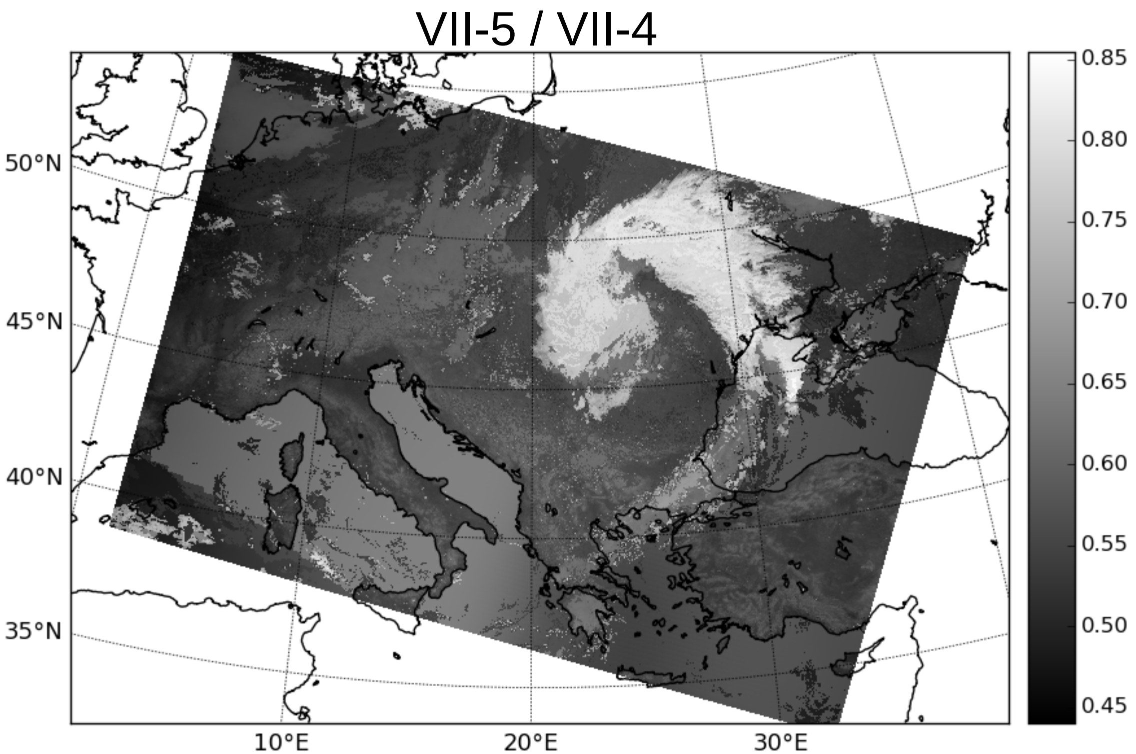
Study on O_2 band Cloud Top Pressure retrieval with METimage - METimCTP -



Final Review
EUMETSAT, Darmstadt
Nov 16th,2015

Mathieu Compiègne (HYGEOS)
on behalf the HYGEOS/LOA team

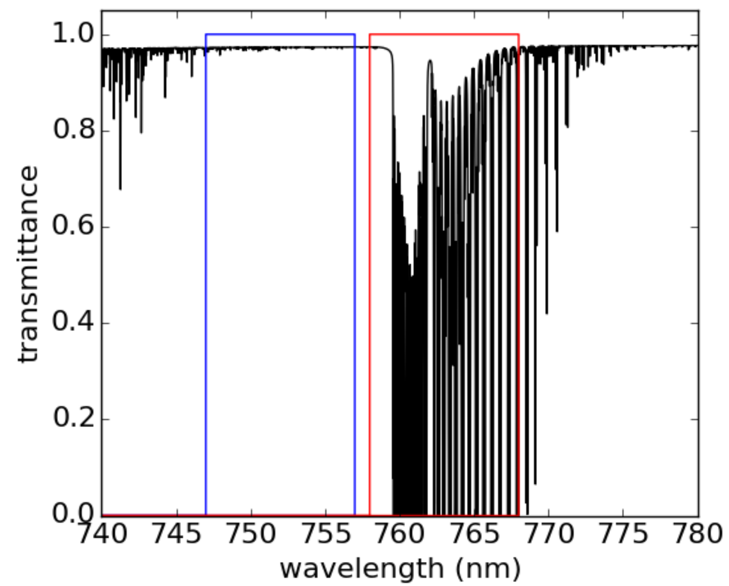
Outlines

- Project overview
- Bibliography and sensitivity study
- Day-1 algorithm and LUTs
- Testing on METimage synthetic data
- Testing on MERIS data
- Conclusion

Project overview

The CTP retrieval algorithm outlines

- Retrieval of cloud top pressure from bands VII-4 and VII-5



- Use of optimal estimate (OE) method with Levenberg-Marquardt iteration process

- Forward model (radiative transfer) to be represented with a Look-Up table to speed-up retrieval

- The algorithm should be independent regarding other METimage L2 cloud product

Project tasks

- Phase I : “day-1” algorithm definition
  - Bibliography (Task 1) & sensitivity study (Task 3) to produce the skeleton of the “Day-1” ATBD and especially LUT entries
  - Selection/description of suitable RTM among various candidates (Task 2)
  - Selection / description of test data (Task 4)

- Phase II : “day-1” algorithm development and testing
  - LUT optimization and computation (Task 5)
  - Algorithm development (Task 6)
  - Testing and reporting on the Day-1 algorithm (Task 6-7)
  - Propose future enhancements (Task 7)

Team

- An industry / academic consortium based in Lille, France
  - **HYGEOS** (industry) is **prime contractor** and provides most of the manpower
  - Laboratoire d'Optique Atmosphérique (academic) mainly supply scientific expertise feedback

- HYGEOS team : Mathieu Compiègne (technical and contractual management) & Didier Ramon

- LOA team : Jérôme Riedi, Philippe Dubuisson, Nicolas Ferlay, Laurent C.-Labonnote

HYGEOS (I)

- HYGEOS is a worker cooperative company founded in 2001:
  - 6 PhD in Physics, 2 computer scientists, 1 system administrator, 1 management assistant
- R&D for Earth (passive) remote sensing
  - Development, validation and application of geophysical products (e.g. MERIS)
  - Prospective and feasibility study for future missions or new products (e.g. 3MI, geo-oculus)
- Radiative transfer experience
  - "In house" GPU based Monte-Carlo model (initial development for CNES)
  - Good mastering of RT common tool boxes (LibRadtran, CNES OS, ARTDECO, Py4Cats, ...)

HYGEOS (II)

- HYGEOS works for CNES, ESA, KORDI, EU, EUMETSAT and has partnership with several research center (LOA, CEA, ULCO, Scripps Institute for oceanography)
- Project management experience
  - Leading the FP7 project “ImagineS”
  - Management tasks in FP6 “geoland” and FP7 “geoland2” projects
  - Lead consortium for GEO-OCULUS ESA study
- Past and current project for EUMETSAT
  - Study on 3MI calibration concept
  - Test data for the EPS-SG instruments METimage and 3MI
  - User Requirements Analysis and Prototype Processor for MSG SEVIRI Water Turbidity Products

Laboratoire d'Optique Atmosphérique

- Academic research laboratory with ~60 people : faculty, research scientists, engineers and grad. students
- Historical POLDER player
- Involved in MODIS, MSG, MERIS
- Strong background in radiative transfer
- Involved in preparation of different candidate follow-on projects (e.g. 3MI)
- Strong expertise in aerosol and cloud remote sensing and modeling

Project timeline

- Project kicked-off on Jan 14th, 2015 with the initial timeline :
  - Phase I deliverable and Mid-term meeting : KO + 3 months
  - Phase II deliverable and final review : KO + 8 months
- Actual Mid-Term meeting on the May 19th, 2015
- Full (first version) delivery sent Nov 2nd, 2015
- Final Review on Nov 16th, 2015

Project deliverable (I)

Deliverable	Description	Type
Task 1		
D1.1	Task 1 Technical report fully describing the bibliography inputs and results/analysis output from the task.	Report
Task 2		
D2.1	Task 2 report describing the candidate RTMs with respect to the assessment criteria and identification of the RTMs suitable for the specific case of CTP-O2 retrieval from METimage.	Report
Task 3		
D3.1	Addition to Phase I Technical Report describing the results from Task 3: Sensitivity study	Report
Task 4		
D4.1	Addition to Phase I Technical report describing the output of Task 4: Selection and description of test data (MERIS and METimage Synthetical)	Report

Project deliverable (II)

Deliverable	Description	Type
Task 5		
D5.1a	MERIS channels LUTs	Data file
D5.1b	METimage channels LUTs	Data file
D5.2	High level code developed to generate the LUT (for the recursive call of RTM)	Script file
D5.3	Technical report for task 5 including • a clear guidelines for the generation of the LUTs using the RTM selected at task 3 • a clear description of the set-up/configuration of the RTM simulations; • a list of all auxiliary data/files needed to run the RTM • a description and justification of the structure/format of the output LUTs.	Report

Project deliverable (III)

Deliverable	Description	Type
Task 6		
D6.1	Prototype code for the METimage (and MERIS) CTP-O2 retrieval	Script files
D6.2	Updated Phase II Technical report describing the code and listing all required auxiliary data/files.	Report
Task 7		
D7.1	Updated Phase II Technical report describing the results from the performance testing including detailed analysis of the limitations of the algorithm and guidelines for future improvements.	Report
D7.2	Presentation material for a final review meeting covering tasks 1 to 7 to be held at the end of the study.	Presentation
D7.3	Final technical report, including review comments from EUMETSAT.	Report

+ D6.3 test and ancillary data (METimage SDS, MERIS)

Bibliography and Sensitivity study

Literature review

- Introduction on cloud height retrieval methods

- Bibliography focused on CTP retrieval with O_2 :
  1) Theoretical (modeling) studies
  2) PARASOL/POLDER : Instrument description, PARASOL operational algorithm, further evolution and studies
  3) MERIS : Instrument description, MERIS CTP algorithm, other MERIS based algorithm
  4) A word about MOS, GOME & SCIAMACHY

- Conclusion on the framework of the METimage CTP-O_2 retrieval

Literature review: Driving parameters for VII-5/VII-4

Parameters	Impact	comment
CTP	Critical	Will be retrieved
COT	Critical	Will be retrieved
Cloud vertical structure (profile, geometrical thickness)	Critical	• Not constrained with METimage instrument • Will be varied through climatology • no multi-layer handling
Cloud phase	important	Will be varied
Surface properties (albedo, pressure)	important	Will be varied
Sun and view geometry	important	Will be varied
Aerosols	moderate	Can be varied
Cloud fraction	important	Not varied (=1)
Cloud particle size	moderate	Not varied
Temperature profile	low	Not varied

Radiative Transfer model review

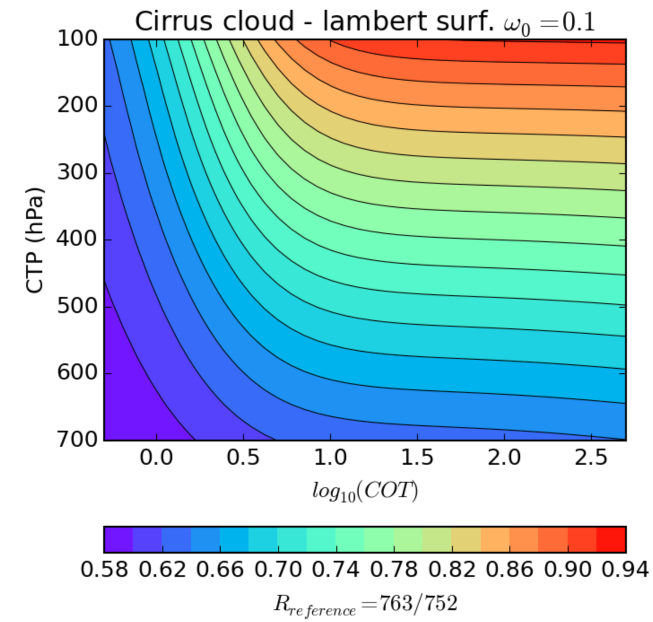
- Overview of RTM requirements for CTP-O_2 retrieval
- Brief overview of some available RTM that fits the requirements:
  - MOMO
  - Sciatran
  - LibRadtran
- Detailed description of the selected RTM : ARTDECO

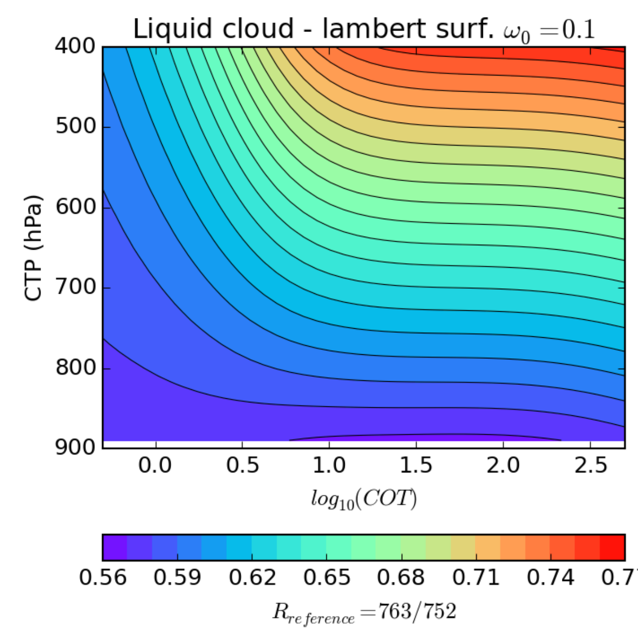
ARTDECO

- Radiative Transfer package for UV-visible to thermal infrared (LibRadtran like)
  - Libraries (AFGL atmosphere profiles, OPAC cloud and aerosols optical properties...)
  - Several phase matrix truncation methods (delta-M, Potter, delta-fit)
  - RTE solvers (adding-doubling, discrete ordinate, Monte-Carlo) and single scattering correction (TMS)
  - Correlated k-distribution method for molecular absorption (down 10 cm^{-1} resolution *or for a given instrumental band*)
- Used for the VIS-SWIR data simulator in EUMETSAT project "Test Data for the EPS-SG instruments METimage and 3MI"
- Soon publicly available through ICARE

Sensitivity of VII-5/VII-4

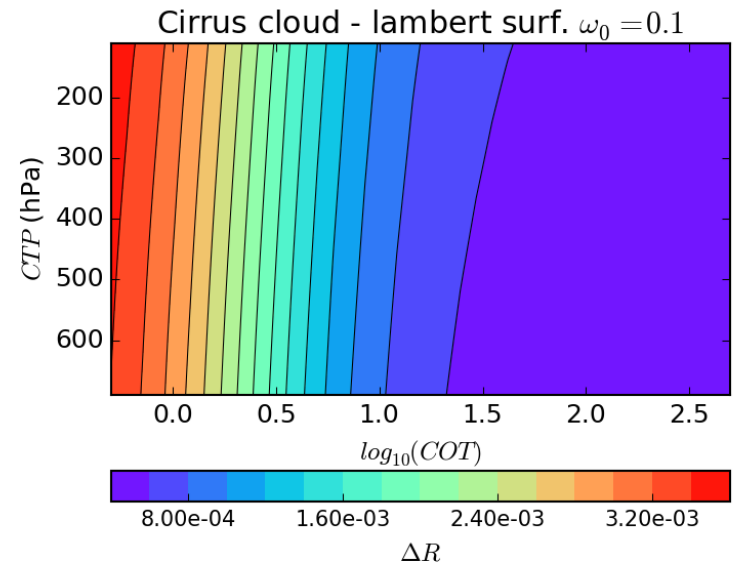
- We compute $R=I_{763}/I_{752}=f(COT, CTP)$ with ARTDECO:
  - Adding-Doubling RTE solver (8 computational angles δ-M truncation, and TMS correction)
  - US 62 atmospheric profile re-sampled to 100 m in cloud
  - Fixed CGT=1.0 km and R_{eff}
  - Lambertian surface, albedo = 0.1
  - SZA=30 deg., view at nadir
- We vary parameters and look at ΔR
- We compute ΔCTP, the CTP variation that produce the same ΔR



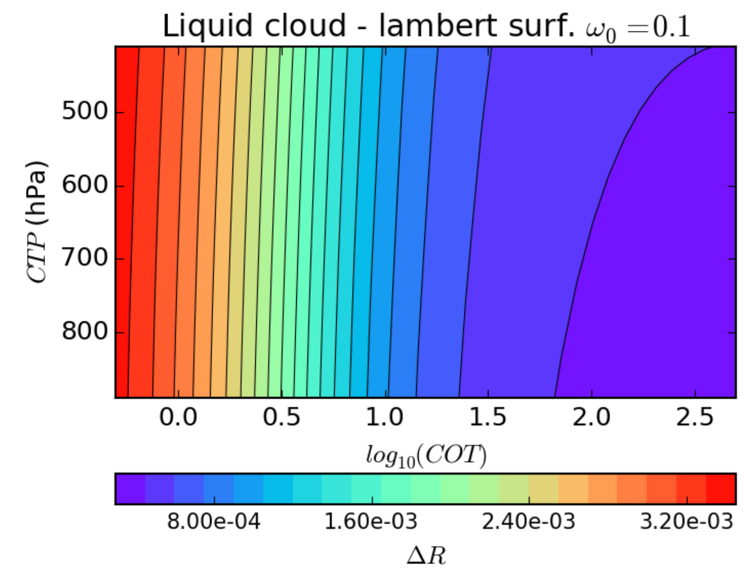


Sensitivity to instrument noise (I)

- Variation of signal ratio (ΔR) due to instrument noise (SNR=500)
  - N_{763} = 20 / SNR   W m^{-2} sr^{-1} µm^{-1}
  - N_{752} = 28 / SNR   W m^{-2} sr^{-1} µm^{-1}

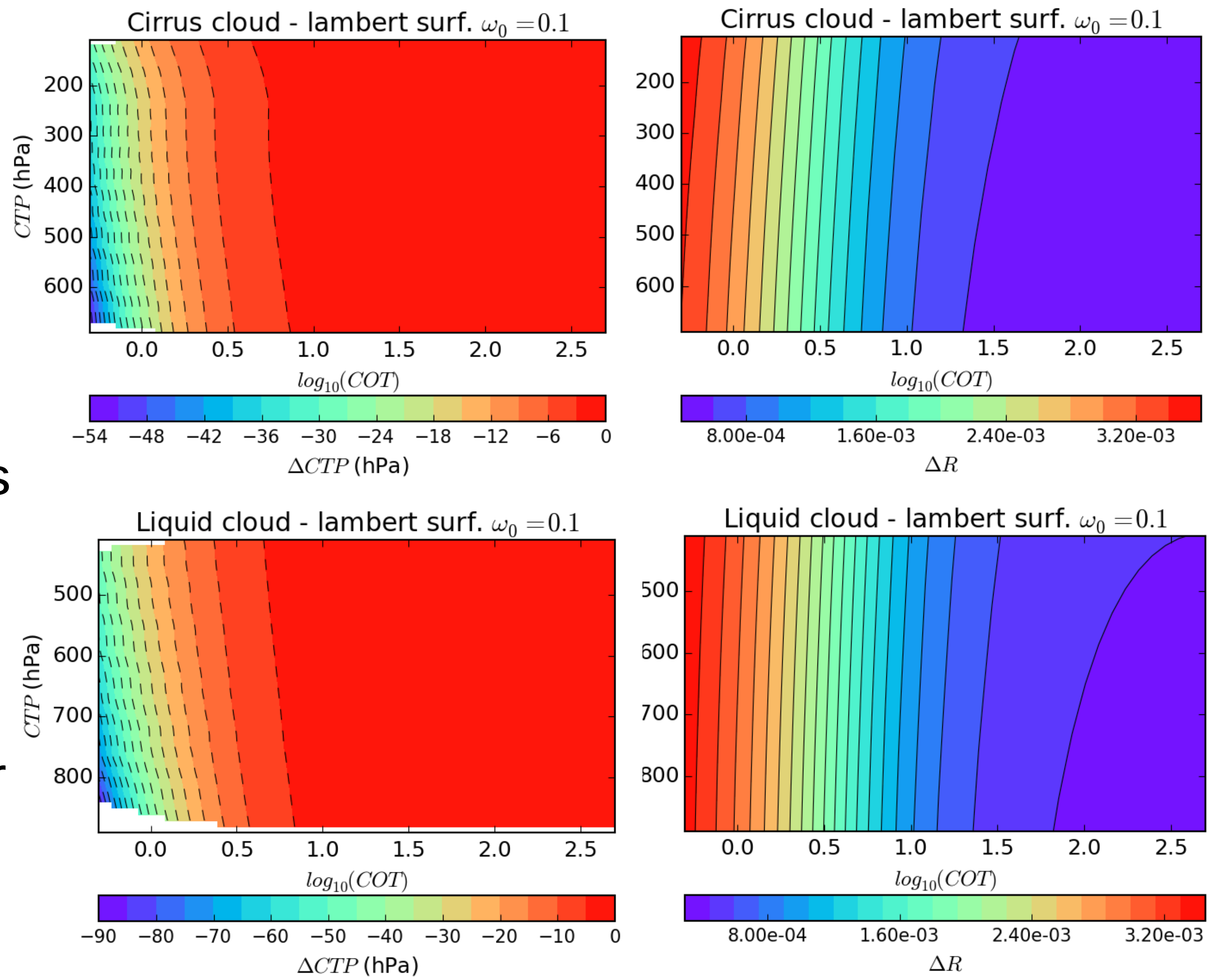


- $\Delta R = R_1 - R_2$ with
  - $R_1 = (I_{763} + N_{763}) / (I_{752} - N_{752})$
  - $R_2 = (I_{763} - N_{763}) / (I_{752} + N_{752})$



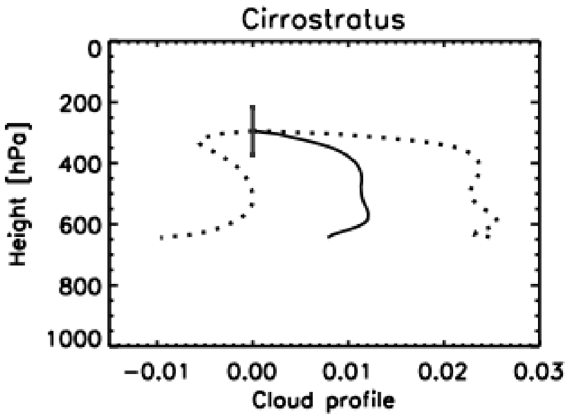
Sensitivity to instrument noise (II)

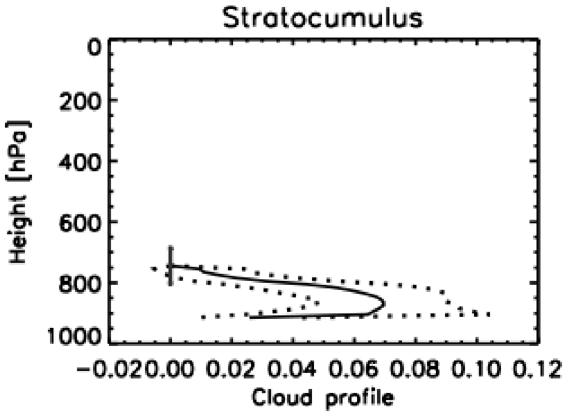
- ΔCTP corresponds to detection limit due to noise
- ΔCTP is greater for thinner clouds
- ΔCTP below 10hPa for clouds with COT greater than ~ 3-4



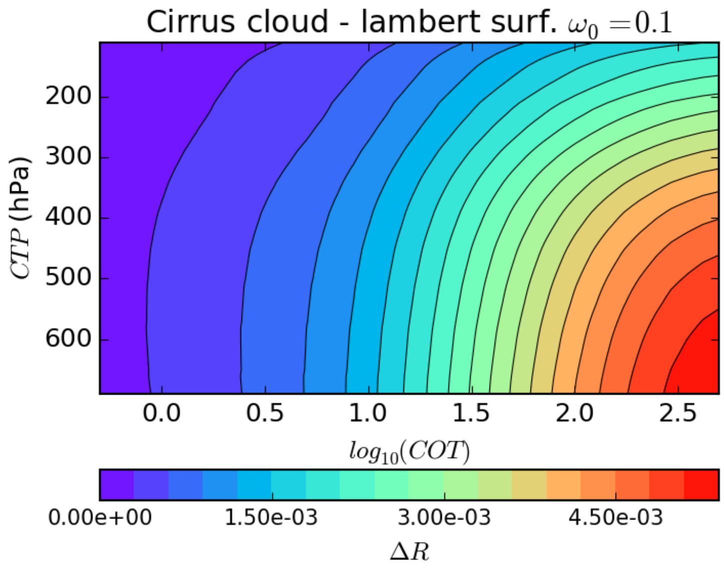
Sensitivity to cloud vertical profile (I)

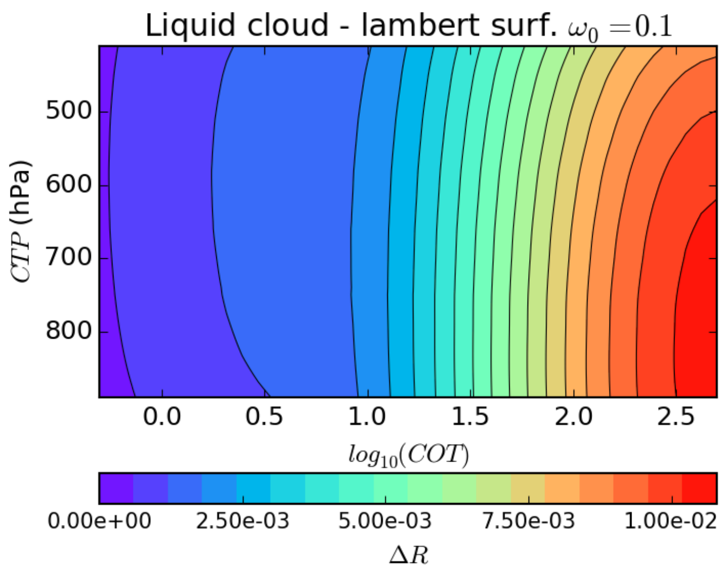
- Variation of signal ratio (ΔR) due to going from homogeneous to CPR vertical profile (CGT = 1.0 km)
  - $\Delta R = R_{HOMOGENEOUS} - R_{CPR}$





CPR profiles,
Carbajal-Henken et al., 2013

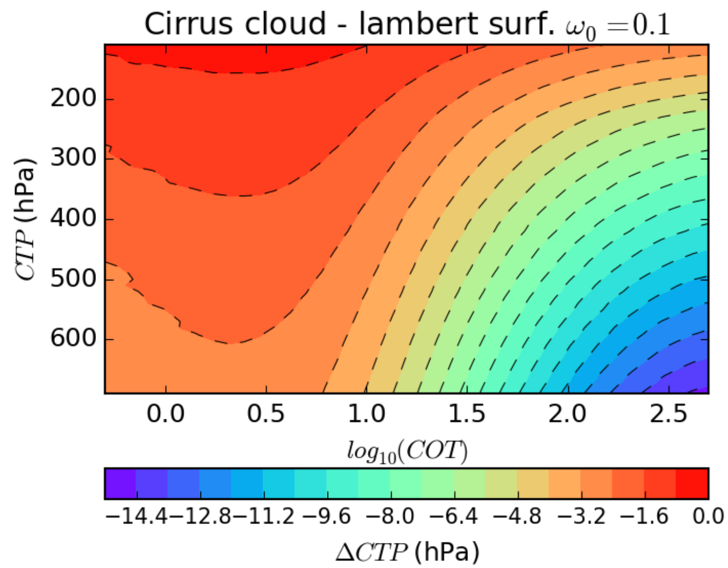


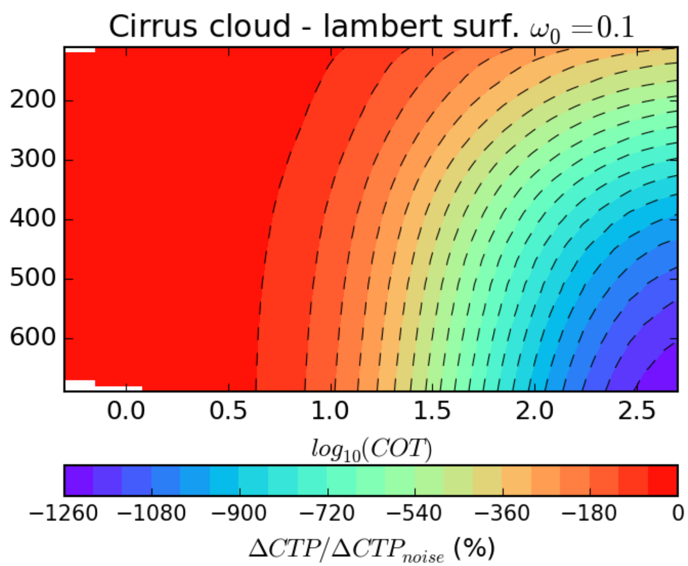


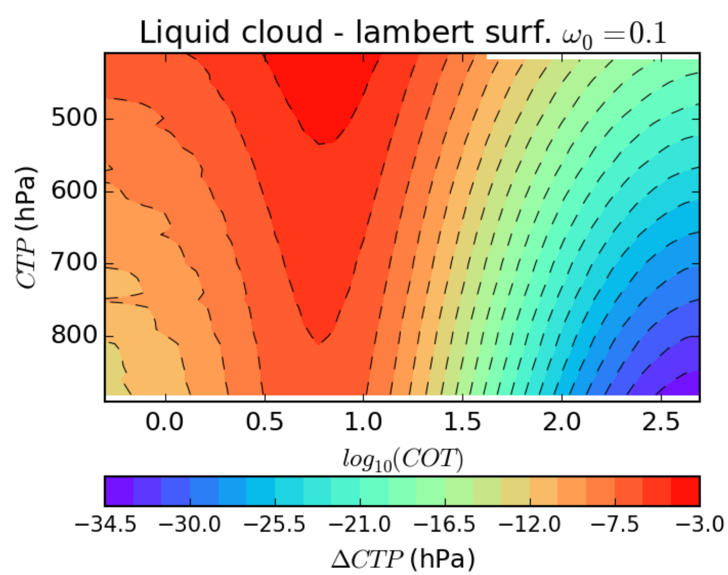
Sensitivity to cloud vertical profile (II)

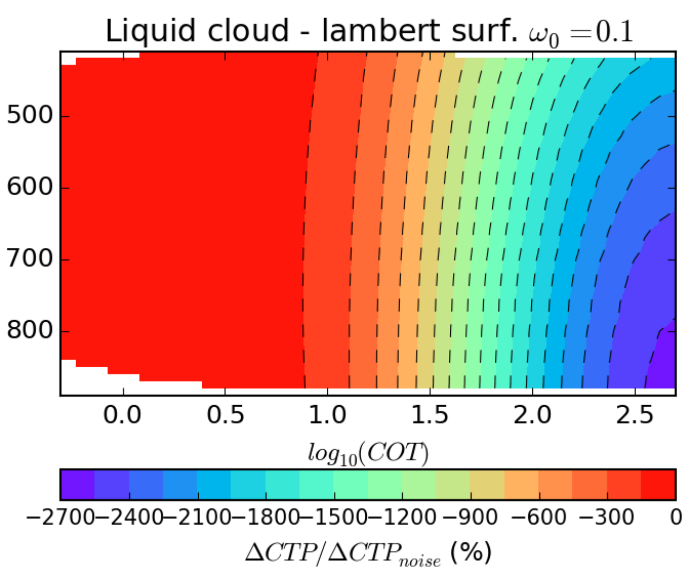
- The impact of vertical profile variation is maximum for thick low level clouds

- The impact is above detection limit for COT greater than ~ 3-5



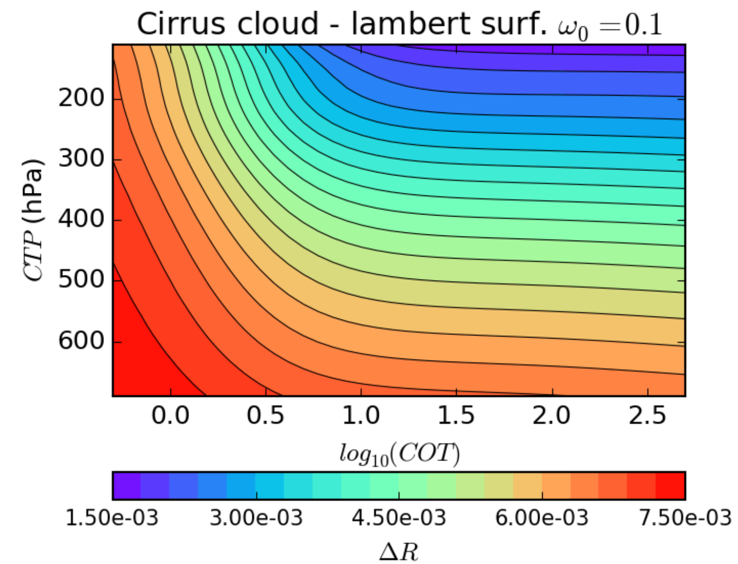


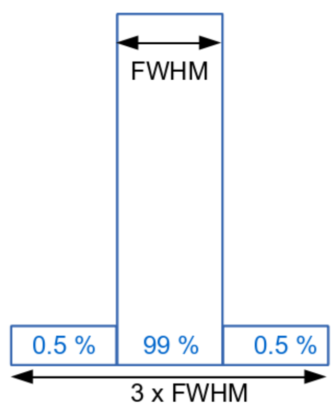




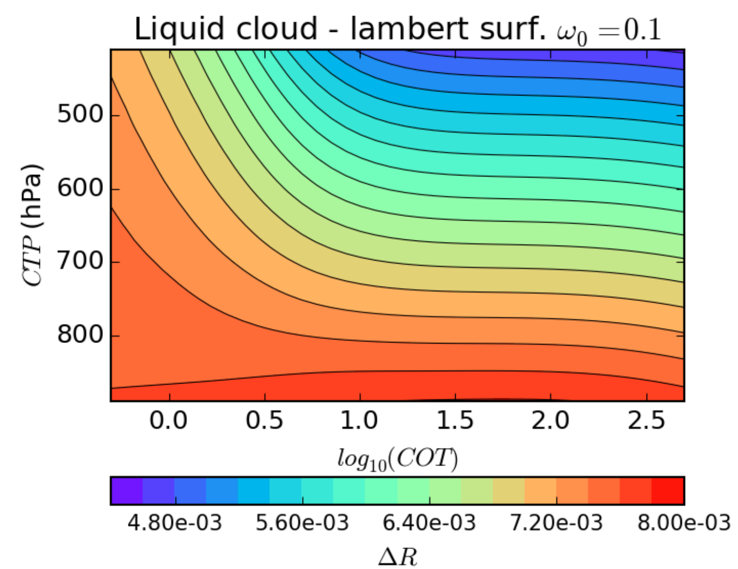
Sensitivity to ISRF wings (I)

- O_2 absorption treated using correlated-k distribution specific to METimage ISRF
- Variation of signal ratio (ΔR) due having 1% or 5% of power in ISRF wings
  - $\Delta R = R_{5\%} - R_{1\%}$





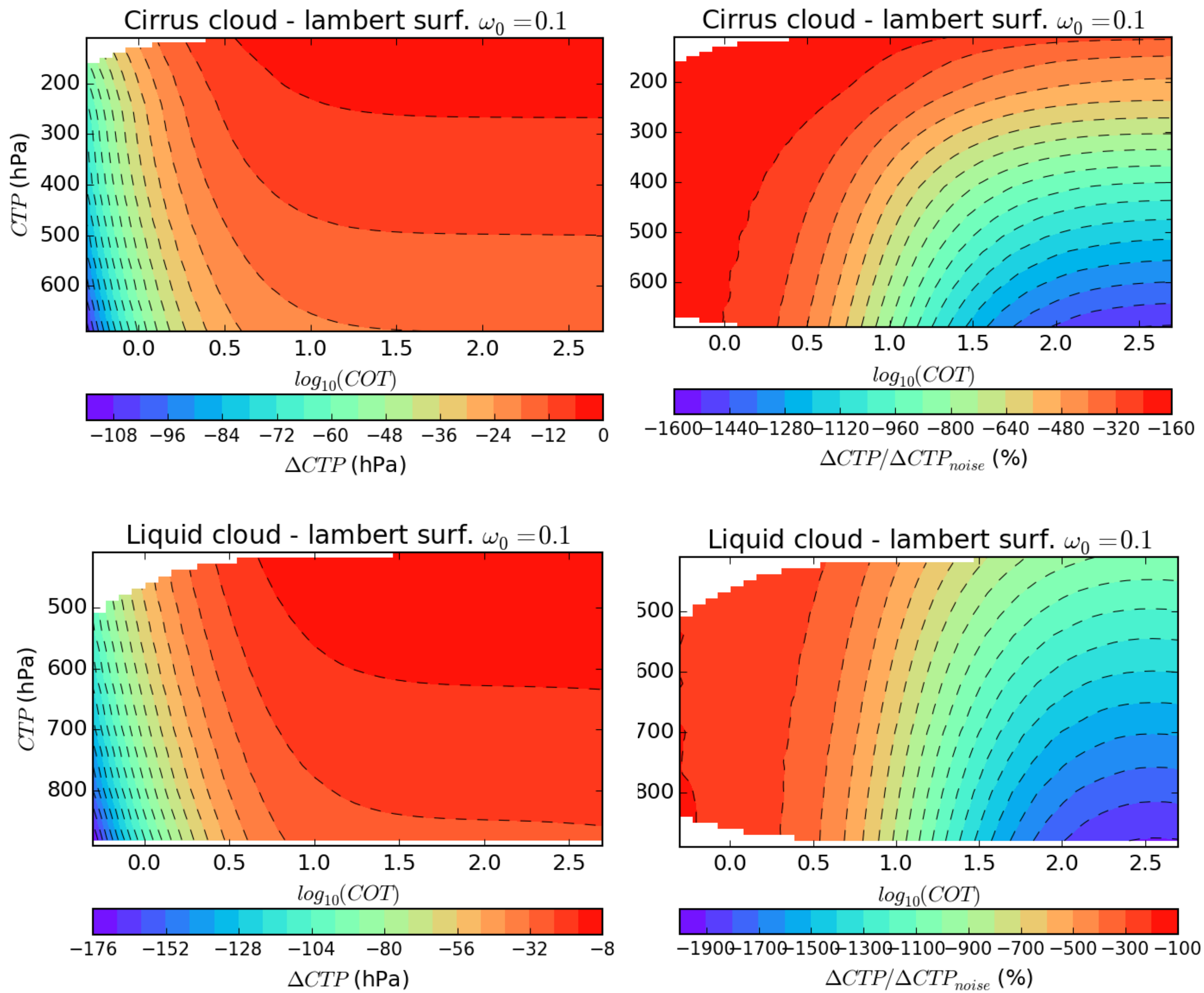
VII-5 channel



Sensitivity to ISRF wings (II)

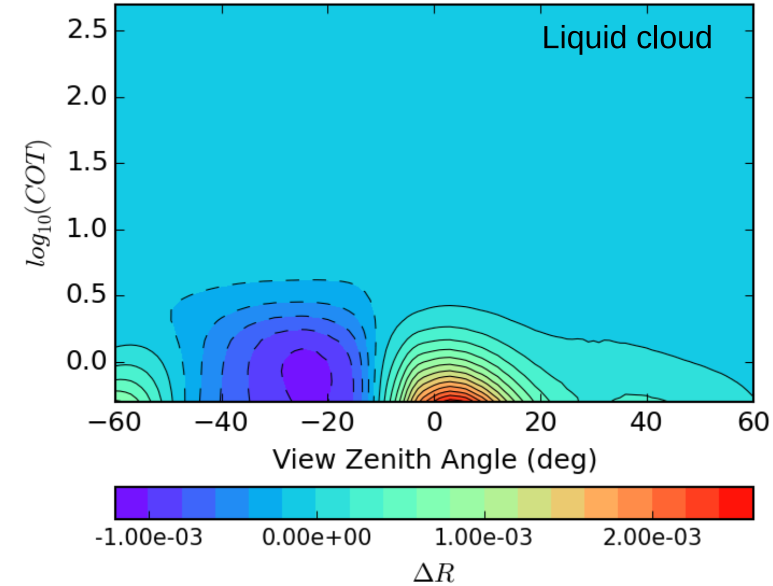
- Impact of ISRF wings is stronger for thin low level clouds

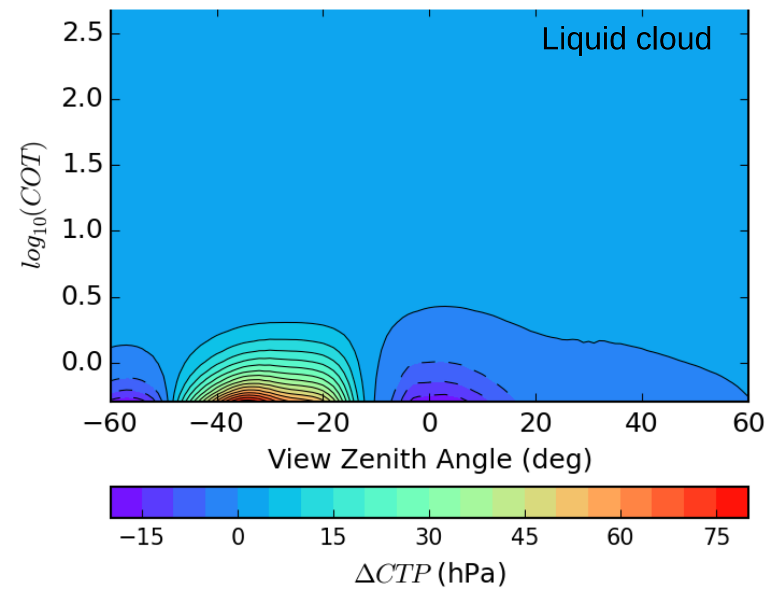
- The impact is above detection limit for COT greater than ~1



Sensitivity to surface BRDF

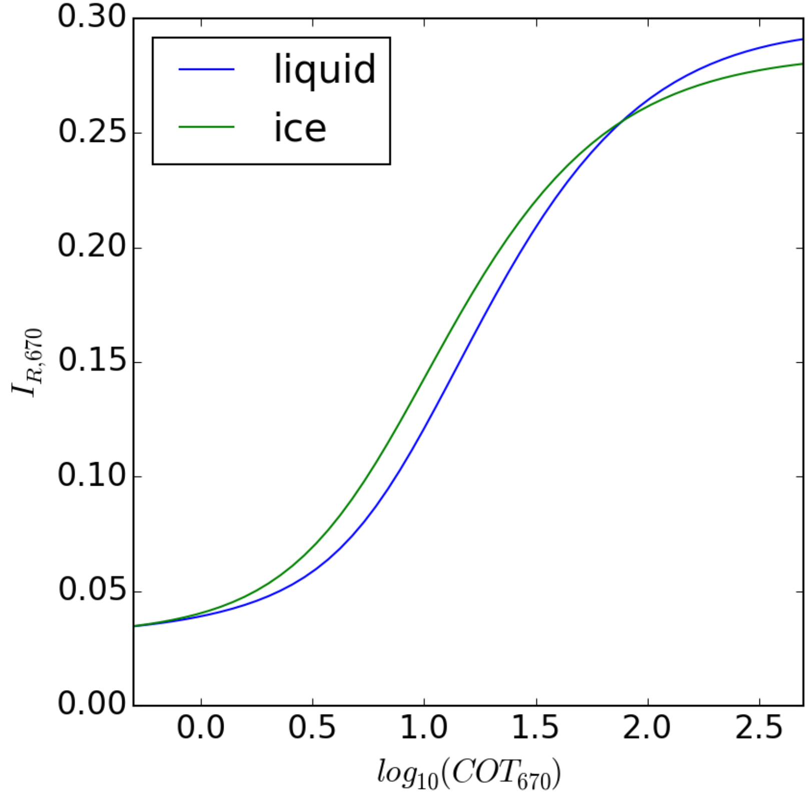
- Impact of the wind-speed on surface BRDF:
  - CTP = 800hPa (liquid cloud here)
  - Ocean glitter
  - SZA =30 deg
  - View in principal plane
- Variation of signal ratio (ΔR) due to wind-speed variation of 5m/s±10%
  - $\Delta R = R_{4.5m/s} - R_{5.5m/s}$
- Impact for clouds with COT smaller than ~4





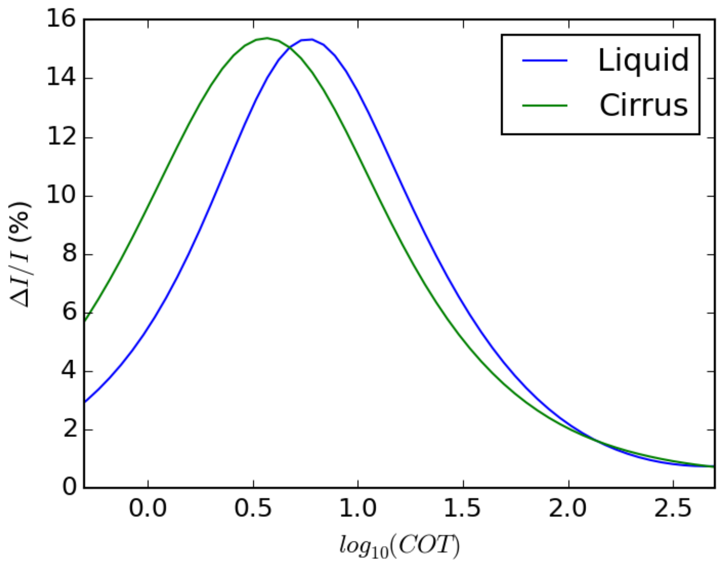
Sensitivity of reflectance

- COT will be retrieved through reflectance (I_R) in visible window channels (VII-3, VII-6)
- We compute I_R=f(COT) and its variability ΔI_R for a given parameter change
- We compute ΔCOT, the COT variation that produces the same ΔI_R)

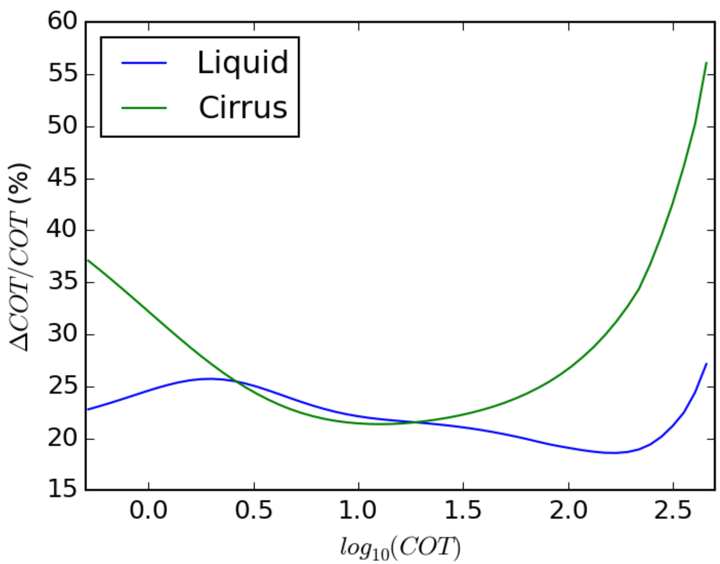


Sensitivity to effective radius (I)

- Variation of reflectance ΔI_R by varying the effective radius from 5 to 30 (60) microns for liquid (ice) clouds
  - $\Delta I_R = I_{Reff\ min} - I_{Reff\ max}$



- The ΔCOT is greater for thin and thick clouds than for moderate COT

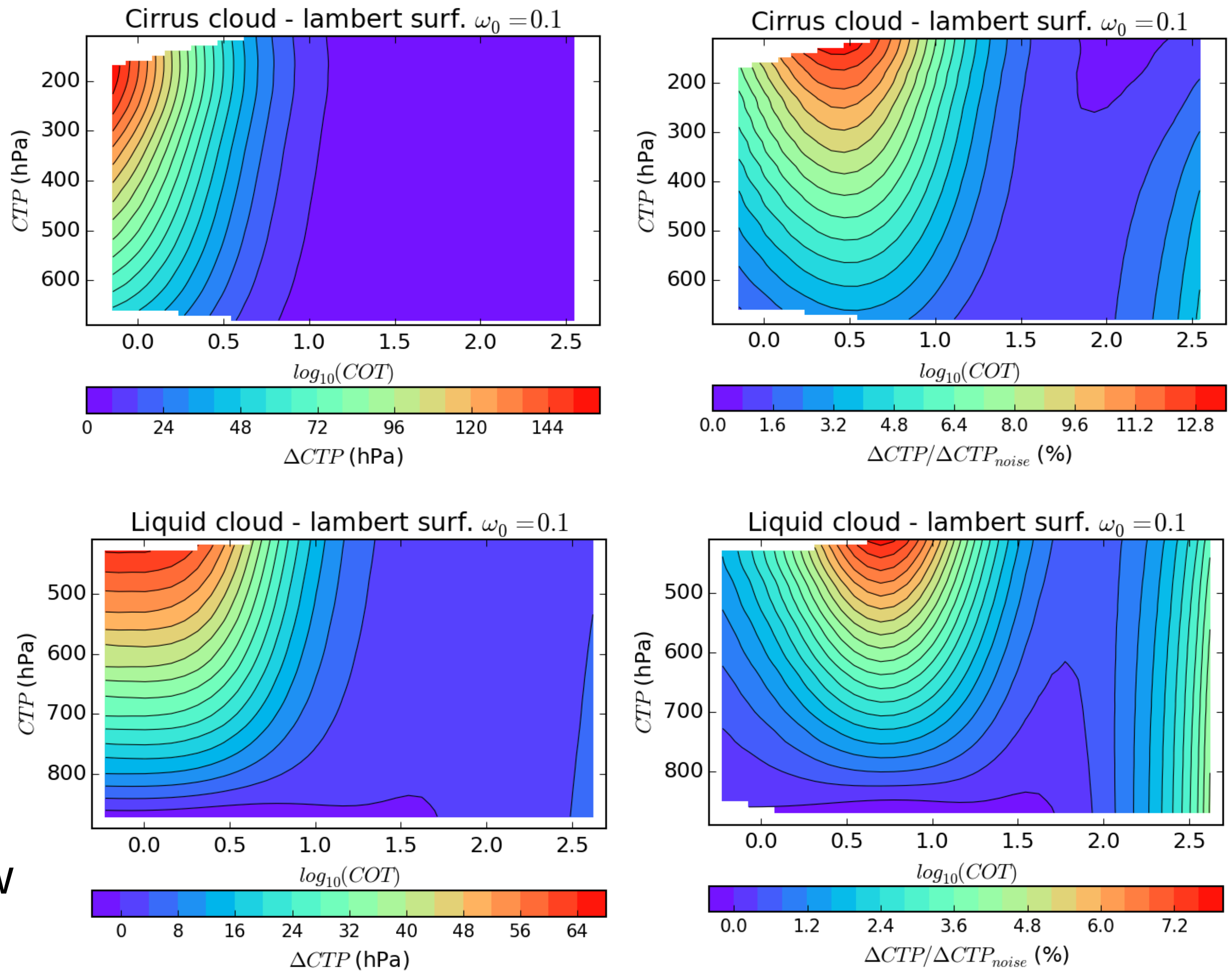


Sensitivity to effective radius (II)

- We compute ΔR due to ΔCOT=f(COT) and the equivalent ΔCTP

- The impact of R_{eff} change on CTP retrieval through ΔCOT error is stronger for high altitude thin clouds

- The impact is below the detection limit



Sensitivity studied parameters

Parameter	$\Delta I_R \rightarrow \Delta COT \rightarrow \Delta CTP$	$\Delta R \rightarrow \Delta CTP$
Instrument noise		X
Cloud Optical Thickness (COT)	X	X
Cloud Vertical profile		X
Cloud Geometrical Thickness (CGT)		X
Ice particle model	X	X
Particles effective radius	X	X
Aerosols presence	X	X
Surface level pressure		X
ISRF wings energy		X
Surface BRDF	X	X
Ozone column	X	

Parameters impact

Parameter	Maximum impact	
	Opacity	Altitude
Instrument noise	thin	all
Cloud Optical Thickness (COT)	thin	high
Cloud Vertical profile	thick	low
Cloud Geometrical Thickness (CGT)	moderate	low
Ice particle model	thin	high
Particles effective radius	thin	high
Aerosols presence (continental or maritime)	thin	all
Surface level pressure	thin	all
ISRF wings energy	thin	all
Surface BRDF	thin	-
Ozone column	thin	high

“Day 1” algorithm
&
LUTs

Day-1 algorithm basis

- Optimal estimate (OE) retrieval with Levenberg-Marquardt iterations
  - State vector : $x = [\log_{10}(COT), CTP]$
  - The measurement vector is [I, R]:
    - $R=I_{763}/I_{752}$
    - $I=I_{670}$ over the land (land is darker at 670nm)
    - $I=I_{865}$ over the ocean (water is darker at 865nm and aerosol impact is lowered)
- The forward model is $F(x, b) = [I_{LUT}(x, b), R_{LUT}(x, b)]$
  - LUT interpolation are linear for CPU demand reason

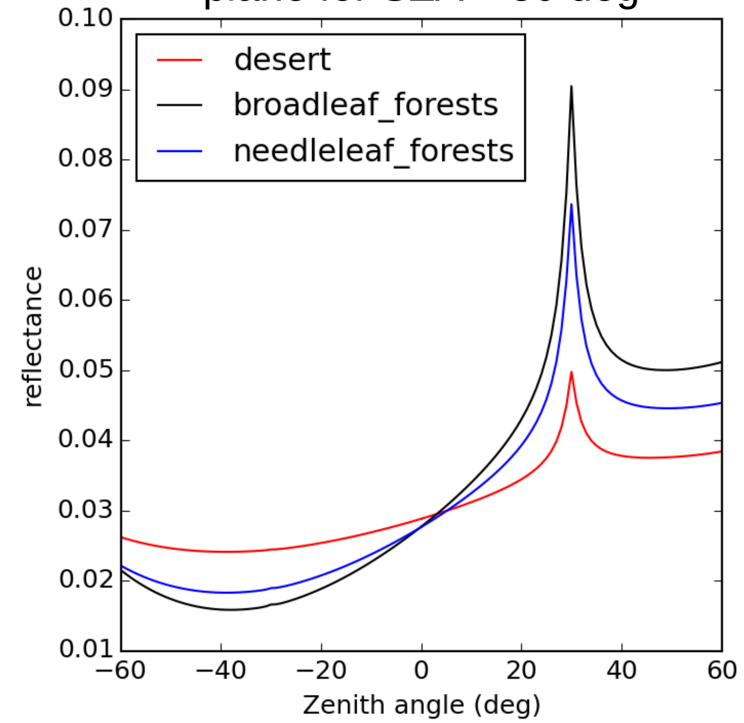
Forward model varying parameters

Varying parameters	Comment
Cloud phase	• 1 (I_{LUT},R_{LUT}) per phase (ice, liquid) • Successive loading at retrieval time
Surface BRDF (surface reflectance directionality)	• 1 (I_{LUT},R_{LUT}) per surface type (water, desert, broad-leaf forest...) • Successive loading at retrieval time
Aerosols	• Constant properties over a LUT (I_{LUT},R_{LUT}) • Can be varied depending on surface type
Cloud vertical structure	Parametrization regarding (COT, CTP)
COT	LUT entry (state parameter)
CTP	LUT entry (state parameter)
Surface pressure	LUT entry (non-retrieved parameter)
Surface albedo or wind-speed	LUT entry (non-retrieved parameter)
Solar Zenith Angle	LUT entry (non-retrieved parameter)
View Zenith Angle	LUT entry (non-retrieved parameter)
Relative Azimuth Angle	LUT entry (non-retrieved parameter)

Surface BRDF types

Surface type	BRDF model
Water (ocean)	Glitter with Cox and Munk (1954) slope distribution + foam and shadowing effect
Desert	Li-Ross model including Hot-Spot (Maignan et al., 2004) with VOLumetric and GEOmetric parameters from BASE*
Grasses / cereal crops	-
Broad-leaf forests	-
Needle-leaf forests	-
Shrubs	-
Savannas	-
snow/ice	Lambertian

Land BRDF in the principal plane for SZA = 30 deg

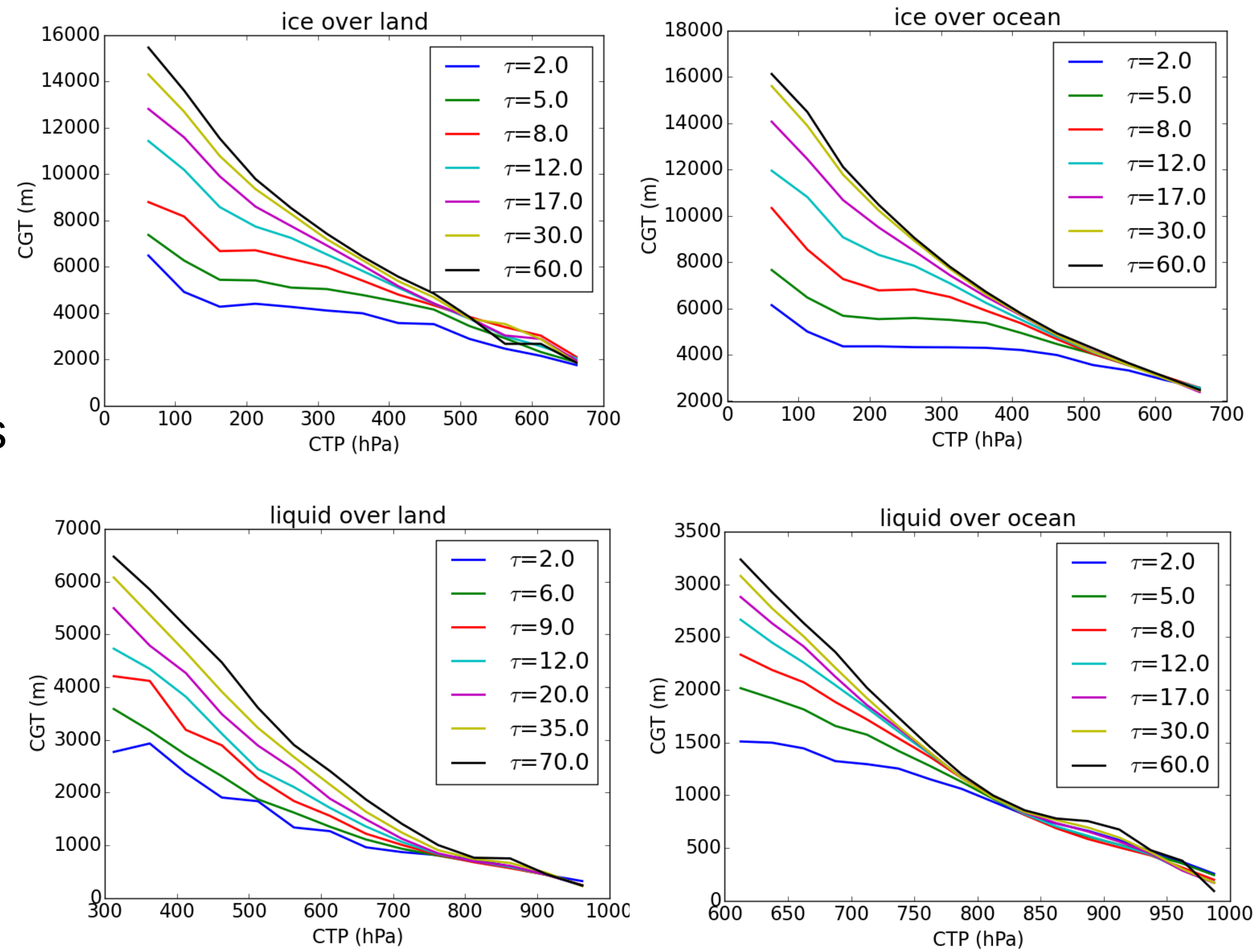


*BASE : Bidirectional Anisotropy Standard shapEs (BASEs) from Bacour and Bréon [2005] (i.e. POLDER/PARASOL climatology)

HYGEOS

Geometrical thickness climatology

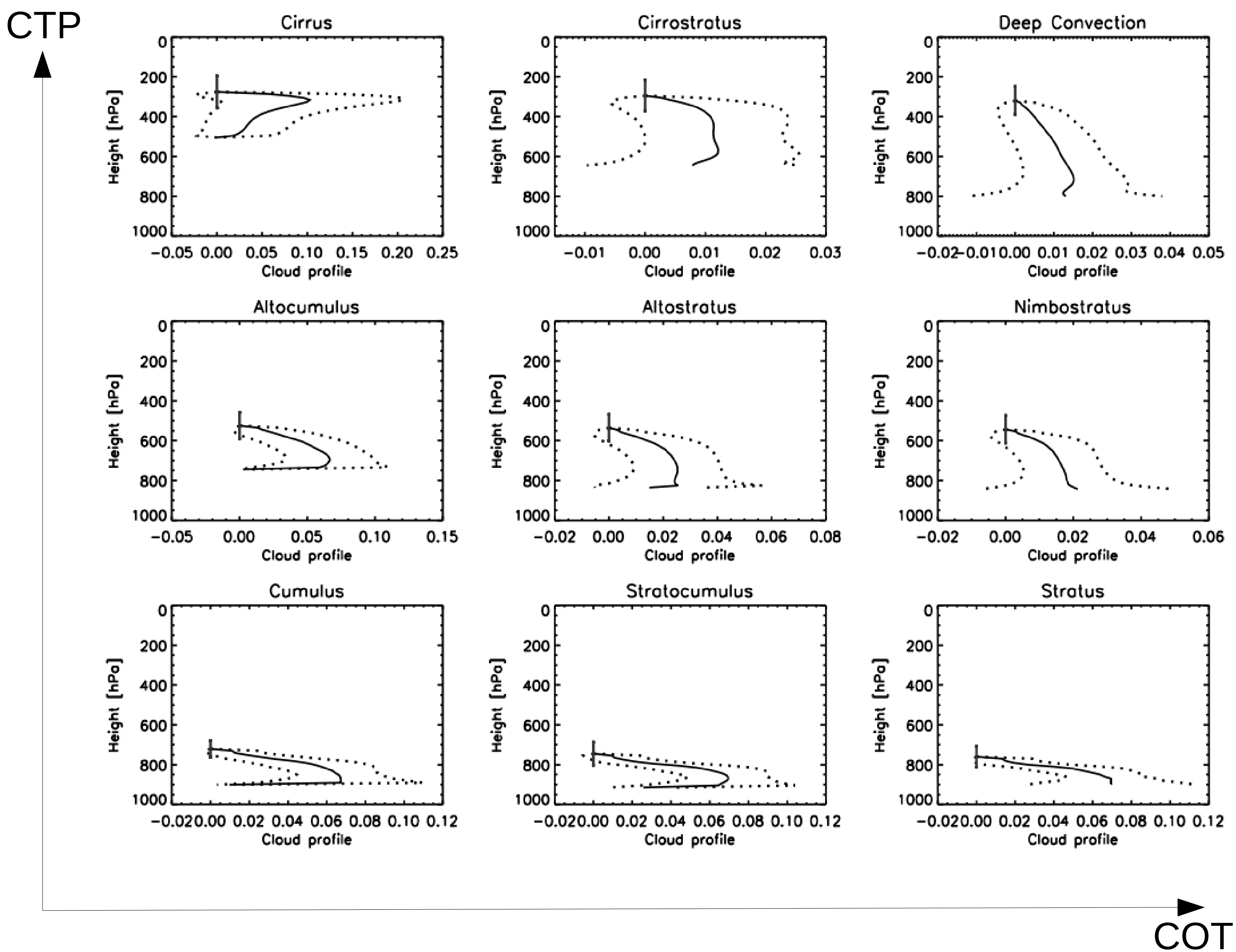
- Climatology CGT=f(COT,CTP) built with 1 year (2008) of CloudSat/Caliop
- Separate climatology for ice and liquid clouds and for ocean and land surfaces
- When building the LUT, CGT is adapted according to that climatology



Vertical profile climatology

- Climatology profile for 9 ISCCP types built with 1 year (2010) of CloudSat data (Carbajal-Henken et al., 2013)

- When building the LUT, we interpolate in (COT, CTP) the profile and adjust its CGT according to the CGT climatology



LUT computation

- RTE solver is an adding and doubling code
  - 8 streams, δ-M truncation + TMS correction (I_R better than 0.4% out of rainbow and glory geometries)
- Optical properties:
  - Liquid cloud are Mie Particle with log-normal size dist. for V_{eff}=0.09 and R_{eff}=14 microns
  - Ice clouds are General Habit Mixture from Baum et al. (2014) with R_{eff}=25 microns
- US62 standard atmospheric profile re-sampled to 1 km out of cloud and 100 m in cloud
- O_2 absorption : specific correlated-k distributions for used channels (METimage and MERIS)
  - transmissions better than 1.5 % regarding line-by-line (airmass < 10)

LUT sampling

	Sampling steps	minimum value	maximum value	# of sample "medium"	# of sample "high"
COT	constant steps in $\log_{10}$(COT)	0.1	500.0	10	20
CTP	constant steps in CTP	50 hPa	1080 hPa	13	30
P_{surf}	constant steps in P_{surf}	850 hPa	1080 hPa	5	10
W_{spd}	constant steps in W_{spd}	1 m/s	15 m/s	3	5
WSA	constant steps in WSA	~0 (~0.5 for snow/ice)	~0.4 (~1.0 for snow/ice)	3	5
SZA	I_{LUT} : constant steps in SZA R_{LUT} : constant steps in cos(SZA)	0^o	70^o	I_{LUT} : 36 R_{LUT} : 9	I_{LUT} : 36 R_{LUT} : 15
VZA	I_{LUT} : constant steps in VZA R_{LUT} : constant steps in cos(VZA)	0^o	70^o	I_{LUT} : 71 R_{LUT} : 10	I_{LUT} : 71 R_{LUT} : 15
RAA	constant steps in RAA	0^o	180^o	I_{LUT} : 181 R_{LUT} : 38	I_{LUT} : 181 R_{LUT} :38

$[I_{LUT}, R_{LUT}]_{\text{high res}}$: 1211 Mo in float32, $[I_{LUT}, R_{LUT}]_{\text{medium res}}$: 81 Mo in float32

Algorithm structure

1) Loading reflectance and ancillary data
2) Ozone absorption correction
3) Retrieval
   - Loop on surface type
     - Loop on cloud phase
       - Load the corresponding LUT [I_{LUT}, R_{LUT}]
       - OE retrieval on pixels of the image with the corresponding surface type and cloud phase
4) Write results in HDF5 file

OE input

- No a-priori is considered (very high co-variance is set)
- The non-retrieved parameters are varied pixel-by-pixel
  - $b = (W_{spd}, P_{surf}, SZA, VZA, RAA)$ over water surface
  - $b = (WSA_{670}, WSA_{752}, P_{surf}, SZA, VZA, RAA)$ over land
- A first guess $x_0 = [\log_{10}(COT_0), CTP_0]$ is computed on pixel-by-pixel basis by 1D interpolation:
  - COT_0 is obtained by looking at the value in I_{LUT} that is the closest to measured I (knowing b).
  - CTP_0 is then obtained by looking at the value in R_{LUT} that is the closest to measured R (knowing b and COT_0).

OE input co-variance

- The input co-variance matrix is $S_\varepsilon = S_y + S_F + S_i$ with
  - S_y is the co-variance due to measurement uncertainties (bias+noise).
  - S_i is a co-variance matrix corresponding to interpolation error on I_{LUT} and R_{LUT}
  - S_F is the co-variance due to the non-retrieved parameters uncertainties. $S_F = K_b\ S_b\ K_b^T$. K_b is the Jacobian (sensitivity) of the forward model regarding non-retrieved parameters. S_b is the co-variance matrix of non-retrieved parameters. S_F should be computed on a pixel-by-pixel basis. However, this computation is time consuming and S_F can then be optionally computed only once for a given value of b.

    Hybrid solution depending on COT_0

OE iterations

- Levenberg-Marquardt Gamma parameter evolution:
  - initialized to 0.1 and is divided by 10 every iteration
  - Within a given iteration, a temporary gamma is multiplied by 5 while the cost function is not lowered
- Iteration process is terminated if at least one of the following conditions is True:
  - Maximum number of iteration reaches ($N_{iterMAX}$=15)
  - The cost function can not be significantly reduced between two iterations (threshold is 1%)
  - the convergence test is less or equal the measurement vector size: $$[y-F(x_i)]S_{\epsilon}^{-1}[y-F(x_i)]\leqslant n_y$$

LUT format & Algorithm implementation

- The LUTs are stored in HDF5 format in float32 (single precision)
- Algorithm implemented in Python
  - one OE generic routine
  - one METimage specific routine (I/O handling and recursive OE call)
  - one MERIS specific routine (I/O handling and recursive OE call)
- Parallelization of the retrieval through HTcondor or SGE
  - retrieval for a 5 min observation METimage granule with 47% of cloudy pixels takes several hours of CPU Intel(R) Xeon(R) CPU @3.30GHz

Input & ancillary data

- Level 1b radiance or reflectance for VII-3 (670nm), VII-4 (752nm), VII-5 (763nm) and VII-6 (865nm) as well as viewing and sun geometry

- Ancillary data needed are:
  - Cloud mask and cloud phase mask
  - The ozone column
  - Ground level atmospheric pressure (or sea level pressure + DEM)
  - The 670 and 752-763 nm surface white sky albedo
  - The wind-speed
  - A land sea mask and Land Cover type (e.g. IGBP classification and optionally : a snow/ice dynamical mask

Surface type mapping

LUT surface type	IGBP type
Broad-leaf forest	Evergreen broad-leaf forest, Deciduous broad-leaf forest
Needle-leaf forest	Evergreen needle-leaf forest, Deciduous needle-leaf forest, mixed forests
Desert	Barren or sparsely vegetated, Urban and built-up
Grasses / cereal crops	Croplands, Grassland, Permanent wetlands, Cropland/natural vegetation mosaic
Savannas	Woody savannas, Savannas
Shrubs	Closed shrub-land, Open shrub-land
Snow/ice	Snow/ice
Water	Water

- The mapping is set in the retrieval routine and can be changed before a retrieval is run
- Additionally, automated switch to “snow/ice” could be set for WSA>threshold

Output files

- The outputs are written in HDF5 format in float32 and contains the following values:
  - The geolocation (latitude and longitude)
  - The retrieved COT at 670 nm (even above ocean where the 865 nm channel is used to retrieve the COT) and its uncertainty
  - The CTP in hPa and its uncertainty
- As test outputs, we also write in file:
  - The first guess state vector (COT_0, CTP_0) and cost function for the first guess state vector
  - The final cost function
  - The number of iterations (stored as INT8)
  - The residual for I (either 670 or 865 nm channel) and for R
  - the separate contribution to uncertainties (on COT and CTP) due to the a-priori, the forward model and the measurement vector uncertainties
  - A flag value describing the state of the pixel (0 non-treated, 1 successful retrieval, 2 failed retrieval or 3 not treated because non retrieved parameters exceeded the range sampled in LUT

Testing on METimage Synthetic Data Set (SDS)

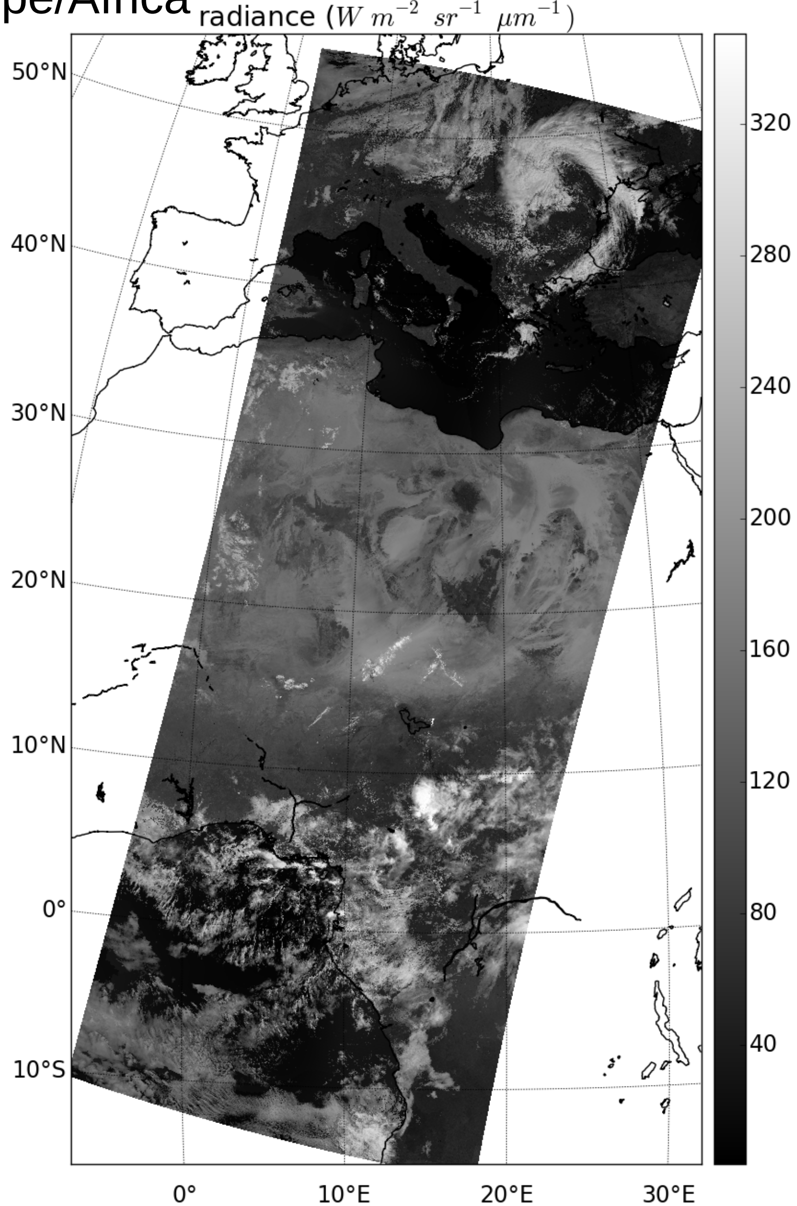
METimage data simulator

- Simulator developed for the former EUMETSAT study : "EPS Second Generation – Test data for the METimage and 3MI instruments"
- Geolocation, View and Sun Geometries produced for each pixel based on instrument sampling characteristics and EPS-SG orbit propagation
- Realistic scene content (surface, aerosols, clouds) for location and time of each pixel mainly from
  - AVHRR products for clouds,
  - MACC reanalysis for aerosols,
  - ECMWF reanalysis for atmospheric profile,
  - MODIS L2 products surface parameters
- TOA radiance (level1b) computed with ARTDECO

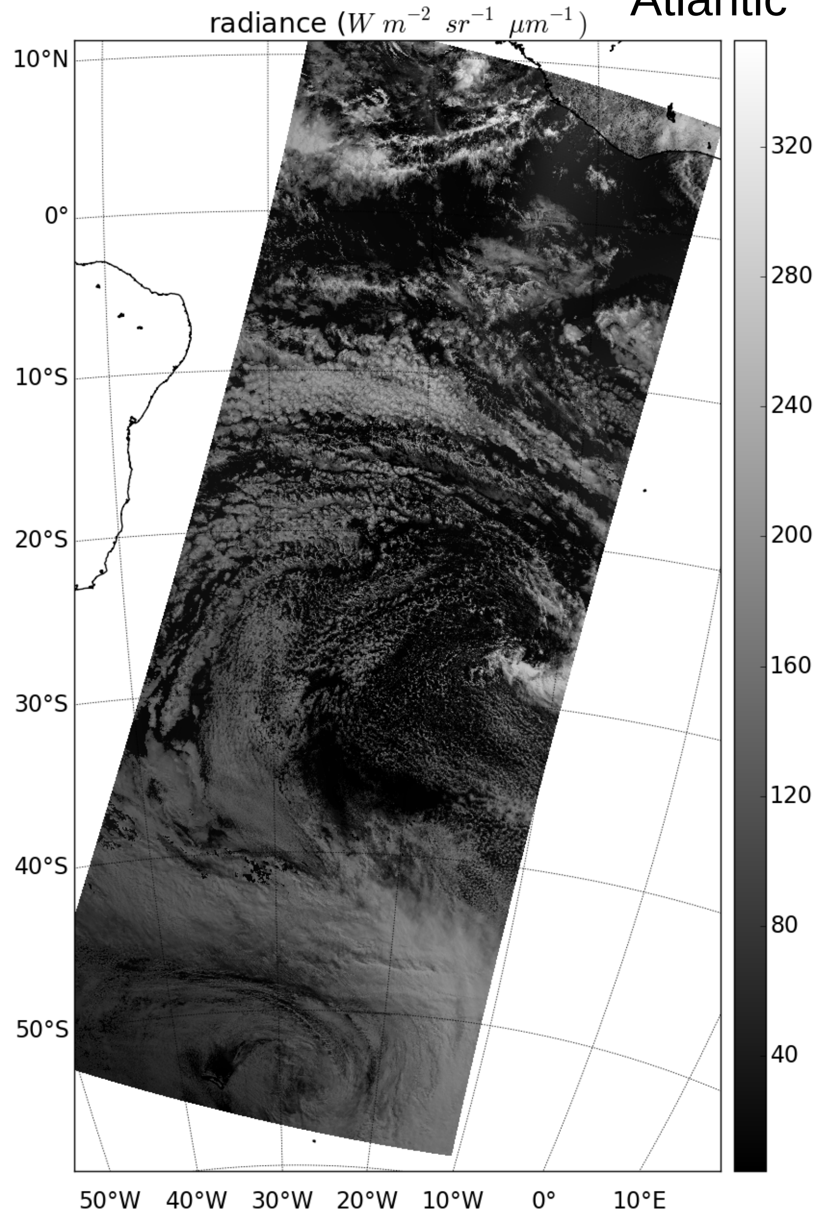
METimage
Synthetic Data Set (SDS)

VII-4

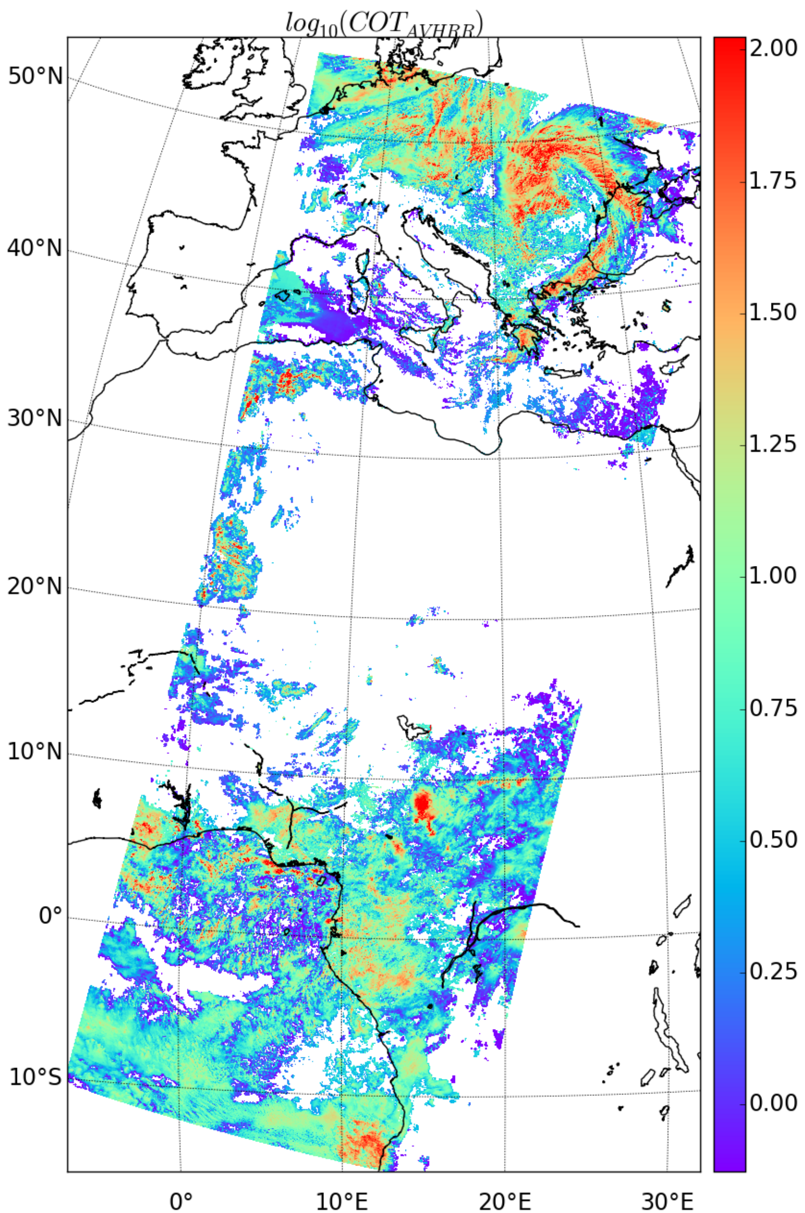
Europe/Africa



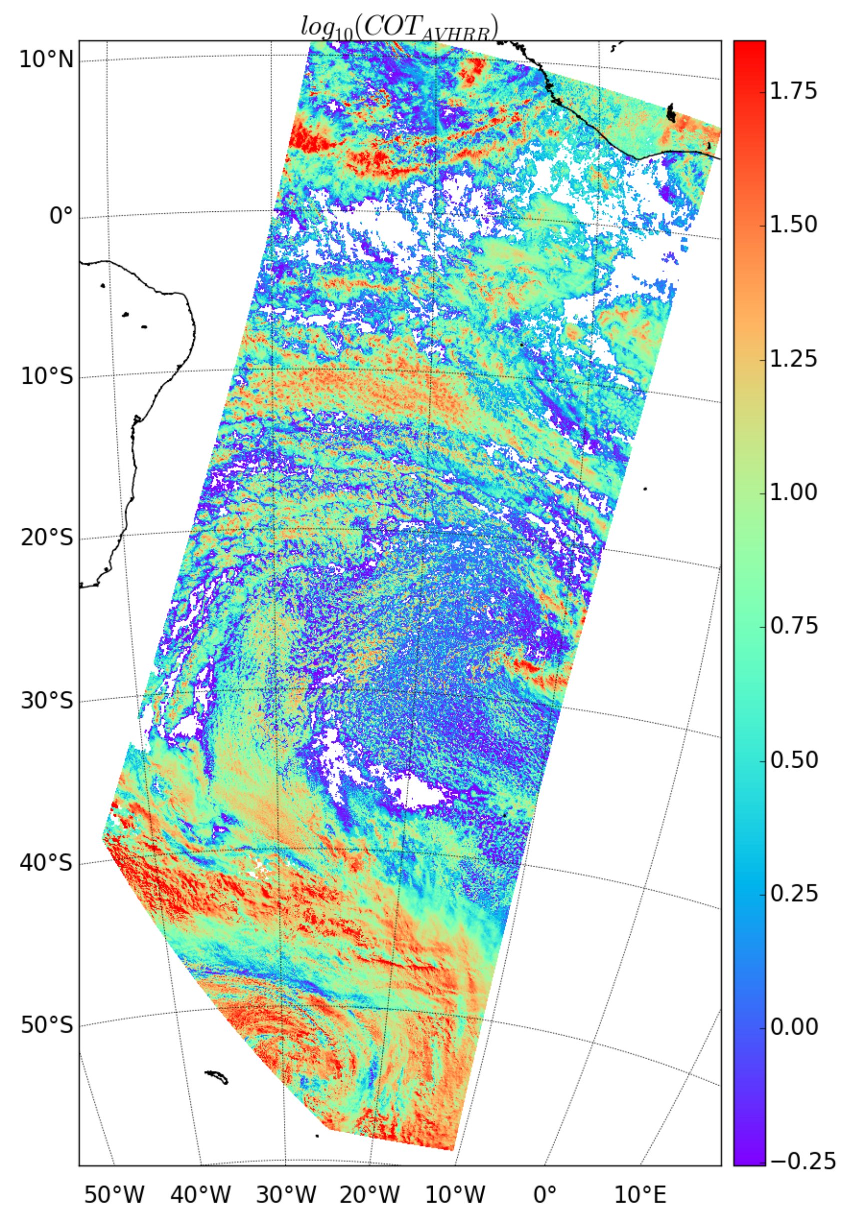
Atlantic



AVHRR COT

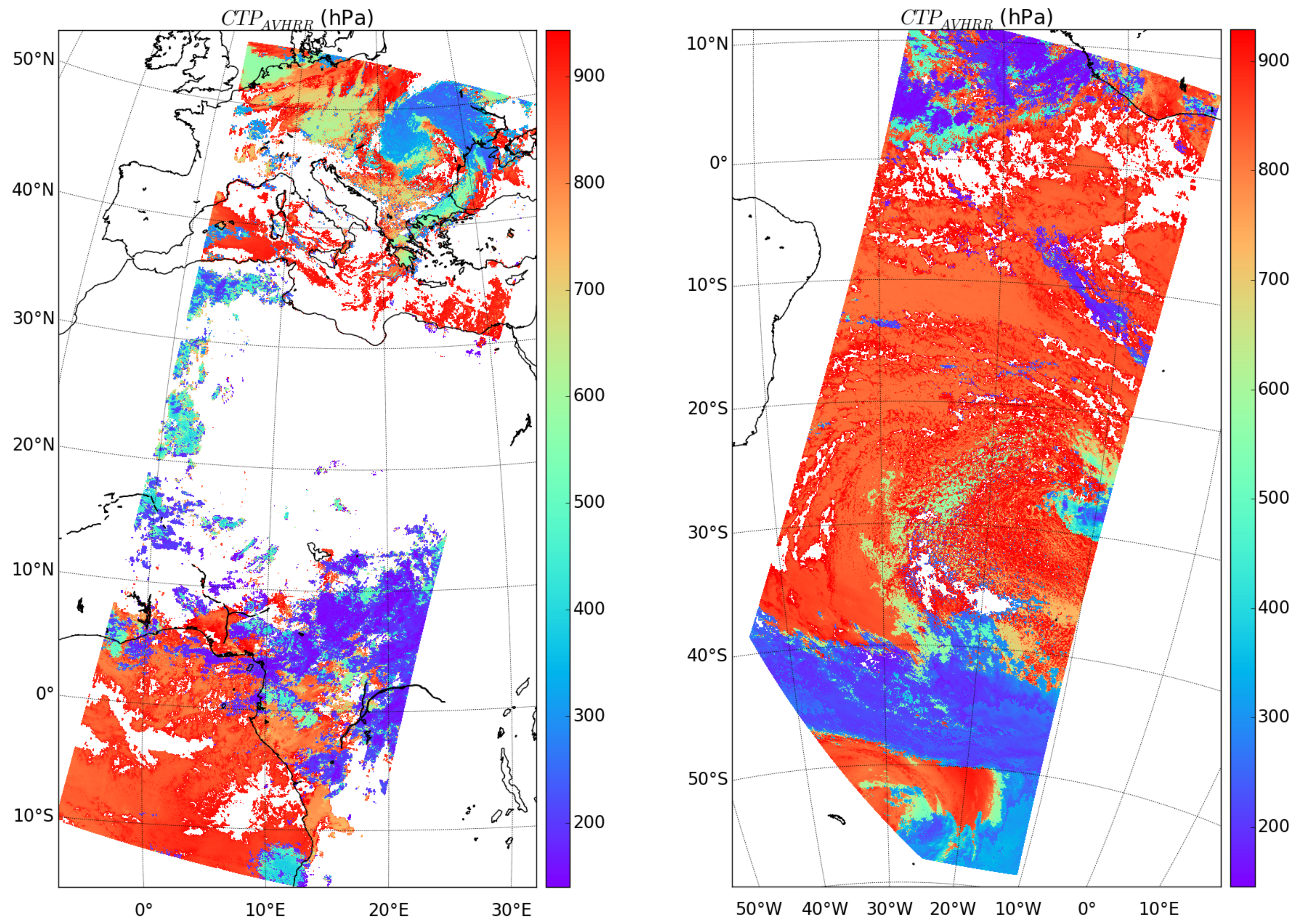


$log_{10}(COT_{AVHRR})$
50°N
40°N
30°N
20°N
10°N
0°
10°S
0°
10°E
20°E
30°E
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00



$log_{10}(COT_{AVHRR})$
10°N
0°
10°S
20°S
30°S
40°S
50°S
50°W
40°W
30°W
20°W
10°W
0°
10°E
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25

AVHRR CTP



CTP_{AVHRR} (hPa)
50°N
40°N
30°N
20°N
10°N
0°
10°S
0°
10°E
20°E
30°E
900
800
700
600
500
400
300
200
CTP_{AVHRR} (hPa)
10°N
0°
10°S
20°S
30°S
40°S
50°S
50°W
40°W
30°W
20°W
10°W
0°
10°E
900
800
700
600
500
400
300
200

Specifics for SDS testing

- To focus on LUT interpolation error, the radiance simulator is re-run with a forward model identical to the one for LUT computation
  - no ozone absorption, constant atmospheric profile = US62
  - fixed cloud particles R_{eff} and varying COT, CTP
  - no aerosols
  - surface BRDF = f(IGBP type) & WSA is varying from MODIS product
  - Varying Wind-speed
- The vertical structure climatology is not implemented in the simulator
  - we build a set of LUT with homogeneous profile and constant CGT=1.0 km

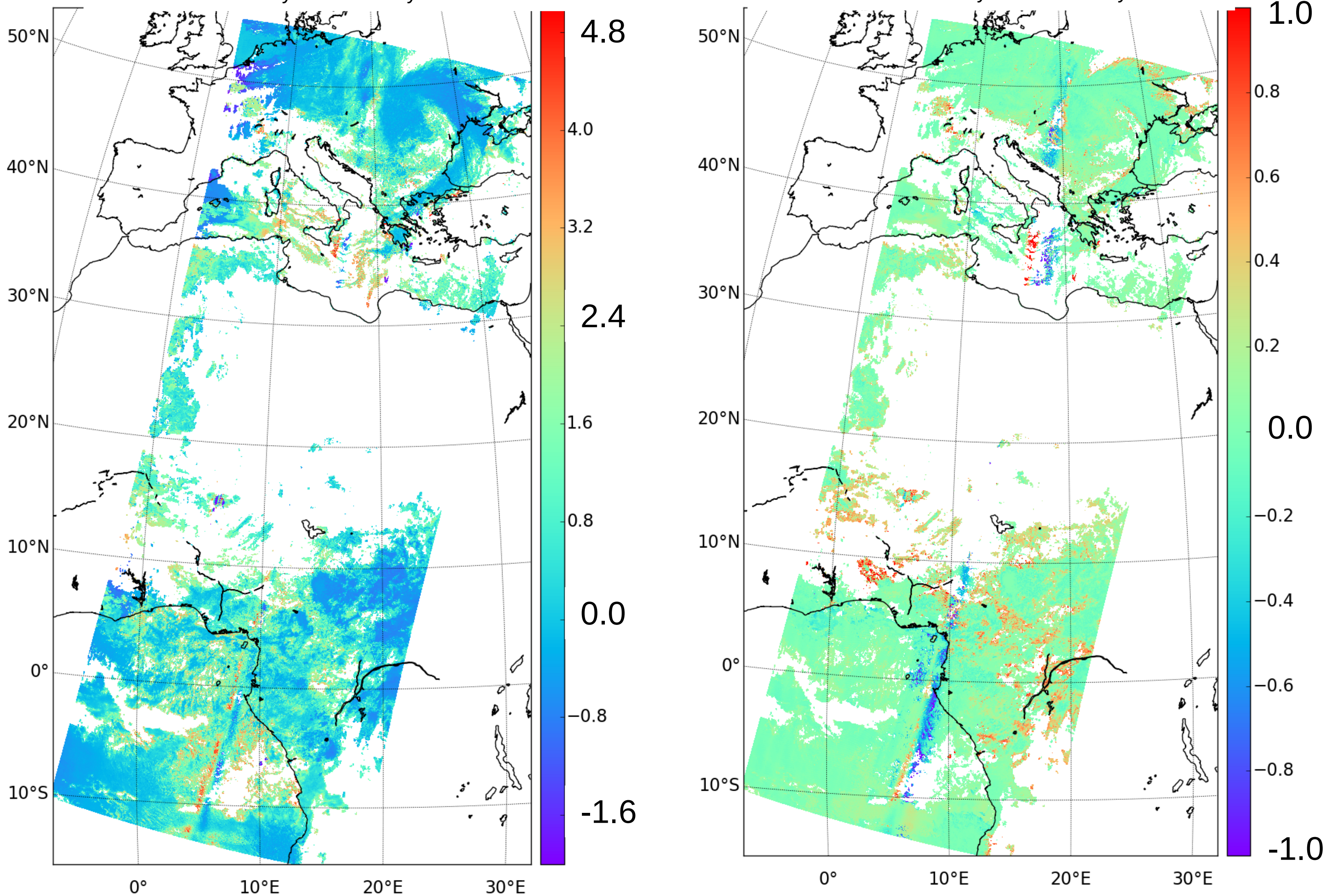
Interpolation error testing

- To study interpolation error in LUT one needs to
  1) compute a very high resolution sample across a given axis (e.g. COT) with fixing other parameters
  2) compare with interpolated values
- To do that for the whole LUT grid points comes back to build a very high resolution LUT
- Other approach:
  - we re-run the simulator but using the LUT as forward model instead of "on-the-fly" RTE solver
  - we compare I_{LUT}, R_{LUT} with $I_{on\text{-}the\text{-}fly}$, $R_{on\text{-}the\text{-}fly}$ ($I_{VII\text{-}3}$ or $I_{VII\text{-}6}$, $R = I_{VII\text{-}5/}I_{VII\text{-}4}$)
  - The histogram of differences shows the interpolation error weighted by the frequency of occurrence of pixel condition over the scene

Interpolation error on high resolution LUTs (I)

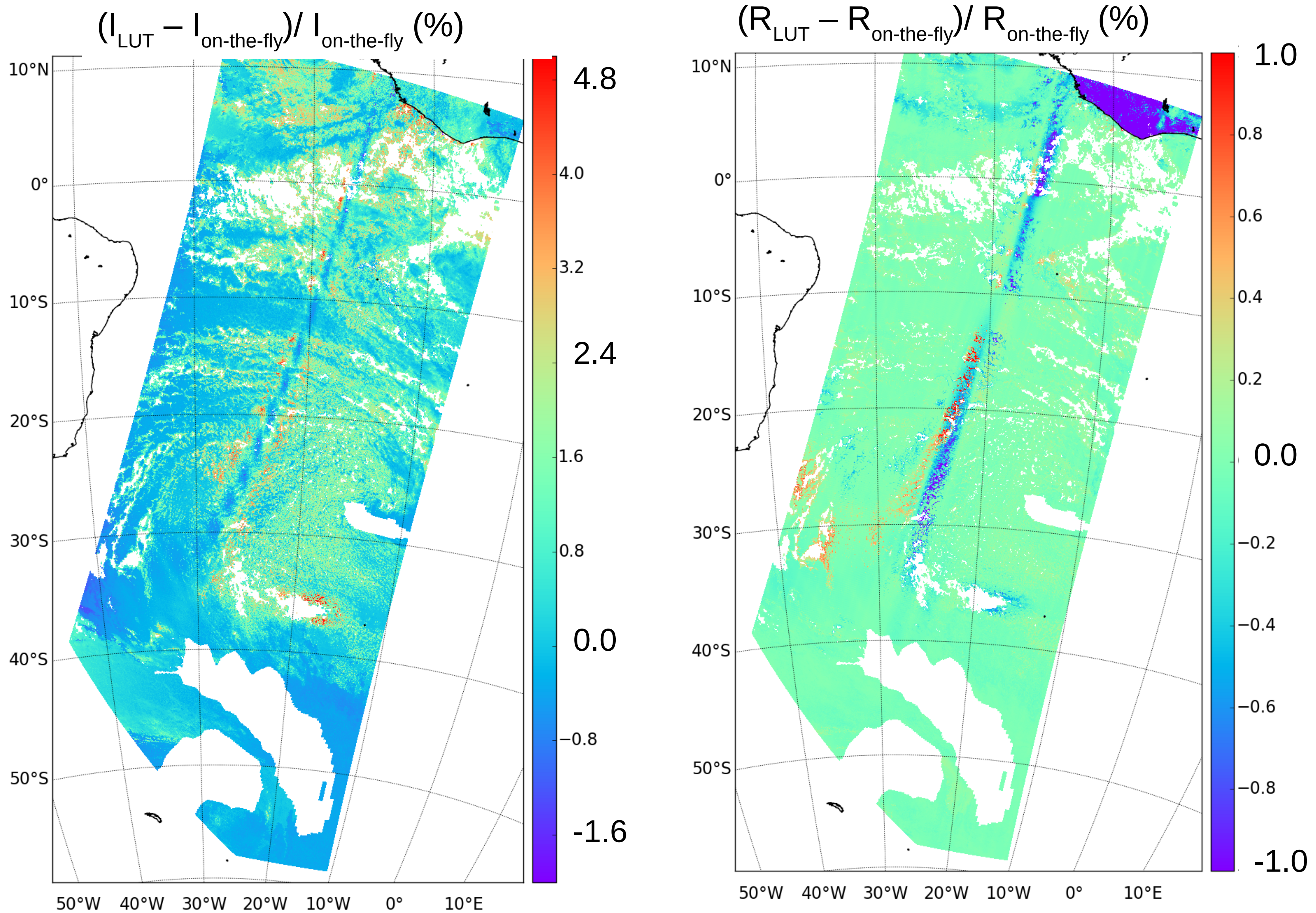
Europe/Africa

$(I_{LUT} - I_{on\text{-}the\text{-}fly}) / I_{on\text{-}the\text{-}fly}$ (%) $(R_{LUT} - R_{on\text{-}the\text{-}fly}) / R_{on\text{-}the\text{-}fly}$ (%)



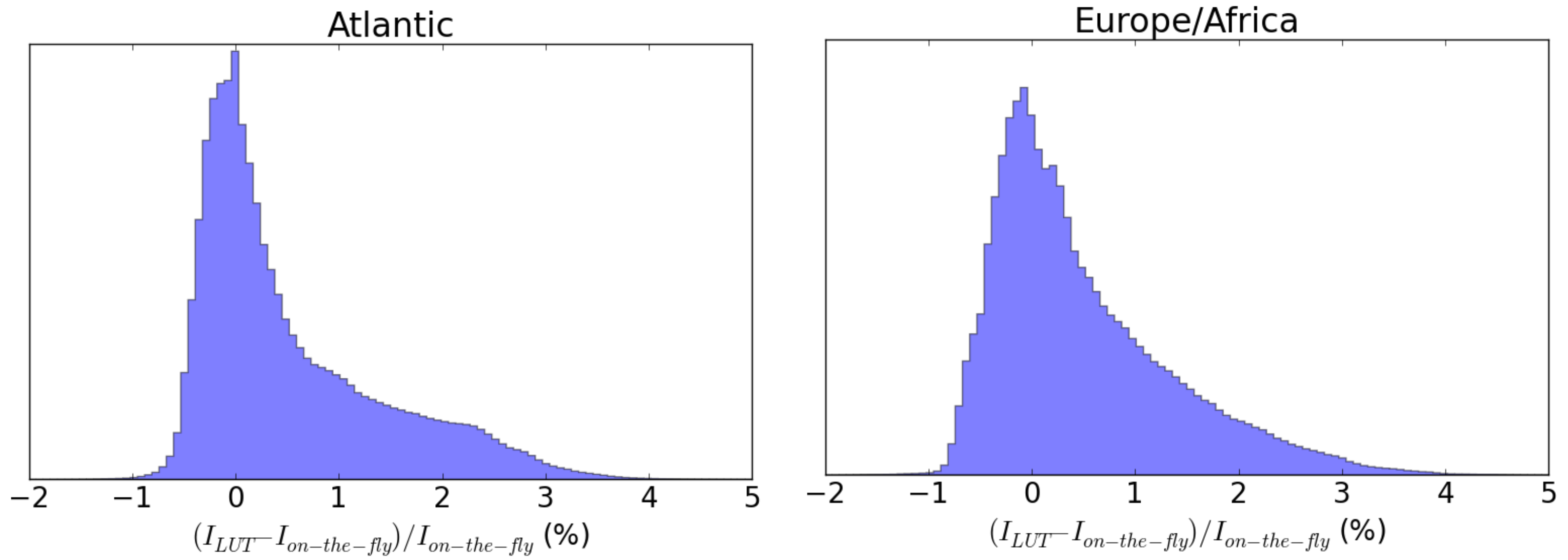
Interpolation error on high resolution LUTs (II)

Atlantic

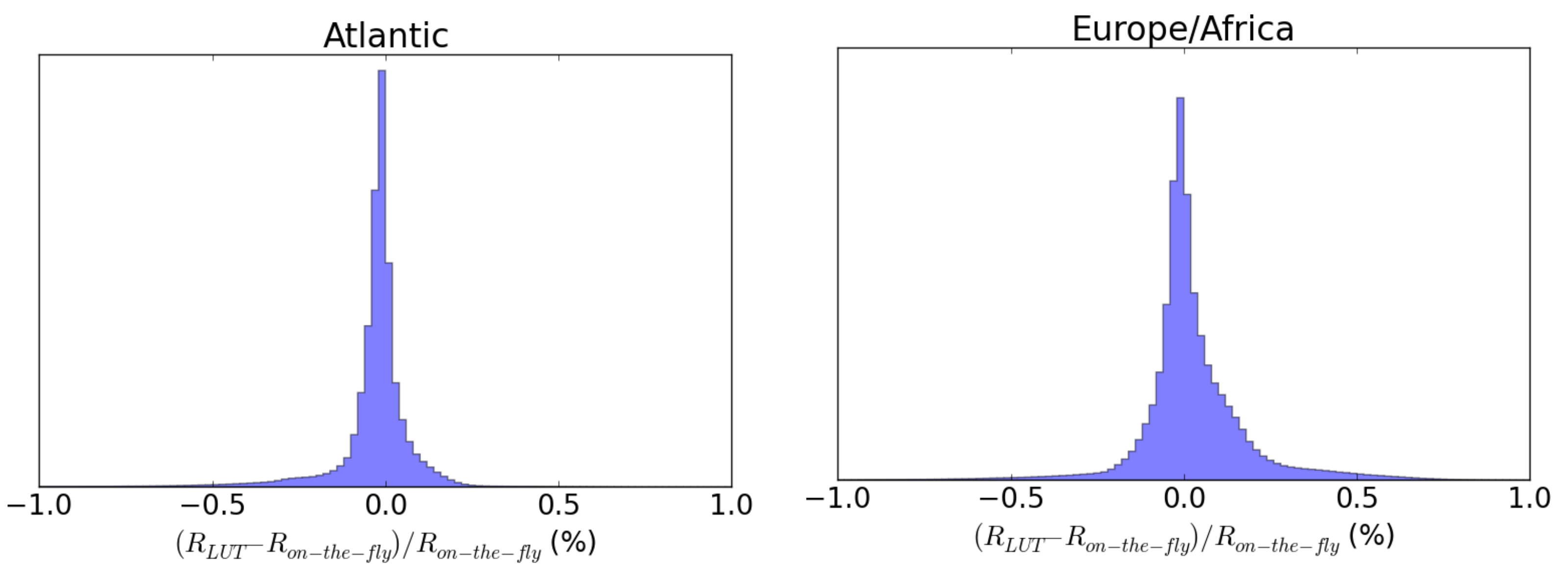


Interpolation error on high resolution LUTs (III)

- Error distribution for I peaks around 0.0 but is biased toward I over estimation (most pixels below ~3%)

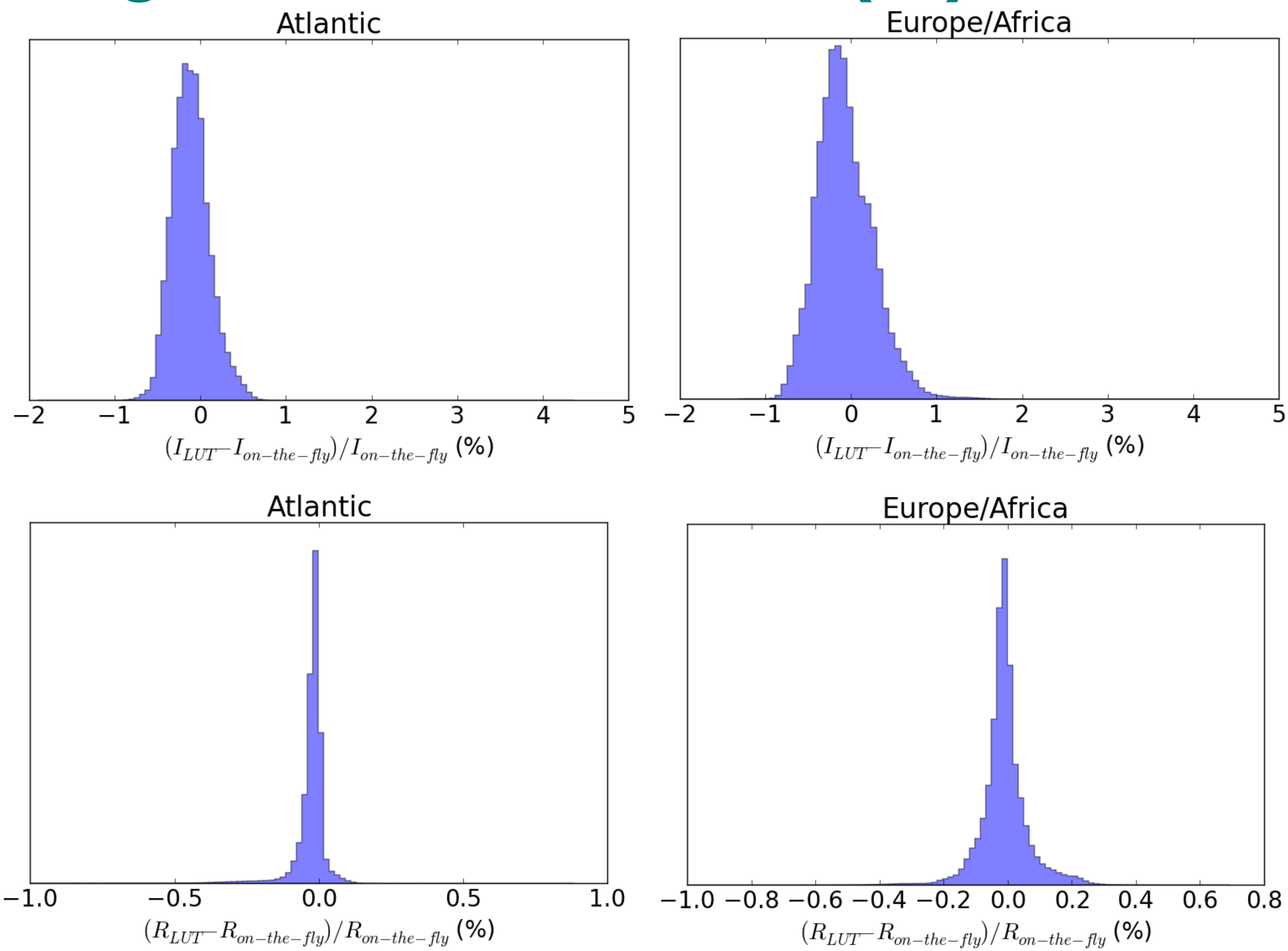


- Error distribution for R peaks around 0.0 and is centered (most pixels below ~0.5%)



Interpolation error on high resolution LUTs (IV)

- Error distribution for I is more symmetric for COT >10 (most pixels below ~1%)
- For R error most pixels are below 0.3 % for COT>10

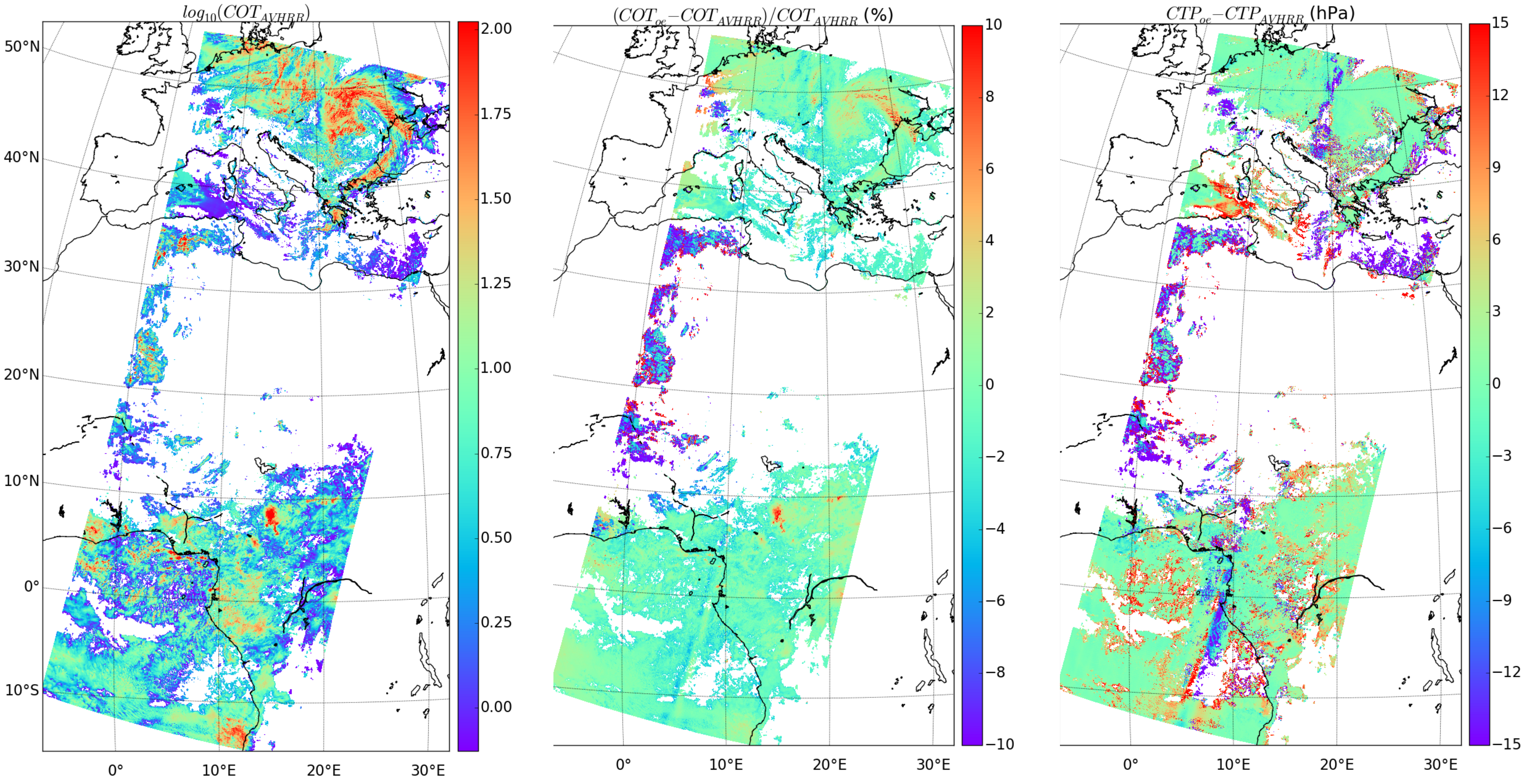


Interpolation error : conclusion

- The interpolation error for I and R is essentially lower than about 3% and 0.5% for high resolution LUTs (1% and 0.3% for COT>10)
- These interpolation errors are below the expected absolute and inter-band bias for METimage
- For medium resolution the interpolation error is essentially lower than 12% and 1% for I and R respectively (1.8% and 0.5% for COT >10)

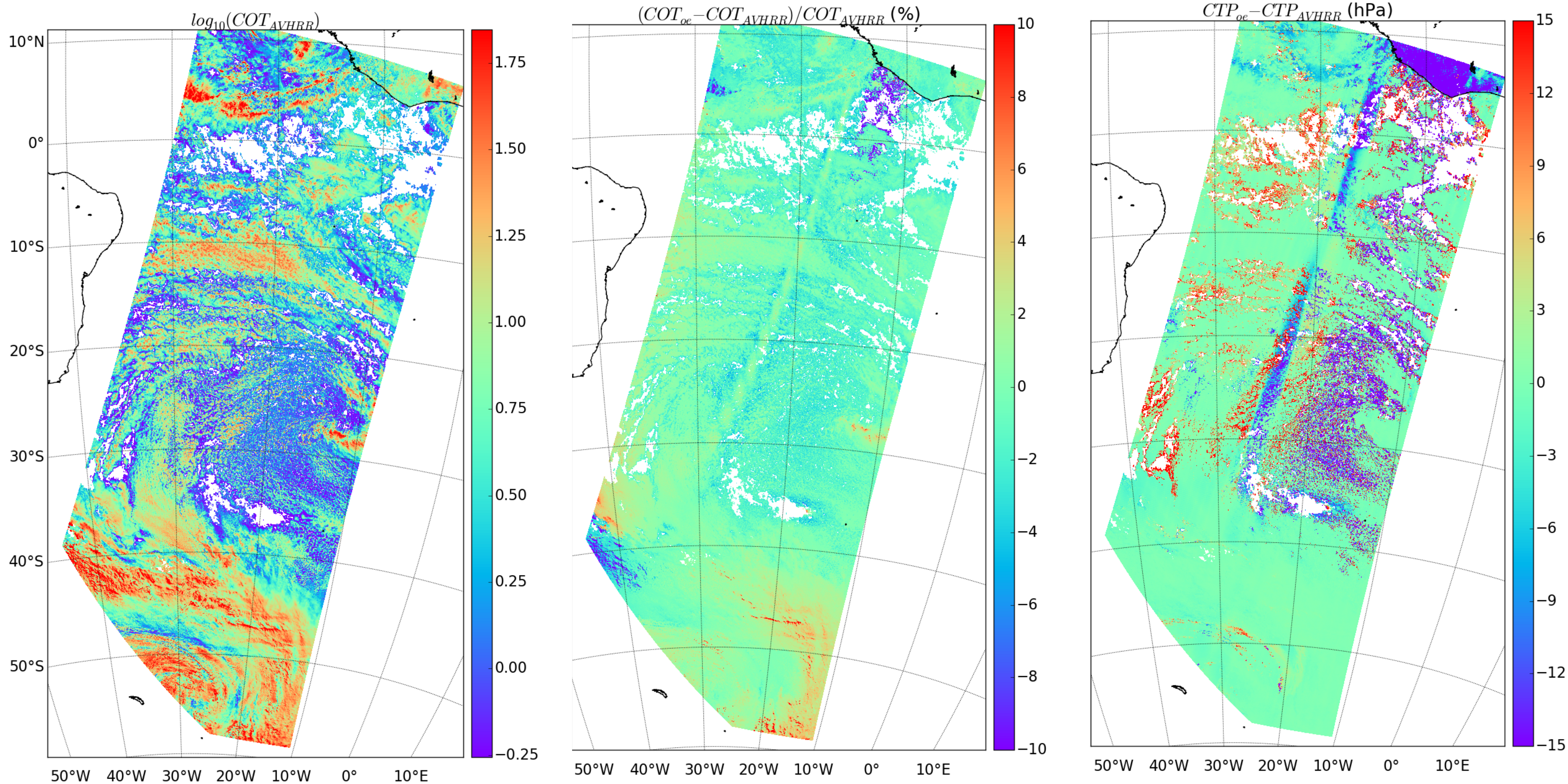
OE retrieval on SDS (I) High res LUT

Europe/Africa



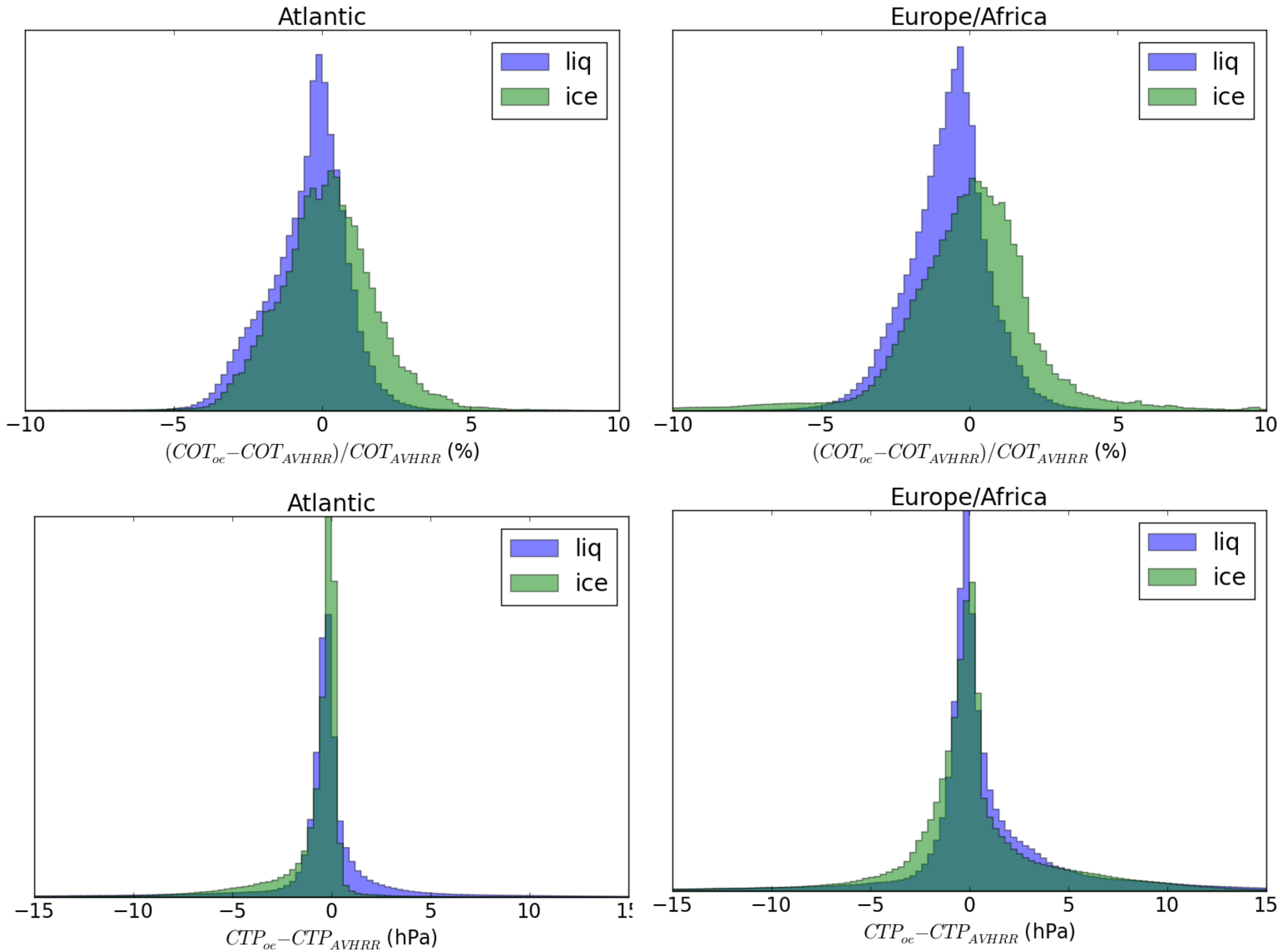
OE retrieval on SDS (II) High res LUT

Atlantic



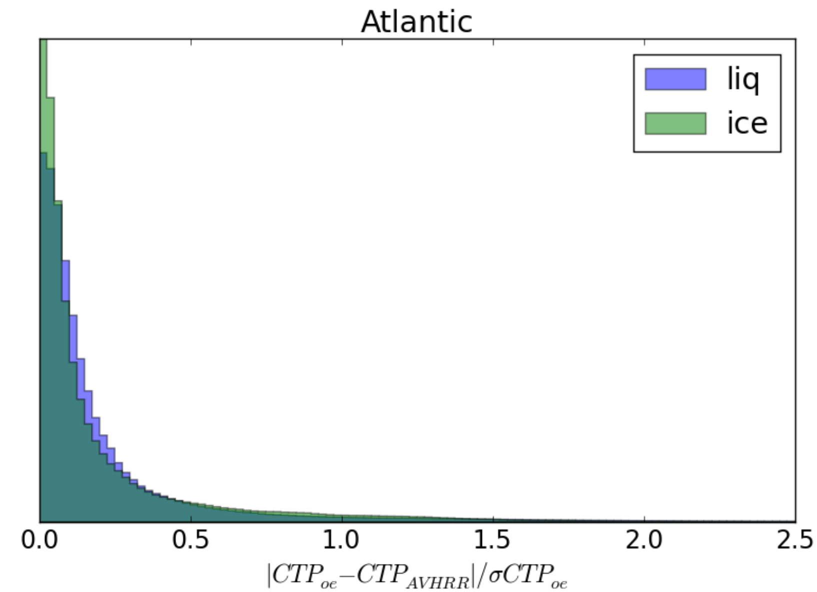
OE retrieval on SDS (III) High res LUT

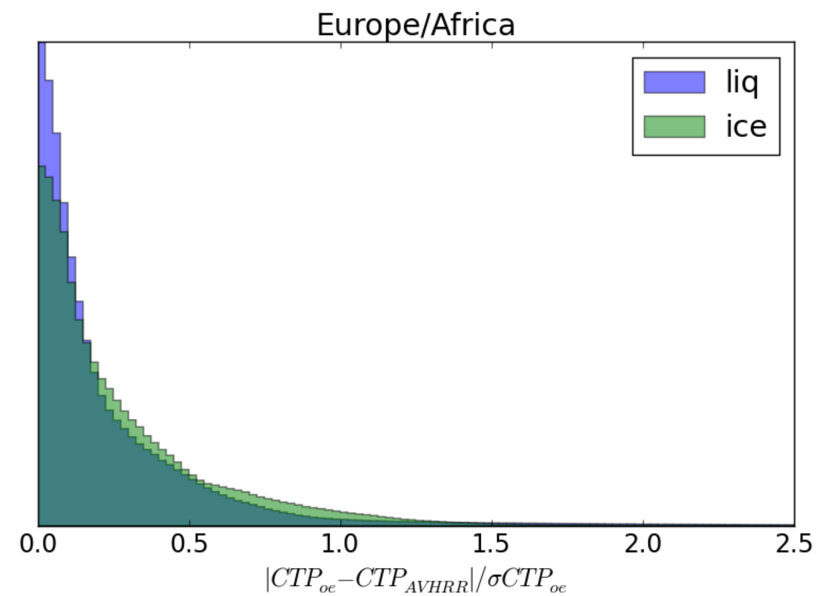
- Error distributions rather centered on 0.0 and symmetric
- Only slight differences between ice and liquid
- Error on CTP is less than ~15hPa for most pixel



OE uncertainty estimate

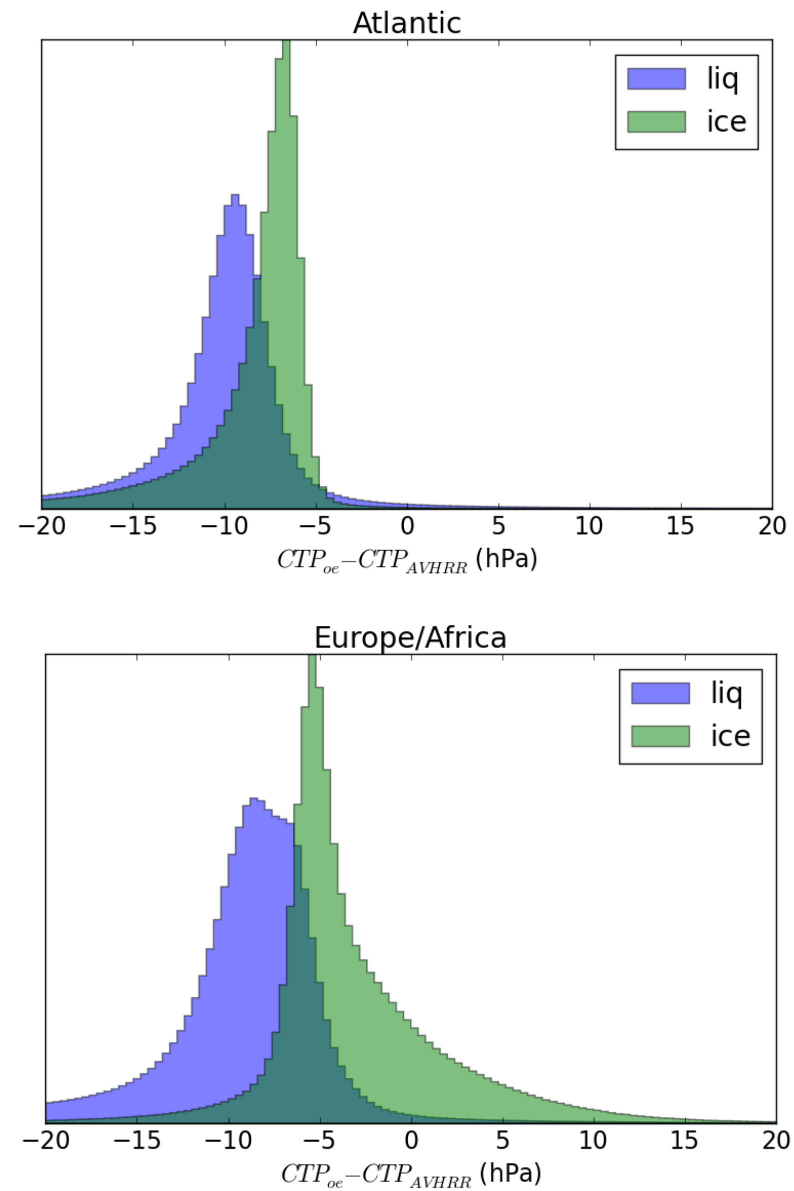
- For the input covariance matrix $S_\varepsilon = S_y + S_F + S_i$ only S_i is not null (interpolation error on I and R)
- The resulting σCTP estimate is well representing the true error since the CTP_{AHVRR} is essentially within $CTP_{OE} \pm 2\sigma CTP_{OE}$





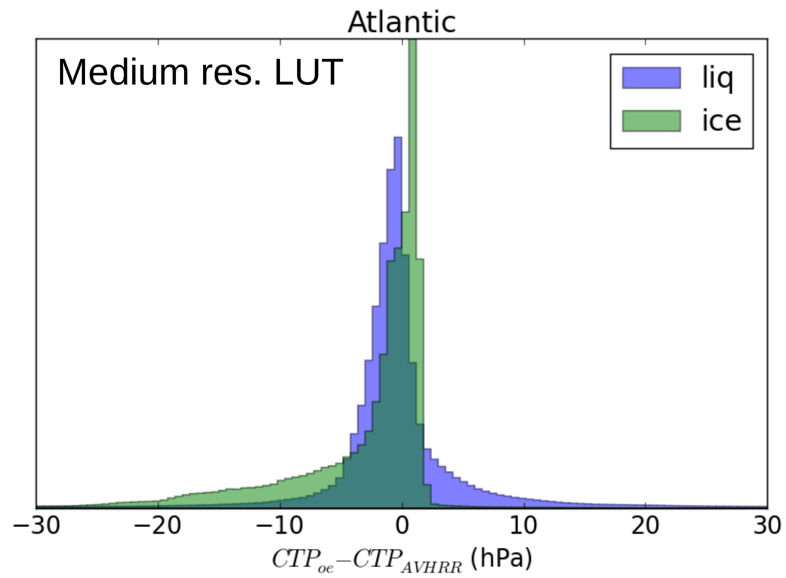
OE retrieval on SDS with noise/bias

- We bias and add noise to the SDS
  - Gaussian noise added to all channels with $\sigma = I_{typical}$ x SNR
  - 0.5% inter-band bias to VII-5/VII-4 (x1.005)
  - 2% absolute bias to VII-3 and VII-6
- Distribution are larger due to noise and shifted by ~6hPa (ice) and 10hPa (liquid) due to inter-band bias

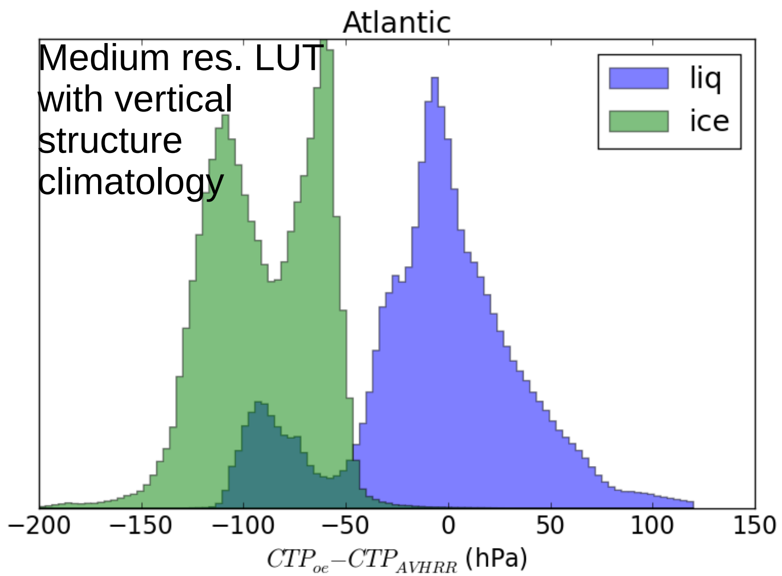


Medium resolution LUT retrieval

- We run the retrieval on SDS with medium resolution LUT
- The error on CTP is less than ~30hPa for most pixels
- The distribution for ice is biased toward under-estimation



- The error explode when using a vertical structure climatology instead of the homogeneous profile with fixed CGT=1.0km



Testing on SDS : Conclusion

- High res. LUT interpolation errors translate to an error on CTP retrieval essentially less ~15hPa (~5hPa for COT>10)
- For medium resolution LUT the error on CTP due to interpolation is up to ~30hPa (~10hPa for COT>10)
- The vertical structure climatology has a huge impact on the CTP retrieval

Testing on MERIS data

MERIS data and ancillary

- We selected 4 MERIS orbits over Europe, Africa and Atlantic ocean
  - February 5th and 15th, 2003 & August 15th and 24th, 2003

- Used ancillary data:
  - wind-speed (stored in MERIS L1b)
  - Ozone column (stored in MERIS L1b)
  - Sea level pressure & DEM (stored in MERIS L1b)
  - Surface IGBP type (MODIS MCD12C1)
  - Surface white sky albedo (8 days composite GlobAlbedo product)
  - Cloud mask (produced from MERIS L1b through VISAT tool)

OE retrieval (I)

- We use medium resolution LUT including the vertical structure climatology
  - Limited amount of time to set-up LUTs
  - Accurate enough regarding other sources of discrepancies with MERIS L2 (e.g. different cloud model...)

- To match the MERIS L2 products, we use the following state vector $x = [I_{753}, I_{761}/I_{753}]$ and liquid phase only

- The algorithm is robust and succeed to retrieve all 4 orbits cloudy pixels without any human intervention

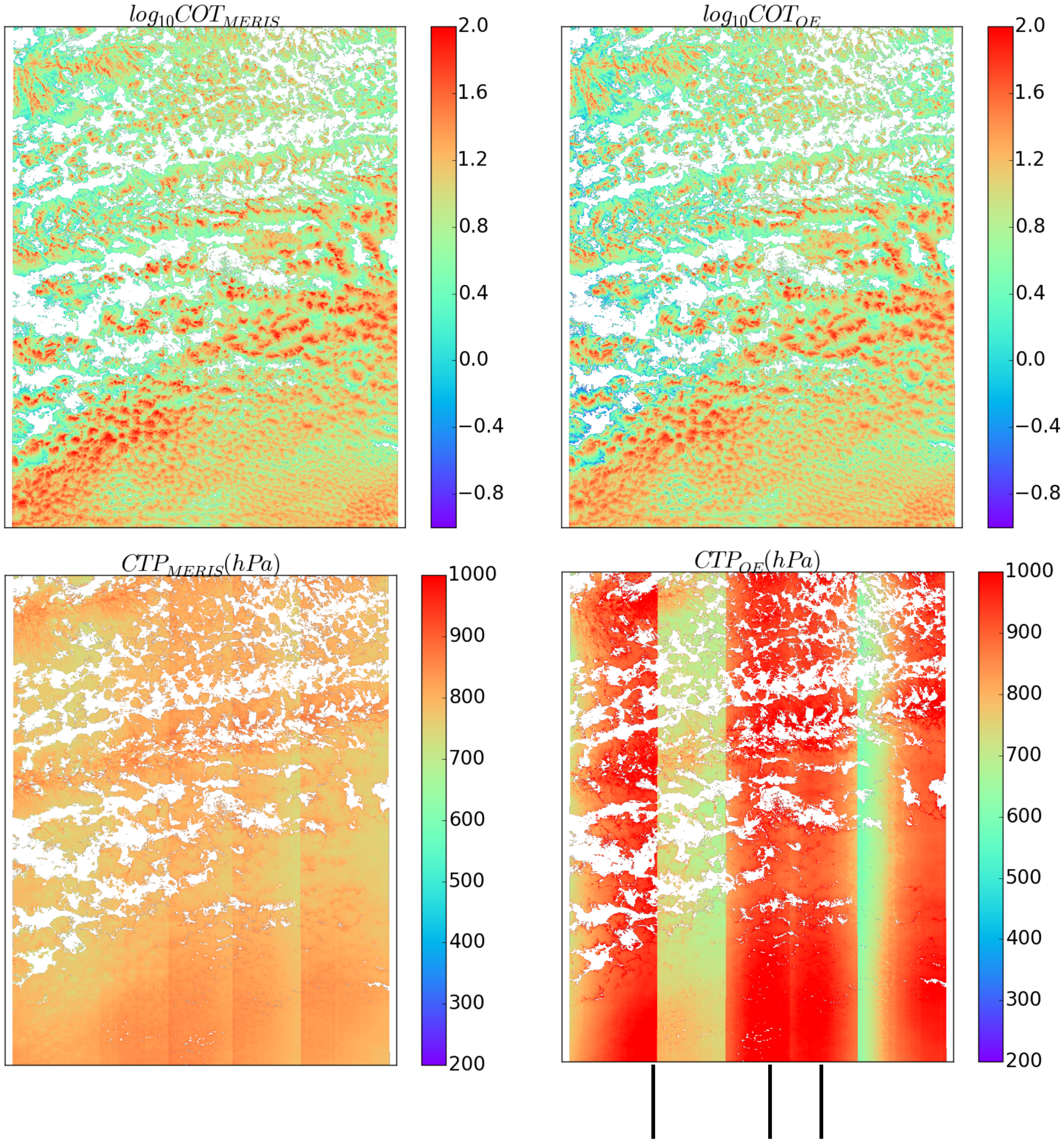
OE retrieval (II)

- For the input co-variance $S_\varepsilon = S_y+S_F+S_i$, we use :
  - A 4% absolute bias on reflectance and 1% inter-band bias for S_y.
  - A LUT interpolation error of 7.0% on I and 0.8% on R for S_i.
  - A single computation of S_f only once for the following parameters (COT =10, CTP = 500.0 hPa, W_{spd} = 5.0 m/s±10%, WSA = 0.2±10%, P_{surf} = 1013.0 hPa ± 0.3%, sza = 50.0±0.25 deg, vza = 20±0.25 deg, raa =94±0.25 deg)

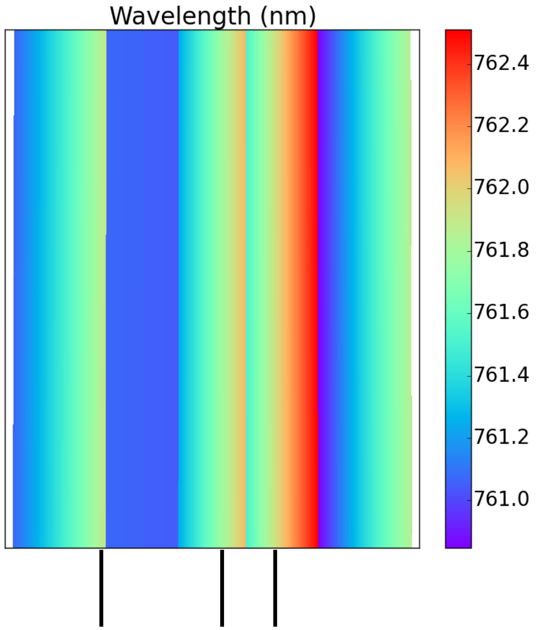
MERIS smile effect and stray light

- We apply the stray light correction (Lindstrot et al. 2010) to channel 11 (761nm) radiance
- In MERIS, the central wavelength of any channel ISRF varies over the detector :
  - This smile effect is especially important for channel 11 (761nm) that falls in the O_2 absorption band
  - The LUT should have a channel 11 central wavelength dimension axis
- We do not account for the smile effect and only have channel 11 centered at 761.875 nm

OE retrieval results
Smile effect illustration

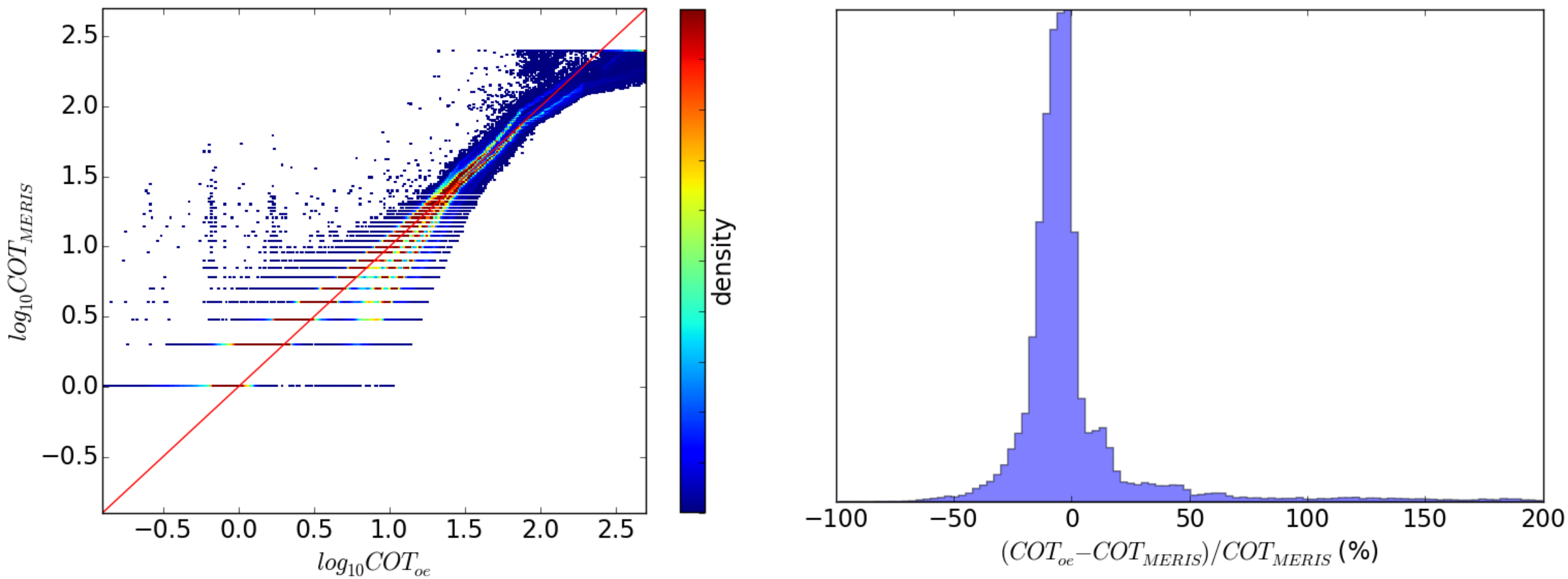


- Stratocumulus layer is at a rather constant altitude
- The smile effect does not affect the COT retrieval
- Smile effect is clearly seen on the CTP_{OE} retrieval



COT retrieval

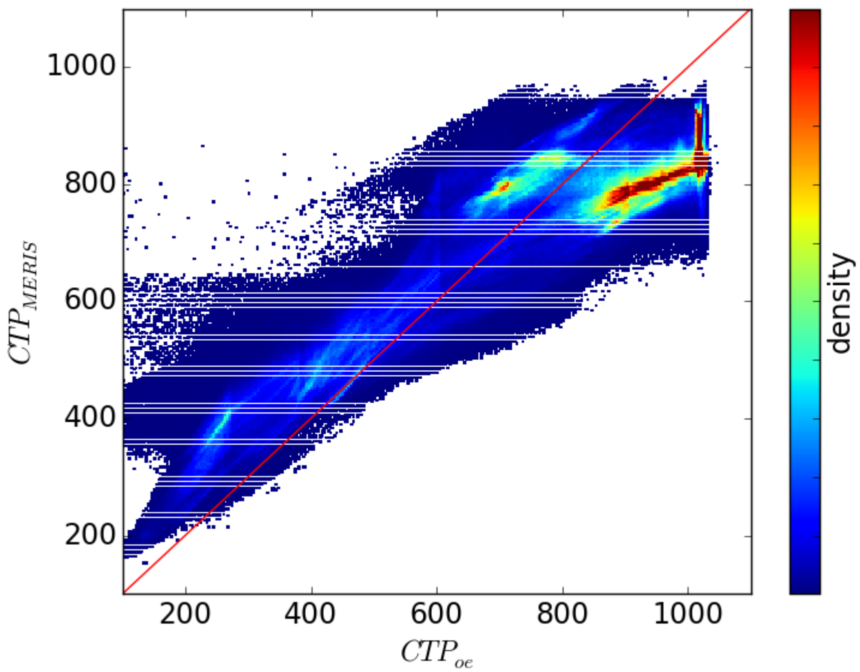
All pixels for orbit of Aug, 24th



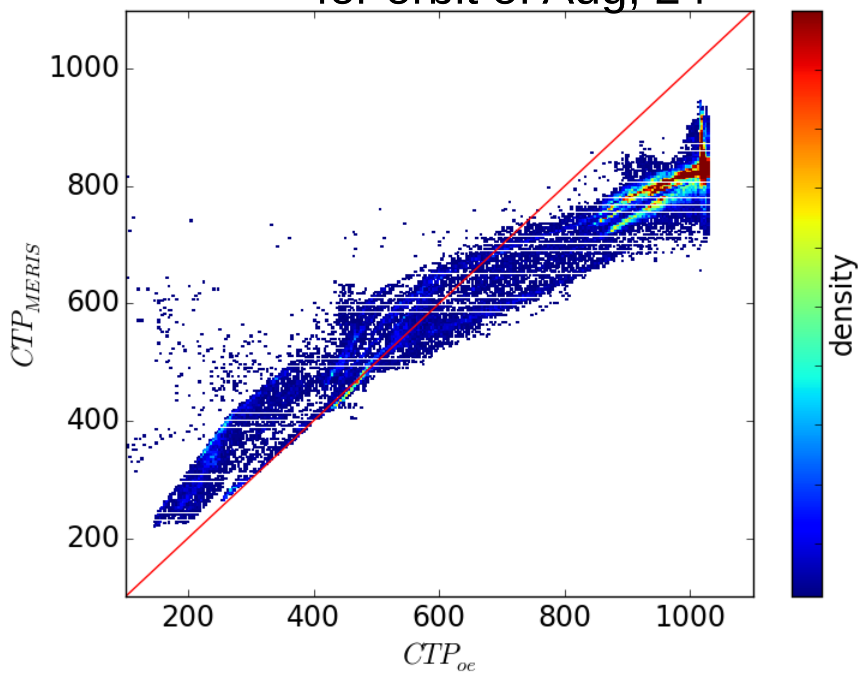
- The COT_{OE} retrieval match $COT_{MERISL2}$ to ±50% for most of the pixels
- The discrepancy between the two retrievals may partially be explained by the difference of cloud models (e.g. R_{eff})
- The tendency seen here is the same for all 4 orbits

CTP retrieval

All pixels for orbit of Aug, 24th



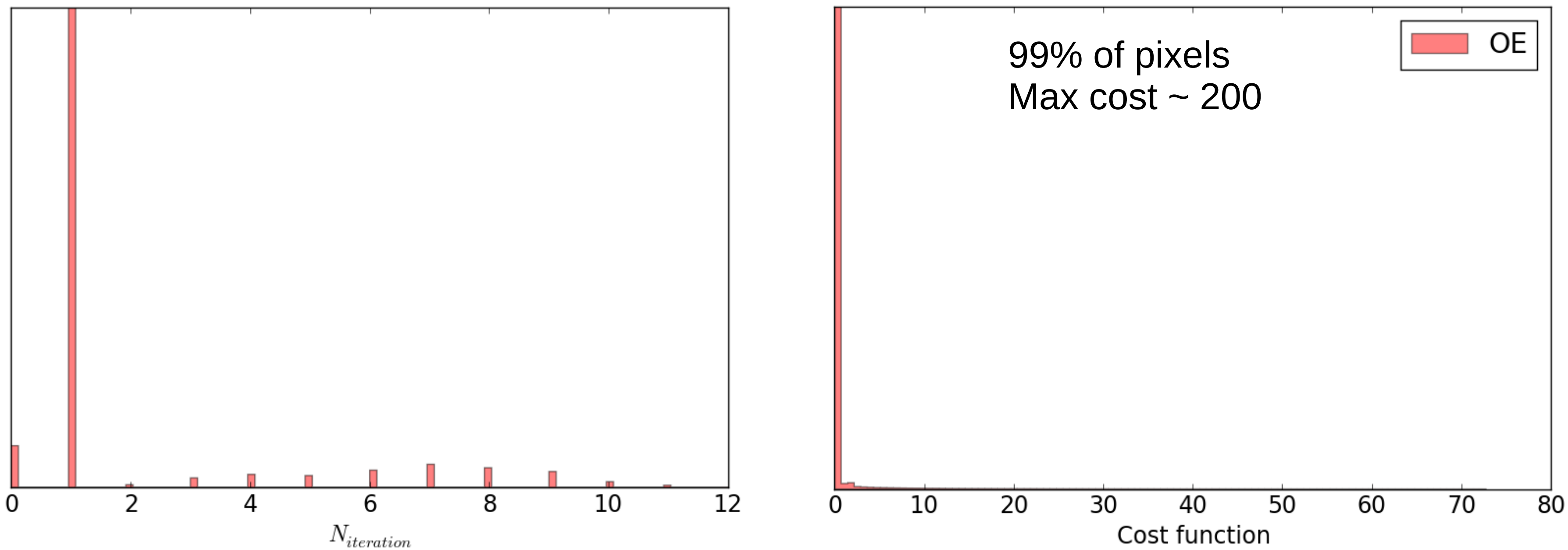
Pixels with λ = 761.875±0.01nm for orbit of Aug, 24th



- The scattering is greatly reduced when only considering pixels with λ= 761.875±0.01nm
- Day-1 algorithm over-estimate CTP for low clouds and under-estimate CTP for high clouds compare to MERISL2
- The tendency seen here is the same for all 4 orbits

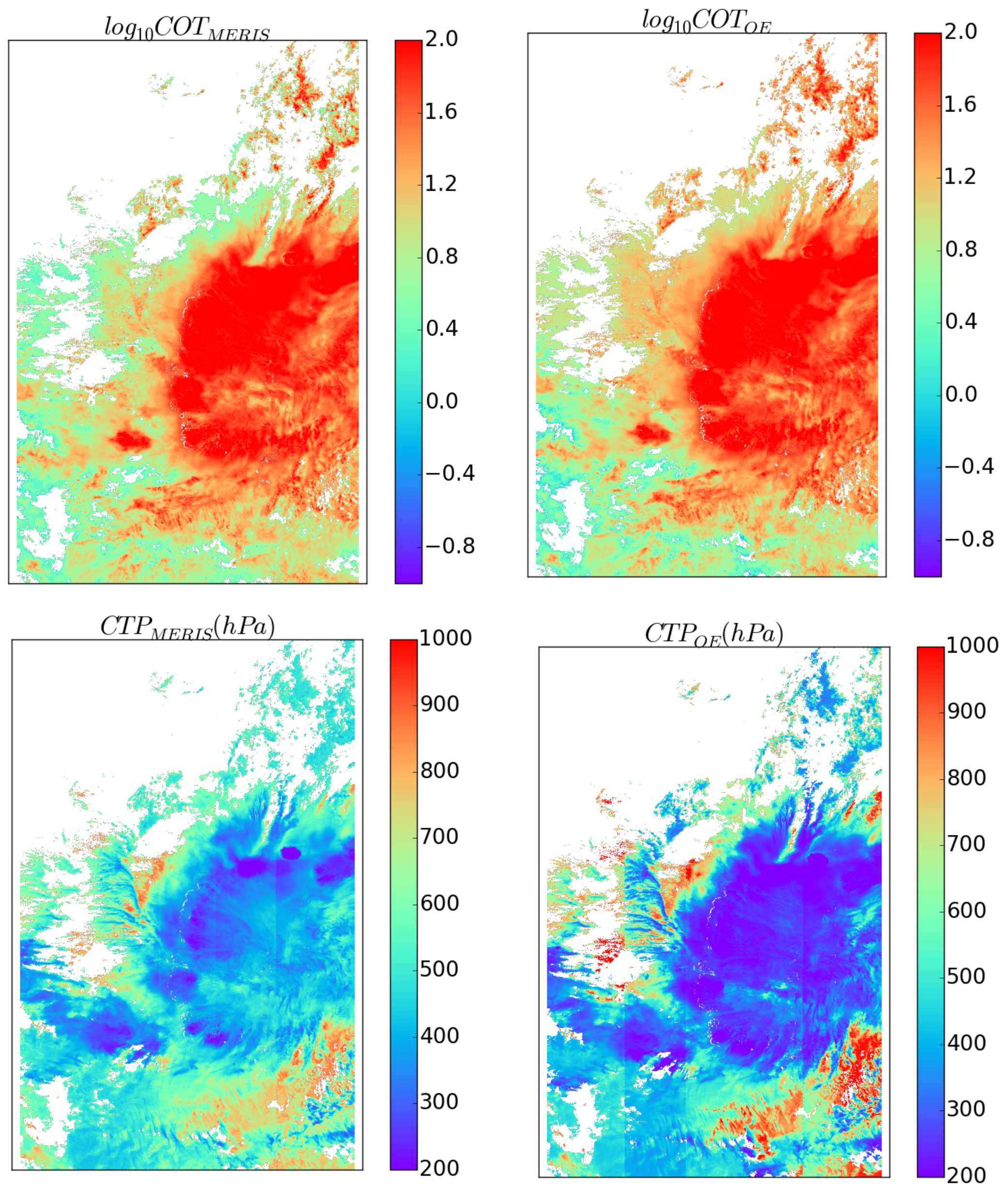
Cost function and number of iterations

Pixels with λ = 761.875±0.01nm for orbit of Aug, 24th

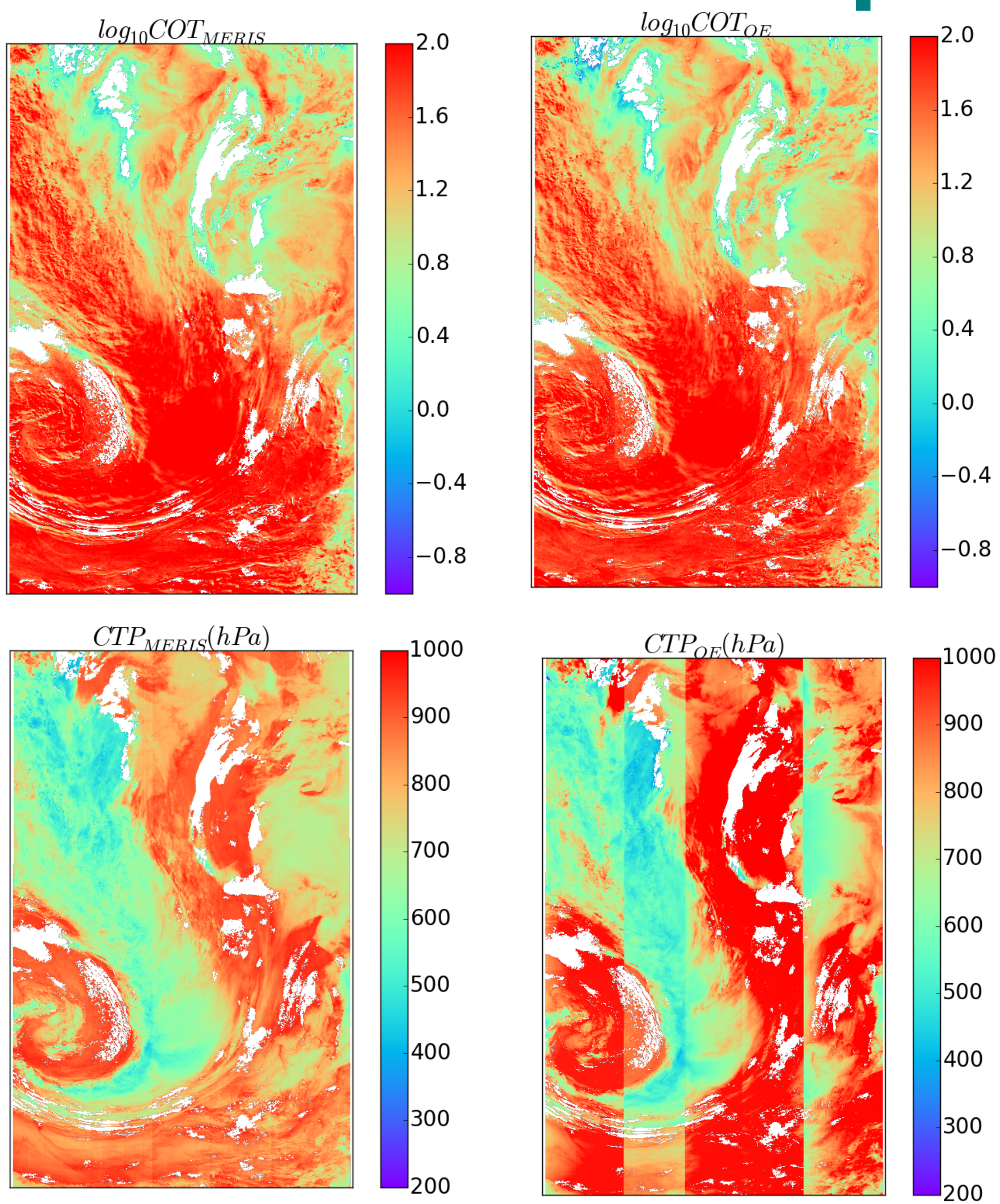


- Most pixels converge after just 1 iteration
  - the first guess is well estimated
- The algorithm converge to a cost function < 2 (n_y) for most pixels

Convective cloud over Africa



Southern Atlantic Depression



Test on MERIS : Conclusion

- The day-1 algorithm is robust and succeed to retrieve almost any cloudy pixels on real data without any human intervention
- The retrieved COT is essentially within ±50% of MERISL2
- The CTP dynamical range retrieved by day-1 algorithm is larger than MERISL2 product
  - Day-1 algorithm over-estimate CTP for low clouds and under-estimate CTP for high clouds
- Discrepancies may partly be explained by the differences between used cloud model (especially vertical structure)

Conclusion

Conclusion

- The bibliography and sensitivity studies allowed to properly identify any critical parameters for the day-1 retrieval
- We produced LUTs with accuracy essentially better than about 3% for I and 0.5% for R, below the expected absolute and inter-band bias for METimage
- The vertical structure in LUTs is varied in a innovative way through two climatologies (profile and CGT=f(COT, CTP))
- The Day-1 algorithm is robust and was successfully applied on four MERIS orbits
- It gives satisfying COT, CTP results compare to the MERIS L2 product considering differences in forward models and possibly remaining instrumental effects

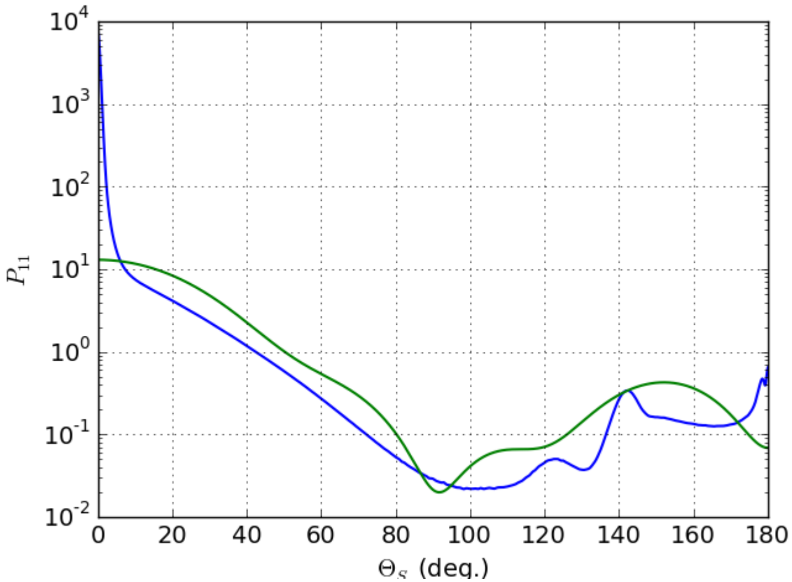
Future evolutions

- Several limitations and short term enhancements are described in the report (e.g. evolution of LUT axis range, evolution of BRDF, number of computational angles for LUT building, OE uncertainty treatment...)
- Other further improvements can include :
  - Cloud vertical structure climatology depending on season and location
  - Computation of the first order of scattering on-the-fly during retrieval and LUT for higher orders
  - Inclusion of thermal infrared band to the measurement vector

The End

HYGEOS

Single scattering correction (I)



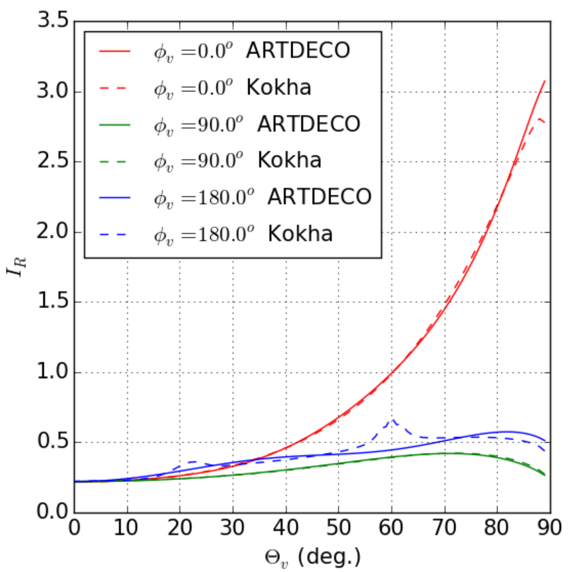
- CPU demand increases with the number of Legendre coefficients (computational angles) for phase matrix expansion

- TMS developed by Nakajima & Tanaka, *jqsrt*, 1988, 40, 51-69
  - Subtract the first order of scattering computed with truncated phase function
  - Add back the first order with the nominal phase function
  - No CPU cost !

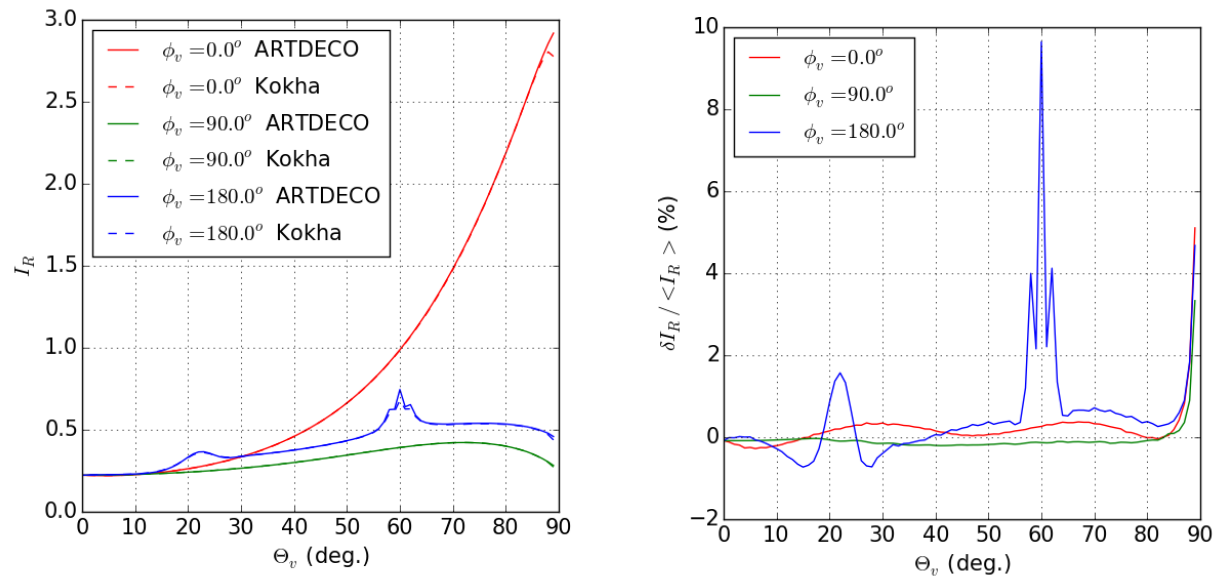
- Demonstration with the Kokhanovsky, *jqsrt*, 2010, 111, 1931-1946 cloud benchmark
  - Pure scattering cloud OD=5.0
  - Solar Zenith Angle = 60 deg
  - Black surface
  - Computation with 8 streams (8 Legendre coeff. D-M truncated)

Single scattering correction (II)

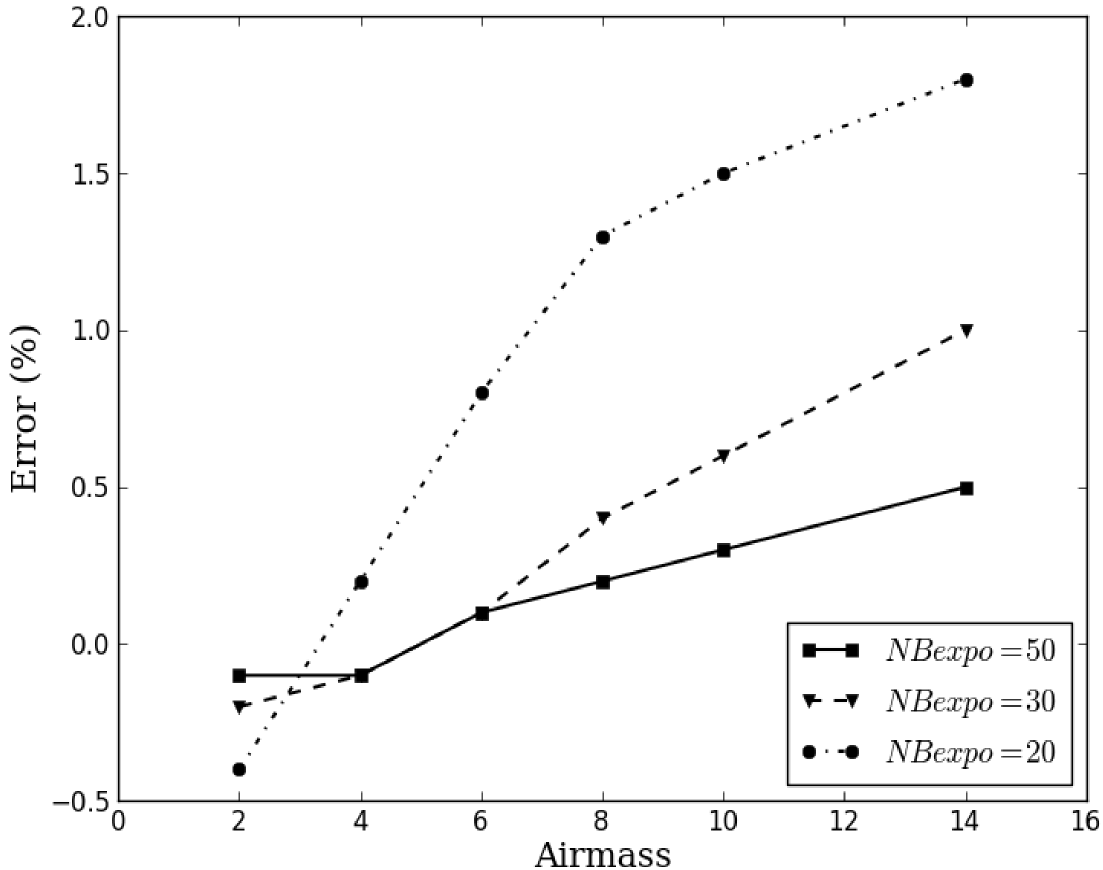
8 streams without TMS



8 streams with TMS



Correlated k-distribution



"Ghost" points in CTP-P_{surf} space