Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Sounding Science at the Jet Propulsion Laboratory

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JPL: 6000 employees
400 in Science
150 in Earth Science
20 in Sounding Science

Sounding science groups at JPL

JPL Sounding Science Team: Originated with AIRS ca. 1988

– *Atmospheric Physics & Weather Group: Science support for AIRS*
  - Has developed into a significant sounding-science research group
  - Funded from NASA R&A (now 50%) , AIRS, S-NPP and other sources

Unique capabilities & expertise in Sounding Science

– *Complete range of expertise, from instruments to atmospheric research*
– Instruments & algorithms: AIRS, AMSU, CrIS, ATMS; L0→L3→climatology
– Data & data products: Thorough understanding; analysis & validation
– Research: Rich research program, high productivity re. published papers
  - In 3 years (2014-16): 24 first-authored papers + 145 co-authors

Related groups: Leverage and collaborations

– "Aerosols and Clouds" group: built around former MISR group
  - LES simulations; Cloud processes
– "Tropospheric Composition" group: built around former TES group
  - Retrieval algorithms, radiative transfer models: trace gases
– "Stratosphere and Upper Troposphere" group: former MLS group
  - Upper tropospheric moisture; WRF simulations
– "Statistical Methods" group
  - Data fusion; machine learning methodologies
– JPL Climate Center
  - Modeling & model assessment; process studies

Wide-ranging areas of expertise

AIRS Project + Atmospheric Physics & Weather Group + other groups

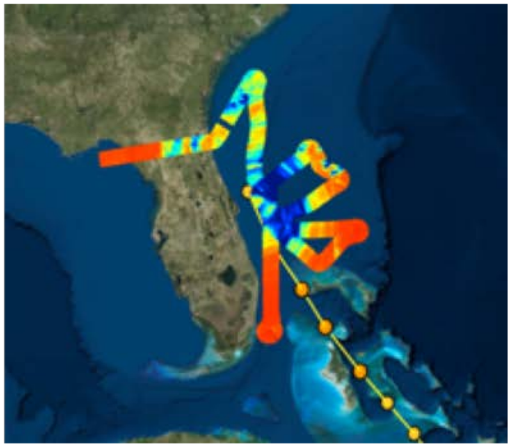
Areas of expertise	Science, application & research areas
Mission concept design & development	Thermodynamics (temperature & water vapor profiles)
Instrument design & development	Weather
Measurement requirements & science traceability	Cloud properties
Technology	Atmospheric wind
Instrument calibration	Precipitation & convection
Infrared spectroscopy	Tropical cyclone observations & analysis
Microwave spectroscopy	Tornado & severe storm processes
Radiative transfer, RTMs	Atmospheric rivers
Instrument simulators	Water resources & hydrology
Atmospheric modeling & simulations	Trace gases & composition
Data analysis & validation	Climate processes, variability & trends
Field experiments, aircraft campaigns	Drought & wildfire detection & prediction
Retrieval algorithms	Volcanic eruptions & emissions
Product development	Vector borne disease prediction
Climatologies	Visualization
Software development	Public outreach

Sounders: From satellites to aircraft

Infrared and **microwave** sounders are both key sensors for atmospheric remote sensing

Aqua satellite: AIRS + AMSU-A1 + AMSU-A2 + HSB

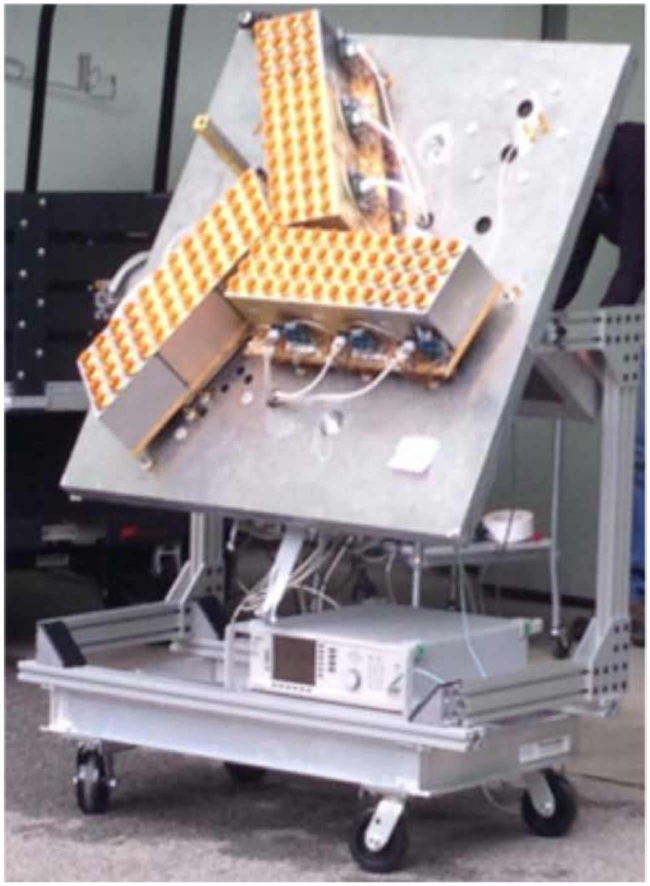
SNPP satellite: CrIS + ATMS

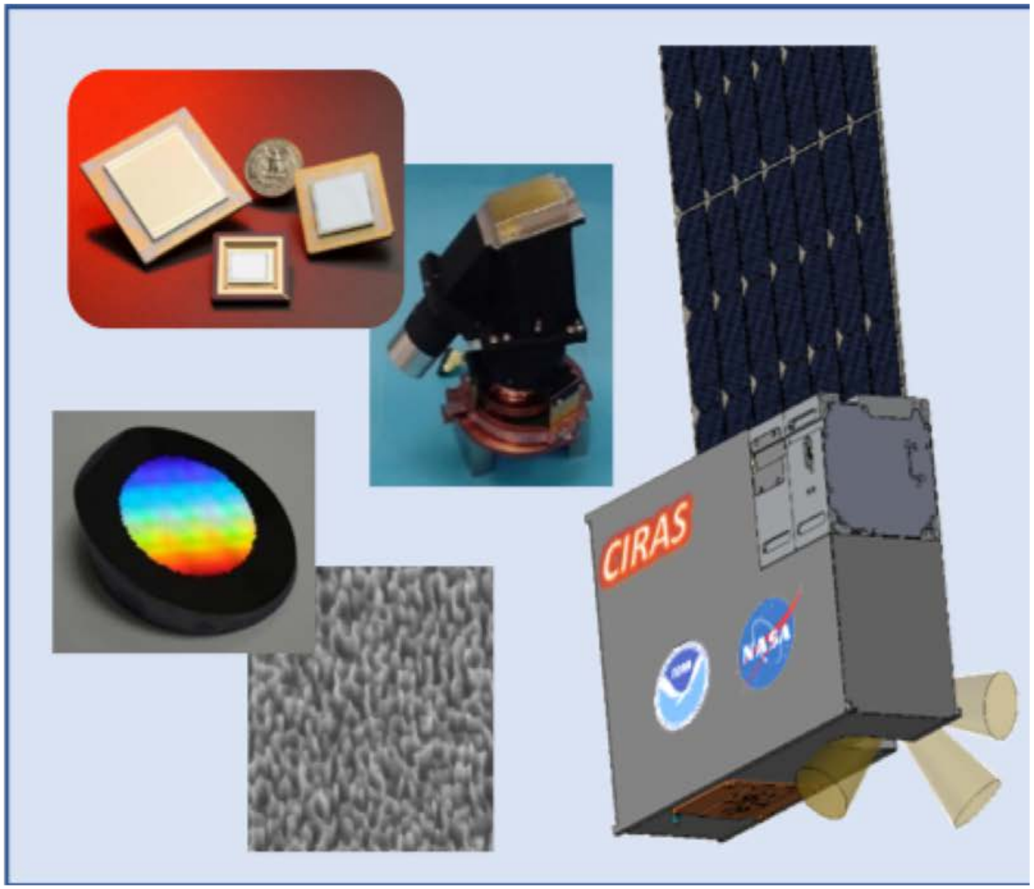


Global Hawk: HAMSR (microwave sounder)

HAMSR obs. Hurricane Matthew

Future sounders: Tech development at JPL





GeoSTAR: Geostationary microwave sounder

CIRAS: CubeSat infrared sounder

Both are ready for mission implementation

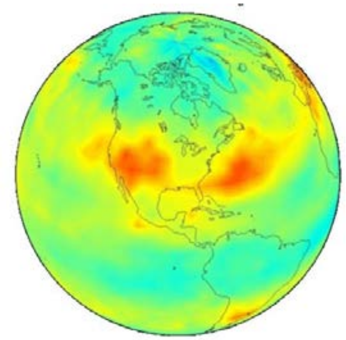
Retrieval systems

AIRS baseline system: Developed by AIRS science team

- ”Unified team algorithm”, now at V6
  - Singular value decomposition (SVD); First guess: Neural network trained on ECMWF
  - Cloud clearing: Cloud variability in 3x3 cluster → “extrapolate” to zero clouds → retrievals
  - Two versions: a) IR + MW; b) IR-only → Move to IR-only as MW sounders fail
- JPL: Testing, integration, coding
- Goddard DAAC (GES DISC): Data production, archiving, distribution
  - L1 (calibrated radiances), L2 (swath-based products), L3 (gridded products)

AIRS CO_2: Add-on algorithm developed at JPL

- Vanishing Partial Derivative (VPD) method
- Global daily mid-tropospheric CO_2
  - Weather-like features



Monthly mean AIRS CO_2

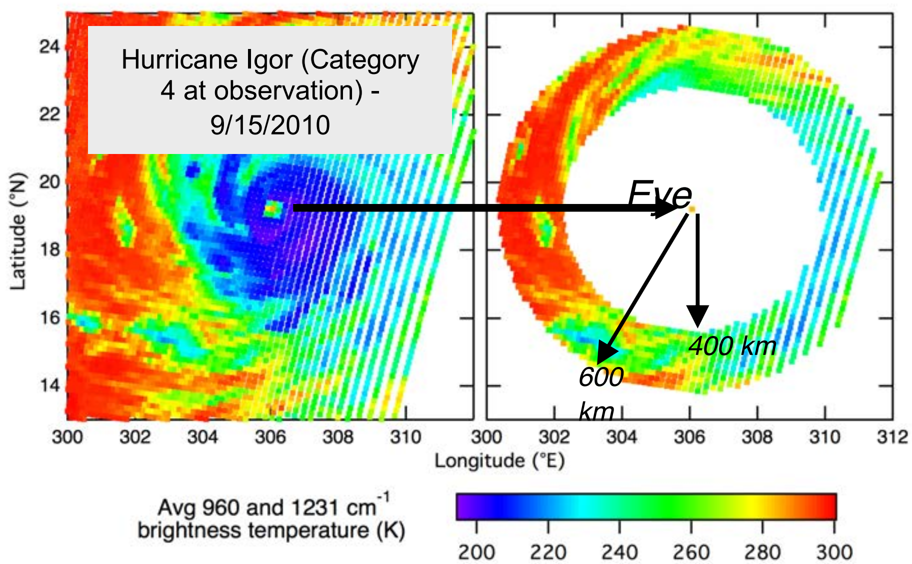
AIRS cloud products: Add-on algorithm developed at JPL

- Delta-four-stream scattering method
- Derived: Cloud phase, particle size, optical thickness

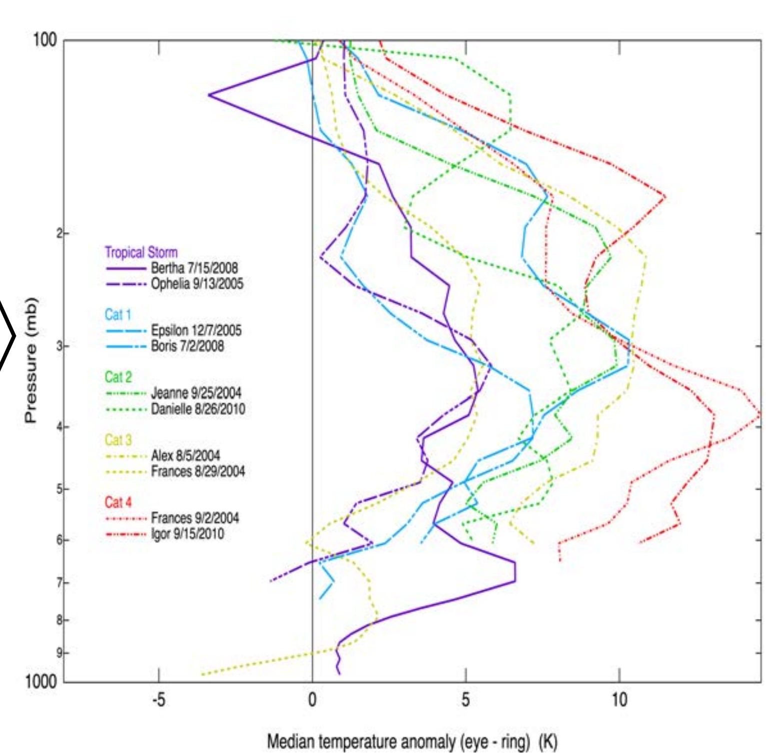
AIRS retrievals in eyes of tropical cyclones

AIRS next generation: Single-FOV retrievals (no cloud clearing)

- Funded by NASA (Irion, PI), now supported by AIRS
- Optimal Estimation (OE) + scattering
- Portable to other sounders: CrIS, IASI, etc.



Calculate median temperature difference between eye and less disturbed ring around hurricane



Microwave retrieval systems

AIRS baseline system: Developed by AIRS science team

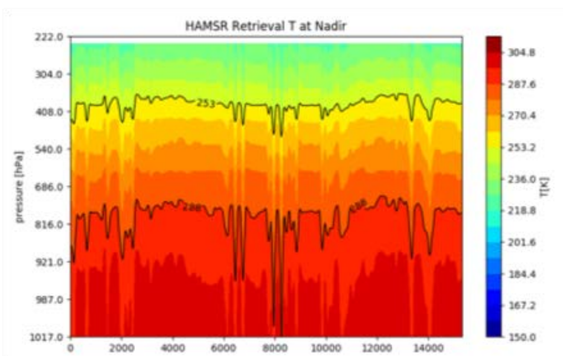
- No longer in full production due to decline & failures of MW instruments

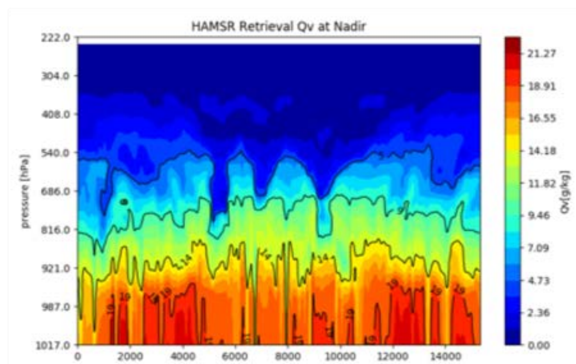
ATMS (SNPP & JPSS): Developed at JPL

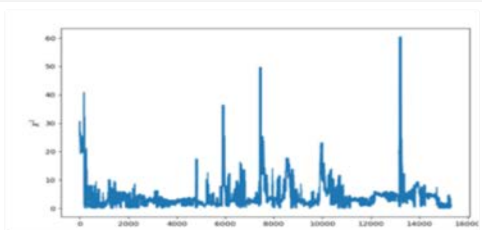
- Funded by NASA
- Two versions: a) “legacy” based on AIRS system; b) new development
  - Currently being assessed at JPL Sounder SIPS
  - One or both to be delivered to DAAC for production

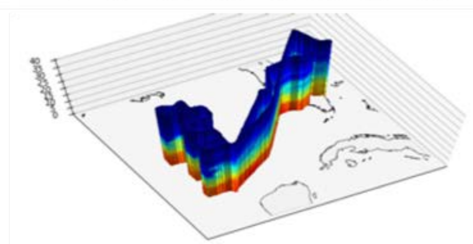
Aircraft application

- New algorithm applied to HAMSR aircraft sounder: Example below









Development of applications

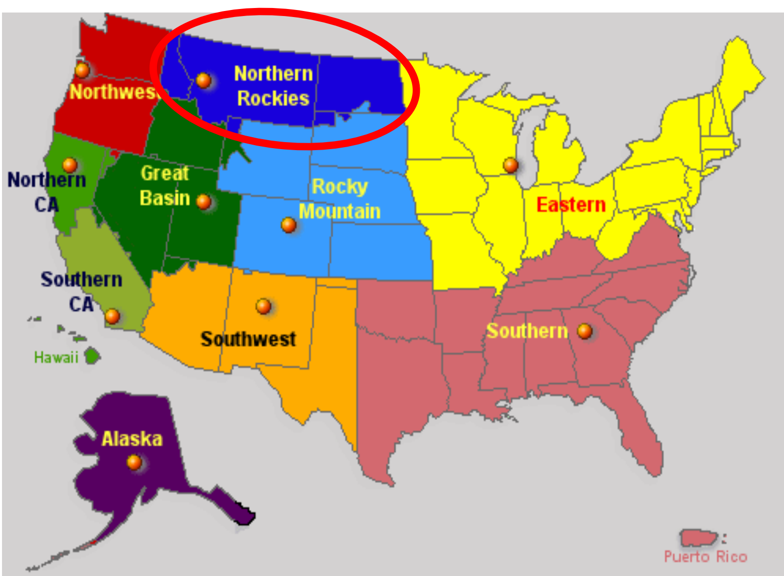
Applications based on spectroscopy

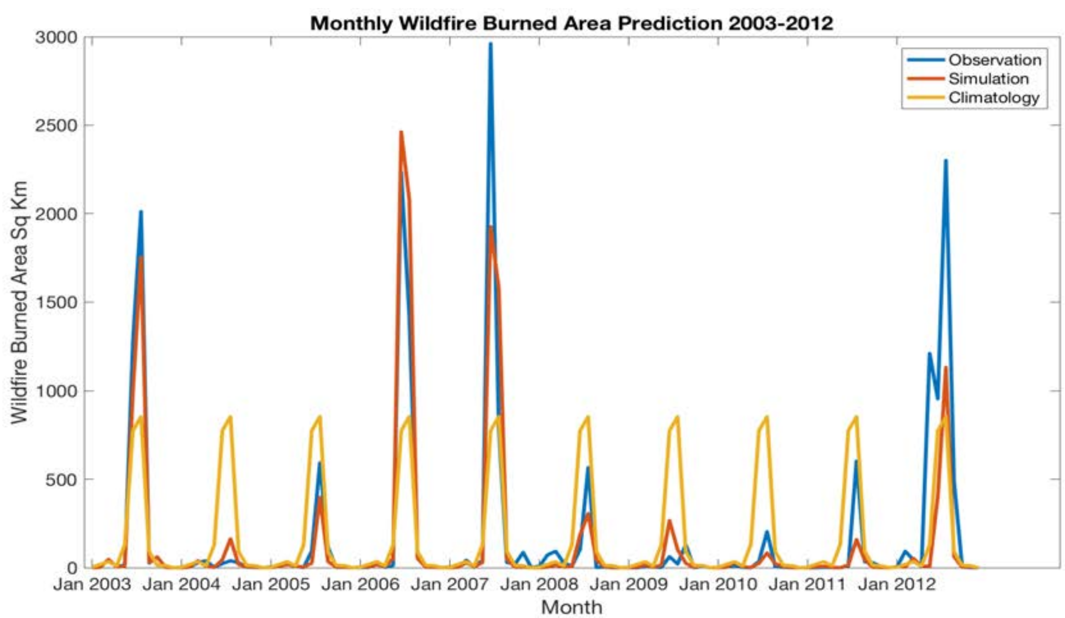
- Volcanic emissions (SO_2, ash)
- Mineral dust, e.g., Saharan Air Layer (SAL) dust

Applications based on near-surface vapor pressure deficit (VPD)

- Drought detection/prediction
- Wildfire conditions/prediction
- Disease conditions: Influenza; vector-borne diseases (dengue, etc.)

Example: Northern Rockies wildfire district: AIRS algorithm shows skill over climatology





Sounder assessment and analysis

Sounding team provides assessment of retrieval systems

- Quick-turnaround benchmark tests during algorithm development
- Preliminary assessments
- Verification of correct implementation
- Validation against reference data sources

Assessment tools and techniques

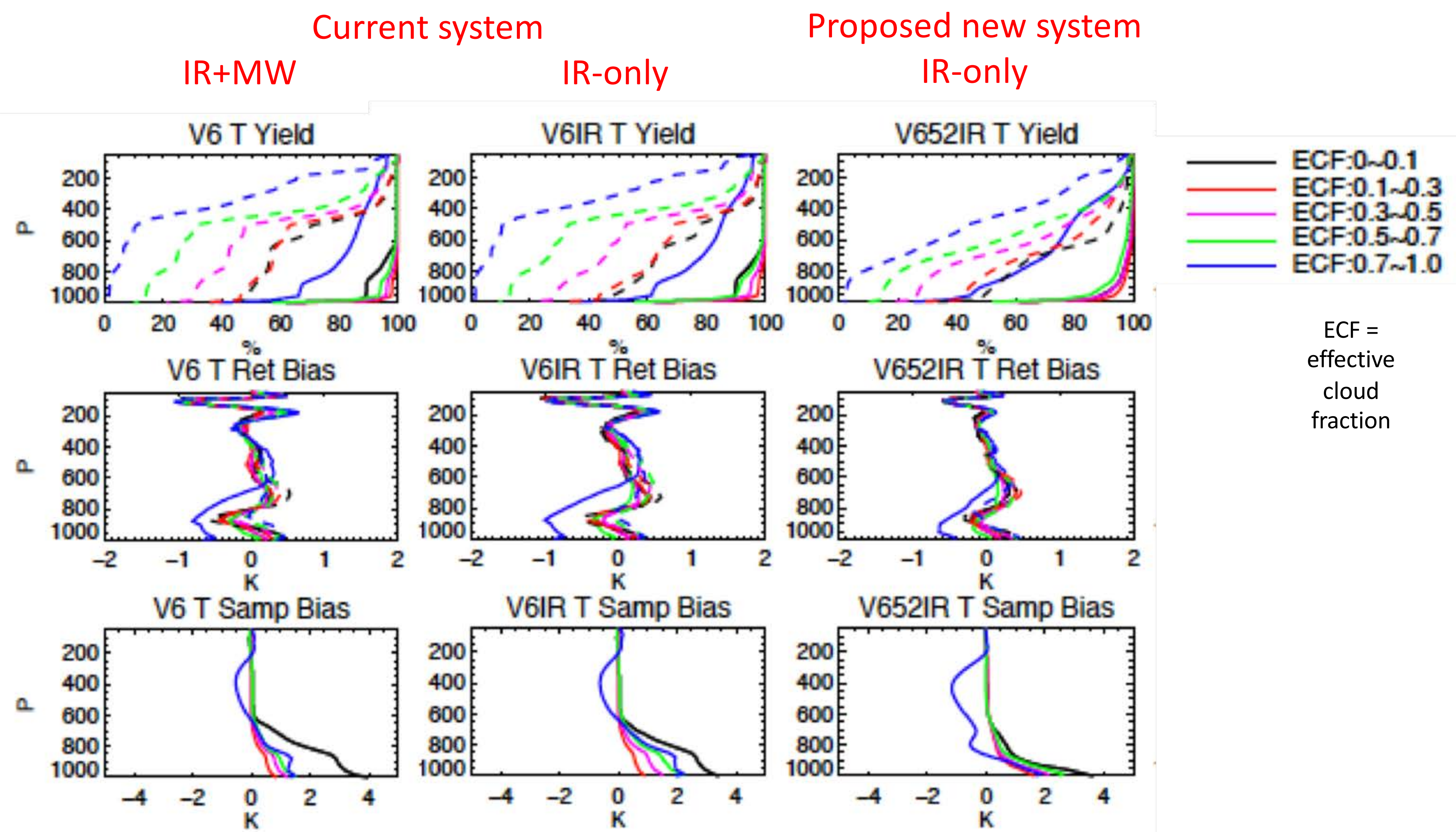
- The analysis team has developed an elaborate set of assessment procedures and corresponding reference data
  - "Sanity checks": simple tests with a few data sets, used to quickly determine whether a development step is on the right track
  - Elaborate and lengthy analyses to fully characterize a new system
  - May be followed by an even more elaborate formal "validation", intended to determine the scientific validity of the retrievals

Reference data sets

- Radiosondes
- Ground met stations, ocean buoys
- Satellite data: GPS-RO, other sounders, cloud imagers, radar
- Aircraft data: field campaigns
- *A data base system for verification/validation data is under development*

Example: AIRS next-gen retrieval system

Comparisons with ECMWF



ECF = effective cloud fraction

Focus on the troposphere

- "Moist thermodynamics", H_2O cycle: *water vapor*, temperature, clouds, precipitation
- Atmospheric processes controlling weather and climate; severe storms

Informed by tropospheric sounders & related sources

- IR sounders: AIRS, CrIS, IASI etc.; MW sounders: AMSU, ATMS etc.
- CYGNSS, GPSRO, GPS-met, raobs, buoys, aircraft

Science questions

- *How do small-scale weather processes interact with the large-scale thermodynamic environment?*
- *What controls the intensity, distribution and likelihood of convective storms, and how can we use satellite observations to improve modeling and prediction of important weather events?*
- *How well do climate models compare to observations, and how can we use global satellite observations to improve the models?*
- *What phenomena relevant to our research themes are not adequately observed and require new observing strategies and systems to be developed?*

Relevant WCRP grand challenges

- *Understanding and Predicting Weather and Climate Extremes:* Extreme weather processes, severe storms
- *Clouds, Circulation and Climate Sensitivity:* Cloud and water vapor processes
- *Water Availability:* Atmospheric branch of water cycle (water vapor, clouds, precipitation)

Surface freshwater exchange over ocean

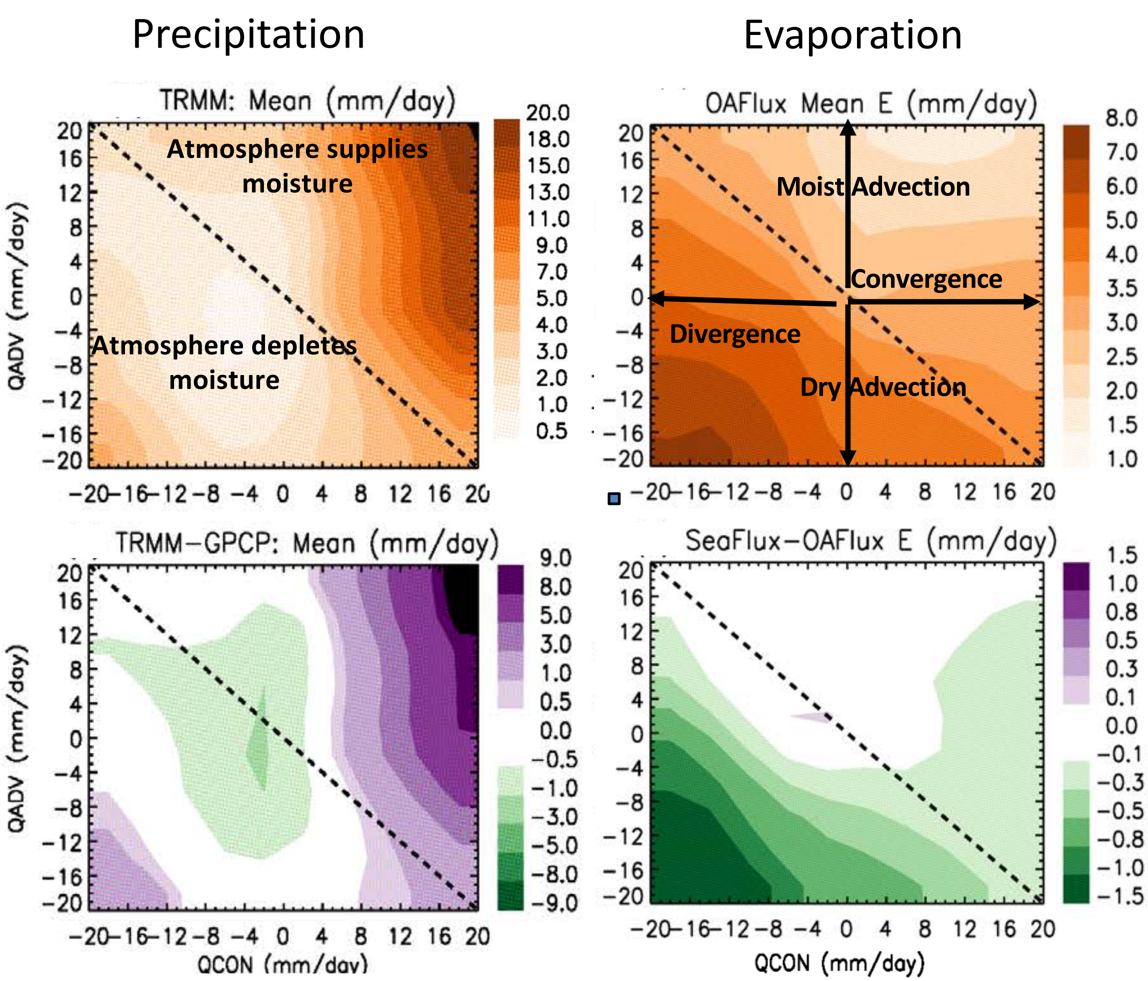


Figure 1. Regime dependent uncertainty analysis of precipitation (left) and evaporation (right) fluxes based on moisture advection (QADV) and moisture tendency by dynamical convergence (QCON). Biases of P and E highly depend on how the atmosphere transports moisture. Dashed lines indicate conditions when moisture flux convergence is zero (i.e., Qadvt + Qcnvg = 0).

Wong, S. et al., "Regime-Dependent Differences in Surface Freshwater Exchange Estimates Over the Ocean," Geophysical Research Letters, 45(2), pp.955-963 (2016)

Problem:

How do discrepancies of commonly used gridded products of precipitation (P) and evaporation (E) depend on atmospheric moisture transport?

Finding:

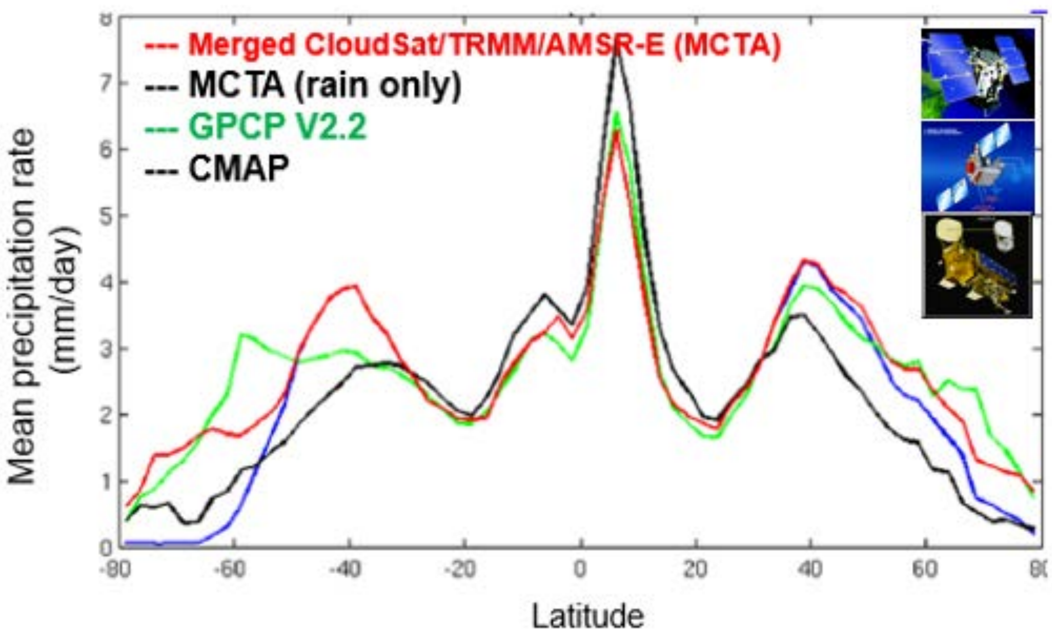
- TRMM has more extreme P in regimes of convergence and more light rain in regimes of moisture flux divergence than GPCP.
- Biases in E among different products (OAFlux, SeaFlux, IFREMER) strongly depend on moisture flux convergence (QADV + QCON).

Significance:

Surface freshwater exchange (P–E) used as a boundary condition to drive ocean circulation models has uncertainties depending on atmospheric moisture transport.

Finding "missing" precipitation

Finding "missing" precipitation: An Update on the Oceanic Precipitation Rate

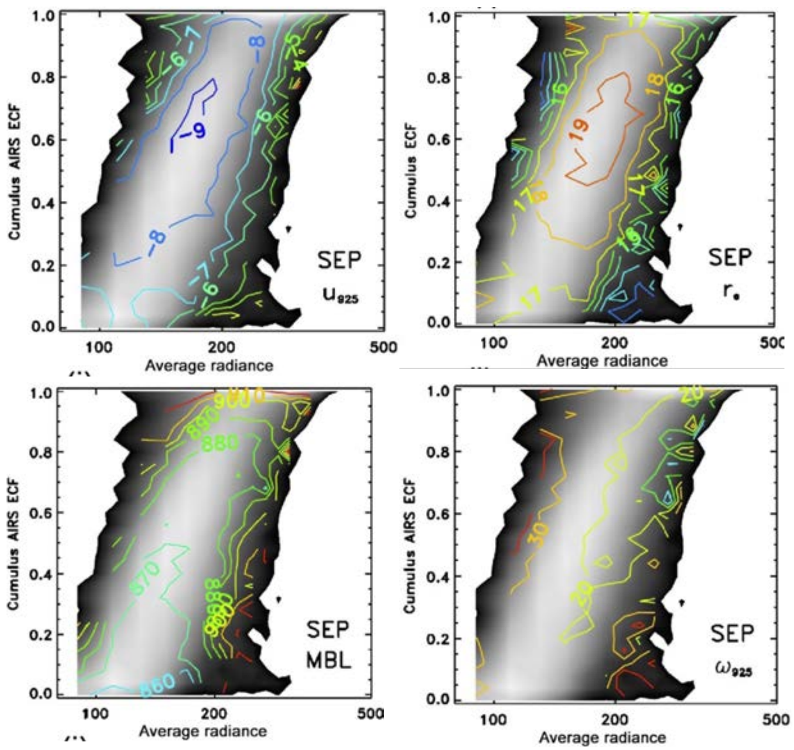


Zonal distribution of oceanic precipitation rate using the new combined estimate and comparison with popular precipitation products.

Behrangi, A. et al., "An update on the oceanic precipitation rate and its zonal distribution in light of advanced observations from space," Journal of Climate, 27(11), pp.3957-3965 (2014)

- **Science Question:** The true amount of precipitation and its zonal distribution has been highly uncertain over ocean, mainly due to lack of ground observation and needed sensitivity from space.
- **Data & Results:** By merging histograms of CloudSat, TRMM , and AMSR-E precipitation data, the largest range of precipitation sensitivity was utilized to quantify snowfall and rainfall from drizzle to the most intense rates.
- **Significance:** Results show that 5 to10% of total precipitation is currently missed over ocean by the popular reference precipitation climatology products (e.g., GPCP and CMAP) and the zonal distribution of precipitation may have not been captured accurately. This is very important for water and energy budget closure studies.

Cloud-thermodynamic-dynamic variability



Joint histograms of MERRA 925 hPa wind speed (upper left), MODIS effective radius (upper right), AIRS MBL depth (lower left), and MERRA 925 hPa vertical velocity (lower right) on top of log counts of visible radiance versus infrared cloud amount

Problem: The global-scale patterns and covariances of subtropical marine boundary layer cloud fraction, atmospheric thermodynamic and dynamic fields remain poorly understood.

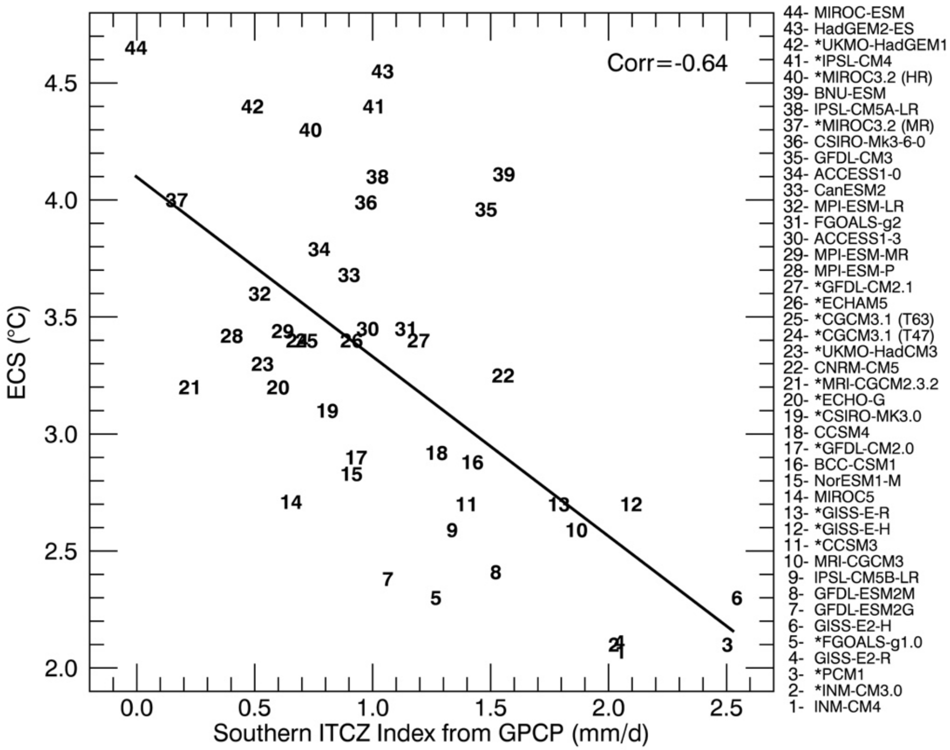
Finding: A method that uses a combination of A-train and MERRA reanalysis data sets has demonstrated that an increase in effective radius within shallow cumulus is strongly related to higher MBL wind speeds and increased precipitation occurrence that was previously demonstrated with surface observations.

Significance: Using remote sensing together with reanalysis, matching at the native pixel and grid scales, an approach that is vastly underutilized, has shown great potential of adding global context to process-level understanding of the strato-cumulus to trade cumulus transition and should be extended to other cloud regimes.

Kahn, B.H. et al., "An A-train and MERRA view of cloud, thermodynamic, and dynamic variability within the subtropical marine boundary layer," Atmospheric Chemistry and Physics, 17(15), p.9451 (2017).

Climate model assessment

Constraining model climate sensitivity and bias with satellite observations



Scatter plot of the southern ITCZ index (x-axis) quantifying the double-ITCZ bias and the equilibrium climate sensitivity (ECS) (y-axis) in 44 global climate models from CMIP3/5.

Tian, B., “Spread of model climate sensitivity linked to double-Intertropical Convergence Zone bias,” Geophysical Research Letters, 42(10), pp.4133-4141 (2015)

Problem:

Despite decades of climate research and model development, two outstanding problems still plague the latest global climate models (GCMs): The double-intertropical convergence zone (ITCZ) bias and the 2−5 C spread of equilibrium climate sensitivity (ECS).

Finding:

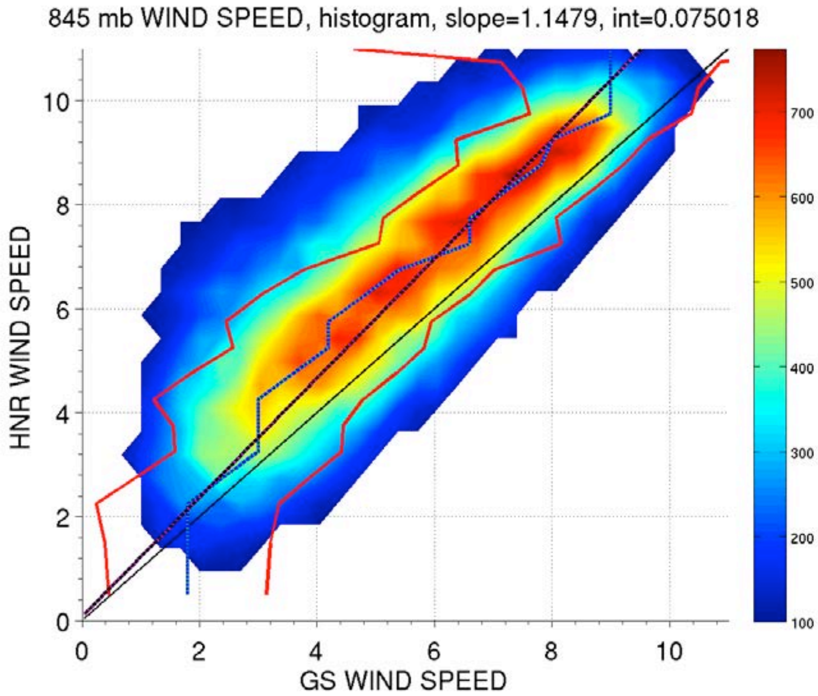
Based on NASA satellite humidity data from Atmospheric Infrared Sounder (AIRS) and NASA satellite rainfall data from GPCP available in Obs4MIPs and 44 GCM outputs from Coupled Model Intercomparison Project Phases 3/5 (CMIP3/5) we show that the double-ITCZ bias and ECS in climate models are negatively correlated. The models with weak (strong) double-ITCZ biases have high (low) ECS values of ~4.1 (2.2) C.

Significance:

This indicates that 1) the double-ITCZ bias is a new emergent constraint for ECS based on which ECS might be in the higher end of its range (~4.0 C); 2) NASA AIRS humidity data and GPCP rainfall data in Obs4MIPs are very useful in improving climate models and future climate prediction.

Atmospheric wind from a GEO MW sounder

Measuring tropospheric wind with microwave sounders



Histogram of simulated AMV wind speed (horizontal axis) vs. nature run “truth” (vertical axis at 845 mb

Lambrigtsen, B.H. et al., “All-Weather Tropospheric 3-D Wind From Microwave Sounders,” IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, (99), pp.1-8 (2018)

Problem:

Tropospheric wind is currently poorly measured but is one of the most desired variables. Polar satellites do not provide frequent enough observations to provide reliable AMV feature tracking. Geostationary imagers track cloud tops only at uncertain heights. Geostationary IR sounders will not be able to penetrate clouds

Finding:

Two simulation studies found that tropospheric wind vectors can be derived by tracking water vapor features measured with microwave sounders with a precision of ±2 m/s (wind speed) and ±15° (wind direction) and negligible bias. With a geostationary microwave sounder, wind measurements can be obtained for the entire hemisphere below the satellite continuously and under all weather conditions with a temporal resolution of 15 minutes and spatial resolution of 25 km or better and vertical resolution of 2-3 km. Wind can also be measured as accurately with a cluster of 3-4 CubeSats spaced 5-10 minutes apart, but temporal and spatial sampling and coverage are not as favorable.

Significance:

The projected accuracy and precision using this method meet WMO requirements for tropospheric wind and will enable significant progress in atmospheric dynamics research and weather prediction, particularly in the tropics, where wind is typically non-geostrophic and therefore not derivable from temperature and pressure fields. A GEO/MW measurement system is particularly capable and could be a good match with a doppler lidar system.

Summary

Sounding science is thriving at JPL

- AIRS has been the focal point since late 1980's
- MLS, TES, MISR, OCO2 collaborations have broadened the scope
- S-NPP and JPSS represent "life after AIRS" → Continuity

AIRS analysis has spawned a vigorous research program

- Intimate understanding of measurements & data → Many papers
- Well funded through NASA's R&A program
- Publishing record is growing rapidly

JPL environment facilitates development of new observing systems

- Easy to assemble a team of experts: *"Just go next door…"*
- JPL wins a large fraction of NASA proposal competitions
- Lively technology development program → New sensors & systems

JPL Sounder Team is a key "resource" for NASA

- Wide range of expertise covering all aspects of sounding science
- Provides anchor of broader sounding science activities
- Close coordination with NASA/GSFC, NOAA, CIMSS, MIT/LL

NASA and JPL have a strong interest in international collaborations

- Comparative analyses to address cross-sensor bias, establish benchmarks
- Develop merged/joint products covering a broad range of "regimes"