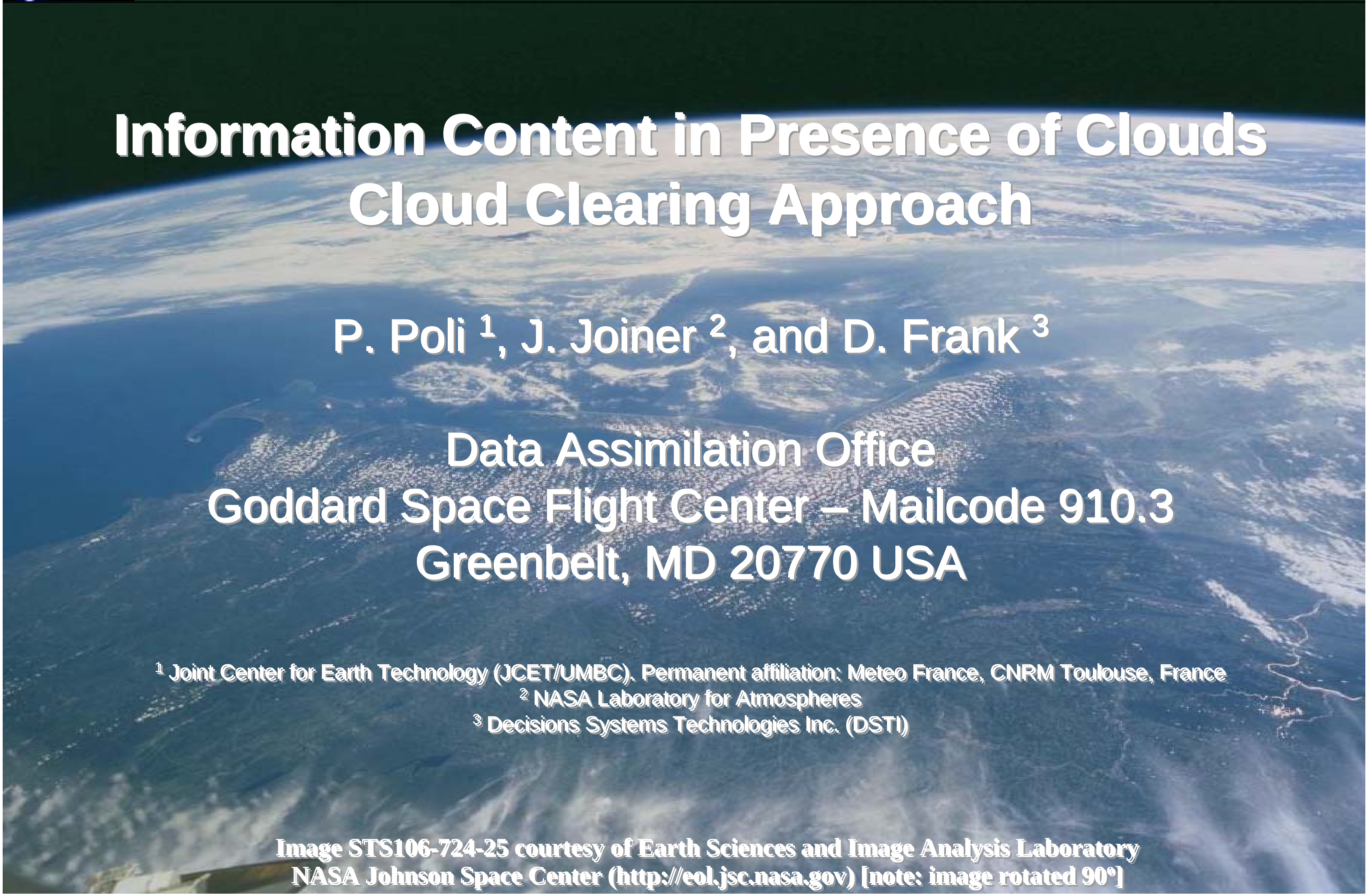
Workshop on Soundings from High Spectral Resolution Infrared Observations
May 6-8, 2003 University of Wisconsin-Madison



Information Content in Presence of Clouds
Cloud Clearing Approach

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Introduction

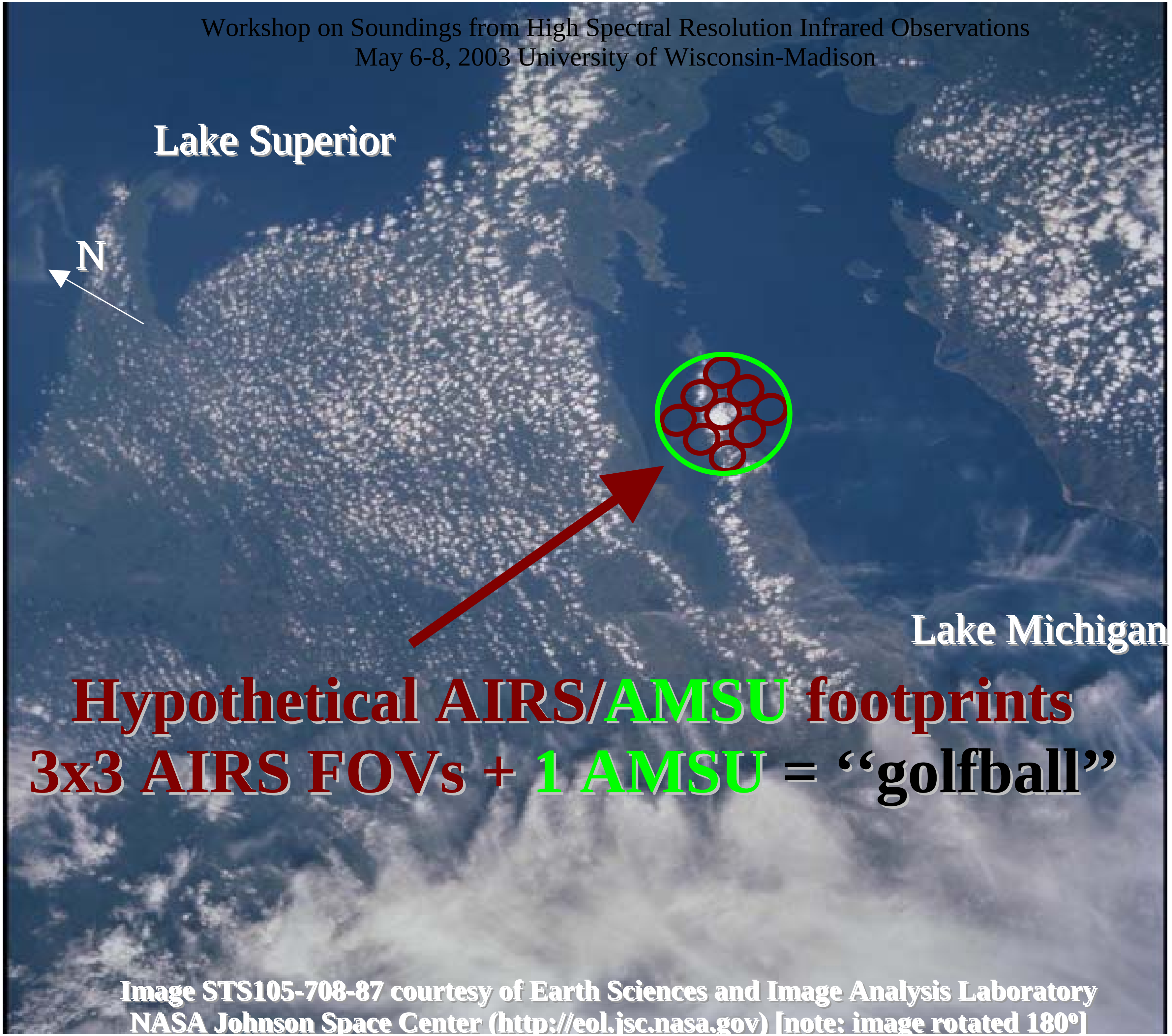
- **''Clear'' areas:**
  Depending on the size of the FOV and the criterion used: only represent 2%-10% of the total IR FOVs
- **Without cloud assimilation:**
  Use of IR data for assimilation into Numerical Weather Prediction (NWP) or climate models is restricted to clear-only
- **Cloud-clearing:**

Process that estimates clear radiances that would have been emitted by an atmosphere which would not contain clouds

Cloud-cleared radiances can then be assimilated

Outline

1. The cloud-clearing problem
2. Review: Cloud-clearing approaches
3. Study: Impact of cloud-clearing on information content with AIRS
4. Example: Cloud-clearing with TOVS data in the Data Assimilation Office Data Assimilation System
5. Conclusions and Future Orientations



Hypothetical AIRS/AMSU footprints

3x3 AIRS FOVs + 1 AMSU = “golfball”

Image STS105-708-87 courtesy of Earth Sciences and Image Analysis Laboratory
NASA Johnson Space Center (http://eol.jsc.nasa.gov) [note: image rotated 180°]

2. Cloud-clearing approaches: 2 types

- **Statistical approaches using clear measurements only:**
  - radiances in cloud areas are treated as missing values
  - in cloudy areas, radiances are constructed from neighboring clear radiances
  - constructed radiances obey pre-defined properties such as latitudinal gradient, spatial variability, and spatial smoothness similar to those of measured adjacent clear radiances [Andretta et al., 1990; Cuomo et al., 1993; Rizzi et al., 1994].

Physical cloud-clearing approaches

- **Physical approaches using clear and cloudy measurements:**

(1) decompose the measured upwelling radiance into a sum:

Clear component + Cloudy component (one component per cloud formation)

(2) assume that clear and cloudy components (incl. cloud emissivities) are constant within adjacent FOVs; only the cloud fractions vary

(3) using adjacent FOVs and several channels, the clear component can be retrieved

No assumptions about the optical properties of the clouds

Single Cloud Formation

Effective cloud fraction in FOV 1

Spectral radiance measured in FOV 1 → $R_1 = N_1 R_{cld}(\varepsilon_1) + (1 - N_1) R_{clear}$

FOV 2 → $R_2 = N_2 R_{cld}(\varepsilon_2) + (1 - N_2) R_{clear}$

Effective cloud fraction in FOV 2

$R_{clear} = (N_2 R_1 - N_1 R_2) / (N_2 - N_1)$ Assuming $\varepsilon_1 = \varepsilon_2$

$R_{cld} = ((1 - N_2) R_1 - (1 - N_1) R_2) / (N_1 - N_2)$

One can rewrite R_{clear} as:

$R_{clear} = (R_1 - N^* R_2) / (1 - N^*)$ where $N^* = N_1 / N_2$

[Smith,1968;McMillin,1978]

$R_{clear} = R_1 + \eta (R_1 - R_2)$ where $\eta = N_1 / (N_2 - N_1) = N^* / (1 - N^*)$

[Chahine,1974]

Multiple Cloud Formation and Noise Amplification

$$\boxed{R_{clear} = R_1 + \eta_1 (R_1 - R_2) + \eta_2 (R_1 - R_3) + \ldots + \eta_K (R_1 - R_{K+1})}$$

(K+1) FOVs are required to solve for R_{clear} with K cloud formations.

CAVEAT: reconstructed radiance R_{clear} may contain an amplified random (measurement) noise σ':

$$\boxed{\sigma'^2 = [\ (1 + \eta_1 + \eta_2 + \ldots + \eta_K)^2 + \eta_1^2 + \eta_2^2 + \ldots + \eta_K^2\ ]\ \sigma^2}$$

σ: random (measurement) noise of radiances $R_1, R_2, \ldots, R_{K+1}$

Practical implementation of cloud-clearing procedures

(1) estimate the clear-column radiance for a subset of IR channels. Can use MW channels and/or *a priori* information from NWP

(2) Invert the previous equation for a subset of IR channels to retrieve $\eta_1,\dots,\eta_K$ [e.g. least-square solver]

(3) Recalculate R_{clear} for ALL the IR channels

(4) Retrieve temperature/constituent/surface information from R_{clear}

(5) From these retrievals repeat (1)-(4) until convergence is achieved

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<u>2 FOVs, K=1:</u> HIRS2/MSU [McMillin and Dean, 1982;Susskind et al., 1984]

<u>3 FOVs, K=2:</u> HIRS2/MSU/SSU [Joiner and Rokke, 2001]

<u>4 FOVs, K=3:</u> 18-channel grating [Chahine et al., 1977]

3. Study: Information Content and Cloud-Clearing with AIRS

- Temperature and/or constituent information is retrieved from real (noisy) measured radiances, using conventional least-squares methods or more evolved variational methods.

- Under variational hypotheses (normal and un-biased errors in background and observations), error covariance matrix of the analyzed retrievals:

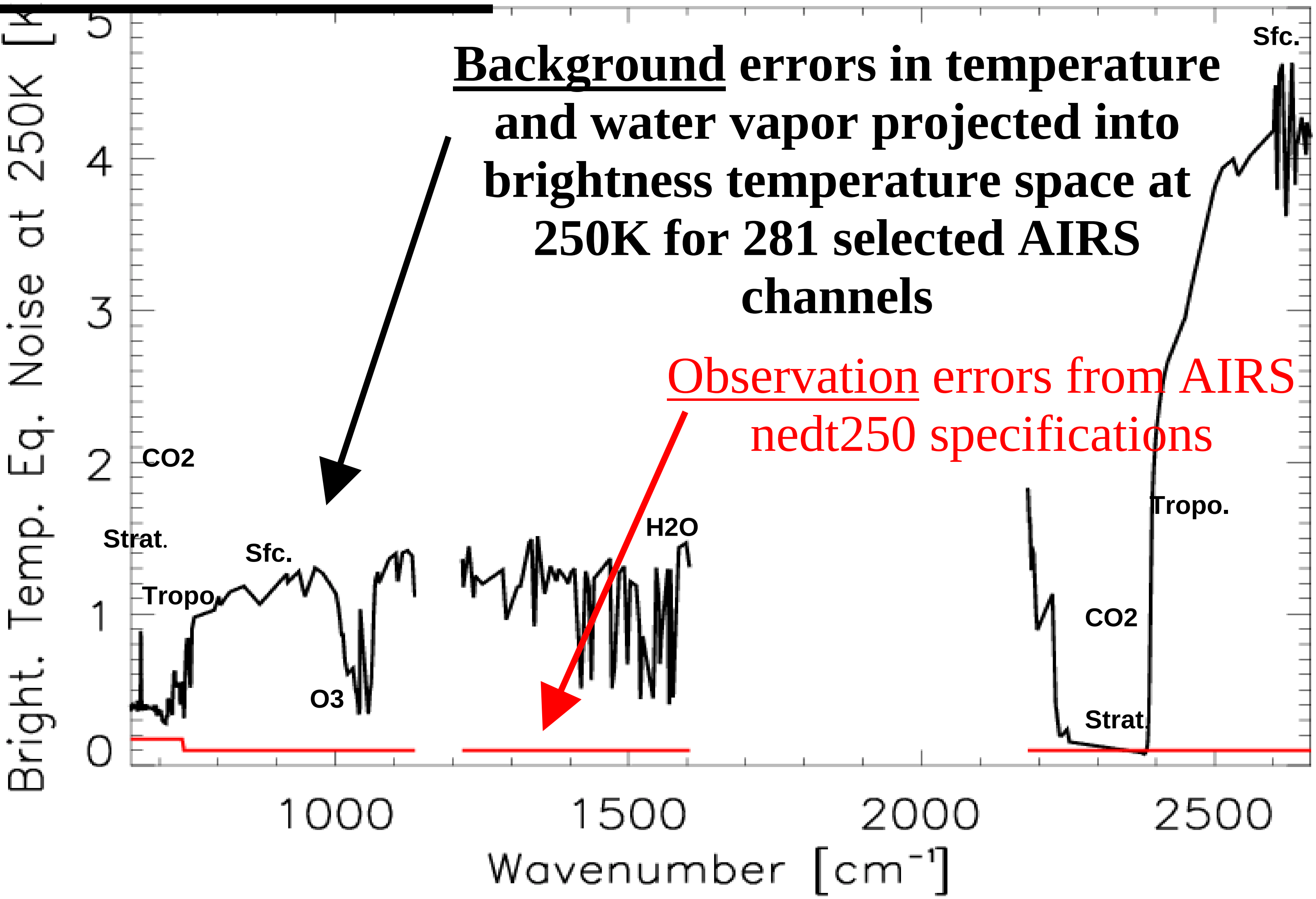
$$\boxed{P^a = (\underline{B}^{-1} + \underline{H}^T\underline{R}^{-1}\underline{H})^{-1}}$$

[e.g. Rodgers, 1990]

$\underline{B}$: background (initial estimate) error covariance matrix
$\underline{R}$: observation (IR radiances) error covariance matrix
$\underline{H}$: tangent linear model of the observation operator (radiative transfer code)
- diagonal terms of P^a: variance of errors in retrieved quantities (temperature, specific humidity,...)
- off-diagonal terms of P^a: covariance between the errors in the retrievals (inter-level correlation or temperature/constituent ambiguity)

Brightness Temperature Noise

CLEAR CASE



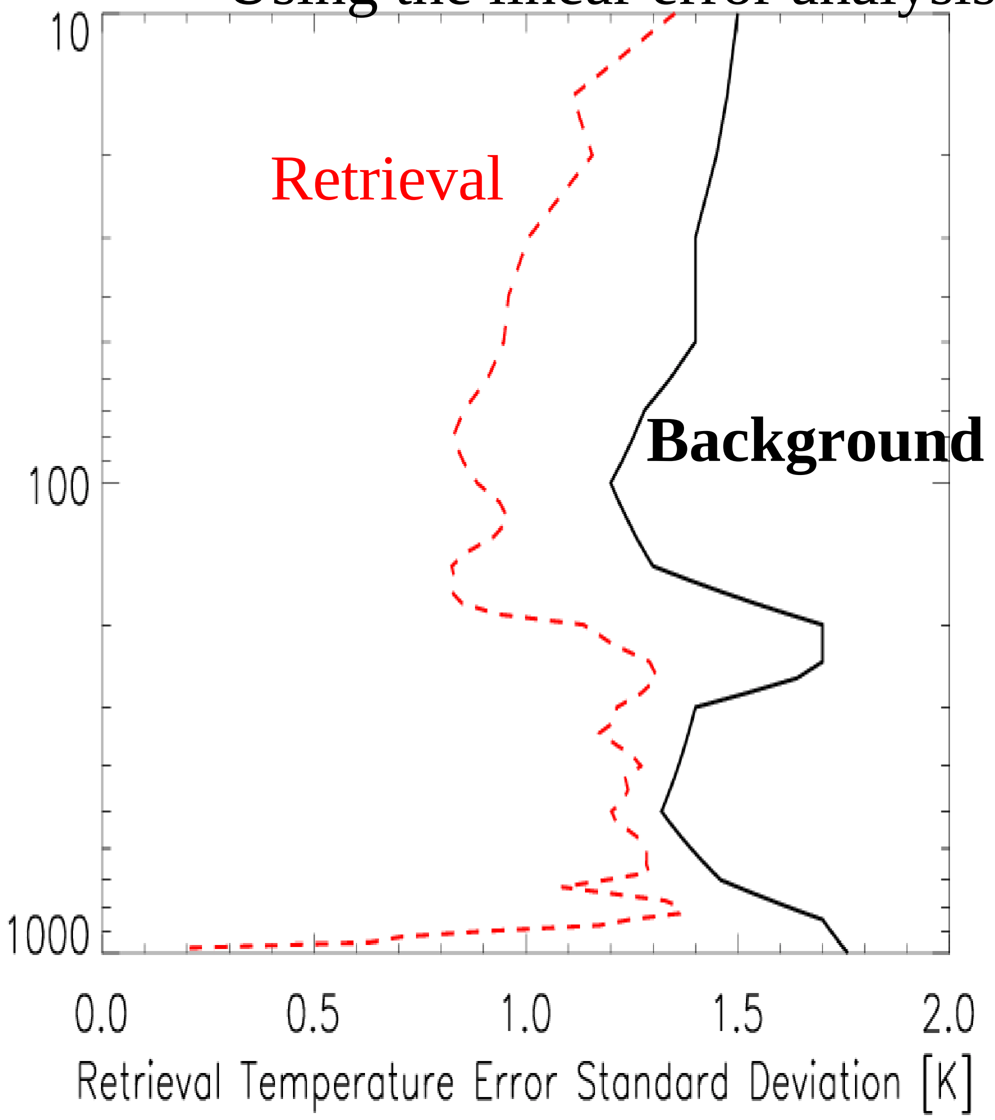
Background errors in temperature and water vapor projected into brightness temperature space at 250K for 281 selected AIRS channels

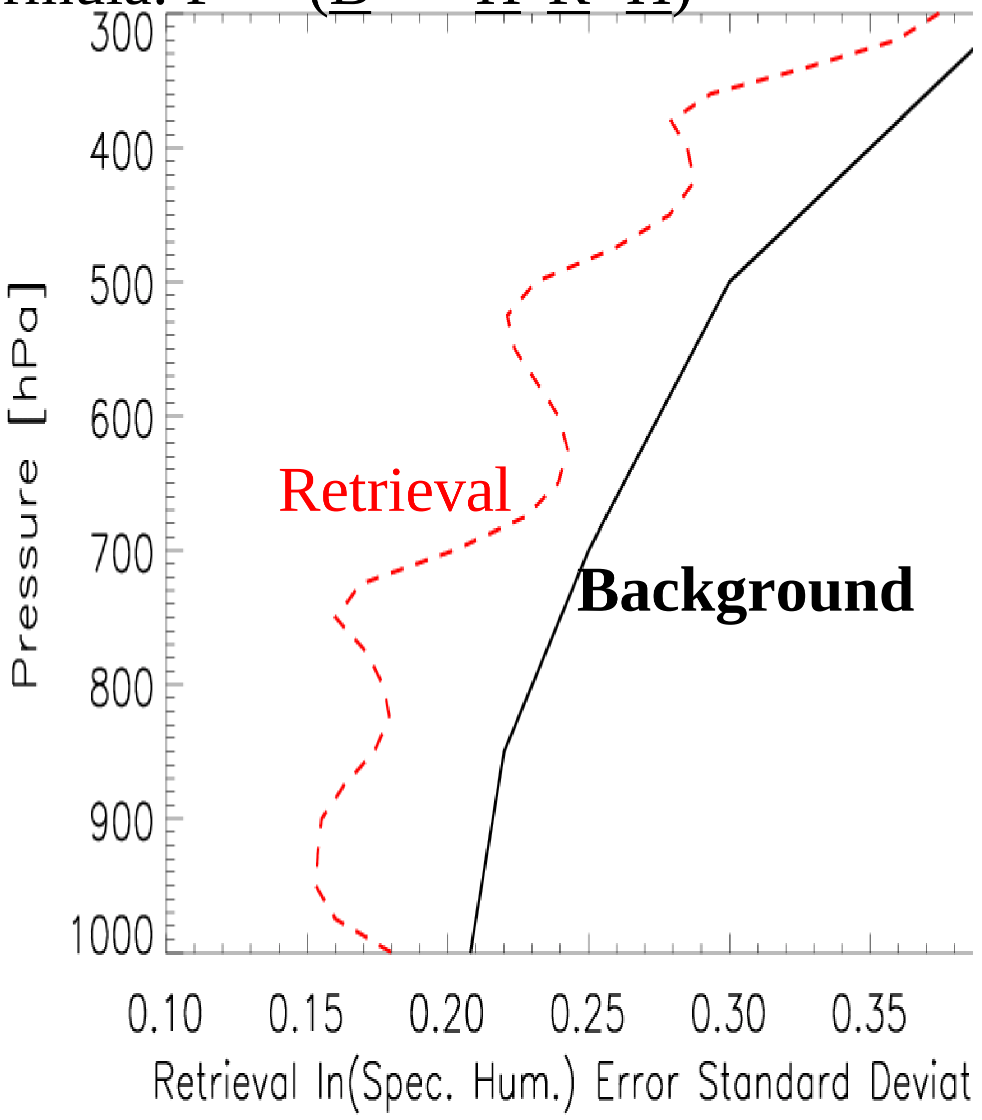
Observation errors from AIRS nedt250 specifications

Simulated AIRS retrieval errors

CLEAR CASE

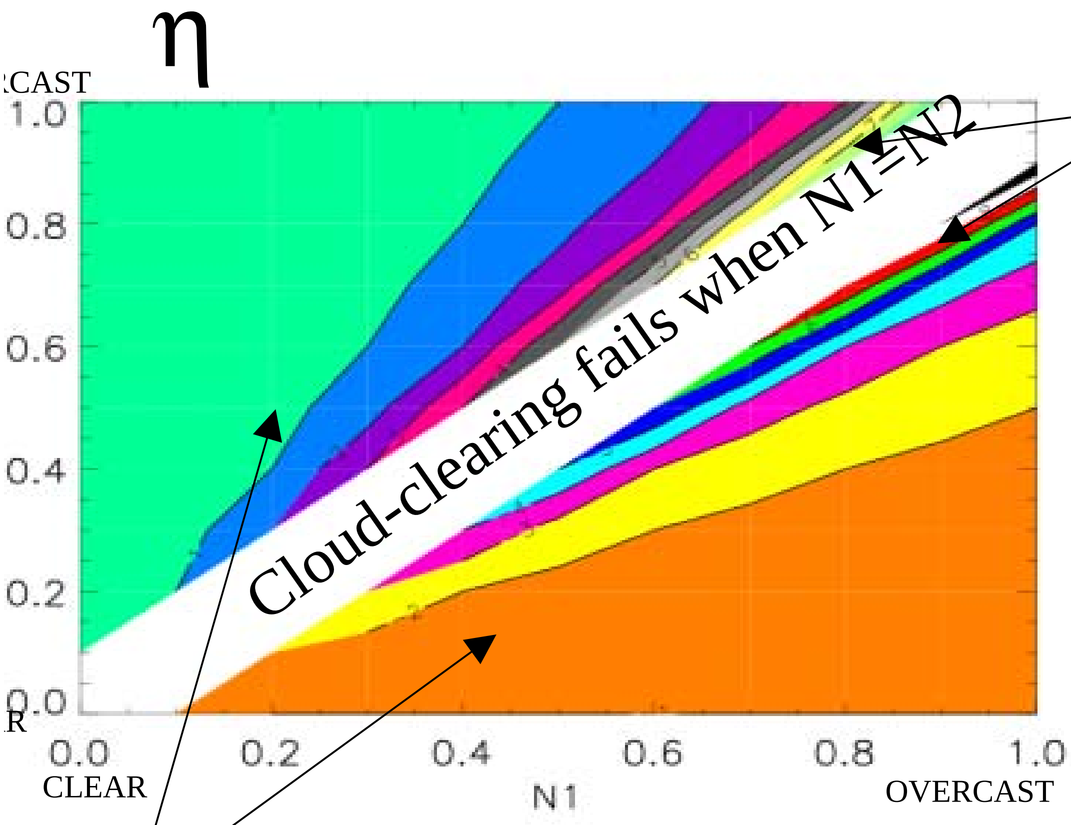
Using the linear error analysis formula: $P^a = (\underline{B}^{-1} + \underline{H}^T\underline{R}^{-1}\underline{H})^{-1}$





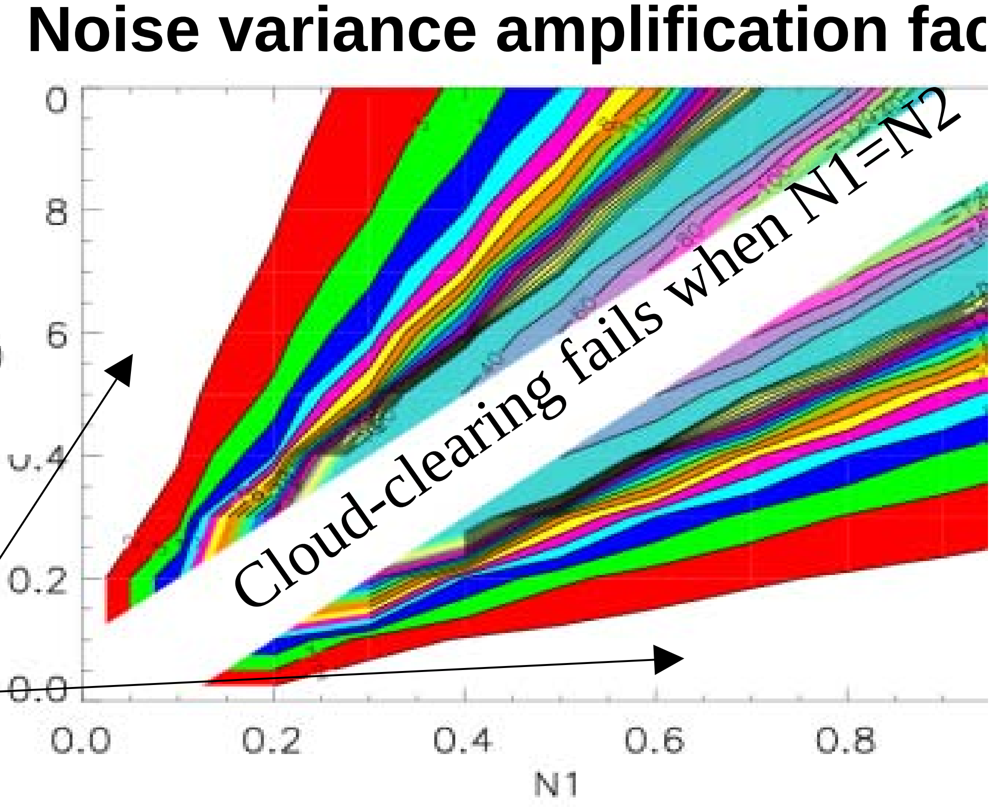
servation noise amplification due to cloud-clearing: single layer cloud

$$R_{clear} = R_1 + \eta\,(R_1 - R_2) \qquad \text{where} \quad \eta = N_1/(N_2 - N_1)$$



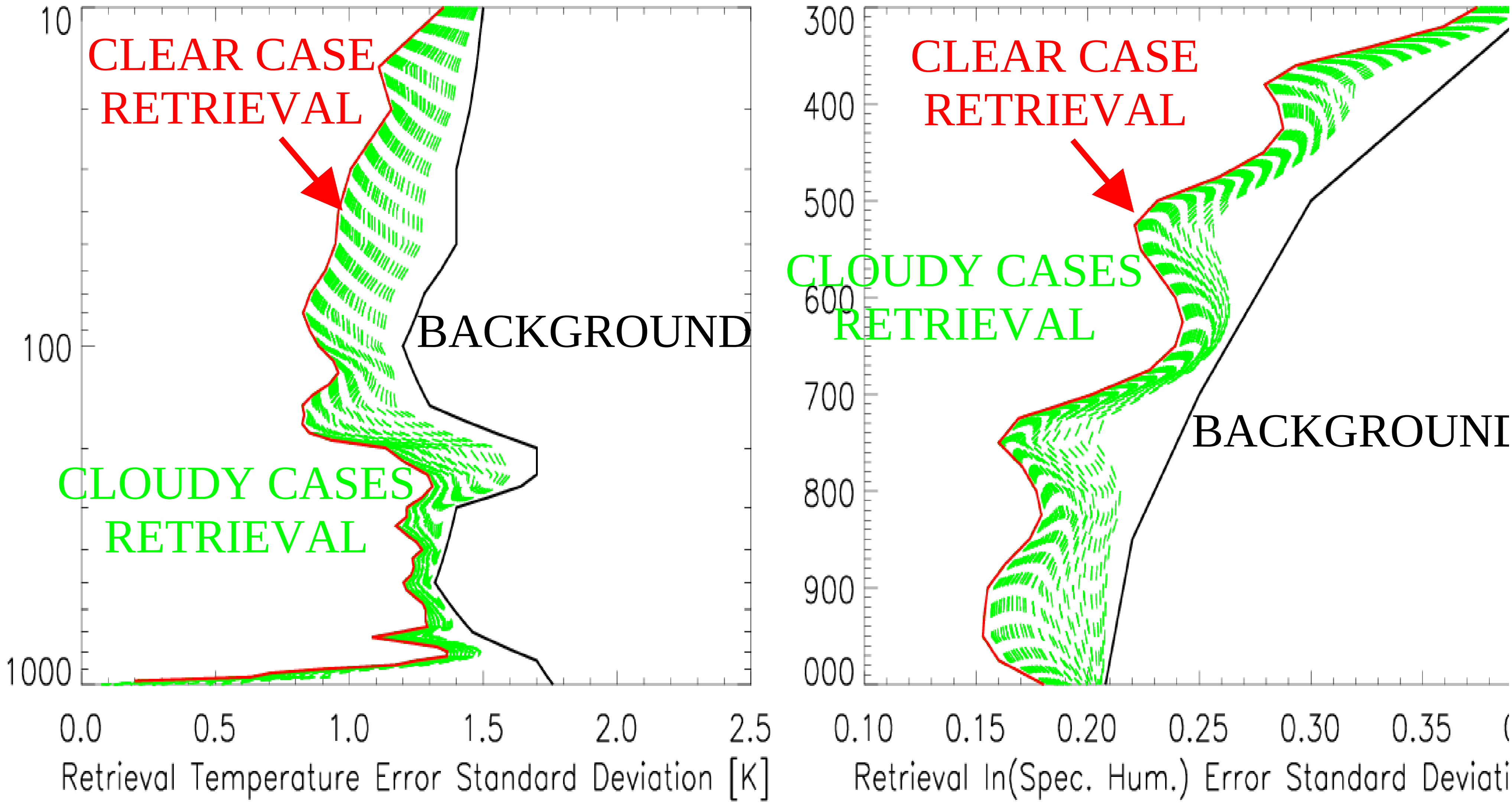
High values of η

Low values of η (between -2 and 2)



Small amplification factor (<2)

Simulated AIRS retrieval errors **with cloud-cleared radiances**

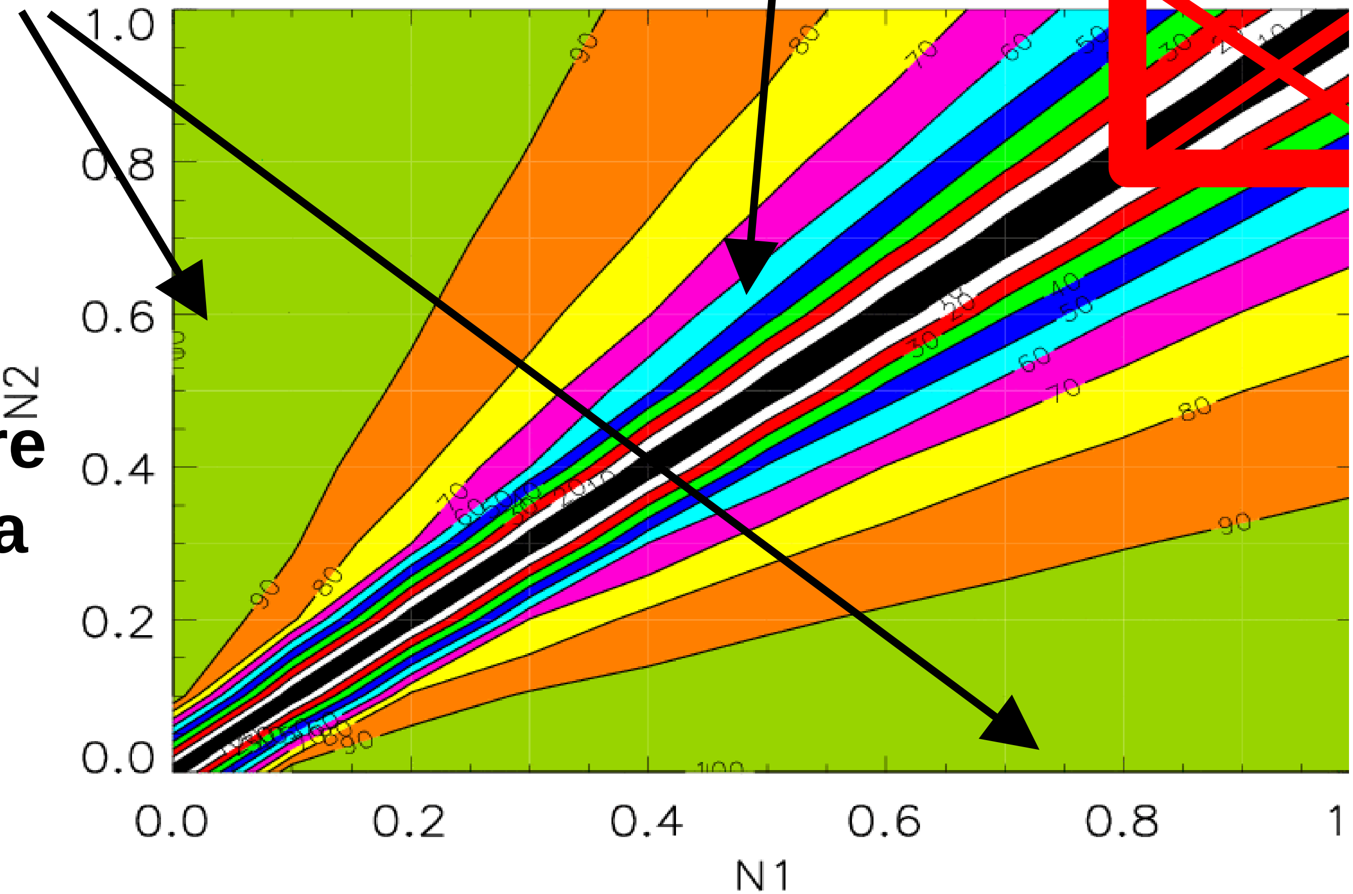


Simulated AIRS retrieval errors **with cloud-cleared radiances**

Retrieval achieves ~90-100% of the
error reduction obtained for the clear case

Retrieval does not reduce
much the errors as what
would be obtained with cl
radiances

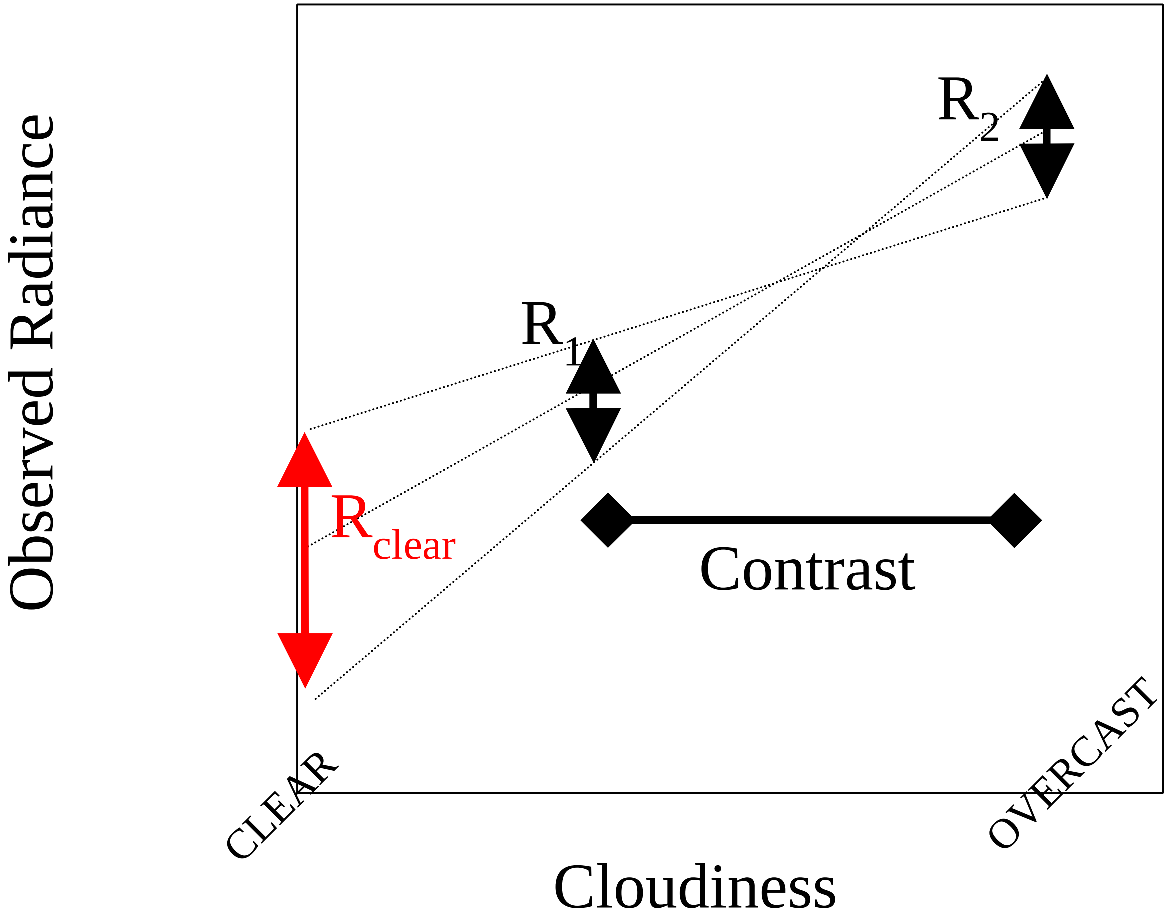
Ratio between
σ(bkg)-σ(cl.cl. ret.)
d σ(bkg)-σ(clear ret.)
%] for the temperature
or std. dev. at 200hPa



More contrast yields better quality retrievals
Only a marginal reduction of error in the retrievals as compared
the background when both N1 and N2 > 80%

Cloud-clearing: an extrapolation ?

$$R_{clear} = R_1 + \eta\,(R_1 - R_2) \qquad \text{where} \quad \eta = N_1/(N_2 - N_1)$$



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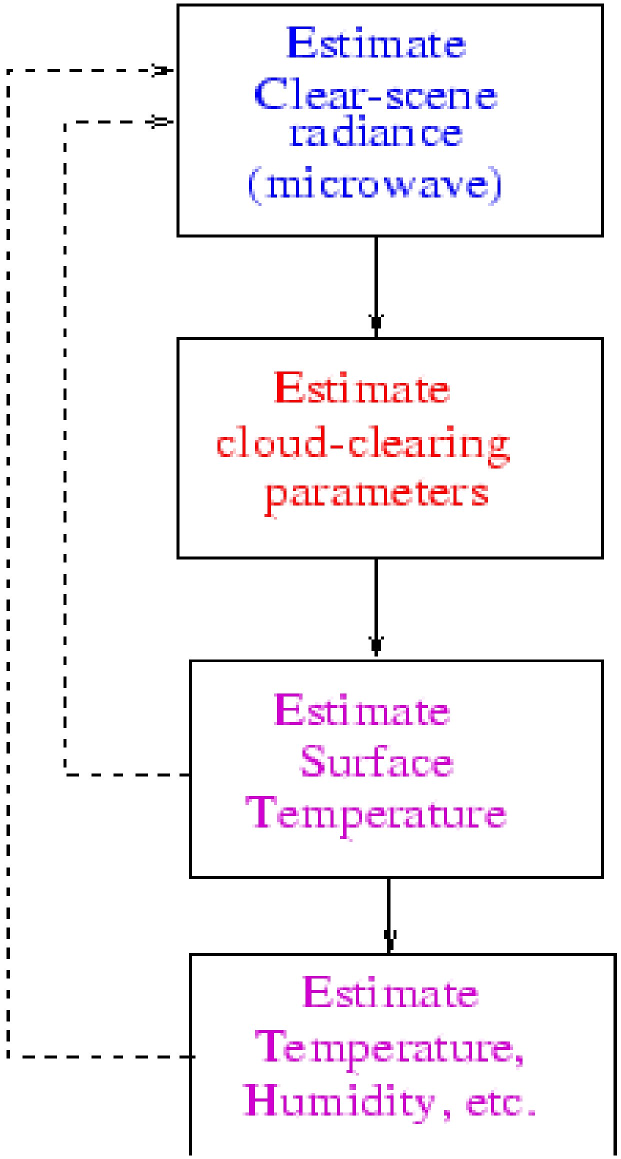
Cloud-clearing with TOVS data: operational at DAO since 2001

Previous Implementations



Estimate Clear-scene radiance (microwave)

Estimate cloud-clearing parameters

Estimate Surface Temperature

Estimate Temperature, Humidity, etc.

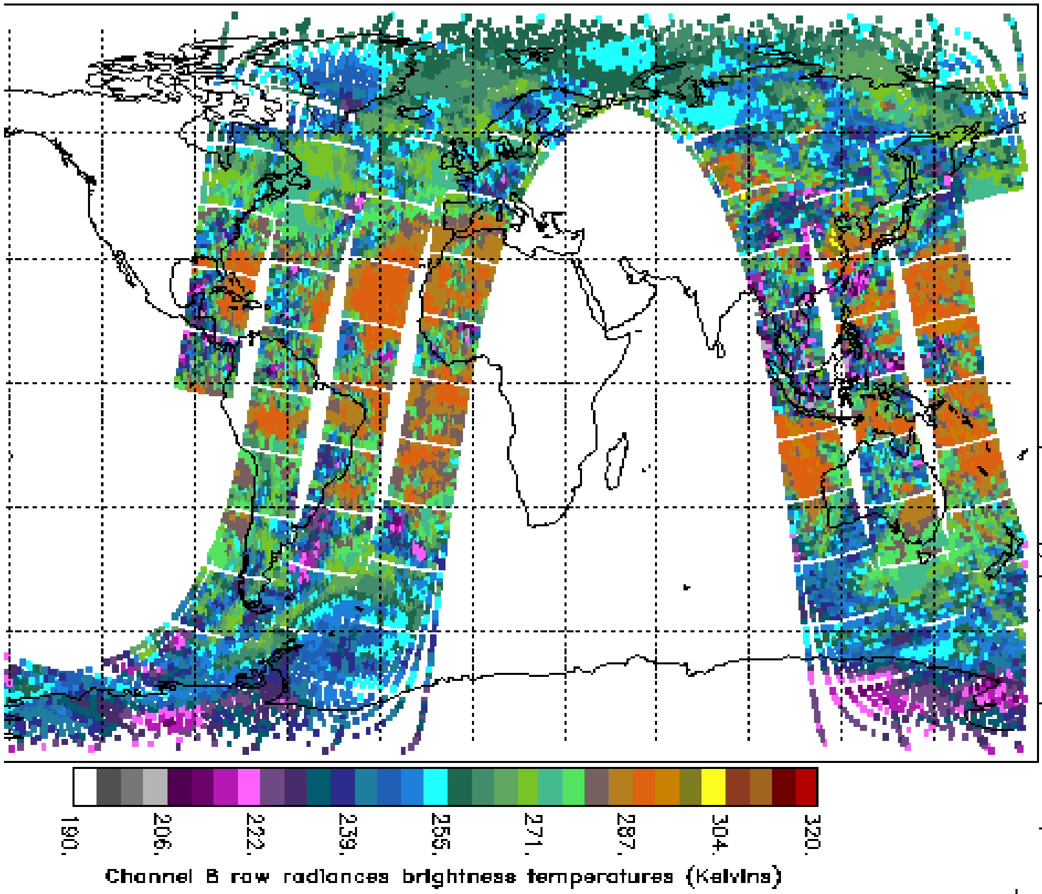
New Implementation

Variational approach using all channels to simultaneous estimate cloud-clearing parameters and atmospheric and surface parameters

1. **Simplicity**
2. **Consistency**
3. Quality Control Built in
4. Physically-based systematic error correction

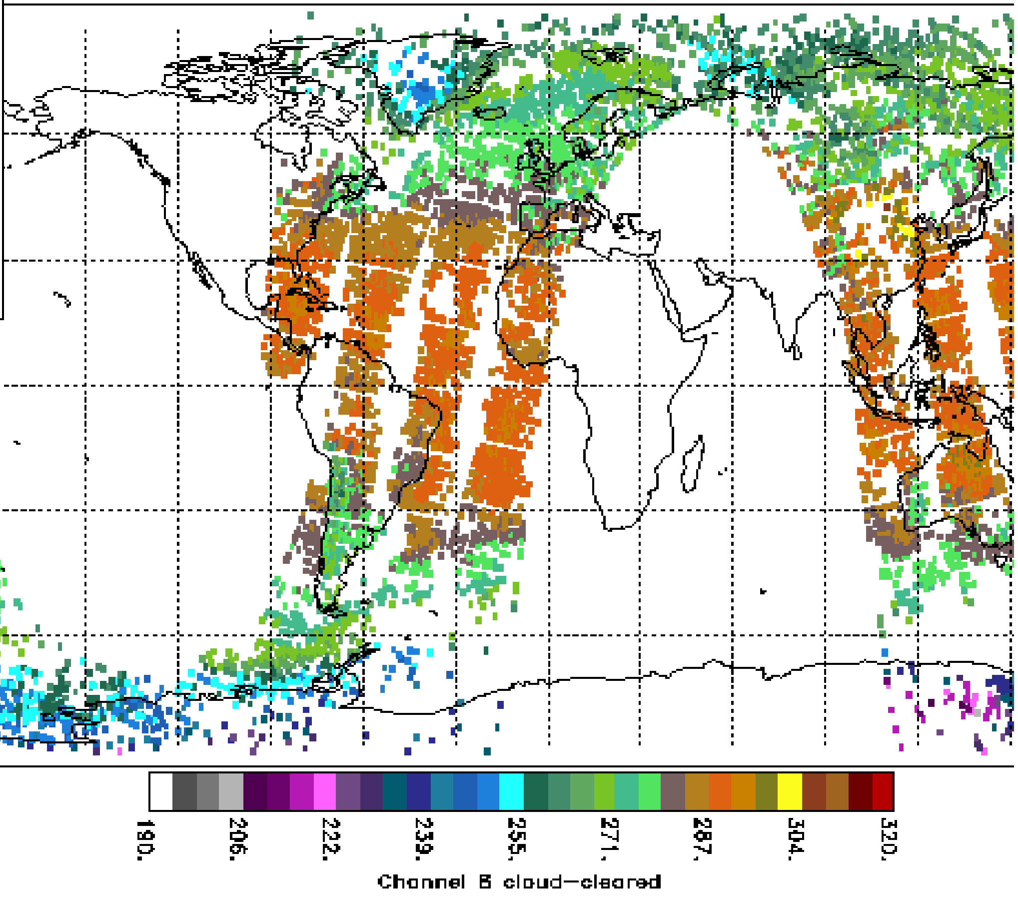
[Joiner and Rokke, 2000]

Cloud-clearing with TOVS data: operational at DAO since 2001

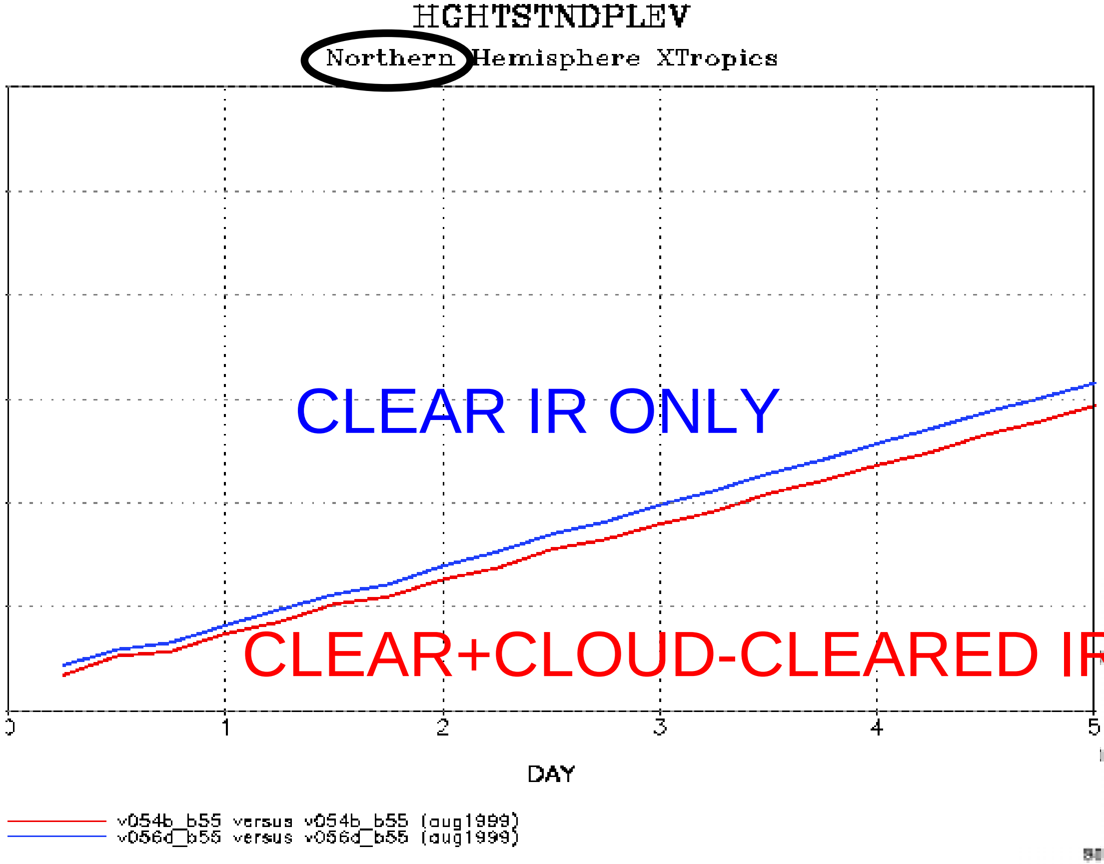


TOVS CHANNEL 8 OBS.
CLEAR AND CLOUDY

AFTER CLOUD-CLEARING



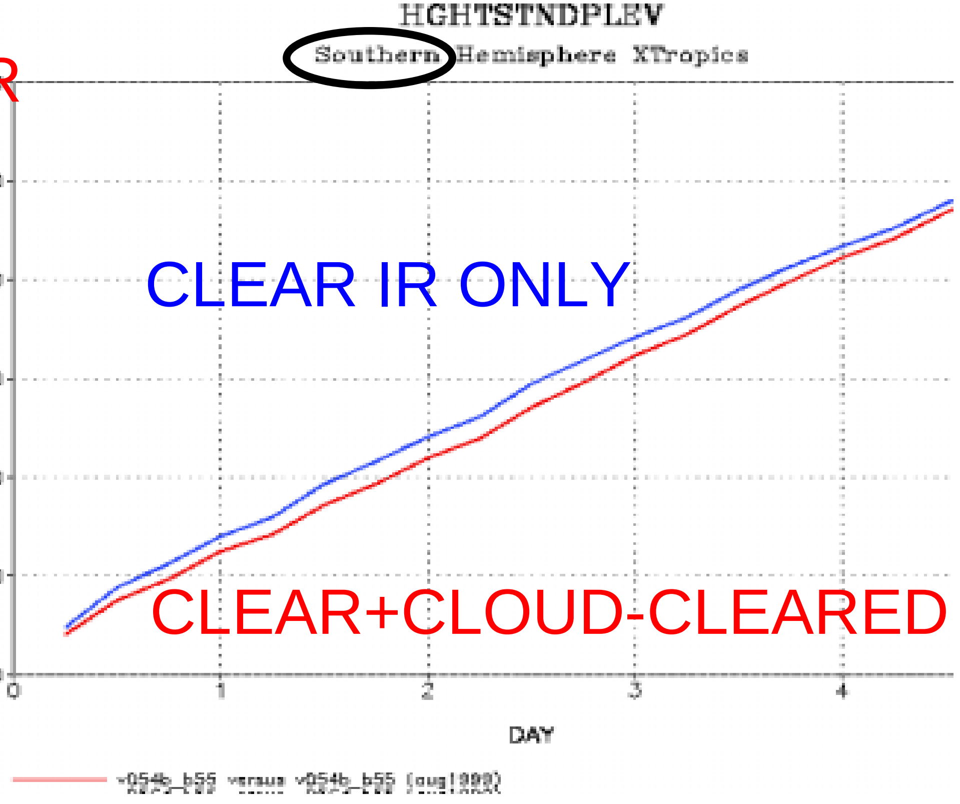
pact of cloud-cleared TOVS data on numerical weather forecast



CLEAR IR ONLY

CLEAR+CLOUD-CLEARED IR

FORECAST SKILLS
RMS ERROR AT 500hPa
(FORECAST MINUS ANALYSI



CLEAR IR ONLY

CLEAR+CLOUD-CLEARED

5. Conclusions and Future Directions

- Cloud-clearing: allows the use of cloudy IR data since no other method is ready for operational data assimilation
- As of today, cloud assimilation still requires further research:
  - requires good knowledge of the optical properties of the cloud
  - more costly
- Cloud-clearing has some intrinsic limitations
  - needs sufficient contrast and pixels <80% cloudy
  - should not be applied to clear channels peaking above the cloud
- With AIRS and high spectral resolution sounders: cloud-clearing will need careful attention (channel selection)
- Future: assimilation of cloudy radiances ... no cloud clearing?