

Effects and magnitudes of some specific errors of GPS RO data and assumptions used in their processing

(inversion biases in the stratopshere)

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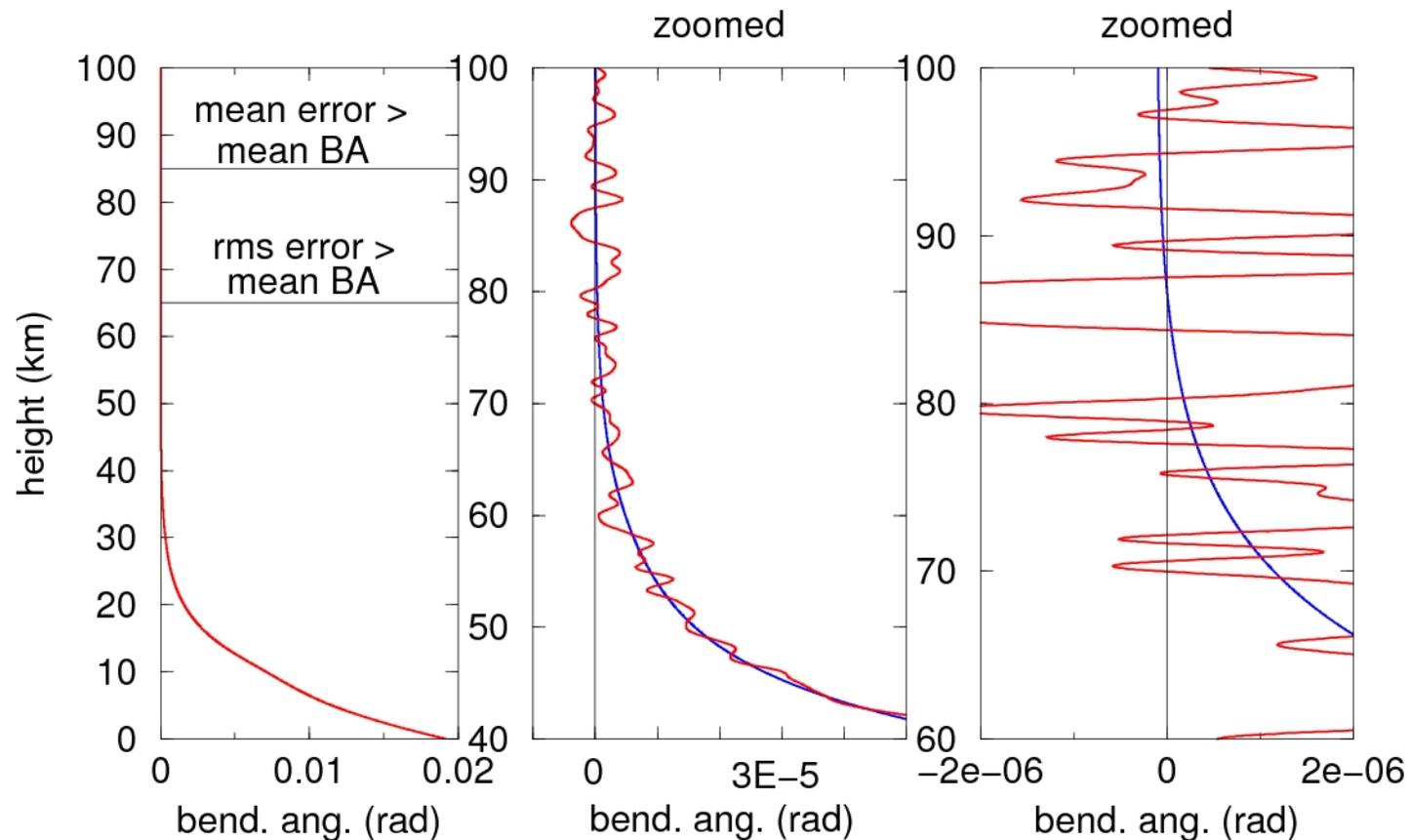
**Workshop on the application of GPS RO to climate
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Main observational errors of RO bending angles in the stratosphere result from incomplete calibration of the ionospheric effects:

RMS error $\sim 2E-6$ rad (dominant error for weather applications)

Mean error $\sim -1E-7$ rad (dominant error for climate monitoring)

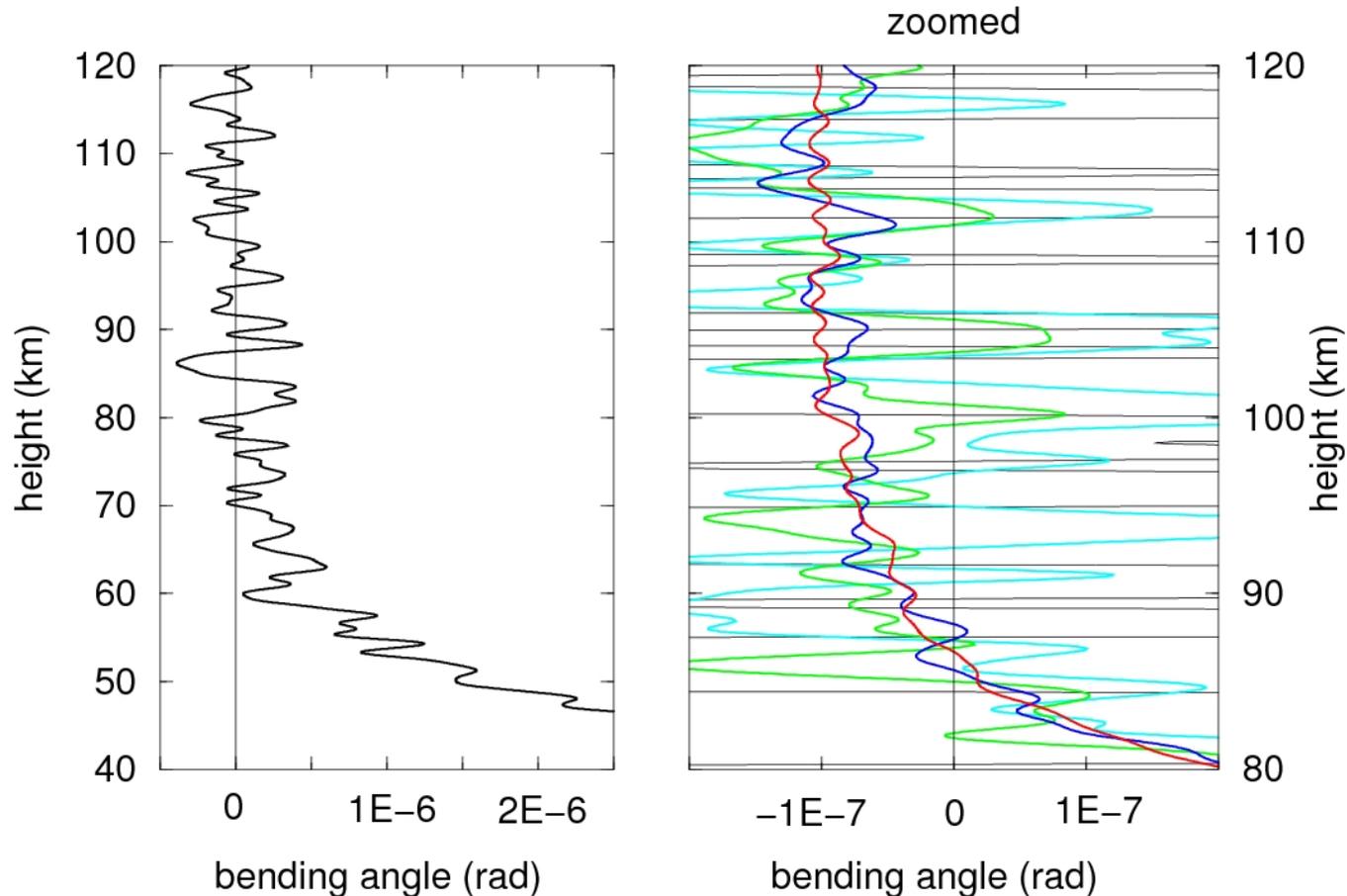
Below 30-40 km mean residual ionospheric error $<0.1\%$ mean BA



- residual ionospheric bias in BA depends on the distribution of electron density in the ionosphere: ranges from $\sim 1\text{E-}8$ (rad) (solar min. night) to $\sim 1\text{-}3\text{E-}7$ rad (solar max. day)
(Hardy et al. 1993; Vorob'ev et al. 1993; Kursinski et al. 1996; Syndergaard 2000; Ao et al. 2007; Mannucci et al. 2008; ...)
- aliasing of solar cycle to climate signal
- the bias error can be reduced by modeling the residual ionospheric calibration effects by ray propagation in the ionospheric models
- estimation of accuracy of such correction is difficult (Gorbunov et al. 1996)

- for individual occultations the residual ionospheric bias error in BA is overshadowed by the residual noise
- for climate monitoring: averaging of large numbers of occultations
- reduction of the noise, possibility to measure and correct for the bias

individual occultation; 100 occultations; 1000 occultations;
10000 occultations; 100000 occultations



Based on the analysis of COSMIC 2007 data it is believed to be possible to correct for the bias with accuracy $\sim 5E-8$ rad. This will result in the residual 0.1% error in BA at 40-45 km.

Phase (Doppler)



local transform
no error propagation

Bending angle



non-local transform (Abel inversion)
error propagation downward

Refractivity (density)

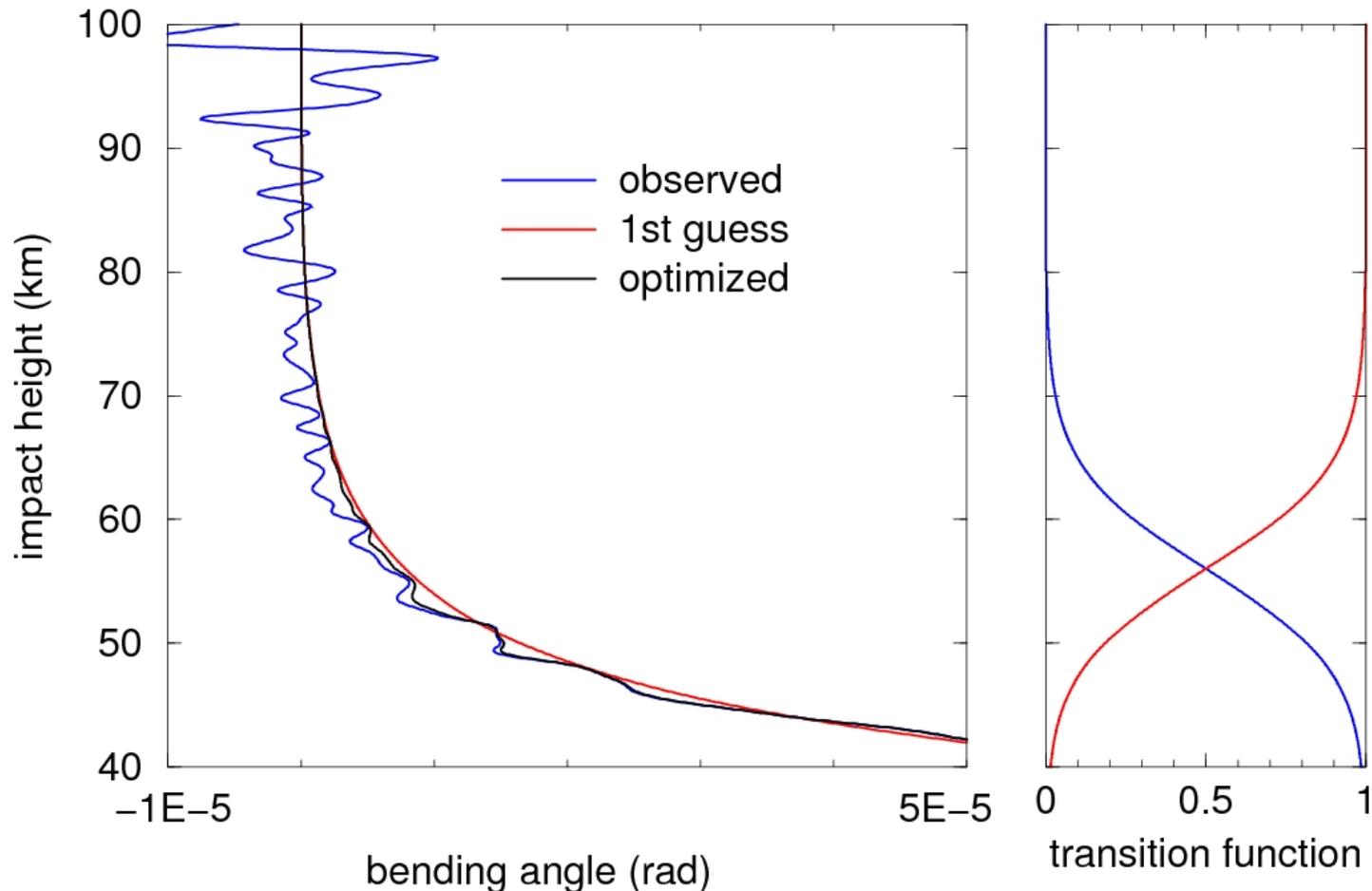


non-local transform (hydrostatic integration)
error propagation downward

Pressure, temperature

Optimization / initialization of BA for the Abel inversion

- replaces the observed BA by 1st guess at large heights
- does not improve quality of BA at those heights
- reduces error propagation to lower heights after the Abel inversion



Optimization / initialization options:

1st guess may be:

- independent on the obs. BA below the transition height
- fitted to the obs. BA below the transition height

the transition height may be:

- fixed
- determined dynamically (based on errors estimated for each occultation individually)

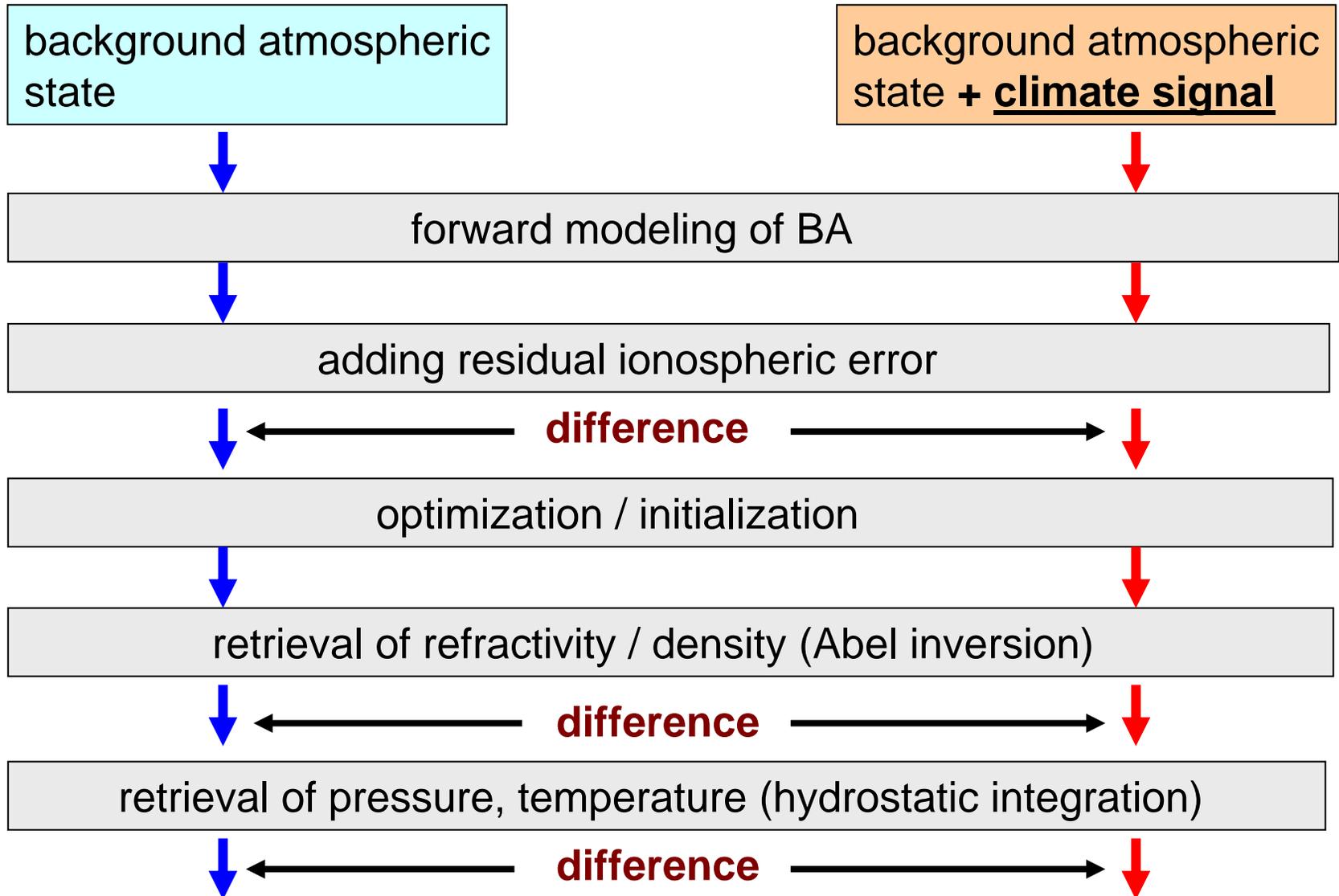
Important:

Optimal RO processing for climate is different from the optimal processing for weather:

- inversions of averaged BA profiles (e.g., zonal means)
- all parameters in the optimization / initialization shall be fixed

Observing System Simulation Experiment (OSSE)

(propagation of climate signal through RO observation=>inversion)

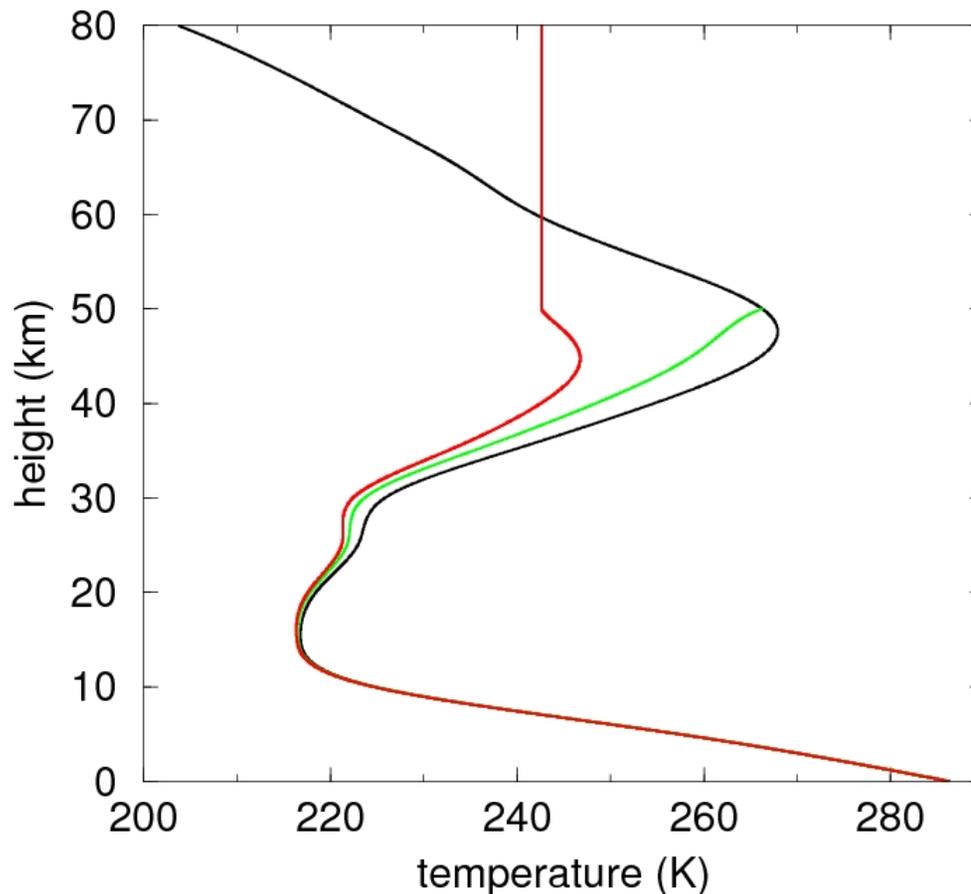


Initialization by exponential extrapolation of the obs. BA (Ao et al. 2006)

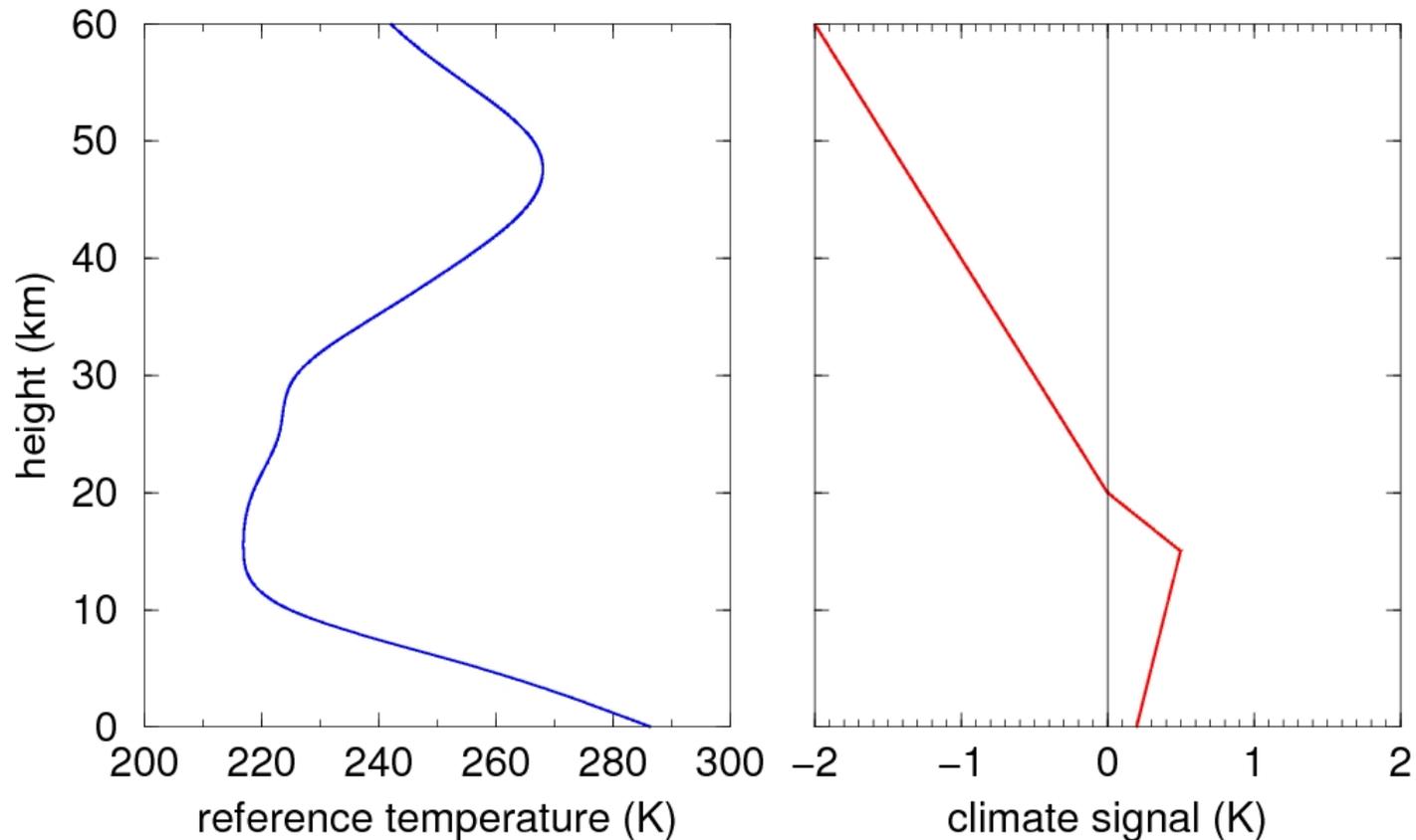
- true temperature

- retrieved temperature w. only initialization of the Abel inv. at 50 km

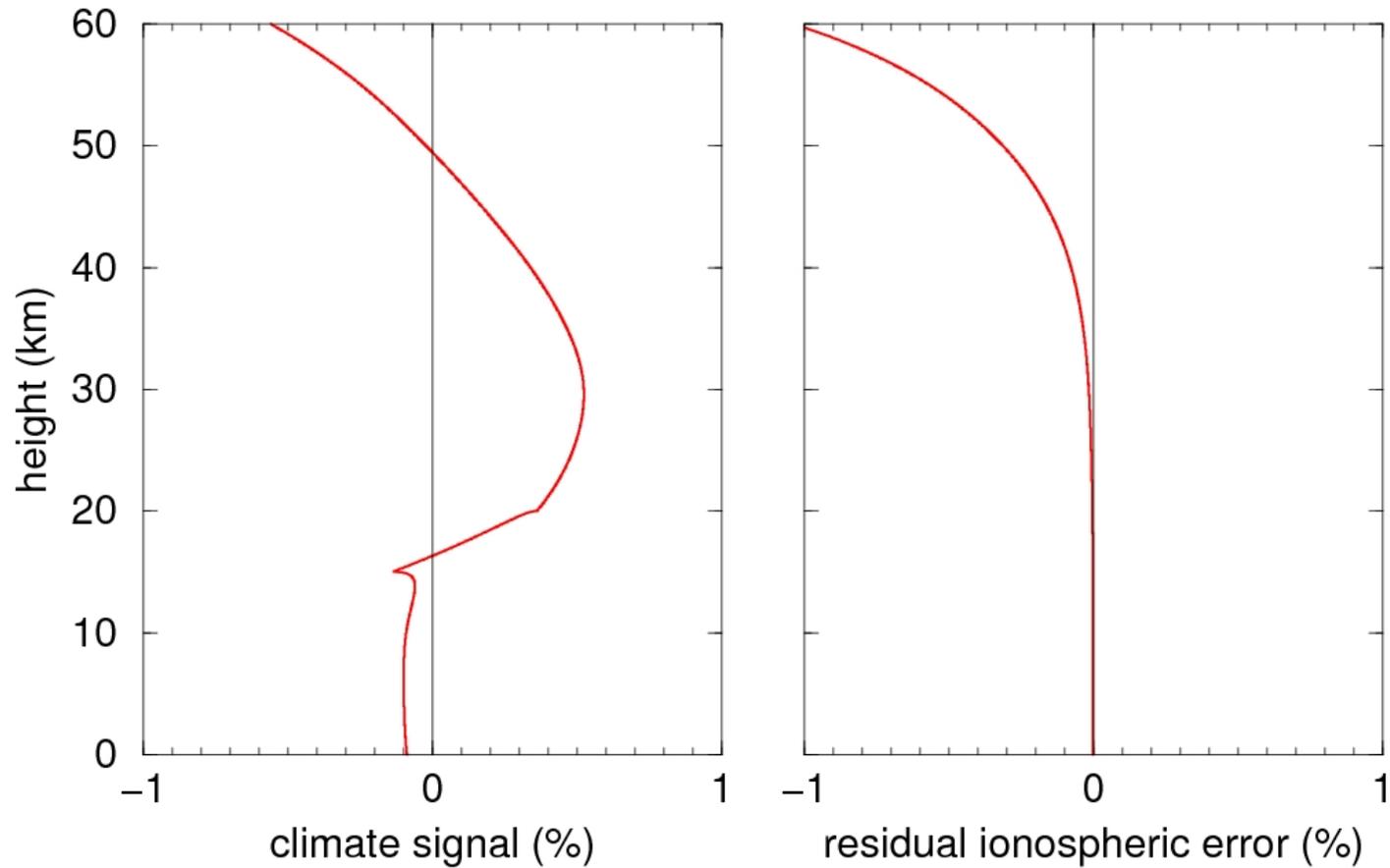
- retrieved temperature with additional initialization of the hydrostatic equation by reference (true) temperature at 50 km



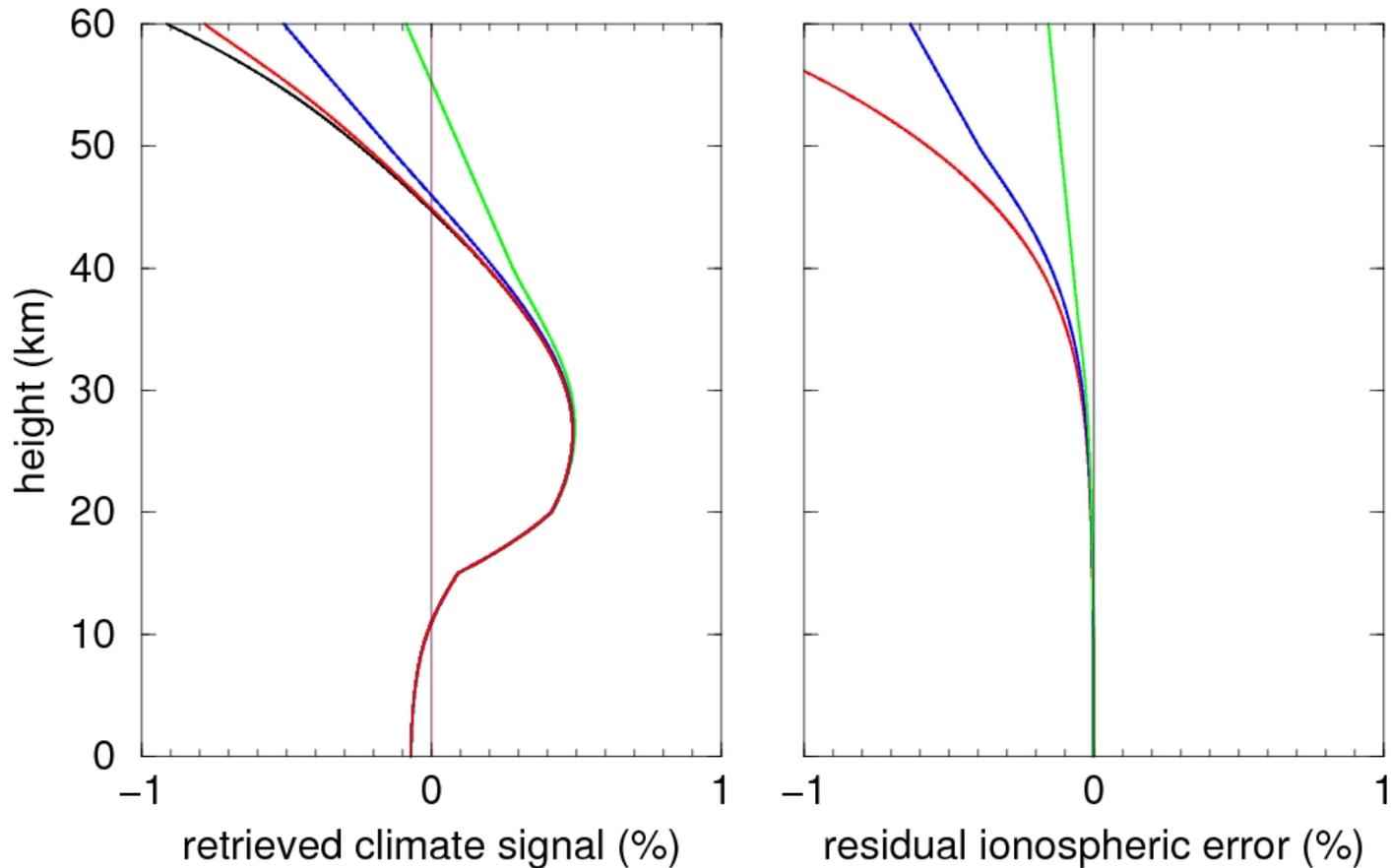
The model of the climate signal used in this study: a simple piecewise-linear approximation of the 25 years temperature trend (2001-2025, low latitudes) from MAECHAM5 climate model (Foelsche et al., 2008)



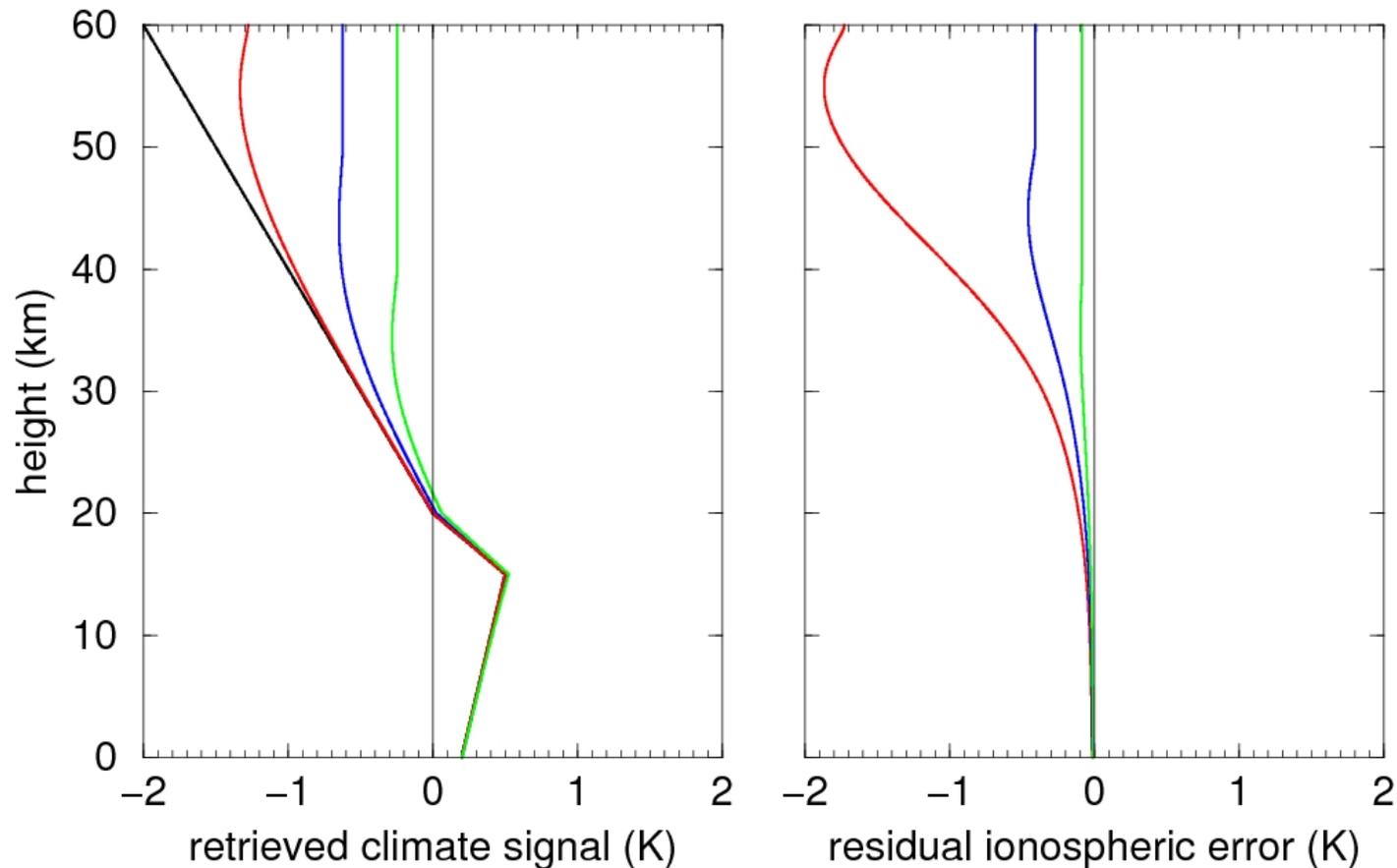
The climate signal in the observed bending angle (BA) and the residual ionospheric error $5E-8$ rad



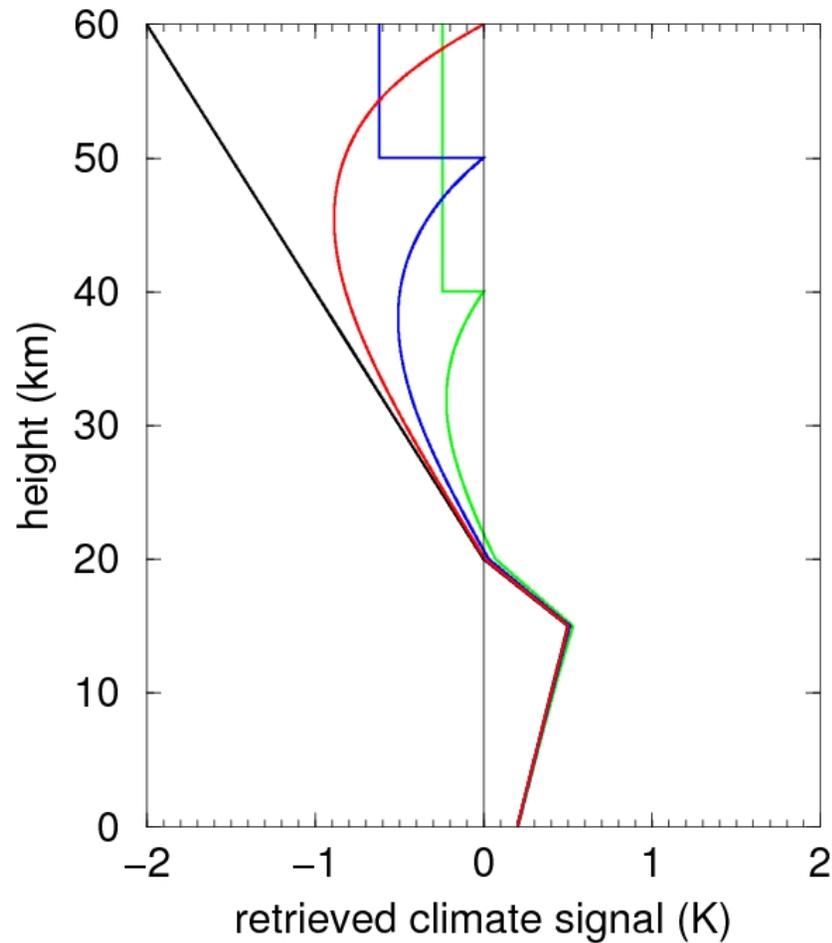
The climate signal in the retrieved refractivity / density with BA initialization starting at: **40 km**; **50 km**; **60 km**; and the effect of residual ionospheric error $5E-8$ rad



The climate signal in the retrieved temperature with BA initialization starting at: **40 km**; **50 km**; **60 km**; and the effect of residual ionospheric error $5E-8$ rad



The climate signal in the retrieved temperature with BA initialization starting at: **40 km**; **50 km**; **60 km**; Temperature initialized to reference model.



RO is remote sensing of atmospheric refractivity (density in dry air)

$$N = CP / T = CR\rho$$

1) Measure density, derive temperature:

$$T(z) = T_0 \frac{\rho_0}{\rho(z)} - \frac{1}{R\rho(z)} \int_z^{z_0} g(z')\rho(z')dz'$$

Error of the initialization exponentially decreases with decreasing height.

2) Measure temperature, derive pressure:

$$p(z) = p_0 \exp\left[-\int_z^{z_0} \frac{g(z')dz'}{RT(z')}\right]$$

Error of the initialization fractionally remains the same at all heights.

Specification of the atmospheric state via density, generally, is better posed problem than via temperature

Summary

Dominant error in the stratosphere for climate applications is the mean residual ionospheric error

This error can be reduced:

- by initialization (optimization) BA
- by modeling using ray tracing & ionospheric model
- by averaging of large amount of RO data

Optimal methods for processing of RO data for climate monitoring and for weather applications are different

Climate processing:

- averaging large amounts of occultations before the inversions
- all parameters of the optimization / initialization must be fixed

Summary (cont.)

Combined effect of the residual ionospheric error and error of the initialization / optimization is smallest in BA, larger in N and further larger in T - due to non-local transformations

Errors of monitoring of climate signal by RO at:

	20 km	30 km
Bending angle :	~0.003%	~0.015%
Refractivity:	~0.01%	~0.045%
Temperature:	~0.1K (~0.045%)	~0.3K (0.14%)

Assimilation of BA by climate models, generally, is preferable over assimilation of N, T. Requires specification of the atmospheric state above the height of interest.