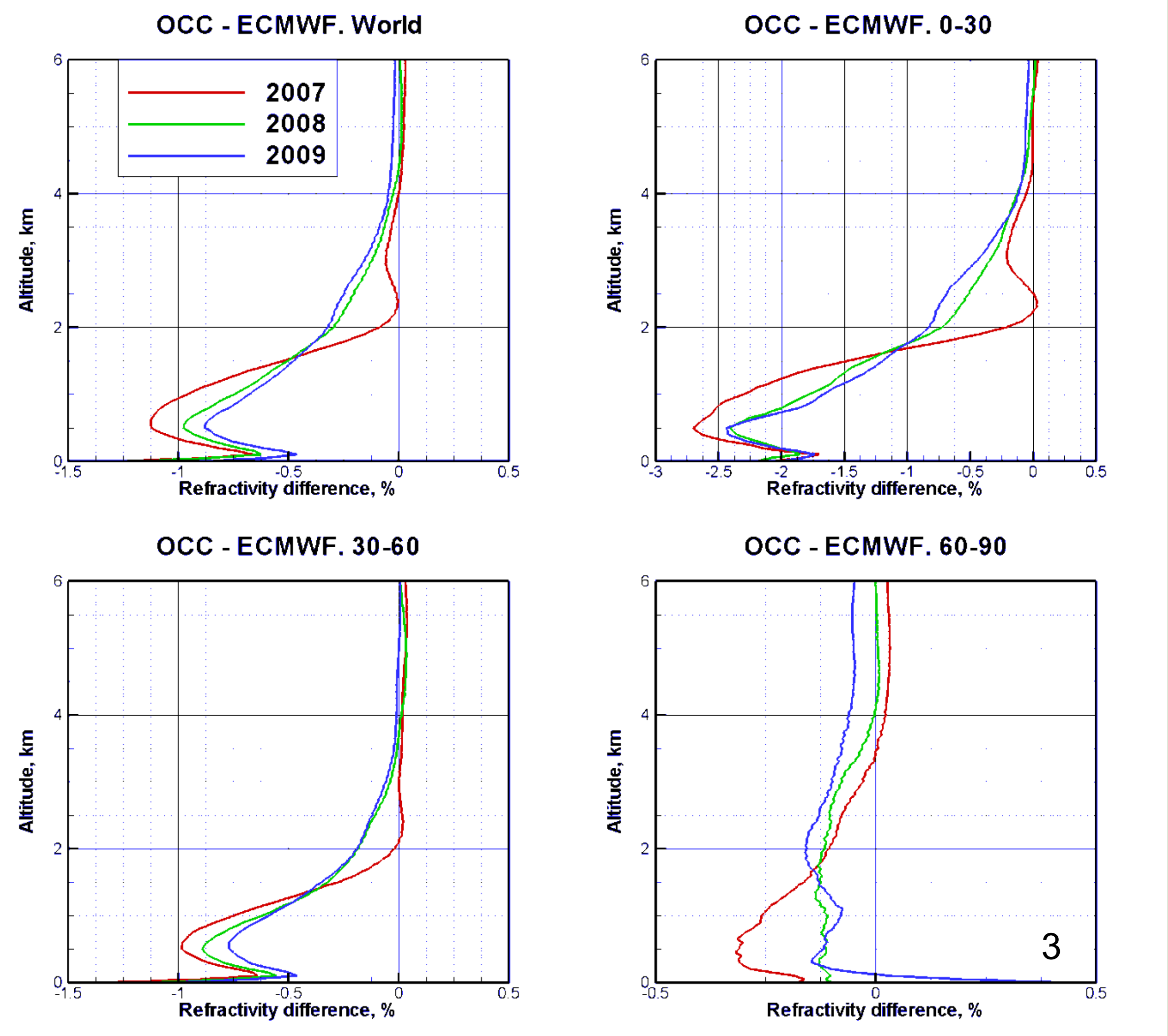


Negative N-bias

Von R. Eshleman and Bjarne S. Haugstad, *Lowest-order Average Effect of Turbulence on Atmospheric Profiles Derived from Radio Occultation*,
The Astrophysical Journal, 214:928-933, 1977

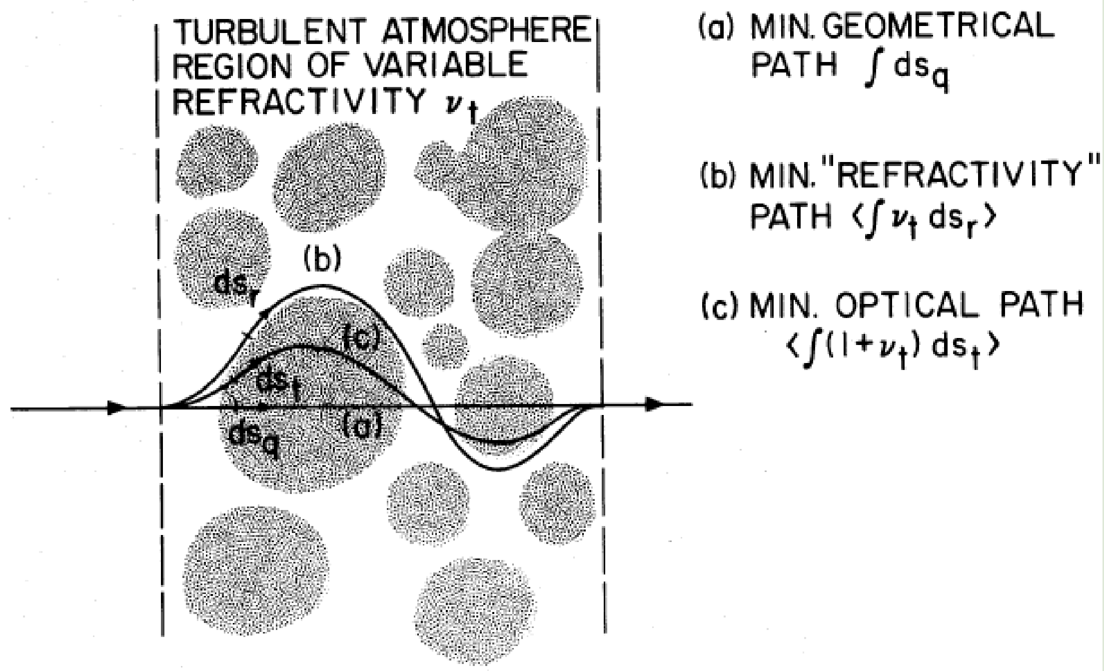
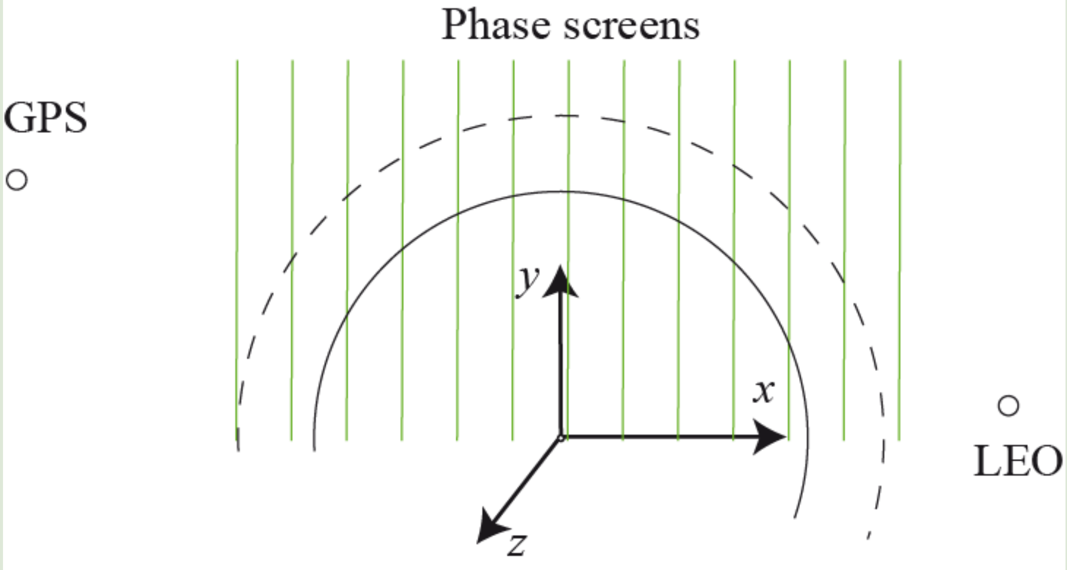


FIG. 3.—Minimum paths for a turbulent medium

Due to the Fermat principle, each ray tends to choose a path through negative fluctuations of refractivity

Phase screens



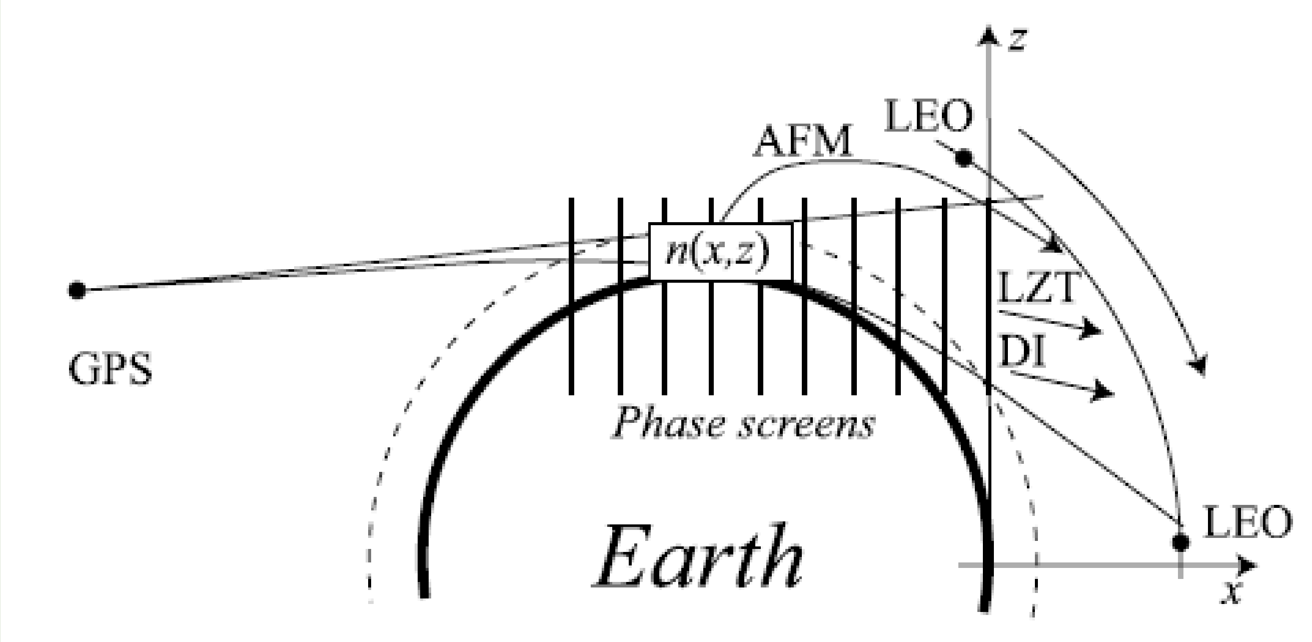
1. Vacuum propagation from GPS to the 1st screen
2. Screen-to-screen propagation:

$$u_{j+1} = \exp\left(ik \int_{x_j}^{x_{j+1}} n\left(x, y\right) dx \right) F^{-1}_{\eta \to y} \exp\left(\sqrt{1 - \eta^2}\, \Delta x \right) F_{y \to \eta} u_j$$

3. Vacuum propagation from the last screen to the LEO orbit

Propagation from the Last Screen

M. E. Gorbunov and K. B. Lauritsen, *Linearized Zverev Transform and its application for modeling radio occultations*, Radio Science, V. 42, RS3023, doi: 10.1029/2006RS003590, 2007



LZT:
Linear
Zverev
transform

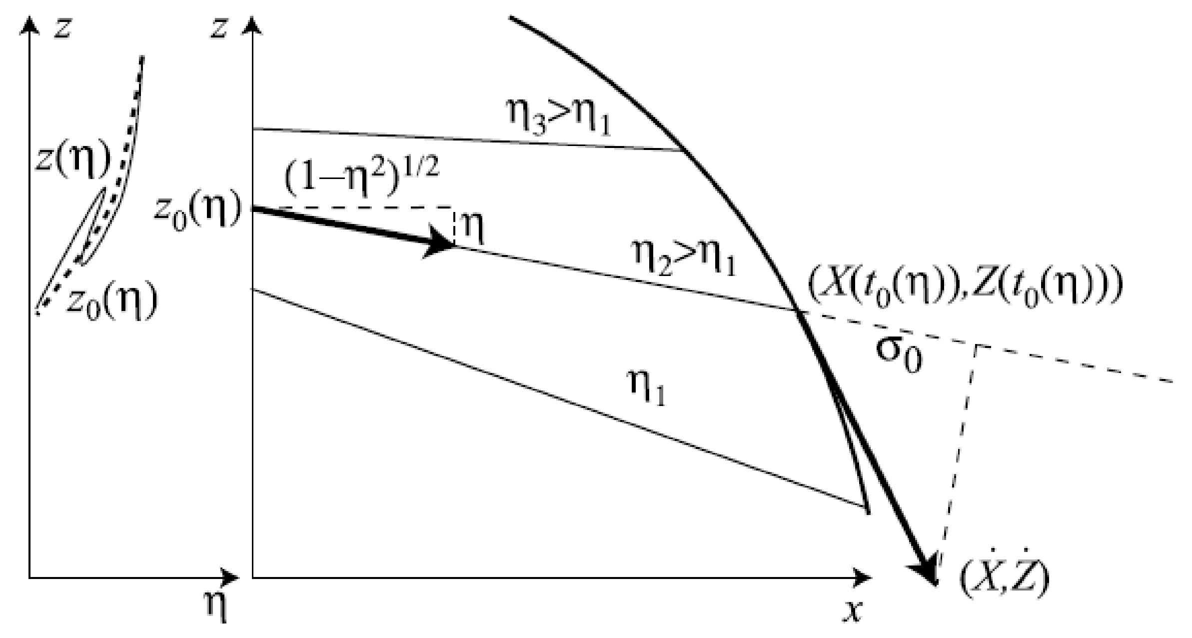
AFM:
Asymptotic
forward
modelling

Diffractive integral (DI):

$$u(t) = \sqrt{\frac{ik}{2\pi}} \int u_0(z) \cos\varphi(z,t) \frac{\exp(ikr(z,t))}{\sqrt{r(z,t)}}\, dz.$$

Propagation from the Last Screen

FIO2 operator linearized:



Linearized Zverev Transform (LZT):

$$u(t) = \sqrt{\frac{ik}{2\pi}} \exp\left(ik \int g(t)dt\right) \times \int \exp(ikt\xi) \frac{\exp\left(-ik \int f(\xi)d\xi\right)\tilde{u}_0(\eta(\xi))}{\dot{Z}(t_0(\xi)) - \dot{X}(t_0(\xi)) \frac{\eta(\xi)}{\sqrt{1-\eta(\xi)^2}}} d\xi.$$

Turbulence Model

Correlation function:

$$\left\langle N(\mathbf{r}_1) N(\mathbf{r}_2) \right\rangle = \int \exp\left(i\boldsymbol{\kappa}(\mathbf{r}_1 - \mathbf{r}_2)\right) \Phi_N(\boldsymbol{\kappa}) d^3\boldsymbol{\kappa}$$

$N(\mathbf{r})$ - turbulent fluctuations of refractivity

$\Phi_N(\boldsymbol{\kappa})$ - turbulence spectrum

Kolomogorov – van Kármán power law isotropic spectrum:

$$\Phi_N(\kappa) = 0.033\, C_n^2 \left(\kappa^2 + \kappa_0^2\right)^{-11/6} \exp\left(-\kappa^2 / \kappa_m^2\right)$$

$\kappa_0 = 2\pi / L_0$	L_0	- external scale
$\kappa_m = 5.92 / \lambda_0$	λ_0	- internal scale

Turbulence Model

Generic power-law spectrum with constant anisotropy:

$$\Phi_N(\kappa) = A\left(\kappa_y^2 + \eta\left(\kappa_x^2 + \kappa_z^2\right) + \kappa_0^2\right)^{-\mu/2} \exp\left(-\kappa^2 / \kappa_m^2\right)$$

A. S. Gurvich and V. Kan, *Structure of air density fluctuations from cosmic observations of star scintillations: 1. 3D spectrum model and retrieval of its parameters*, Izvestiya, Oceanic and Atmospheric Physics, 2003, 38, No 3, p. 300-310.

A. S. Gurvich and V. L. Brekhovskikh, *Study of the turbulence and inner waves in the stratosphere based on the observations of stellar scintillations from space: a model of scintillation spectra*, Waves Random Media 11 (2001) 163-181.

$\mu = 5$ for internal gravity waves

$\eta \sim 30 - 100$

Turbulence Model

Optical path fluctuations:

$$\Psi(x,\Delta x,y,z) = \int_{x}^{x+\Delta x} N(x',y,z)\,dx'$$

$$\left\langle \Psi(x,\Delta x,y',z')\,\Psi(x,\Delta x,y'',z'') \right\rangle =$$

$$= \int \exp\left(i\mu_y\left(y'-y''\right) + i\mu_z\left(z'-z''\right)\right)\Phi_\Psi(\boldsymbol{\mu})\,d\mu_y\,d\mu_z$$

$$\Phi_\Psi(\boldsymbol{\mu}) = \Delta x^2 \int \mathrm{sinc}^2\left(\frac{\Delta x\,\kappa_x}{2}\right)\Phi_N\left(\kappa_x,\mu_y,\mu_z\right)d\kappa_x$$

Thick layer approximation:

$$\Phi_\Psi(\boldsymbol{\mu}) = 2\pi\,\Delta x\,\Phi_N\left(0,\mu_y,\mu_z\right)$$

$$\Phi_\Psi^{1D}(\mu_z) = \int \Phi_\Psi(\boldsymbol{\mu})\,d\mu_y$$

WOP simulation results

ECMWF: local N-profile

COSMIC: BA, N obtained from CT2-retrieval of COSMIC data

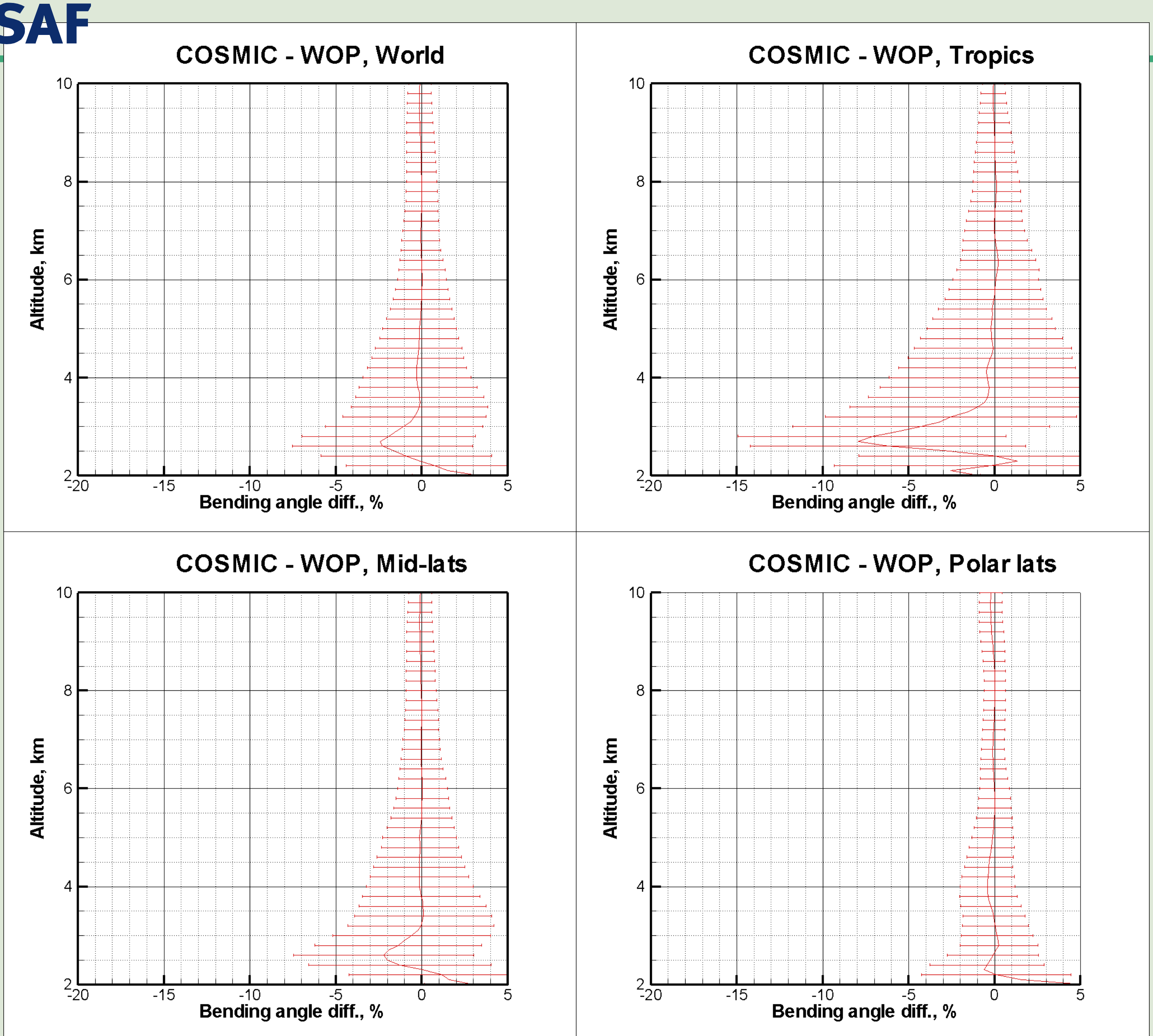
WOP: Simulation with ECMWF field without turbulence; BA, N obtained from CT2

WOP_turb: Simulation with turbulence; BA, N obtained from CT2

a) weak turbulence
b) strong turbulence (twice as strong as (a))

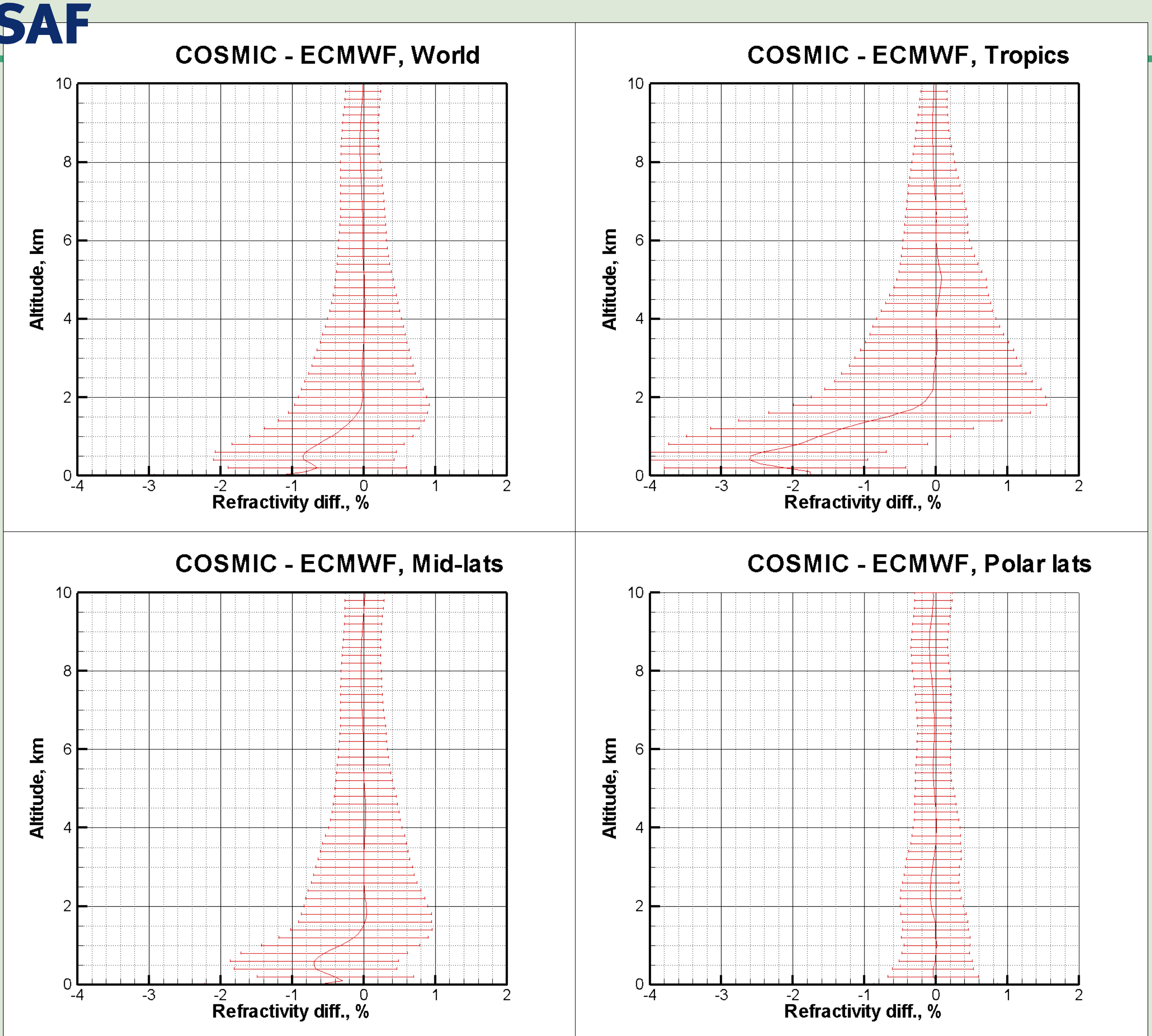
Strong turbulence

1)



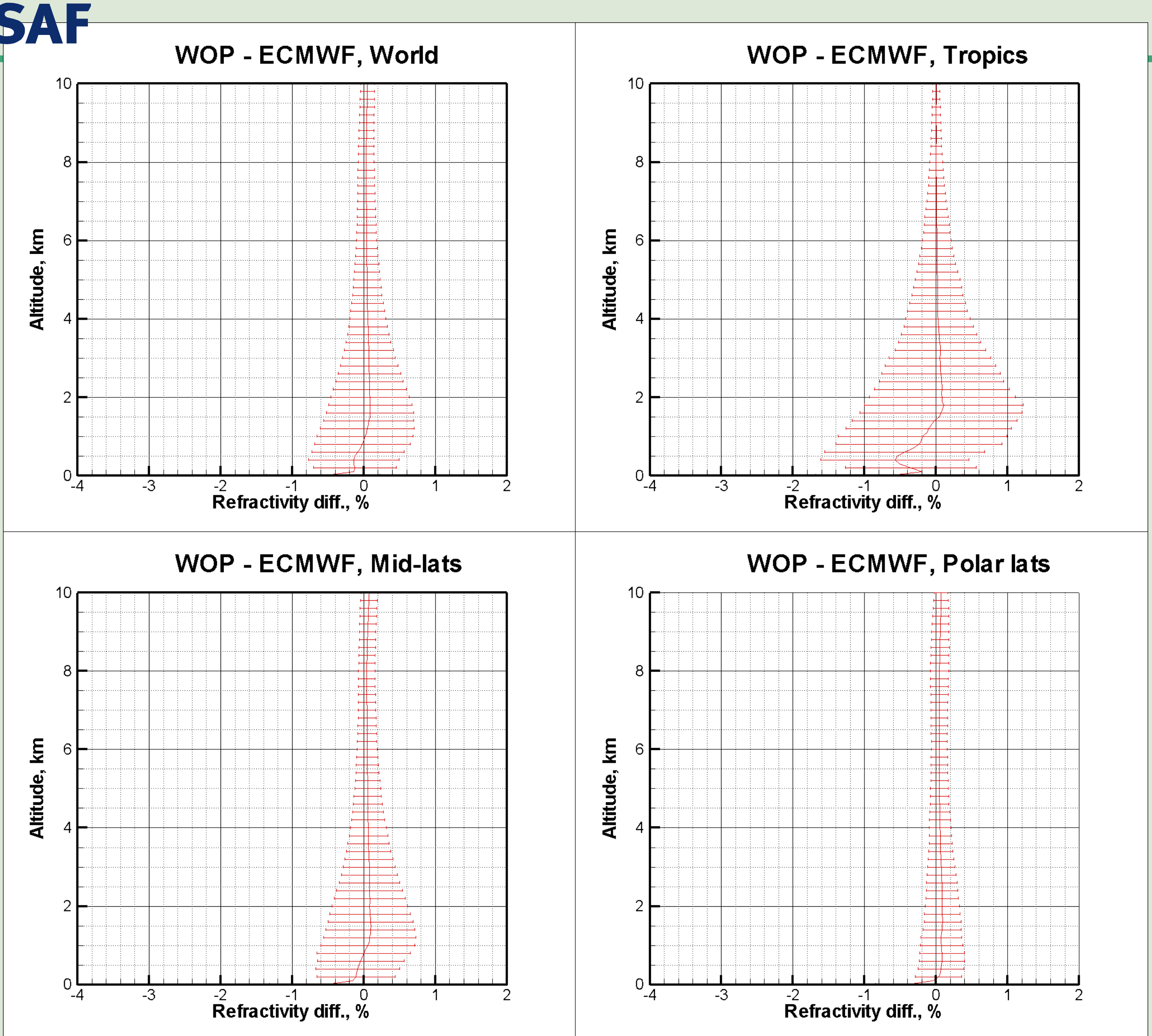
Strong turbulence

2)



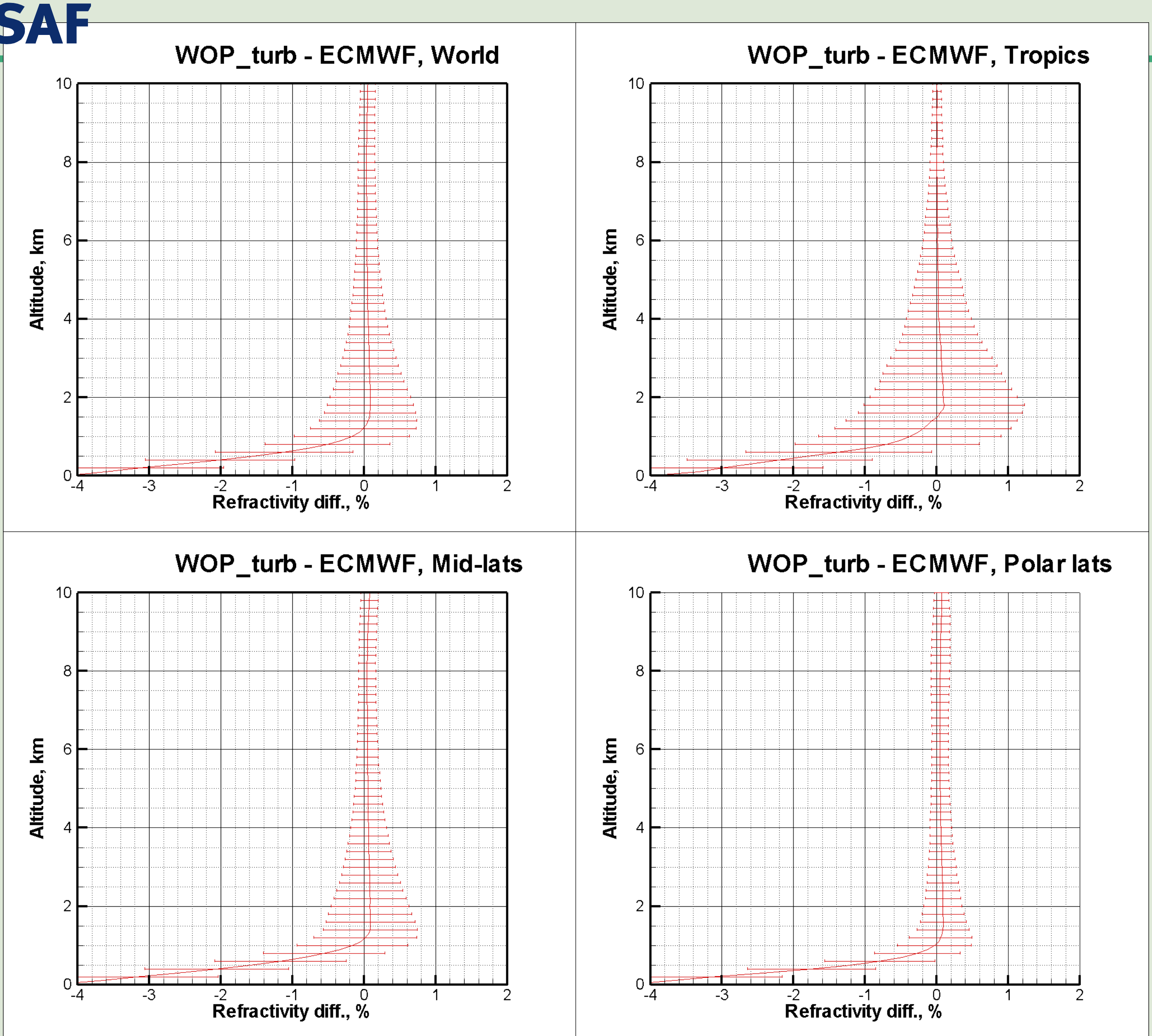
Strong turbulence

3)



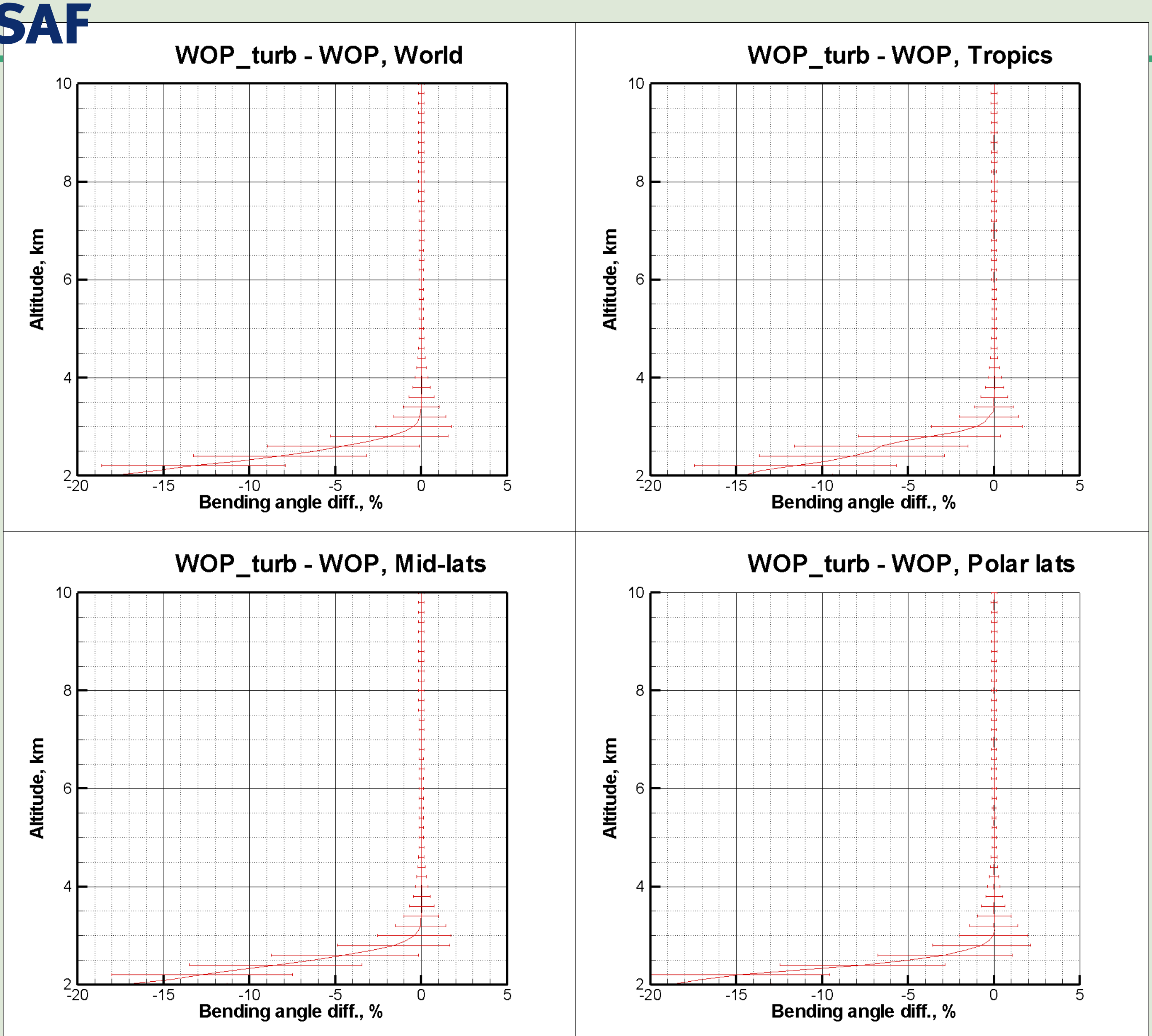
Strong turbulence

4)



Strong turbulence

5)



WOP_turb - WOP, World

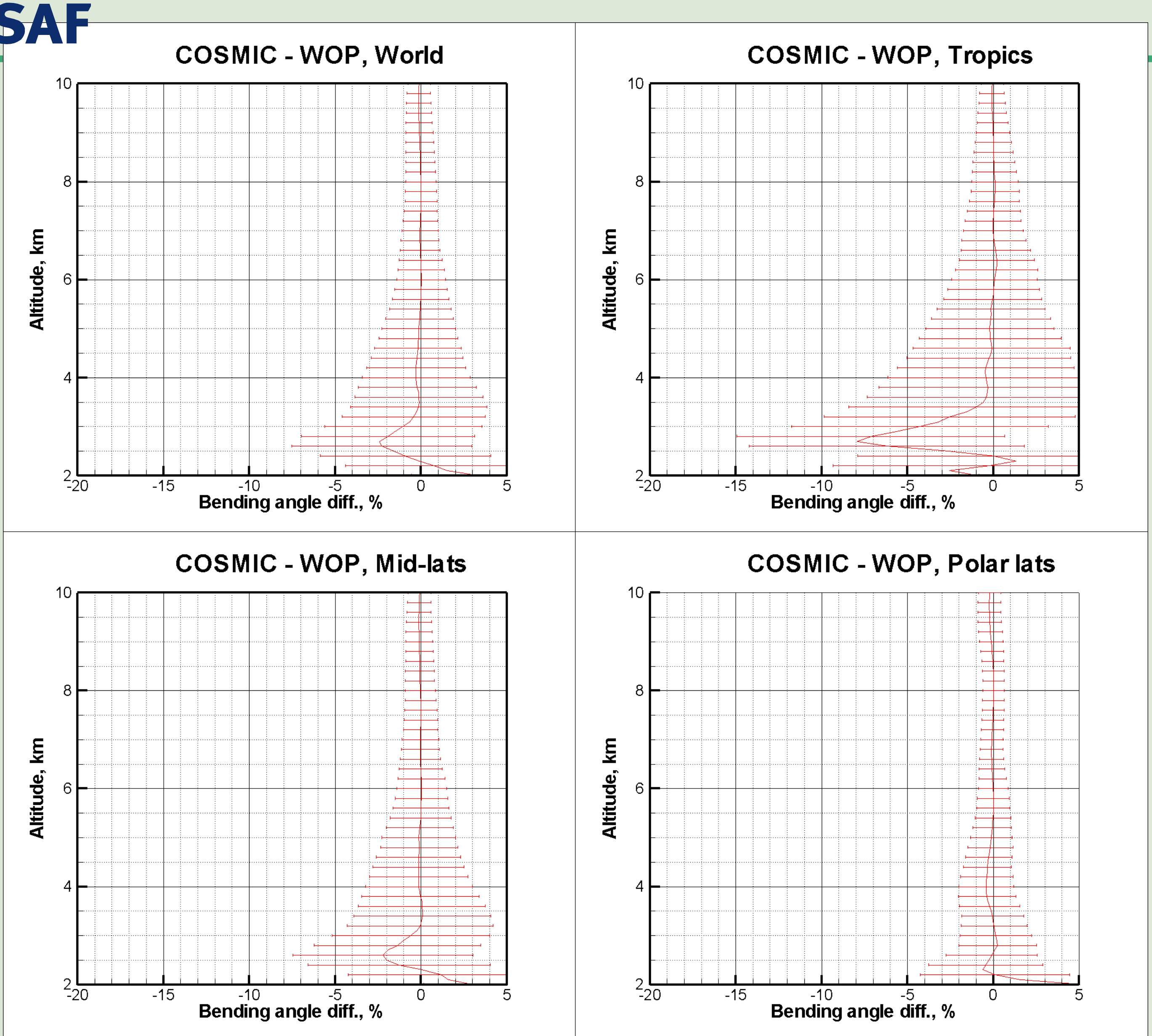
WOP_turb - WOP, Tropics

WOP_turb - WOP, Mid-lats

WOP_turb - WOP, Polar lats

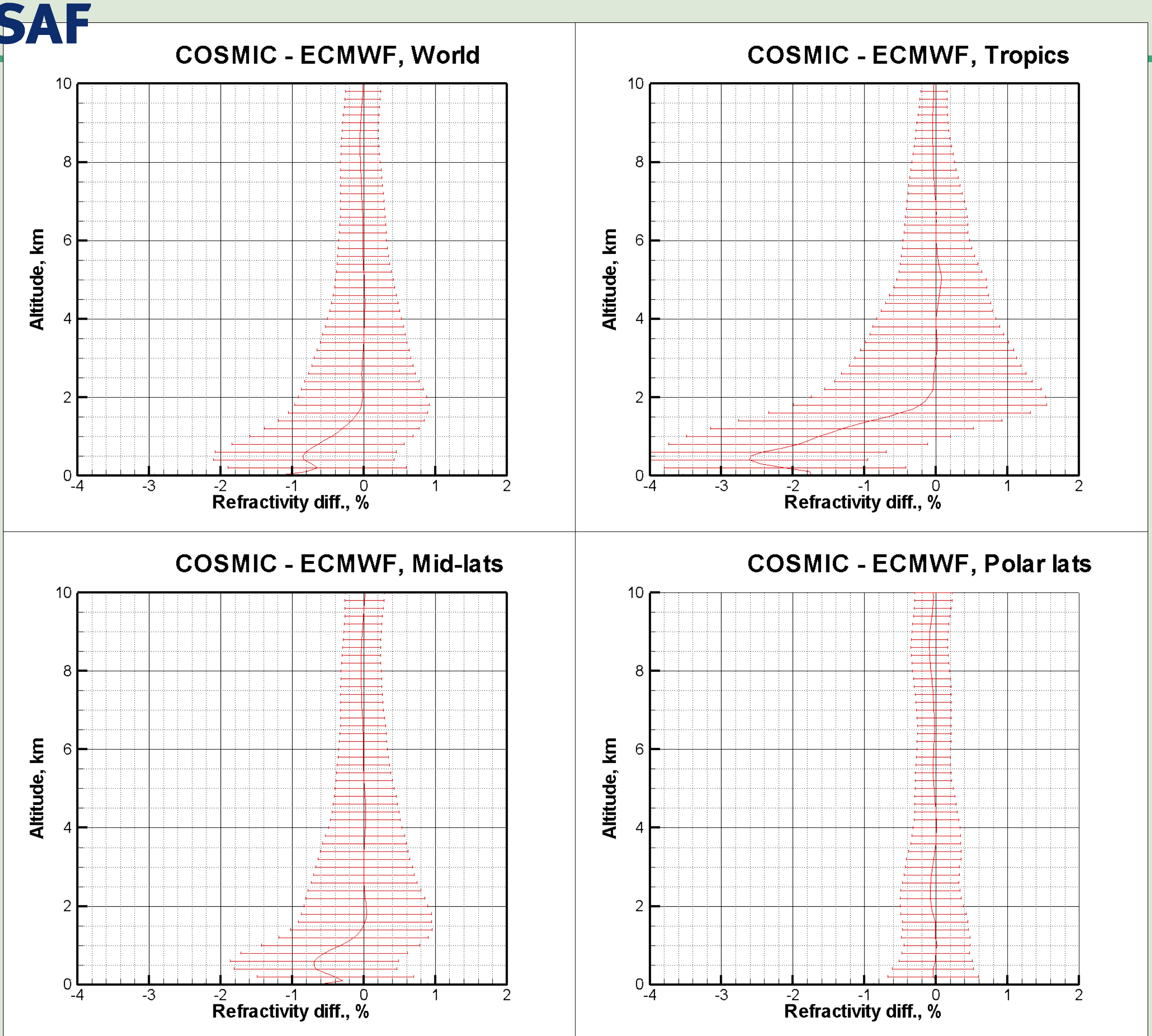
Weak turbulence

1)



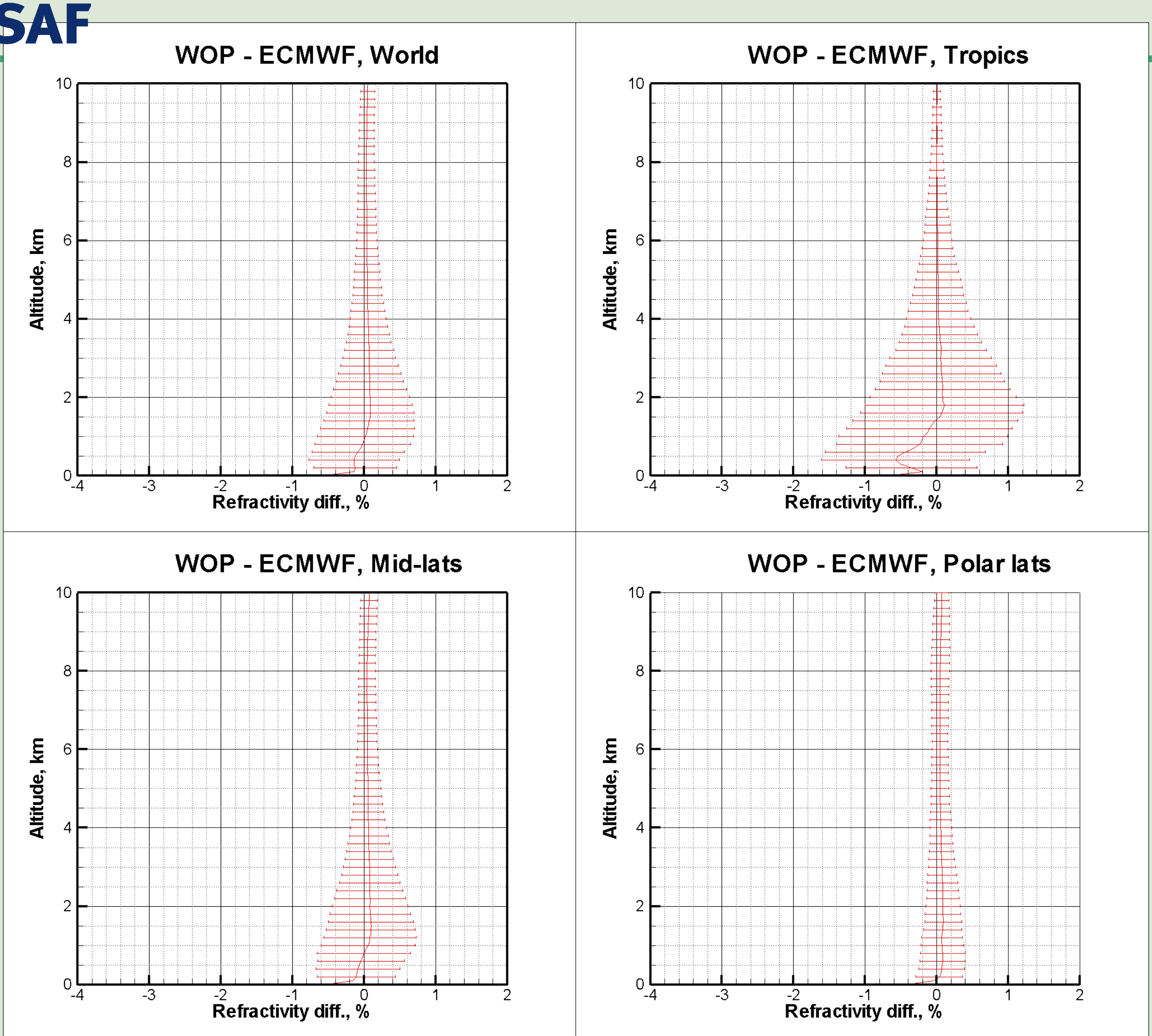
Weak turbulence

2)



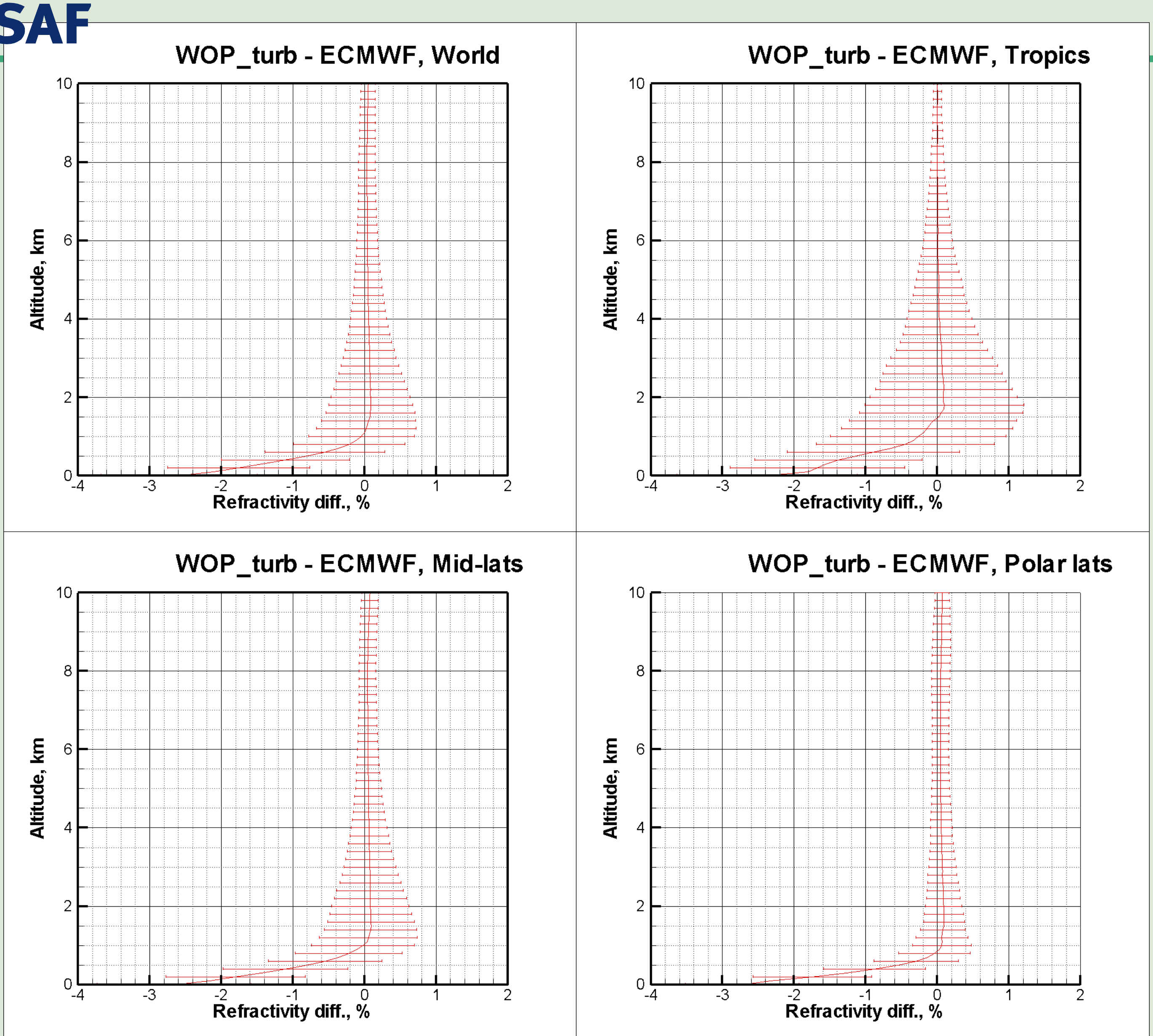
Weak turbulence

3)



Weak turbulence

4)



WOP_turb - ECMWF, World

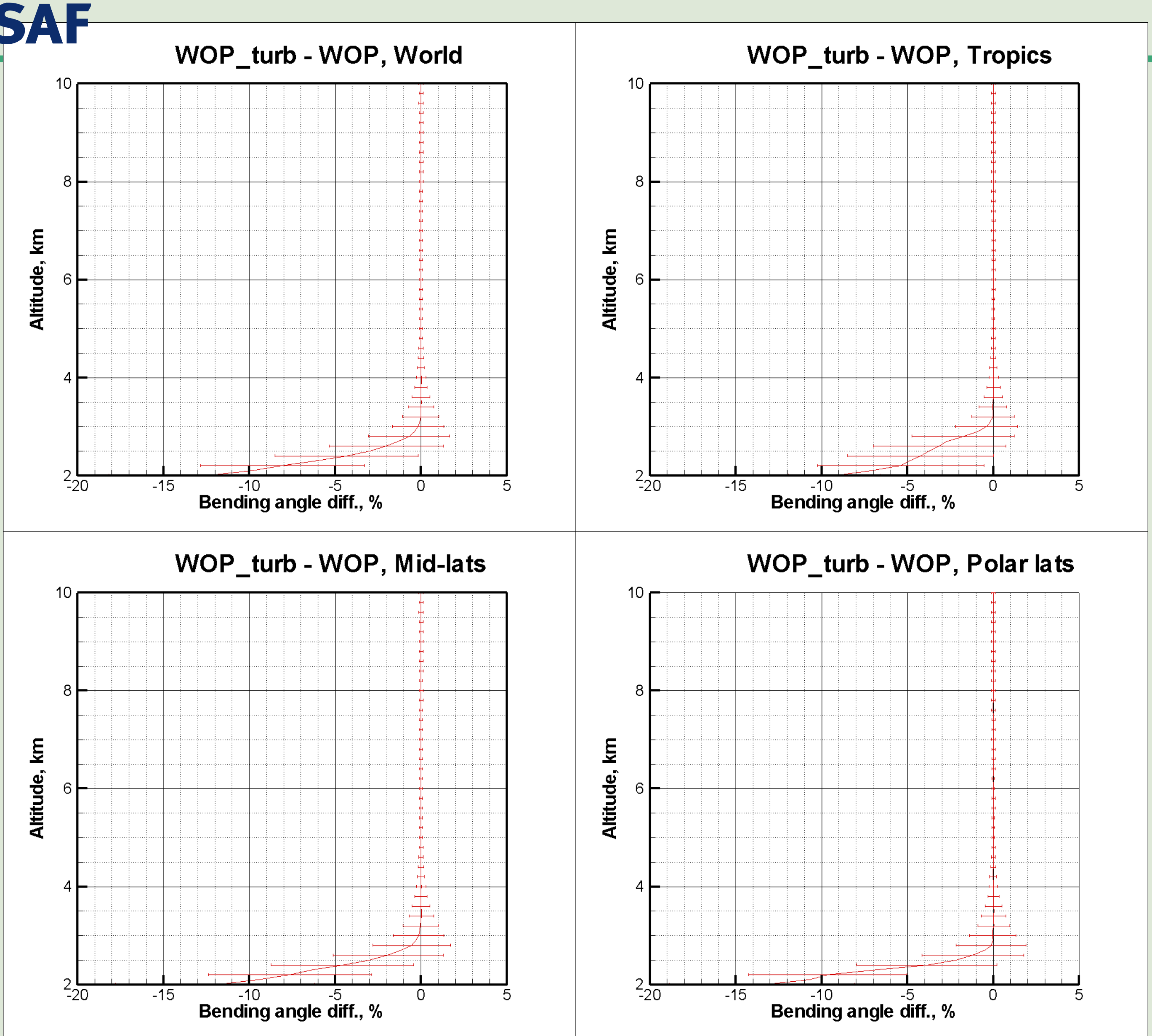
WOP_turb - ECMWF, Tropics

WOP_turb - ECMWF, Mid-lats

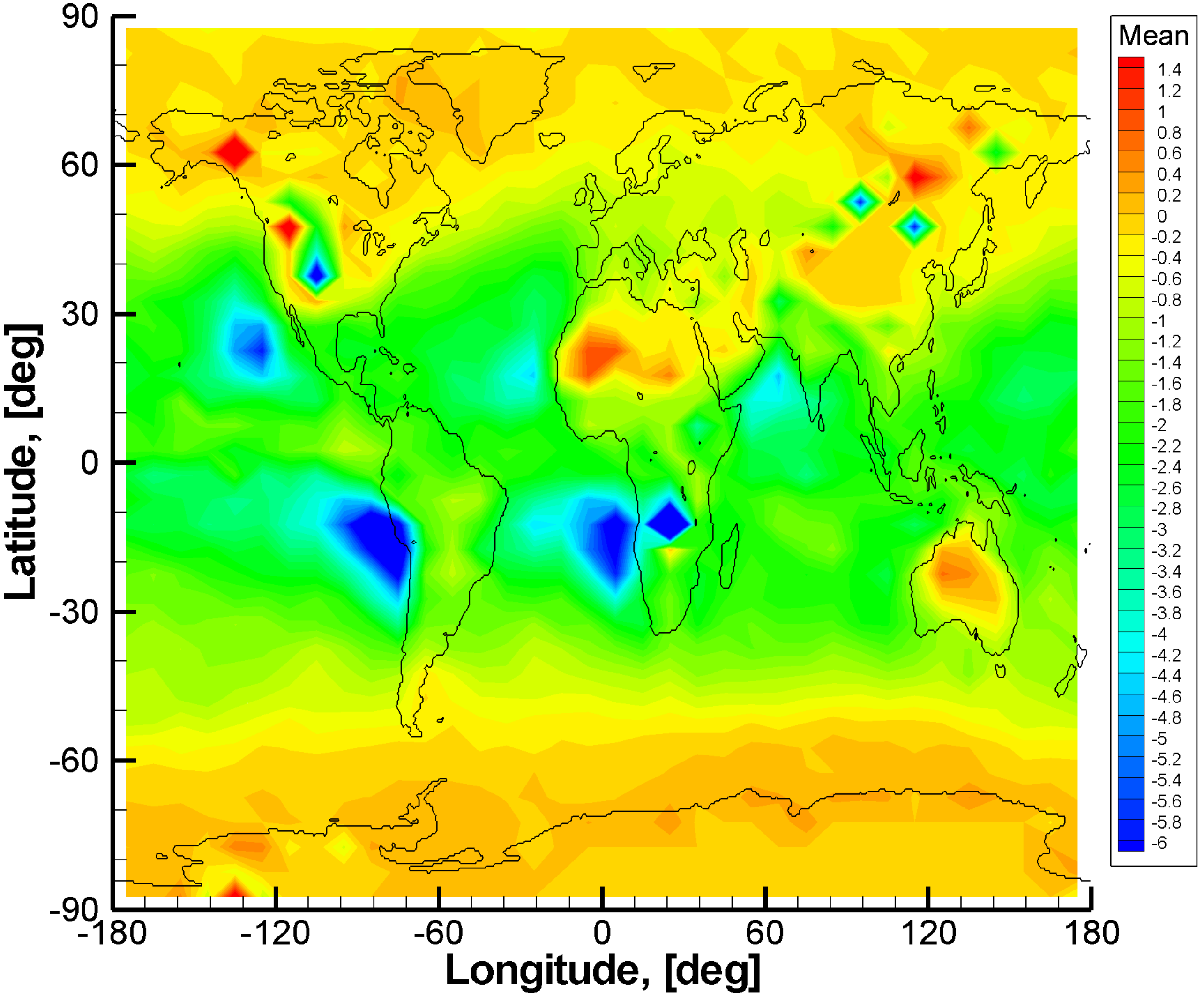
WOP_turb - ECMWF, Polar lats

Weak turbulence

5)

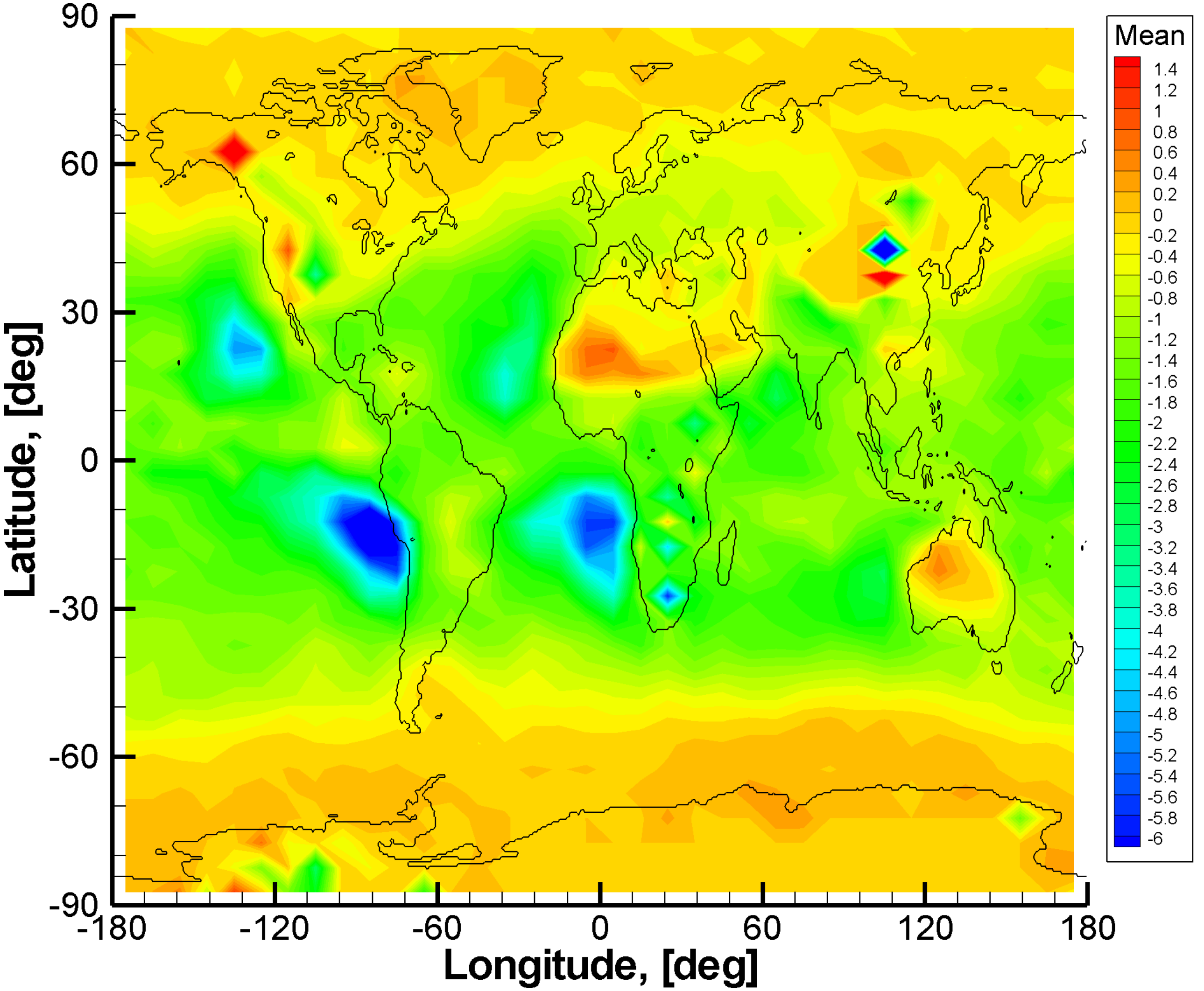


COSMIC Statistics



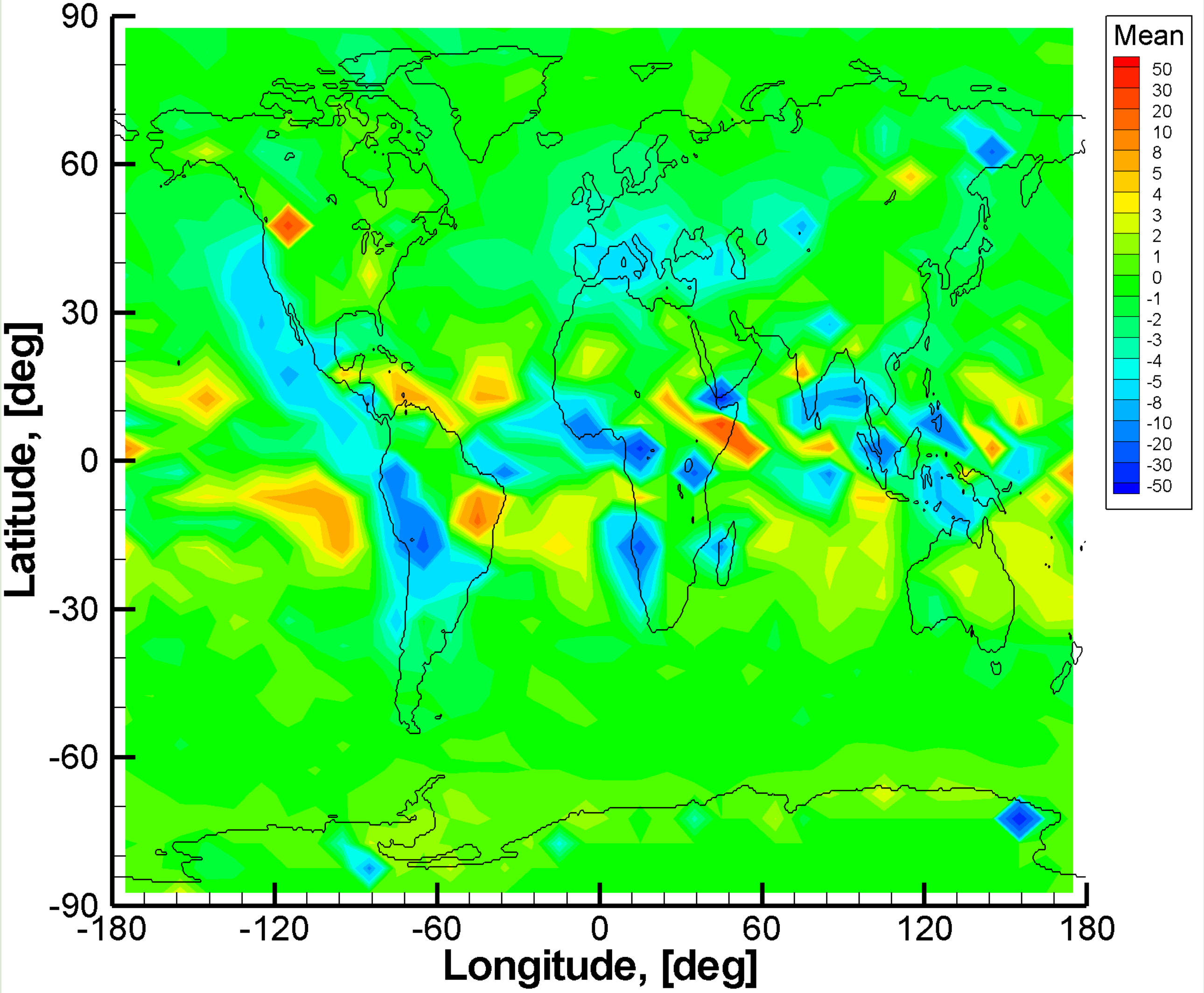
COSMIC–ECMWF refractivities (O-B/B, %) at an altitude of 0.6 km

COSMIC Statistics



COSMIC–ECMWF refractivities (O-B/B, %) at an altitude of 0.8 km

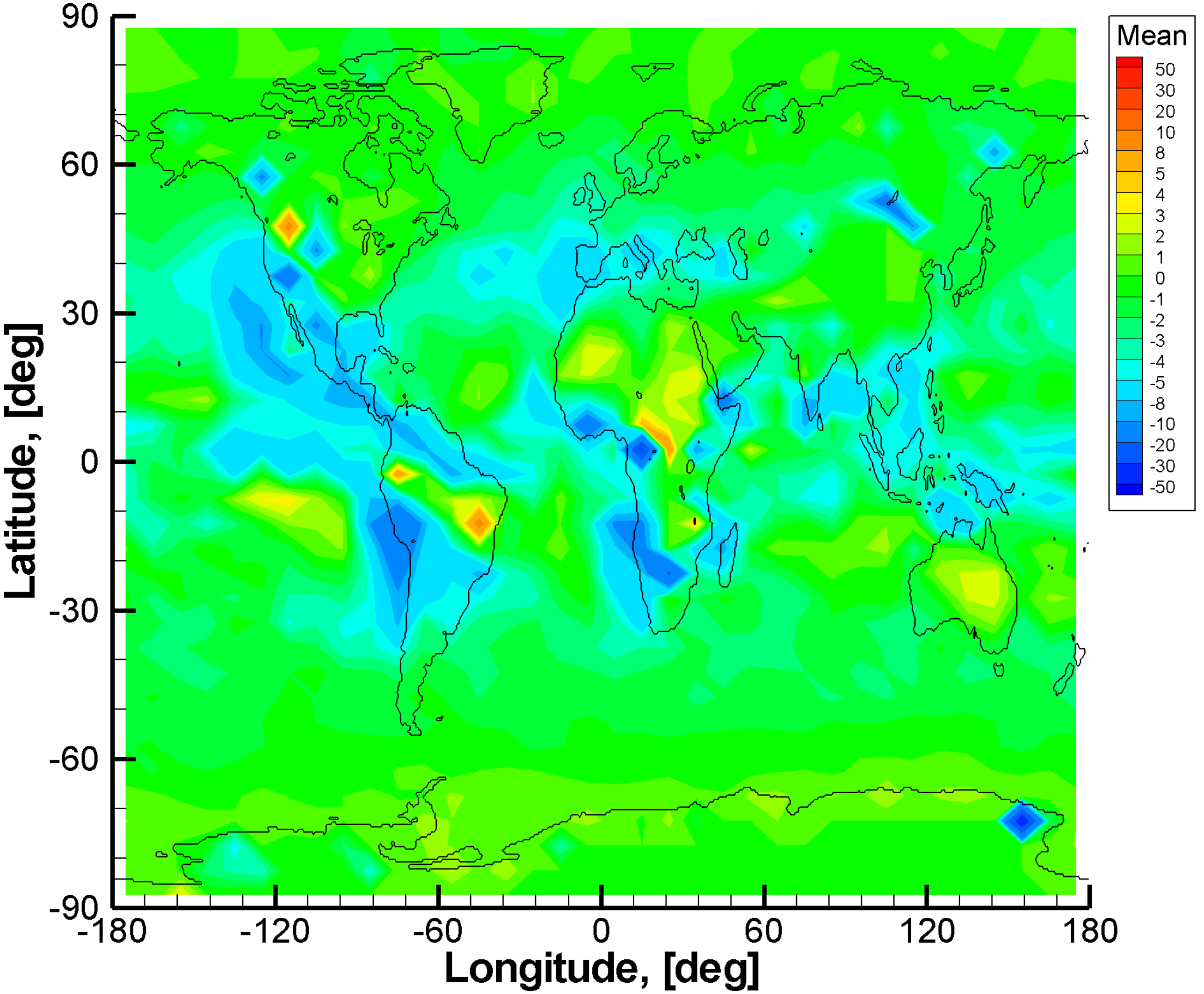
COSMIC Statistics



COSMIC–ECMWF bending angles (O-B/B, %) at an impact height of 2.4 km

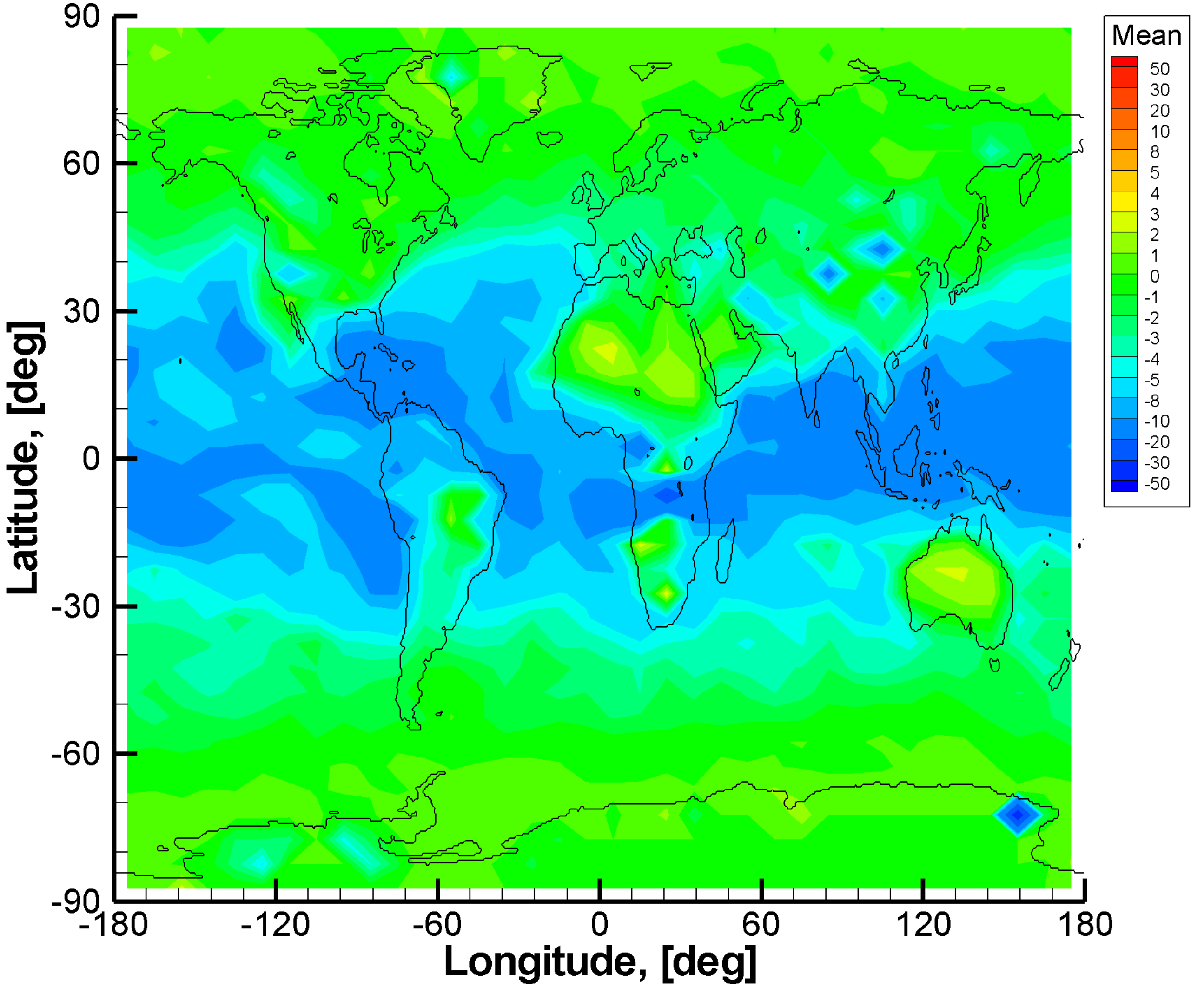
ROM SAF

COSMIC Statistics



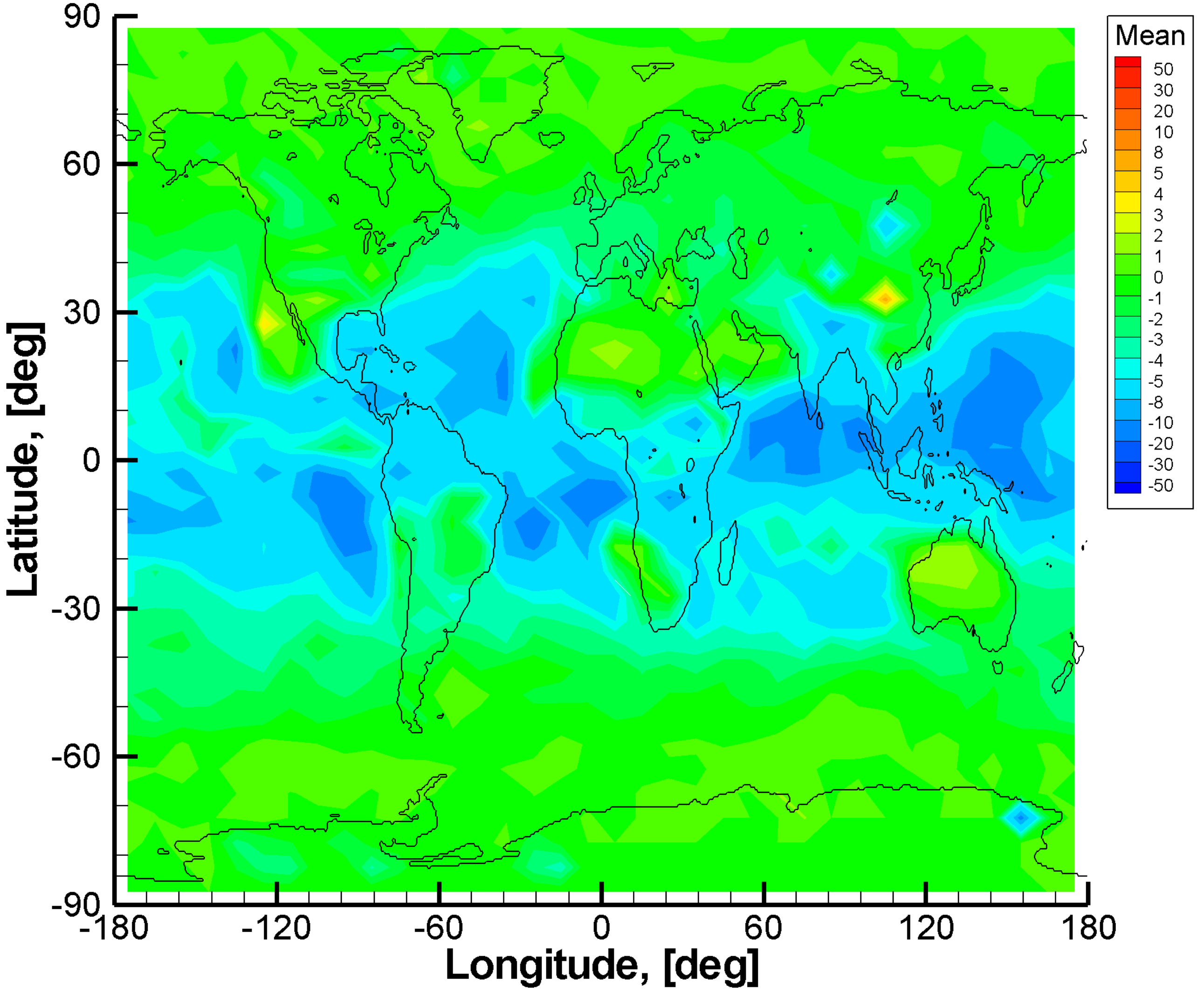
COSMIC–ECMWF bending angles (O-B/B, %) at an impact height of 2.5 km

COSMIC Statistics



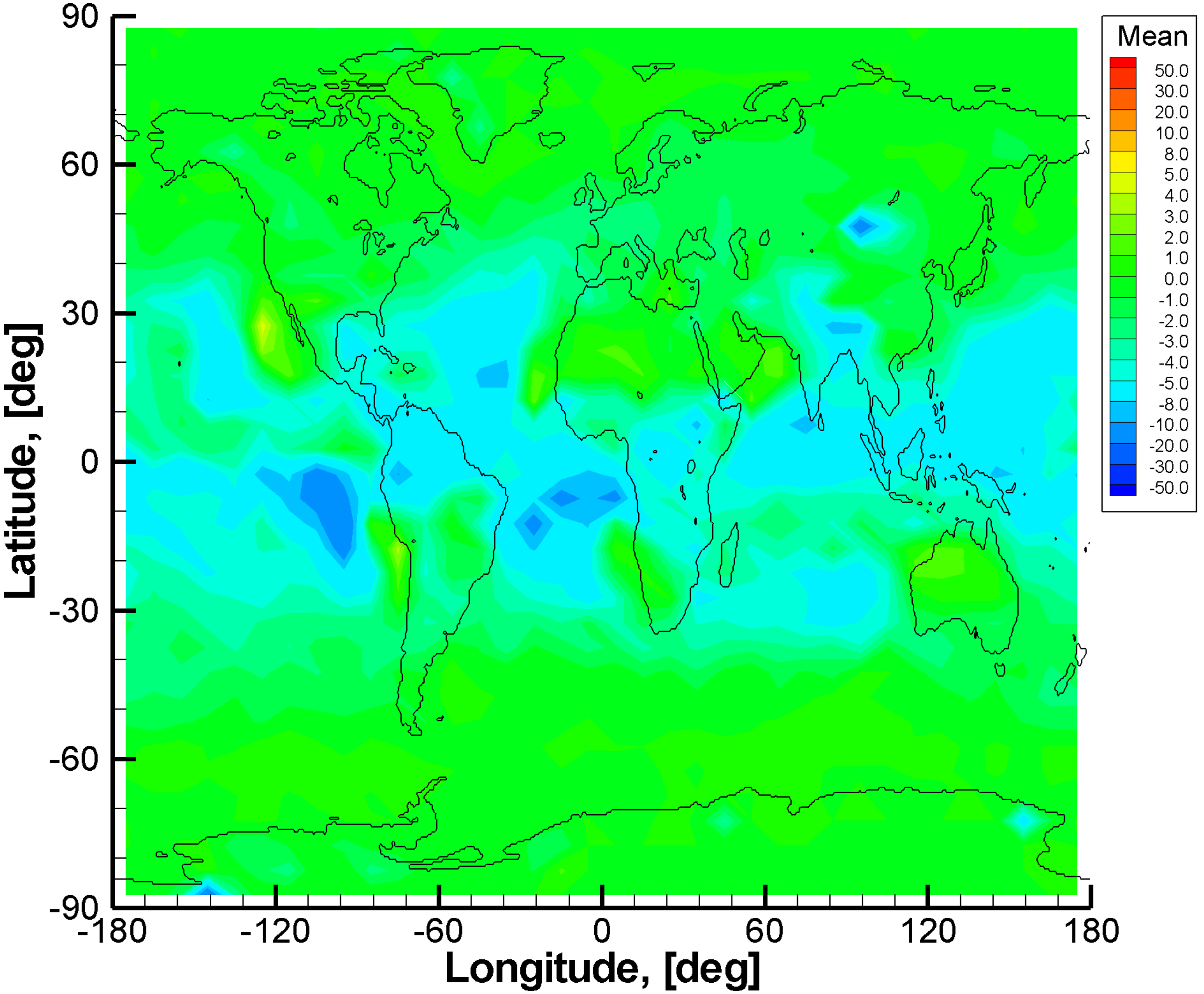
COSMIC–ECMWF bending angles (O-B/B, %) at an impact height of 2.7 km

COSMIC Statistics



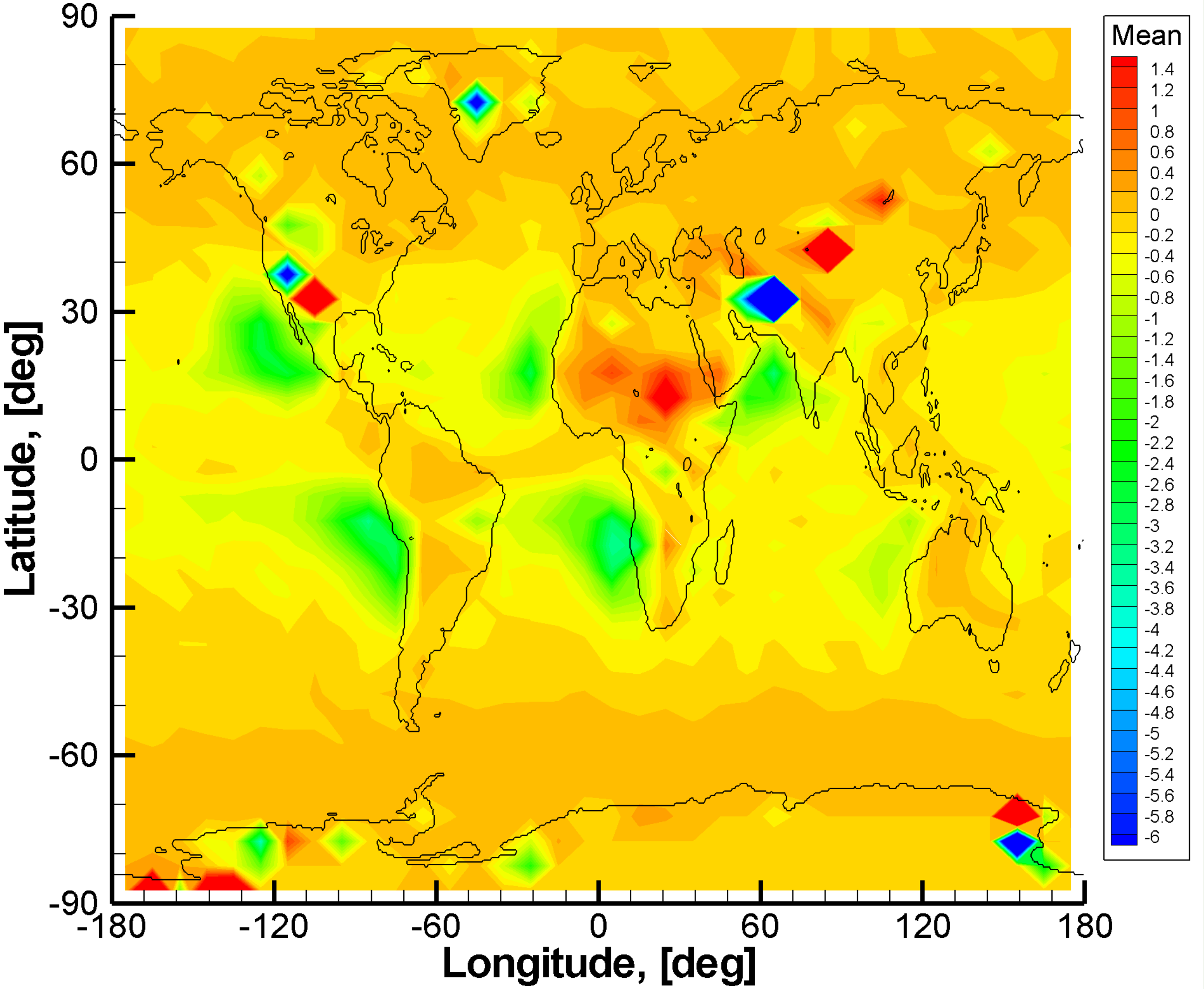
COSMIC–ECMWF bending angles (O-B/B, %) at an impact height of 2.9 km

COSMIC Statistics



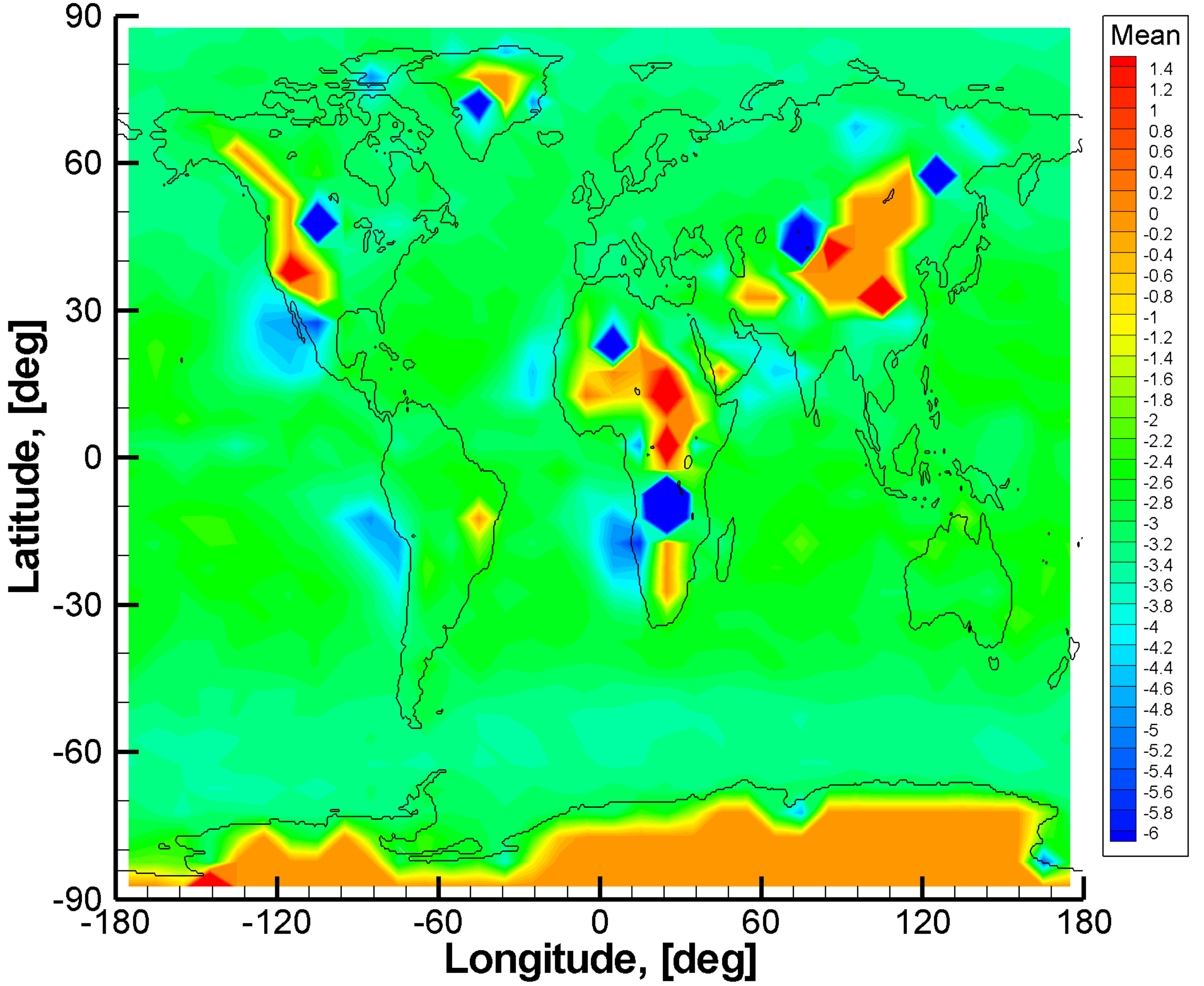
COSMIC–ECMWF bending angles (O-B/B, %) at an impact height of 3.0 km

ECMWF-based Simulation



WOP–ECMWF refractivity retrieval error (O-B/B, %) at an altitude of 0.5 km

ECMWF-based Simulation



WOP_turb–ECMWF refractivity retrieval error (O-B/B, %) at an altitude of 0.5 km

Conclusions

1. Fluctuations as one of the sources of systematic RO retrievals error has been considered early by Eshleman and Haugstad (1977).
2. A simple theoretical explanation of this effect is based on the Fermat principle. However, accurate theoretical estimates for decimeter radio waves taking into account regular refraction and realistic fluctuation levels are not straightforward.
3. To arrive at estimates of this effect we performed numerical simulations by the phase screen method with a fluctuating component in the phase screen optical paths.
4. The fluctuations we are cnsidering are not necessarily turbulence. They belong to a larger scale range. We use an effective Kolmogorov – van Kármán spectrum with parameters tuned in such a way to comply with typical amplitude fluctuation strength.
5. We show that it is possible to obtain realistic magnitudes of the N-bias in the simulated retrievals.

Acknowledgments

This work was supported by a Visiting Scientist activity by the Radio Occultation Meteorology Satellite Application Facility (ROM SAF) and by the Russian Foundation for Basic Research (grant 12-05-00335-a)