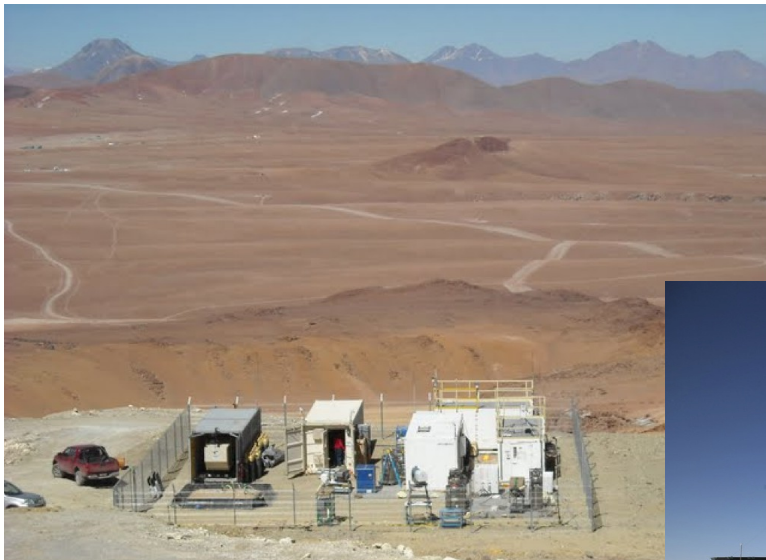
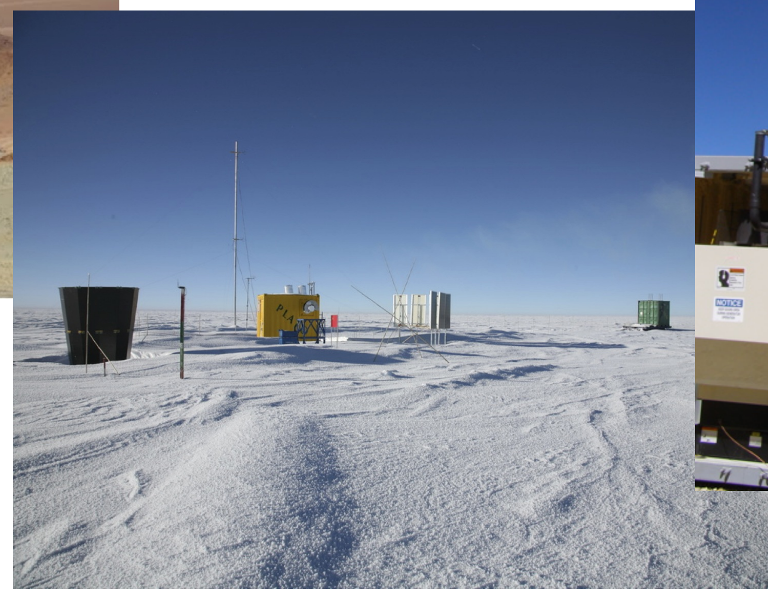
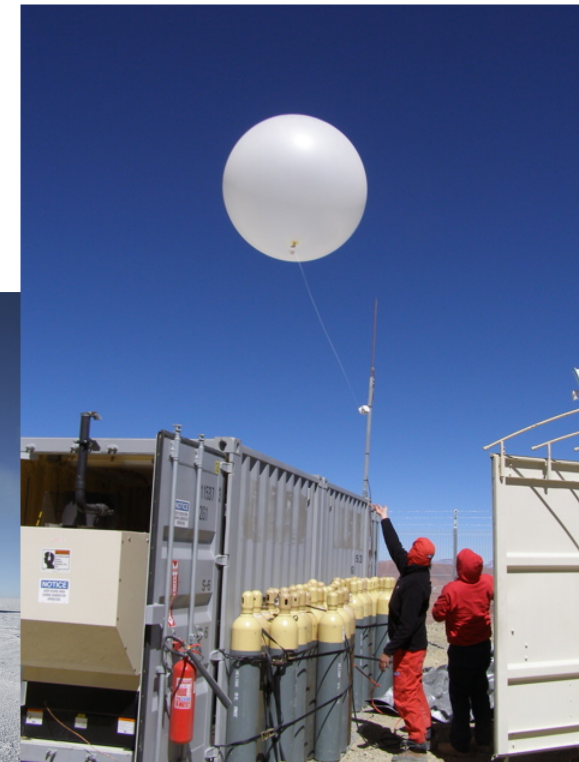
Atmospheric transmission in the millimeter and submillimeter bands







Scott Paine

Smithsonian Astrophysical Observatory

Topics

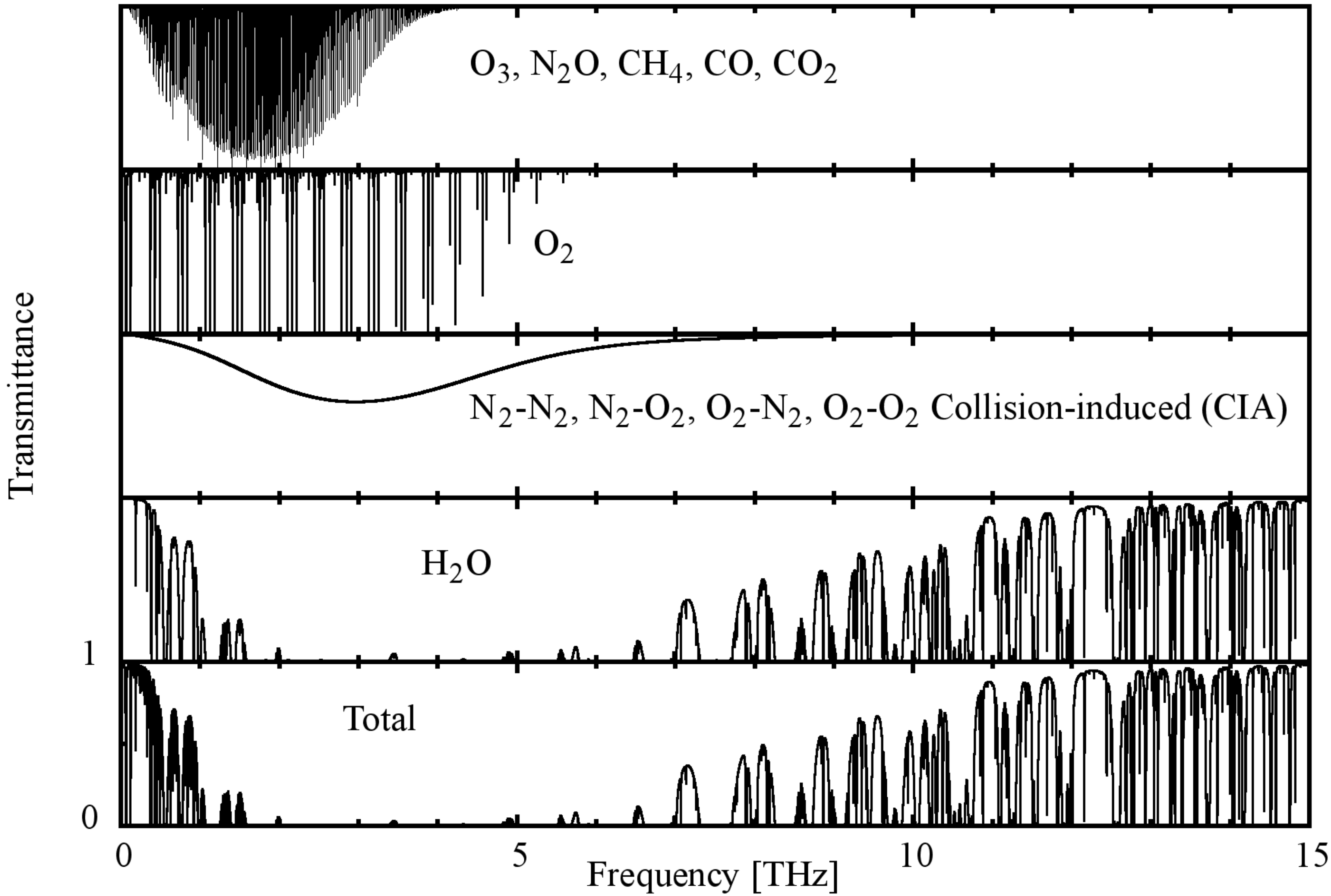
Spectroscopy

- The millimeter / submillimeter spectrum
- Improving models for the spectral absorption of water vapor
  - Importance for modeling the Earth's climate
  - Two field experiments in Chile and Antarctica

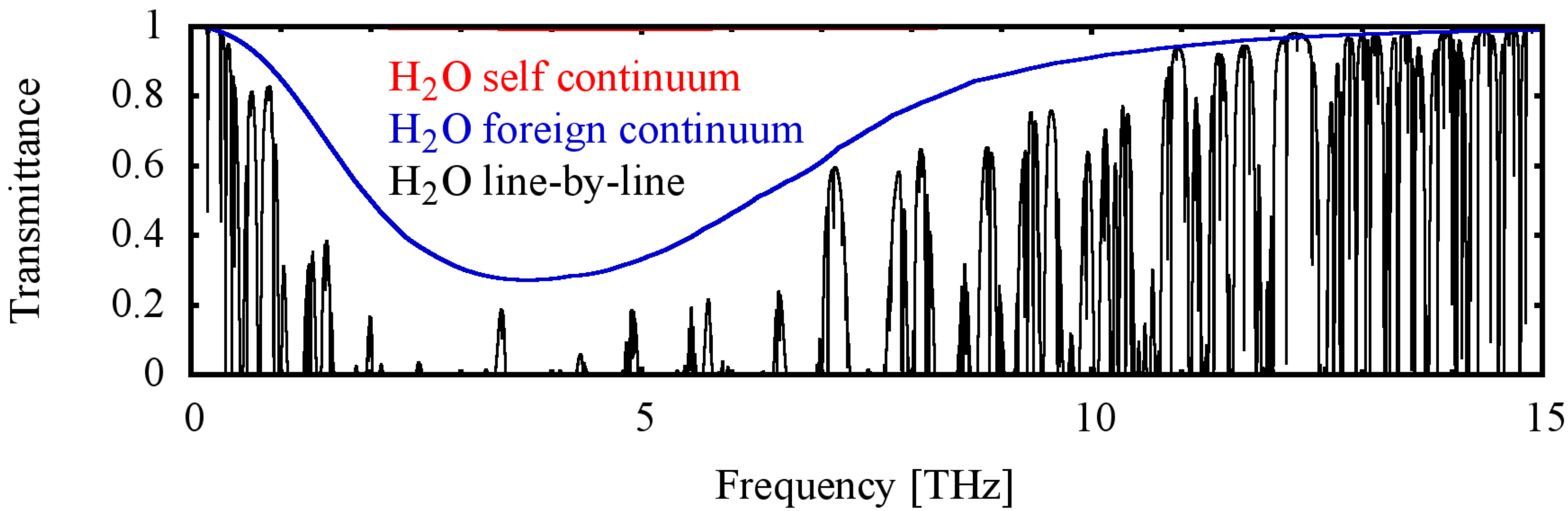
The atmospheric state

- In-situ measurements with radiosondes
- The past atmospheric state – meteorological reanalyses
- Radio climatology from reanalysis

Submillimeter transmittance from the mid-troposphere

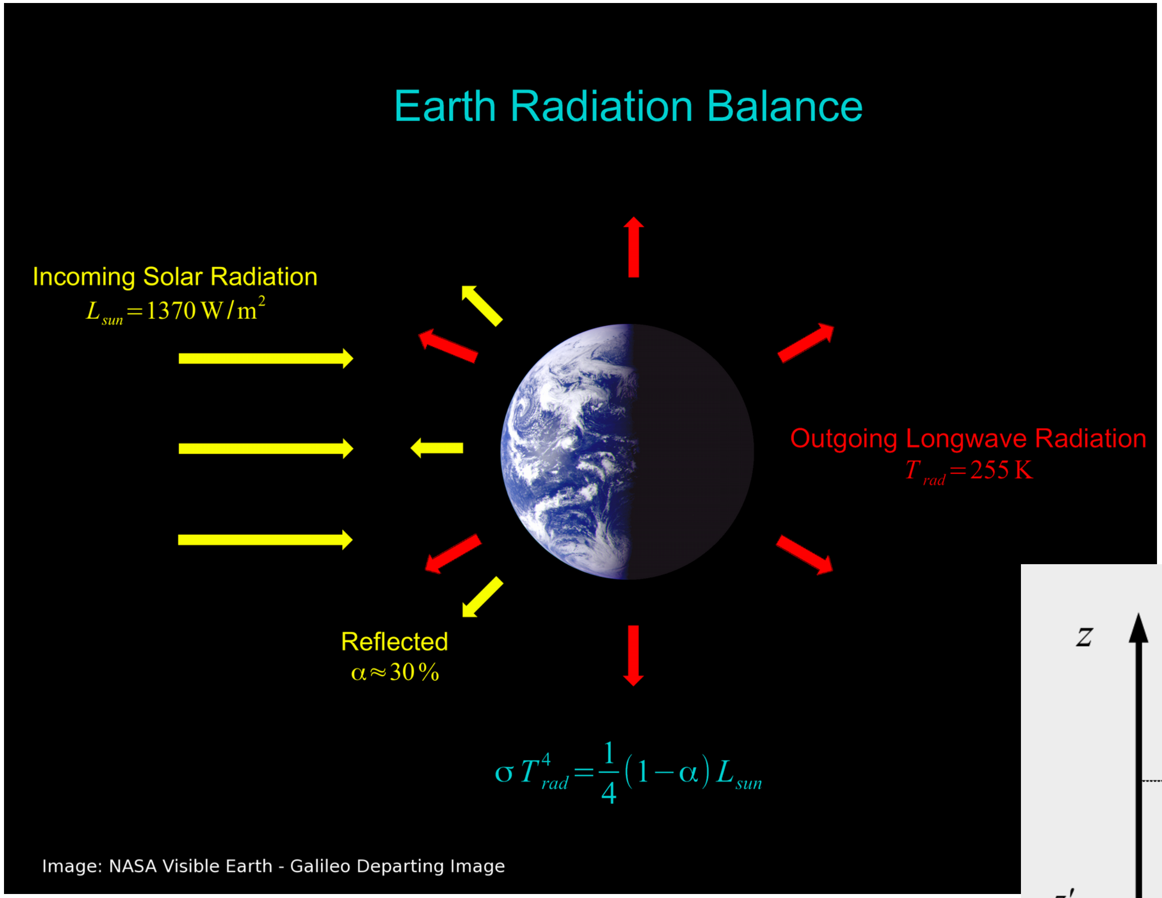


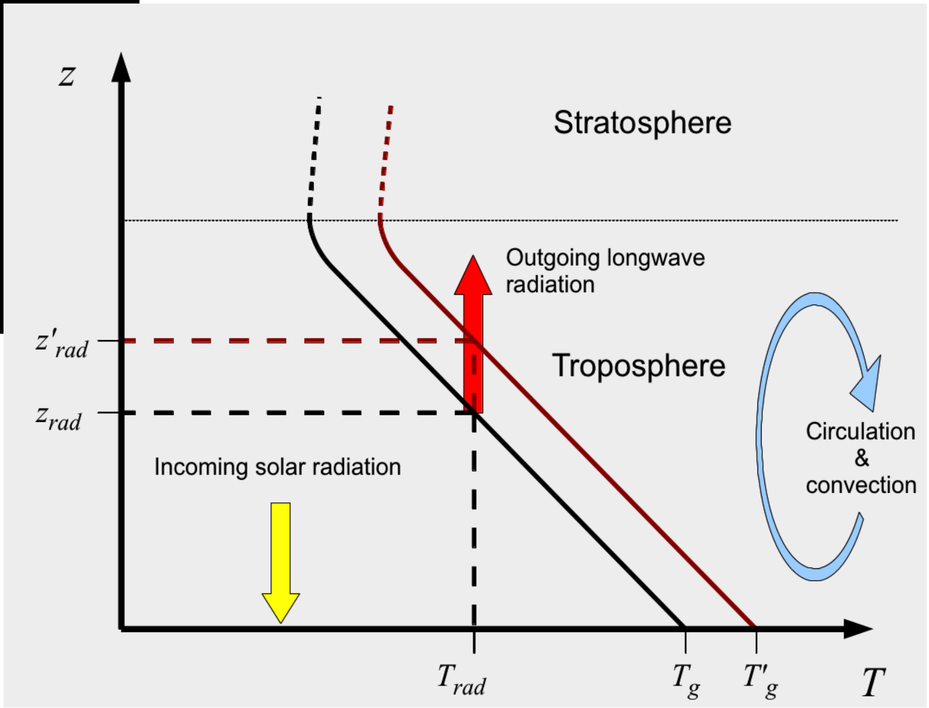
Water vapor absorption – lines plus continuum



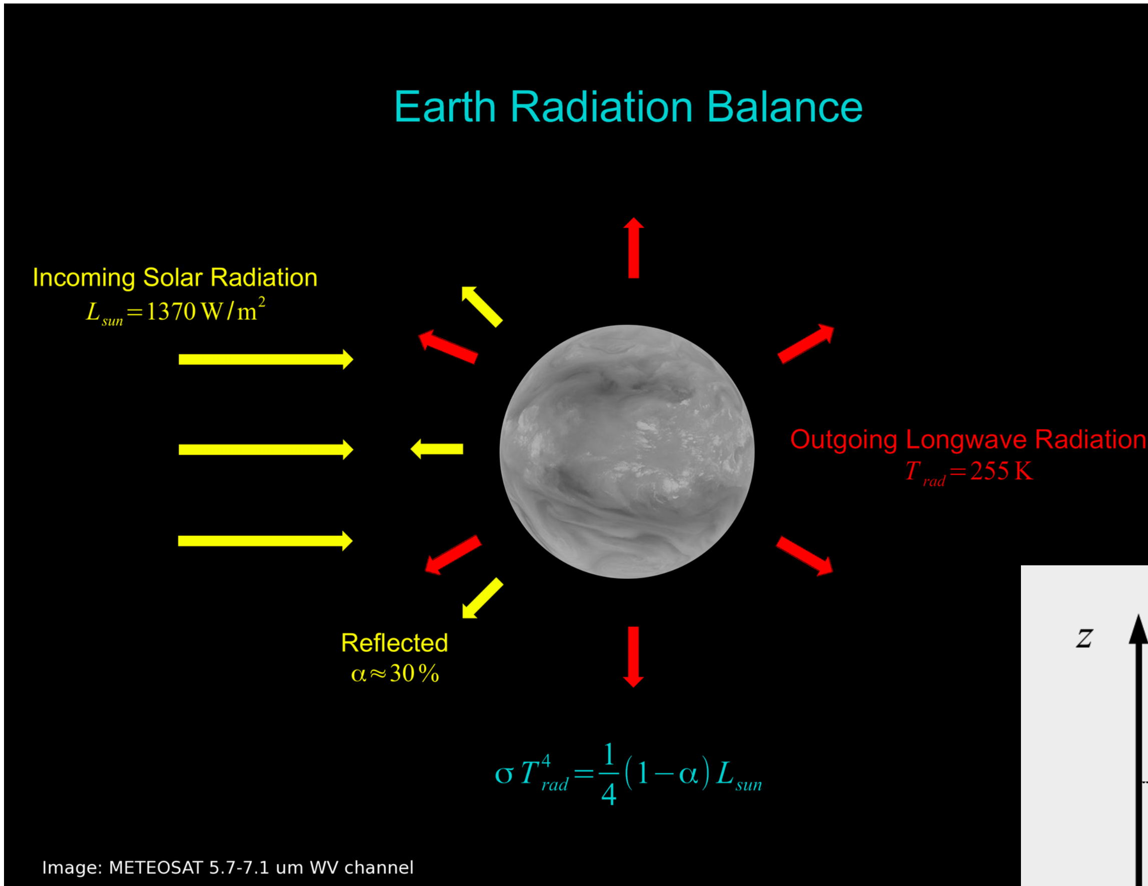
- Empirical continuum models far line wings and other collisional physics
- Here, the self continuum is small – but not so in the lower troposphere!
- Regularly-updated “standard model” is MT_CKD (Mlawer, et al.)
- Key driver of atmospheric radiative-convective equilibrium...

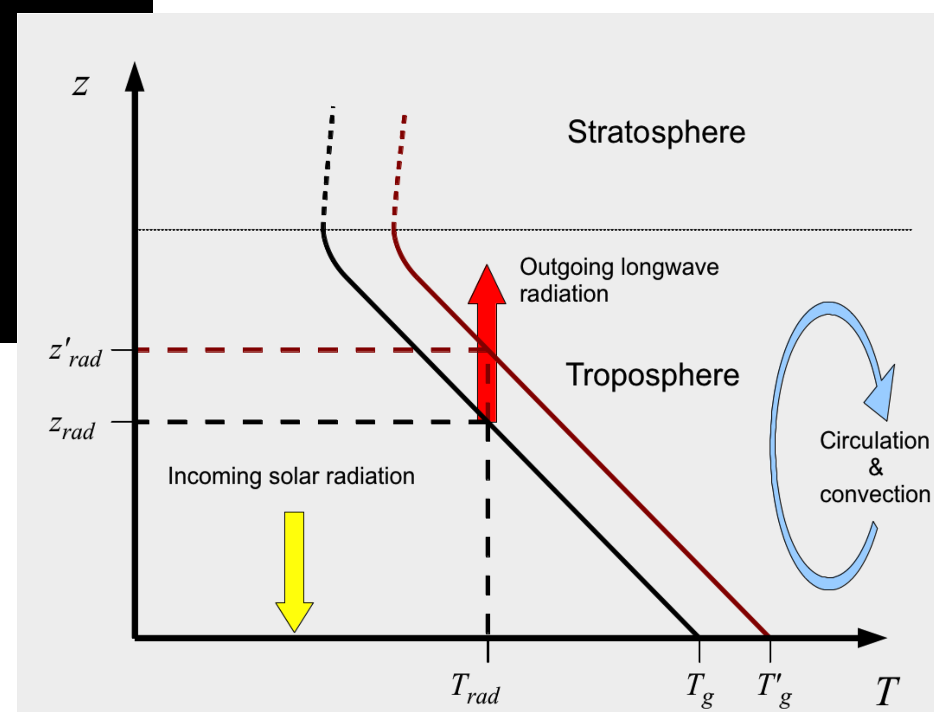
Gray gas greenhouse effect





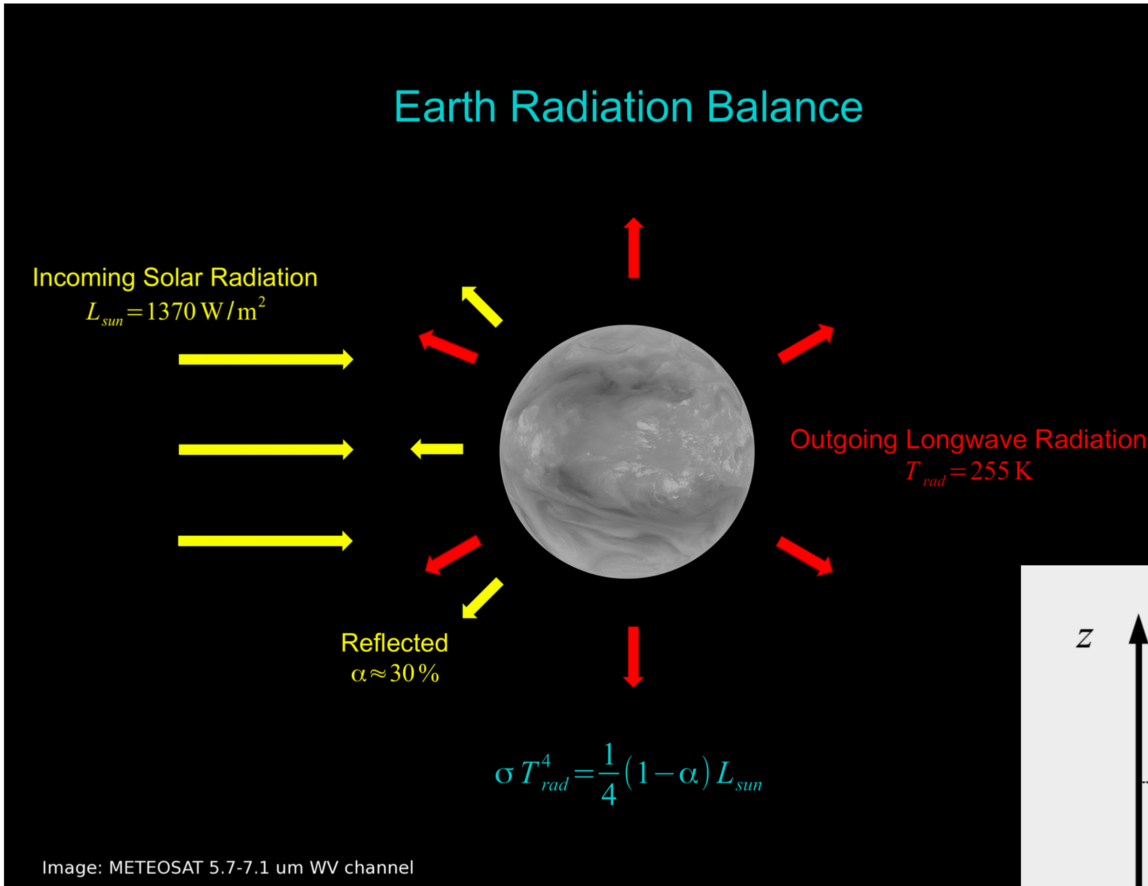
Gray gas greenhouse effect





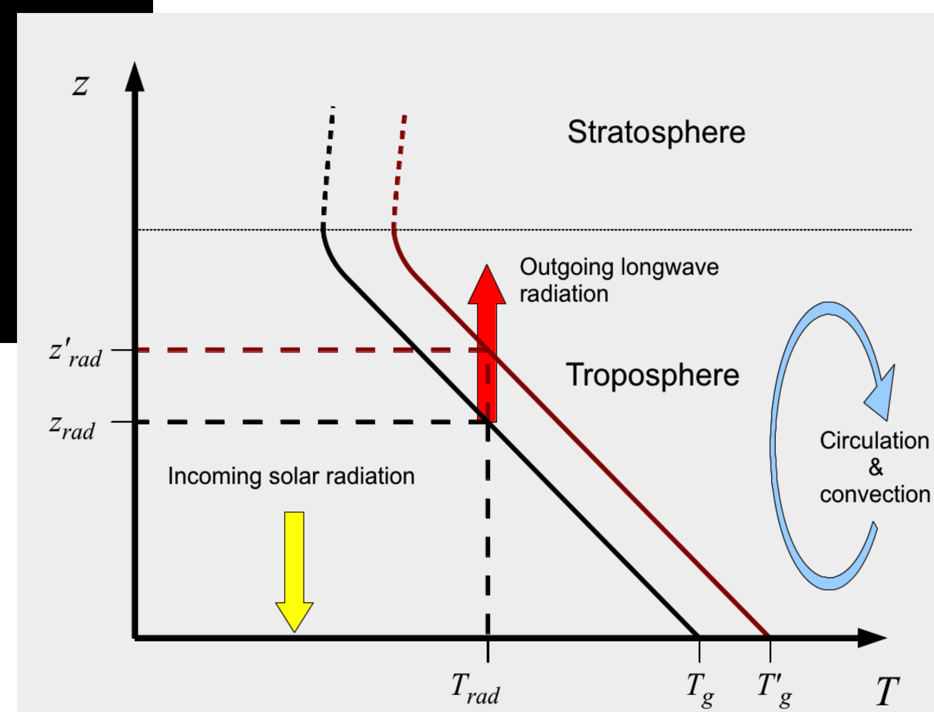
CORF Meeting · Woods Hole · 2018 October 15
S. Paine

Gray gas greenhouse effect



Real atmosphere:

- Clouds
- Lapse rate feedback
- Not gray...



Radiative cooling rate – Clough diagram

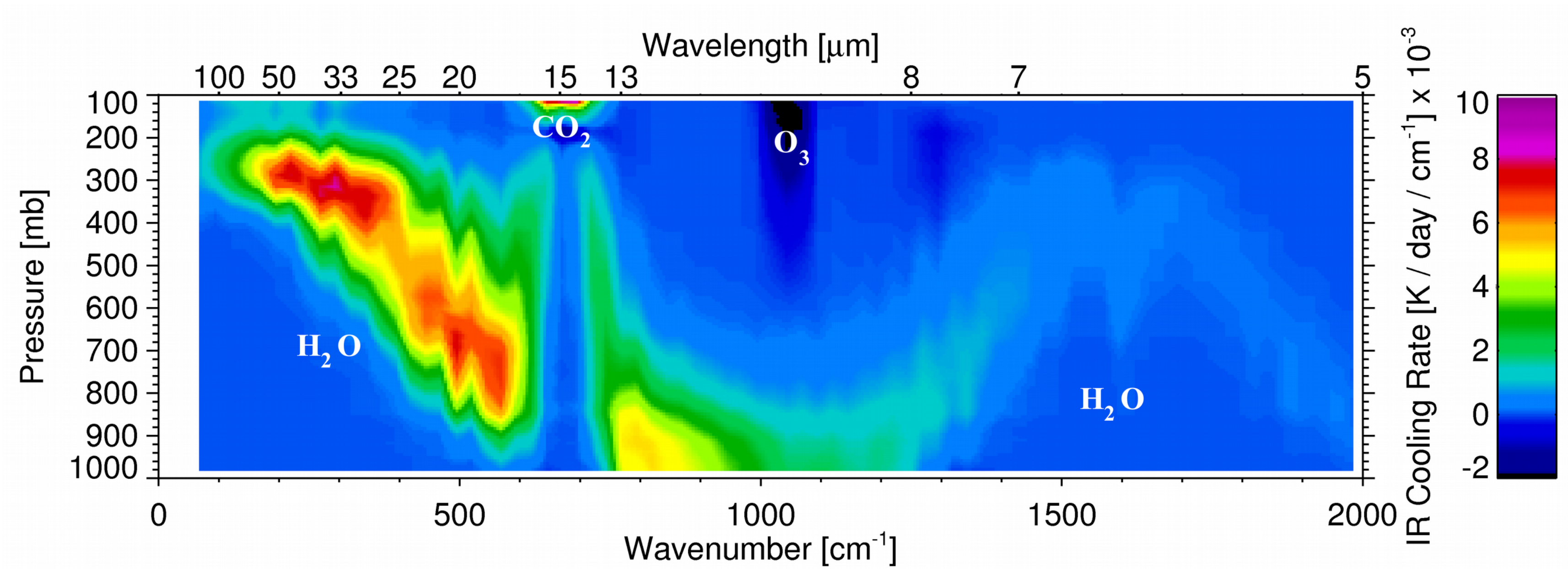
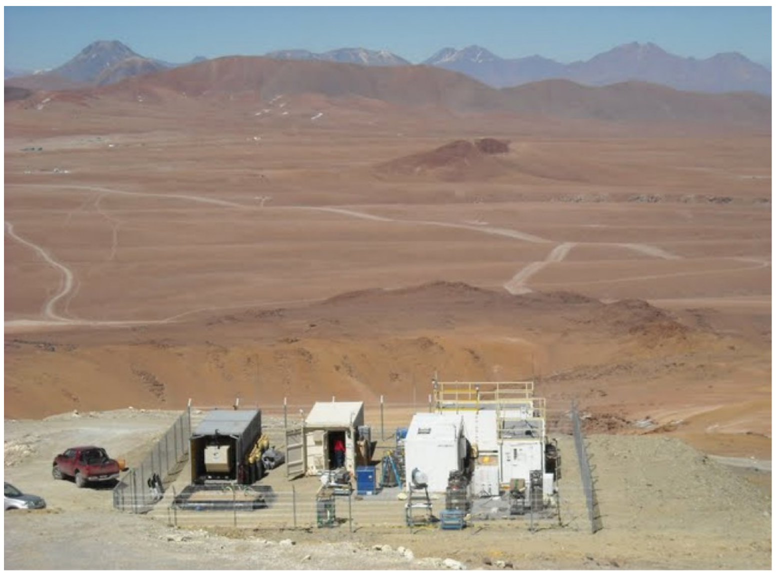


Figure: Turner and Mlawer (2010) BAMS 91:911

- Water vapor drives the cooling rate (flux divergence / heat capacity) through the troposphere.
- Continuum dominates in windows between strong lines and bands.
- Accurate H_2O spectroscopy is an essential part of climate models.
- Lab measurements under atmospheric conditions are very difficult.

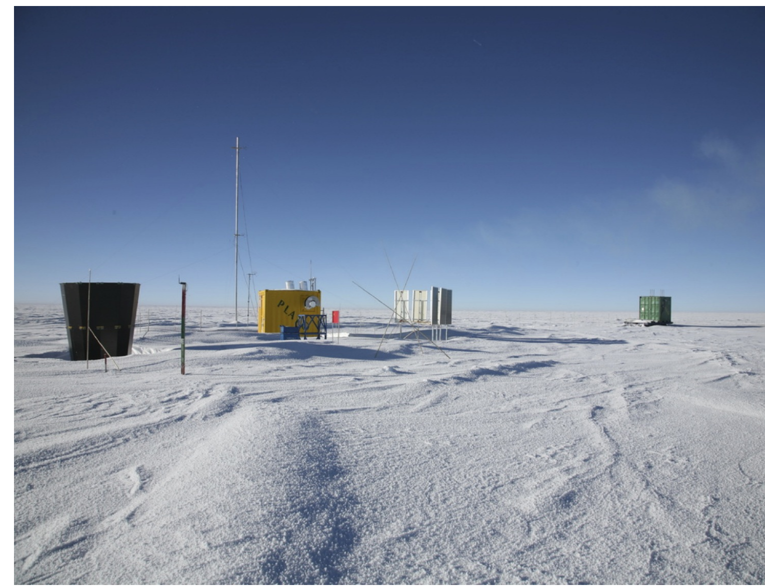
Two field experiments targeting H_2O spectroscopy

General method – Use differences between measured radiance spectra and computed spectra based on an estimate of the atmospheric state to improve spectral data.



RHUBC-II – Cerro Toco, Chile

- Multiple spectrometers covering submillimeter through infrared
- Atmospheric state from radiosondes augmented by microwave radiometers



Dome A, Antarctica

- Broadband submillimeter spectrometer
- Atmospheric state from meteorological reanalysis, recalibrated using spectral sub-bands

The RHUBC-II Campaign

Cerro Toco, Chile, 2009

Principal Investigators

Eli Mlawer, Atmospheric and Environmental Research, Inc.
Dave Turner, NOAA

Collaborating Institutions / Instrument PI's

NASA Langley Research Center, USA / Marty Mlynczak

Instituto de Fisica Applicata, Italy / Luca Palchetti

University of Denver, USA / Tom Hawat

University of Cologne, Germany / Susanne Crewell

Smithsonian Astrophysical Observatory / Scott Paine

Argonne National Laboratory / Maria Cadeddu, Rich Coulter

Supported by DOE ARM program, with additional support from institutional collaborators.

SAO supported in part by SI endowment funds.

RHUBC-II instruments

- Radiosondes and surface meteorology
- Millimeter-wave temperature and RH profiling radiometers
- Four Fourier transform spectrometers covering entire thermal IR

RHUBC-II – spectral coverage over entire thermal IR

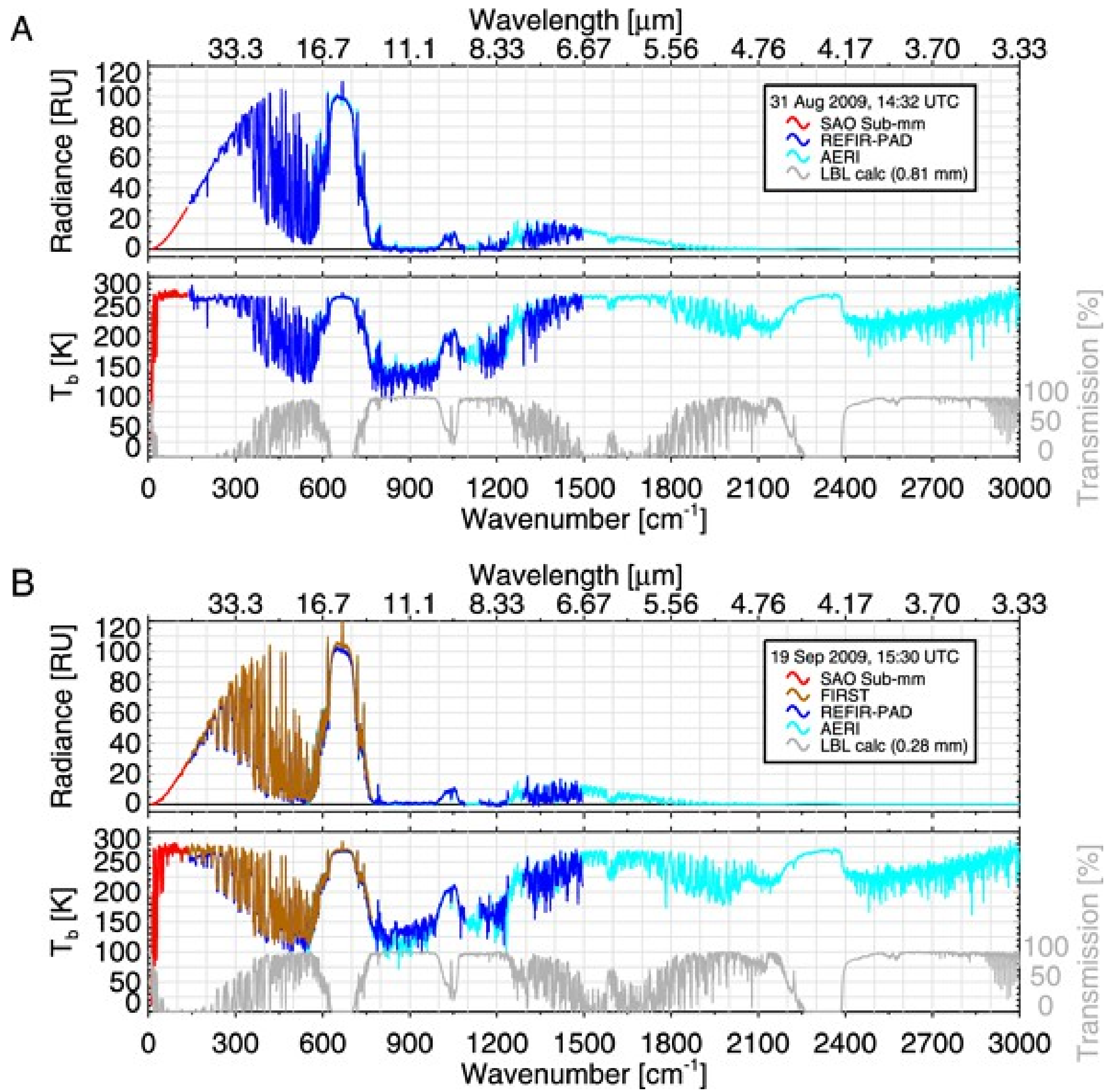


Figure: Turner, et al. 2012 GRL 39:L10801

RHUBC-II – H_2O pure rotation band

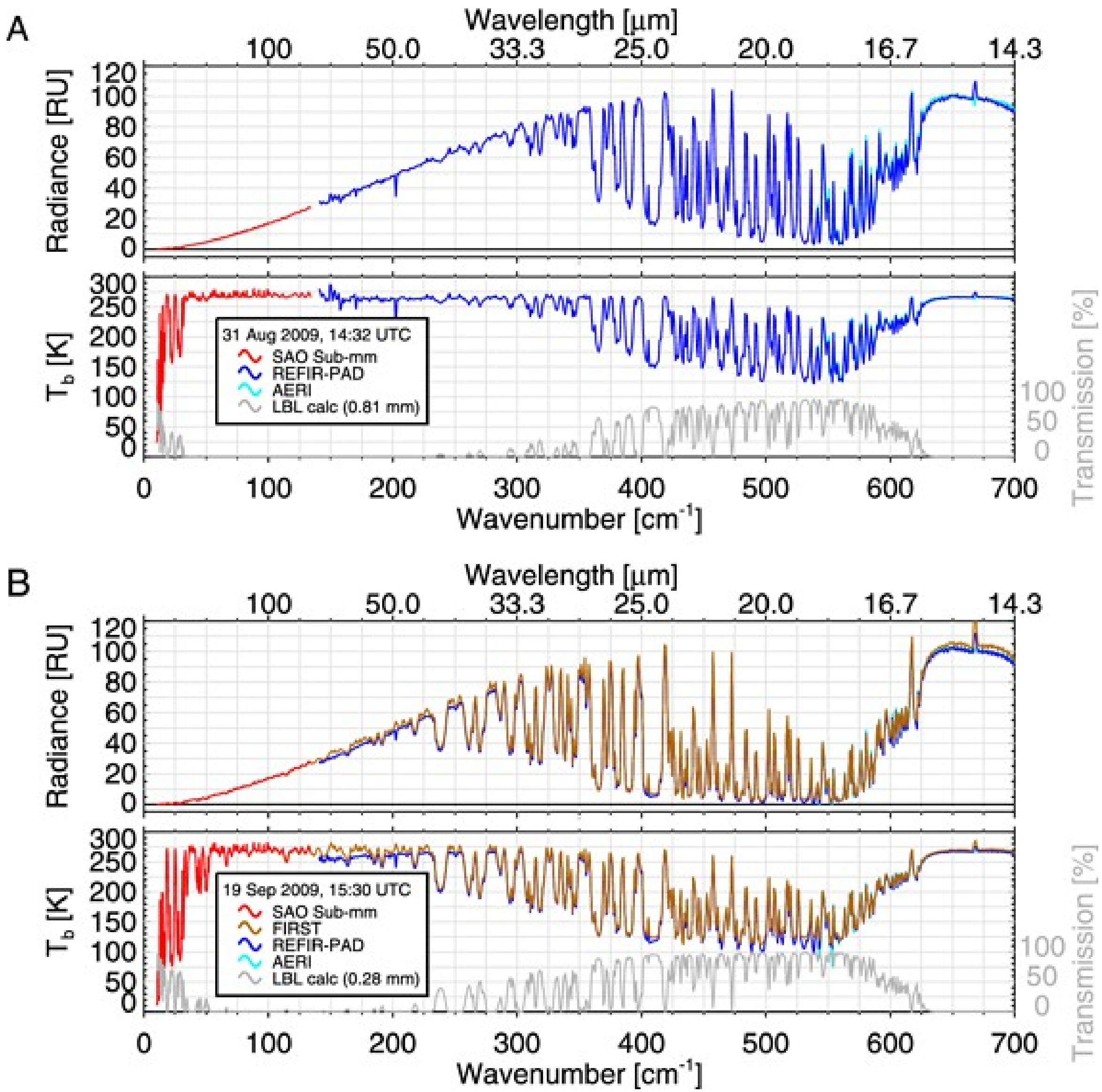
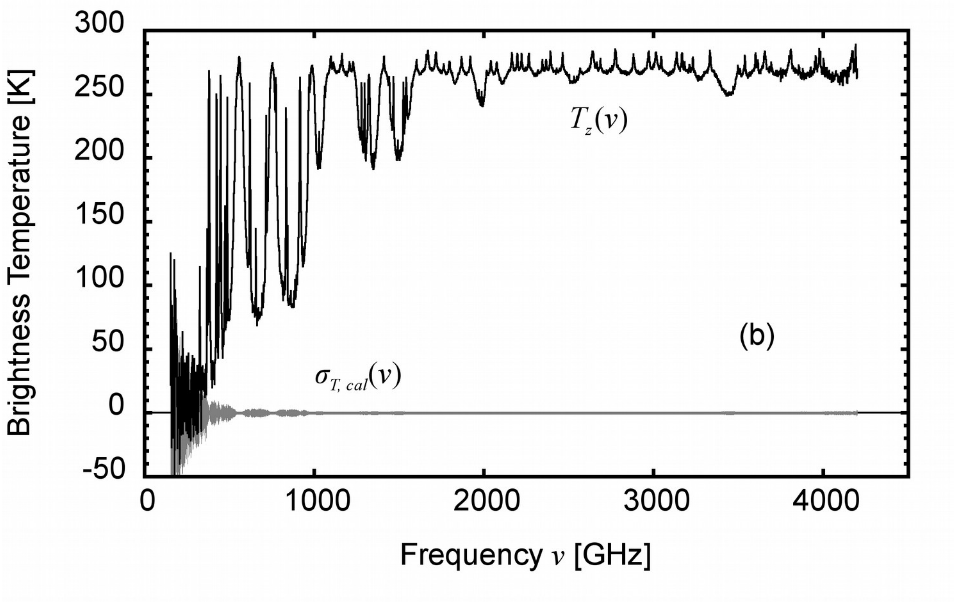


Figure: Turner, et al. 2012 GRL 39:L10801

RHUBC-II atmospheric state

- Sondes aren’t perfect
  - Sensitive to solar radiation
  - Humidity sensor offsets
  - Response time
  - Flight path in mountain turbulence
- Augmented by millimeter wave (183 GHz) radiometry (~2 DOF)
- Additional iterative adjustment during spectral residuals analysis

RHUBC-II submillimeter spectra

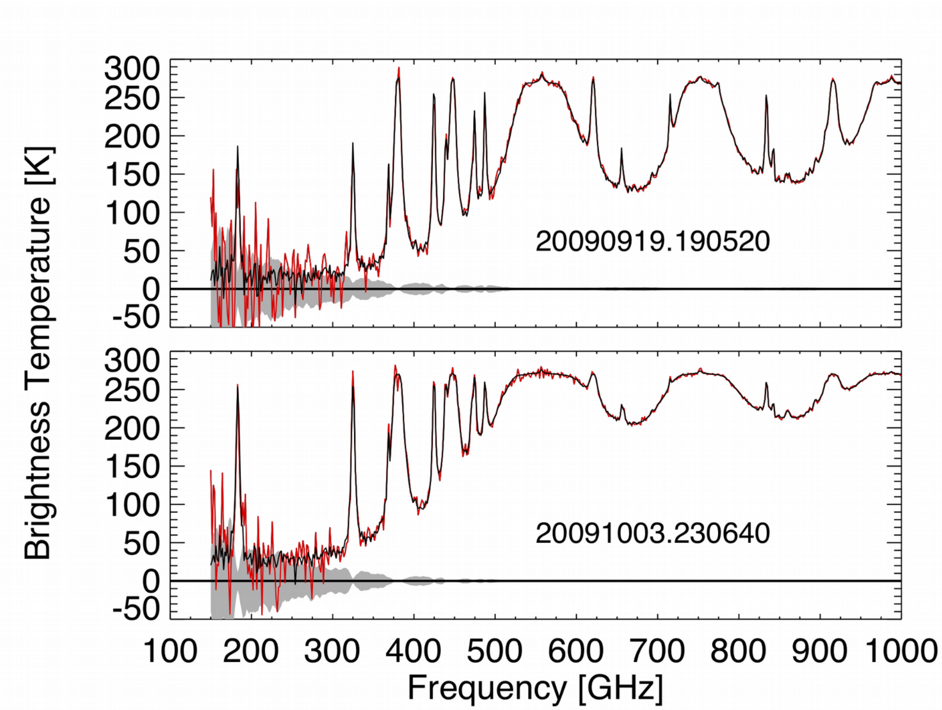


Calibrated T_b product

114 cases with PWV < 0.3 mm (bin 1)

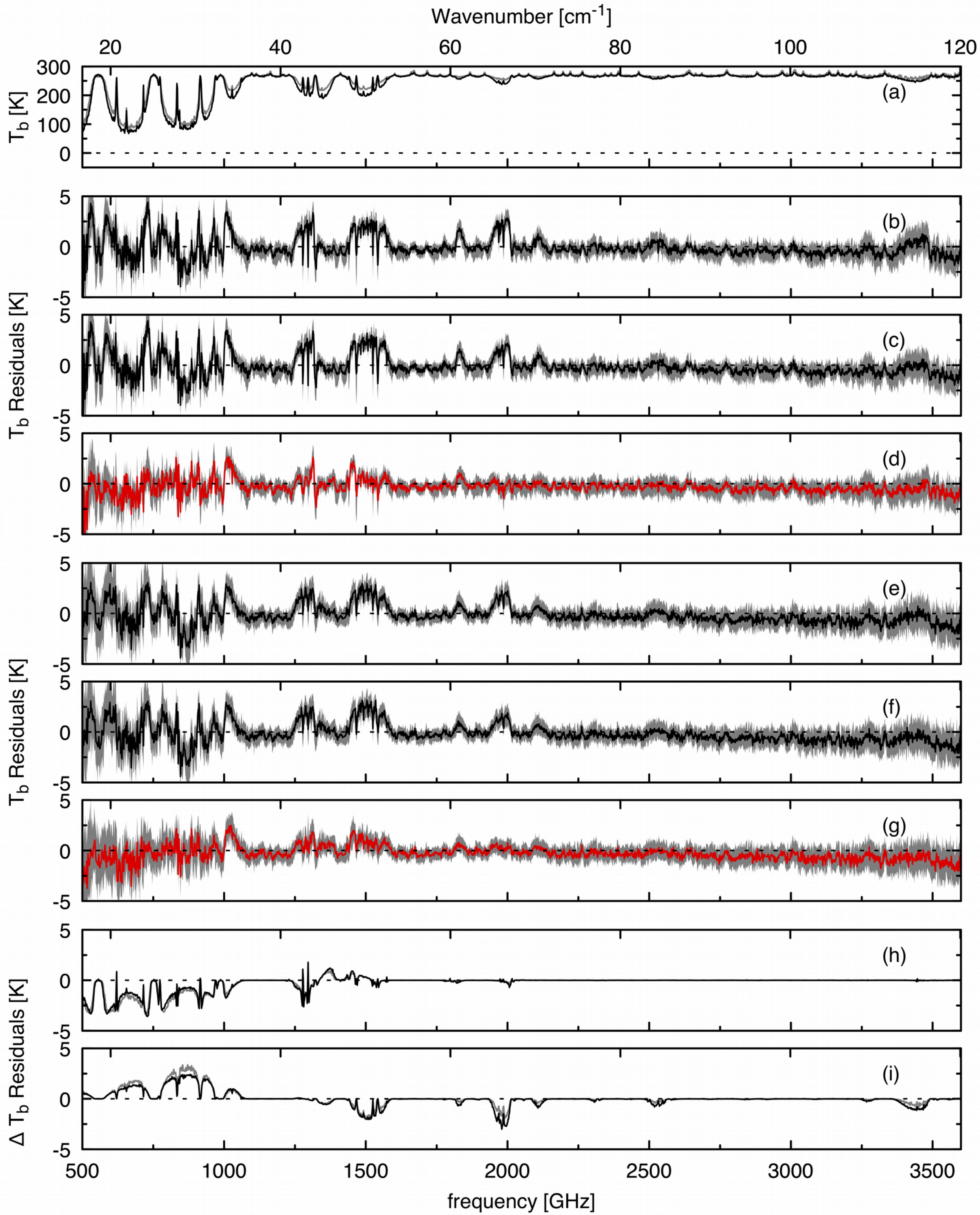
132 cases with 0.3 mm < PWV < 0.5 mm (bin 2)

PCA filtered



Figures: Paine and Turner 2013 IEEE Trans. Geosci. Remote Sens. 51:5187

RHUBC-II submillimeter residuals



Median T_b for two dry PWV bins

PWV < 0.3 mm (bin 1)

AER 3.4.2 lines + MT_CKD_2.8 continuum

HITRAN 2012 + MT_CKD_2.8

AER 3.5 + MT_CKD_3.0

0.3 < PWV < 0.5 mm (bin 2)

AER 3.4.2 + MT_CKD_2.8

HITRAN 2012 + MT_CKD_2.8

AER 3.5 + MT_CKD_3.0

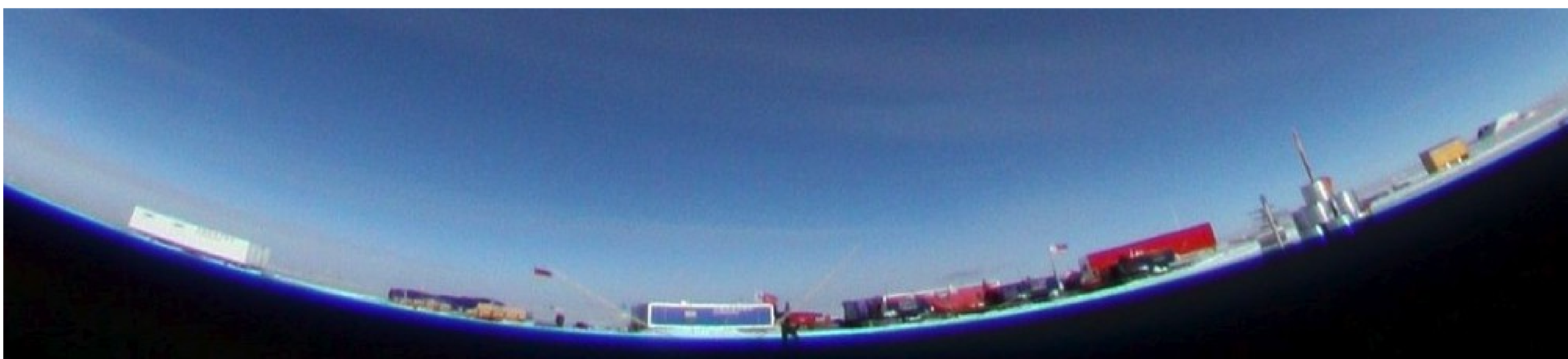
Changes due to line widths

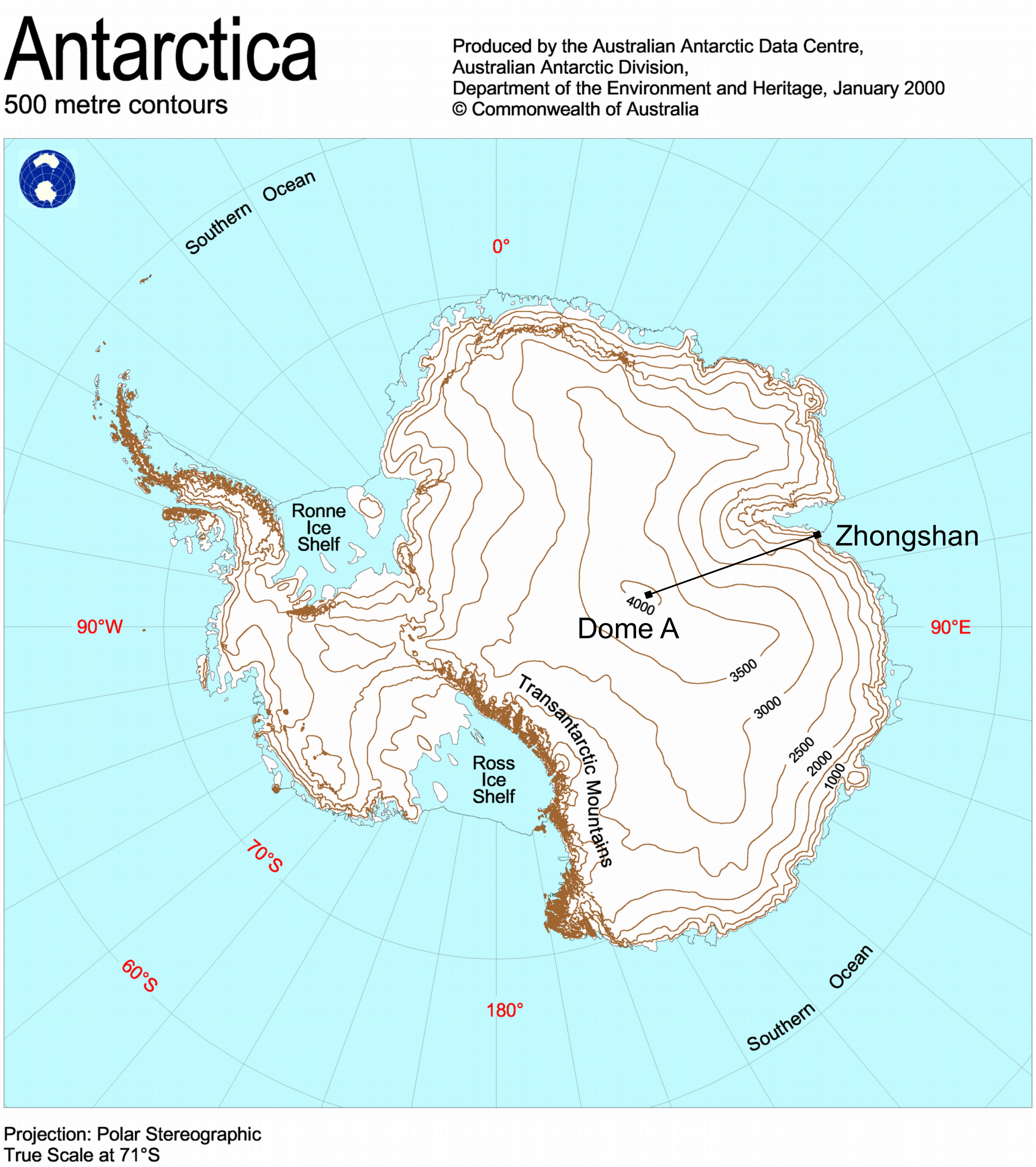
Changes due to continuum

Figure: Mlawer, et al. 2018 Submitted to JGR Atmospheres

Dome A, Antarctica

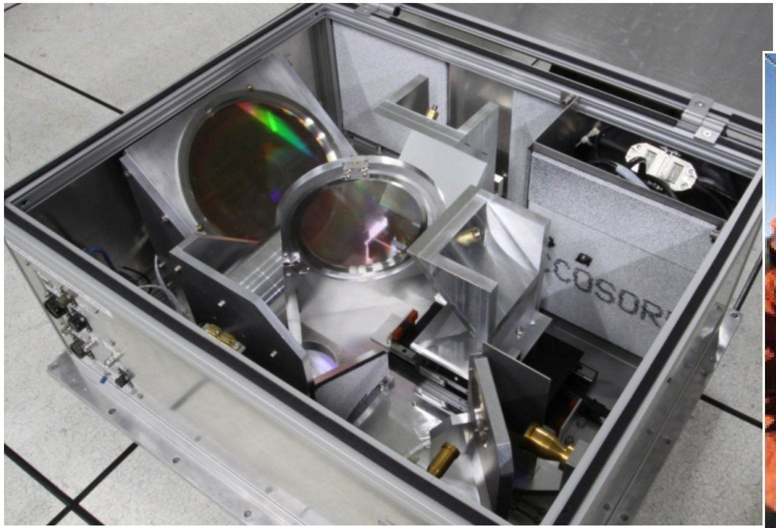
- Highest point on Antarctic Plateau (4100 m.a.s.l., 550 – 600 mbar)
- Cold (winter $T_g \sim 200$ K), extremely dry, low winds.
- Research station under development by Polar Research Institute of China.
- Collaboration between SAO and group headed by Shengcai Shi at Purple Mountain Observatory, Nanjing, to deploy a far-infrared FTS.
- Instrument support module by UNSW (J. Storey, M. Ashley, et al.).




Antarctica
500 metre contours
Produced by the Australian Antarctic Data Centre,
Australian Antarctic Division,
Department of the Environment and Heritage, January 2000
© Commonwealth of Australia
Southern Ocean
0°
Ronne Ice Shelf
Zhongshan
4000
Dome A
90°W
90°E
3500
3000
Transantarctic Mountains
2500
2000
1000
Ross Ice Shelf
70°S
60°S
180°
Southern Ocean
Projection: Polar Stereographic
True Scale at 71°S

Dome A FTS

- Spectral coverage 25 cm^{-1} – 500 cm^{-1} in two bands.
- SAO / PMO design, fabrication by QMC Instruments (UK) and Blue Sky Spectroscopy (Canada).
- Installed in UNSW PLATO module by PRIC 4th traverse team in Jan. 2010.



Dome A transmittance statistics (isothermal approximation)

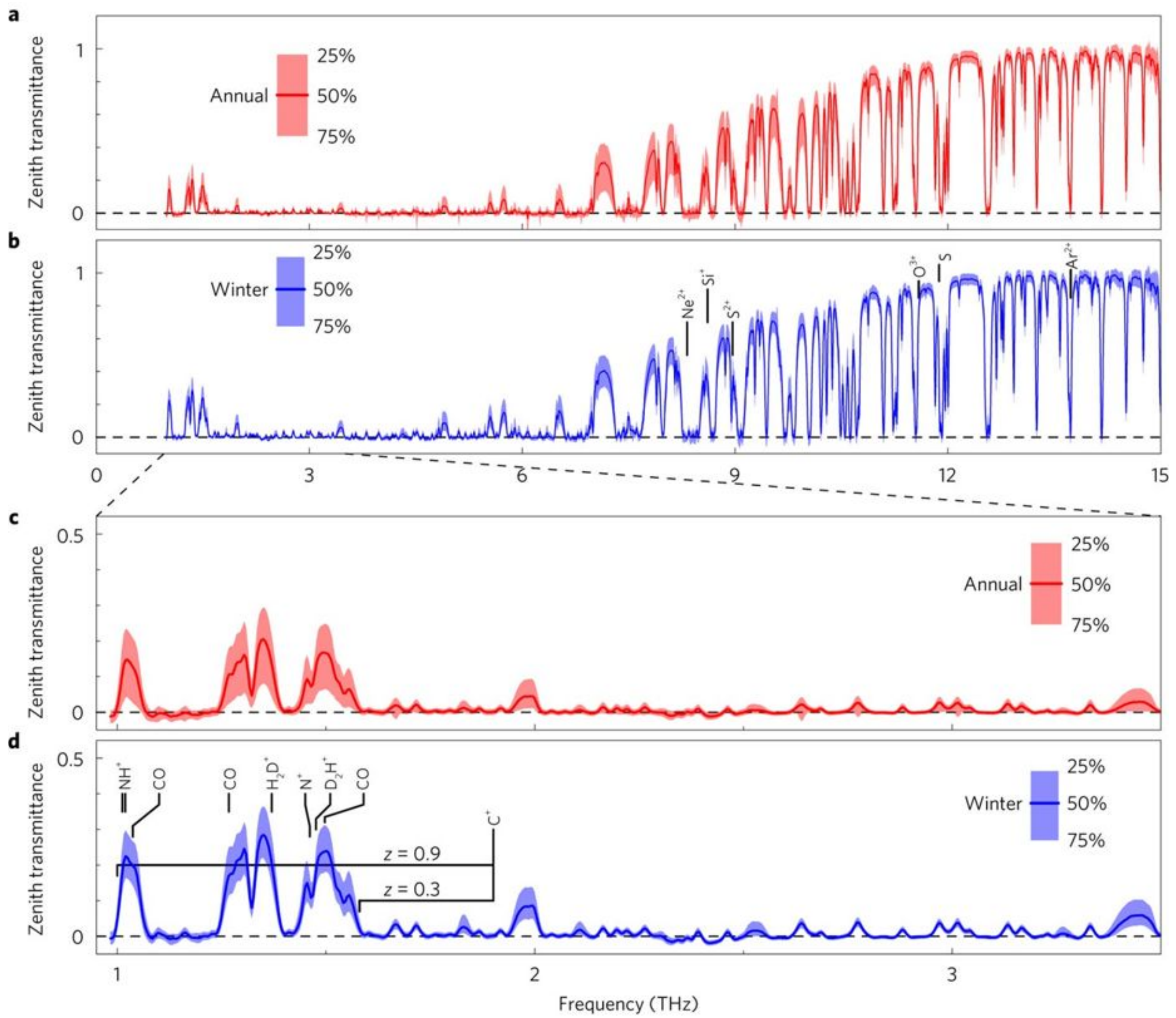
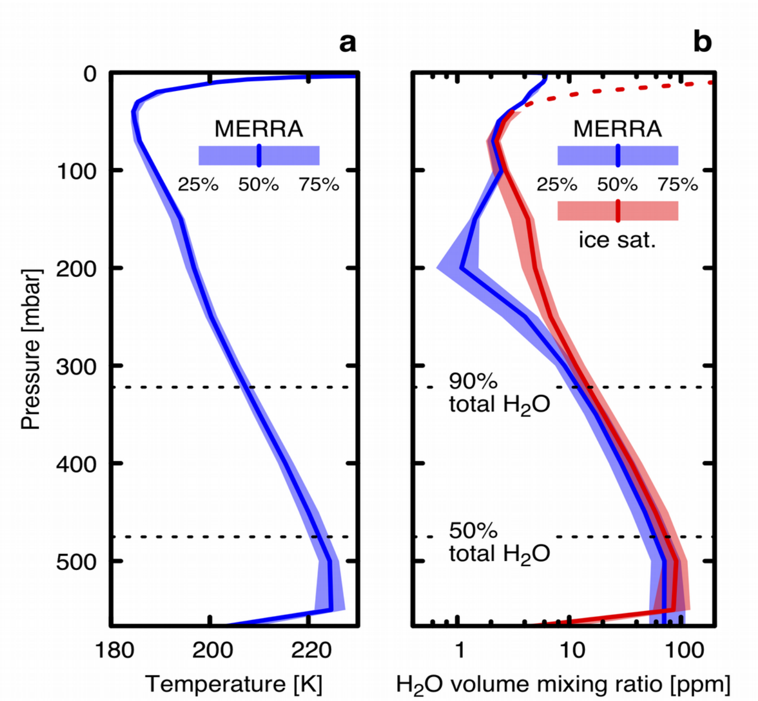
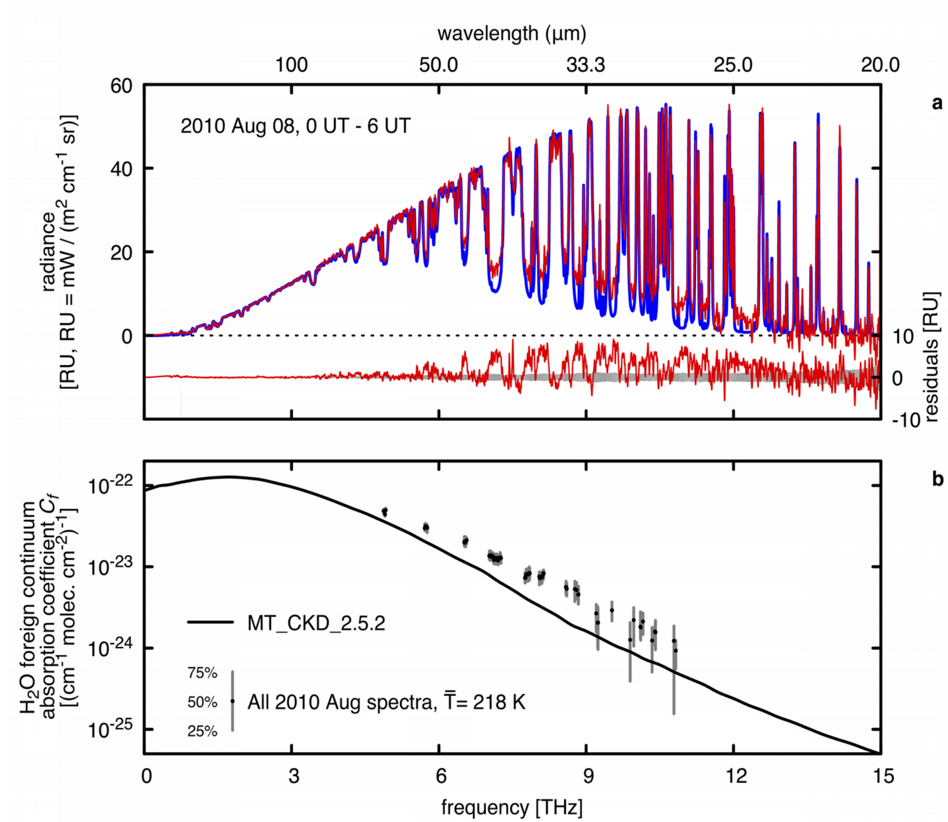


Figure: Shi, et al. 2016 Nat. Astron. 1:1

Dome A continuum study



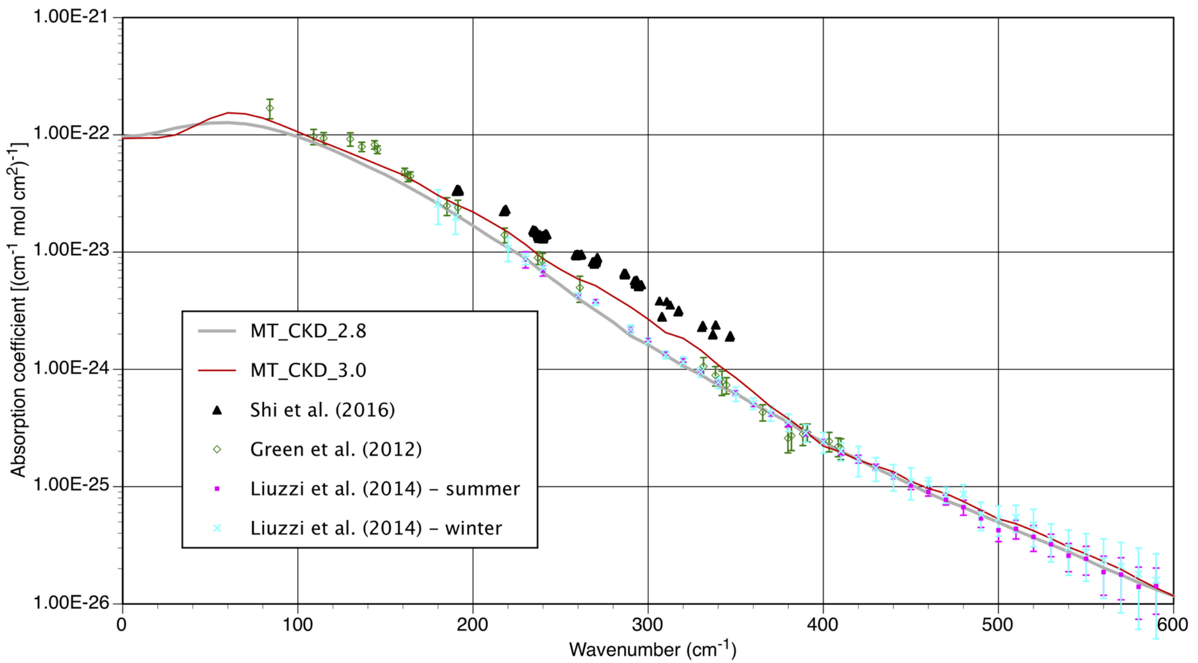


Analysis method:

- Start with reanalysis (MERRA) profiles, fit surface inversion temperature and scale H_2O column using band edge channels (2 DOF).
- Attribute residuals in transmission windows to continuum adjustment
- Quartile H_2O scale factors relative to MERRA were 1.06 / 1.21 / 1.43

Figure: Shi, et al. 2016 Nat. Astron. 1:1

H_2O foreign continuum comparison



- Dome A analysis implies higher adjustment, larger than the 20% - 30% estimated errors in RHUBC-II derived continuum in the overlapping spectral region.
- H_2O line spectroscopy improvements (also from RHUBC) could affect results in Dome A continuum derivation.
- Plan to revisit the Dome A data set using updated reanalysis (MERRA2), new spectral data, and improved data screening for clear sky.

Figure: Mlawer, et al. 2018 Submitted to JGR Atmospheres

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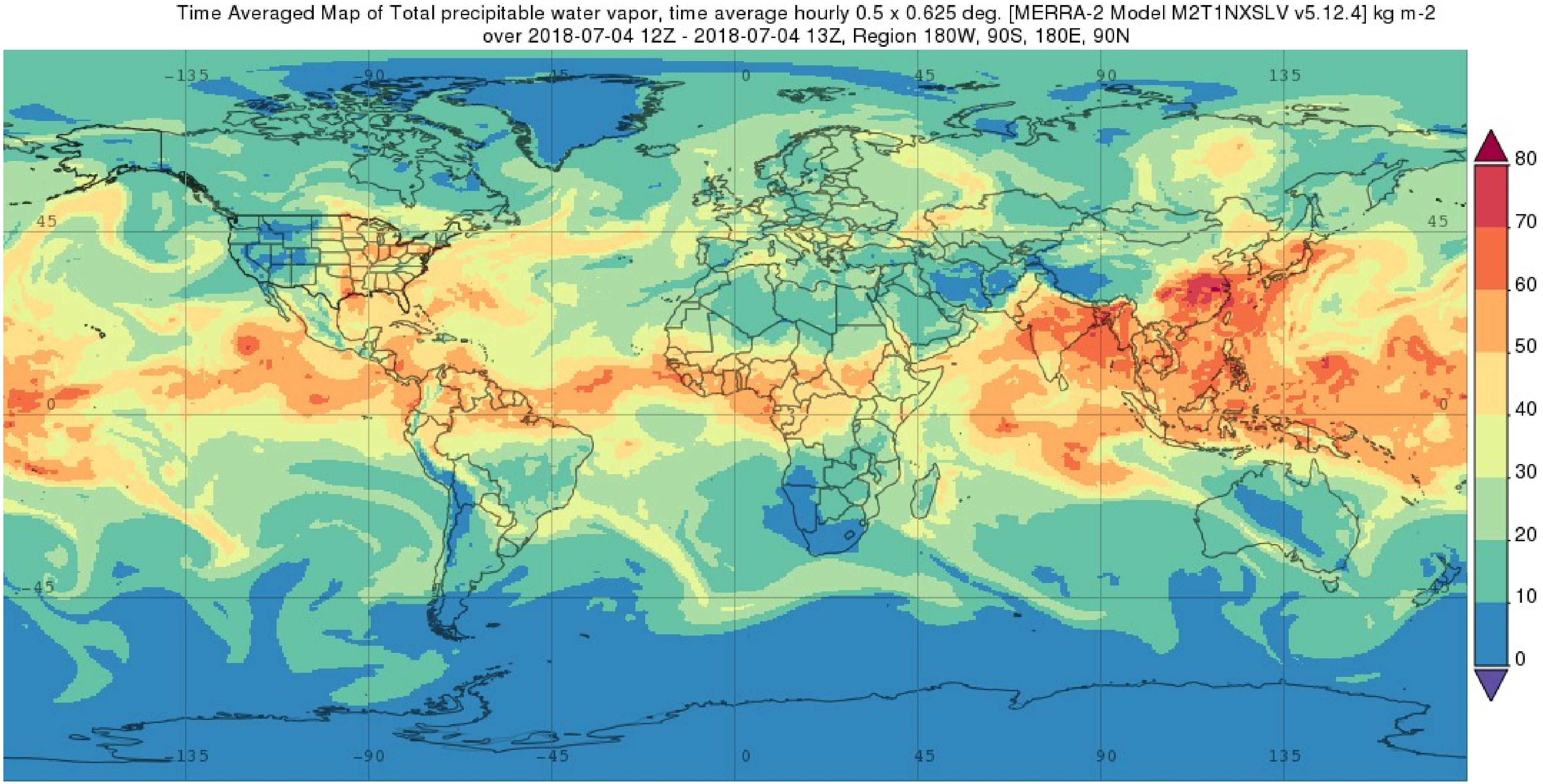
Reanalysis – the past atmospheric state

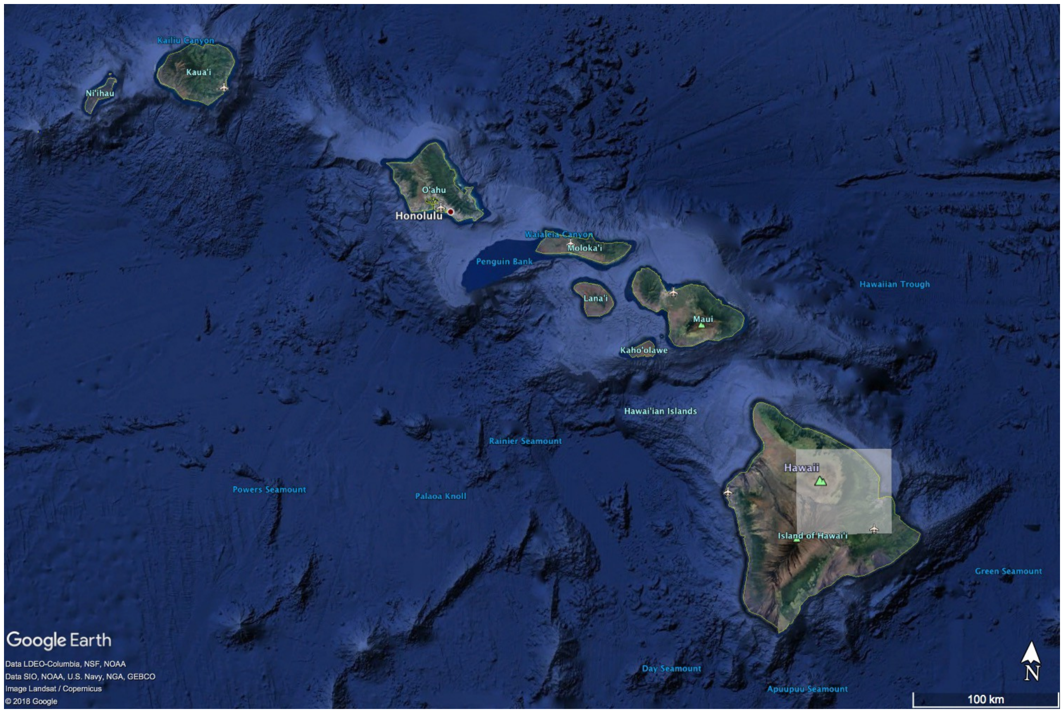
- Goal – assimilate the growing archive of remote and in-situ measurements of the atmosphere into a best-estimate of the past atmospheric state.
- Lots of measurements, but the system has *way* more degrees of freedom
- General idea – use a GCM to model the system, add forcing terms to assimilate measurements, and let the model run
- Continuously-updated examples: NASA MERRA-2, ECMWF ERA-Interim

Example – PWV snapshot from MERRA-2



Total precipitable water integrated over 42 MERRA vertical levels

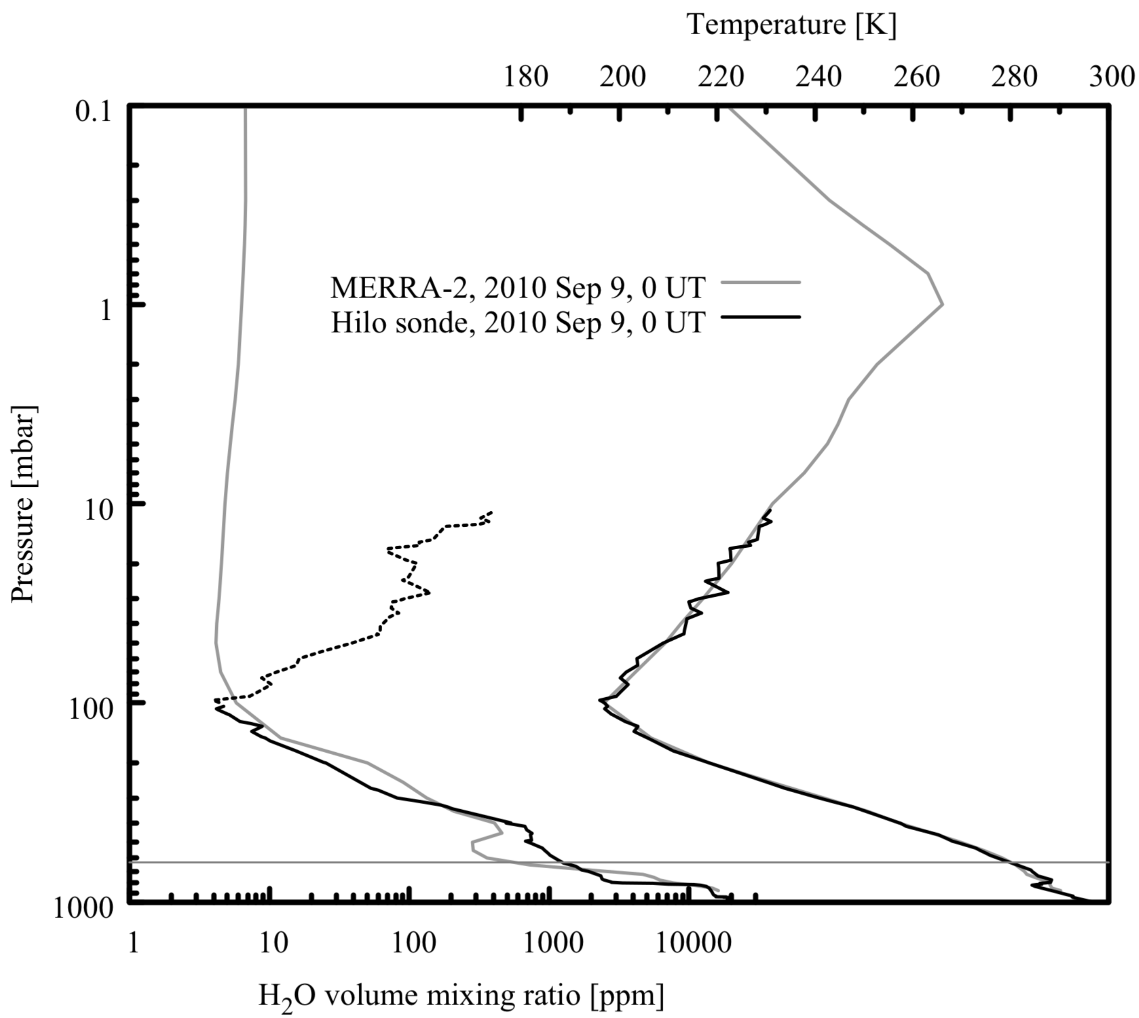
Example – a 10-year point climatology for MaunaKea, Hawaii



- Horizontally interpolate MERRA-2 grid (shaded box) to MaunaKea (green symbol)
- Compile 10-year statistics for vertical profiles
- Use quantile profiles to drive radiative transfer code

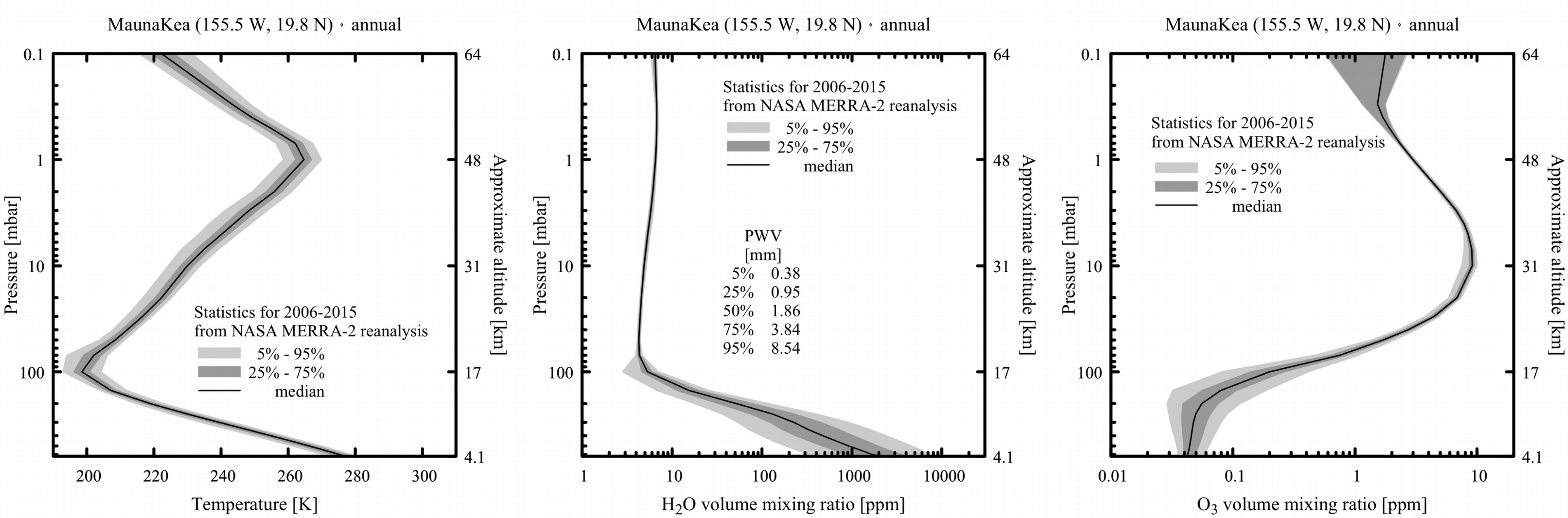
- Here, consider a vertical path for astronomical site characterization
- Same method applies for other paths and applications, e.g. radio communication link or interference assessment

Typical Hilo, Hawaii sonde vs. MERRA-2



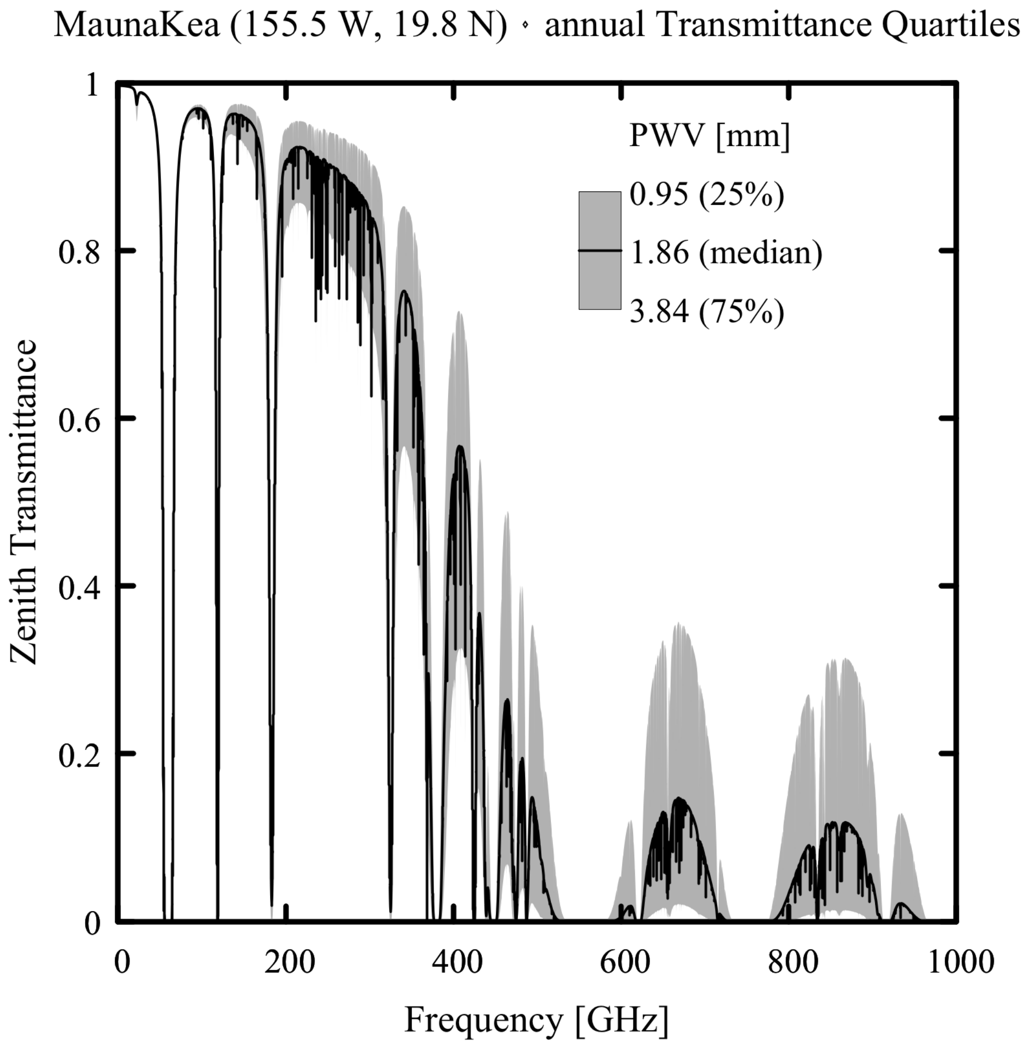
Note that this sounding itself will have been statistically assimilated into the reanalysis.

MaunaKea – 10-year vertical profile statistics from MERRA-2



- Percentile profiles from observatory height upwards
- Input to radiative transfer code (*am*)

Predicted vs. measured site statistics



Comparison with 2006-2015 225 GHz optical depth quartiles from operational site monitor (CSO tipper)

quartile	CSO tipping radiometer	model	difference
25	0.068	0.051	0.017
50	0.106	0.087	0.019
75	0.185	0.170	0.015

- Constant difference suggests dry bias in measurement or model.
- Here, we had long-term radiometry data, but reanalysis data can be used to produce a “virtual site test” of the long-term properties of any site, which can be validated with a comparatively short run of local radiometric data.

Final comments

- For astronomy and radio propagation applications in the millimeter and submillimeter bands, spectral data and radiative transfer codes are very good, and well-validated.
- Combining up-to-date RT codes with modern reanalysis data sets, it is possible to accurately estimate the propagation characteristics of any given site.
- Improvements are still needed for secure modeling of atmospheric radiation in the submillimeter / FIR band, and for critical remote sensing applications throughout the millimeter and submillimeter bands.