QOSAP activities in support of the next generation of satellite architecture at NOAA

NOAA

SAT Meeting
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Outline

- Background on quantitative assessments
- Introduction to the QOSAP program
- Observing System Experiments (OSEs)
- Observing System Simulation Experiments (OSSEs)
- Final remarks

Today’s modeling and observing systems capabilities: Observing System Experiments (OSEs)

- Can we do better? - Optimize use of current observations in current modeling systems
  - Enhanced data assimilation strategies
  - More realistic characterization of observations
  - Management of large volume of data
  - Timeliness for model upgrades

- Can we leverage existing observations not currently utilized?
  - Driven by requirements and priorities
  - Investment in personnel and HPC resources

Looking ahead and simulating the future: Observing System Simulation Experiments (OSSEs)

- Costs of developing, deploying and maintaining new space-based architectures typically exceed $100-500 million/instrument
- Need to provide quantitative information on the impact of proposed observing systems in the next planned generation of numerical weather prediction systems
- Help inform major decisions by evaluating the impact of alternative mix of current and/or proposed instruments for better understanding and prediction of Earth Systems
- OSSE studies provide an ideal platform for this
  - Analyze tradeoffs (coverage, resolution, accuracy and data redundancy)
  - Optimize data assimilation and modeling strategies

Cost-benefit analysis for better planning and decision making

Realism and interpretation of OSSE results

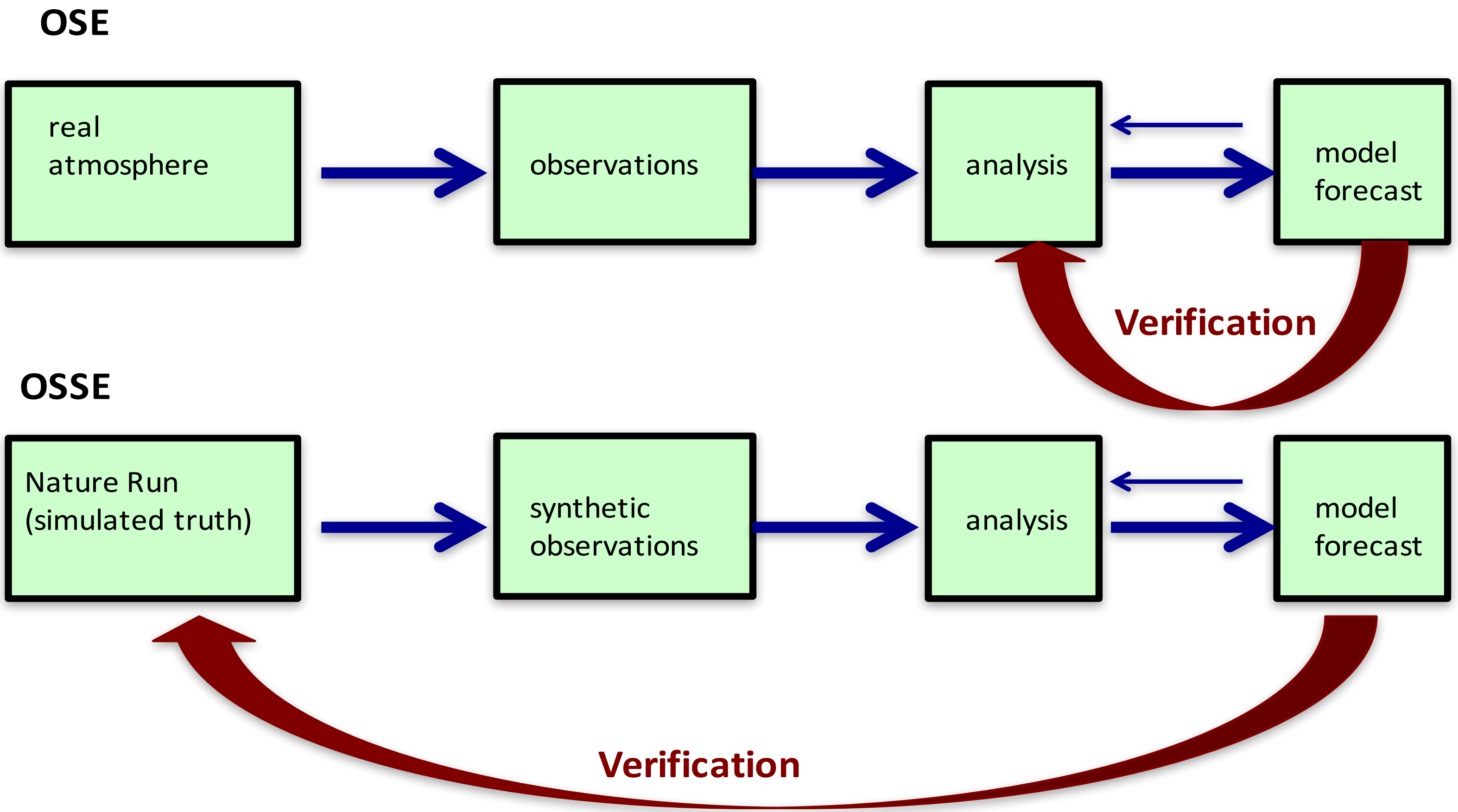
- Will the study be completed in time to be useful?
- Is the predictability of the forecast model realistic?
- Are the coverage and error characteristics of simulated observations realistic?
- Are the forecast accuracy of the model and impacts of existing observing systems in the OSSE comparable to the real world?
- Have the limitations of the OSSE system been determined? (Conclusions should not be drawn beyond these limitations)

Are the costs of observing system deployment justified by the benefits?

Challenges

- Computer power
- Breadth of information (a lot of pieces in play)
- Resilience of the overall observing system
- Statistics vs. individual weather events
- Choosing the right verification metrics

OSE (real) vs. OSSE (simulated)



The truth is unknown

The truth is known

QOSAP Program

- Established in 2014 as a NOAA Program, with the primary objective of increasing the use of quantitative assessments for proposed changes to the global observing system.
- Program based at OAR with representatives from all the NOAA Line Offices.
- Primary quantitative assessment tools used by QOSAP are Observing System Simulation Experiments (OSSEs) and Observing System Experiments (OSEs).
- Maintain/develop/update NOAA “OSSE/OSE ready” capabilities for environmental applications.
- Provide recommendations to the OSC/NOSC for changes to the configuration of NOAA’s observing systems and overall portfolio to maximize the benefit to NOAA and its constituents.
- Work with NOAA Line Offices conducting OSE/OSSEs to follow the NOSC Impact Assessment Framework Memo “Guidance on the Process to Define, Design, Execute, Review & Report on Observing Systems Value and Impact Assessments”, of March 22, 2018.

Current capabilities under QOSAP

- Global Atmospheric OSSE/OSE systems
  - NASA and ECMWF nature runs; NOAA FV3GFS model
- Hurricane OSSE/OSE system under development
  - High-resolution ECMWF nature run; HWRF (HAFS) model
- Framework for nowcasting applications
  - Deep neural network (DNN)
  - Exploring use of high-resolution ECMWF NR
- Implementation of current capabilities on Cloud/AWS environment
- Initial work towards building an ocean OSSE/OSE system
  - Ultimately, add fisheries & marine ecosystems component
- Initial discussions to build a Space Weather OSSE-type capability
- Potential new initiatives identified by the Line Offices
  - Fire, air quality, flooding, atmospheric rivers
  - Sampling strategies; tradeoff studies for field-campaign applications

Consolidated Observing Systems Simulator (COSS)

Agile, NR model agnostic

DWL/LIPAS for 3D winds in collaboration with KNMI

Process Input Data

COSS

Simulation type
- Perfect observations
- Error addition

- FV3GFS Global OSSE system calibrated with two different NR (G5NR and ECO1280)
- Hurricane OSSE system under development

Conventional Observations
- ECO1280
- G5NR

Aircraft Observations
- Aircraft Reports
  - ECO1280
  - G5NR

AMV Observations
- ECO1280
- G5NR

GNSS-RO
- Refractivity
  - ECO1280
  - G5NR
- Bending Angle
  - ECO1280
  - G5NR

Radiances
- CRTM
  - G5NR
    - Clear-Sky
  - ECO1280
    - Clear-Sky
    - All-Sky
  - 32 sensors

Current NOAA global OSSE system

- ECMWF ECO1280 (~ 9km) nature run
  - Based on the ECMWF operational configuration between November 2016 - July 2017
  - 14 months: 00 UTC Sep 30, 2015 – Nov 30, 2016.
- QOSAP COSS package to generate error-added observations.
- Simulated conventional, RO profiles and MW/IR radiances under cloudy conditions.
- Ongoing efforts to incorporate 3D active and passive winds from space.
  - Doppler Wind Lidar observations in collaboration with EUMETSAT/KNMI
  - 3D passive Atmospheric Motion Vector winds (tracking moisture features)
- OSSE system calibrated with the FV3GFS data assimilation and forecast system
  - October-November with observing architecture operational in 2015.
  - **June-July with observing architecture operational in 2020.**

OSSE Baseline-Control

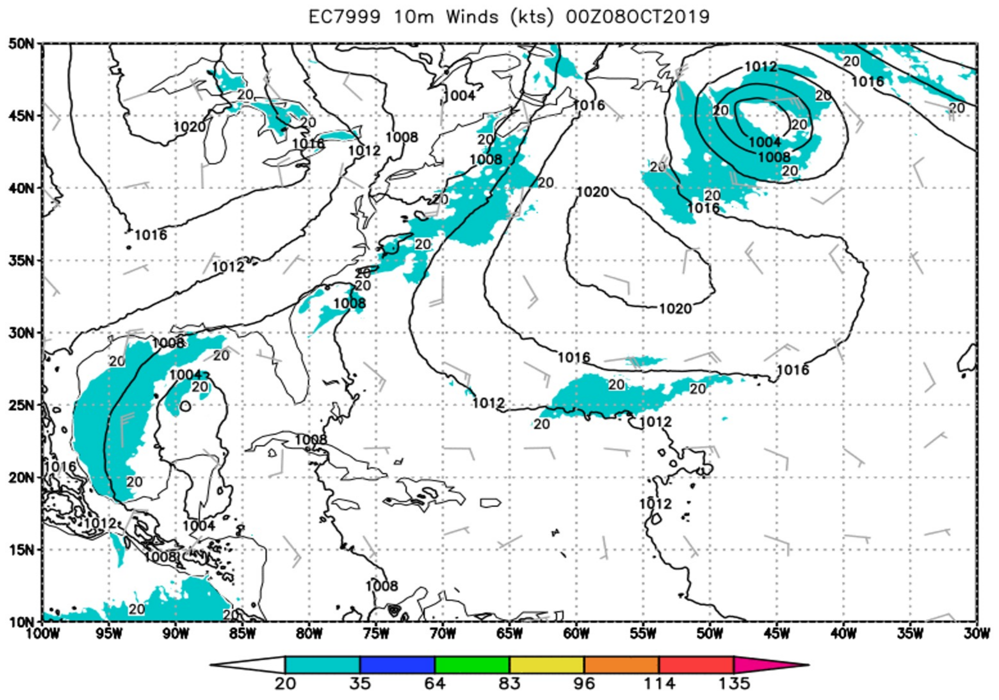
- NR Selected time period: June 1 – July 30, 2016.
- Simulated error-added observations based on June-July 2020 observing system.
  - Satellite radiances at observation location generated at 145-km resolution.
  - Observations at 9 km resolution were also generated for use in selected experiments.
- Use of NOAA FV3GFS v16.1.1 data assimilation system (operational in May 2021) – it includes COSMIC-2, 127 vertical levels, and new physics.
- System run at research resolution.
- Calibrated against the “real world”.

Satellite	Instrument	RO
MetOp-A	amsu-a, iasi, avhrr	MetOp-A (003)
MetOp-B	amsua-a, mhs, iasi	MetOp-B (004)
NOAA15	amsu-a	COSMIC-2 (750-755)
NOAA18	amsu-a, avhrr	TerraSAR-X (042)
NOAA19	amsu-a, mhs	MetOp-C (005)
F17	ssmis	Tandem-X (043)
M08	seviri	KOMPSAT-5 (825)
Suomi-NPP	atms	
Aqua	airs, amsu-a	
NOAA20	cris-fsr, atms	

Hurricane OSSE System

- ○ **Season 1**: 1 November 2018 00 UTC — 1 March 2019 00 UTC
- ○ **Season 2**: 1 August 2019 00 UTC — 1 November 2019 00 UTC

ECMWF ECO7999; 1.4 km resolution NR



Storm from the nature run has been selected

- High temporal resolution (**15 minute**) output
- Late October storm forming out of the Central American gyre
- Tracks north into Gulf of Mexico strengthening before **landfall** in Florida
- Crosses into Atlantic up eastern seaboard
- Timeline:
  - Genesis: 00Z October 09
  - Peak Intensity: 15Z October 13
  - Landfall: 12Z October 14
  - Atlantic Re-emerge: 03Z October 15
  - Dissipation: 18Z October 17
  - **Total time: ~8.5 days**

This research used resources of the Oak Ridge Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC05-00OR22725.

A Baseline for Global Weather and Climate Simulations at 1 km Resolution; Wedi, N. P., Polichtchouk, I., Dueben, P., Anantharaj, V. G., Bauer, P., Boussetta, S., et al. (2020). A baseline for global weather and climate simulations at 1 km resolution. Journal of Advances in Modeling Earth Systems, 12, e2020MS002192. https://doi.org/10.1029/2020MS002192.

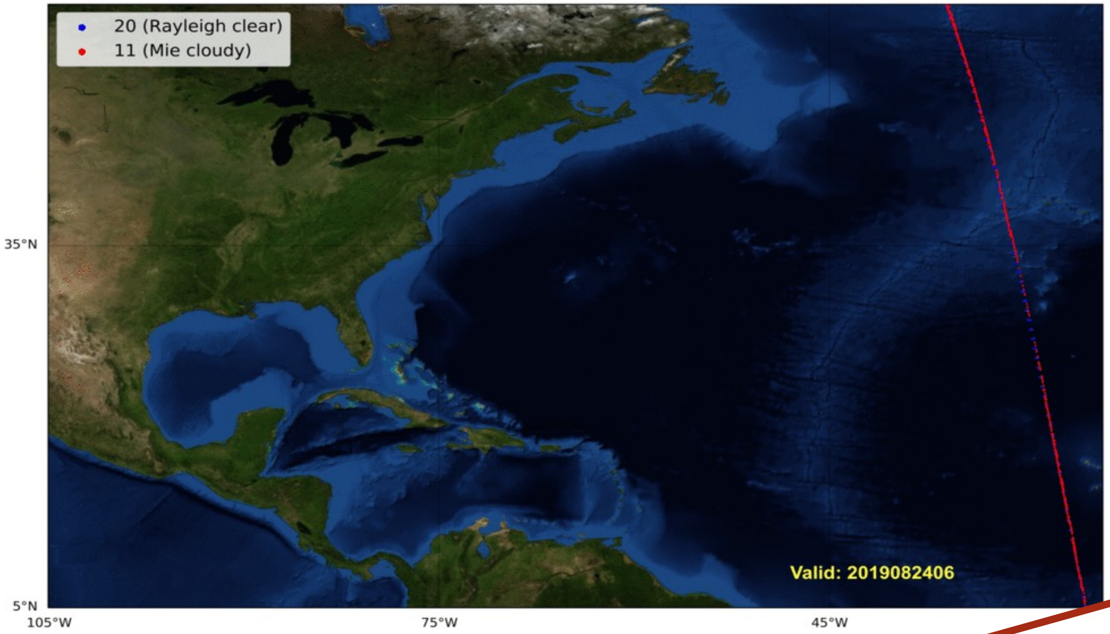
Request from SAT to focus on specific results

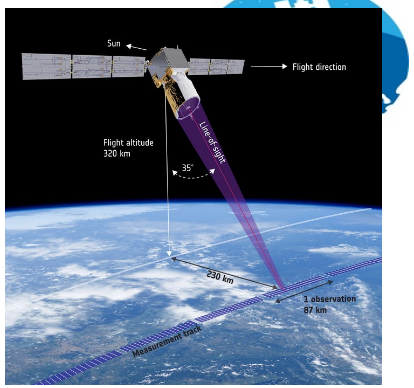
- **Aspects that could inform SAT about what has value (and how much this relative value is) in the next-gen architecture (especially space architecture)**
  - Swarm of limited capability satellites versus limited number of satellites with more capabilities
  - Active vs passive measurement of wind
  - Staggered vs train-like deployment of sounders
  - Relative Impacts of different sensors characteristic (noise, freq, etc) on the overall impact(s)
  - Relative impact of sensors (RO, MW, IR, etc) from different platforms
  - Saturation level: of RO for example, but for other sensors as well.
  - Elements to inform on the level of complementarity of sensors (surface vs space, MW vs IR, RO, etc)

Funded work completed, ongoing or planned that address the questions - at least partially.

OSE: AEOLUS

- Cal/Val activities with models and airplane data (P3 and G-IV).
- Quantify /optimize impact in global (FV3GFS) and hurricane (HWRF).
- **Investigate complementarity between Aeolus and meso AMVs (ongoing work).**

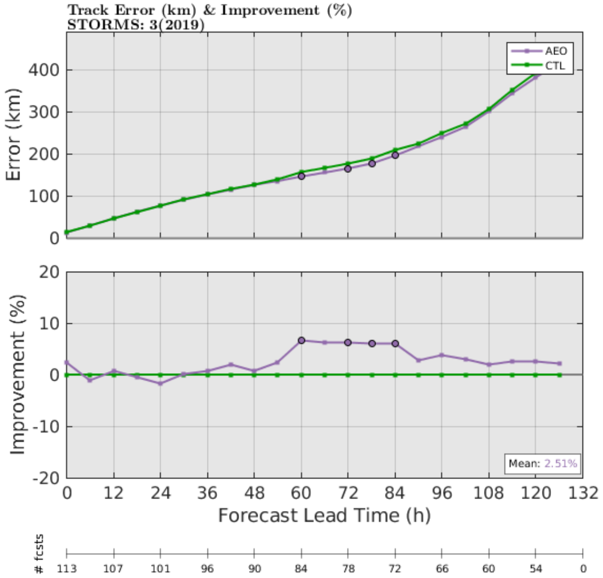


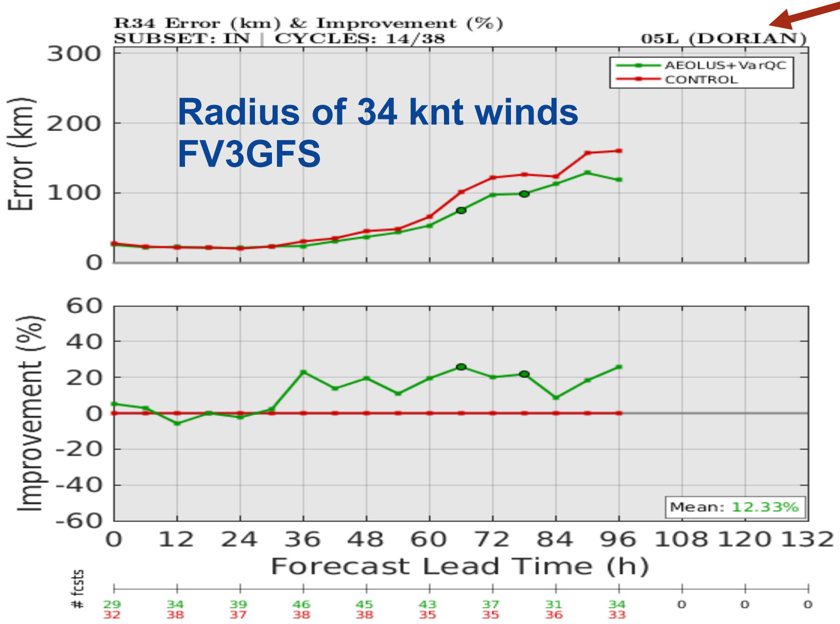


Courtesy: ESA/ATG medialab

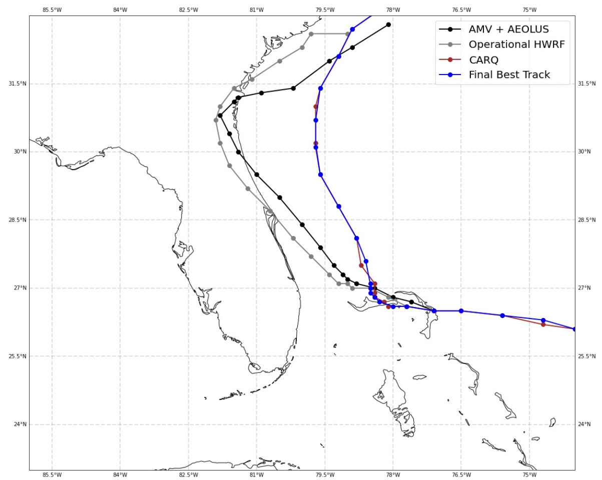
Dorian (24-30 Sept 2019)

HWRF, Atlantic Basin TCs (3)



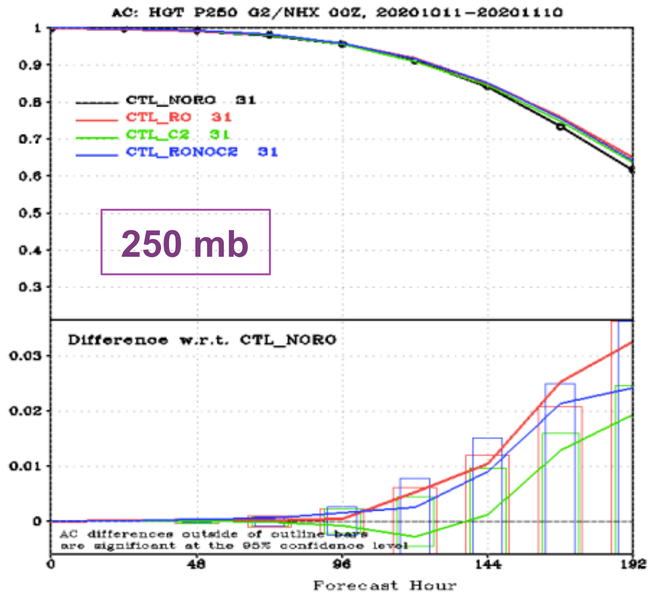


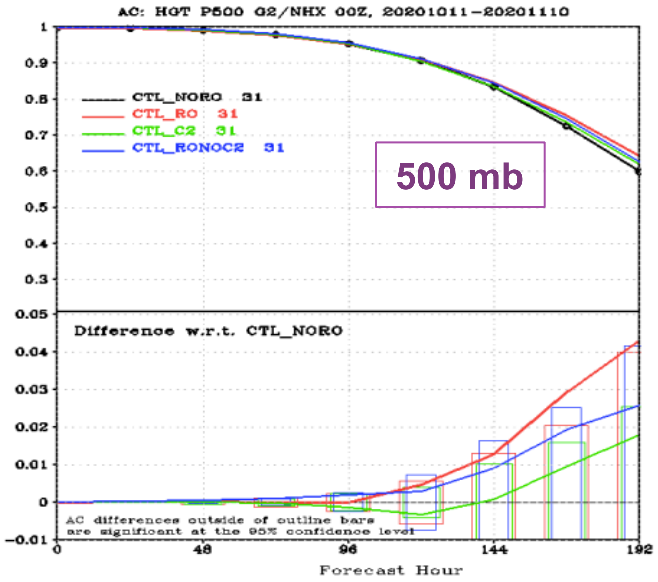
Forecast track (0h – 126-h)
Initial tests in HWRF with AMVs and Aeolus



OSE: RO impact from different sources

NH





CTL_noRO: operational configuration without RO

CTL_C2: CTL_noRO + COSMIC-2

CTL_RO: CTL_noRO + all RO

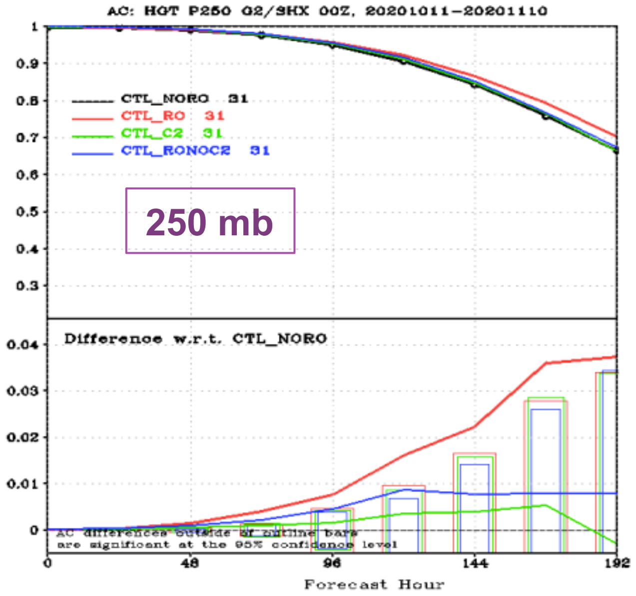
CTL_ROnoC2: CTL_noRO + all RO except C2

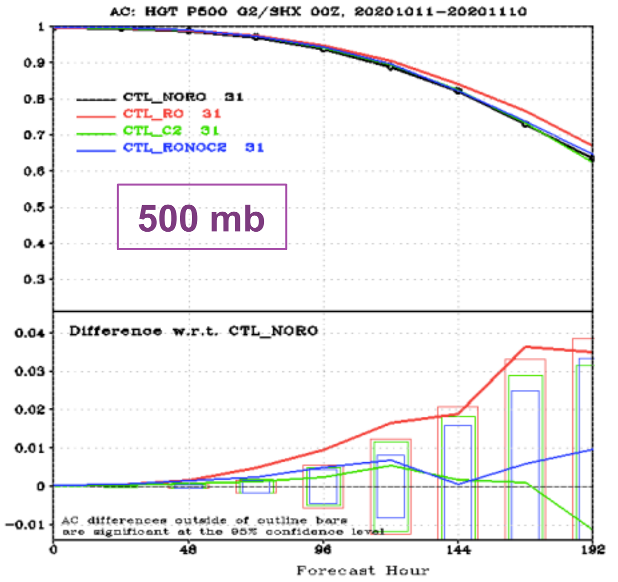
Geopotential heights anomaly correlation

- Overall, positive impact from all sources (impact is larger in NH)
- Non-C2 has larger impact than C2 (difference is larger in NH)
- Best results when all RO assimilated (larger benefits in SH, combined benefits over individual benefits are larger in SH)

FV3GFS V16.2, October-November 2020

SH

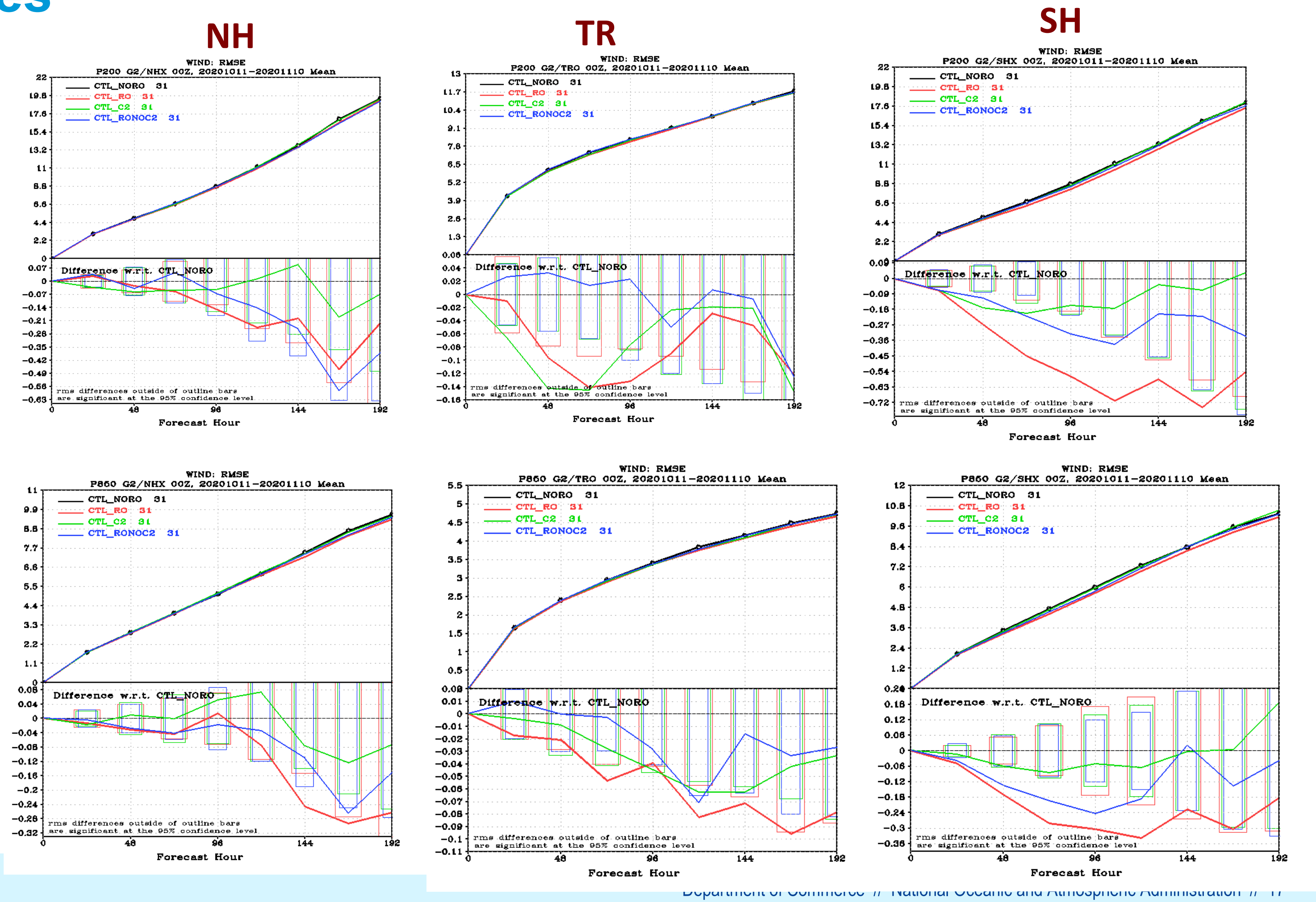




OSE: RO impact from different sources

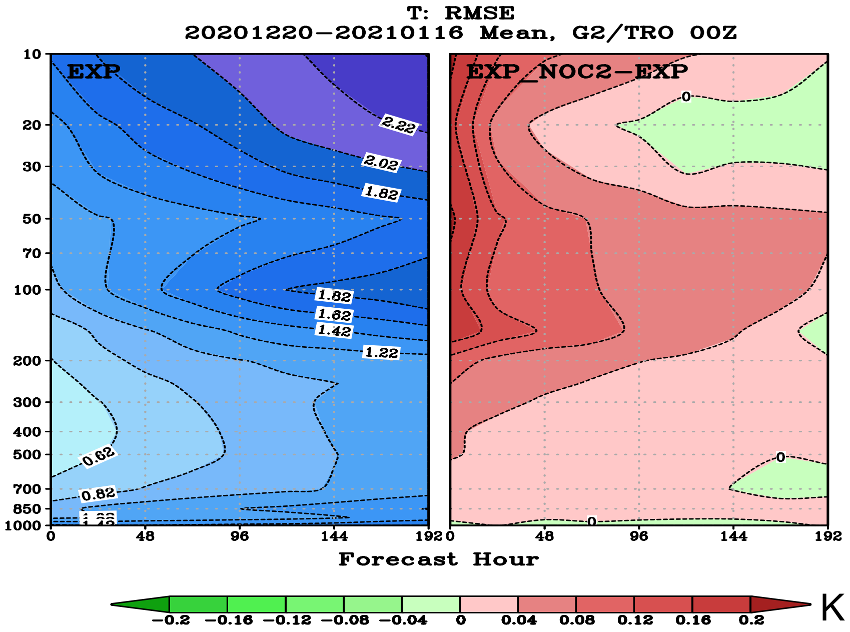
Winds RMSE (self-analysis)

- Overall, positive impact from all data sources (impact from C2 is larger in the TR and impact from non-C2 is larger in SH and NH)
- Best results when when all RO assimilated (larger in SH, combined benefits are larger in SH)



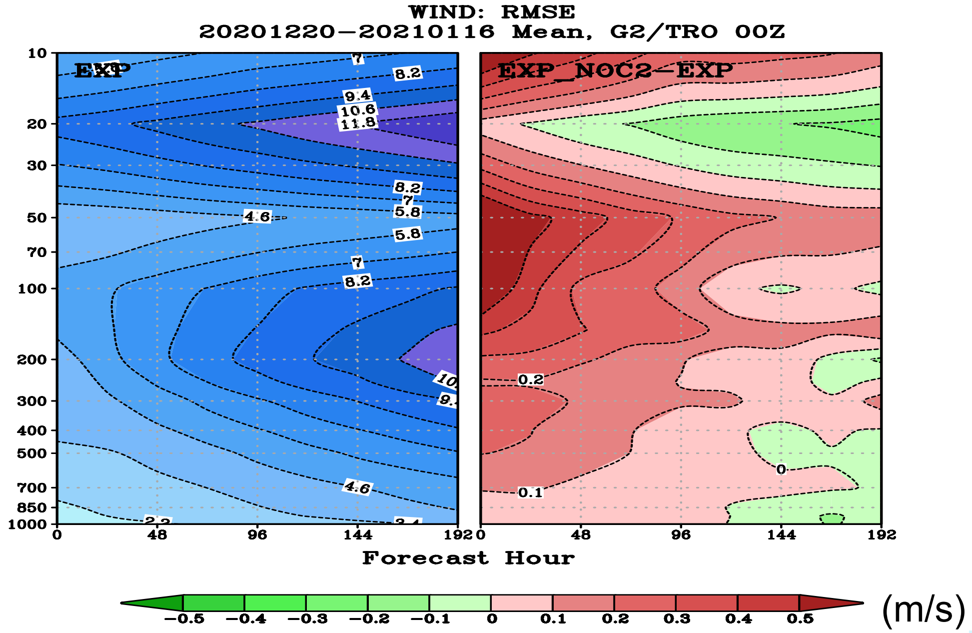
OSE: Radio Occultation exploitation/optimization

- Ongoing work to improve RO data assimilation algorithms in current NWP to increase RO impact.
- Continue to quantify RO impact from different RO sources (COSMIC-2, CWDP).
- New missions (Sentinel-6, GRACE-FO, CWDP DO4+, low-level MetOP).
- Sampling distribution strategies.
- Global, hurricane, and severe storms.
- “Saturation” studies with real observations.



Recent COSMIC-2 impact in Tropics

Positive
Negative

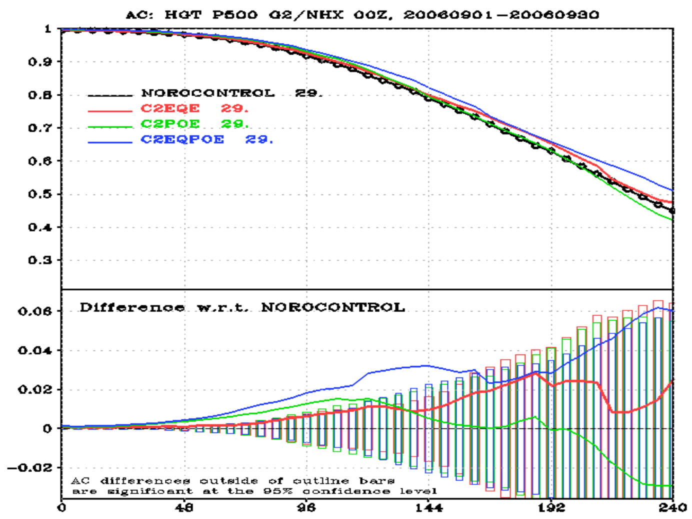


OSSE: RO impact with originally planned COSMIC-2

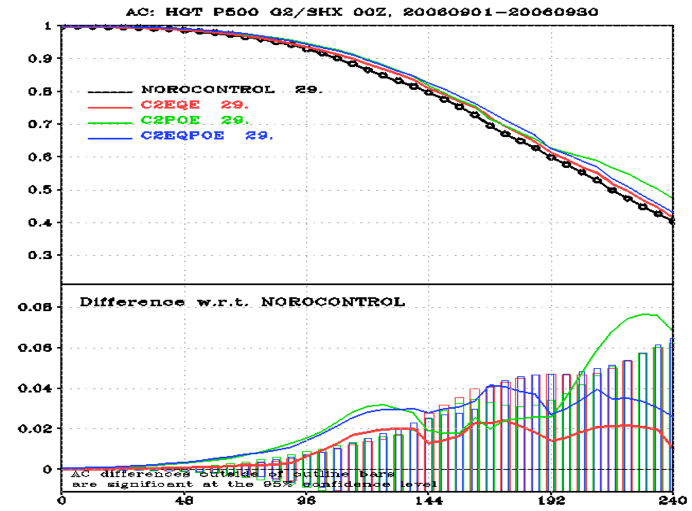
Experiment name	C2 observations	Model	Observation type
NOROCONTROL	N/A	FV3GFS	N/A
C2EQE	**Equatorial (6 sat)**	FV3GFS	Bending angle
C2POE	**Polar (6 sat)**	FV3GFS	Bending angle
C2EQPOE	Equatorial + polar	FV3GFS	Bending angle

- Earlier OSSEs with GFS showed that the largest benefit in NWP skill from COSMIC-2A (”equatorial” component) was to improve tropical winds, and that global RO coverage was necessary to improve weather forecast skill globally. (“Polar” component was needed).
- Recent OSSEs with FV3GFS show increased impact from COSMIC-2A, particularly in the NH. This improvement is attributed to changes in the data assimilation system. **Earlier findings indicating that globally distributed RO observations are more important than denser sampling of the tropical latitudes in order to improve weather prediction globally remain valid.**

AC 500-hPa NHX (20N – 80N)



AC 500-hPa SHX (20S – 80S)



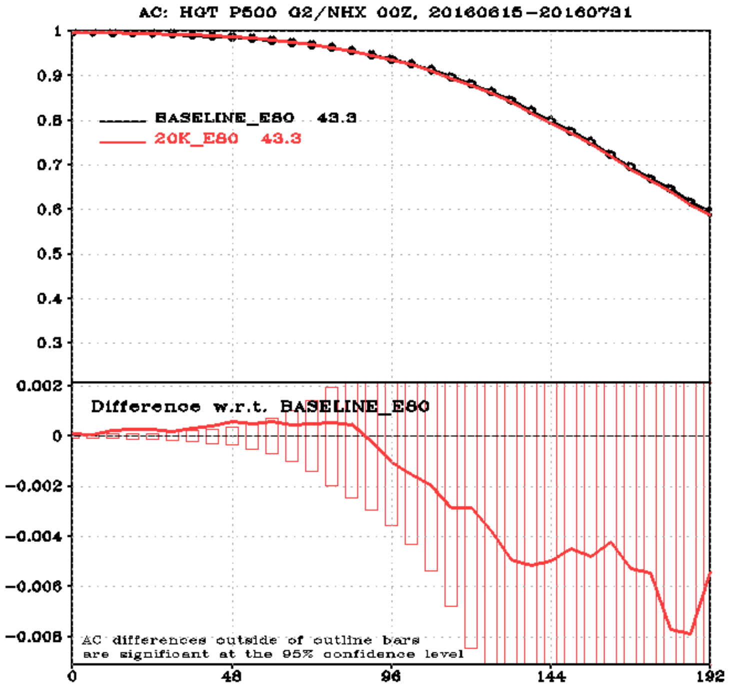
OSSE: Saturation studies with RO observations (ongoing work)

Quantify impact from 20K, 50K, 100K, 100K+ RO profiles/day

BASELINE_E80: Baseline configuration (~ 6,000 RO profiles/day)

20K_E80: Baseline + 20,000 RO profiles/day

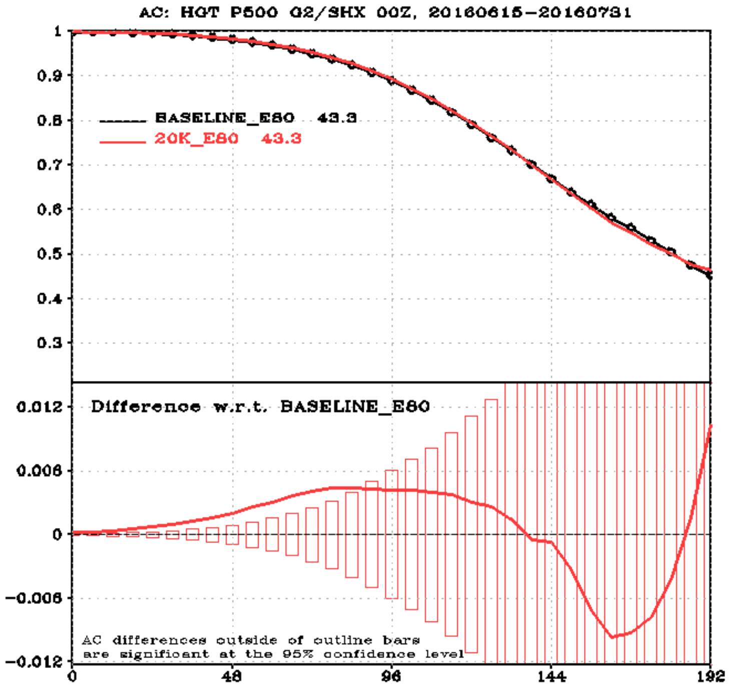
Anomaly correlation 500-hPa geopotential heights
Northern Hemisphere extra-tropics



Forecast hour

Benefits from RO assimilation extend beyond current number of profiles

Anomaly correlation 500-hPa geopotential heights
Southern Hemisphere extra-tropics

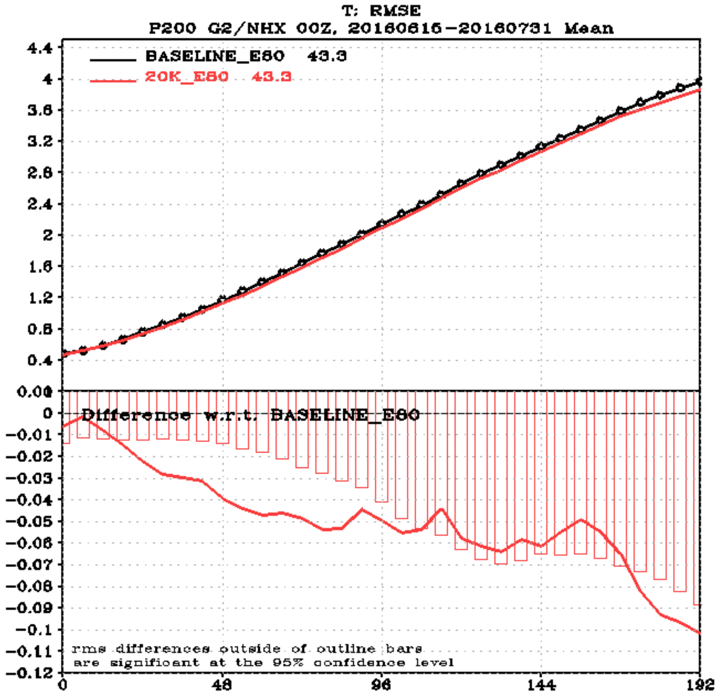


Forecast hour

200 hPa RMS Temperature error

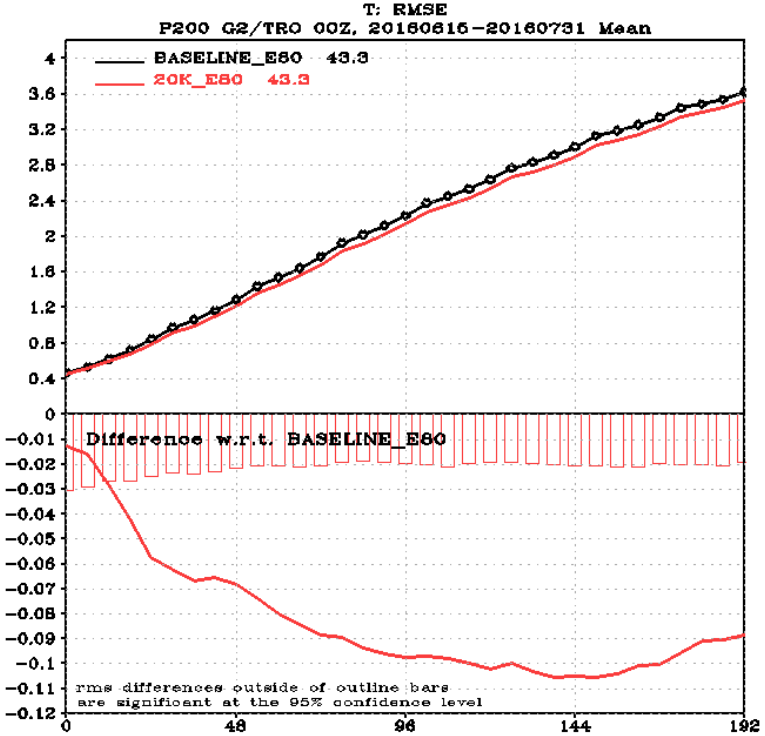
BASELINE_E80: Baseline configuration (~ 6,000 RO profiles/day)
20K_E80: Baseline + 20,000 RO profiles/day

Northern Hemisphere extra-tropics



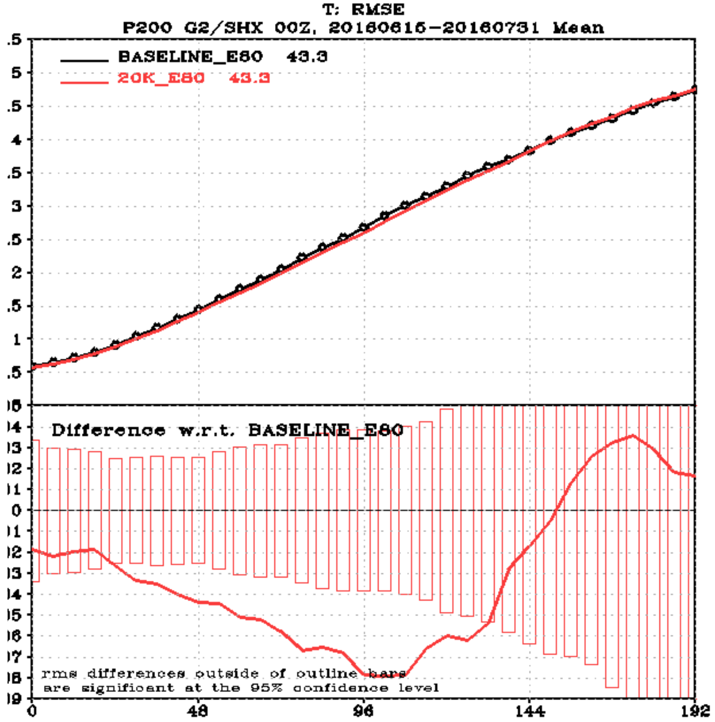
Forecast hour

Tropics



Forecast hour

Southern Hemisphere extra-tropics

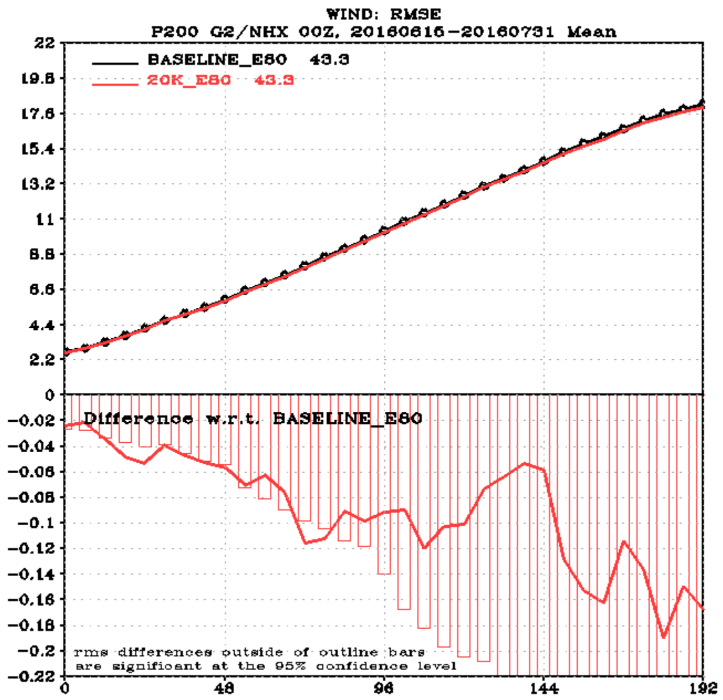


Forecast hour

200 hPa RMS Wind error

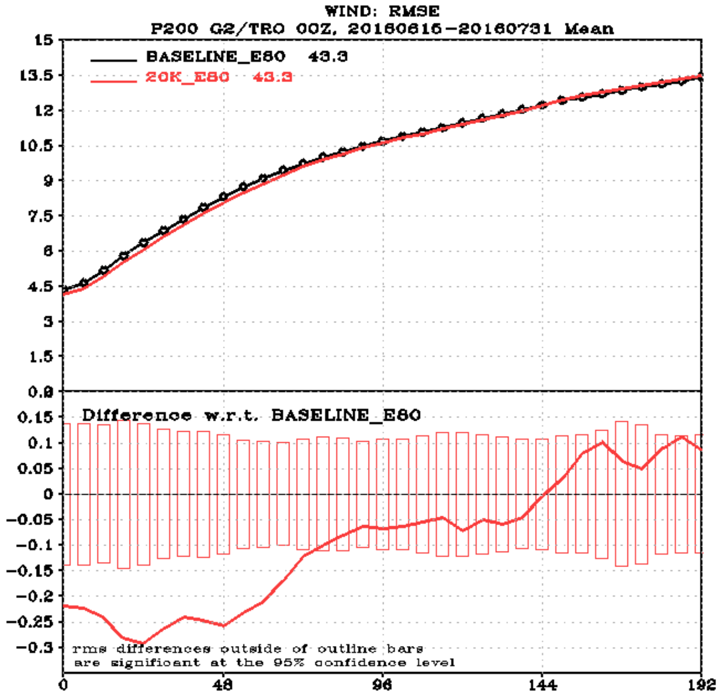
BASELINE_E80: Baseline configuration (~ RO profiles/day)
20K_E80: Baseline + 20,000 RO profiles/day

Northern Hemisphere extra-tropics



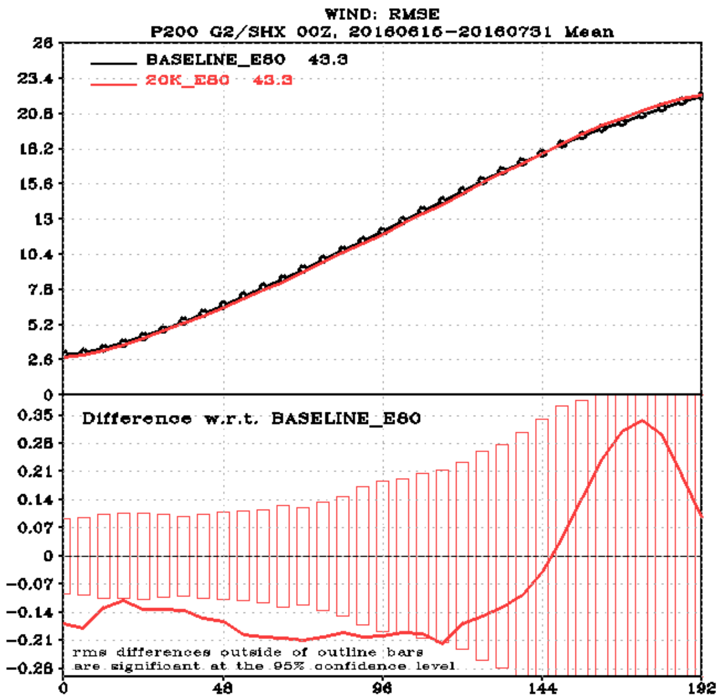
Forecast hour

Tropics



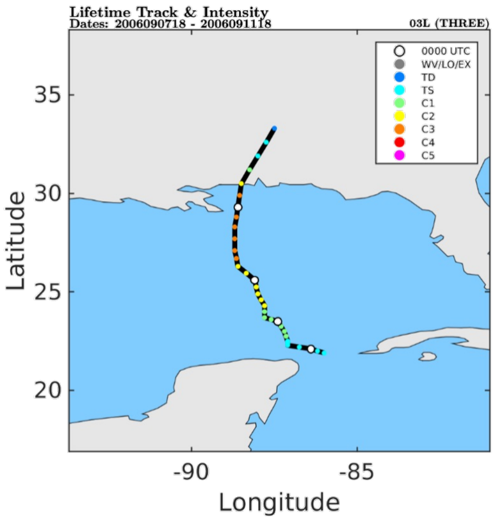
Forecast hour

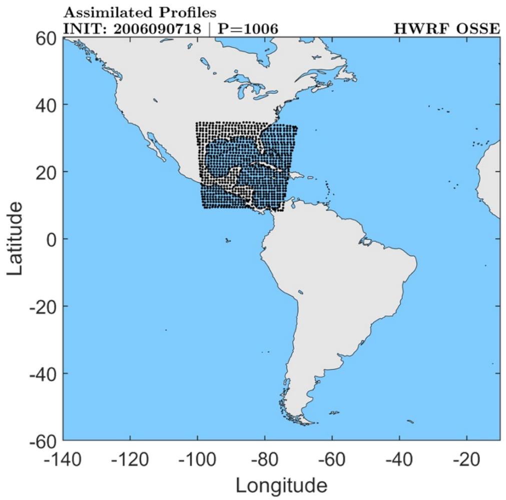
Southern Hemisphere extra-tropics



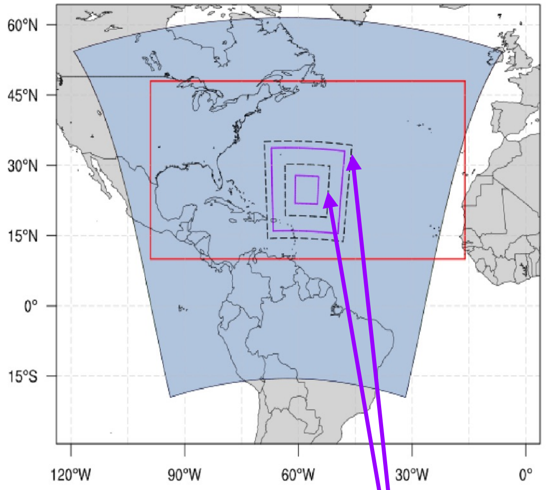
Forecast hour

OSSE: Geo-HSS impact on hurricane prediction



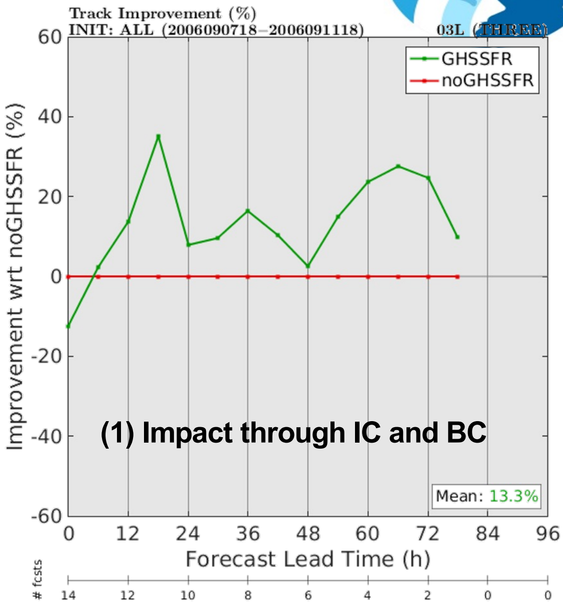


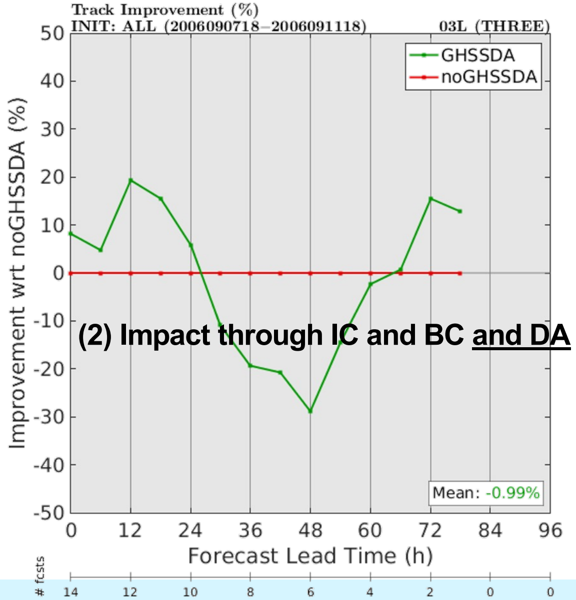
Slight positive/neutral impact on track forecast



1 fixed parent domain (13.5 km)

2 nested moving domains (4.5 km and 1.5 km). DA only occurs on these 2 domains





- Simulation of Geostationary Hyperspectral Infrared Sounder (STAR orbit simulator).
  - Simulate scan geometry/geolocation/FOV size from 75° W (~4 km
  - Full disk, ½ hourly resolution; Meso-sector, 5-minute resolution (1000 x 1000 km)
  - Spectral coverage: IASI 616 subset
- Limitation: assimilation in HWRF in only one inner domain.
- **Experiments should be repeated with the high-resolution ECMWF nature run for more realistic results.**

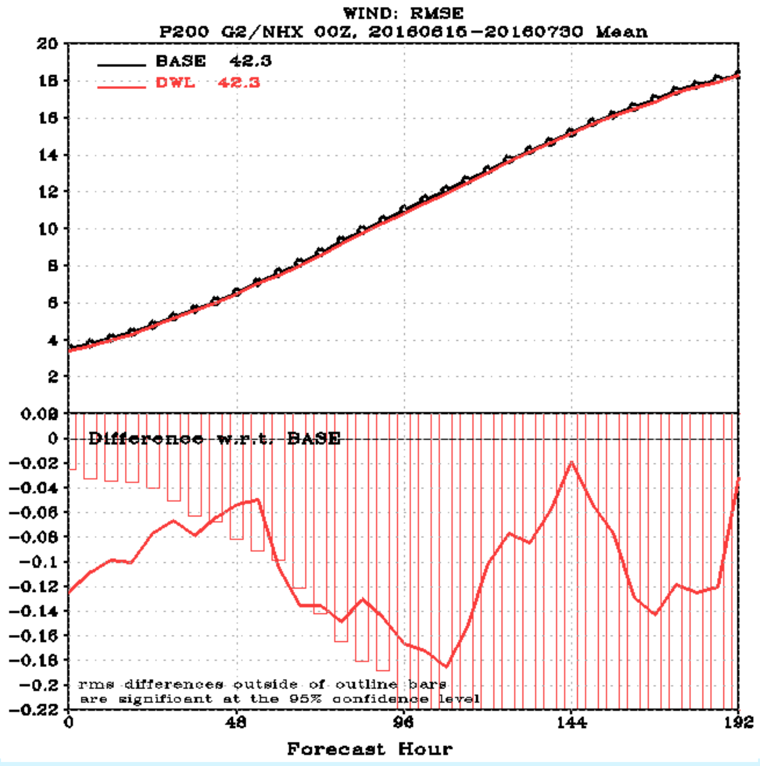
OSSEs in support of Aeolus Follow-On (EUMETSAT/KNMI)

BASE: Baseline control configuration
DWL: Baseline + Aeolus

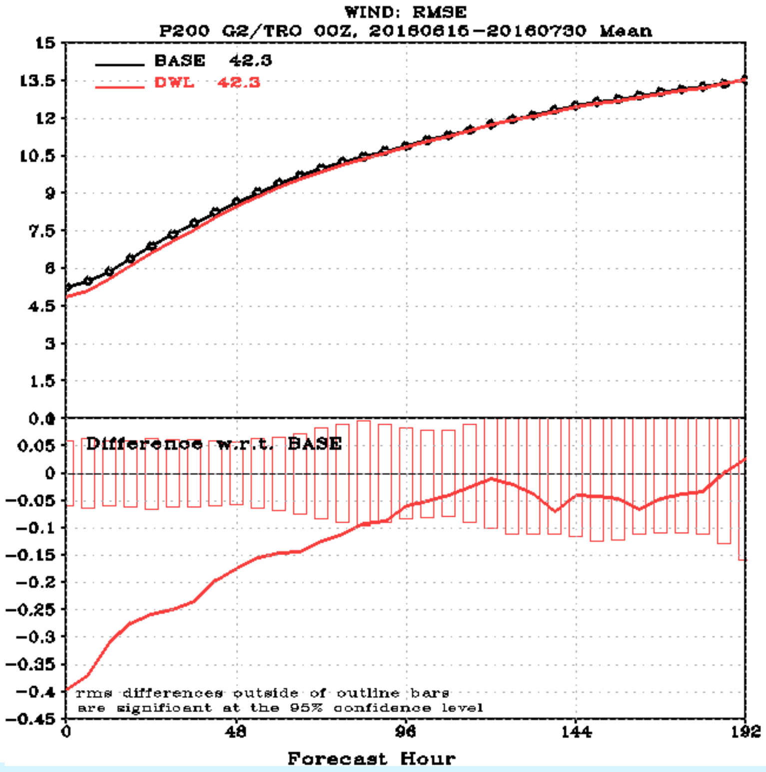
- We completed an OSSE with Aeolus
- Ongoing work to run an OSSE with Aeolus-FO

200 hPa RMS Wind error

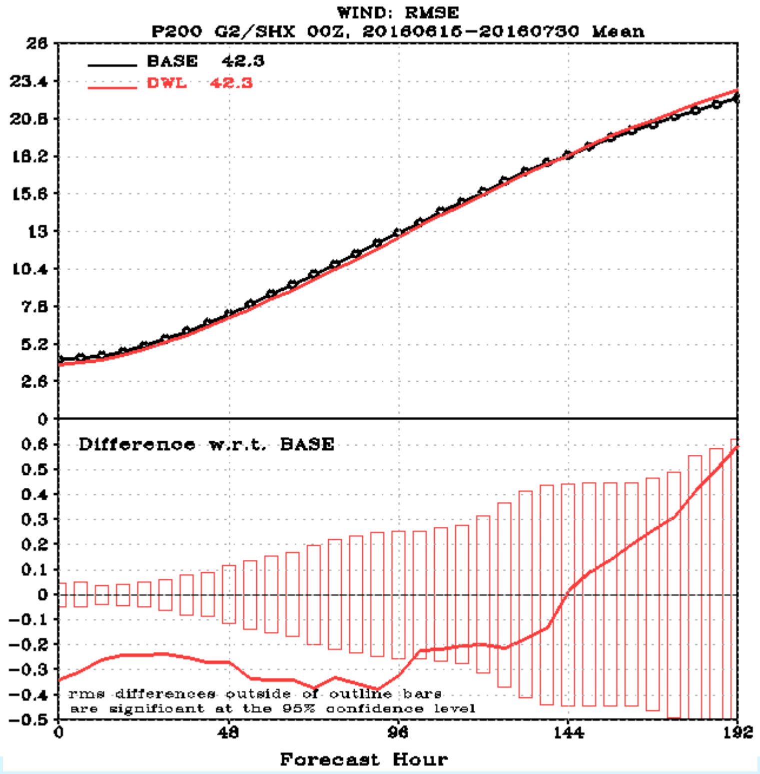
Northern Hemisphere extra-tropics



Tropics



Southern Hemisphere extra-tropics



OSSE: Satellite architecture trade-offs

- NOAA conducted a study to plan for the next generation of weather satellites – NOAA Satellite Observing System Architecture (NSOSA).
- Outlined new capabilities and architectures which NOAA should invest in.
- Generated architectural questions that could be addressed by observing system simulation experiments (OSSEs).
- Benefits from existing observing systems to be combined with potential enhancements from non-yet-existing capabilities.
- Key questions to address:
  - Relative value of sounding quality and quantity for global NWP – to support decision making on sounder performance versus satellite numbers.
  - Value of global wind observations and their value relative to enhanced sounding, relative value of different approaches to global wind observations (active versus passive).

NSOSA Study Performance levels

- **Study Threshold (ST)**
  - IR: 15 km horizontal res, 2 km vertical res, 180 min latency, 1 K and 2 g/kg accuracy, 12 h update rate
  - MW: 50 km horizontal res, 4 km vertical res, 165 min latency, 2 K accuracy, 12 h update rate
  - GNSSRO: 5,000 prof/day, 90 min latency, 800 V/V (C1 level)
- **Program of Record 2025 (POR2025)**
  - IR: 14 km horizontal res, 1.5 km vertical res, 50 min latency, 1 K and 0.2 g/kg accuracy, 6 h update rate (CrIS/JPSS, IASI NG/EUMETSAT)
  - MW: 32 km horizontal res, 3 km vertical res, 50 min latency, 1 K accuracy, 5.8 h update rate (ATMS/JPSS, MWS/EUMETSAT)
  - GNSSRO: 8,000 prof/day (C2 + 2 EPS-SG), 30 min latency, 1600 V/V (C2 level)
- **Expected Performance (EXP)**
  - IR: 10 km horizontal res, 1.5 km vertical res, 60 min latency, 0.75 K and 0.2 g/kg accuracy, 3 h update rate
  - MW: 25 km horizontal res, 3 km vertical res, 45 min latency, 1.5 K accuracy, 3 h update rate
  - GNSSRO: 20,000 prof/day, 30 min latency, 1600 V/V (C2 level)
- **Maximum Effective (ME)**
  - IR: 1 km horizontal res, 1 km vertical res, 15 min latency, 0.5 K and 0.15 g/kg accuracy, 1 h update rate
  - MW: 5 km horizontal res, 2 km vertical res, 15 min latency, 1 K accuracy, 1 h update rate
  - GNSSRO: 50,000 prof/day, 10 min latency, 2000 V/V

Configuration for sounding quality/quantity OSSEs

- **Controls**
  - ST level
  - POR2025

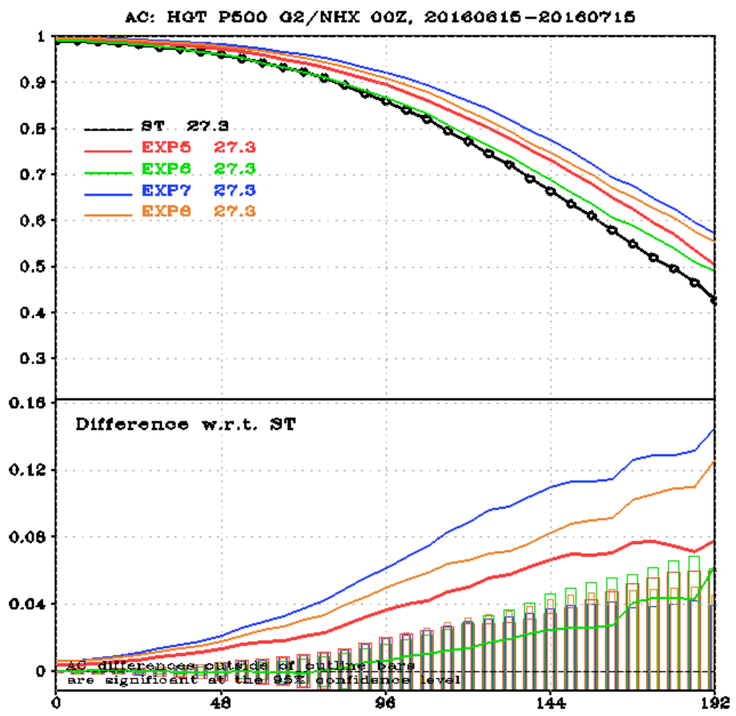
- **Quality vs Quality Trades Experiments**
  - Exp 4: ST with RO data quality improved to the ME level.
  - Exp 5: ST with RO quantity (but not quality) improved to the ME level.
  - Exp 6: ST with MW quality improved to the ME level.
  - Exp 7: ST with MW and IR data quantity improved to the ME level.
  - Exp 8: ST with IR, MW, and RO improved to the EXP level.

Considerations on Performance Levels in OSSEs

- Horizontal resolution: limited by 9 km spatial resolution of NR. NWP thinning still done at 145 km.
- Vertical resolution: number of channels.
- Temporal resolution: limited to 3 h due to NR temporal resolution.
- Accuracy: Small sensitivity within range of proposed perturbations.
- Cloudy MW radiances are assimilated in operational model; but only clear-sky IR. All all-sky (cloudy + precipitation) expected in future NWP operational updates.
- Latency: not addressed in OSSEs. Not too relevant in current global NWP at NOAA unless high data latency.
- Revisit rate – drives number of satellites and orbits.
- RO: higher SNR does not necessarily mean higher accuracy.
- Experimental period: June 1 – July 15 with verification time period: June 15 – July 15.
- Focus on Global NWP.
- Quantitative information on relative NWP skill between experiments rather than absolute skill.

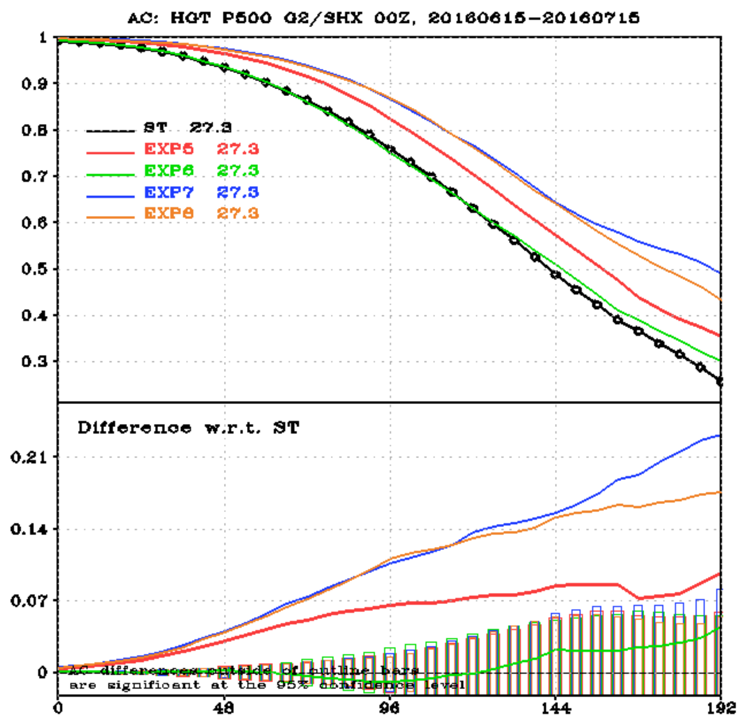
EXP5: ST with 50,000 RO profiles/day
EXP6: ST with MW at highest horizontal resolution (9 km)
EXP7: ST with MW/IR at highest revisit rate (12 orbits each)
EXP8: ST with MW/IR with 4 orbits each and 18 km horizontal resolution, and 20,000 RO profiles/day

Anomaly correlation 500-hPa geopotential heights
Northern Hemisphere extra-tropics



Forecast hour

Anomaly correlation 500-hPa geopotential heights
Southern Hemisphere extra-tropics



Forecast hour

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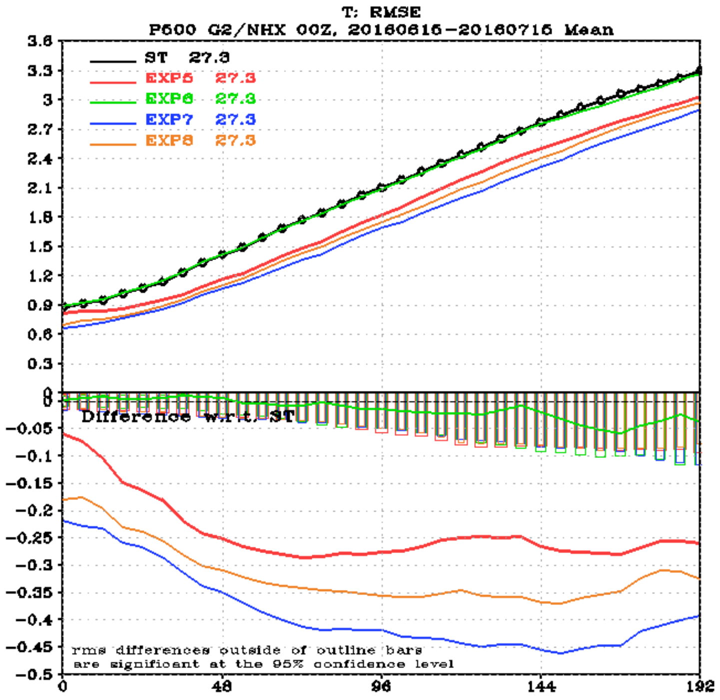
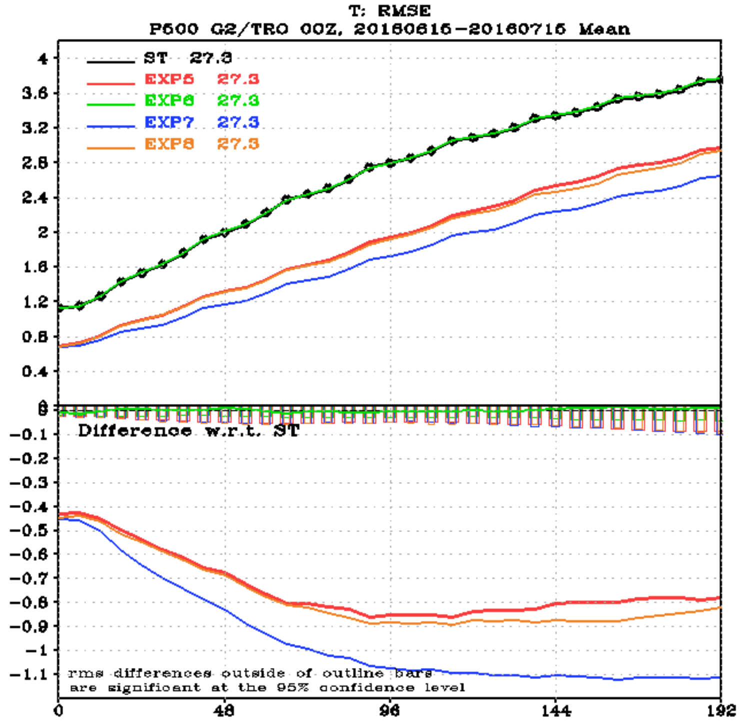
500 hPa RMS Temperature error

Northern Hemisphere extra-tropics



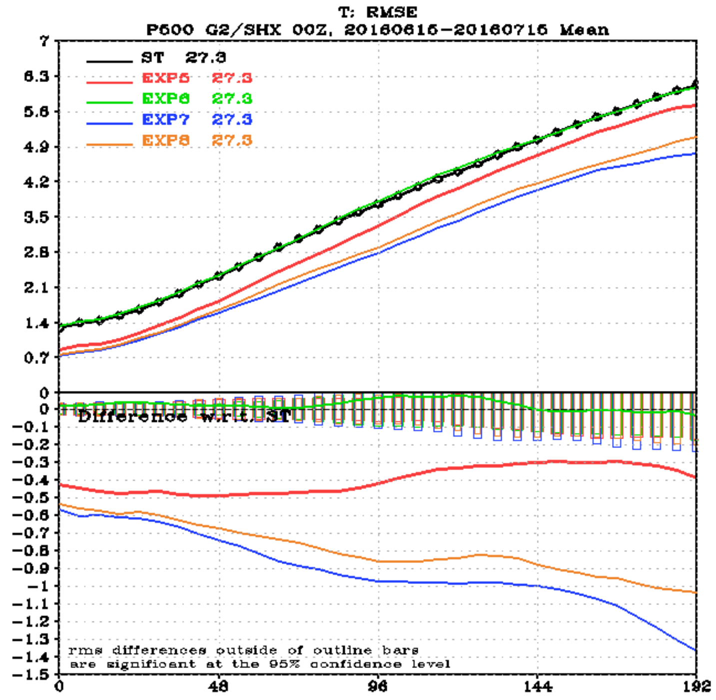
Forecast hour

Tropics



Forecast hour

Southern Hemisphere extra-tropics

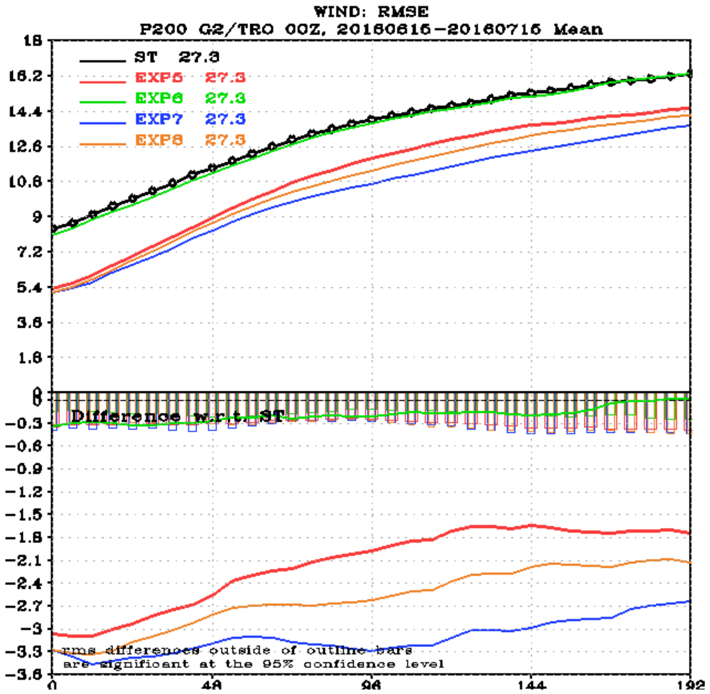


Forecast hour

EXP5: ST with 50,000 RO profiles/day
EXP6: ST with MW at highest horizontal resolution (9 km)
EXP7: ST with MW/IR at highest revisit rate (12 orbits each)
EXP8: ST with MW/IR with 4 orbits each and 18 km horizontal resolution, and 20,000 RO profiles/day

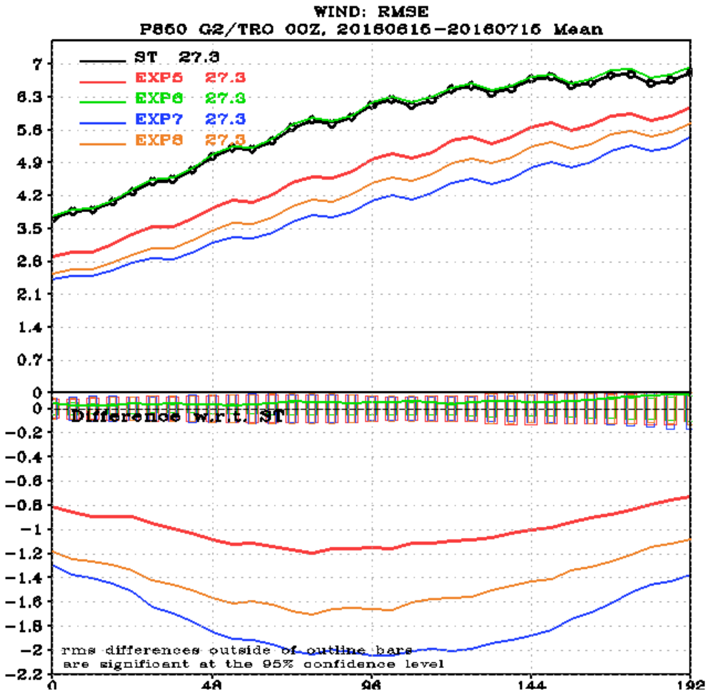
RMS WIND error: Tropics

200 hPa



Forecast hour

850 hPa



Forecast hour

Concluding thoughts on trade-offs OSSEs

- Significantly increasing the revisit rate for satellite radiance soundings produces the largest benefits.
- Large positive impact is found when the number of RO soundings/day is increased well beyond current values.
- RO can be used as a mitigation strategy for MW/IR sounding revisit rate, particularly in the Tropics.
- Fewer benefits result from increasing the horizontal resolution of MW satellite radiances, likely due to the current 145 km-thinning in global NWP.

OSSE: Active (DWL) vs. passive (AMV) approaches

Experiments design is ongoing work

- Active approach: one DWL versus two DWLs (Aeolus-type)
- Passive approach
  - AMVs from 9 satellites, with 3 in a single orbit and spaced no more than 15 minutes apart
  - AMVs from 9 evenly distributed sun-synchronous orbits
- MW/IR satellite configuration: 3 MW and 3 IR
  - MW/IR pairs collocated on a single platform: 3 satellites in 3 orbits
  - 6 instruments in separate orbits, evenly distributed on sun-synchronous orbits.
- MW/IR/AMVs configuration: 9 satellites (TBD)

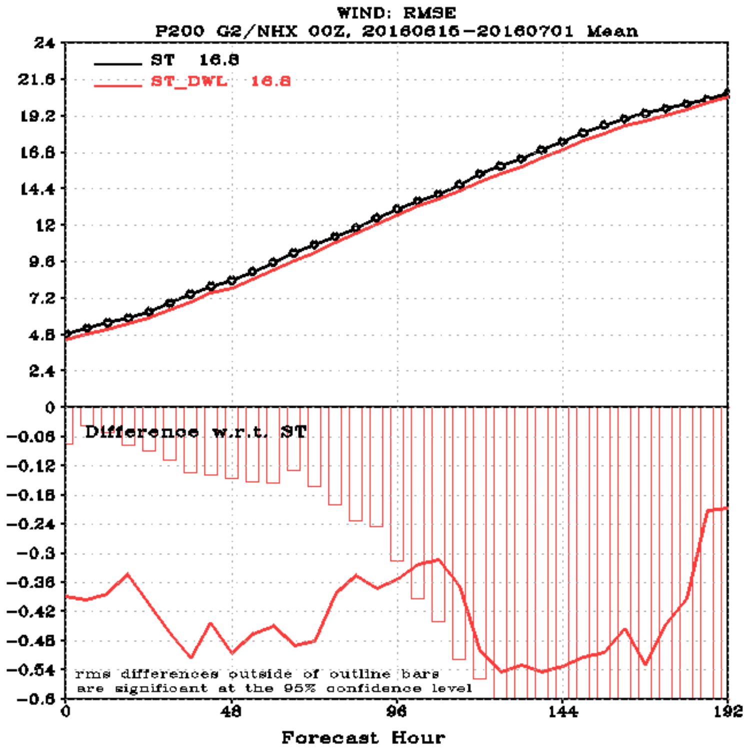
OSSE: DWL (Aeolus) impact

ST: Study Threshold
STL_DWL: ST + Aeolus (experiment not finished yet)

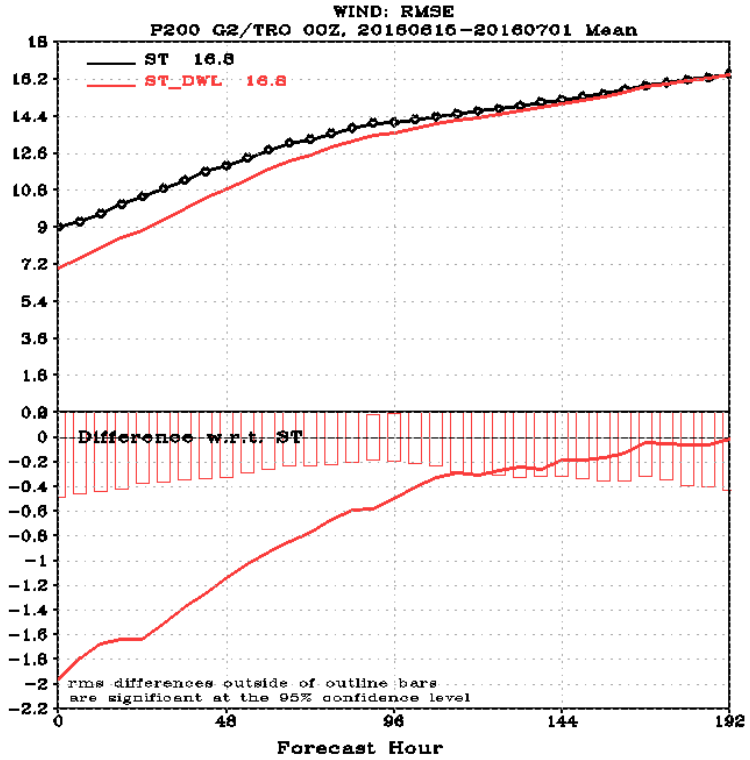
****The second DWL configuration is currently being designed**

200 hPa RMS Wind error

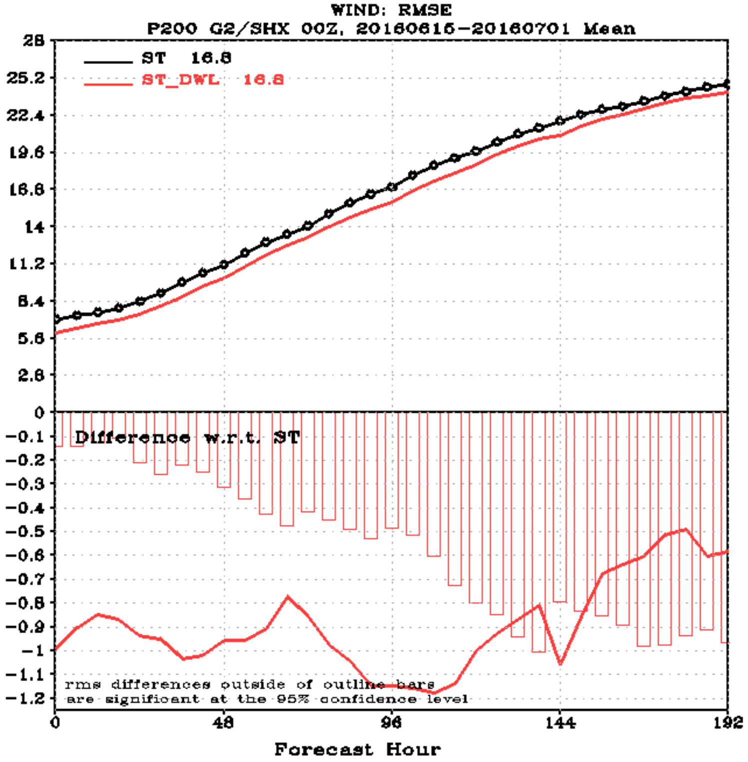
Northern Hemisphere extra-tropics



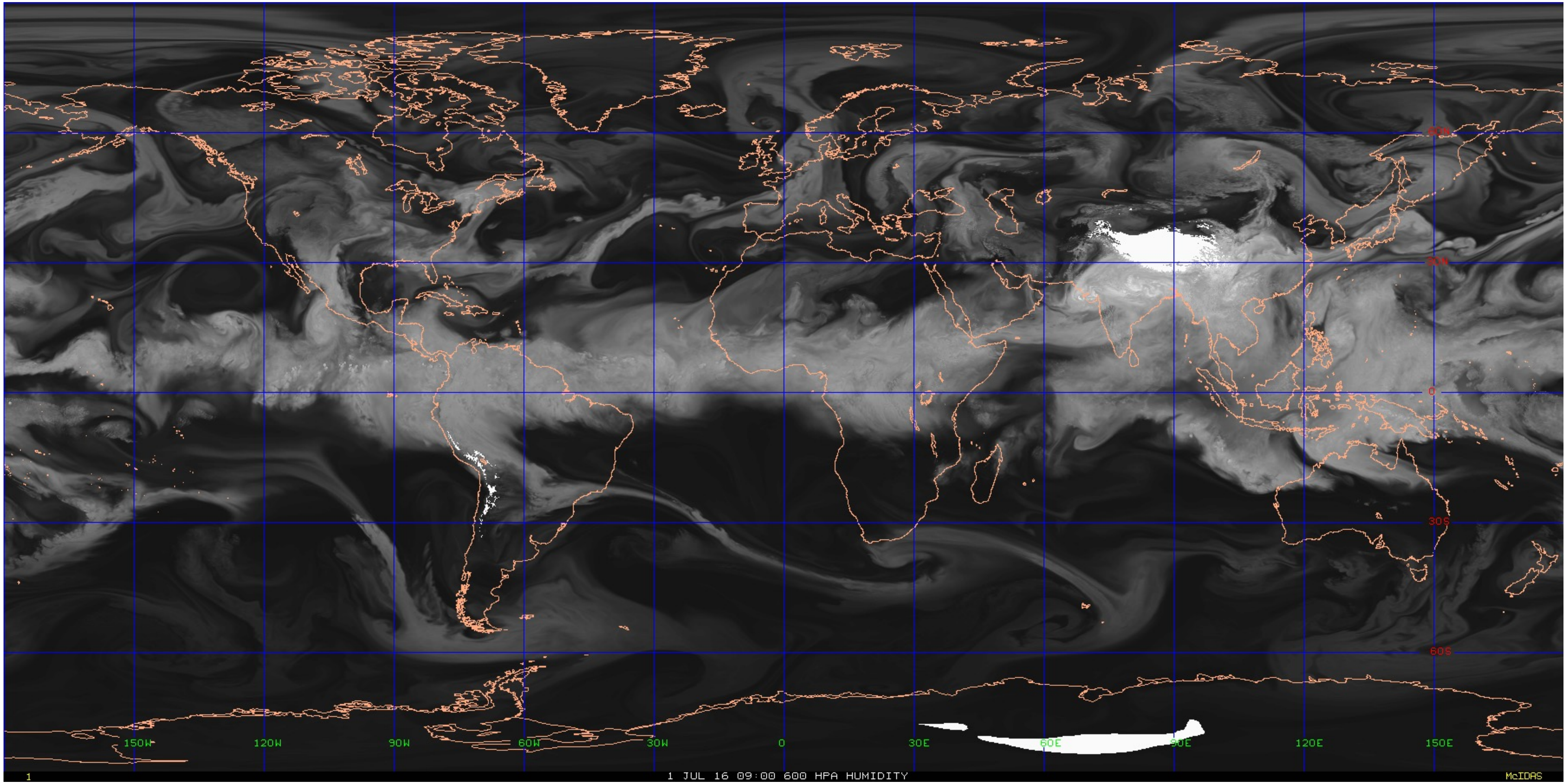
Tropics



Southern Hemisphere extra-tropics

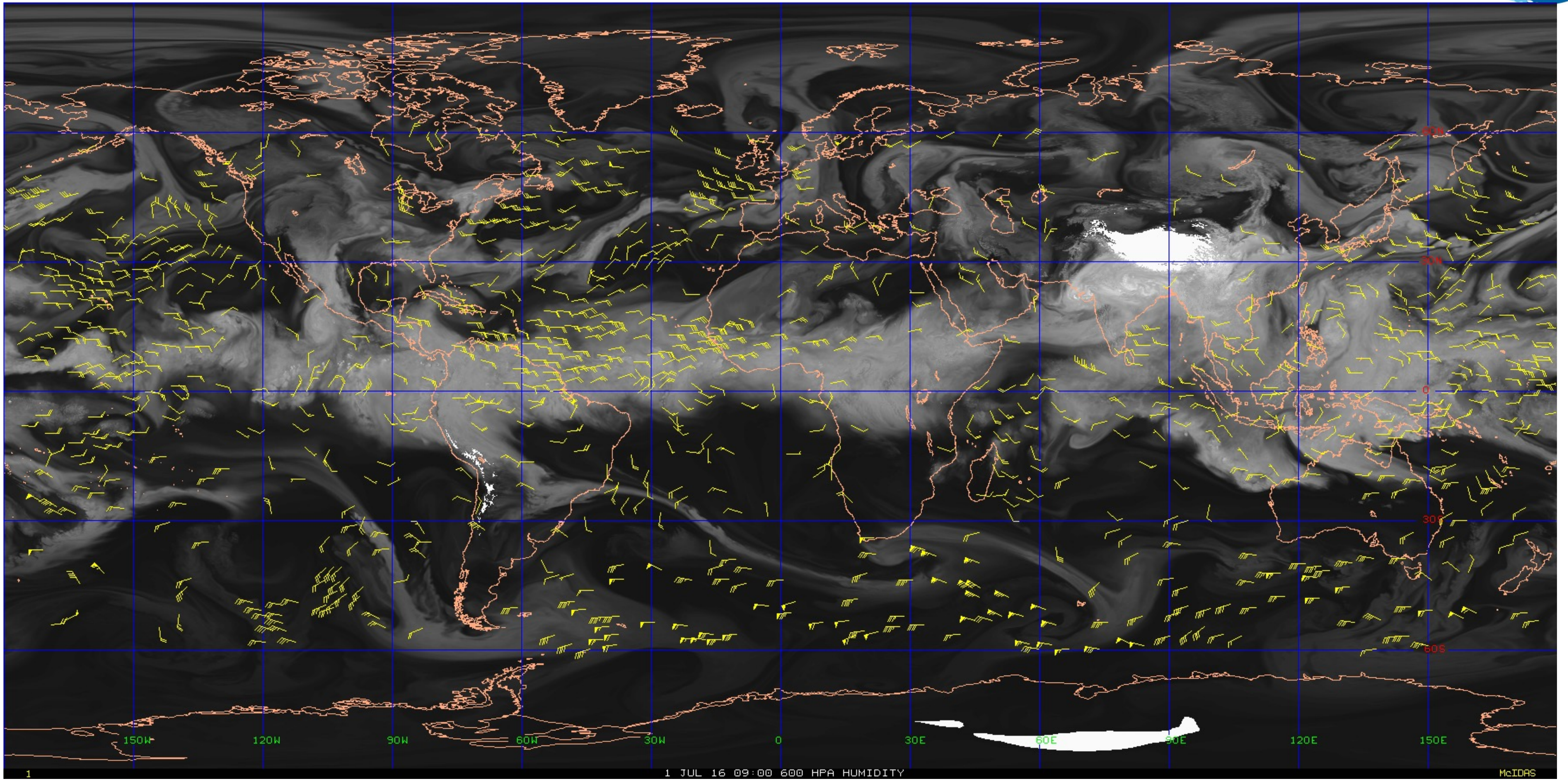


Generating AMVs: ECO1280 humidity field



600 hPa humidity from 01 July 2016 at 0900, 1200, 1500 UTC.

ECO1280 humidity field with AMVs



600 hPa humidity from 01 July 2016 at 0900, 1200, 1500 UTC with derived AMVs

Final Remarks

- QOSAP was stablished to address NOAA's capability gap in conducting quantitative assessments of current and proposed observing systems.
- Provides core capability to conduct OSSEs and OSEs.
- Some experiments have been completed or are underway to help guide planning and decision making for the next generation of satellite architecture.
- Additional questions can be addressed with OSEs and OSSEs to continue to support NOAA's mission.

Questions?