Cloud Detection

General Aspects I: What is a cloud?

- "I can tell you, if I see ..."
- "A visible aggregate of minute water droplets and/or ice particles in the atmosphere above the earth's surface"

- "Global total cloud amount (fractional cloud cover) is about 0.68 (±0.03), when considering clouds with optical depth > 0.1. The value increases to 0.74 when considering clouds with optical depth < 0.01 (e.g., CALIPSO) and decreases to about 0.56 when clouds with optical depth > 2 are considered (e.g., POLDER)" [GEWEX Cloud assessment 2012 Stubenrauch et.al]

General Aspects II: Naming

- **Cloud detection**: the full process that results in a per-pixel cloud or cloud free (probability or portion) quantification. This could be binary (cloudy/cloud free), multi class categorical (yes/unknown/no or yes/propbaly/probably_not/no) or continuous measure (probability of cloud contamination or probability of cloud free or cloud coverage or ...)

General Aspects II: Naming

- **Cloud mask**: a binary mask (in the same projection of the satellite image) where pixel with a distinct cloud incidence (e.g. probably cloudy or cloud contaminated or cloud free or probably cloud free or ...) are masked out. Cloud masks are sometimes classified as
    - cloud free conservative for applications that do not allow cloud contamination (e.g. the remote sensing of land-, sea- and ice surface temperatures, of total column water vapour or of aerosol optical properties),
    - cloud conservative for most cloud remote sensing applications and
    - climatologically conservative which means that they should not be biased in particular with respect to instrumental improvements or calibration changes within decades.

General Aspects II: Naming

- **Cloud test**: A cloud test is a test for a **distinct** physical cloud feature, e.g. brightness or temperature or specific emissions which results in a **single** measure.
(((However, it is difficult to follow this discrimination too strictly, since many cloud tests use combinations of more features (e.g. temperature and emissivity) to calculate their measure.)))

General Aspects II: Naming

- **Cloud test-combination-methodologies:** The methods to combine the outcome of the respective tests.

General Aspects III: some heritage missions

•AVHRR / CLAVR / PATMOS [Saunders &Kriebel 1988, AVHRR 2004, Lavanant 2002, Dybbroe 2005 (1,2), Heidinger 2012, Pavolonis et al. 2004]: since 1978, an AVHRR like cloud detection might be needed for consistent climate observations.
•MODIS / VIIRS [Ack2010, Bak2012]:
•MTG / MSG /GOES-R: SEVIRI, FCI, ABI: descent from AVHRR. But viewing and illumination geometry differ. Additionally radiometry will be inferior.
•(A)ATSR(2) / SLSTR [Donlon et al., 2012] descent from AVHRR, but SST focused
.
•MERIS / OLCI [Donlon et al., 2012]: **O**cean and **L**and **C**olour **I**mager Unique channel in the oxygen absorption band at 0.76 µm, which is sensitive to the effective scattering scaling height [Preusker et al 2006, Lindstrot et al. 2010]

General Aspects IV: cloud tests

rely on a *contrast* between a cloud free, a cloud contaminated and/or a cloudy *feature set:*

- Spectral features. :
  - brightness and whiteness in the VIS/NIR,
  - obscured atmospheric absorption in the VIS/NIR/SWIR
  - obscured spectral surface features (e.g. NDVI)
  - obscured atmospheric or surface emission in TIR
  - spectral features of scattering, absorption (dust vs. water clouds vs. ice clouds)
  - spectral features of emission (“split window”)

General Aspects IV: cloud tests

- Spatial features like
  - standard deviation of apparent brightness temperatures above sea surfaces within a macro pixel
  - linear features for detecting contrails (Mannstein et al., 1999)
  - more sophisticate texture measures (Schroeder et al., 2002)
- Temporal features, (only applicable, if the same object is observed several times):
  - on geostationary orbits
  - when investigating time series
  - at high latitudes for polar orbiter

General Aspects IV: cloud tests

- Indirect tests, that do not directly use cloud features
  - polar night cloud detection. Some tests are using the suppressed radiative cooling of the surface, if clouds are present
  - non converging downstream retrievals. Here the presence of a cloud is assumed, if a L2 algorithm (e.g. sea surface temperature) is not converging or produces unlikely results. (**avoid logical traps**!)

General Aspects V: test combinations

- threshold based decision trees. The classical way and used in the majority of all operational agencies.
- Cumulative measures, where the individual test results are cumulated (weighted sums, multiplied ...) to calculate a final measure. Eventually all these methods are based on the mathematical theory of *fuzzy measures* (e.g. MODIS)
- Maximum likelihood methods, where the probability of a class membership (e.g cloudy) is calculated from the probability density functions of the individual cloud tests
- Brute force supervised and unsupervised learning methods (artificial neural networks, support vector machines, cluster analyses,...)

Some Tests

examples

Solar Brightness Thresholds

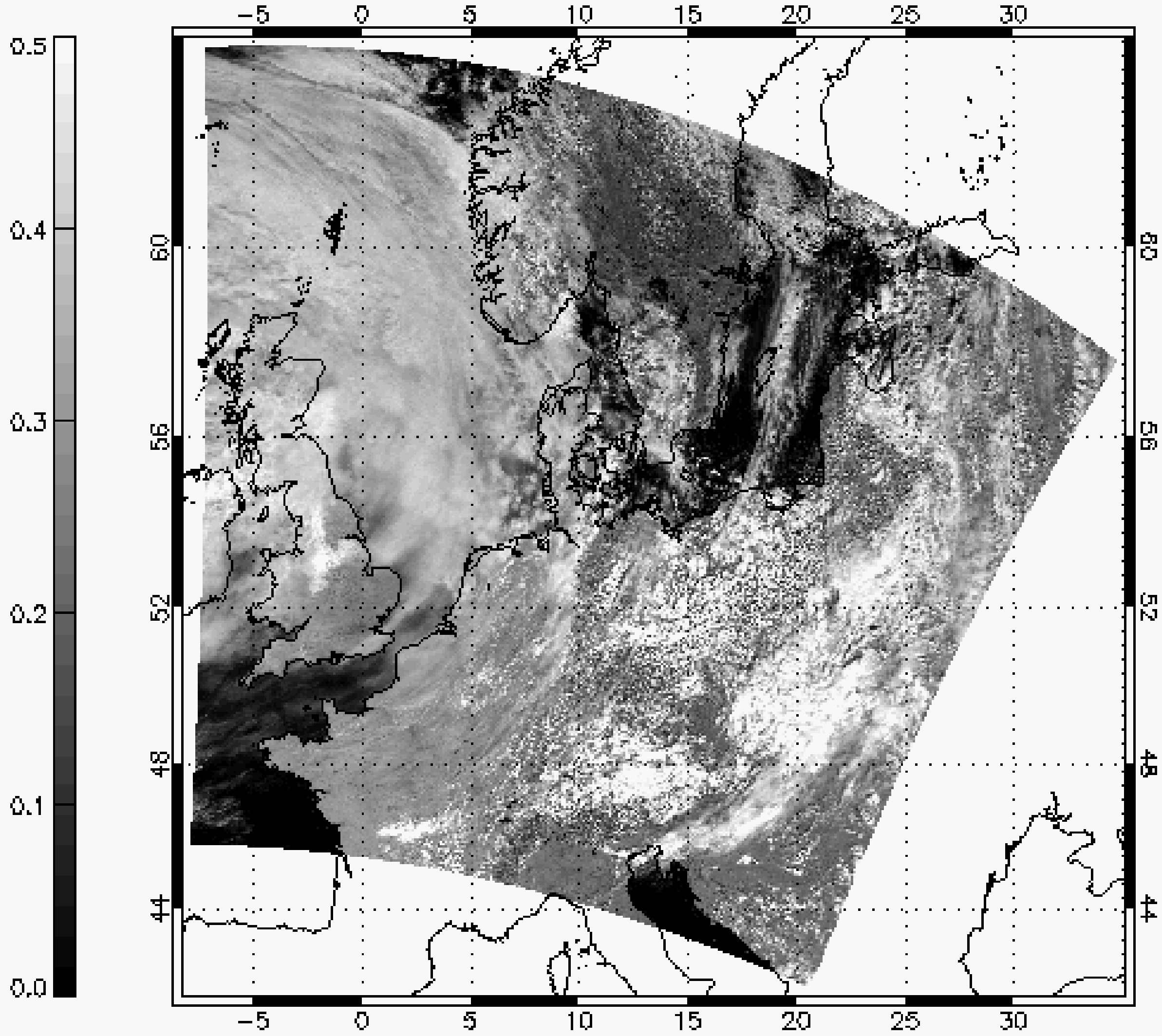
- What the test detects and in what conditions:
  - visible contrast of a bright cloud to a darker background.
- The basic physics of the test

$$\text{cloudy if } \rho^{o} - \rho^{b} > \Delta\rho t$$

ρb: climatology, knowledge (e.g. Ocean),
albedomaps RTM (Rayleigh, Glint ...)

- Limitations: thin/broken clouds, bright surfaces, bad illuminations

Solar Brightness Thresholds



R1.38 water vapor

- What the test detects and in what conditions:
  - The test detects all clouds above a certain height during day

- The basic physics of the test

cloudy if $\rho^{o}1.38 > \rho^{t}1.38$

ρt: sea/land

- Limitations: high elevation, dry atmospheres, bad illumination

R1.38 water vapor

Gao, Bo-Cai, Yoram J. Kaufman, 1995: Selection of the 1.375-µm MODIS Channel for Remote Sensing of Cirrus Clouds and Stratospheric Aerosols from Space. J. Atmos. Sci., 52, 4231–4237.

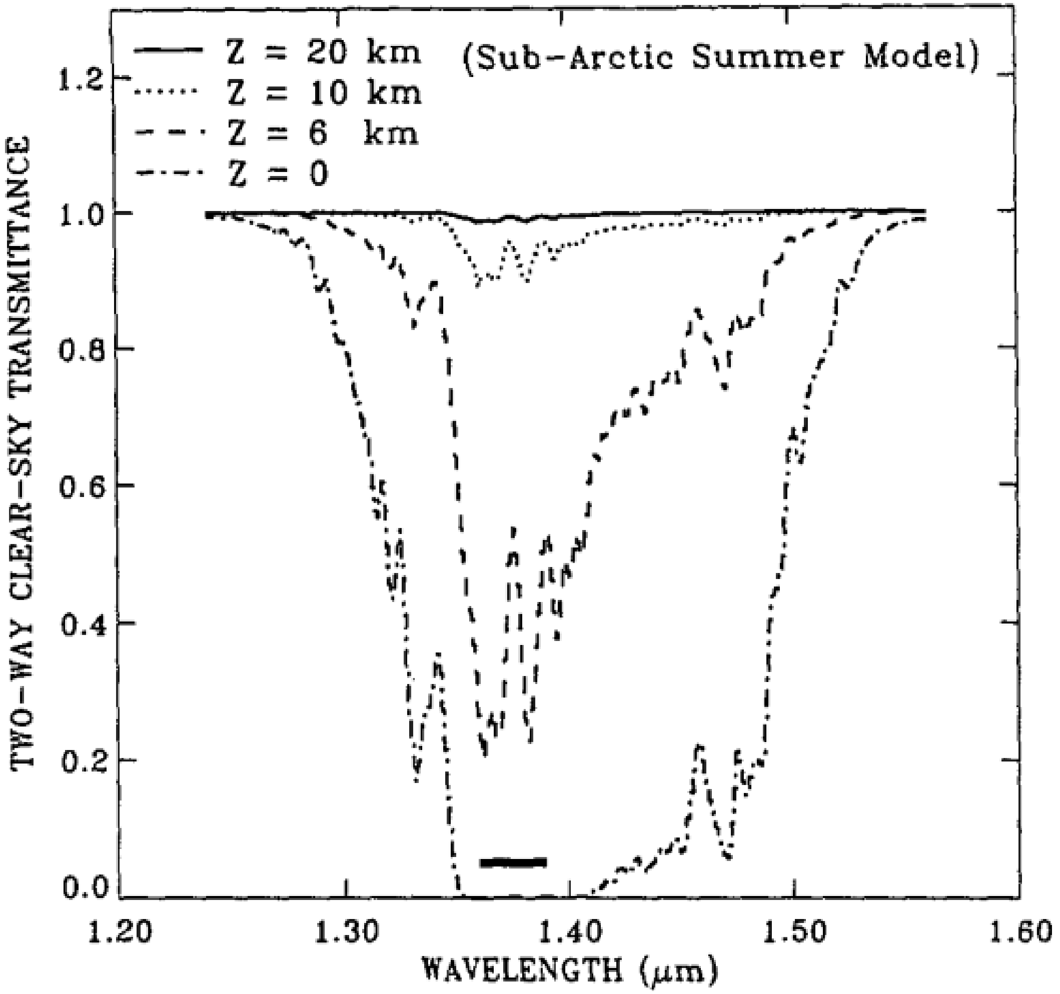


FIG. 3. Two-way path clear-sky transmittance spectra for the sub-Arctic summer atmospheric model (2.1 cm of precipitable water). Incoming segment of the path has 45 degree zenith angle and ends at altitude *Z* (where 100% reflection is assumed); outgoing segment has 0 degree zenith angle. The *Z*s are chosen at 0, 6, 10, and 20 km.

R1.38 water vapor

Gao, Bo-Cai, Yoram J. Kaufman, 1995: Selection of the 1.375-µm MODIS Channel for Remote Sensing of Cirrus Clouds and Stratospheric Aerosols from Space. J. Atmos. Sci., 52, 4231–4237.

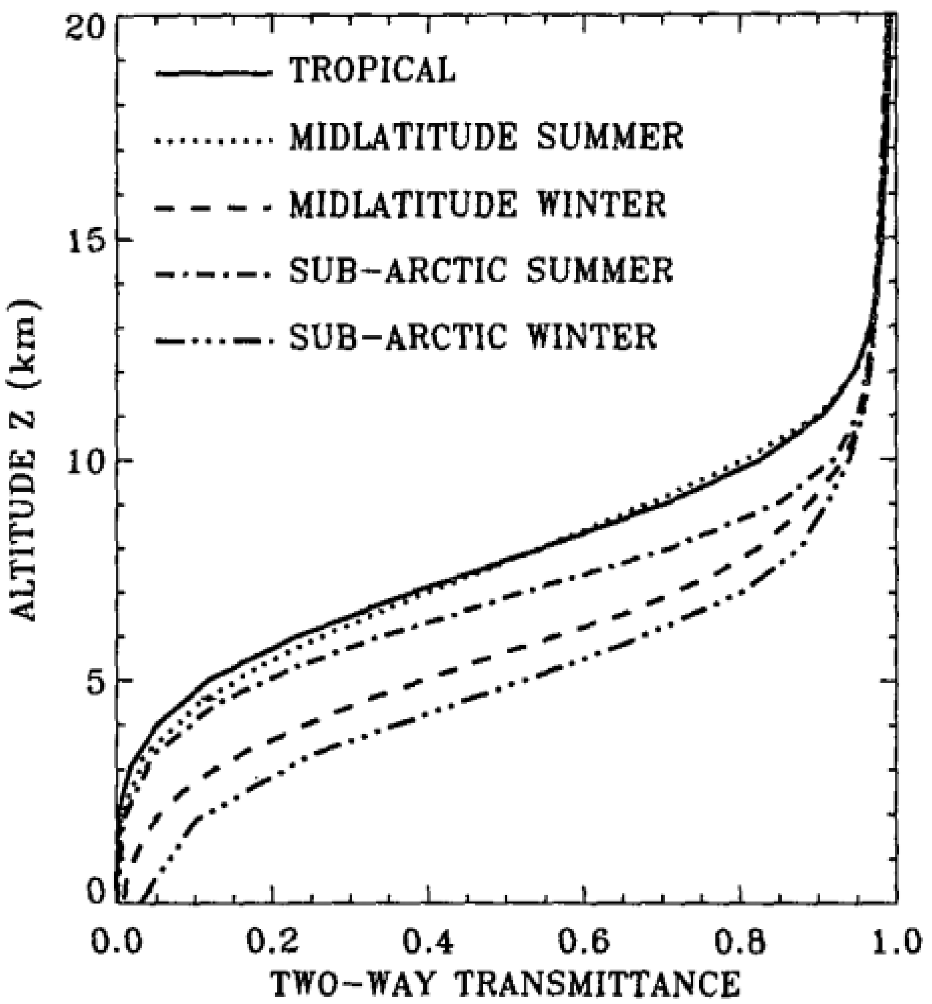
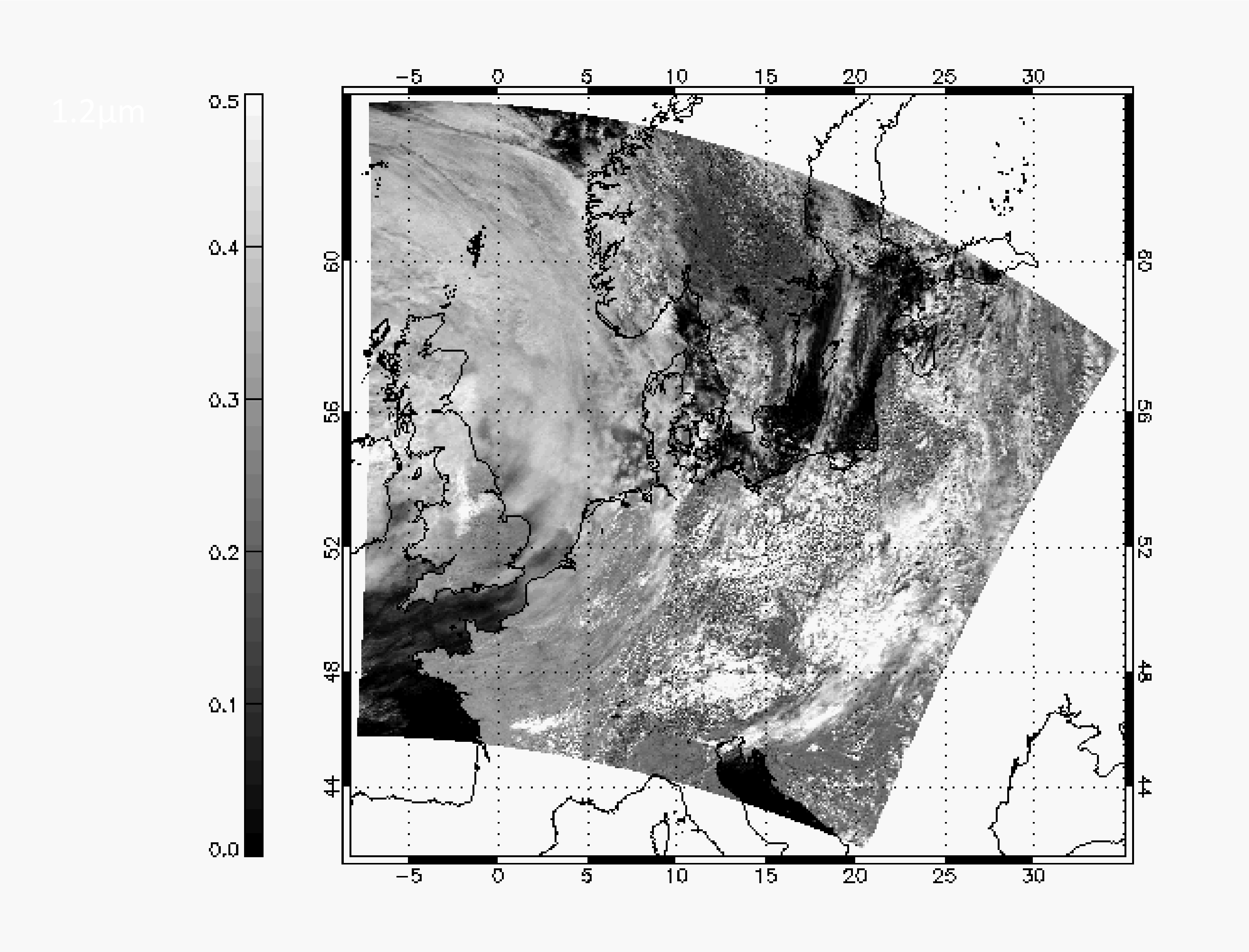
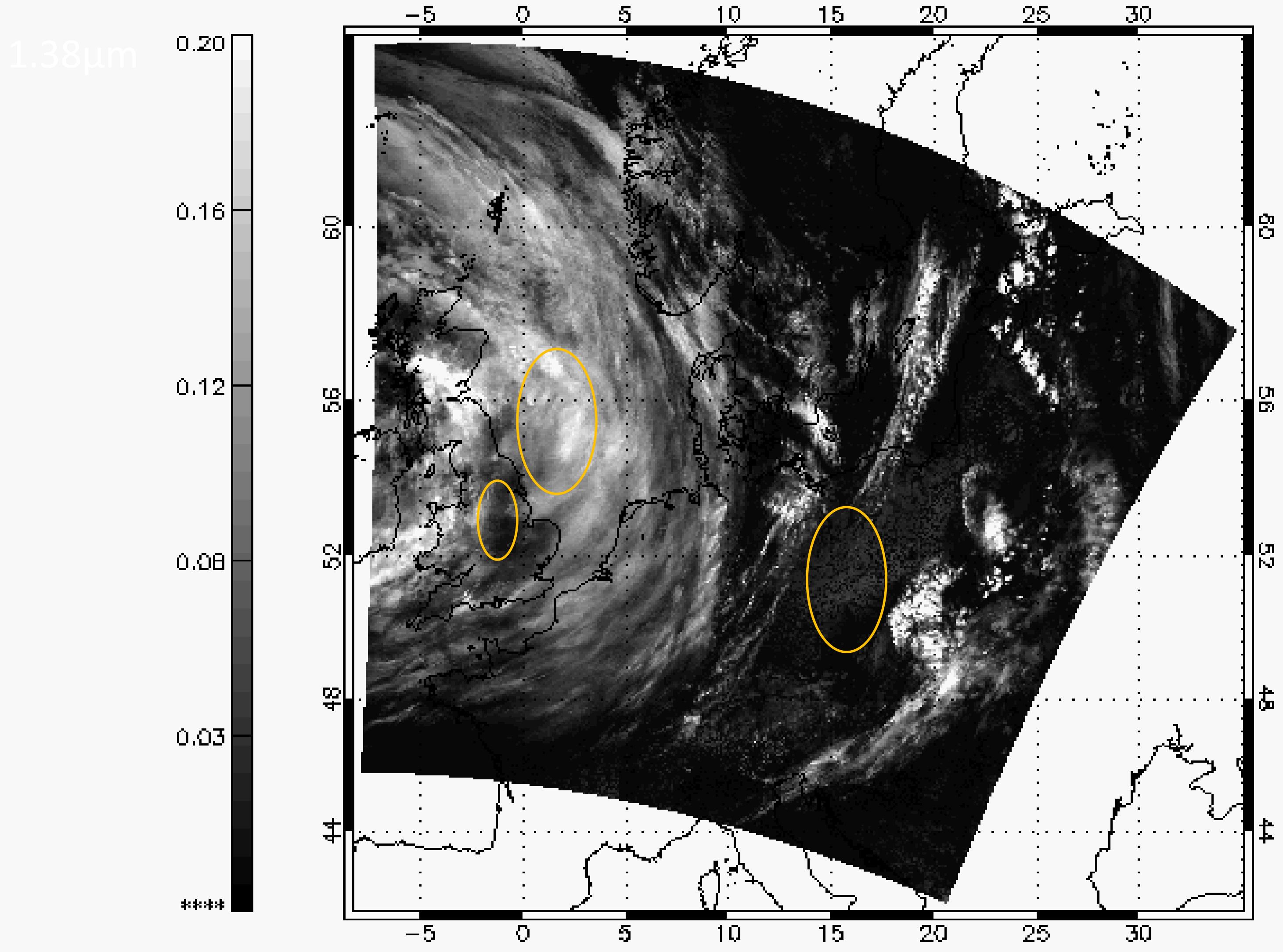


FIG. 4. The mean two-way transmittance in the bandpass of the MODIS channel centered at 1.375 μm with a width of 30 nm as a function of altitude Z for the LOWTRAN 7 models. The illumination and observation directions are as in Fig. 3.

R1.38 water vapor



R1.38 water vapor



BT11 (Gross-IR) Test

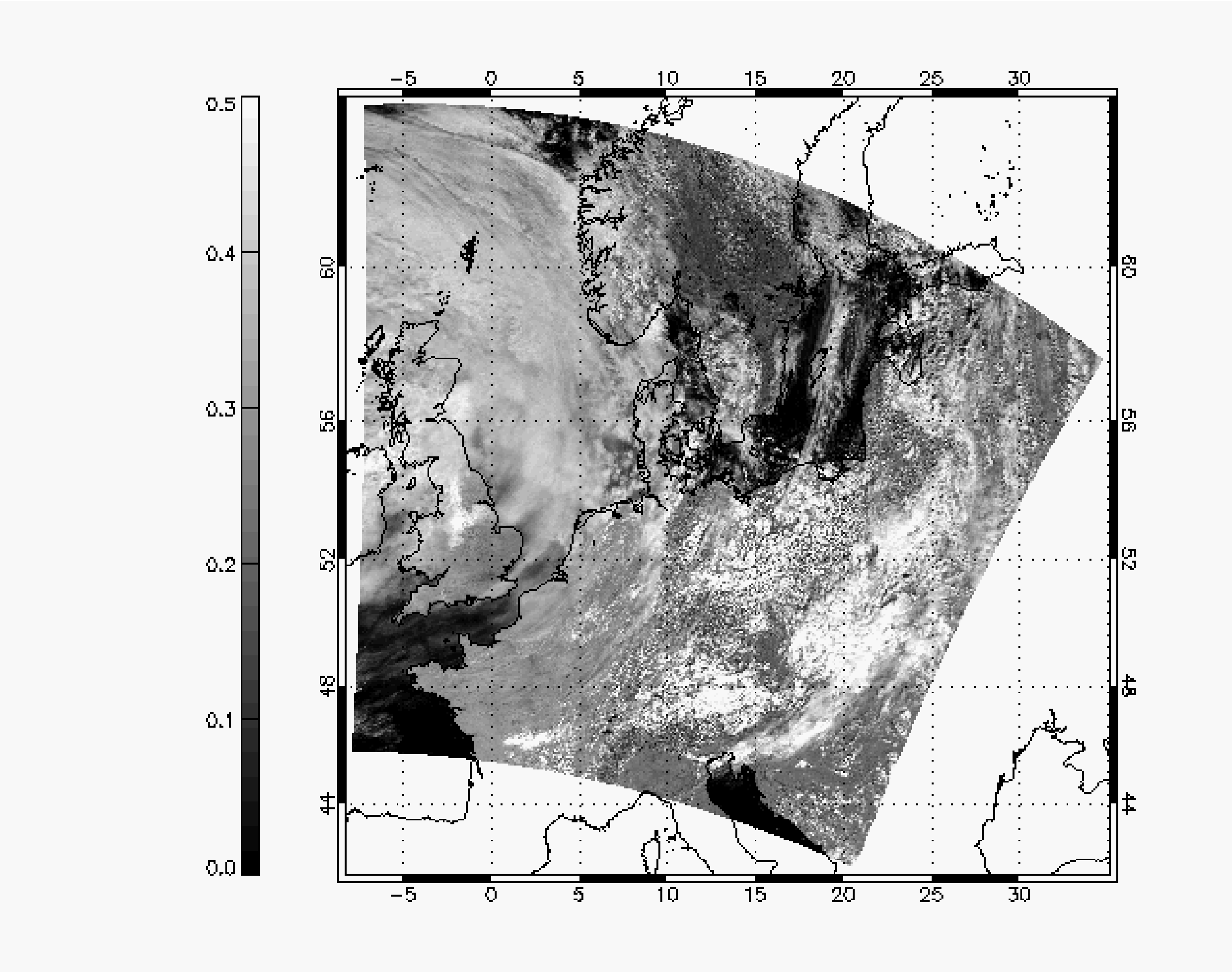
- What the test detects and in what conditions:
  - The test detects opaque cold clouds above all surfaces during day and night.

- The basic physics of the test

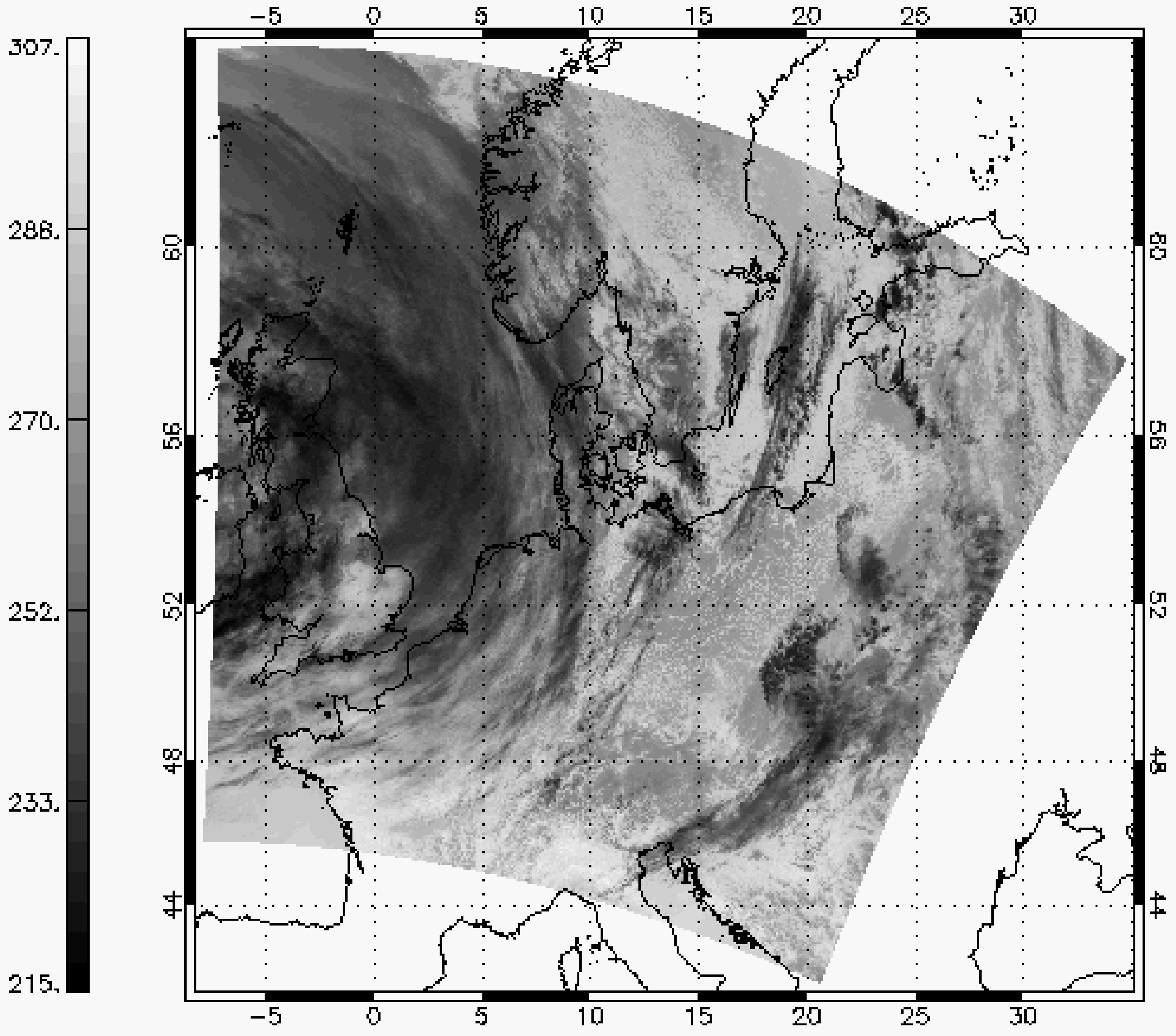
cloudy if $BTb-BTo > \Delta BTt$ or $BTb > BTo$

- Limitations: low level warm cloud, thin clouds and strong inversions

BT11



BT11



BT7, high clouds

- What the test detects and in what conditions:
  - The test detects clouds with high tops, over all surface types, during day and night..

- The basic physics of the test:

BT6.7µm and BT7.3µm peak around 300hPa and 500hPa

cloudy if BTcalc_clear_sky-BTo > ΔBTt

or BTcalc_clear_sky > BTo

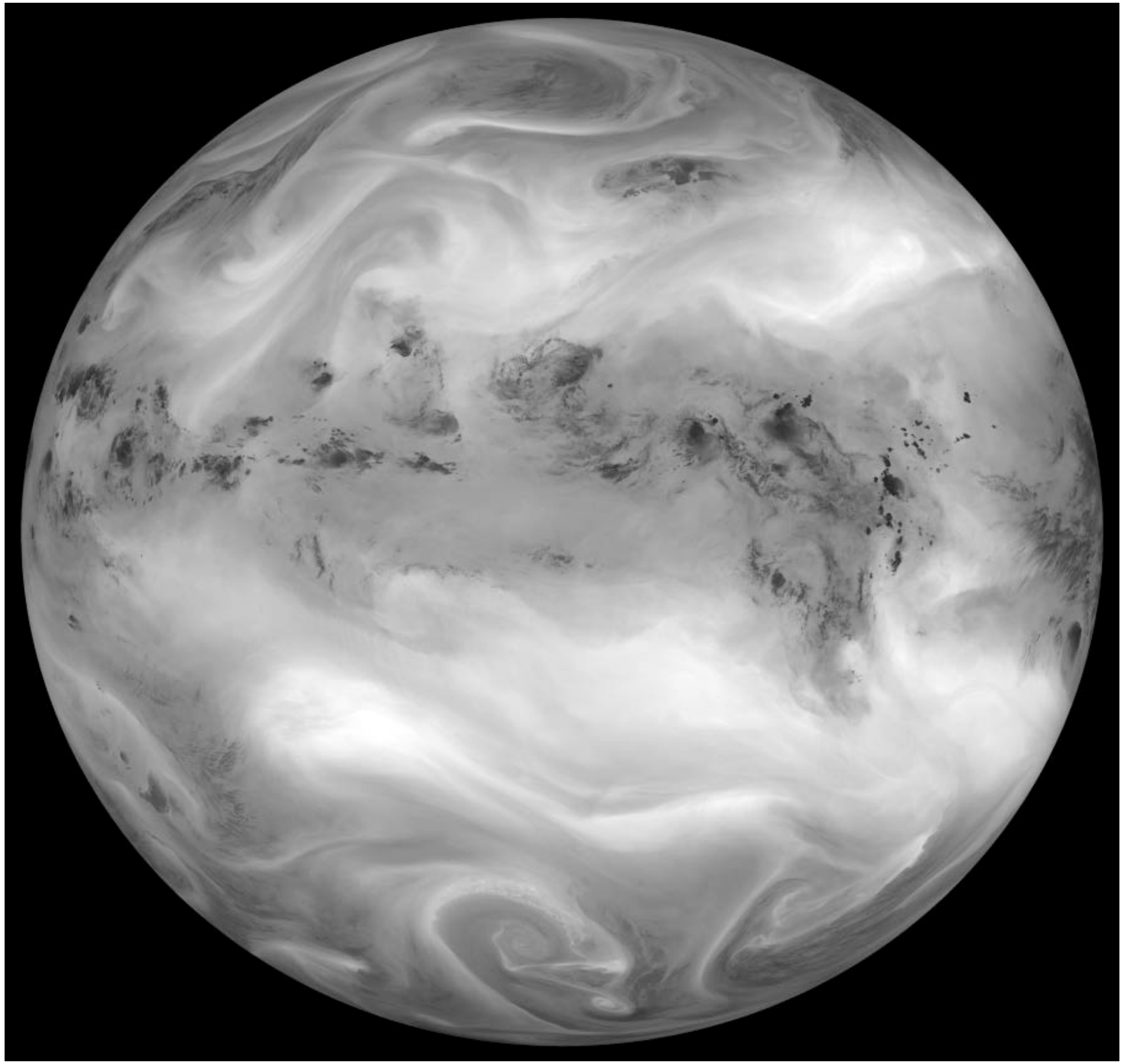
or BTo-BTrefference < ΔBTt

or BTo $\approx$ BTreference

(reference e.g. BT11)

- Limitations: low level clouds, low water vapor (high elevations,)

BT7, high clouds



Split window

- What the test detects and in what conditions:

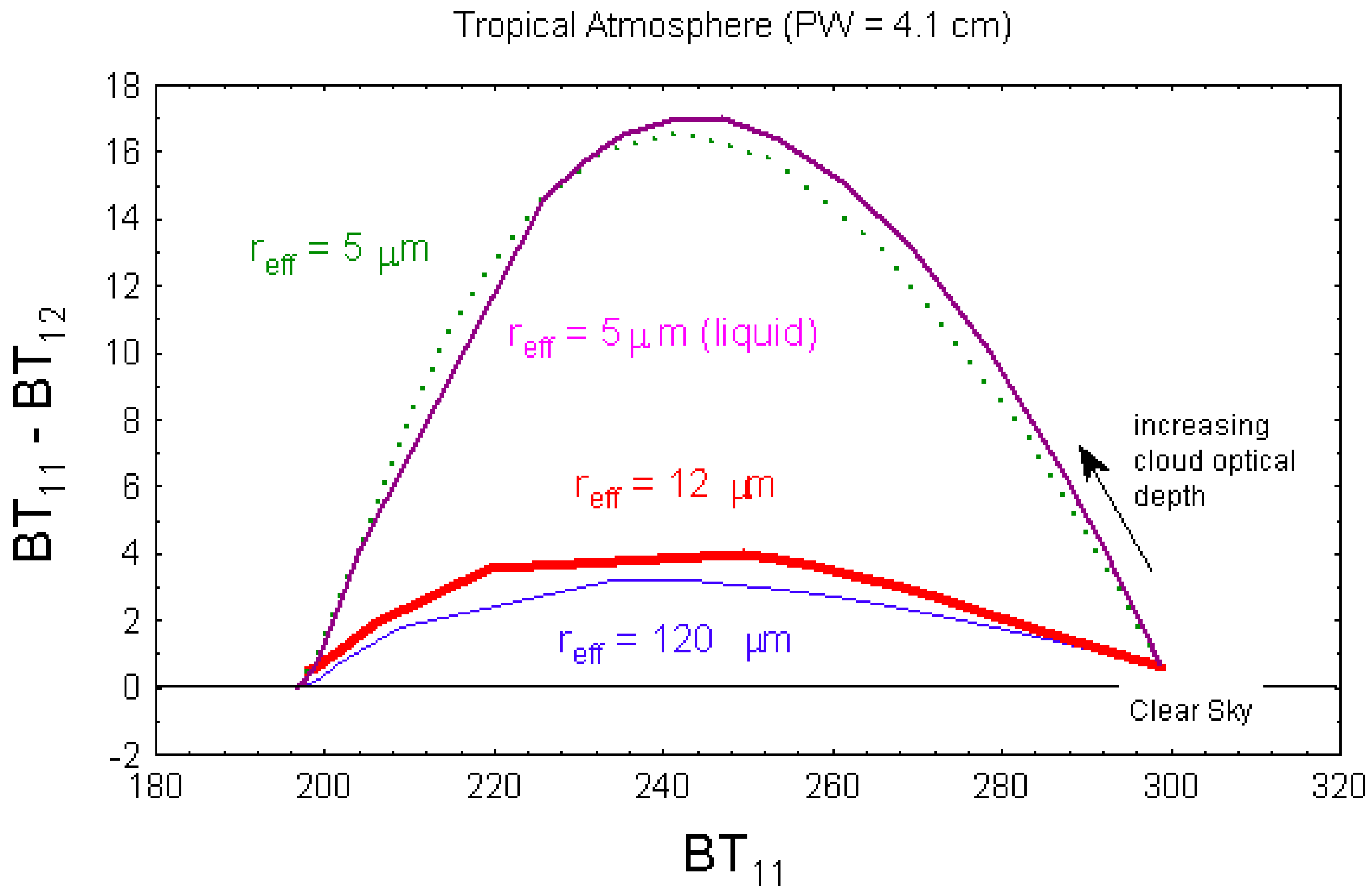
The test detects semitransparent high clouds under all conditions

- The basic physics of the test:
  - Different water emission/absorption at 8.6µm, 11µm, 12µm

thin cloud if $\Delta BT^{o} > \Delta BTt$

- Limitations: restricted to cold BT11, (low water vapour (BT12!), non desert (BT8.6))

Split window



pos. BT37 -BT11 night, mixed scene test

- What the test detects and in what conditions:
  - The test detects broken or thin clouds above warm surfaces during night
- The basic physics of the test:
  - Nonlinearity of Planck, BT39 responds more to the warm fraction of the FOV than BT11. Small diff. only for clear or opaque scenes.

    broken cloud if BT37o-BT11o > ΔBTt
- Limitations:
  - significant thermal contrast between surface and cloud is needed. → Low level warm clouds, moist warm atmospheres, cold surfaces reduce the discriminating power.

BT37-BT4

- What the test detects and in what conditions:
  - The test detects opaque clouds during day above dark surfaces (sun glint free ocean or green vegetation).
- The basic physics of the test:
  - The brightness temperature difference between 3.7µm and 4µm eliminates the emissive part. The residual difference emanates from the solar part

cloud if $BT37o - BT4o > \Delta BTt$

- Limitations:
  - Ice, snow, sand (coastline, deserts) , glint can produce ambiguous results

CO_2

- What the test detects and in what conditions:
  - The test detects middle and high clouds over all surfaces during day and night.
- The basic physics of the test:
  - The test detects the thermal contrast of a high (cold) cloud to the warmer thermal emission of carbon dioxide around 13.5µm.

cloud if BT11calculated_clear_sky > BT11o

- Limitations:
  - Misses low level clouds and very thin clouds, is sensitive to thermal inversions
  - Is more used for cloud characterisation than for cloud detection (it is e.g. not part of the NWC SAF)

O2

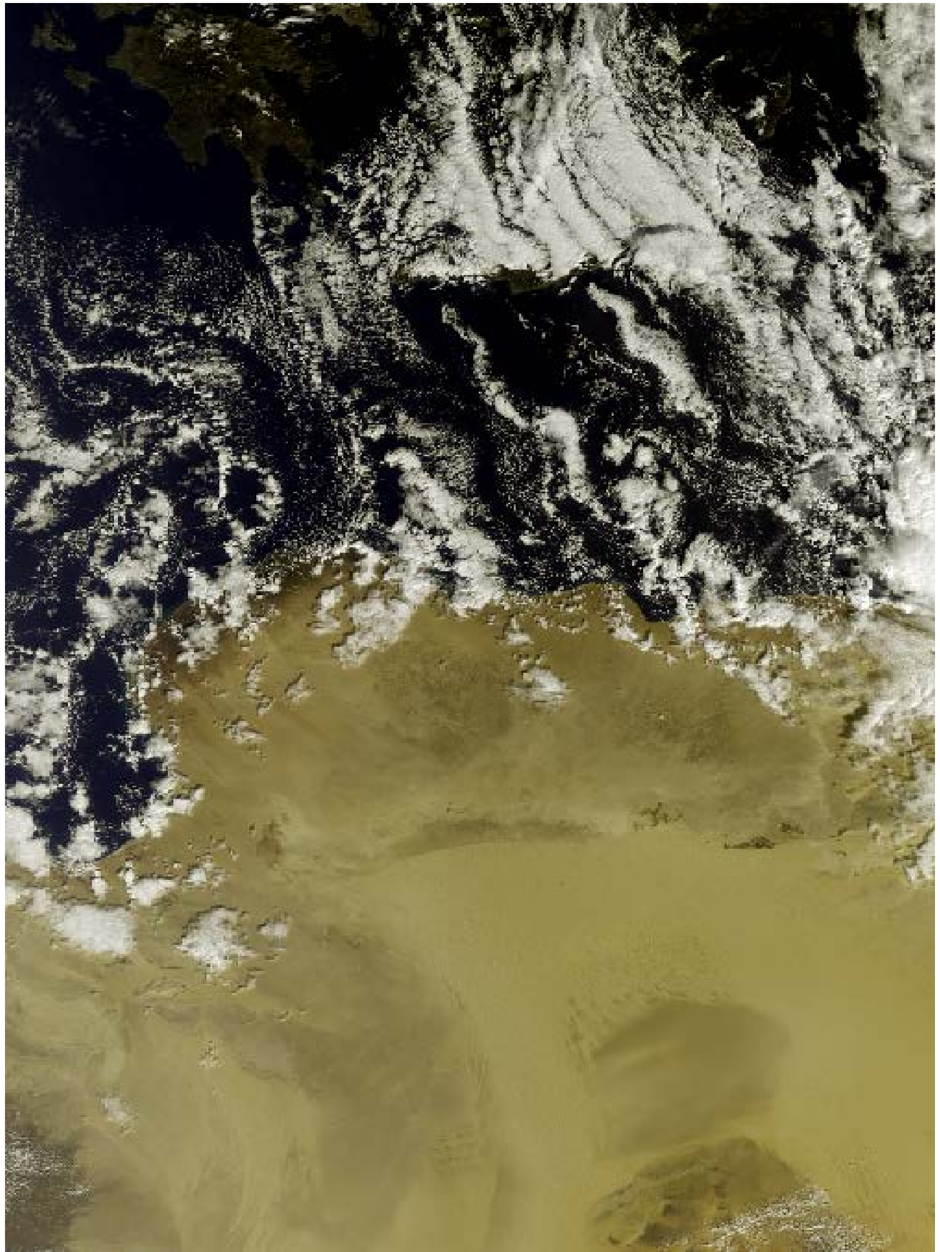
- What the test detects and in what conditions:
  - The test detects opaque clouds over bright surfaces and opaque and semitransparent clouds over dark surfaces (ocean) during day light conditions.
- The basic physics of the test:
  - Simplified models(no-scattering for Polder, single scattering and Rayleigh corrected for MERIS/OLCI) are used to estimate the *apparent* height/pressure of a scatterer.

$$\text{Cloud if } p_{surf} - p_{app} > \Delta pt$$

- Limitations:
  - No discrimination between high aerosol layers and thin clouds
  - bright surfaces dominate the signal if cloud has a low optical depth.
  - Clean atmospheres above dark ground may have a low apparent pressure (see later)

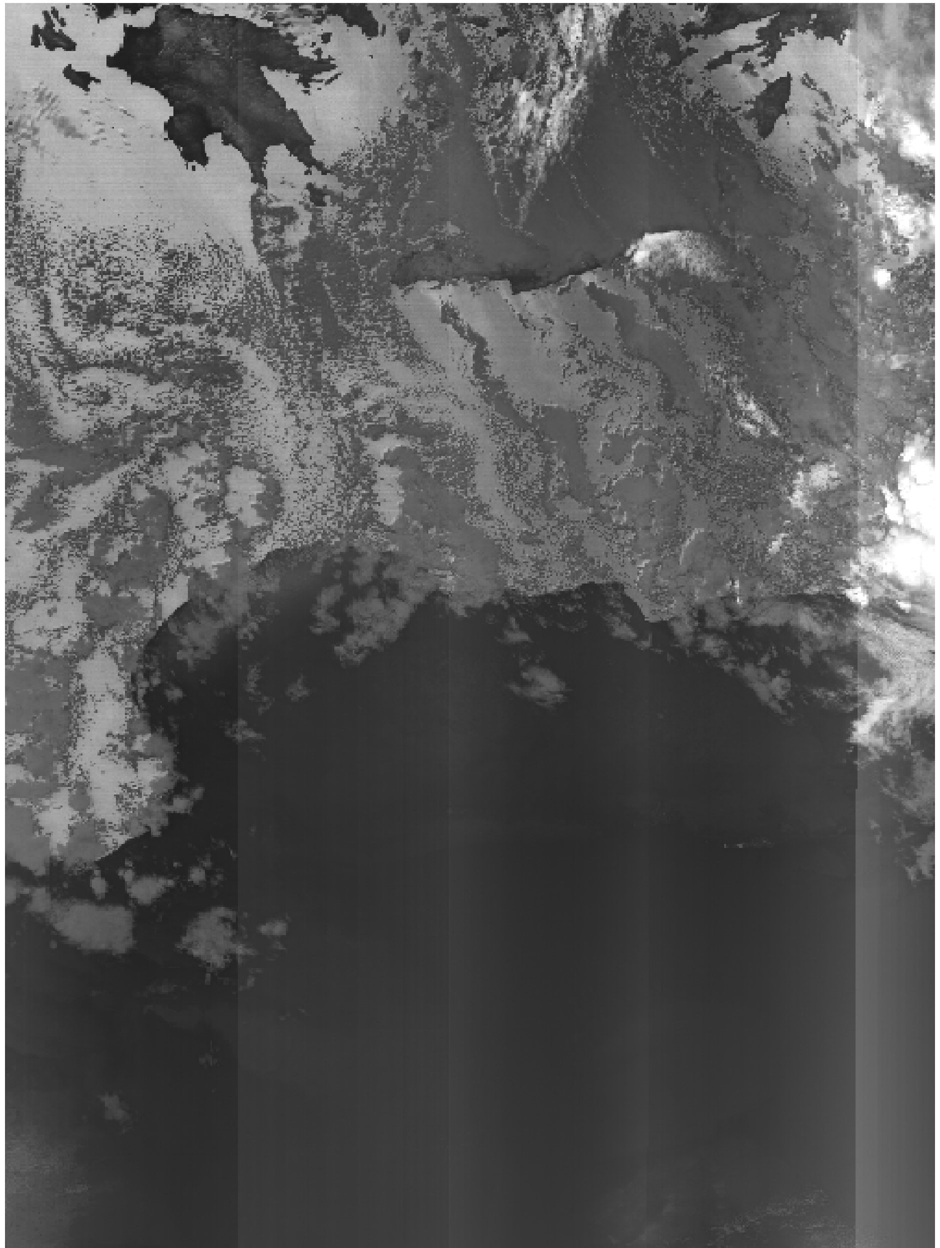
Example II: Oxygen absorption test (0.76μm)

RGB



Example II: Oxygen absorption test (0.76μm)

Apparent
O2 transmission



Uniformity tests

- What the test detects and in what conditions:
  - The tests detect small broken clouds, thin cirrus or cloud edges .
- The basic physics of the test:
  - spatial variability of **spectral** features is often higher above clouds than above natural surfaces
  - Commonly used spectral features are: BT11-Tsurface, r06, BT37-BT12 and ...
  - Standard deviation σ from a 3x3 or 5x5 field is computed.
  - Used in conjunctions:

Cloudy if $\sigma_a o > \sigma_a t$ and $\sigma_b o > \sigma_b t$

(using generic spectral features *a*, *b*)

- Limitations:
  - heterogeneous regions , thermal fronts over ocean, can produce false positives.

Snow detection, NDSI

- What the test detects and in what conditions:
  - Detects snow
- The basic physics of the test:
  - The *normalized difference snow index* (NDSI) uses VIS (0.55µm) and SWIR (1.6µm or 2.1µm, where snow absorbs more than clouds)

snow if cold and :

$$NDSI = (RVIS - RSWIR) / (RVIS + RSWIR) > NDSIT$$

- Limitations:
  - Ambiguity with ice clouds and different sand.

Generalised Bayesian

- What the test detects and in what conditions:
  - All types of clouds under all conditions
- The basic physics of the test:
  - Calculates the probability *c* (of cloud free or cloudy) under the condition of a measurement *Y*

$$P(c|Y)= P(Y|c) * P(c) / P(Y)$$

  - Needs the probability of a measurement *Y* under the condition *c.* P(Y|c) requires many RTM calculations.
- Limitations:
  - Seems to have a high potential, but this has not yet been substantiated in an operational environment. (SST!)

Optimum cloud analysis /Grape ...

- What the test detects and in what conditions:
  - All types of clouds under all conditions
- The basic physics of the test:
  - OCA is a cloud optical parameter retrieval. If optical thickness is $<\varepsilon$, then there is no cloud
- Limitations:
  - A converging cloud algorithm does not guaranty a cloud
  - ((A non-converging cloud algorithm does not mean that there is no cloud. (Could be a deficit in the forward operator)))

Cloud detection scheemes with channel subsetting for historically consistent time series!!

Validation

- Active Instruments (RADAR LIDAR):
  - Almost perfect, if spatial and temporal overlap
  - Examples : Caliop , CloudSat, Earthcare
  - No viewing angle dependency
- Ground based:
  - CloudNet super sites, Aeronet, Arm
  - good to find deficits,
  - but not for global accuracy quantification
- Different satellite missions
  - Clouds are too fast for different orbiter
  - L3 is very difficult to interpret but indispensable to detect deficits
  - Geos
- Manually selected data
  - Best if hyper spectral multi instrument ... Images are used
  - Select→ Charact vs Charact→Select !!
- Glint detection
  - Use AATSR/MISR/POLDER to learn (not done until now)
- Measures:
  - POD,FAR, depend on selected test data (*SkillScores) ???