# Twenty Years of Infrared Hyperspectral Satellite Measurements

From Spectroscopy to Climate Workshop
Princeton Center for Theoretical Sciences


Sergio DeSouza-Machado[1]


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[1] UMBC JCET

# Thanks


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# Outline

- Some history
- What is a hyperspectral sounder
  - Instruments : AIRS, CrIS, IASI
- What is needed to use hyperspectral data : spectroscopy, radiative transfer, retrievals
  - 2380-2400 $cm^{-1}$ very important for T(z) remote sensing
  - we have worked very hard to improve/use 4 um NLTE, $CO_2$ line mixing , $CO_2$/WV/N2 continuum
  - cloud clearing 3x3 → single footprint, AI?
- Value : weather (data assimilation), atmospheric composition, climate, applications
- Observational record for climate studies
  - Hard to do physical inversions (cloud contamination, spectroscopy/RTA inaccuracies in fast models), instrument problems
  - so hourly L2 is cumbersome to re-process, has problems, → monthly L3 has problems
  - We focus on using accurate psuedo LBL codes, to do inversions of *radiance* trends and anomalies of radiances gridded in space and time
- Future and continuity
  - CHIRP : Climate Hyperspectral Infrared Product AIRS+CriS 2002/09 → 2040

# Short History

- Sit on a hilltop/crow nest → instruments on board balloons/kites/carrier pigeons → WW1,2 aircraft
- Technology improved - telescopes, lenses, cameras, thermometers, barometers, hygrometers
- V2 rockets (1946-1950s), Korean War, Sputnik (1957) : can put crude cameras/instruments on board satellites
- 1960 : TIROS (Television IR Operational Satellite) $\sim$ 1 year lifetimes, 5 channels (6-6.5,8-12,8-30 $\mu m$, plus NIR and VIS), 55 km footprint
- HIRS (1970s) 12-20 chan, 10 km footprint, 3-10 $cm^{-1}$ width
- Now regularly launch satellites with new technology instruments : sonar, radar, lidar, visible imagers, microwave and infrared sounders
- For the most part detected radiation needs to be converted into physical variables (temperature (K), water vapor and trace gas amounts (g/g), cloud amounts (loading g/m2, eff particle size um, cloud top/bottom mb) etc. Inversions are NOT easy

# Hyperspectral (or Advanced) Infrared Sounders

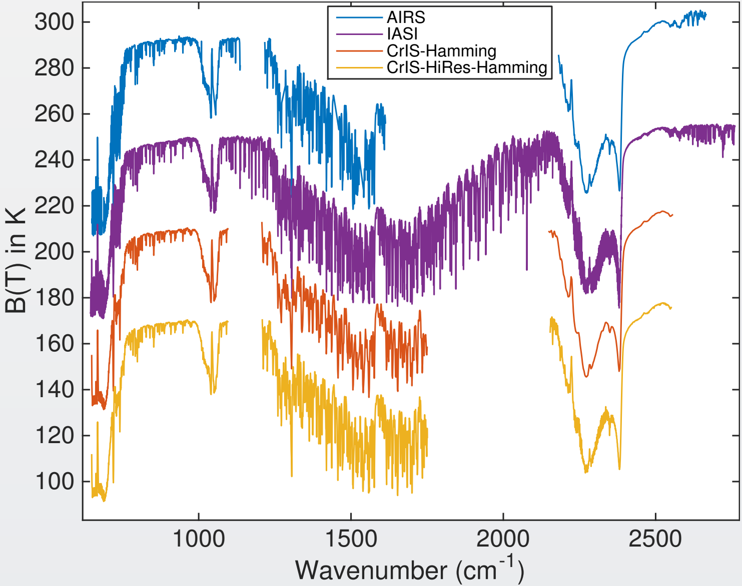
- Thousands of high spectral resolution, low noise channels spanning infrared
- Weighting functions gives high vertical resolution atmospheric sounding information which captures T(z) from surface to stratosphere ($\sim$ 1 km), WV(z) from surface to UT/LS, $O_3$, $CO_2$, $CH_4$ etc
- Radiance Data assimilation into numerical weather prediction (NWP) models improves medium range forecast skill
- Typically only in Polar Orbiting Sun Synchronous Orbits (two daily views of Planet)
- Plan to put into Geostationary Satellite as well (GEOX??)
- Trace Gas Studies/Atmospheric Composition
- Climate Process Studies and Radiance Trending
- Examples
  - Atmospheric Infrared Sounder (AIRS) NASA Aqua 2002/09 - 2022?
  - Infrared Atmospheric Sounding Interferometer (IASI) on EUMETSAT Metop series 2007 -
  - Cross-track Infrared Sounder (CrIS) on Suomi-NPP (SNPP) and Joint Polar Satellite System (JPSS) series 2012 - 2040

## Satellite Measurements: ~12-km footprints, full coverage 2X/day

| | | |
|---|---|---|
| AIRS | 2002 - 202X?? | 1:30 orbit |
| CrIS | 2012 - 204X? | 1:30 orbit |
| 1 SNPP-CrIS, 4 on JPSS | | |
| IASI | 2007 - 204X? | 9:30 orbit |
| 3 on METOP-A series | | |
| 3 on METOP-SG series (2024) | | |
| (IASI-1 CDR available on request) | | |
| CHIRP (AIRS+CrIS) | 2002 - 204X | 1:30 orbit |
| "Virtual" L1c for climate | | |

Each sensor produces ~2-3 million observations (spectra) daily.
15 km footprint at nadir, $\times$ 2 daily coverage of Earth (more views over higher latitudes than equator), 16 day repeat cycle

# Example BT(K) Spectra



# Some Impacts

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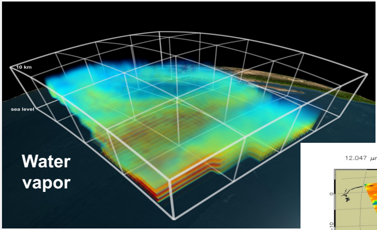
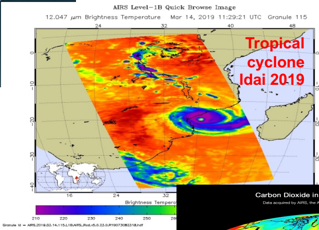
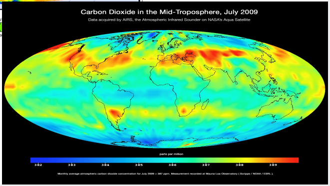
## Atmospheric Infrared Sounder AIRS/AMSU/HSB




First measurements of the three-dimensional structure of temperature and water vapor from a global perspective




AIRS radically improved global weather forecasts




First maps of the global meandering of carbon dioxide

# Some Impacts

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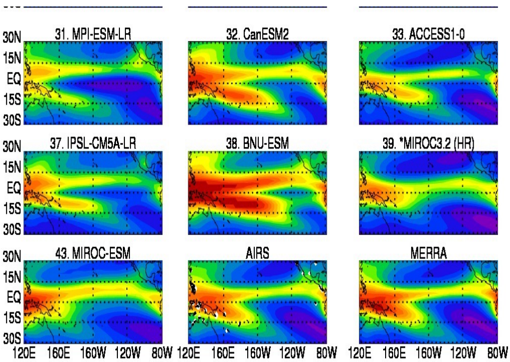
## AIRS and Climate Model Validation




500 hPa humidity from AIRS and CMIP climate models

AIRS data was used extensively to evaluate climate models from the latest Climate Model Intercomparison Project (CMIP6)

These models are the foundation for the most recent IPCC Assessment Report (AR6)

AIRS data and papers were cited numerous times in the latest IPCC

Tian and co-authors

# OLR in the IR → Far-IR

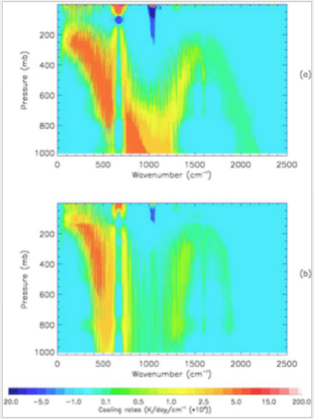
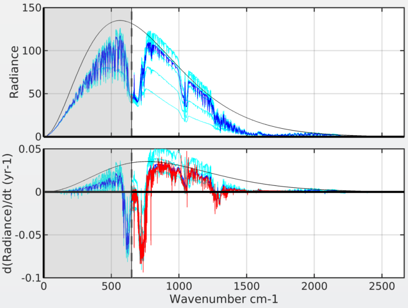



**Figure 5.** Cooling rate across the infrared and from the surface to TOA, in units of K $d^{-1}$ $(cm^{-1})^{-1}$. (a) Tropical and (b) subarctic winter standard atmospheres (reprinted from *Brindley and Harries* [1998], copyright 1998, with permission from Elsevier).

- Far-IR WV emission dominates atmospheric cooling, esp. in descending tropical regions
- AIRS observed mid-IR WV has sensitivity where (WV) OLR is large in far-IR
- Allows computation of feedbacks from AIRS retrievals using computed OLR driven by mid-IR WV retrievals

# Radiance Spectra and rates (synthetic and observed)



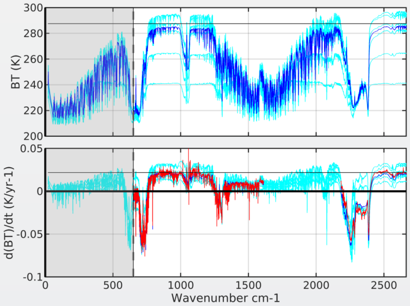

6 average profiles : Tropical Ocean/Land, MidLat Ocean/Land, Polar Ocean/Land (from ERA5)

*Flux under AIRS/full curve ~ 148, 257 W/m2, Ratio ~ 0.58*

*$\Delta$ OLR ~ 0.028 W/m2/yr : FIR = 0.007, 15um = -0.013, window = 0.034 W/m2/yr*

- Notice the overlay of observed vs computed radiance trends!
- Cos wgt Mean surf temp, $\Delta$ surf temp = 287 K,0.022 K/yr
- 640 -2780 $cm^{-1}$: hyperspectral sounder channels
- 792 $cm^{-1}$: 792 $CO_2$ Q branch (2.2ppmv → 0.06 K/year)
- 1305 $cm^{-1}$: $CH_4$ (5 ppb/yr)
- 1000 $cm^{-1}$: O3
- AIRS see UT and some LS WV, so can “account” for changes seen by FIR instruments
- No clouds in these simulations

# BT Spectra and rates (synthetic and observed)




6 average profiles : Tropical Ocean/Land, MidLat Ocean/Land, Polar Ocean/Land (from ERA5)

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# Radiative Transfer codes : Accuracy vs Speed

**Line by line codes : accuracy**

- Use latest HITRAN/GEISA databases; accurate; too slow for operational use
- GENLN2 (Dave Edwards) - 15 um $CO_2$ line mixing from L.Strow
- LBLRTM (AER) WV,N2/O2/other gases continuum, $CO_2$/$CH_4$ line mixing, spans MW to UV
- kCARTA (UMBC) *HITRAN (2020), MT-CKD 3.2,$CO_2$/$CH_4$ linemixing from LBLRTM, 605-2830 $cm^{-1}$ at 0.0025 $cm^{-1}$ resolution (25 sec), 15-44000 $cm^{-1}$ (5 min), jacobians, fluxes, scattering*

**Fast Models : speed**

- Parametrized fast codes for clear sky cloud clearing retrievals
- We use 49 regression profiles to span a variety of Earth climates; ECMWF has eg 25000
- SARTA (UMBC) *used by NASA and NOAA for operational L2 retrievals of AIRS/CrIS, IASI*
- PCRTM (NASA Langley)
- RTTOVS (ECMWF) Data Assimilation
- Sigma IASI (U. of Basilicata, Italy)

# Radiative Transfer Models (con'd)

**Spectroscopy**

- HITRAN released every 4 years
- H2020 : self consistent changes to O3 line intensities (MW to UV) $\Delta BT(K) \sim 0.5K$ at 10 um
- Uncertainty estimates : $\delta(BT) \sim$ 0.2 K at TOA
- Line mixing models; speed dependent Voigt line shapes used in other spectral regions
- AER : new WV continuum in Fall 2022 (TIR region); H2020 $CO_2/CH_4$ linemixing
- GEISA database (France) is very similar to HITRAN

**Non local thermodynamic equilibrium**

- NLTE mostly affects the 4.3 um $CO_2$ band (nadir sounding)
- Manuel Lopez Puertas (Granada, Spain) has developed models upper atmosphere NLTE vibrational temperatures
- UMBC developed a fast model using this database
- We don't worry too much about strat/meso temperatures and atmospheric concentrations (cannot see with nadir sounders)

# Impact of Spectral Uncertainties (Δ (BT) at TOA)

**Perturbations to**
GEISA vs HITRAN, wavenumber unc, pressure line shift unc

→ ≤ 0.1 K RMS differences

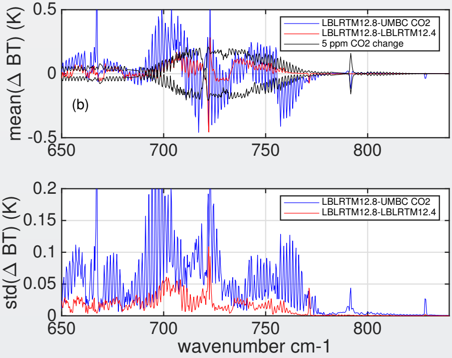
**Spectroscopic Database**
LBLTMv12.8 15 $\mu m$ $CO_2$ line mixing

versus

LBLRTM 12.4 (red) UMBCLBL (blue)

But integral over wavenumber

should give similar fluxes



# Radiative Transfer Models (con'd)

**Surface properties**

- Ocean emissivity : Masuda model (1988,2006) $\epsilon(\nu, wspeed)$
- Land Emissivity : Dan Zhou (NASA Langley) and CAMEL (U. Wisc) $\epsilon(\nu, YY/MM)$

**Scattering**

- DISORT (Stamnes et. al. 1988) : Very accurate, but slow
- Parameterization for LongWave Scattering (Chou et. al 1999) : Very fast, about 2 K errors
- PCLSAM fix (Tang. et. al 2018) : Needs more work

**Clouds and Aerosols (dme $\geq$ 3 um)**

- Complex cloud models (Maximum Random Overlap) give smooth heating profiles, multiple sub pixels are computationally costly
- Simple cloud models (TwoSlab) are fast and quite accurate, spikes at cloud slab boundaries
- RRTM (AER) has in-built fast RTA for flux calculations, handles scattering, 3-4 gaussian angles
- ecRad (Robin Hogan, ECMWF) developed flux model for ECWMF

# Operational Retrievals

### Typical Hyperspectral Sounder

- Atmospheric Infrared Sounder, operational since 2002/09
- Diffraction grating instrument, 2378 channels, 500 pristine channels (Strow/Machado AMT 2018) of resolution about 0.5-2 cm-1, 15 km diameter footprint
- 1.30 am/pm equator crossing time, twice daily views of Earth, 16 day repeat cycle
- 90 xtrack x 135 atrack spectra every 6 minutes
- Roughly 2.92 million allsky spectra daily x 20 years!

### Typical Operational Retrieval

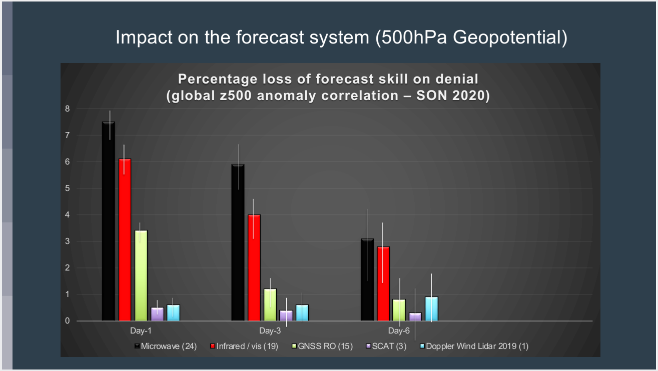
- Cloud clearing process
  - reduces spatial resolution from 15 km to 3x3 or 45 km
  - "increases" spectral noise, and hence retrieval uncertainty
  - fails when scenes are uniform eg MBL, dust, clear
- T(z), WV(z), surface temp, trace gases, clouds, emissivity
- AIRS v7 : neural network first guess, 2 sec/FOR, Lots of QA,
- NOAA CLIMCAPS MERRA2 first guess, simpler QA, 0.7 sec/FOR
- Single Footprint? Artificial Intelligence?

# Impact on Weather Forecasts 1

Many more MW sounders than IR sounders, plus they see through clouds, so they have greater impact

Temperature usually well known in time and space

NWP uses IR information for highly variable WV



# Impact on Weather Forecasts 2

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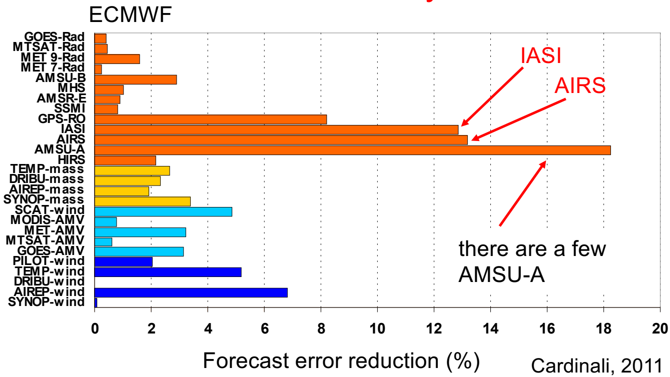
## AIRS, Weather Prediction and Re-Analysis




Cardinali, 2011 + several more studies

AIRS has been absolutely critical:

- For improving forecasts over last 20 years
- For improving re-analysis products (ERA, MERRA)

# L2 Retrievals : AIRS v7

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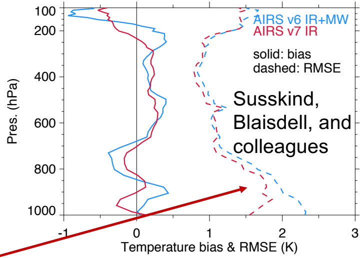
## AIRS Version 7

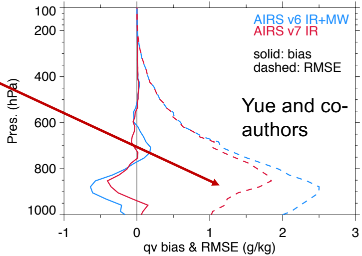
AIRS version 7 L2 and L3 is publicly available at DAAC for full mission (since July 2020)

Evaluation against 500 sondes over subtropical Pacific (MAGIC campaign)

AIRS v7 improves temperature and water vapor retrievals in lower atmosphere (PBL)

AIRS single-footprint retrievals are being evaluated



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## Unified Sounder Retrieval Algorithm

CLIMCAPS Aqua/AIRS has been publicly released June 2021

CLIMCAPS uses radiances from all sounders on Aqua, SNPP, and JPSS-1/NOAA-20

Vertical profiles of temperature, water vapor, trace gases, cloud and surface properties

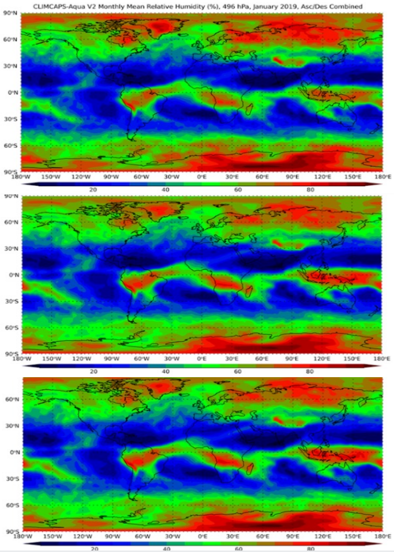


**Figure: Relative humidity (Jan. 2019) at 500 hPa from Aqua (IR-only), SNPP and NOAA-20 satellites, from CLIMCAPS (Smith and Barnet, 2020)**

# Monitoring Severe Weather

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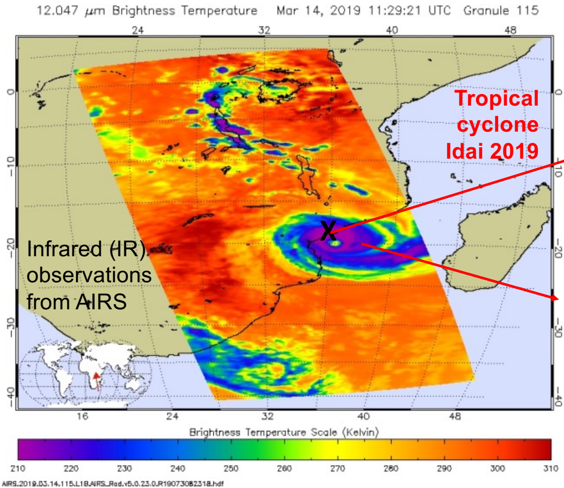
## Severe Weather from Space: How Severe Storms Change with Climate




Beira, Mozambique

Severe storms have very cold cloud tops

# Changes to Severe Weather Storms

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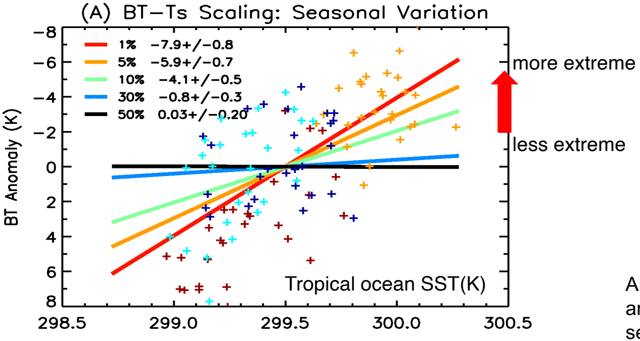
## AIRS radiances and Severe Weather

Extreme storms have cold cloud tops




Red line: very cold cloud tops

Points: colors refer to seasons

Aumann, Wong, and co-authors – several papers

- Very cold cloud temperatures decrease fast with warmer ocean
- More severe storms increase faster with ocean temperatures
- Could imply significant future increase in severe storms

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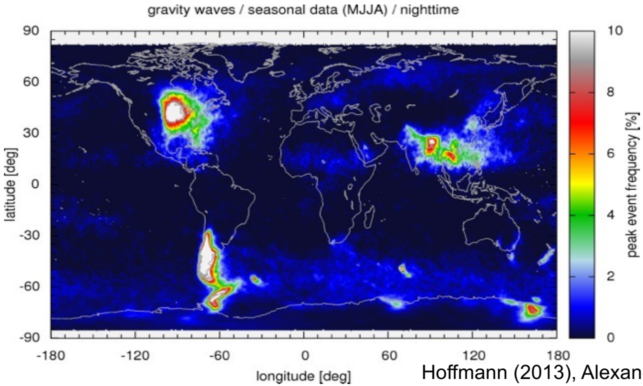
# AIRS and Atmospheric Gravity Waves: A Discovery Story




Hoffmann (2013), Alexander and co-authors – several publications

- Key gravity wave source regions identified by AIRS
- AIRS has helped discover a new key Asian monsoon region

# Helping Understand Science

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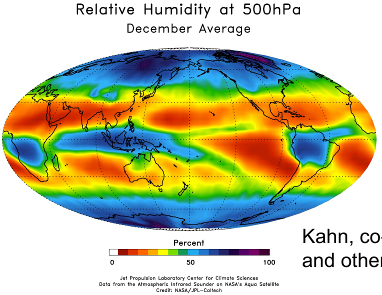
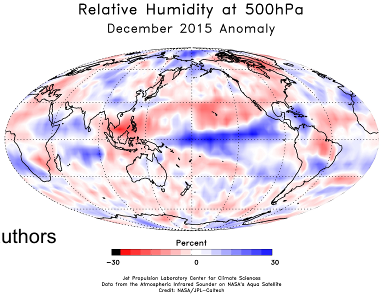
## Ocean-Atmosphere Variability: ENSO

AIRS probes into the vertical structure of the atmosphere: e.g. Significant ENSO changes in mid-tropospheric relative humidity




Kahn, co-authors and others




Long records allow to study several ENSO events and to better understand the impacts of - and what controls - ENSO

## Helping Understand Science

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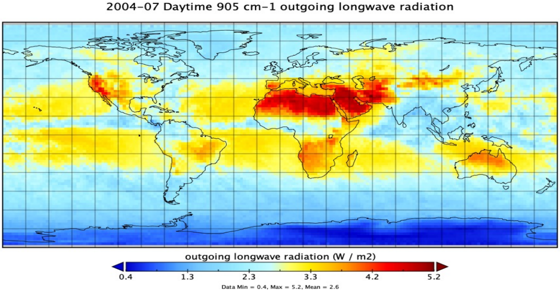
# AIRS Spectral OLR

New L3 monthly spectral outgoing longwave radiation (OLR) product (developed by Xianglei Huang et al, 2008, 2010, 2014):

- Spectrally resolved OLR, spatially gridded in 2° x 2° grid cells
- Spectral flux at 10 $cm^{-1}$ resolution
- Compared against CERES and re-analyses
- Contains information on trends in narrow bands
- Data record: 2002 – present



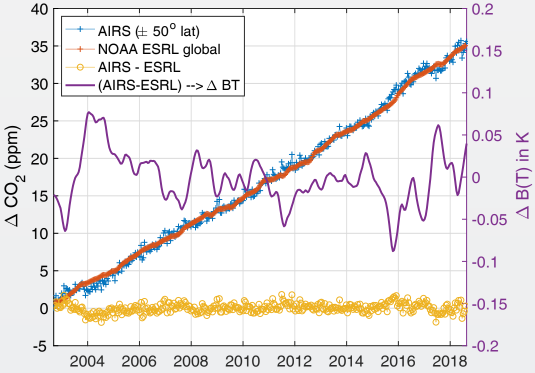
# Climate Studies and The Future

- AIRS record : 20 years (started 2002/09, still working well)
- Aqua platform running out of power by 2026 (flight maneuvers + come down safely), slowly de-orbit from A-Train but still provide data at different time than 1.30 am/pm
- NASA may turn mission off in couple years (budget pressure)
- CrIS (NOAA) already in orbit for weather purposes CHIRP product for continuity

# Overall Approach

- Driven by Level 2 + Time $\neq$ Climate
- Full sampling not required for climate
- Manipulate data in radiance space "as long as possible" before retrievals
- Reduce sensitivity to calibration and RTA bias (radiance anomalies)
- Optimal estimation retrievals regularized more by smoothing than a-priori
- Develop analysis approaches that encourage more researchers to use radiances, rather than complicated Level 2 products for climate research, with quick turnaround.

# AIRS Stability Validation (Clear Ocean Scenes Time Series)




- $CO_2$ trend (using 400 "good" channels) suggests stability: -0.023 ± 0.009 K/decade. Picks up ENSO related variations in $CO_2$ growth at the 0.04K with good S/N
- $CH_4$ and $N_2O$ trends exhibit small offsets (known events, fixable)
- (AIRS - GHRSST) SST trends:): -0.022 ± 0.012 K/decade
- This approach provides strong evidence of inherent radiometric stability at the climate level

# Radiance Sampling

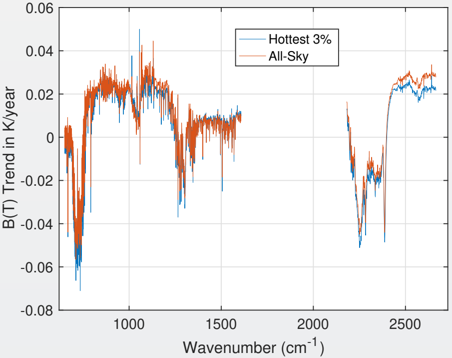
- Early testing shows identical surface T trends with 1%, 3%, 5%, and 10% hottest scenes per 16-day gridded lat/lon cell (3x5 lat/lon).
- Will this sampling provide accurate profile trends?
- Careful sampling of cloudier scenes does not preclude retrievals, just more care in cloud parameter a-priori values and parameterization
    - Hyperspectral IR retrievals really need footprint matched cloud parameters from MODIS (like CERES uses). Univ. Wisconsin has already generated this product for CrIS from VIIRS!
- Subsequent results used 3% surface T sampling (from 1231 $cm^{-1}$ channel)

Trend retrievals in next few slides take ~1 hour max, so reprocessing is trivial.

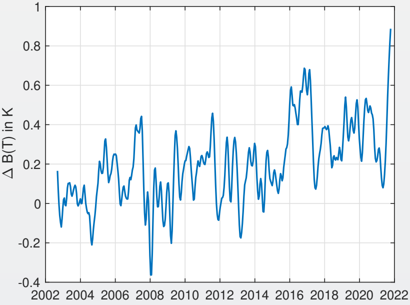
Resampling (say for fixed cloud forcing) takes ~2 days.

# Global IR Radiance Trends and Surface-T Anomalies

## Global Trends: Clear vs All-Sky

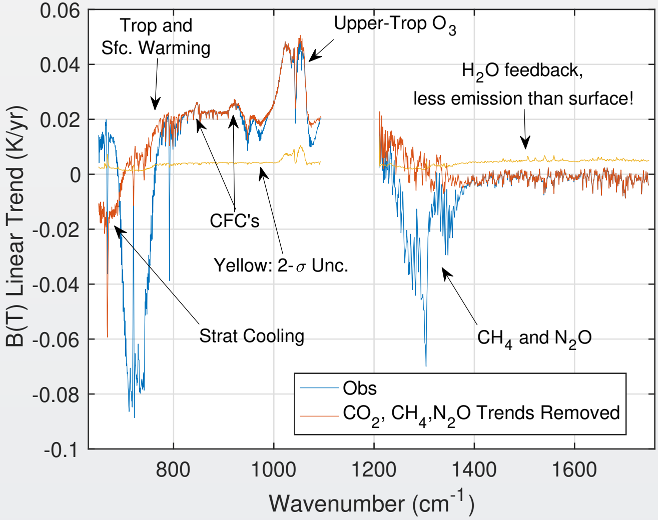



## Tsurface Global Anomaly



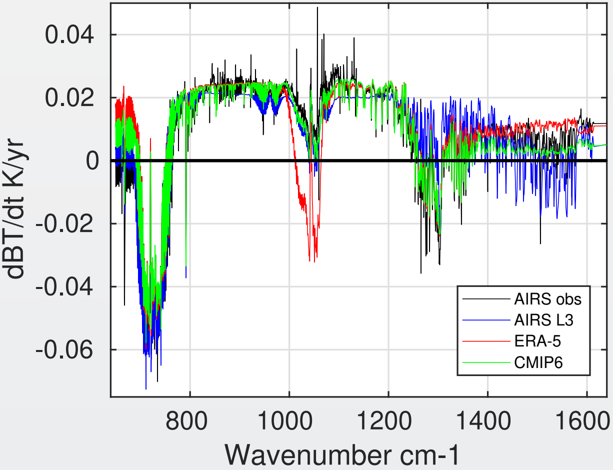

- "Clear" 3% hot sampling trends almost same as all-sky
- Zonally averaged uncertainties (inter-annual variability) ~0.05K/Decade
- Good AIRS channels: stability ~0.02K/Decade
- Some water band drifts of up to ~0.04K/Decade (can be fixed)
- Shortwave known drifts (higher for cold scenes)

# Follow-On Sensor: SNPP CrIS 8-Year Trends



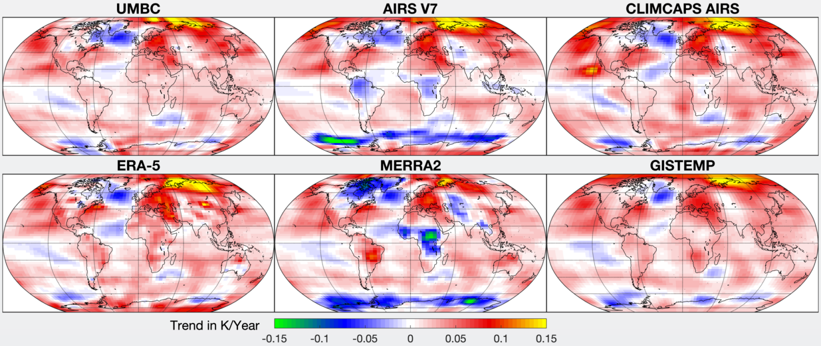

Clear ocean scenes
Less "hash" due to nature of FTS instrumentation

# Spectral Trends



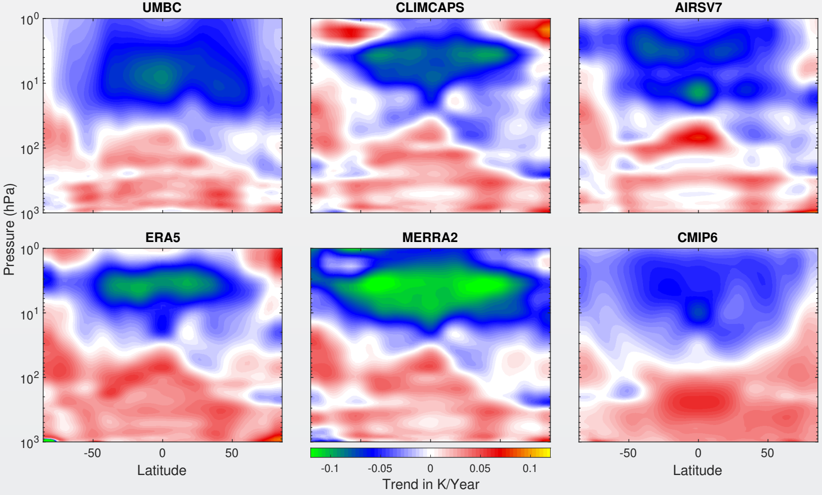

2002/09-2021/08 trends (ERA5, AIRS V7), 2002/09-2014/08 (CMIP6 ensemble)
UMBC retrieved trends (not shown) agree with AIRS observed trends
Note the different dBT/dt in the 1300-1600 $cm^{-1}$ WV 6.7 $\mu m$ region

# Surface Temperature Trend Comparisons




| Data Source | Spatial Correlation (w/ UMBC) |
|---|---|
| CLIMCAPS AIRS | 0.82 |
| GISTEMP | 0.74 |
| AIRS V7 | 0.70 |
| ERA-5 | 0.66 |
| MERRA2 | 0.53 |

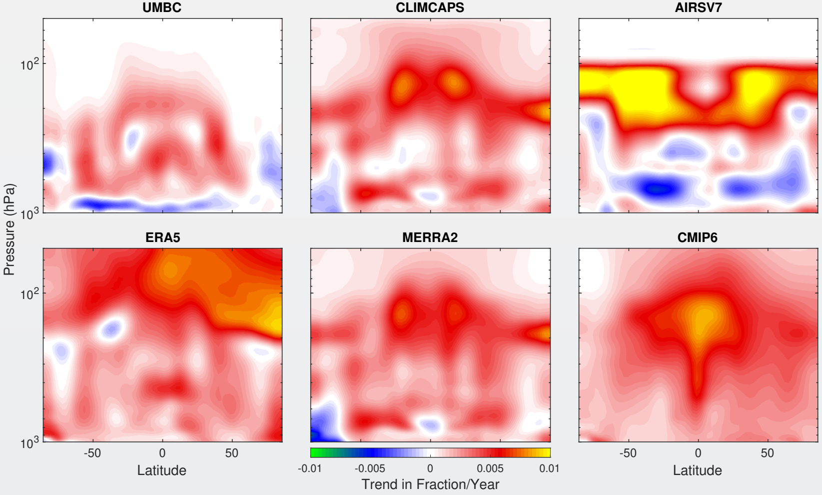
# Zonal T(z) Trends (with CMIP6 to 2014)




IR does have null space near the tropopause. But trends change sign there as well, as they should.

UMBC uncertainties ~0.01K/year (inter-annual variability)

# Water Vapor Trends (with CMIP6 to 2014)

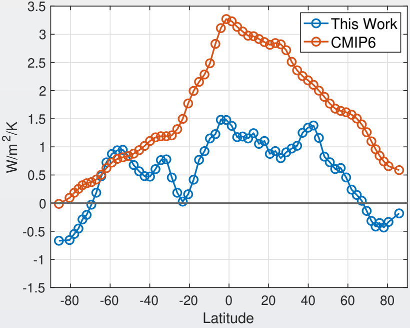



- UMBC a-priori of zero influencing upper-trop WV
- Quick test using MLS trends as a-priori for UMBC upper-trop

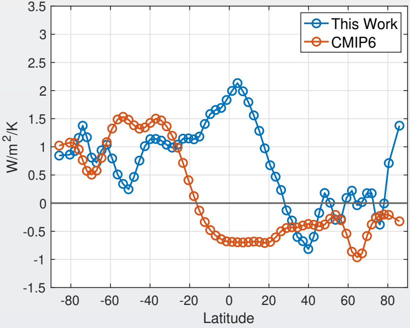
# Climate Feedback Estimation from Trend Retrievals

- CMIP period ends 2014 compared to our 2002-2021 time period
- OLR differences directly from trends, no use of inter-annual variability for kernels
- UMBC results similar to ERA-5 (not shown).
- Cannot use MERRA2 surface T due to poor trends.

**$\lambda$ WV**



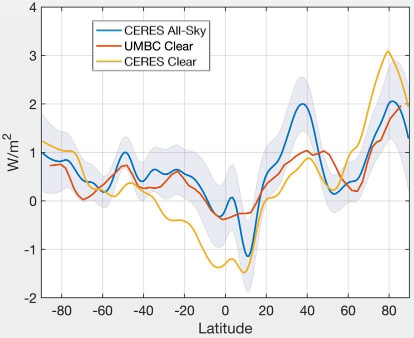

**$\lambda$ Lapse Rate**



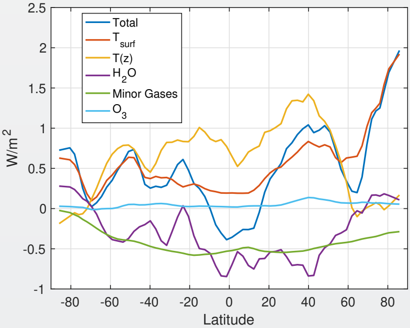

Note Positive lapse rate feedback in tropics for 2002-2022.

# OLR Clear Sky Trends from AIRS (UMBC version)

### Total Δ OLR (clear) over 19 Years




### Components from AIRS Trends




- UMBC clear closest to CERES All-Sky (but not perfect)
- Hints for these differences seen in cloud forcing PDFs (in two slides)

# Summary and Future

- Hyperspectral IR observations are a unique dataset to monitor and understand climate change, for weather prediction and reanalysis, and to evaluate climate models
- Hyperspectral IR radiances provide insights into the physics of the climate system that are not possible using broadband observations
- We are starting to successfully merge hyperspectral IR radiances from different instruments which is critical for climate monitoring (GPSRO, MLS, MODIS/VIIRS)
- We will continue to improve these merged products using more sophisticated approaches and including additional observations
- But we need to keep these hyperspectral IR instruments alive and stable for as long as technically possible and continue to produce climate-level calibrated radiances

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

# L1 Stability and Continuity

**Long (20 years) and remarkably stable record of AIRS hyperspectral radiances/brightness temperatures**

AIRS record is long and stable enough to address key climate questions

*Strow and DeSouza-Machado* (*Atmos Meas Tech*, 2020):

- present a novel generic methodology to study L1 stability
- establish stability of AIRS blackbody and 100's of channels to $\sim 0 \pm 0.02$ K/decade using independent standards (e.g., $CO_2$, SST)

Continuity - Combining AIRS, CrIS, and IASI:
Climate Hyperspectral InfraRed Product (CHIRP)

Consistent climate-level radiance time series spanning AIRS + CrIS

# Summary

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**Jet Propulsion Laboratory**
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Pasadena, California

## Summary

- AIRS is 1st hyperspectral IR sounder and was launched in 2002
- Provides global daily observations of key atmospheric properties
- Climate monitoring of key properties (e.g., T, q, $CO_2$, CO, OLR, clouds)
- Critical to address key climate questions: e.g. How clouds and extreme weather change with climate; How Arctic responds to climate change.

**Historical legacy of AIRS: Long (20 years) and remarkably stable record of AIRS hyperspectral radiances**

Climate science requires ability to measure trends of order 0.1 K/decade

**AIRS instrument trends/drifts are < 0.1 K/decade**

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# Future

- Remarkably accurate and stable AIRS 20-year record is unique for climate monitoring: forcings, feedbacks, extremes
- Budget pressure on Aqua (EOS)
- Great excitement to use/assimilate AIRS at different times of day ➢ significant potential impact on weather forecasts
- AIRS/CrIS/(IASI) continuity: CHIRP, CLIMCAPS, others
- PBL: Decadal Survey Incubation Targeted Observable
- But nothing can replace a few more years of AIRS
- The best is yet to come