Advances in Atmospheric Science Using Radio Occultation Observations

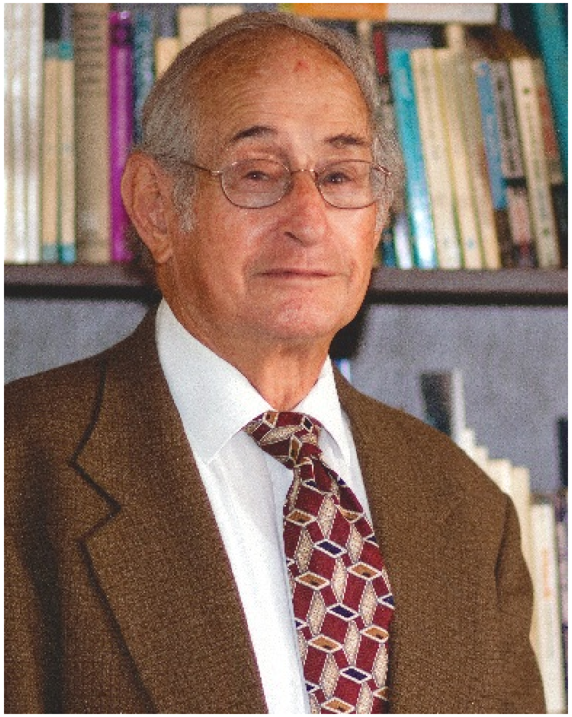
Using the (still!) world's most accurate and precise thermometer from space

Richard A. Anthes

19 September 2019

Helsingør, Denmark
19-25 September, 2019

Tribute to Ben Herman (1929-2018)

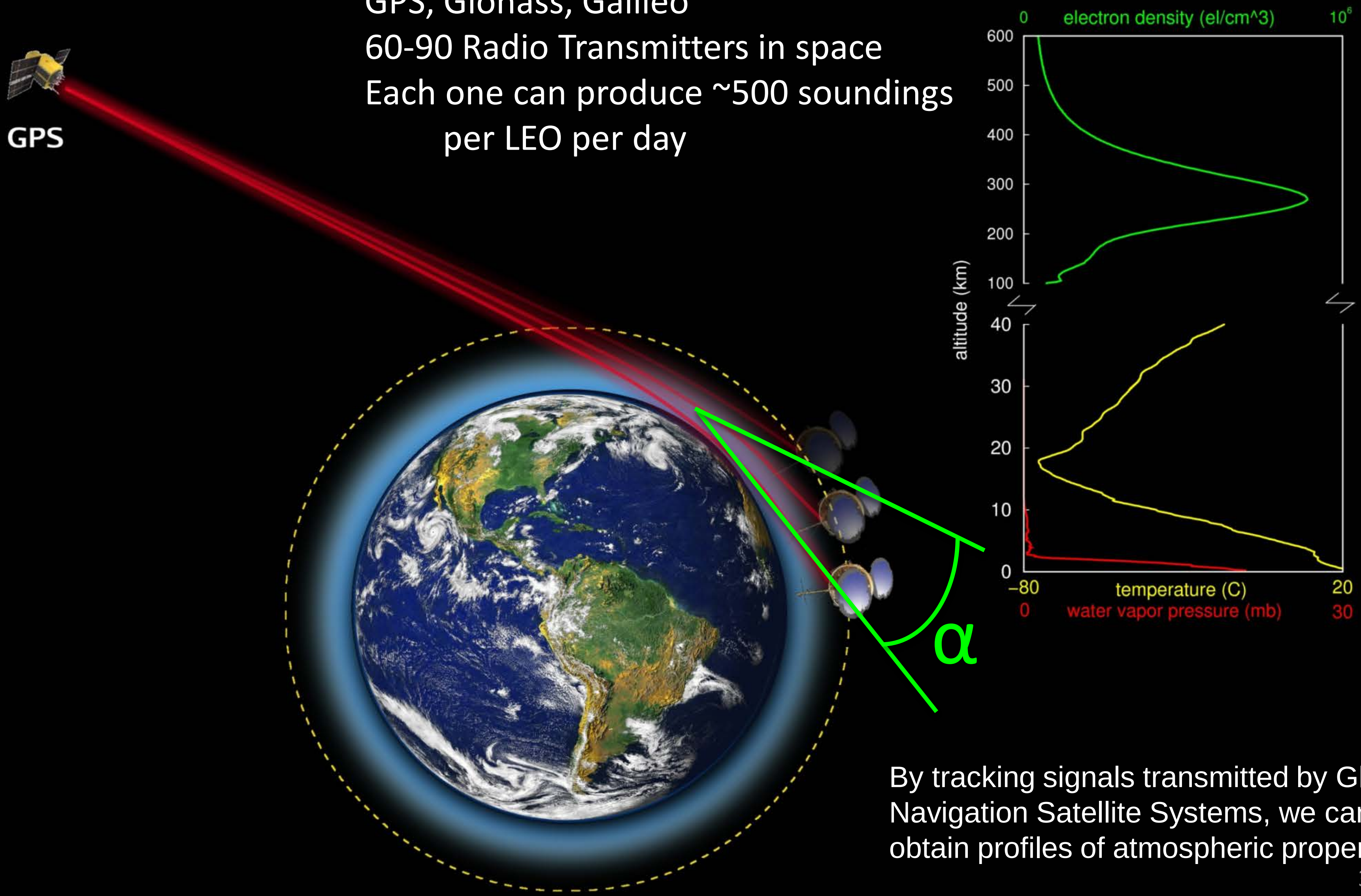


Summer 1992
Rick (nervously) Ben, will it work?
Ben: Yes, I think so.

This gave me all I needed to proceed with GPS/MET!

For our guests: Introduction to Radio Occultation

GPS, Glonass, Galileo
60-90 Radio Transmitters in space
Each one can produce ~500 soundings
per LEO per day



By tracking signals transmitted by Global Navigation Satellite Systems, we can obtain profiles of atmospheric properties.

Characteristics of RO Data

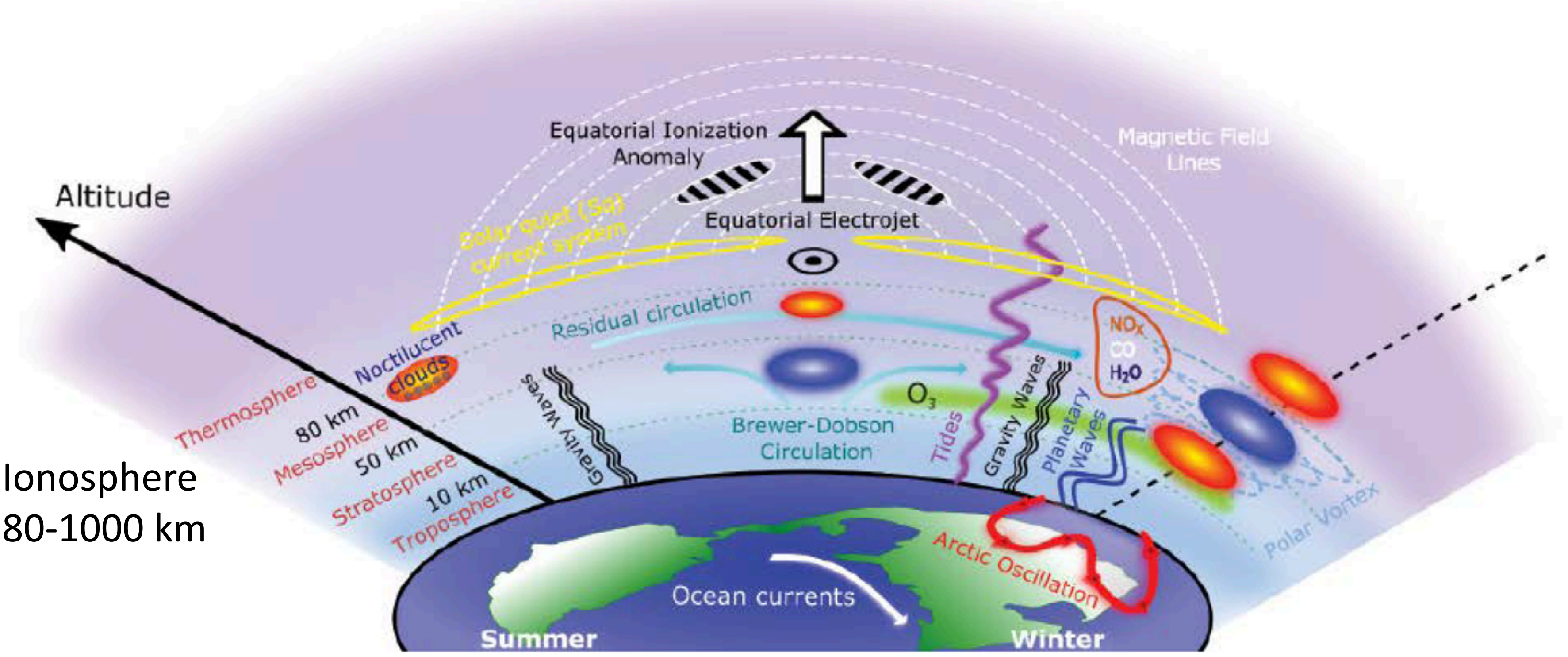
- Limb sounding geometry complementary to ground and space nadir viewing instruments
- Global coverage
- Profiles ionosphere, stratosphere and troposphere
- High accuracy (equivalent to <0.5 K; average accuracy <0.1 K)
- High precision (0.02-0.05 K)
- High vertical resolution (0.1 km near surface – 1 km tropopause)
- Only system from space to profile atmospheric boundary layer (ABL)
- All weather-minimally affected by aerosols, clouds or precipitation
- Absolute TEC accuracy < 1-3 TECU
- Relative TEC accuracy < 0.3 TECU
- Independent height and pressure
- Requires no first guess sounding
- No calibration required
- Climate benchmark quality-tied to SI standards
- Independent of processing center
- Independent of mission
- No instrument drift
- No satellite-to-satellite bias
- Compact sensor, low power, low cost

All of these characteristics have been demonstrated in peer-reviewed literature.

Scientific Uses of Radio Occultation Data

- **Weather**
  - Improve global weather analyses, particularly over data sparse regions such as the oceans, tropics, and polar regions
  - Increase accuracy of numerical weather forecasts
  - Improve understanding of tropical, mid-latitude and polar weather systems and their interactions
- **Ionosphere and Space Weather**
  - Observe global electronic density distribution
  - Improve the analysis and prediction of space weather
  - Improve monitoring/prediction of scintillation (e.g. equatorial plasma bubbles, sporadic E clouds)
- **Climate**
  - Monitor climate change and variability with unprecedented accuracy- **World's most accurate, precise, and stable thermometer from space!**
  - Evaluate global climate models and analyses
  - Calibrate infrared and microwave sensors and retrieval algorithms

Although this talk does not cover advances in ionospheric research and space weather, RO provides the only observing system to measure the troposphere, stratosphere and Ionosphere simultaneously. Following two slides were prepared by Nick Pedatella, UCAR COSMIC and NCAR HAO.



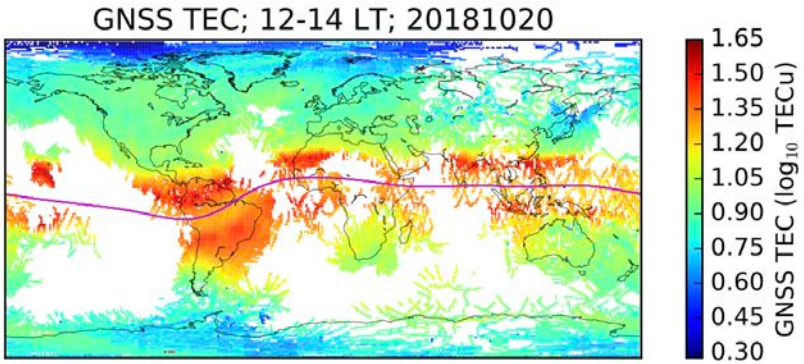
Ionosphere
80-1000 km

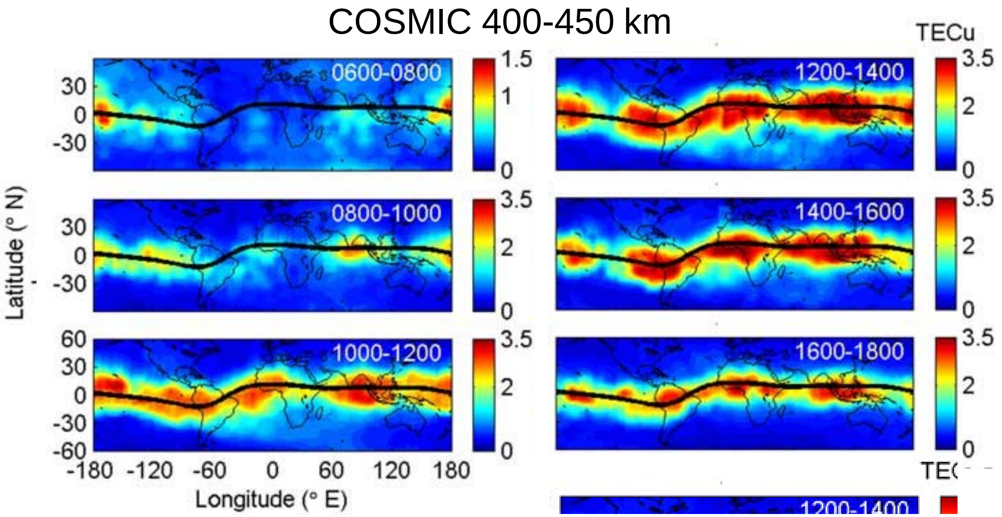
Fig. 1. Schematic of the coupling processes and atmospheric variability that occur during sudden stratospheric warming events. Red and blue circles denote regions of warming and cooling, respectively.

Pedatella, N.M. et al., 2018: How Sudden Stratospheric Warmings Affect the Whole Atmosphere. Earth and Space Science News, June 2018 pp. 35-38, Eos.org Ionosphere

- COSMIC provided one of the first prolonged set of observations of the global ionosphere, filling in critical gaps over the oceans.

- New insights into the global structures of the ionosphere, such as how the ionosphere varies in longitude at different local times and seasons.



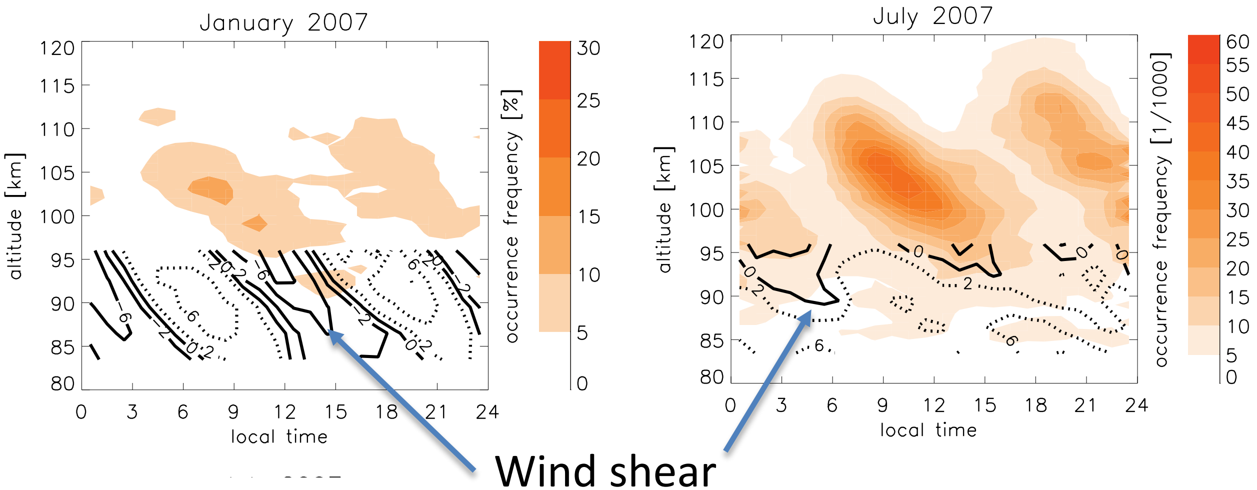


(Lin et al., 2007)

- COSMIC enabled height-resolved global observations of sporadic E layers (thin structures in E-region).

- Clear altitude and local time dependence consistent with the wind shear of the atmosphere semidiurnal tide. Provides insight into the formation mechanisms (top figures).

- Also provide first global view of sporadic E layers (bottom figures)



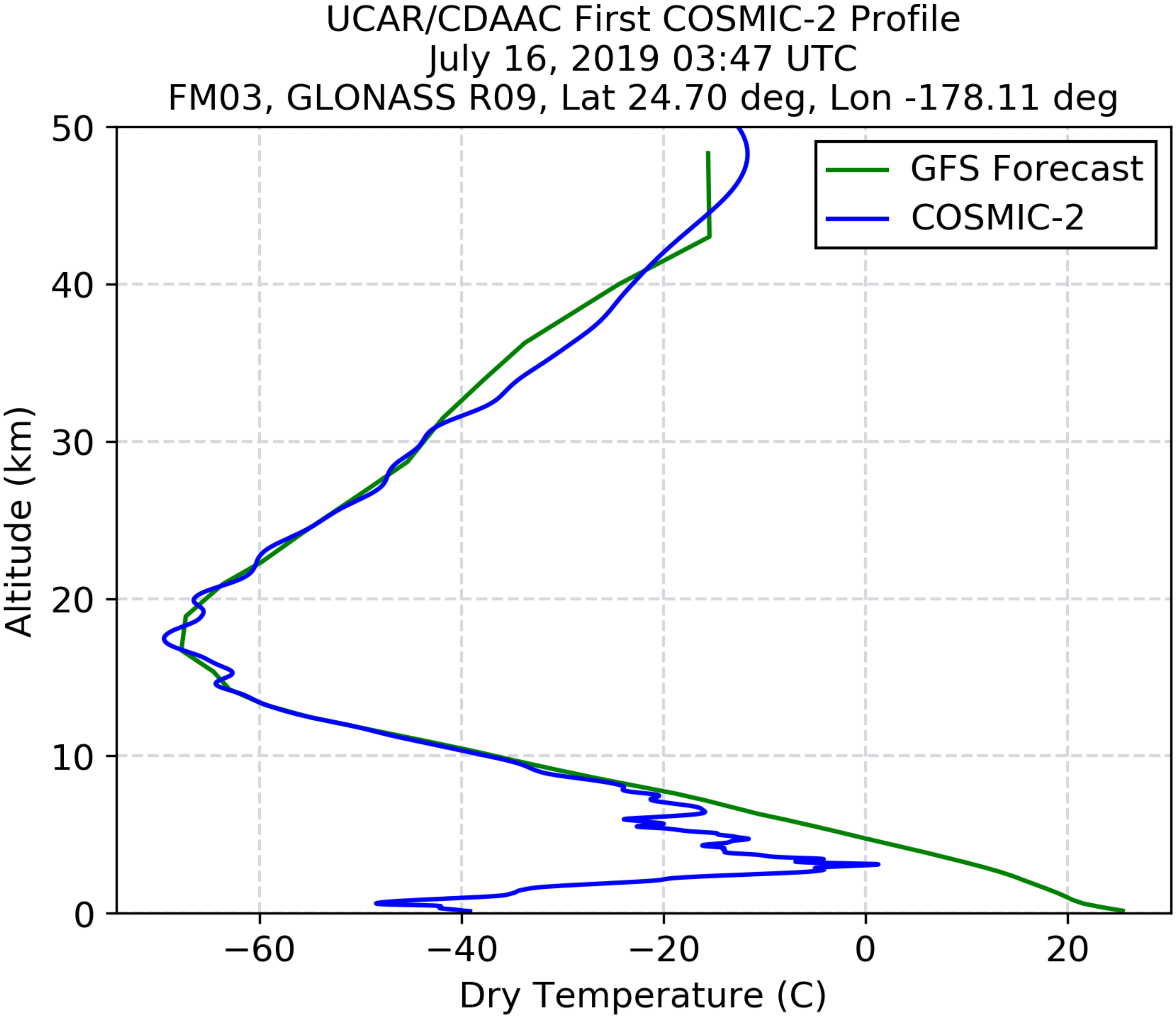
Wind shear

(Arras et al., 2009; Arras and Wickert, 2017)

COSMIC-1 and 2

Constellation Observing System for Meteorology, Ionosphere and Climate

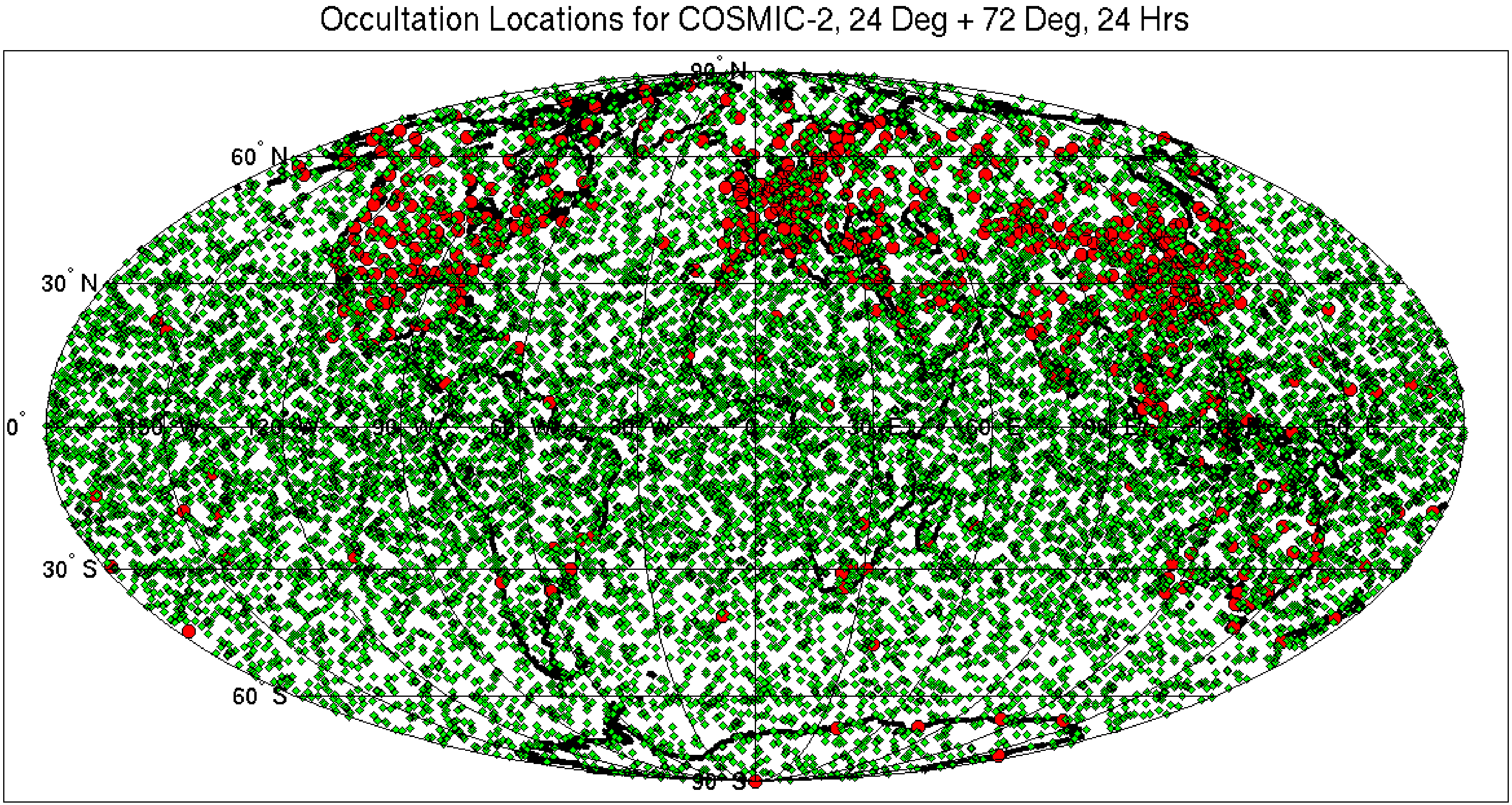
COSMIC-1 Launch
April 15, 2006
COSMIC-2 Launch
June 24, 2019


UCAR/CDAAC First COSMIC-2 Profile
July 16, 2019 03:47 UTC
FM03, GLONASS R09, Lat 24.70 deg, Lon -178.11 deg
GFS Forecast
COSMIC-2
Altitude (km)
50
40
30
20
10
0
−60
−40
−20
0
20
Dry Temperature (C)

Some of the Usual Suspects-a few days after launch

Back Row: Tyson Hager, Tom Meehan (JPL), Doug Hunt, Gavin James, Jan Weiss, Matt Hoekstra, Jeremiah Sjoberg, Qian Wu. Next row: Paul Strauss (Aerospace) ,Maggie Sleziak-Sallee, Clara Chew, Jeff Tien(JPL), Silvia Agnona, Iurii Cherniak, Ayesha Summers, Hailing Zhang, Pat Steincamp, Mark Seymour (NOAA), Nick Pedatella, Emily Lauer, Sergey Sokolovskiy, John Braun Tae-Kwon Wee, Min-Yang Chou. Front row: Rick Anthes, Willie Lopez, Teresa Vanhove, Hannah Huelsing, Bill Schreiner. (July 2019)

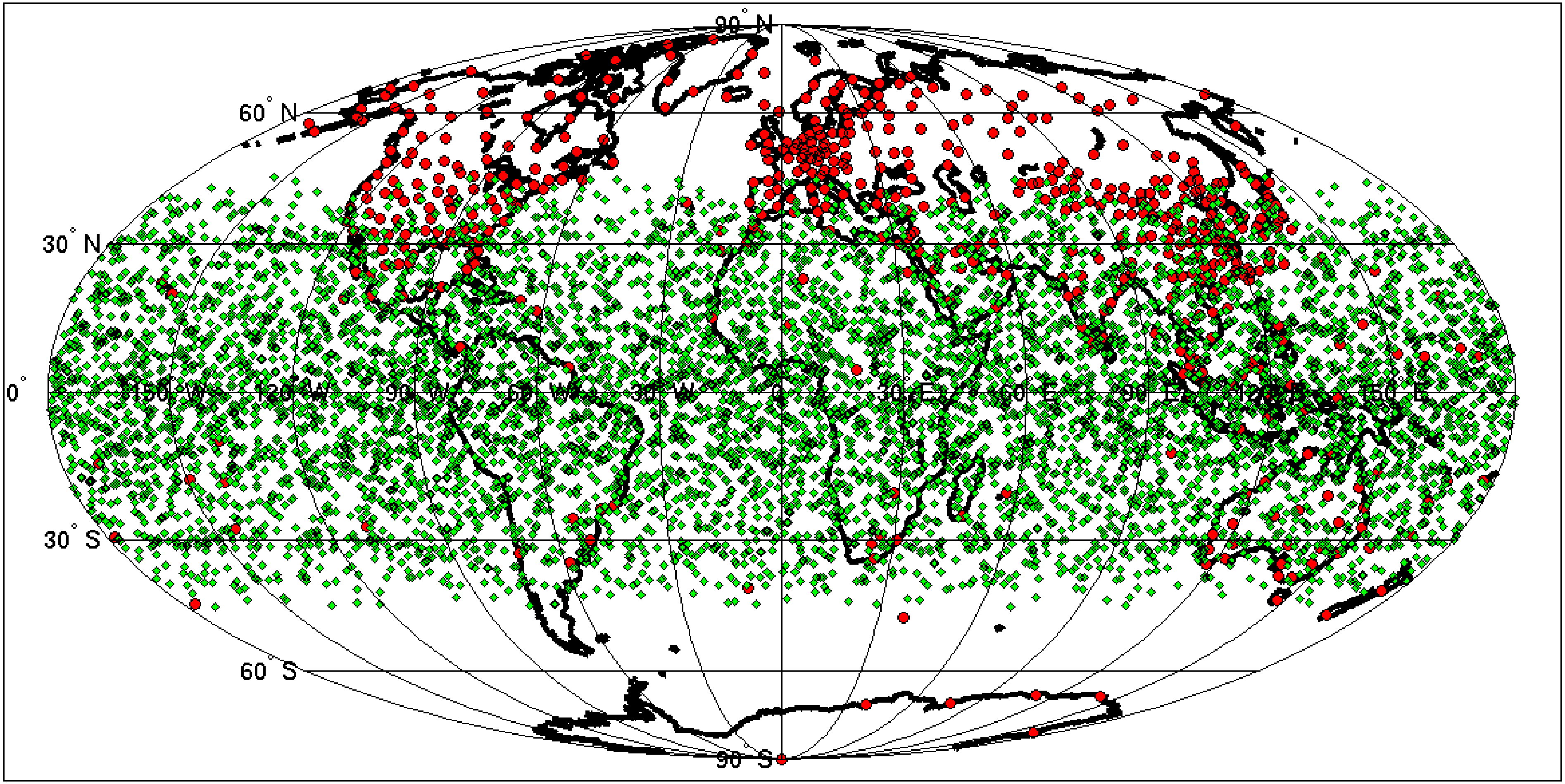
Original COSMIC-2 Plan



Final COSMIC-2

COSMIC 2-B cancelled October 2017

Occultation Locations for COSMIC-2, 24 Deg, 24 Hrs



Publications before and after COSMIC-1 launch

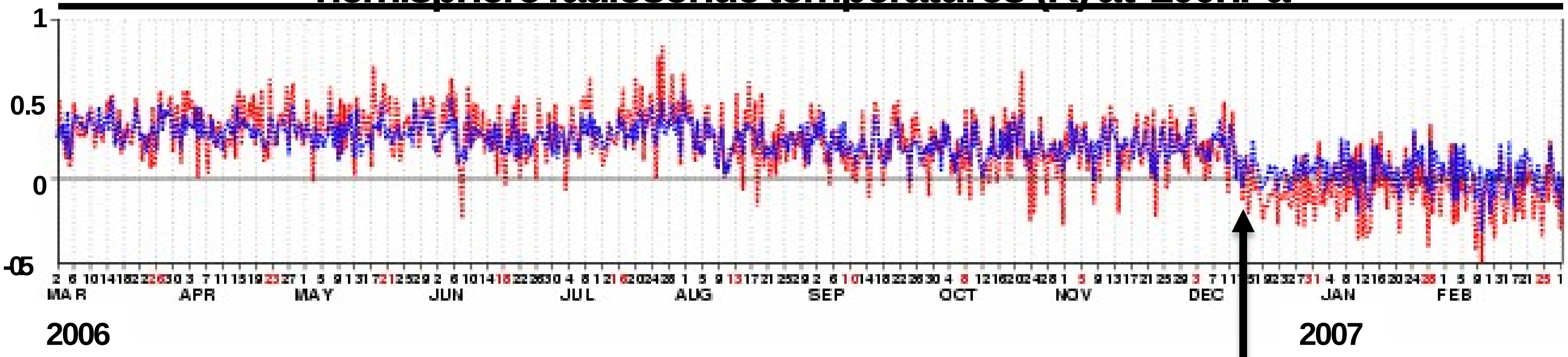
	1995-2005	2006-2019
Radio occultation	484	1469
RO and (COSMIC OR FORMOSAT-3)	14	554
RO and weather	81	315
RO and climate	49	482
RO and (space wx or ionosphere)	144	710

Web of Science 11 Aug 2019


RO
background
skill
Weather
weather
accuracy
C/NOFS
model
anchor
bias
3DVAR
anomaly
observations
prediction
data
NWP
saving
radio
assimilation
COSMIC
reduction
refractivity
models
error
forecasts
improvement
Sandy
SAC-C
precision
improved
correlation
typhoon
ECMWF
drift
angle
improvements
METOP
cost
numerical
covariance
CHAMP
occultation
NCEP
stability
hurricane
bending
increment
storms
winter
lives
Office
4DVAR
function

ECMWF Implementation of COSMIC

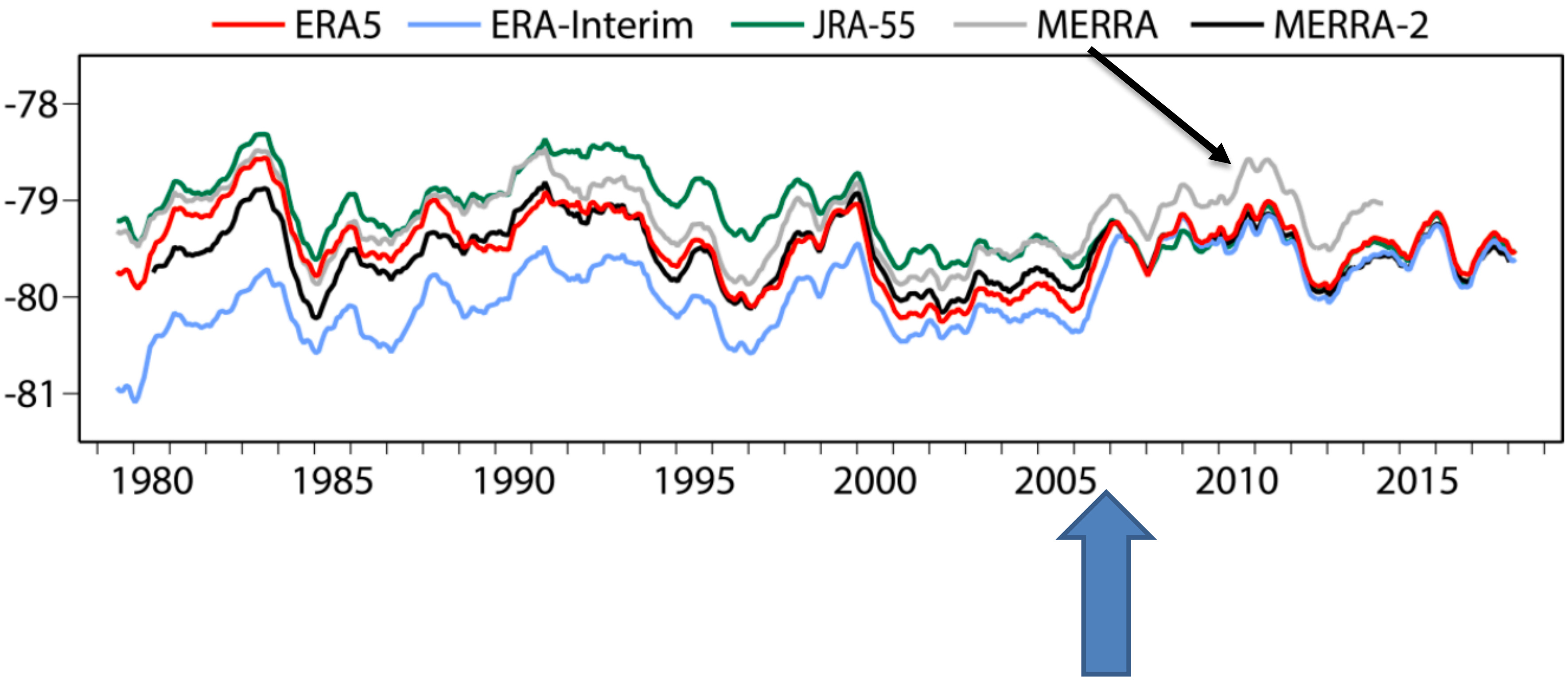
Mean departures of analysis (blue) and background (red) from southern hemisphere radiosonde temperatures (K) at 100hPa



- Operational implementation (Dec 6, 2006)

Effect on Reanalysis

MERRA only reanalysis that does not assimilate RO observations



COSMIC Launch Apr 2006

From A. Simmons, ECMWF (Ho et al. BAMS 2019)

RO identification of dry bias in models where heavy precipitation occurs

- Dry bias in ERA, ECH and GFS in heavy precipitation leads to negative model N bias

$$N = 77.6\frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

Padullés et al. Atmos. Chem and Phys. 2018

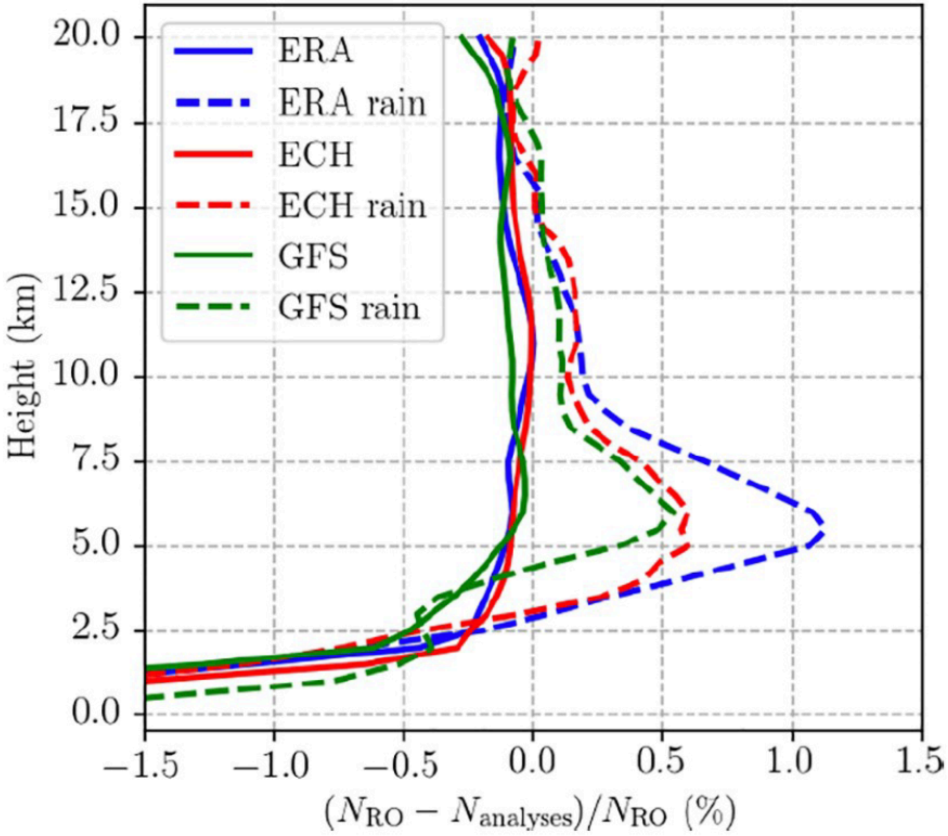
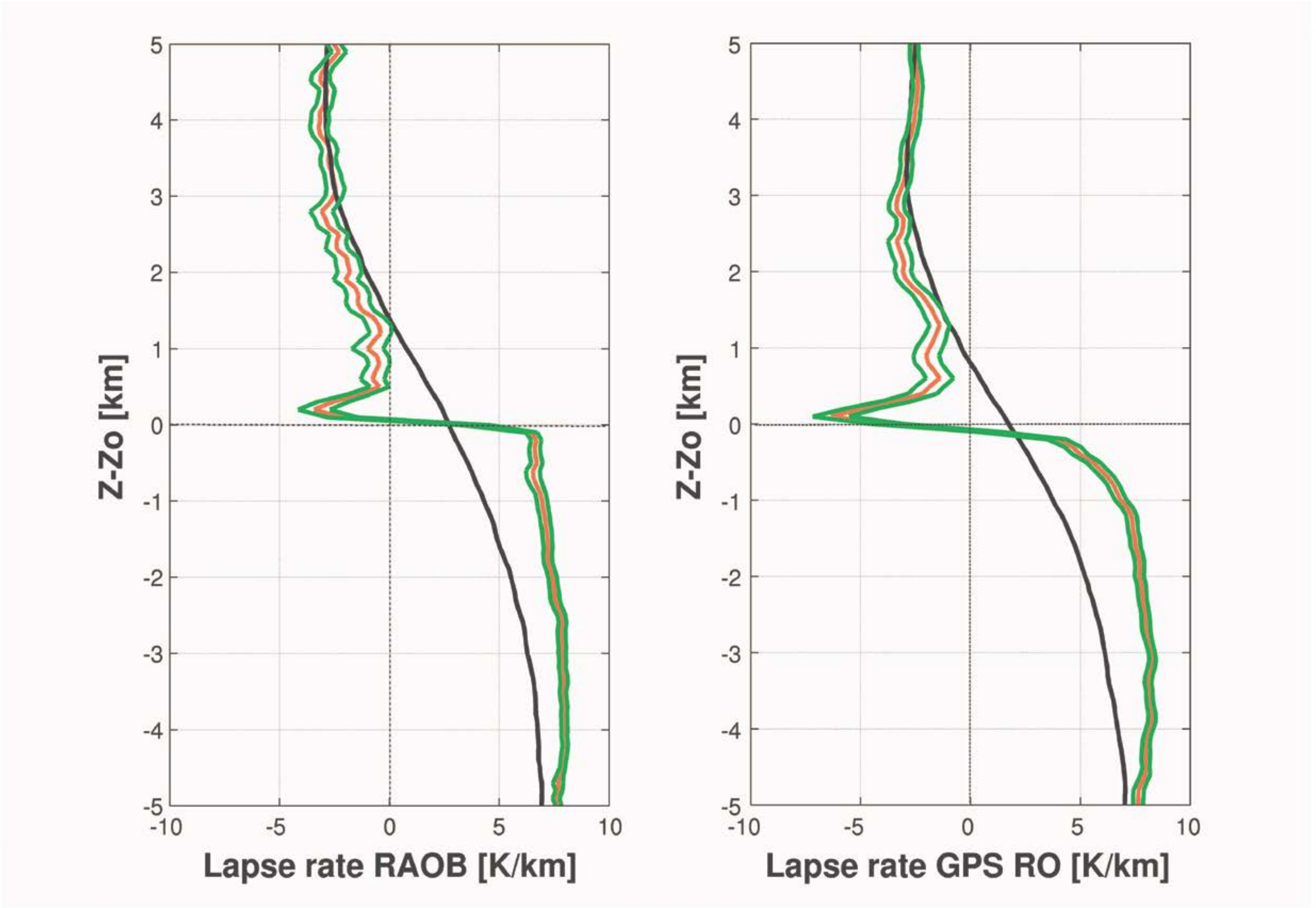


Fig. 11. Fractional difference between the RO-observed refractivity and that from ERA-Interim (blue), ECMWF high-resolution analysis (red), NCEP GFS operational analysis (green) over the region from 60°S to 60°N for 2016. The COSMIC RO profiles are divided into no rain (solid) and heavy rain (dashed).

RO and tropical cyclones

- Considerable uncertainties in analyses over the tropics
- RO observations are of high vertical resolution and high accuracy and minimally affected by clouds and precipitation
- Advantages for tropical cyclone observation and prediction:
  - Water vapor: Important for convective development, genesis, intensity, track and precipitation forecasts
  - Temperature: Important for large-scale circulations and track forecasts
  - Can estimate intensity of TC using RO
- COSMIC-1 has demonstrated significant impact in TC forecasts; COSMIC-2 with 5X number of higher quality observations will be significantly better (we hope!)

Lapse rates with respect to cloud top from radiosonde and COSMIC RO in Typhoon Krosa (2007)



Biondi et al. JGR 2013

$T_{storm} - T_{clim}$

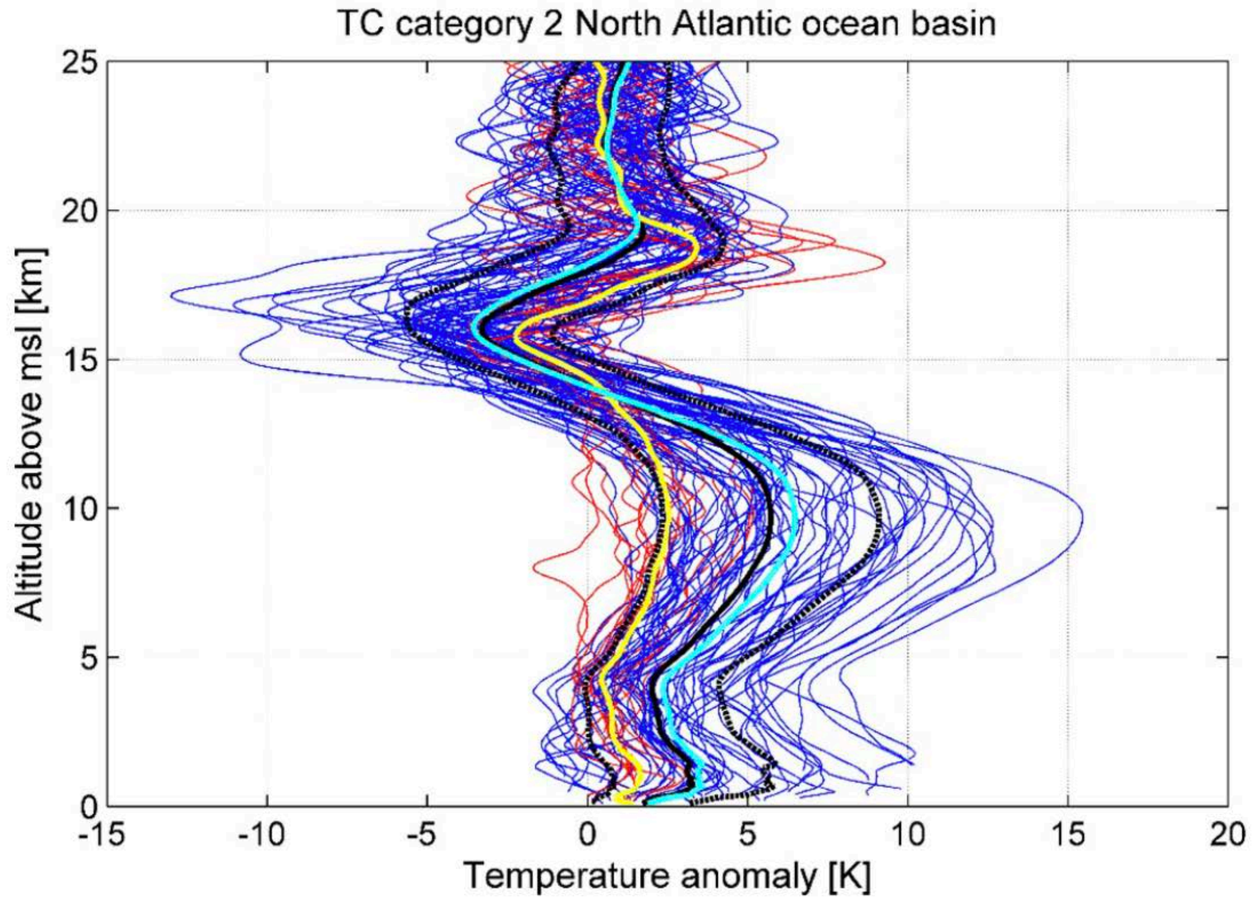
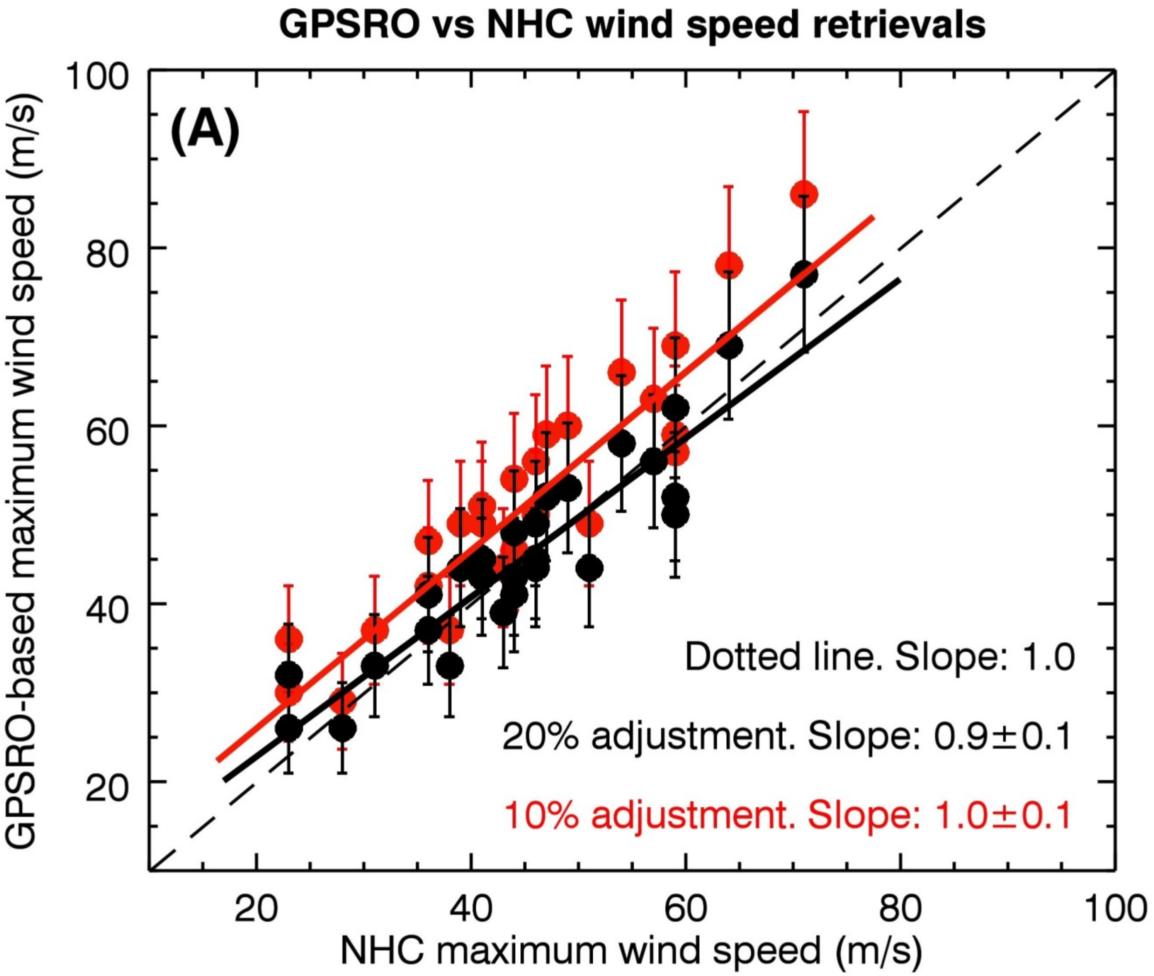


Fig. 13. RO temperature anomaly profiles during TC category 2 in the North Atlantic Ocean basin. Tropical profiles (red), extratropical profiles (blue), mean tropical (yellow), mean extratropical (light blue), mean of all profiles and ± standard deviation (black). (Source: Fig. 5 from Biondi et al., 2015). (For in-

Tropical cyclone intensity from RO

Outflow temperatures in the eyewall region of 27 hurricanes in 2004–2011 were obtained from RO. With ocean surface temperatures from NASA Modern Era-Retrospective Analysis for Research and Applications (MERRA), it was possible to estimate hurricane intensities using a simplified hurricane model.



Observational tests of hurricane intensity estimations using GPS radio occultations. Vergados, Luo, Emanuel, and Mannucci, 2014, *JGR*

RO Impact on TC track forecasts
327 cases Pacific typhoons 2008-2010

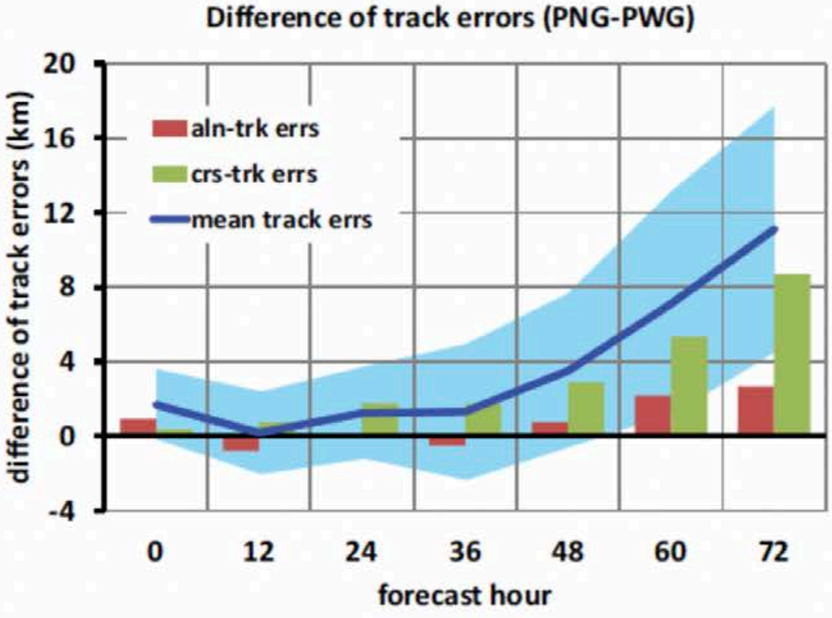
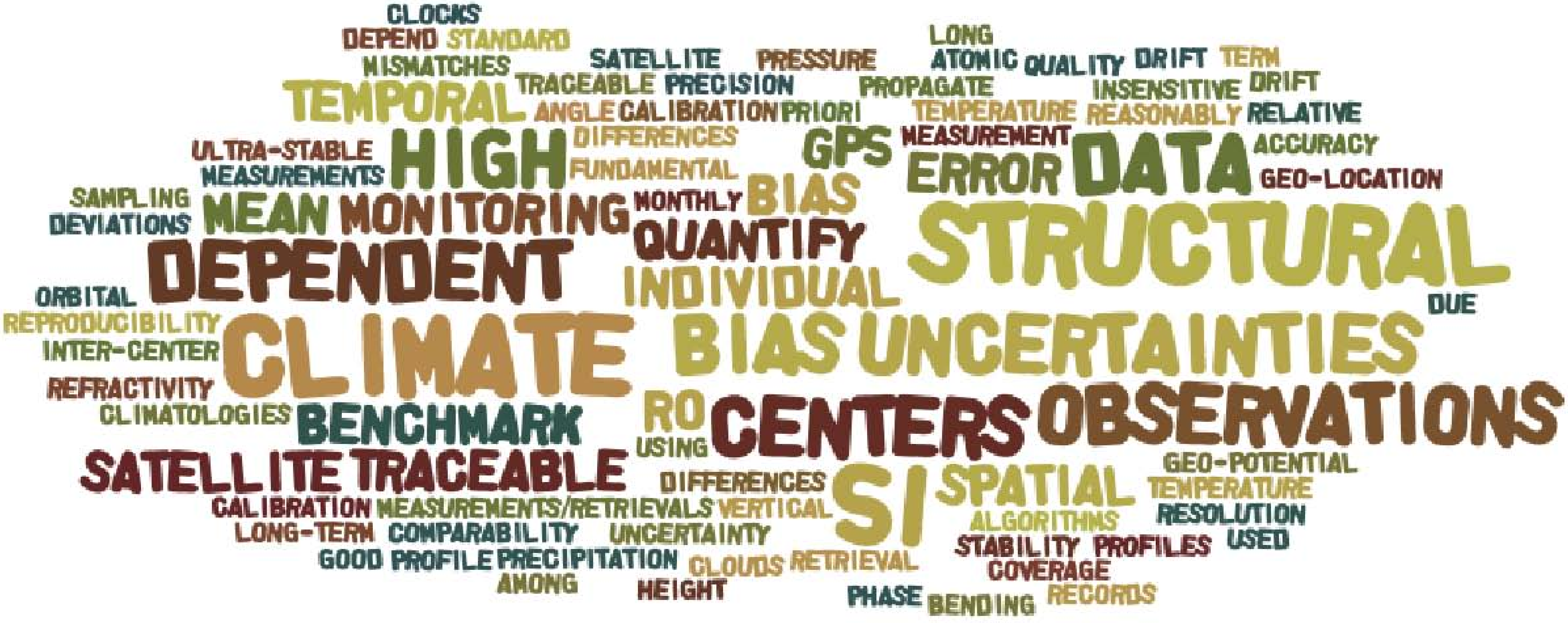


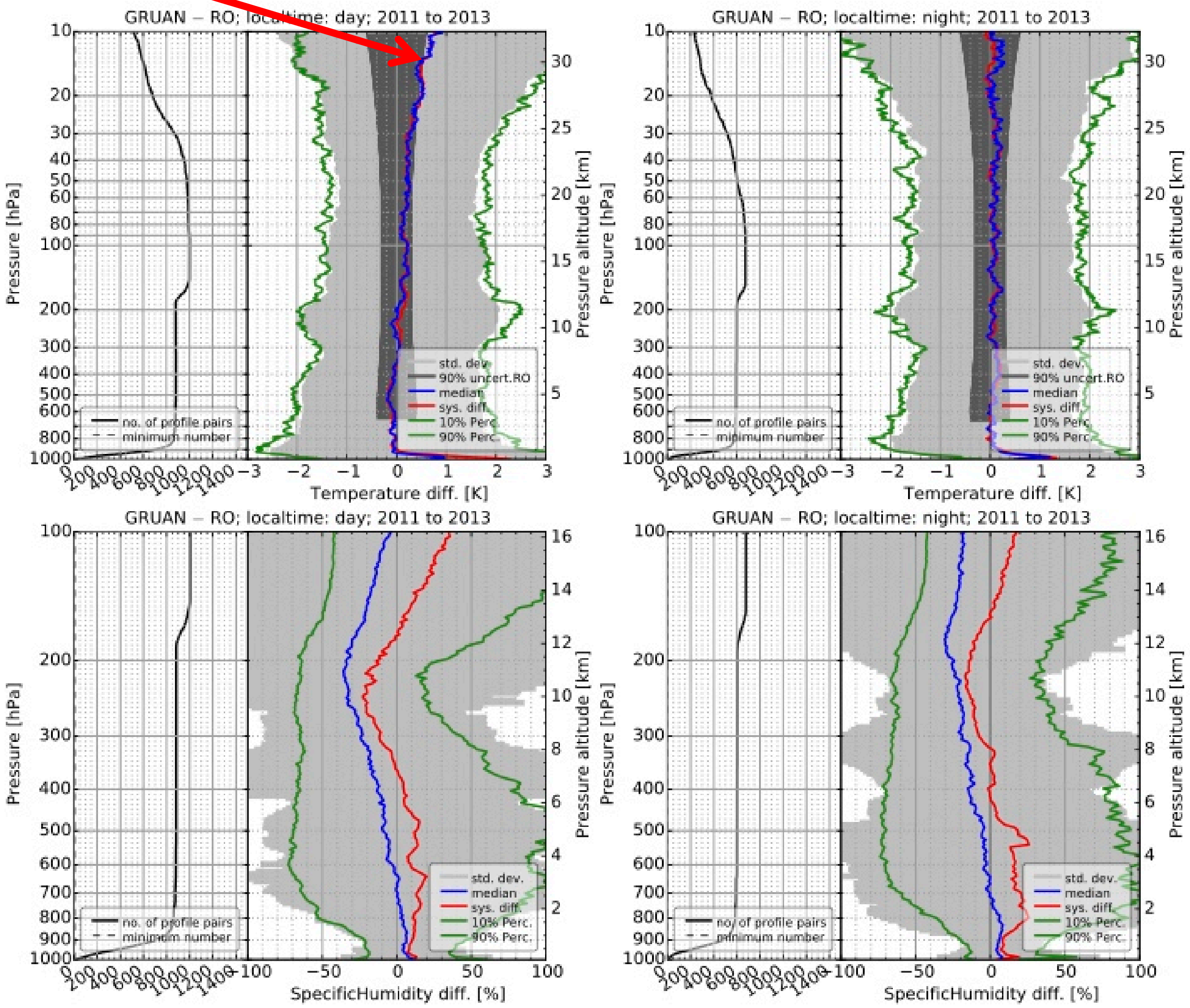
Figure 5. Difference between mean track errors, along-track errors and cross-track errors of PNG and PWG.

Figure 8. Difference in track errors associated with no-RO forecast (PNG) and forecasts with RO (PWG). A positive number means that the RO forecasts have less error. (Chen et al., 2015)


CLOCKS
DEPEND
STANDARD
LONG
MISMATCHES
SATELLITE
PRESSURE
ATOMIC
QUALITY
DRIFT
TERM
TEMPORAL
TRACEABLE
PRECISION
PROPAGATE
INSENSITIVE
DRIFT
ANGLE
CALIBRATION
PRIORI
TEMPERATURE
REASONABLY
RELATIVE
DIFFERENCES
MEASUREMENT
ULTRA-STABLE
HIGH
GPS
DATA
ACCURACY
MEASUREMENTS
FUNDAMENTAL
ERROR
GEO-LOCATION
SAMPLING
MONTHLY
BIAS
DEVIATIONS
MEAN
MONITORING
STRUCTURAL
QUANTIFY
DEPENDENT
INDIVIDUAL
ORBITAL
DUE
REPRODUCIBILITY
CLIMATE
BIAS
UNCERTAINTIES
INTER-CENTER
REFRACTIVITY
RO
CENTERS
OBSERVATIONS
CLIMATOLOGIES
BENCHMARK
USING
GEO-POTENTIAL
SATELLITE
TRACEABLE
DIFFERENCES
SI
SPATIAL
TEMPERATURE
CALIBRATION
MEASUREMENTS/RETRIEVALS
VERTICAL
ALGORITHMS
RESOLUTION
LONG-TERM
COMPARABILITY
UNCERTAINTY
STABILITY
PROFILES
USED
GOOD
PROFILE
PRECIPITATION
CLOUDS
RETRIEVAL
COVERAGE
AMONG
HEIGHT
PHASE
BENDING
RECORDS

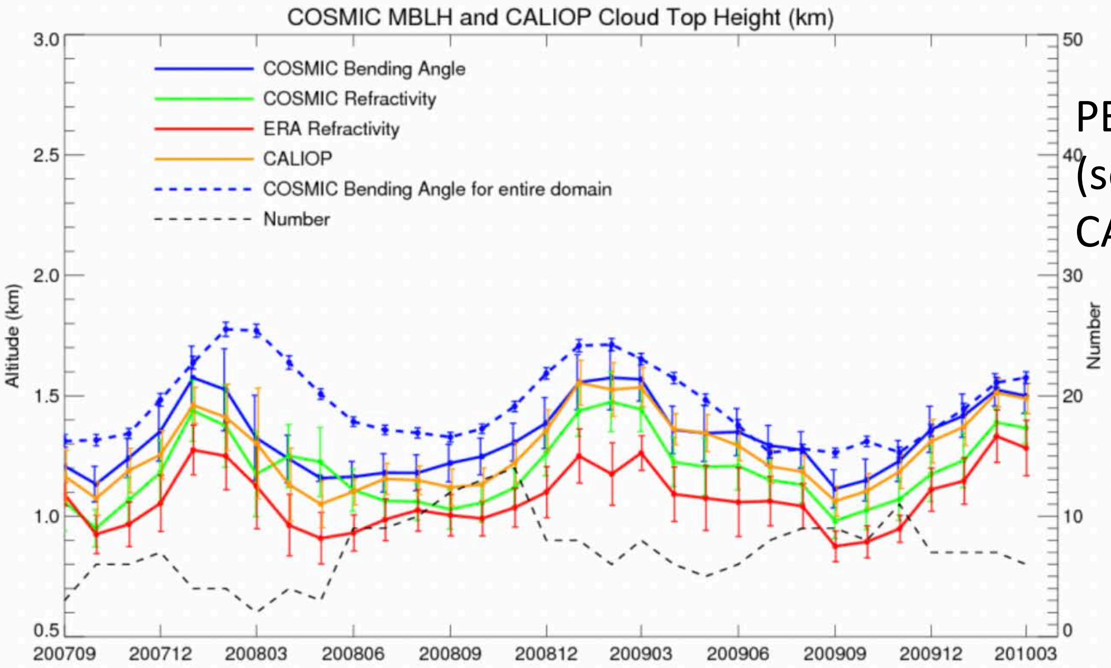
RO compared to climate-quality radiosondes

Warm bias 0.5K



Ladstädter, Steiner, Schwärz and Kirchengast, 2015 AMT

Observations of PBL Height



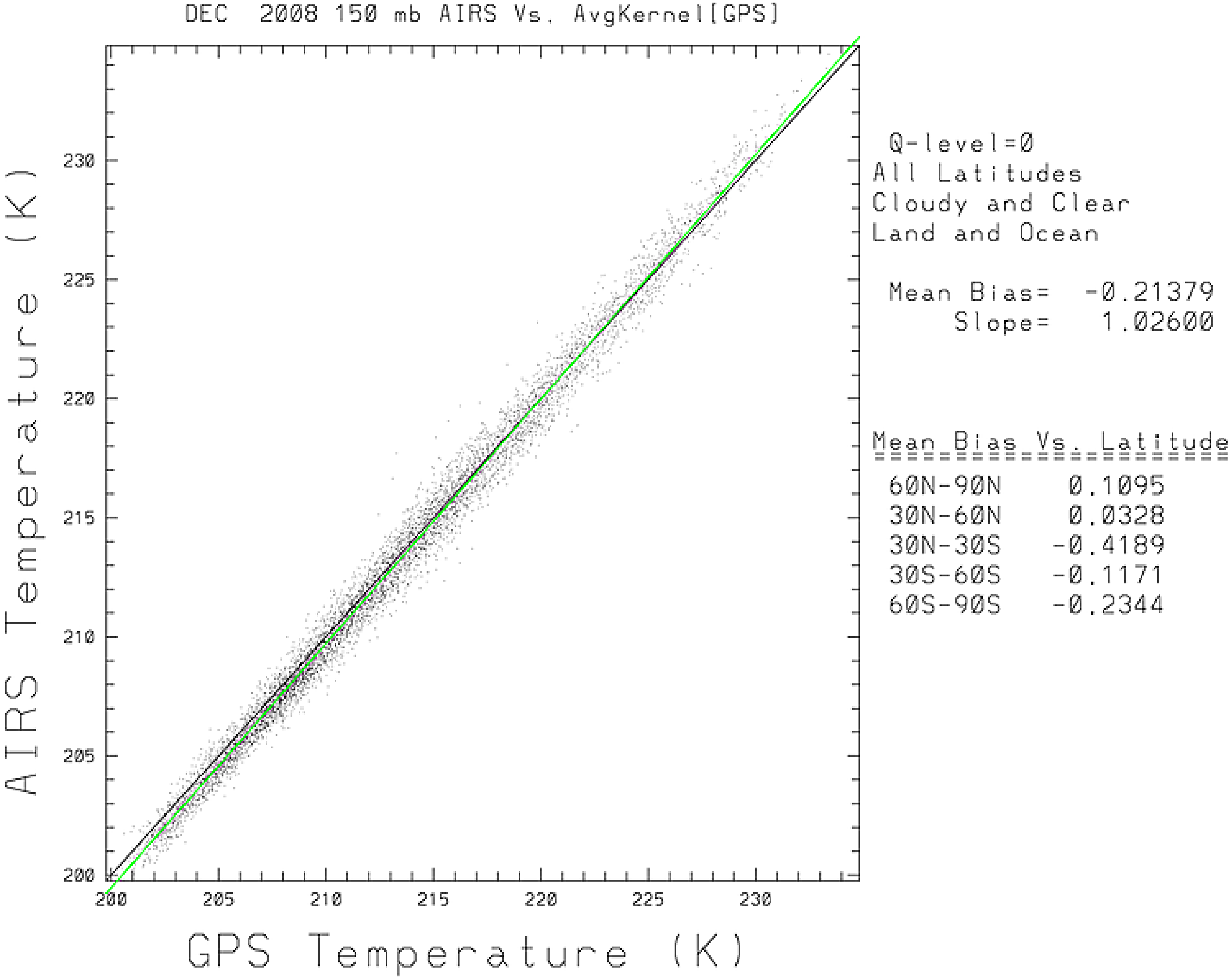
PBL height estimated from RO BA (solid blue) agrees best with CALIOP PBL height (orange)

Figure 9. Three-month running means from September 2007 to March 2010 for the MBLH computed from RO bending angles and refractivity, the ERA-Interim refractivity profiles, $\mathrm{MBLH_{CALIOP}}$, and the $\mathrm{MBLH_{BA}}$ from the entire VOCALS region. (Fig. 12 of Ho et al., 2015)

Cal/Val of IR and MW sounding
AIRS vs. COSMIC Temperature (K)

Corr ~ 1.0

We can use the defined slope and offset to calibrate AIRS temperatures



Q-level=0
All Latitudes
Cloudy and Clear
Land and Ocean

Mean Bias= -0.21379
Slope= 1.02600

Mean Bias Vs. Latitude	
60N-90N	0.1095
30N-60N	0.0328
30N-30S	-0.4189
30S-60S	-0.1171
60S-90S	-0.2344

Ben Ho, 2014

Agreement here is very good, validating AIRS retrieval algorithms and calibration

SSM/I vs. COSMIC Precipitable Water

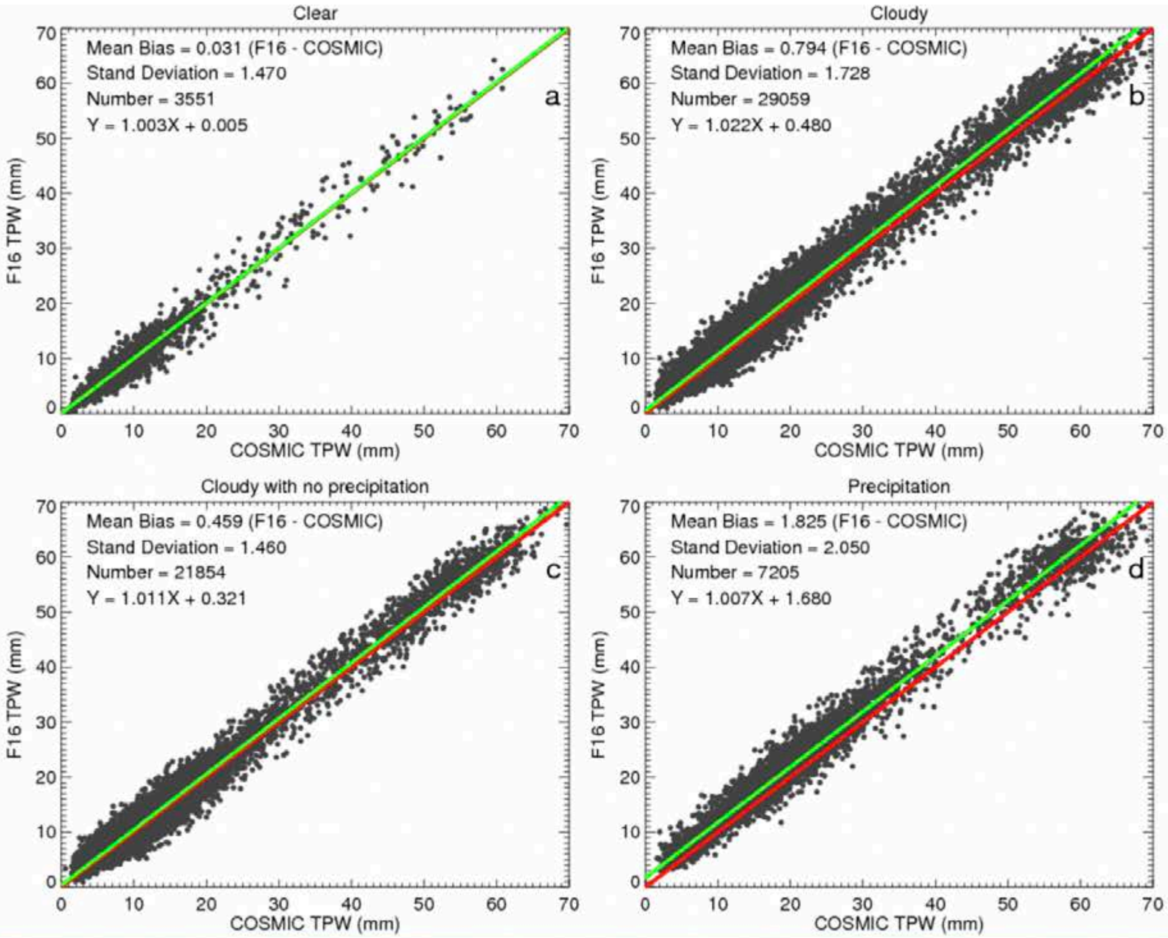
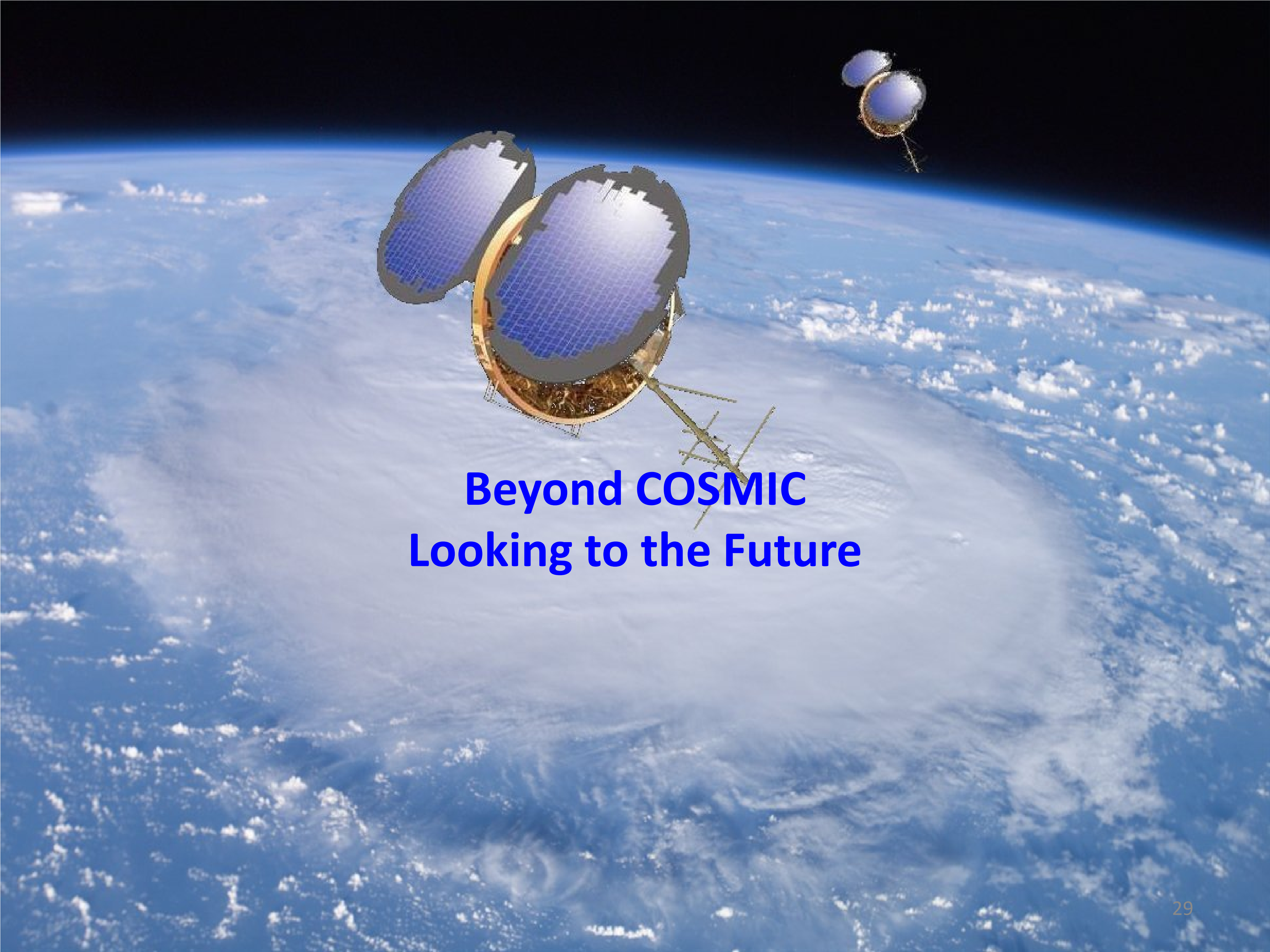


Figure 12. Scatter plots for the COSMIC and RSS Version 7.0 F16 SSM/I vs. COSMIC RO pairs under a) clear, b) cloudy, c) cloudy but non-precipitating, and d) precipitating conditions (Schröder et al., 2017).

Agreement gets slightly worse for clouds and precipitation



Beyond COSMIC
Looking to the Future

RO and Heavy Precipitation (ROHP)

- Dual Polarization RO
- Detect and quantify rain rate in heavy precip
- On PAZ satellite (launched 28 February 2018)
- Cardellach et al. 2019: Sensing heavy precipitation with GNSS polarimetric radio occultation. *Geophys. Res. Lett.*

RO and Heavy Precipitation (ROHP)

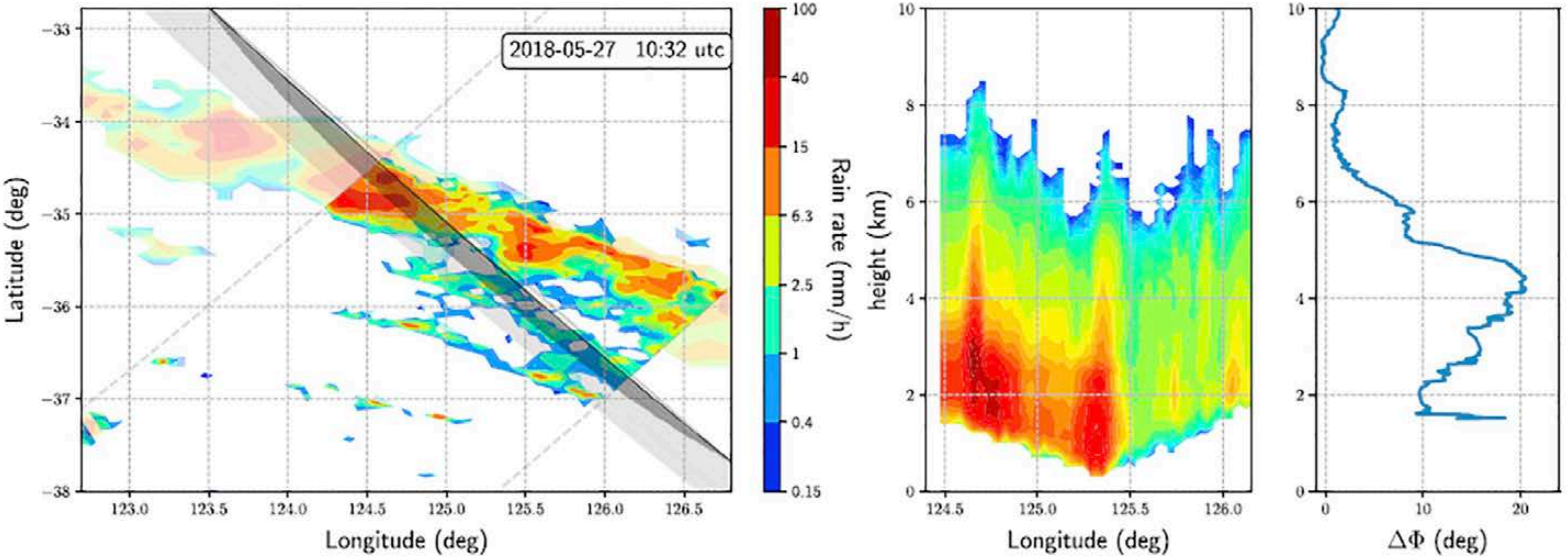
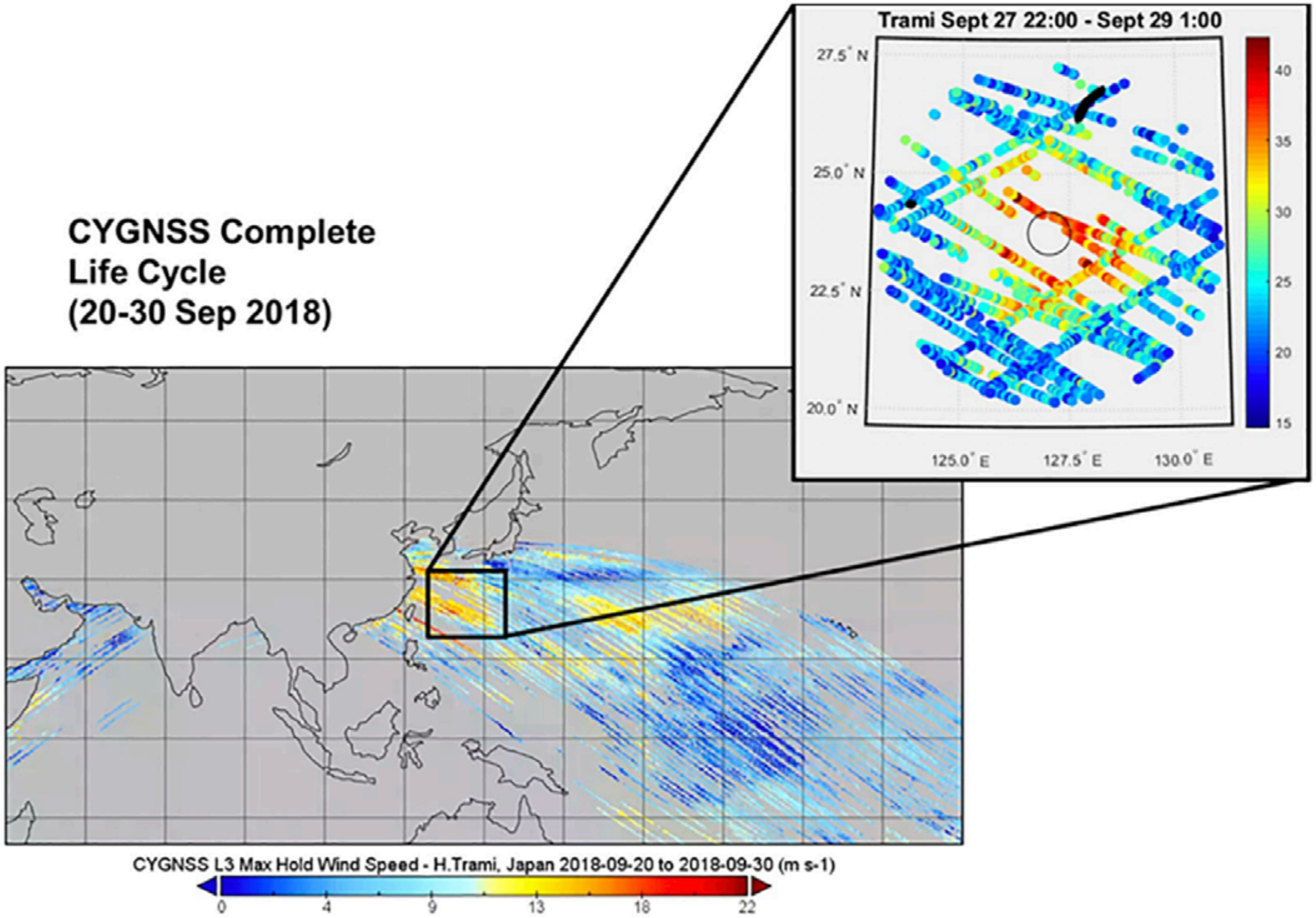


Fig. 10. Left: ROHP-PAZ path superimposed on GPM (Global Precipitation Measurement) precipitation. Middle: vertical precipitation structure from GPM interpolated to plane of ROHP-PAZ observational plane. Right: vertical profile of Δϕ (phase delay difference of horizontal and vertical polarized signals) measured by ROHP-PAZ. The Δϕ profile shows relatively large values where the GPM radar observes precipitation. (Source: Fig. 1 from Cardellach et al., 2019).

GNSS Reflectometry (GNSS-R)

- GNSS signal reflection off Earth’s Surface
- Land, airborne, spaceborne platforms
- Ocean roughness (sfc wind speed), sea level height, tsunami and storm surge detection, sea ice, soil moisture, vegetation, snow depth

CYGNSS (CYclone GNSS Satellite System)



CYGNSS Daily Composite (28 Sep 2018)

CYGNSS Complete Life Cycle (20-30 Sep 2018)

Fig. 17. CYGNSS wind speed measurements of Typhoon Trami in September 2018. Lower left image: composite over the period 20–30 September 2018 of all wind speed measurements. Upper right insert: measurements of 28 September re-gridded to a storm-centric coordinate system to highlight the wind speed structure in the inner core. (Source: Ruf et al., 2018).

Space Platform Requirements Working Group (SPRWG) NSOSA Architecture Study

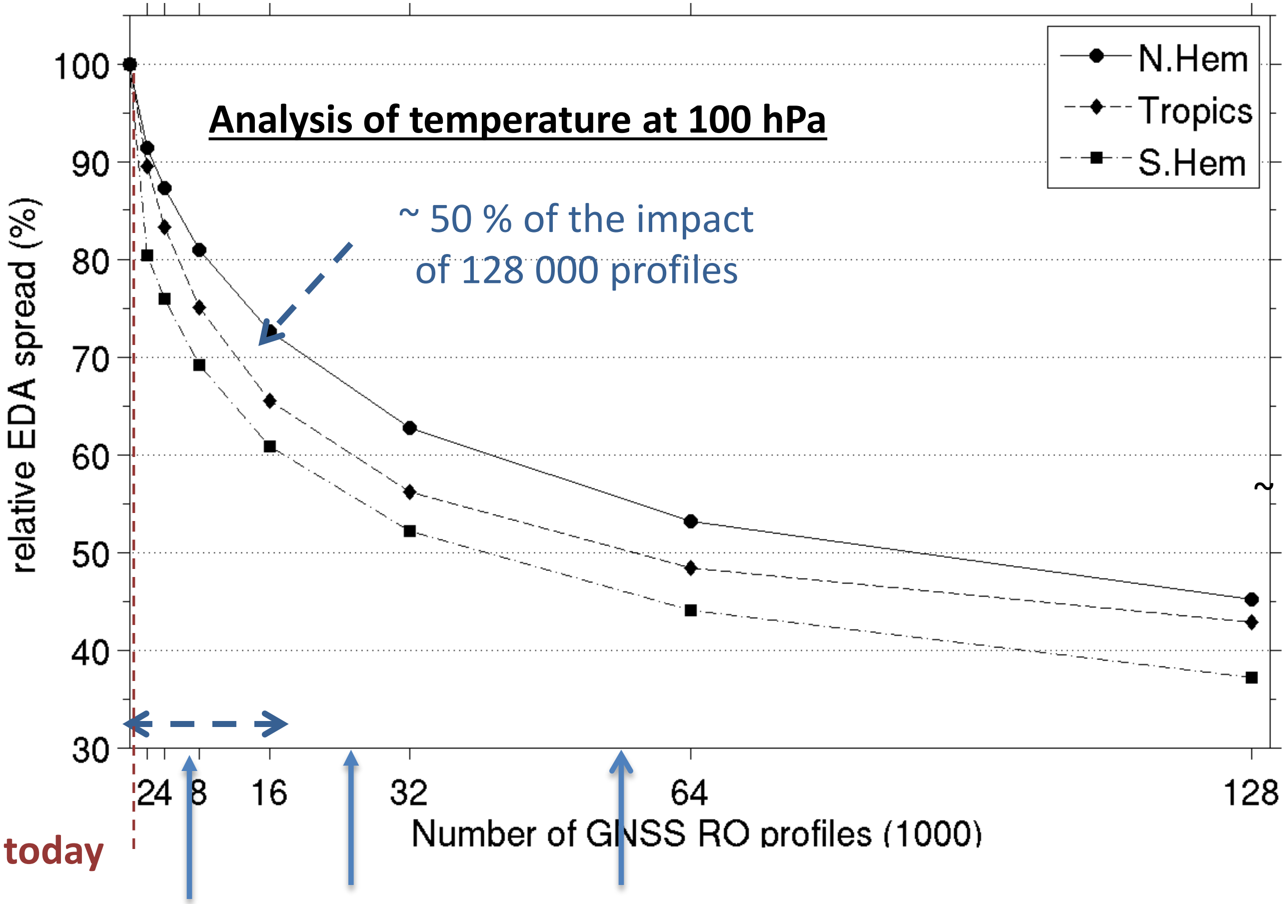
Anthes et al. BAMS September 2019

Comprehensive study recommending objectives and their attributes for NOAA’s satellite systems for 2030 and beyond-in priority order

Priorities for Improvement over Program of Record 2025

1. Assurance of core capabilities
2. Global 3D Winds
3. Regional (CONUS) weather imagery
4. Global RO
5. Global weather imagery
6. Global MW soundings
7. Global IR soundings
8. 31 additional objectives

RO Impact vs. number



Analysis of temperature at 100 hPa

~ 50 % of the impact of 128 000 profiles

~ 25 million bending angles per day

today

ST 5000

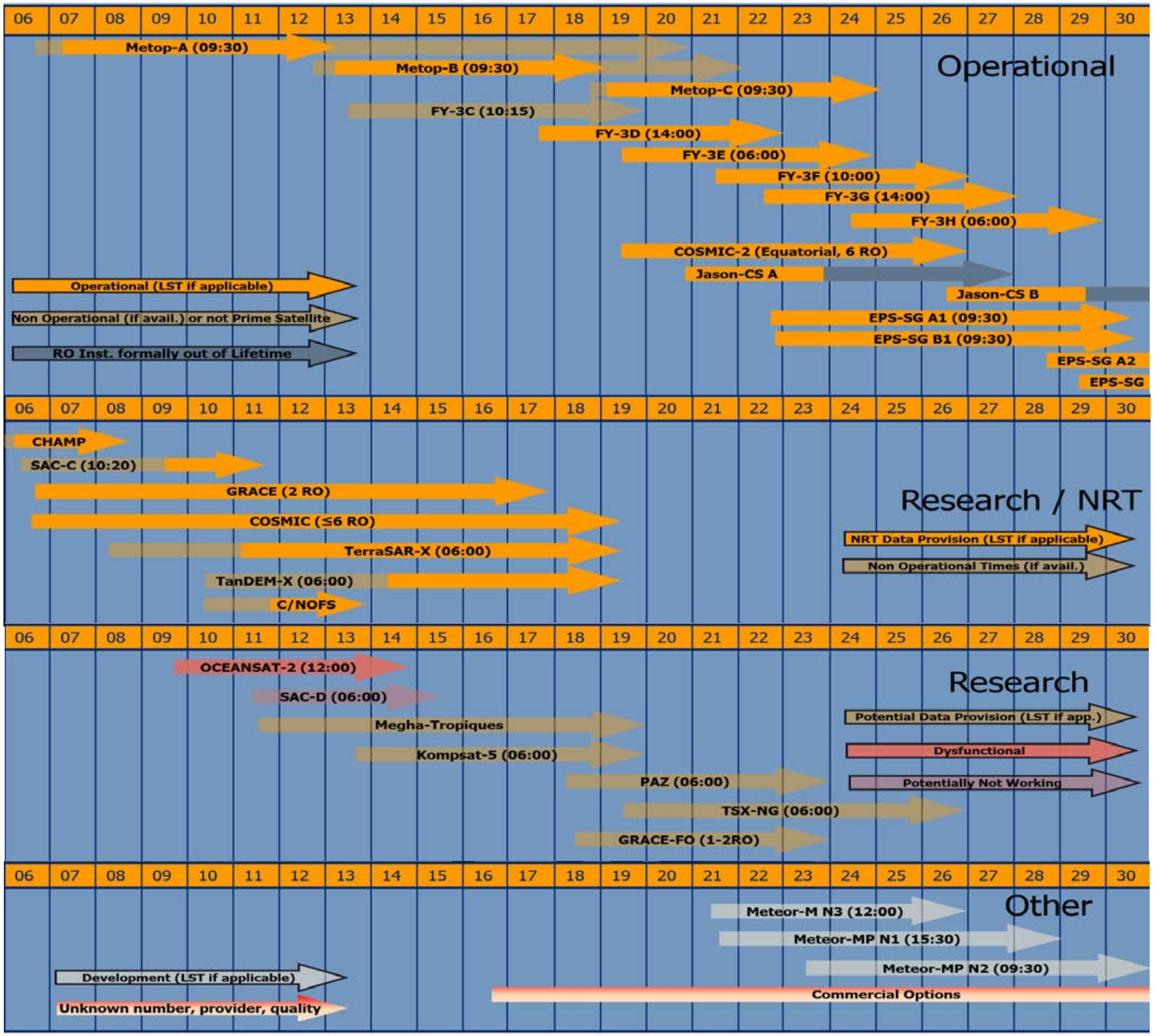
Exp 20,000

ME 50,000

(SPRWG levels of performance)

Harnisch, Healy, Baur, English, 2013: Mon. Wea. Rev.

Future RO missions



Source: Axel von Engeln, January 2019

Summary

- Radio Occultation is a proven high-impact and low-cost global observing system
- Only observing system to give information on ionosphere, stratosphere and troposphere simultaneously
- Significant positive impact on weather forecasts at all major international weather centers
- Contributes to weather, climate and space weather
- Future uncertain—need more RO constellations (private sector role?)

Acknowledgments

- NSF, NASA, NOAA, USAF
- Taiwan’s NSPO
- JPL
- Many investigators around the world
- Other RO Missions, GPS/MET, CHAMP, SAC-C, GRACE, TerraSAR-X, C/NOFS, Metop-A/GRAS

UCAR NSF NASA USAF NOAA NSPO ONR

Additional slides

Some of these results were reported in the following recent publications:

Anthes, R.A. and W. S. Schreiner, 2019: Six new satellites watch the atmosphere over Earth's Equator. Eos Earth and Space Science News, AGU, 30 August 2019. https://eos.org/science-updates/six-new-satellites-watch-the-atmosphere-over-earths-equator

Ho, S.-P., R.A. Anthes, C.O. Ao, S. Healy, A. Horanyi, D. Hunt, A.J. Mannucci, N. Pedatella, W.J. Randel, A. Simmons, A. Steiner, F. Xie, X. Yue, and Z. Zeng, 2019. The COSMIC-FORMOSAT-3 radio occultation mission after 12 years: accomplishments, remaining challenges, and potential impacts of COSMIC-2. Bull. Am.
Meteorol. Soc. 100, online version:
https://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-18-0290.1

Bonafoni, S., R. Biondi, H. Brenot and R. Anthes, 2019: Radio occultation and ground-based GNSS products for observing, understanding and predicting extreme events: a review. *Atmos. Research*, 230, 1-18
https://doi.org/10.1016/j.atmosres.2019.104624

Three-cornered hat estimates of error standard deviations ERAi, MERRA-2, JRA-55 and COSMIC-1 RO (Global 1-7 Jan 2008)