Status of the Community Long-term Infrared & Microwave Coupled Atmospheric Product System (CLIMCAPS): Status and Preliminary Results

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… and past efforts of Eric Maddy

NASA Sounder Science Team Meeting
Thursday, Oct. 26, 2017, Session 5, 8:00 am

CLIMCAPS has NASA AIRS Algorithm Heritage

- CLIMCAPS is based on NOAA-Unique Combined Atmospheric Processing System (NUCAPS)
  - NUCAPS-Metop has been operational since 2008
    - 2008 to present Metop-A/IASI/AMSU/MHS + AVHRR
    - 2012 to present Metop-B/IASI/AMSU/MHS
  - NUCAPS-NPP went operational in early 2014
  - NUCAPS is based on AIRS methodology, v.5.9
    - V.6 was not available until 2013
    - NOAA users require consistency between Metop/NPP/JPSS
  - *NUCAPS is fully capable of running AIRS/AMSU*
    - Have not had resources to do so since ~2012
  - NUCAPS now has many users (T, q, O_3, CO, and CH_4)
    - See talks at this meeting by, N. Smith (Wed. 1:00 & 2:40), N. Nalli (Wed. 1:20, Thu. 1:20), A. Wheeler (Wed. 3:20), T. Reale (Wed. 3:40), and A. Gambacorta (Thu. 9:20), F. Iturbide-Sanchez (Thu. 11:20)

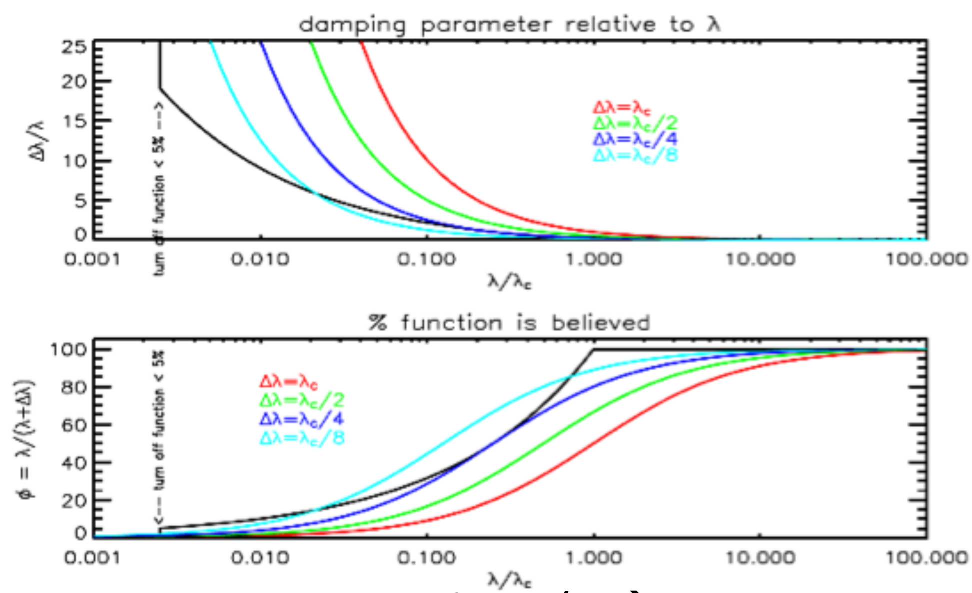
CLIMCAPS retains many components of the AIRS Methodology

- (see Sep. 14, 2016 NASA STM presentation) for additional details
  - **… and … detailed derivations for NUCAPS are in rs_notes.pdf available on my google drive at http://goo.gl/pJfYAo**
  - **Details of CLIMCAPS theory will be added in December**
- Cloud clearing
  - Uses spatial information to correct for clouds
  - Allows other state components (SST/LST, T(p), q(p), $\varepsilon(\upsilon)$, $O_3(p)$, CO(p), etc.) to be derived independently of clouds from spectral information
  - But, a-priori used for cloud clearing is extremely important.
    - Iteration of cloud clearing causes biases and confounds error characterization … CLIMCAPS currently has 2 steps
- Uses all space sounding assets
  - Microwave radiances used for both for information content and quality control
  - Imager data implicitly used via emissivity a-priori

CLIMCAPS retains the AIRS information content analysis

- Embedded information content (IC) analysis
  - Retain components that have high signal-to-noise, S/N
  - *Requires accurate estimates of **all** noise terms, N*
  - Single optimization parameter, $1/\lambda_c$, defines S/N threshold
    - e.g., T(p) retrieval uses $1/\sqrt{\lambda_c} = 5$, $\lambda = (S/N)^2$

Top Panel: shows the damping parameter as a function of λ/λ_c for a AIRS methodology (black) and minimum variance methods (colors)
Bottom Panel: Same curves but shown as percent believed.
Embedded IC allows retaining high S/N components 100% (without damping) while dramatically reducing the impact of low S/N components.



Higher S/N →

CLIMCAPS uses NUCAPS Rapid R2O Approach*

- Instrument specific components are handled in a preprocessor
  - CLIMCAPS preprocessor handles all formats of ATMS and CrIS level.1 formats
    - Performs reversible Hamming apodization
    - Reads (NASA level.1) or computes (IDPS SDR) fraction of land and surface altitude
    - Derives variance of fraction of land and surface altitude over CrIS field of regard
  - Creates co-located full geophysical state from GFS forecast
    - Supports both wgrib-1 and wgrib-2 formats
    - NUCAPS uses the GFS surface pressure.
    - NUCAPS and CLIMCAPS use GFS T(p) and q(p) for monitoring of operational performance
  - Creates co-located full geophysical state from Merra2 reanalysis
    - Merra2 (**inst3_3d_asm_Nv)** T(p), q(p) and Psurf used as CLIMCAPS a-priori
  - Creates co-located full geophysical state from ECMWF analysis/forecast
    - T(p) and q(p) used as proxy for truth in off-line evaluations
- System can operate as NUCAPS or CLIMCAPS
  - Namelists are used to define the system, only one code
- Operational code is identical to science code
  - Diagnostics and comparisons to “truth” are simply turned off in operations

* Described, in detail in NOAA/STAR Research Project Plan, 5/19/2004

Model versus Model-independent

- For 20+ years the AIRS community has attempted to make a model-independent system
  - modern data assimilation does an incredible job with T(p)
  - Hypothesis: the statistical step, based on one satellite, does not provide a stable or well characterized a-priori
- Many retrieval systems already use model forecasts
  - Keep that in mind when comparing systems
    - NOAA/MiRS and NOAA/NUCAPS are model-independent
    - Most SFOV approaches are using a model a-priori
  - Use of of NCEP model in NUCAPS is an open discussion
- CLIMCAPS uses Merra2 reanalysis
  - **NOTE: results shown here and similar to those shown in 2005 using GFS as a-priori within AIRS v.4 system**

Why Merra2? (versus forecast models)

- NASA has made commitment to focus on minimizing the temporal discontinuities in Merra-X during the satellite era
- *Merra2 is also available in real time*
- Main complaint about Merra2 is that it is not perfect
  - Errors in Merra2 will be corrected where we have skill
- We will become a "user" of Merra2
  - A lesson learned from NUCAPS: Users force you to look at your product in new ways
- Synergy between NASA sounding and NASA reanalysis science *communities* will
  1. Help improve both CLIMCAPS and Merra2
  2. Enable a better characterization and understanding of the entire Earth system (clouds, q(p), trace gases, etc.)

CLIMCAPS uses the CAMEL land emissivity database

- CAMEL is Combined ASTER & MODIS Emissivity over Land
  - Developed under the NASA MEaSURES program
  - Higher spectral resolution product than used in AIRS v.6
  - Has location dependent uncertainties partitioned for computational errors, temporal, and spatial variance
- CLIMCAPS uses both the emissivity values and uncertainty estimates
  - *Emissivity uncertainty estimate used in IC of all retrieval steps.*
  - Currently use monthly climatology derived from 2008 (the “best” year of the dataset)
- CLIMCAPS uses AIRS v.6 methodology to combine CAMEL land emissivity with an ice model and Masuda ocean model to provide an emissivity value (with uncertainty) globally.

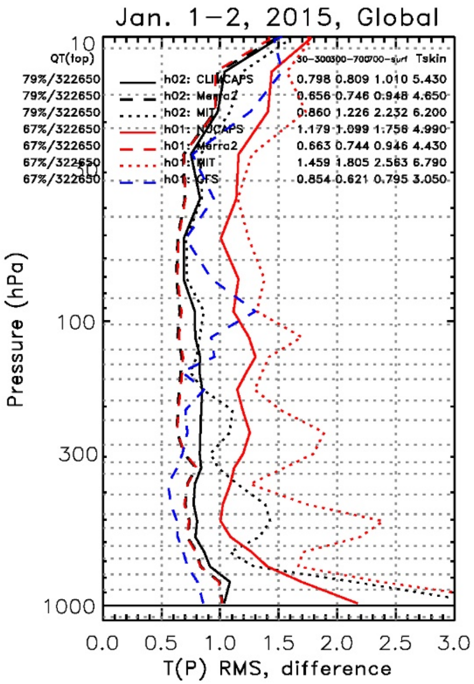
Other new features in CLIMCAPS

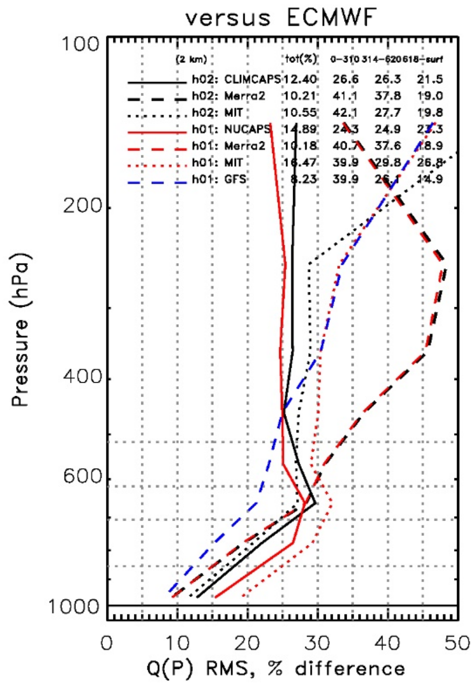
- Improved error due to CO_2
  - NUCAPS over-estimated the uncertainty in CO_2
- Added error estimate of methane within the water retrieval
  - Improves q(p) at ~700 mbar
- Added uncertainty estimate for surface pressure
  - Currently $\delta P_{surf} = 2 + 10*f_{LAND}$
  - In near future will use $dPsurf/dz*SDV_{FOR}(z)$ (dz f/ preprocessor)
- CLIMCAPS propagates the error from one step to the next
  - Goal is to propagate full error covariance, $\delta X \delta X^T$, including $\delta R \delta R^T$ from cloud clearing
  - Infrastructure is in place, code is backward compatible
    - NUCAPS reads a 1-D error estimate and propagates a diagonal uncertainty estimate using an ad-hoc vertical correlation
    - CLIMCAPS reads a global Merra2 uncertainty covariance ($\delta T \delta T^T$, $\delta q \delta q^T$)
    - Other $\delta X \delta X^T$ terms derived from climatological values

Performance of CLIMCAPS (Jan. 1, 2015: Global RMS)

- CLIMCAPS RMS is better than ~1K throughout troposphere
  - 79% yield in BL
- CLIMCAPS T(p) is dramically improved for both coupled and microwave-only ("MIT" steps)
- Retrieval agrees with (does not degrade) Merra2 T(p)
  - Retrieval is optimized to believe radiances, not a-priori, so it will adjust Merra2, if needed
- Retrieval improves Merra2 q(p) above 600 hPa

Similar results were shown in 2005 using GFS as a-priori within the AIRS ST v.4 system

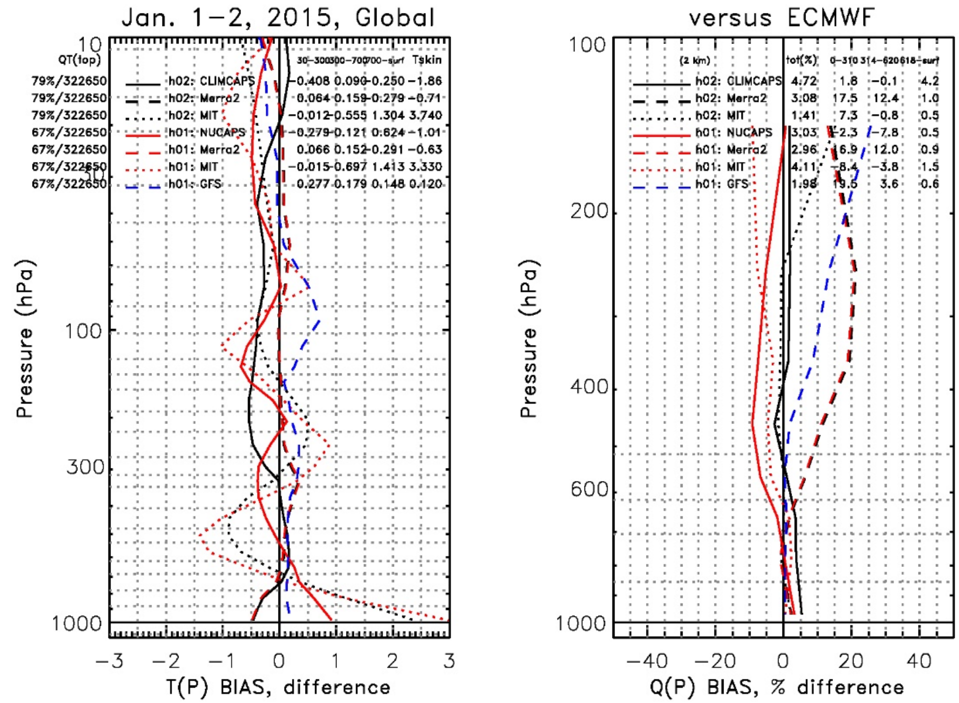




- **CLIMCAPS system (79% yield)**
- **NUCAPS system (67% yield)**
- **GFS (dashed) shown for NUCAPS comparison**
- **Dashed curves are Merra2 for accepted cases (CLIMCAPS, NUCAPS)**
- **Dotted curves are associated microwave only ("MIT") step for CLIMCAPS, NUCAPS**

Performance of CLIMCAPS (Jan. 1, 2015: Global BIAS)

- BIAS (w.r.t. ECMWF) has less vertical structure and is small at lowest layer (0.5K versus 1.0K RMS)
- Microwave-only step has large bias despite using Merra2 as a-priori



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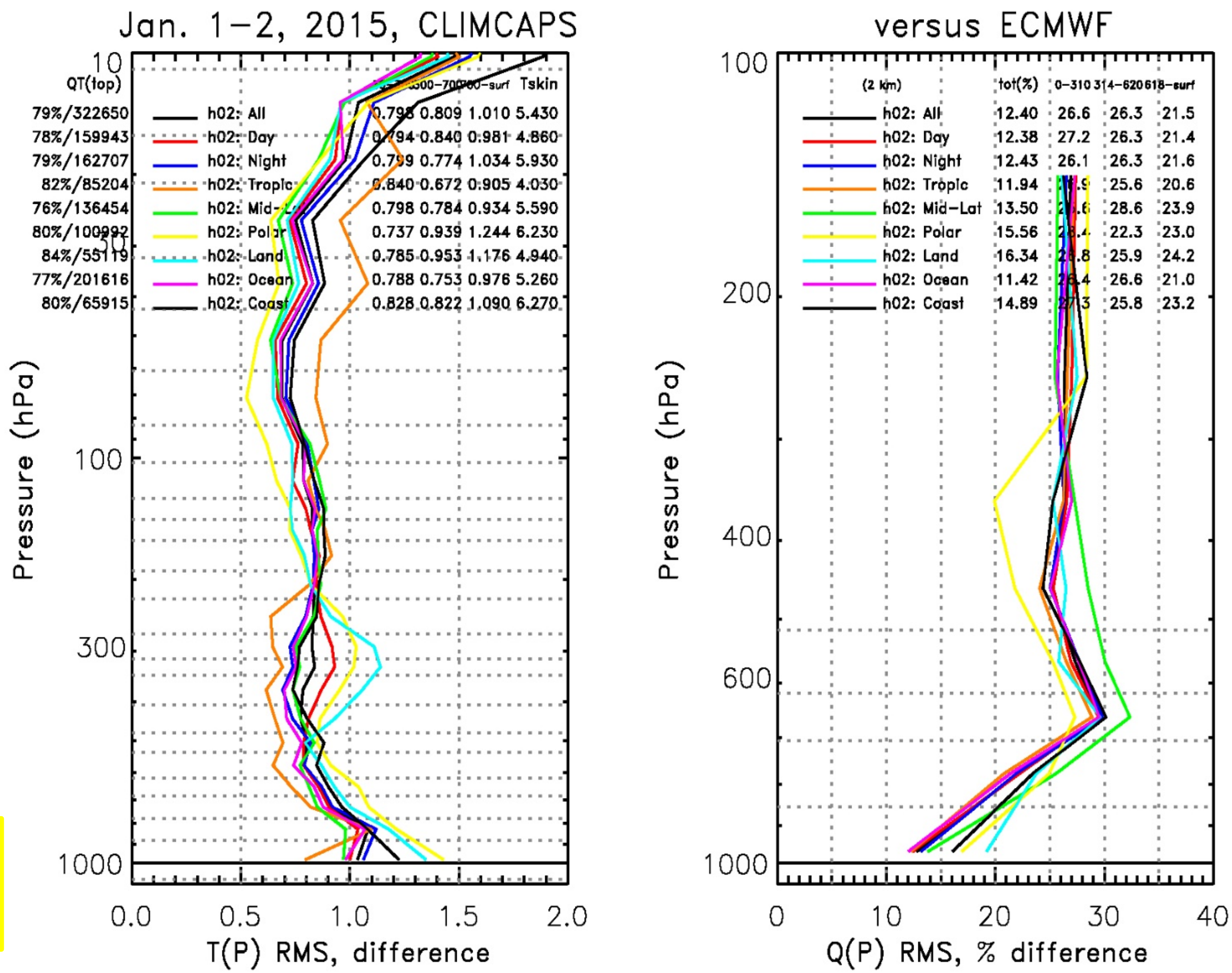
CLIMCAPS statistics for various domains

CLIMCAPS yield varies from 77 to 84% and has similar T(p) and q(p) statistics over many domains

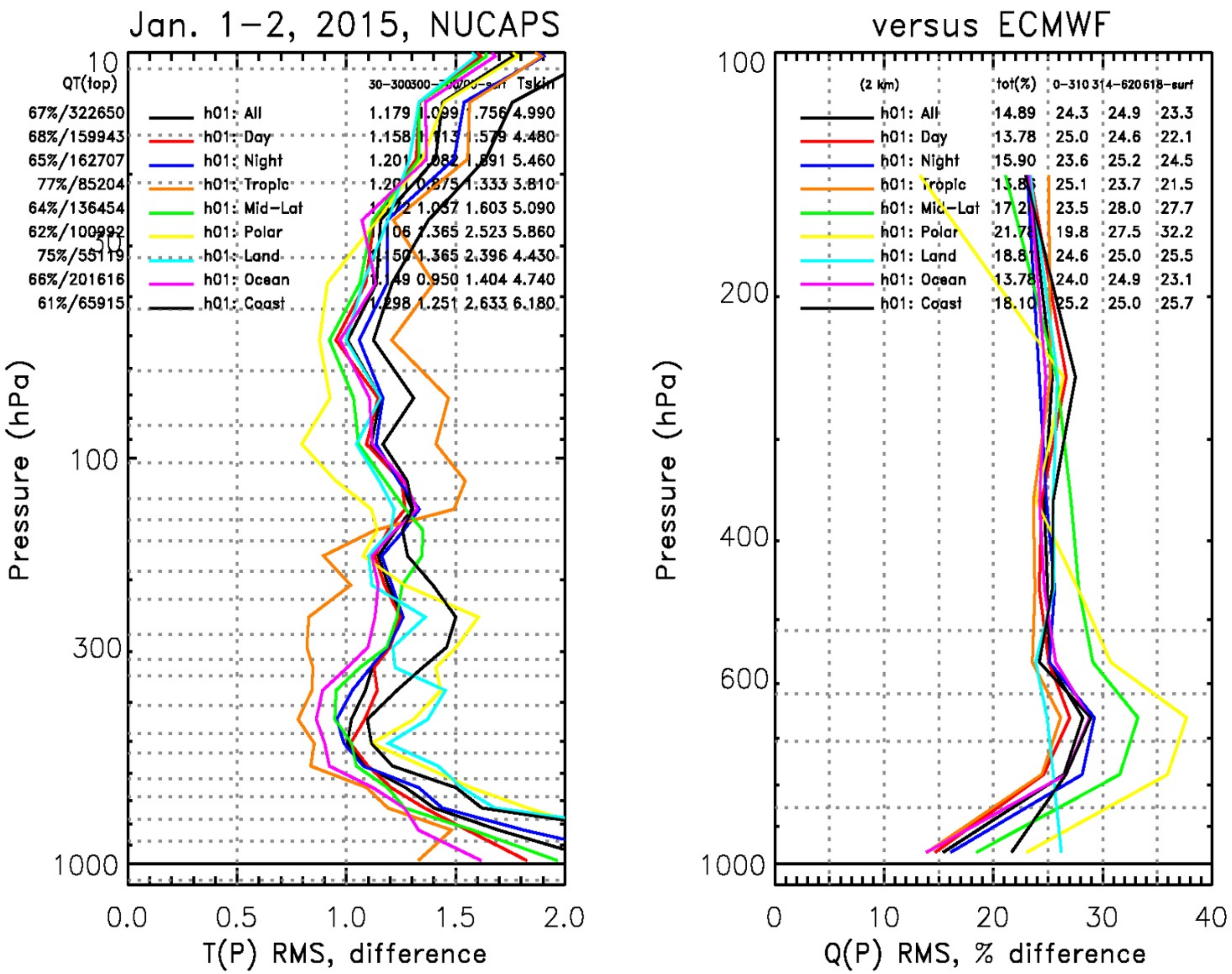


Stability is required for a climate product

NUCAPS statistics for various domains

NUCAPS yield varies from 61% (Coast) to 77% (Topics) with a high variance in T(p) over these domains

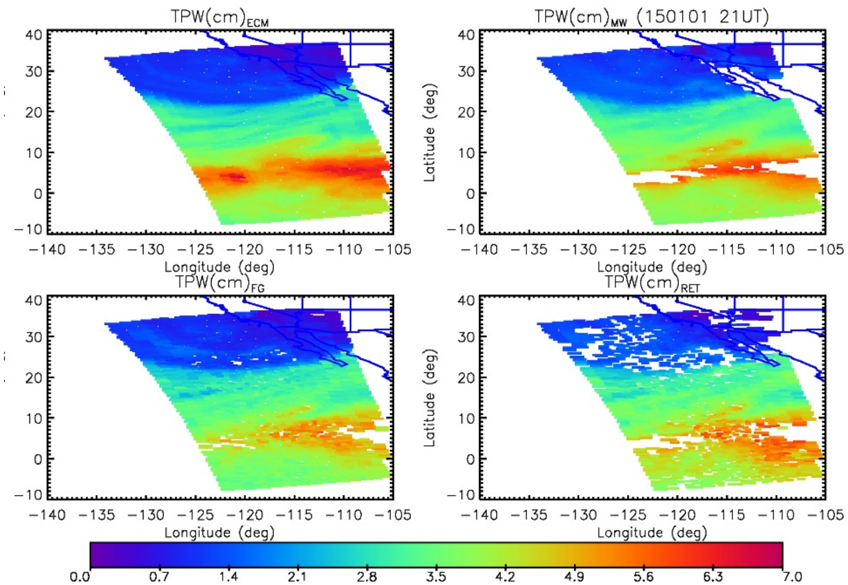
NOTE: Recent NUCAPS upgrade has higher yield, but still has high variance over these domains



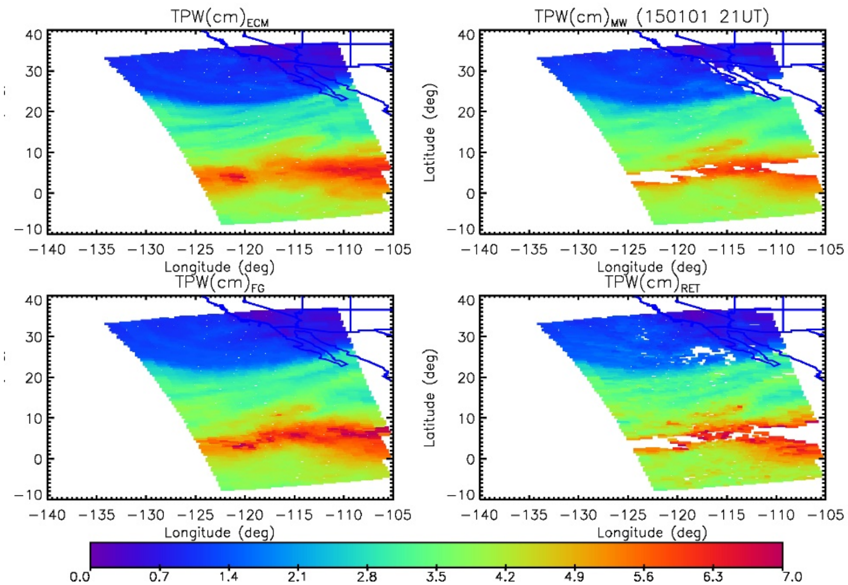
CLIMCAPS has less spatial "speckle"

- Upper left: ECMWF is spatially smooth due to model physics
- Upper right: MIT retrieval is also relatively smooth
- Lower Left: Regression for NUCAPS and Merra2 for CLIMCAPS
- Lower Right: Physical system (believes ~50% of a-priori)

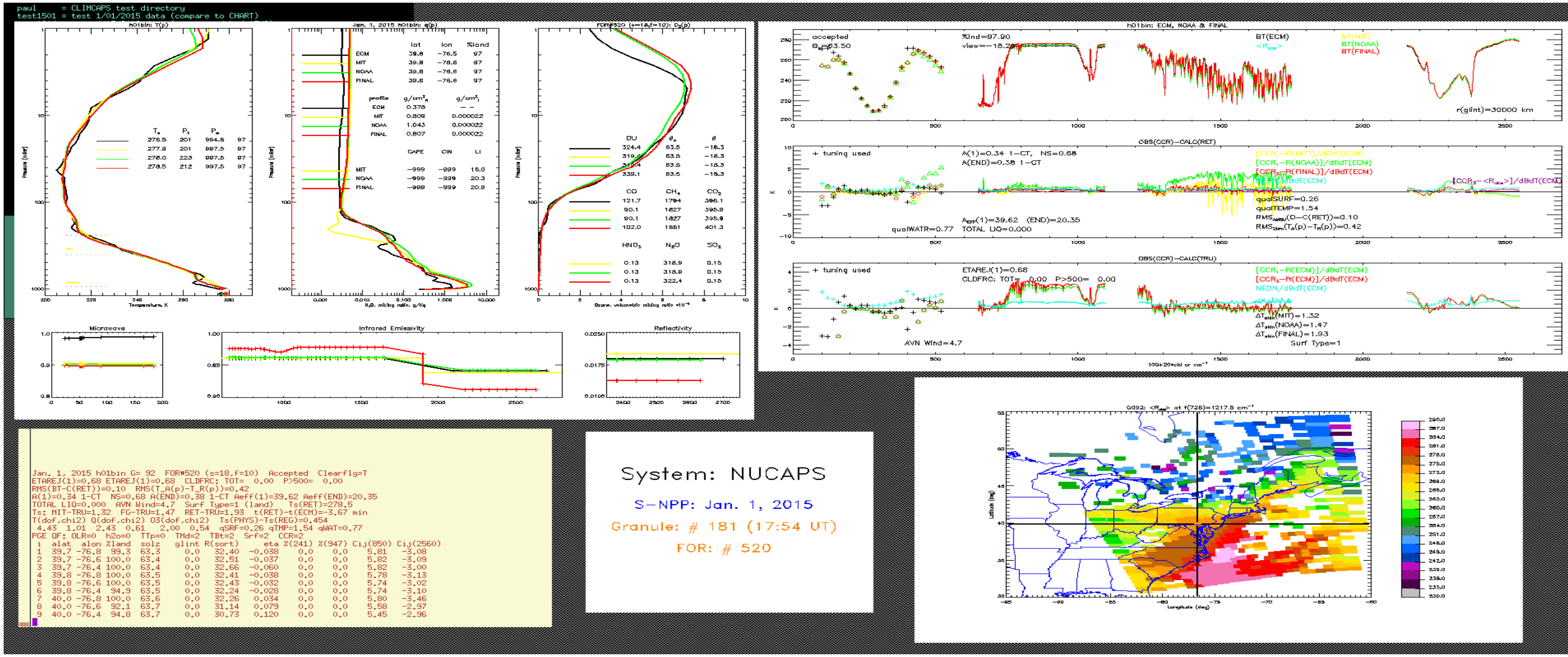
NUCAPS System



CLIMCAPS System



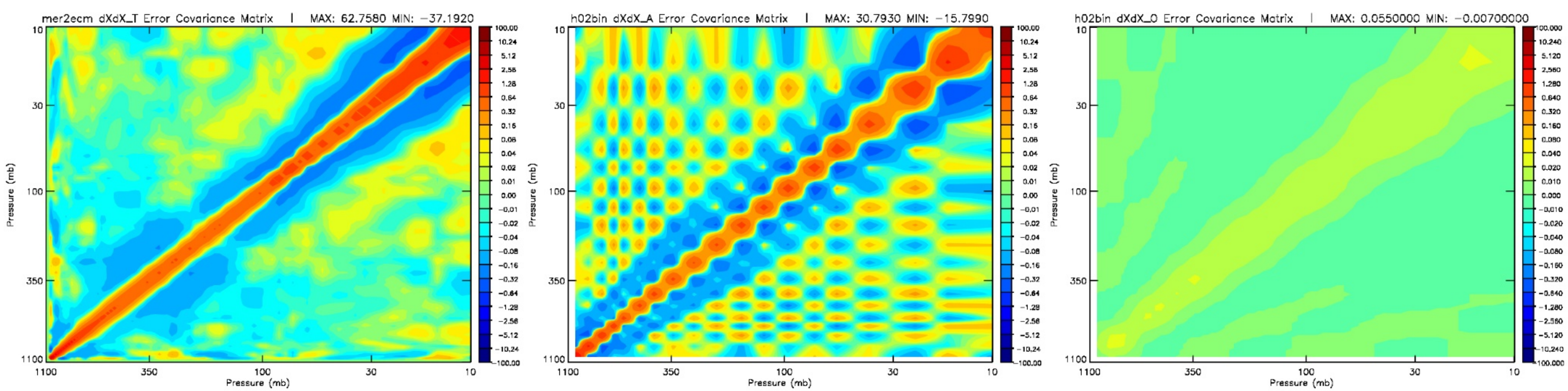
Single Case over USA: NUCAPS versus CLIMCAPS



- Yield of CLIMCAPS allows more cases to be utilized
- Diagnostics show that variability in the regression step causes poorer cloud clearing and causes T(p) to miss an inversion
- NUCAPS q(p) suffers due to poor regression a-priori
- q(p) departures are within null-space (residuals w.r.t. ECMWF unchanged)

Uncertainty covariance, $\delta T \delta T^T$ for this scene

- Error covariance & averaging kernels are related through the a-priori covariance
- Error can be mapped through our trapezoids and SVD transformation such that the amount of the a-priori in our solution can be known and analyzed
- Below is the input error covariance (left panel) and the retrieval error covariance components for the case shown on the previous page.
  - The middle panel is how much of the a-priori leaks through (~50%)
  - The far right panel is the error covariance of the measurements (very low due to $\lambda_c=(0.2)^2$).
- Most of the scene-to-scene variability in the error will be from the fraction of the a-priori that leaks through – ***and that is a strong function of cloud homogeneity***



COV(Merra2-ECMWF)

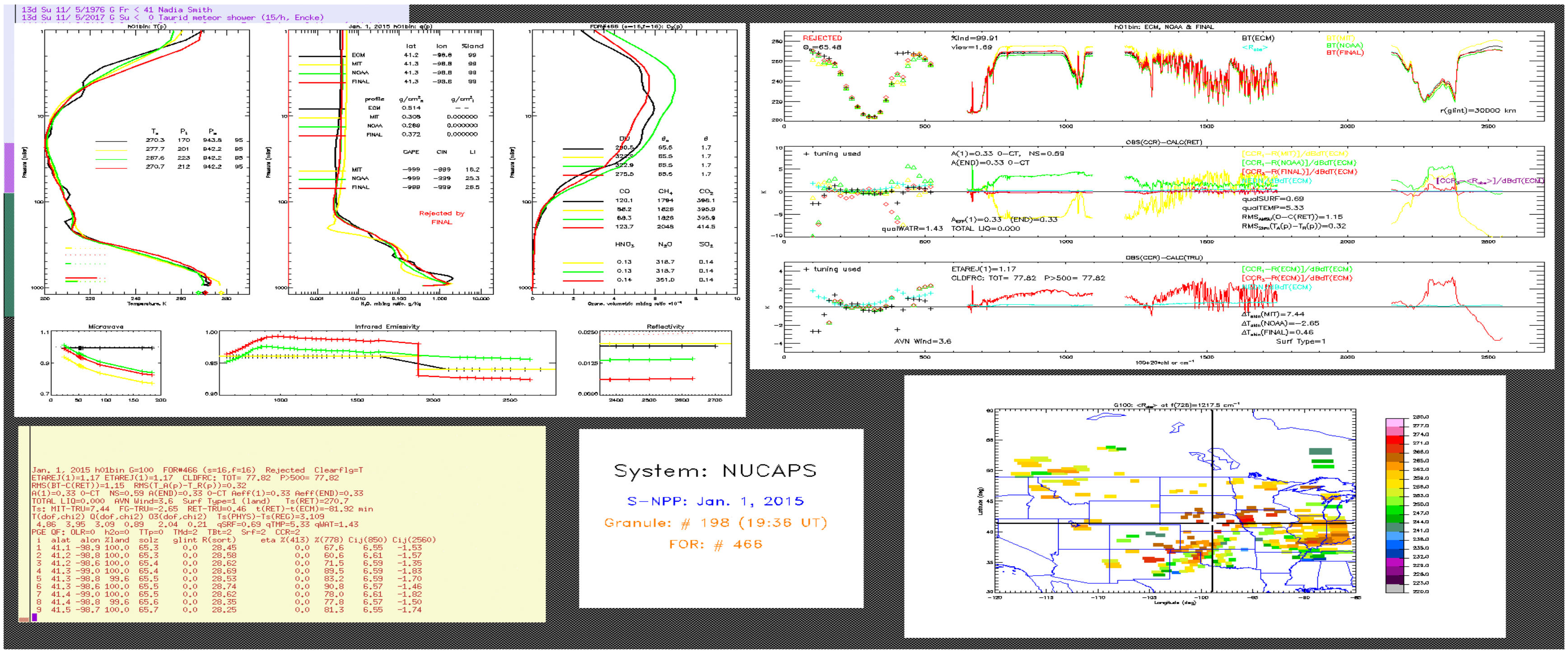
$$G_{L,L} \equiv F_{L,j} \cdot U_{j,k} \cdot (I_{k,k} - \phi_{k,k}) \cdot U^T_{k,j} \cdot F^{-1}_{j,L}$$

$$\left(\delta T \delta T^T_{L,L}\right)^A = G_{L,L} \cdot \left(\delta T \delta T^T_{L,L}\right)^{M-E} \cdot G^T_{L,L}$$

$$\left(\delta T \delta T^T_{L,L}\right)^O = Z_{L,k} \cdot \left(\frac{1}{\lambda_{k,k}}\right) \cdot Z^T_{k,L}$$

$$Z_{L,k} \equiv F_{L,j} \cdot U_{j,k} \cdot \phi_{k,k}$$

Another case over USA: NUCAPS versus CLIMCAPS

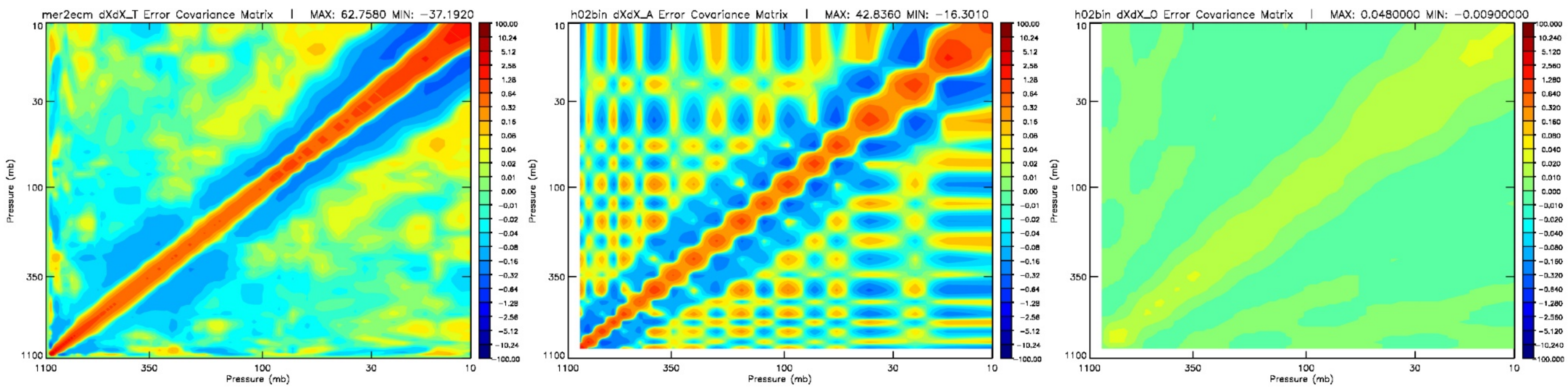


- Yield of CLIMCAPS allows many more cases to be utilized
- Diagnostics show that CLIMCAPS q(p) moves away from Merra2 and towards ECMWF.
- NUCAPS q(p) suffered due to poor regression a-priori
- Both answers are within null-space as residuals w.r.t. ECMWF are the same

Minimal sampling bias is required for a climate product (i.e., should relax to a-priori)

Error covariance of the case shown on previous slide

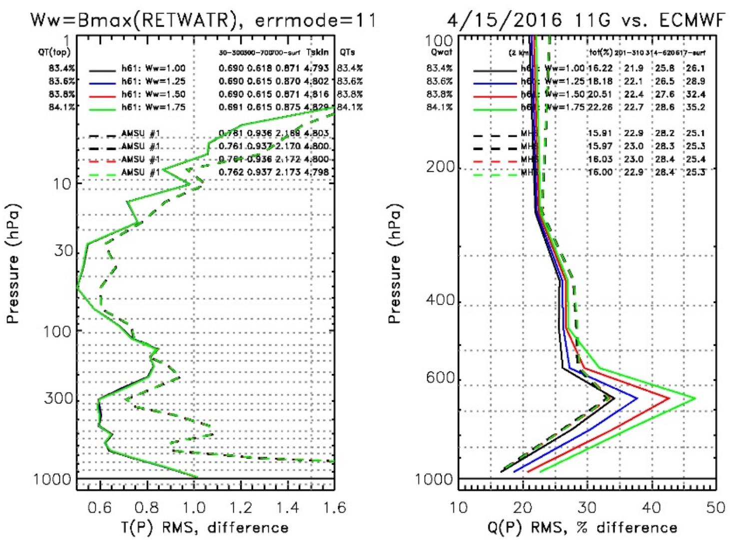
- This scene has similar information content to the previous example and, therefore the error covariances is similar.
- However, if you blink with the previous example there are subtle differences in the correlation of the a-priori
- There is a tremendous amount to be learned from analysis of error covariance including what structures, present in Merra2, we believe
  - and how much our trapezoids have distorted the state
  - e.g., can use error estimates to make rational decisions on the utility of other basis functions (triangles, or orthogonal functions)

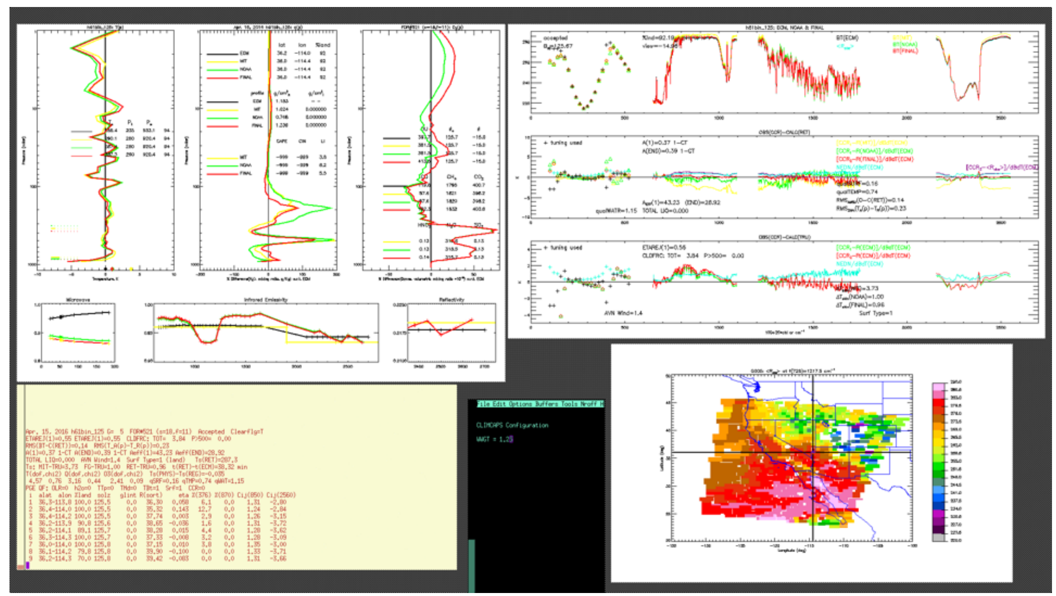


Characterization of error is a requirement for a climate product

Optimization Runs
Can we increase S/N?

- We varied S/N threshold, from 1.0 to 1/1.75
- RMS w.r.t. ECMWF degraded with decreased damping
  - many individual cases improved, but others are degrade
  - Open question as to whether these null-space “errors” are real, or not
  - Aqua & NUCAPS validation has provided numerous high quality sondes in extreme events





Note: these kinds of “optimization” runs demonstrate that the “ideal” retrieval with a good a-priori is one that is heavily damped

Characterizing response to extreme events is necessary for a climate product

Analysis of CLIMCAPS: Retrieval is over-damped

- Confirms comments made previously by Bill Irion
  - It can be traced to large cloud clearing errors
  - Some of this is due to lack of instrument information content (i.e., large null space in lower troposphere) in nearly homogeneous cloud environments
    - But our information content is not zero below the clouds
- CLIMCAPS system has a plethora of diagnostics
  - Cloud clearing is sensitive to assumptions about $\delta X \delta X^T$
    - Iteration of cloud clearing induces a cold bias feedback
  - CLIMCAPS has only one cloud clearing step
    - AIRS v.6 has 4 iterations
  - We can now remove an inflated error term
    - was necessary to mitigate the cold bias feedback
    - Will evaluate this next week

Stable response to clouds is necessary for a climate product

The Value of CLIMCAPS

- The CLIMCAPS T(p) product is not independent of Merra2
  - Departures mostly reflect a “correction” to our satellite time and line of sight observation geometry
  - Most of the differences are in our null-space
- But Merra2 T(p) stabilizes our CrIS+ATMS cloud clearing and temperature retrieval
  - Spatial and vertical structures are more reasonable since they satisfy model dynamics, continuity, and thermodynamics
  - Yield is significantly higher, especially in lower troposphere
  - T(p) statistics are dramatically improved
- The value of CLIMCAPS will be the impact of the knowledge of propagated error on the downstream steps: q(p), O_3(p), CO, CH_4, CO_2, HNO_3, N_2O, SO_2, etc.
  - We now have a stable a-priori (T(p), q(p), and $\varepsilon(\upsilon)$) to retrieve these constituent products
  - We are using simple trace gas climatologies.
    - All structure in our product comes from the radiances

Infrared constituent products are both direct and indirect climate products

Status of the CLIMCAPS Development

- The preprocessor is complete & running at JPL/SIPS
  - Used by both CLIMCAPS and CHART (Susskind Alg.)
  - Gracefully handles lost ATMS granules, level-1 QC, etc.
  - Works with Nominal (NSR) or Full Spectral Resolution (FSR)
  - Takes ~4 CPU-hours per day of S-NPP data to run
- CLIMCAPS science code is running on JPL/SIPS
  - Takes ~17 CPU-hours per day of S-NPP data to run
    - ~10% more than NUCAPS (due to 100x100 eigenvector decomposition) in T(p) and q(p) steps
  - Preliminary results are promising.
  - We have propagated error through T(p) retrieval and used it in the q(p) retrieval (3 eigenvectors).
  - We have $\delta q \delta q^T$ covariance ready to install.
  - Merra2 can be used when cloud clearing fails; however, we output the failed CLIMCAPS product so that it can be evaluated
  - We need to do additional work on compression of error covariance for the output file – will be focus of the next couple months.

Final Thoughts

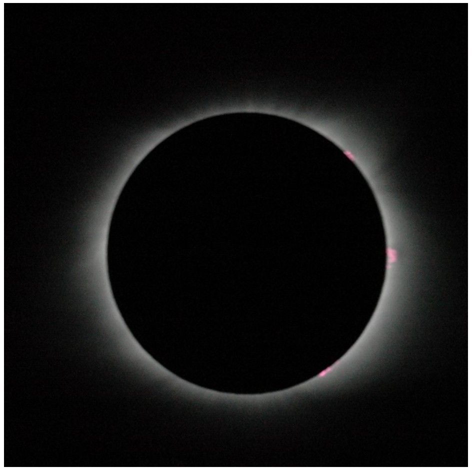
- There will always more work to do
  - CLIMCAPS cloud clearing & T(p) products are a significant improvement over statistical a-priori with iterative cloud clearing
  - SIPS should begin ***processing*** of 8 months of CLIMCAPS in December
    - I encourage ***independent evaluation*** by SIPS and others
- CLIMCAPS can use either NSR and FSR CrIS radiances
  - NUCAPS is already operational at NOAA with FSR
    - we have everything ready to go (SARTA, optimization, instrument noise files, etc.)
- The "C" in CLIMCAPS is important.
  - The CLIMCAPS code *is* the NUCAPS code
    - I have trained 20+ scientists with the NUCAPS theory (e.g., see rs_notes.pdf at **http://goo.gl/pJfYAo**) , the code itself, and the environment necessary to run it
    - The weather community has embraced and understands NUCAPS
  - Within our ROSES proposal we have plans to engage the climate community in the same manner as we did with the weather community

Community collaboration is necessary for acceptance of a climate product

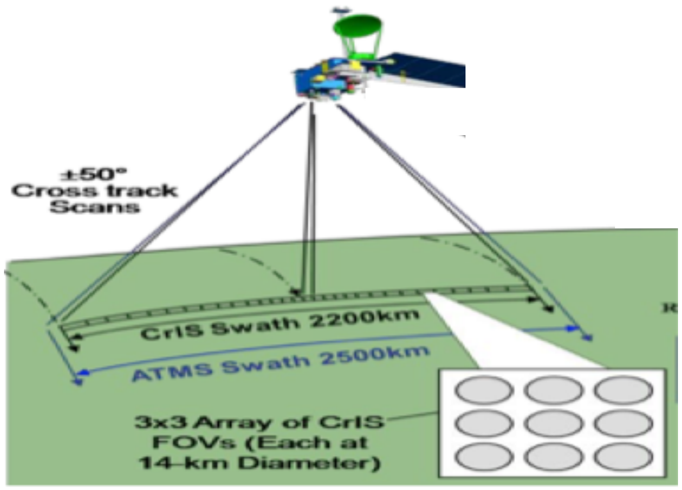
THANK YOU FOR YOUR ATTENTION

QUESTIONS?

Aug. 21, 2017 Eclipse in Dubois, Wyoming

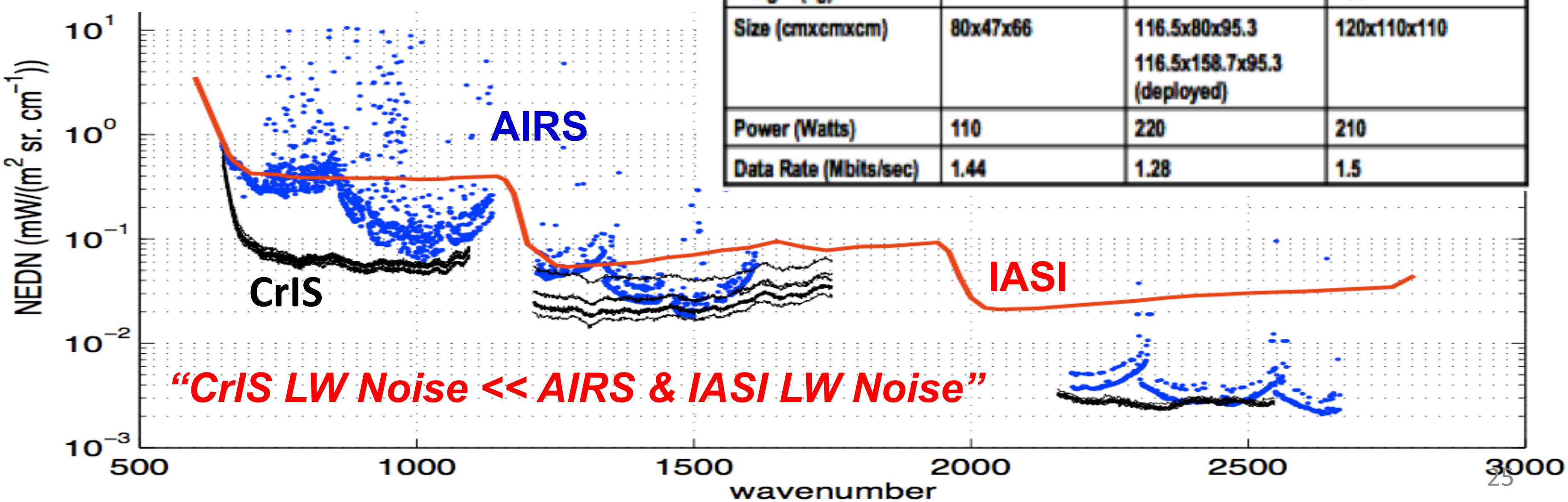


Cross-Track Infrared Sounder (CrIS)



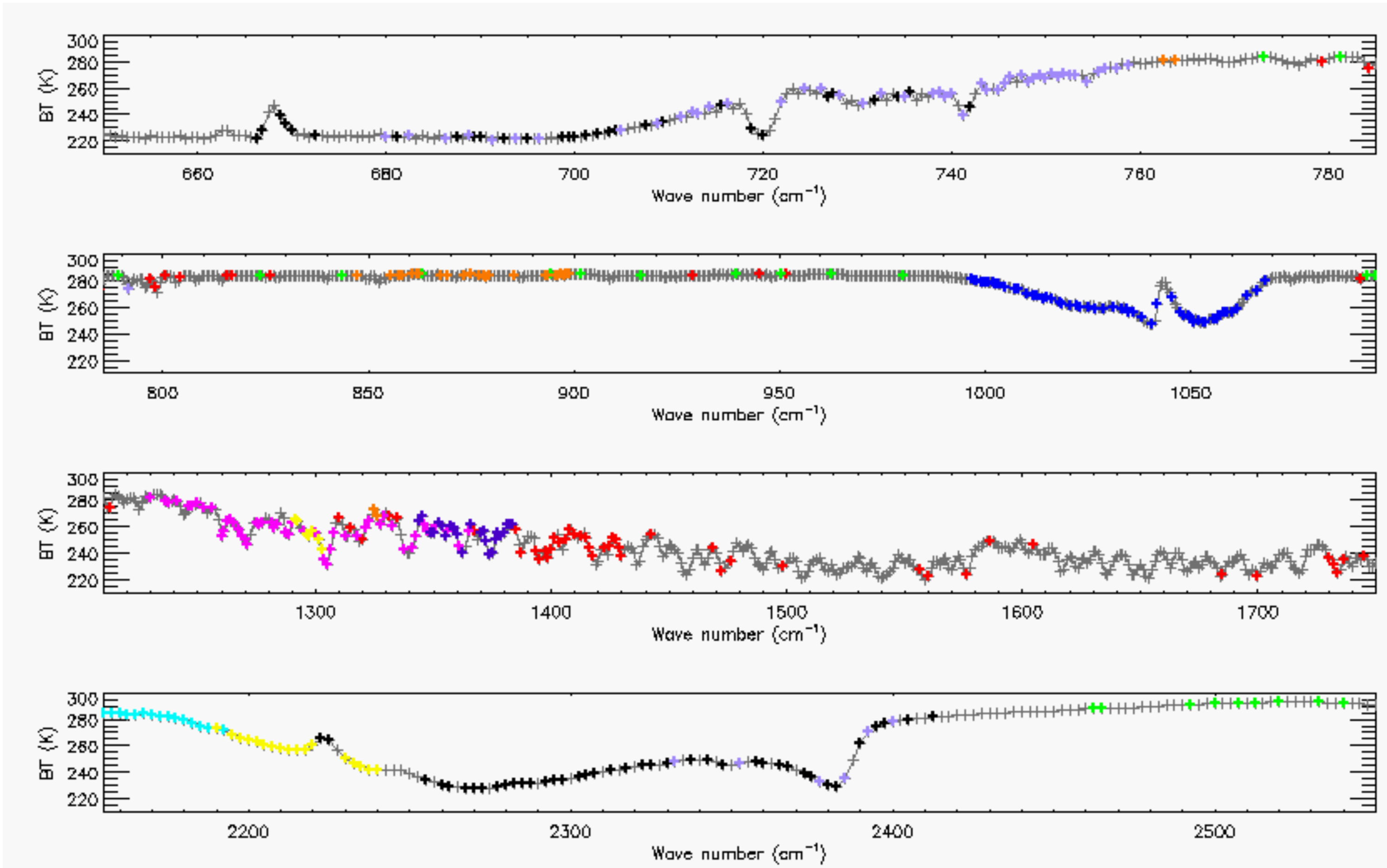
- Michelson Interferometer
- Spectral range: 650 to 2550 cm^{-1}
- Three bands, each a 3 x 3 HdCdTe focal plane
- Cooling: passive, 4-stages, 85K
- Radiometric Calibration: 310 K Blackbody and cold space view
- Low noise, NEDT ranges from 0.05 K to 0. 5 K

	CrIS (on NPP)	AIRS (on EOS Aqua)	IASI (on MetOp)
Weight (kg)	147	177	236
Size (cmxcmxcm)	80x47x66	116.5x80x95.3 116.5x158.7x95.3 (deployed)	120x110x110
Power (Watts)	110	220	210
Data Rate (Mbits/sec)	1.44	1.28	1.5



NOAA NESDIS NSR CrIS channel selection (399/1305 channels)

EDR	#chns
Temp	87
Surf	24
H2O	62
O3	53
CO	27
CH4	54
N2O	24
SO2	54
HNO3	28
CO2	53

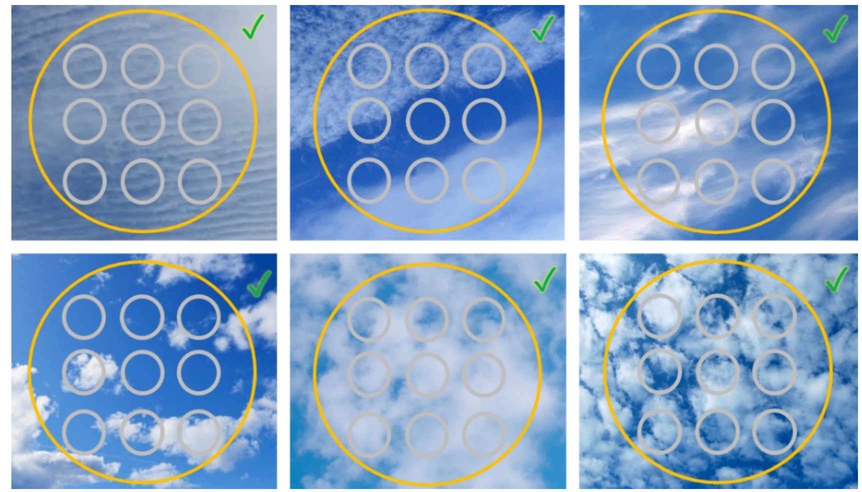


REF: A. Gambacorta and C. Barnet., Methodology and information content of the NOAA NESDIS operational channel selection for the Cross-Track Infrared Sounder (CrIS), IEEE, Vol. 51, Issue 6, 2013

NUCAPS uses cloud clearing to retrieve in partially cloudy scenes

Cloud Clearing **succeeds** when NUCAPS footprint has **cloud variability**; i.e. when the CrIS footprints have variable cloud fractions

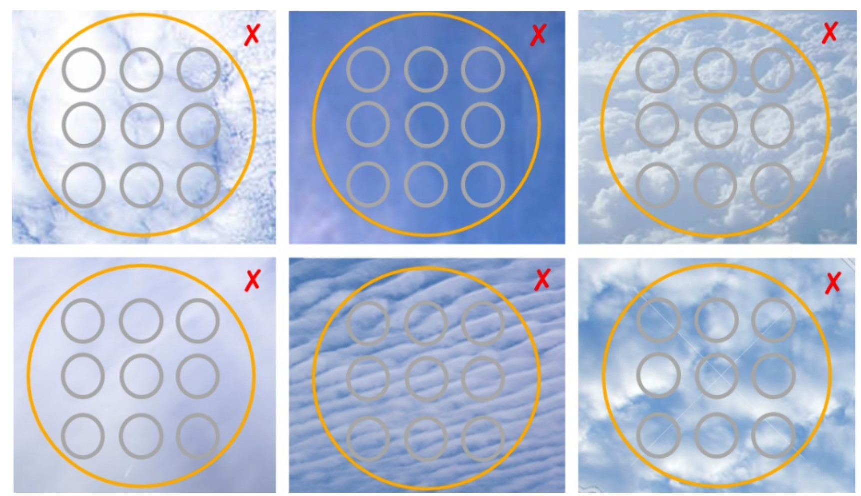
~2% probability a CrIS FOV is clear
~5% probability a CrIS FOR is clear
But ~70-80% of scenes can be cloud cleared
→ even if no single FOV is clear



Cloud Clearing **FAILS** when NUCAPS footprint is **uniformly cloudy**, *i.e.* when each CrIS FOV has the same cloud fraction

Scene does not have to be overcast

Even a small amount of <u>*uniform*</u> clouds needs to be rejected



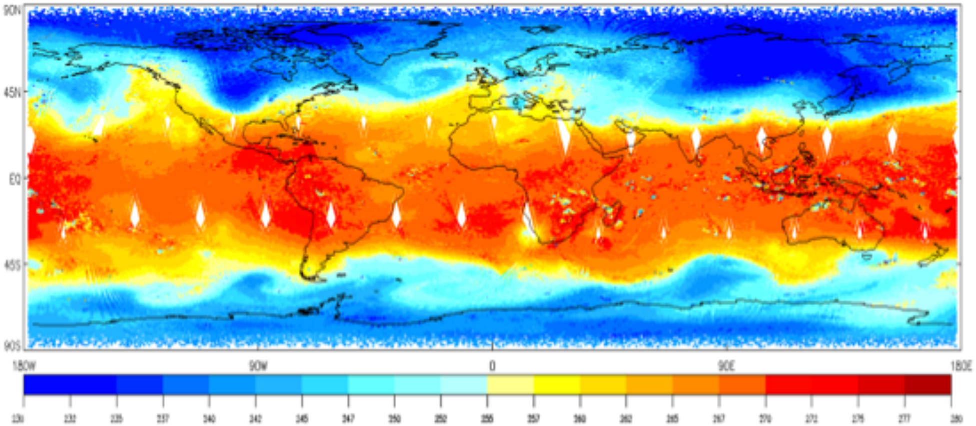
NUCAPS field of regard (FOR) =
set of 9 CrIS field of view (FOV)

Operational and experimental NUCAPS retrieval products

Retrieval Product	Spectral Region Used (cm^{-1})
Cloud Clearing Parameters (4 *linear* parameters)	660 – 750 2200 – 2400
Cloud fraction and Cloud Top Pressure and Temperature	660 - 750
Surface temperature (LST, SST), emissivity and solar reflectivity	800 – 950, 1210 – 1230, 2400 - 2550
Temperature, T(p)	660 - 750 2200 - 2400
Water Vapor, q(p)	780 – 1090 1200 - 1750
Ozone, O_3(p)	990 – 1070
Carbon Monoxide, CO(p)	2155 – 2220
Methane, CH_4(p)	1220 - 1350
Carbon Dioxide, CO_2(p)	660 – 760, 980, 2200 - 2400
Nitrous Oxide, N_2O(p)	1290 - 1300 2190 - 2240
Nitric Acid, HNO_3(p)	760 - 1320
Sulfur, Dioxide, SO_2(p)	1343 - 1383

NUCAPS Temperature retrieval @ 500mb

(January 5th 2014 Polar Vortex Anomaly)



NUCAPS Ozone retrieval @ 500mb