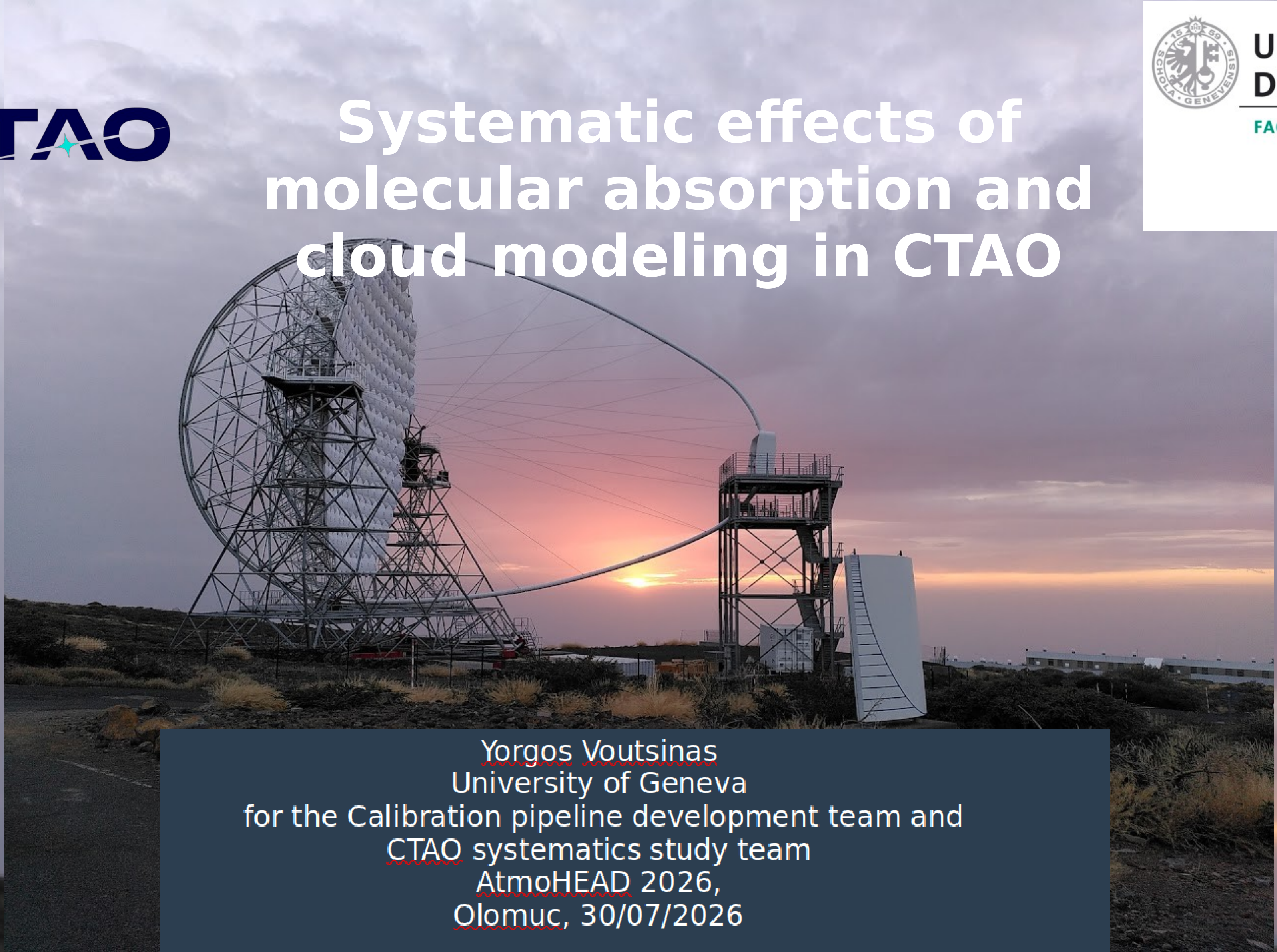
Systematic effects of molecular absorption and cloud modeling in CTAO



Yorgos Voutsinas
University of Geneva
for the Calibration pipeline development team and
CTAO systematics study team
AtmoHEAD 2026,
Olomuc, 30/07/2026

Extinction processes overview

Rayleigh scattering

- The dominant extinction mechanism (unless aerosol concentrations are high)
- Strong wavelength dependence
- Depends on the number density and refractive index profile of the atmosphere

Aerosols / Clouds

- Fast components (variation timescale ~ O(min) for clouds)
- Weaker wavelength dependence (shape, size and composition of the aerosols)
- Clouds: extinction depends on altitude, thickness, optical depth profile

Molecular absorption

- Gases with absorption bands in the optical / UV spectrum
- Non-well-mixed gases

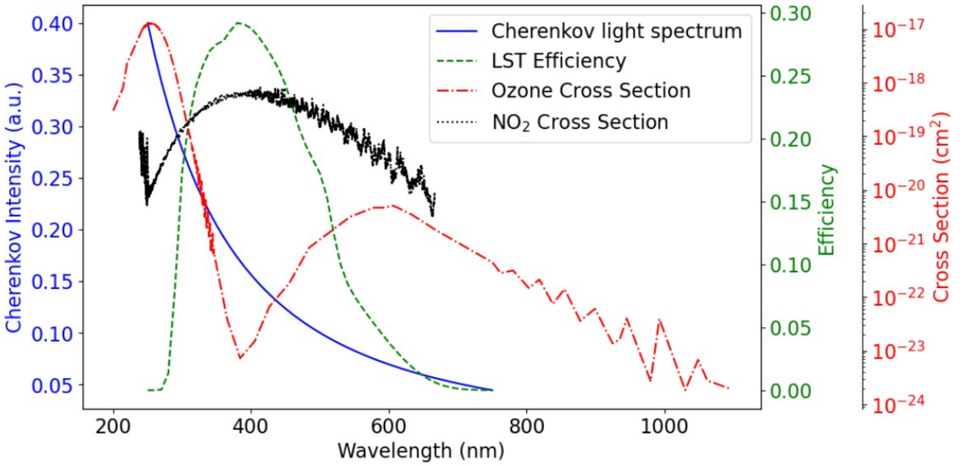
Motivations

Molecular absorption

- Seasonal and event-driven variations in ozone and NO_x at various pressure levels over the CTAO sites during night time

Clouds

- Recent studies on cloud characterisation over CTAO-North site [D. Dominis Prester et al, Universe 2024, 10(9), 349]
- Preliminary assessment of the effect of realistically modelled clouds over La Palma in CTAO-North performance
- Comparison with 'binary' clouds [M. Pecimotika et al, JCAP06(2023)011] in order to assess the systematic bias introduced through the cloud modelling



Cherenkov spectrum at emission point vs telescope optical throughput and absorbing molecules cross sections

Molecular absorption methodology

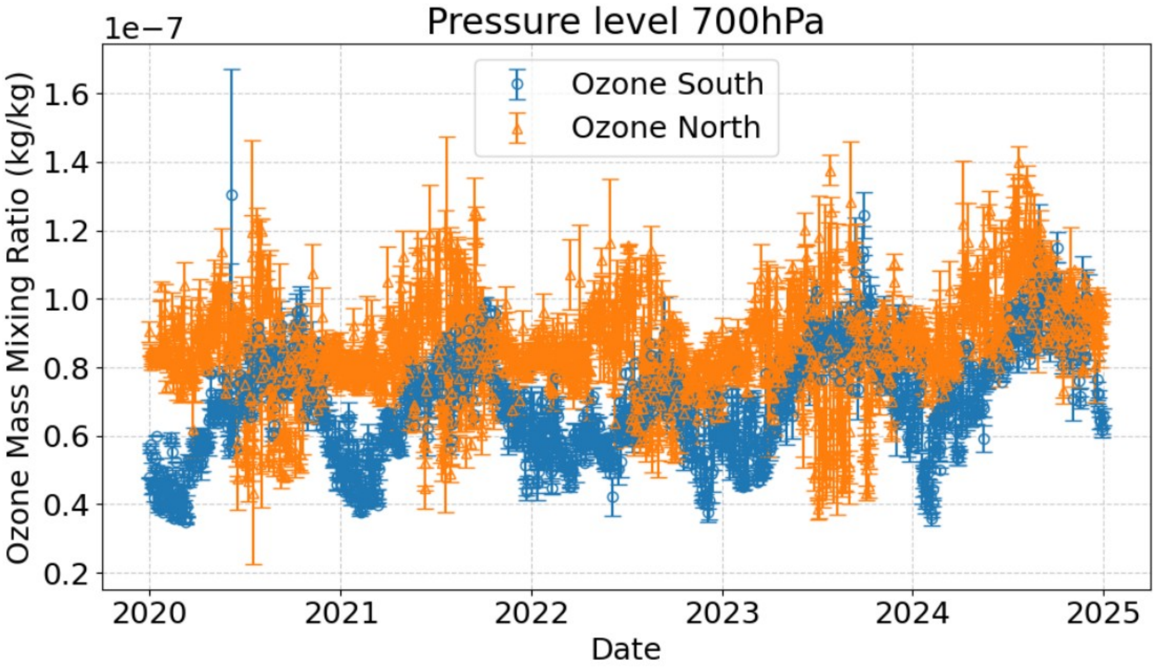
Methodology

- Study of the mixing ratio altitude profiles via processing of ECMWF (ERA-5, EAC-4) datasets available through Copernicus
- Produce Molecular Absorption Profiles (MAPs): optical depth per altitude per wavelength
- Apply MAPs in full simulation productions
- Run the reconstruction pipeline

Ozone mixing ratios variation

Ozone Mixing Ratios (MR) in the Troposphere depends on:

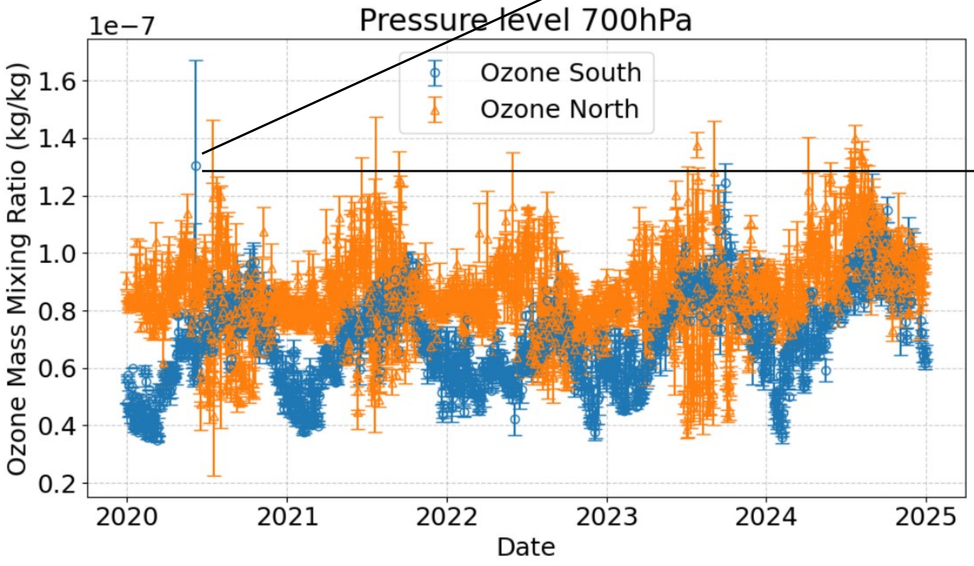
- Regular seasonal variation
- Stratosphere to Troposphere Transport (STT events)
  - Accounts for most of ozone MR variability in the Troposphere
  - Can be classified in deep and shallow events
- Horizontal intercontinental transport of pollutants.

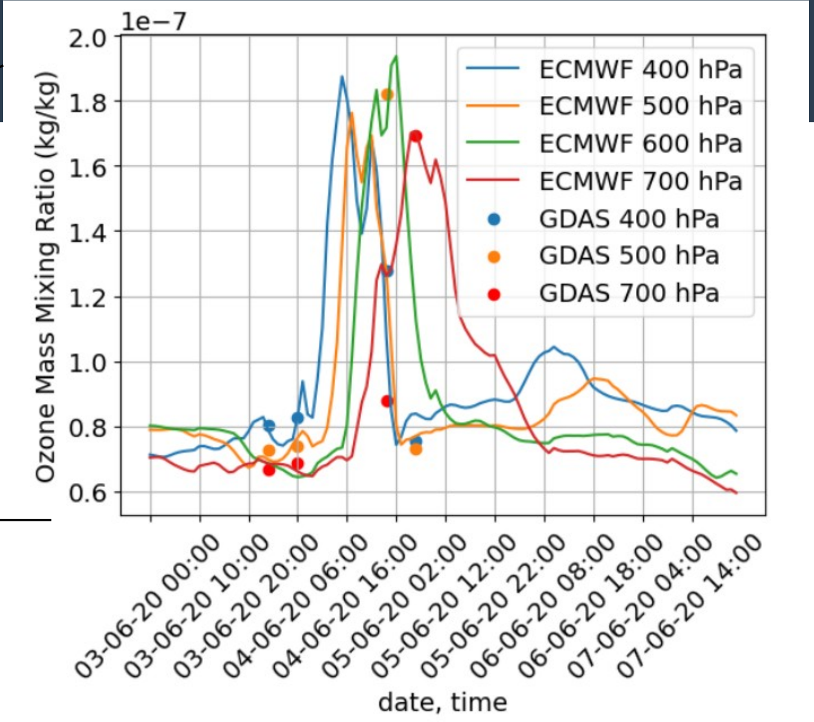


Deep STT events

Reach the Planetary Boundary Layer

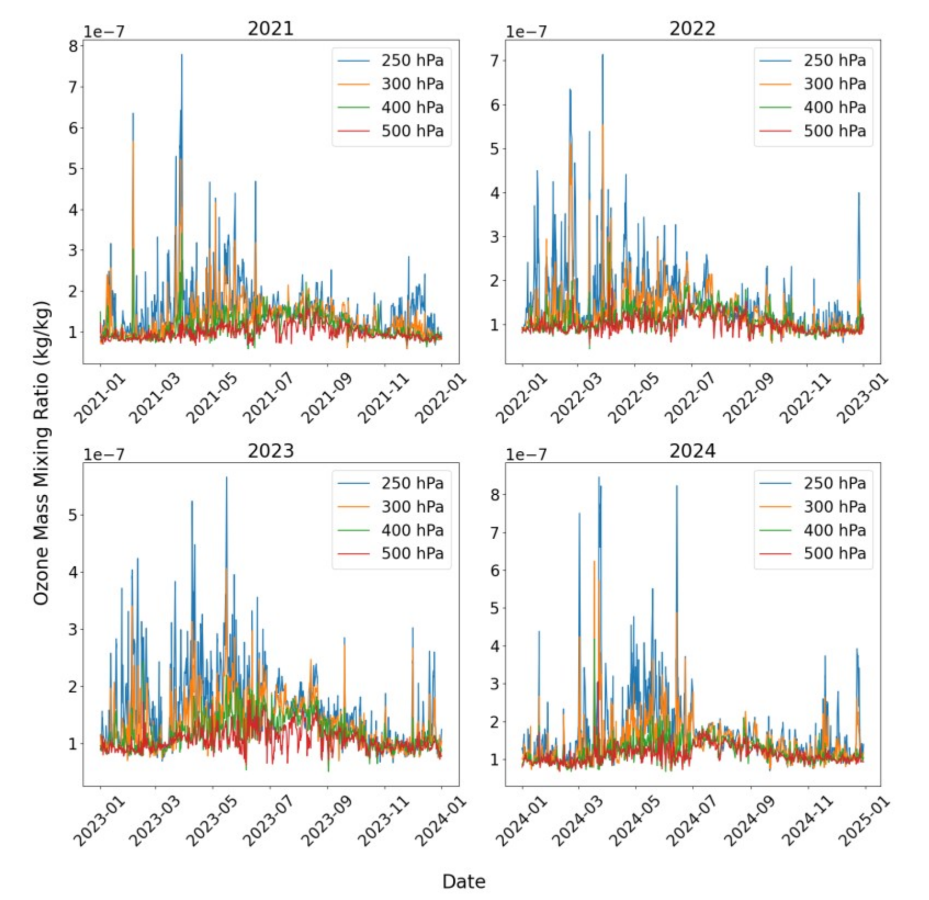
Rather rare over the CTAO sites





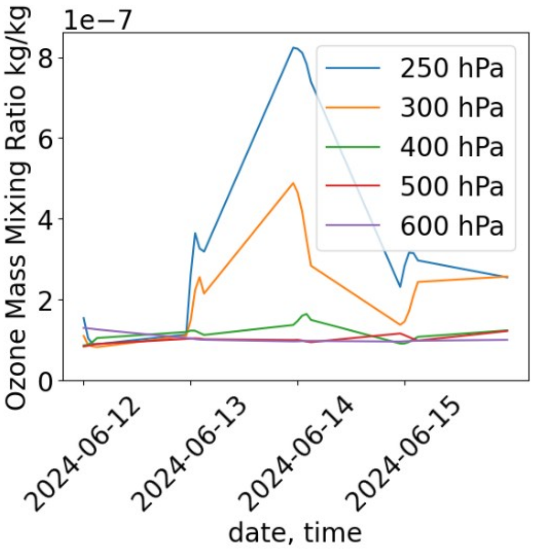
STT event observed over CTAO-South on 5th of June 2020
It was further studied via full simulations and reconstruction

Shallow STT events



Affecting the upper troposphere

The frequency of STT events is higher at lower pressure levels



Shallow STT event that took place over CTAO-North in June 2024 under favourable weather conditions, i.e. the telescopes would have been operational

NO_x MR variations

NO_x MR in remote locations affected by

- Anthropogenic factors, mainly aircraft emissions
- Natural factors, mainly lightning

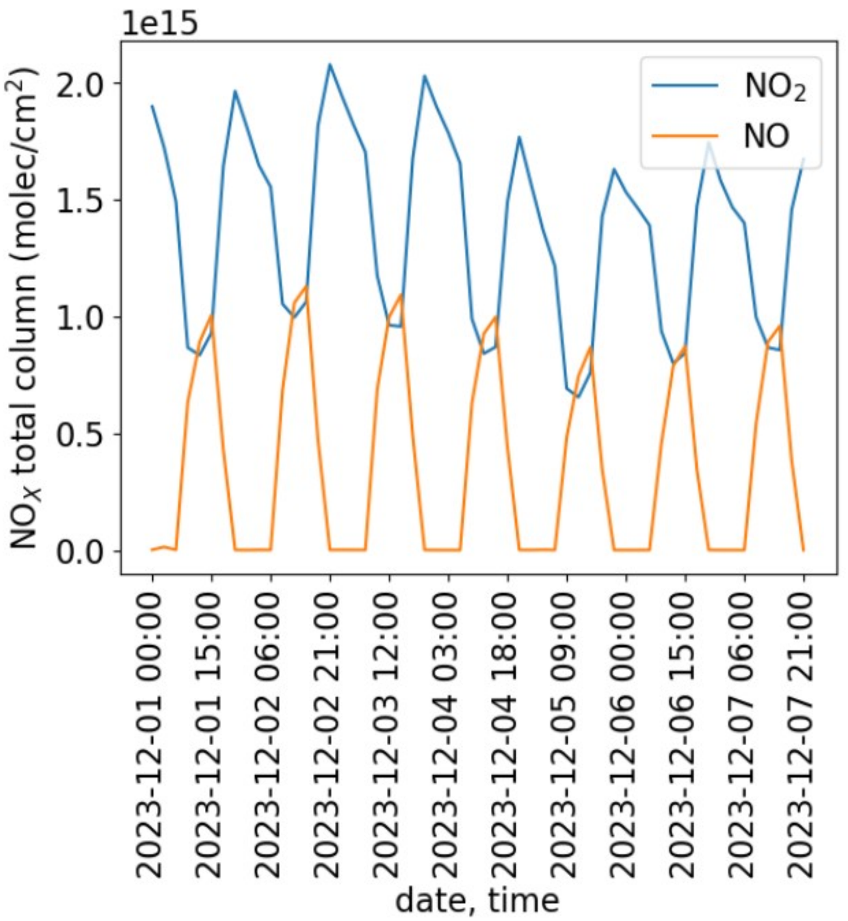
NO_x play dual role, both as Cherenkov liight absorbers and as catalysts for ozone production

NO mixing ratios are significantly reduced during nighttime

- Not examined further in the context of this study

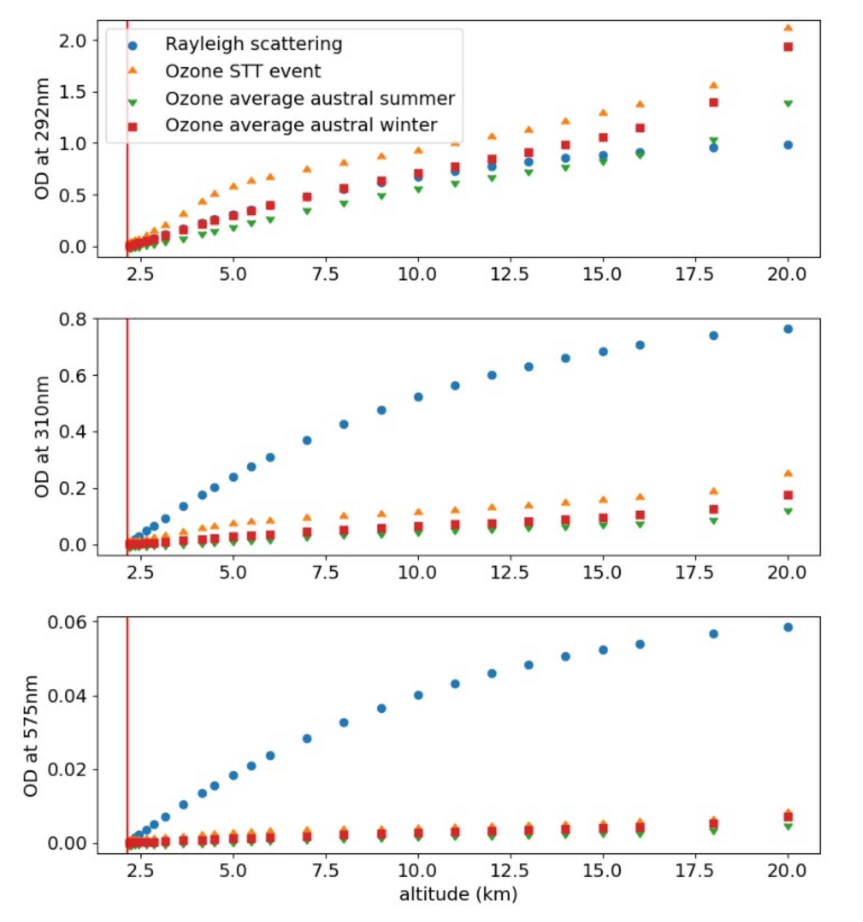
Concerning NO_2 we examined the effect on Cherenkov light transmission with and without the inclusion of a NO_2 MAP

- The effect was estimated to be ~0.02%



Total column of NOx during the first week of December 2023 at CTAO-North

Optical depth profiles



Comparison of ozone absorption optical depth profiles (seasonsl and including STT events) with pure Rayleigh scattering extinctions profiles

- At very short wavelengths (Hartley band) ozone contribution is comparable or larger than Rayleigh scattering
- The ozone MR increase in lower Troposphere during STT events is clearly visible

Simulations

Motivation

- Increased ozone is expected to induce a bias on image intensity and the trigger effective area

Methodology

- Construct Molecular Extinction Profiles (MEPs) combining an average Rayleigh scattering extinction profile with the MAP
- Run the simulations (CORSIKA & sim_telarray) substituting each time the corresponding atmospheric extinction profile while using the CTAO PROD6 configuration
- Estimate the effect on image size per telescope type and the array trigger effective area

Simulation results CTAO-North

Trigger effective area

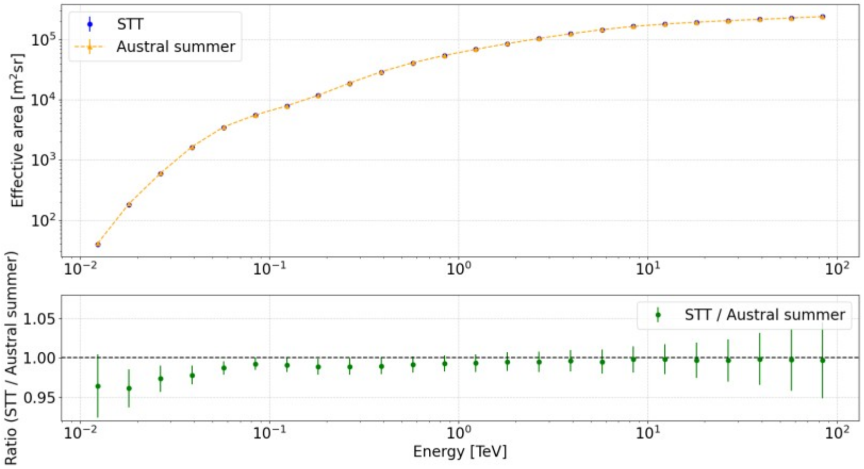
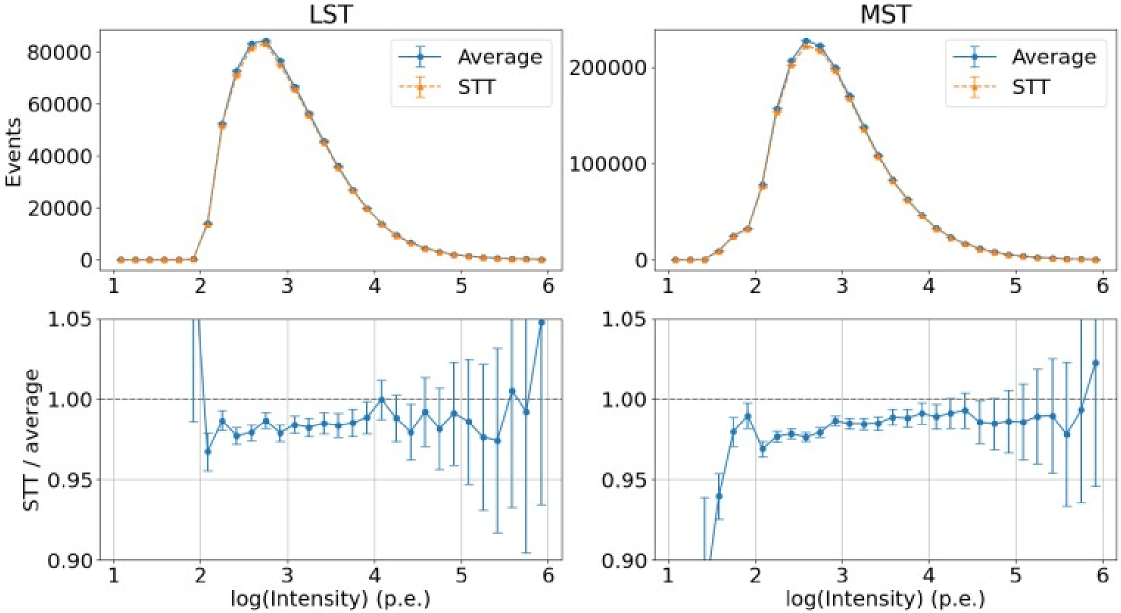


Image intensity



Energy reconstruction

Motivation

- Examine the effect of ozone variations on energy bias and energy resolution

Methodology

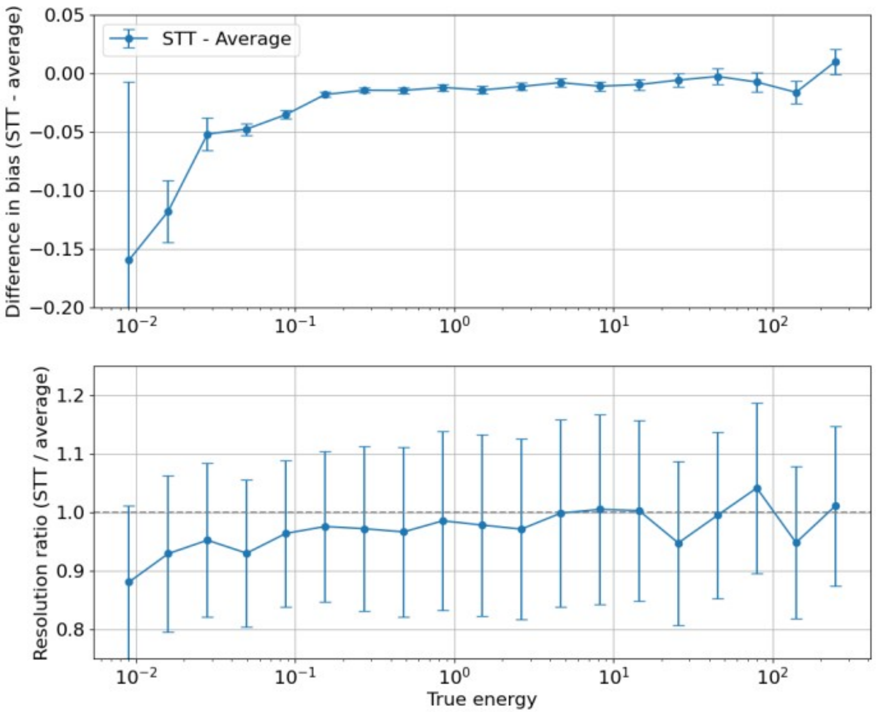
- Process the simulation results with ctapipe
- Train the energy regressor with an average (no STT) extinction profile
- Apply the same regressor both to average and extreme STT simulation data
- Probe the effect of ozone in case of no ozone calibration

Purely comparative study

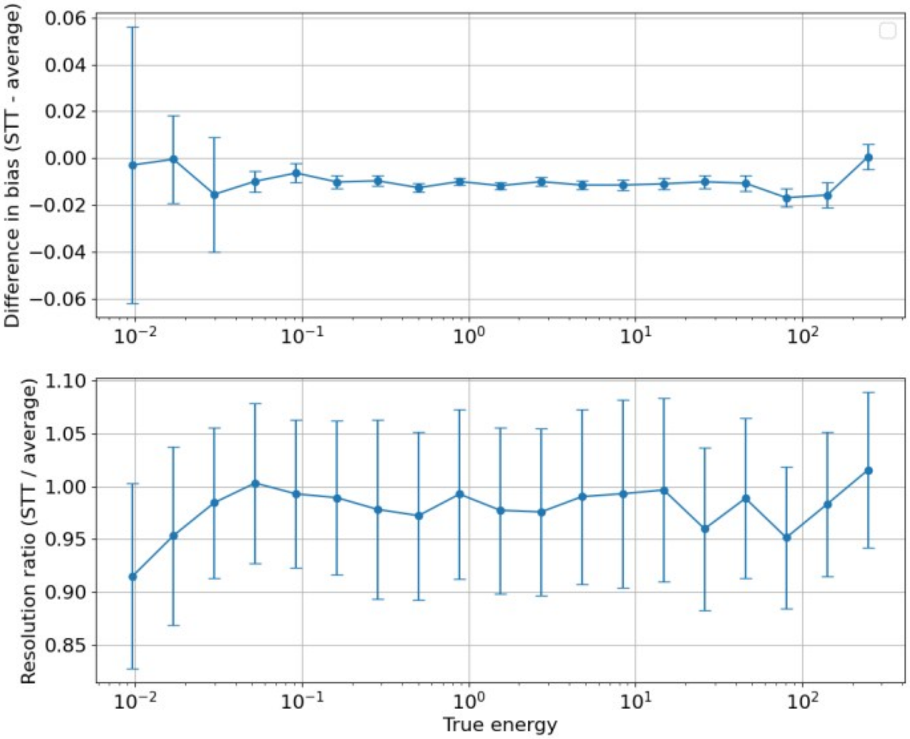
- Only ratios and differences are discussed

Reconstruction results

North



South



Molecular absorption conclusion

Ozone is the main absorbing molecule in the wavelength range of interest

- The impact of No_x is expected to be very small

Deep STT events are rare whereas shallow occur often over both observatories

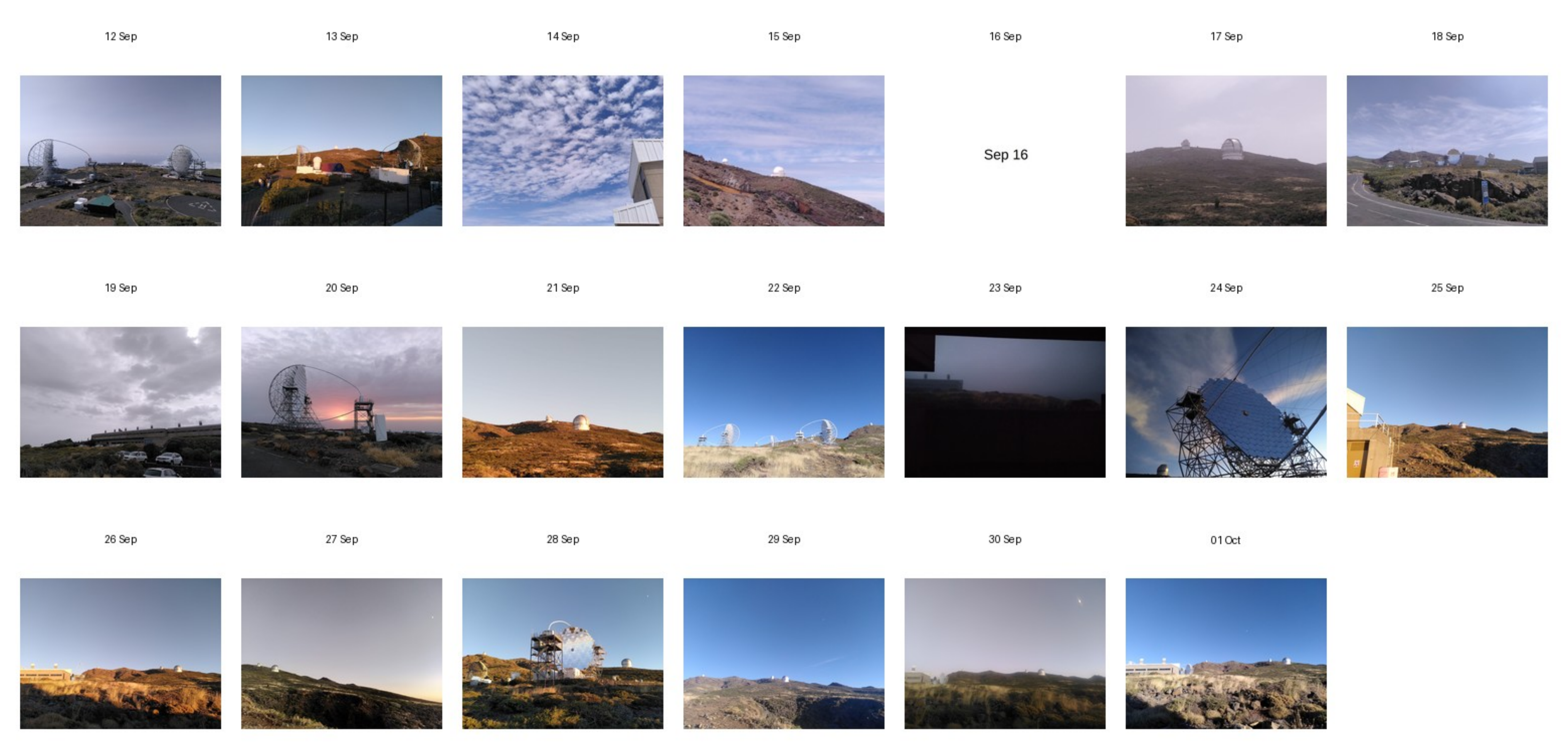
- Both have an impact on CTAO performance
- 2-3% reduction in image intensity (size < 10^3 phe), 1-2% in the range 10^3-10^4 phe
- Energy dependent effects in trigger effective area, manifested especially below 50 GeV
- Effect on energy bias at the level of 1–2% over most of the considered energy range
- No significant effect on the energy resolution within uncertainties

Within the framework of the study

- Identified publicly available atmospheric datasets
- Developed the tools to process these datasets and produce MAPs
- Outlined an ozone calibration strategy

Clouds

Aerosols and clouds



Clouds over La Palma

After multi-year analysis of MAGIC LIDAR data

- C. Fruck et al, MNRAS 515, 4520–4550 (2022)

Clouds over La Palma follow a double Lorentzian optical depth distribution

- D. Dominis Prester et al, Universe 2024, 10(9), 349

$$f(x) = C \cdot \left(\frac{(1-A_2)\cdot\sigma_1}{\pi\cdot((x-x_1)^2+\sigma_1^2)} + \frac{A_2\cdot\sigma_2}{\pi\cdot((x-x_2)^2+\sigma_2^2)} \right)$$

	Altitude (km a.s.l)	Center (km a.s.l)	Extension (m)	VAOD
summer	7 – 10	9.3	≤ 200	10^{-3} - 1
winter	8 - 11		≤ 400 OR ≥ 450	10^{-3} - 1

Double Lorentzian clouds

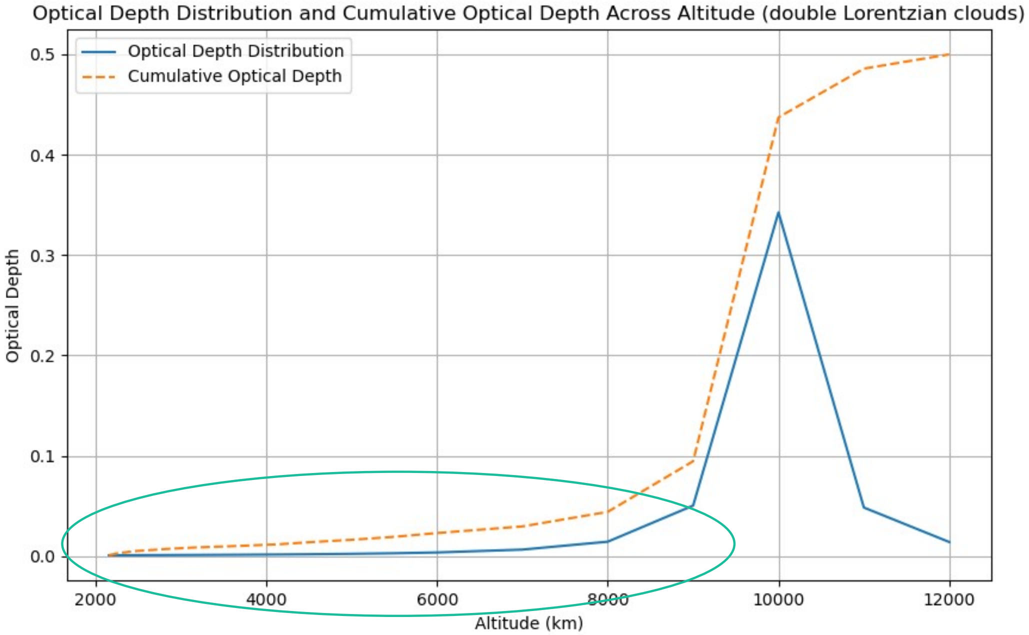
Functionality to produce clouds

- Fit results from D. Dominis Prester et al

Case	x_1 (m)	σ_1 (m)	A_2 (1)	x_2 (m)	σ_2 (m)	C (1)
low clouds	-2	35	0.53	-46	210	0.98
medium altitude clouds, VOD<0.2	10	7	0.99	-2	266	1.08
medium altitude clouds, 0.2<VOD<0.5	18	19	0.98	-12	473	1.18
medium altitude clouds, VOD>0.5	20	35	0.98	-22	589	1.22
summer clouds (July, August)	1	24	0.87	24	226	0.97

Configuration with the Angstrom coefficient, the VOD, the altitude and the altitude binning (granularity)

- Example white winter cloud at 10km a.s.l. with a VOD = 0.5
- A cut at the tails should be applied



Does cloud modeling matter?

Comparison with ‘binary’ clouds

M. Pecimotika et al, JCAP06(2023)011

- 36 clouds over Northern array, 1km extension, combinations of:
- 6 different altitudes: 3km, 5km, 7km, 9km, 11km, 13km a.s.l.
- 6 different transmissions: 0.95, 0.90, 0.80, 0.75, 0.60, 0.50 → (0.05, 0.11, 0.22, 0.29, 0.51, 0.69)
- Zenith = 20^0
- 4LSTs and 15MSTs (Omega configuration)

Binary vs realistic clouds

Comparing a binary cloud with a realistic ‘Lorentzian’ one featuring the same optical depth and altitude

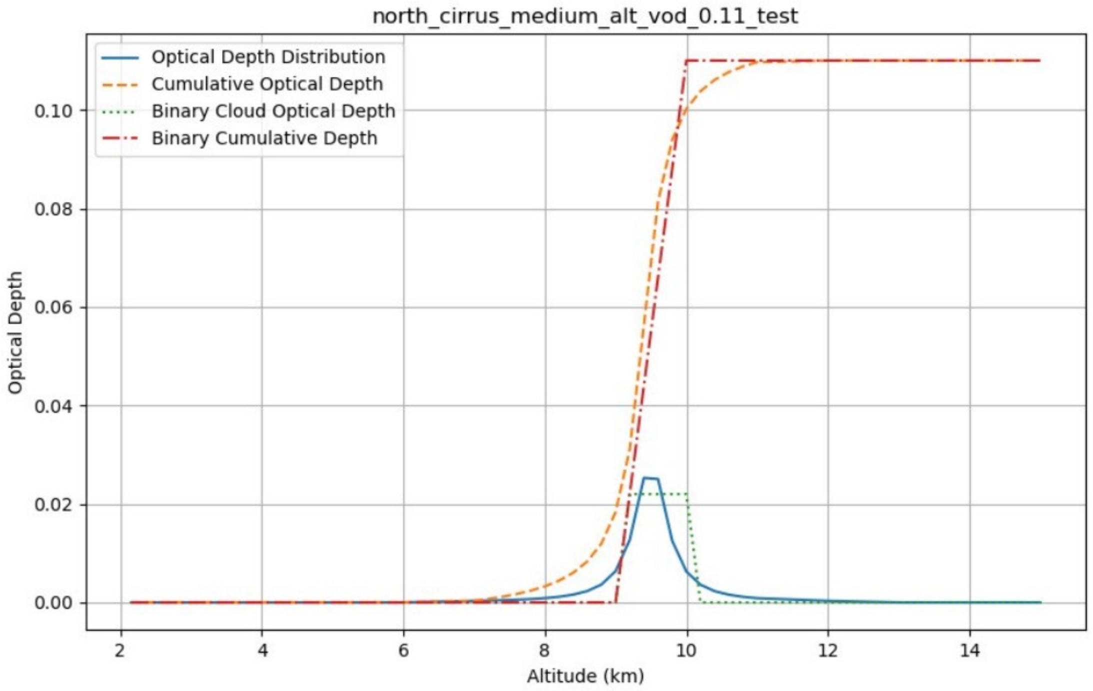
- Cloud thickness is different

Study ongoing, results still under production

- Purely comparative study, since different reconstruction software has been used

However some useful results have been obtained

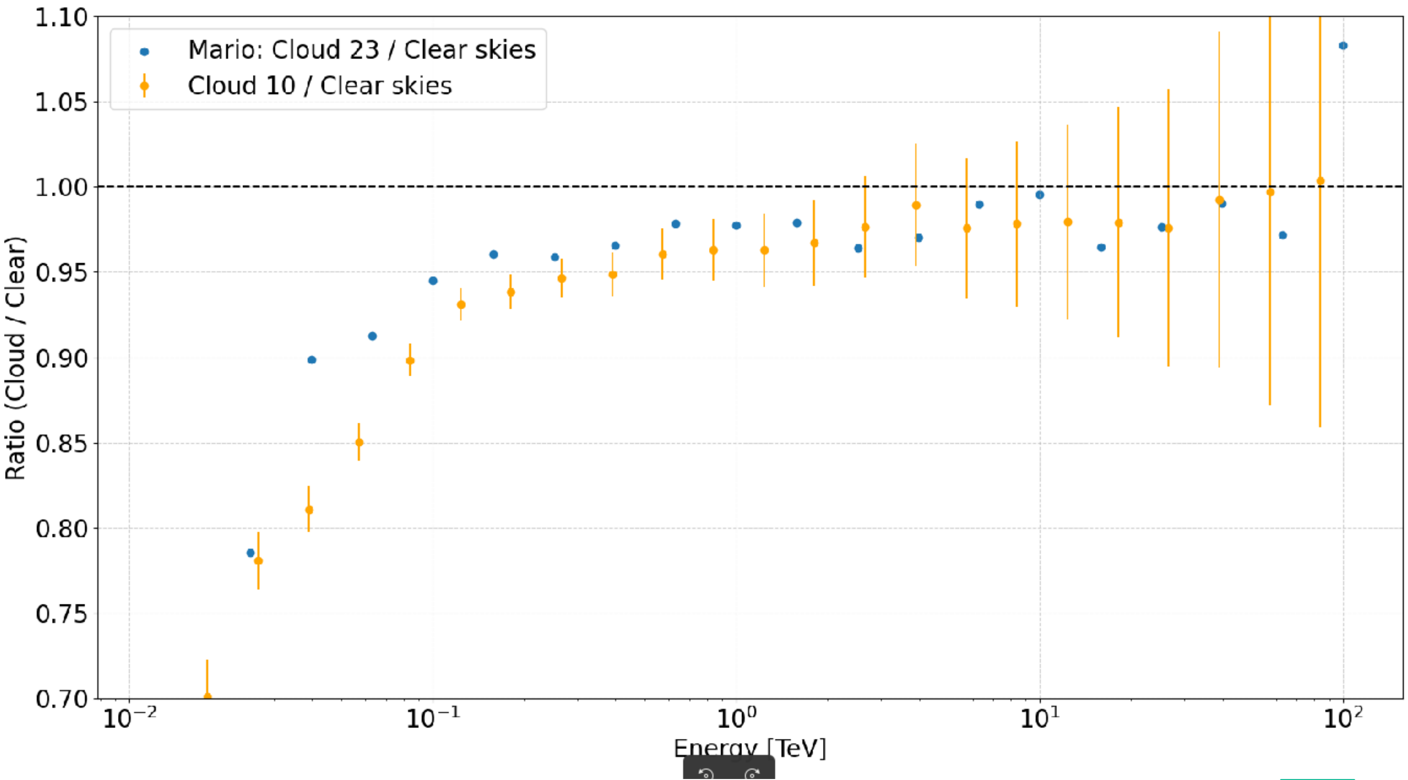
- The computational cost of the simulations is largely independent of the optical-depth binning of the cloud.
- We can fully exploit the LIDAR resolution



Preliminary simulation results

Preliminary study of the effect of each cloud model vs clear skies

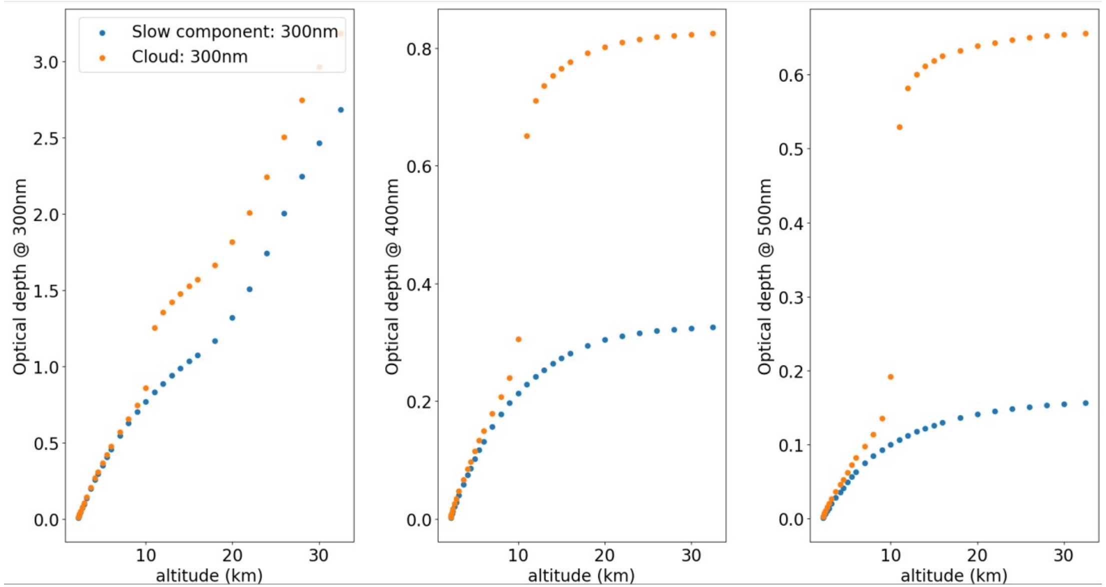
- Effective area ratio cloud profile / clear skies (binary clouds)
- Trigger effective area ratio cloud profile / clear skies (Lorentzian clouds)
- The results suggest that cloud modelling affects the reconstructed performance.



Next steps

Study the effect on CTAO performance of about 10 realistic ‘Lorentzian’ cloud models, corresponding to the observed clouds over the CTAO-North site

- Simulation produced
- Reconstruction under production
- Cloud profile combined with the standard extinction profile used for CTAO simulations assuming ‘white’ clouds



Backup

STT events, South