On tropical variability in NOAA's Unified Forecast System - impact of convection and ocean coupling

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Motivation

- The forthcoming Global Forecasting System GFSv17/GEFSv13 will be the first global forecast applications to become operational under the UFS infrastructure.
- As such, it will be the first versions of the GFS/GEFS that are fully coupled earth system models.
- The GFSv17/GEFSv13 and SFSv1 includes innovations which have been included in so-called “coupled prototypes” coordinated between NOAA and the community under the UFSR2O project in a stepwise manner.
- In this presentation we will provide a concise overview of the incremental changes introduced to the cumulus convection parameterization schemes (both shallow and deep) during the prototype phases spanning from GFSv16 to the forthcoming GFSv17/GEFSv13, with a close eye on variability in the tropics, primarily driven by equatorial waves interacting with moist convective processes.
- We will also share new diagnostic capabilities developed at PSL to assess tropical variability in the global UFS applications.

P6 → P7 → P8 → HR1 → HR2 → HR3

P6

Land: **Noah**
PBL: **TKE-EDMF**
Microphysics: **GFDL MP**
Deep convection: **saSAS**
Shallow convection: **saMF**
Radiation: **RRTMG**
Gravity wave drag: **uGWDv0**

P7

Land: **Noah-MP +**
Compositing surface layer variables, albedo/emissivity
PBL: **TKE-EDMF**
Reduced background diffusivity, limit PBL updraft overshoot.
Microphysics: **GFDL MP**
Deep convection: **saSAS**
Stricter trigger criteria, reduced entr. rate, reduced rain evap. rate
Shallow convection: **saMF**
Radiation: **RRTMG**
MERRA2 aerosols
Gravity wave drag: **uGWDv0**

P8

Land: **Noah-MP**
Tuning, use CICE albedo in atm, new ice climatology, VIIRS based land/lake mask, spun up land IC's.
PBL: **TKE-EDMF**
Positivie definite massflux scheme, reduced entrainment rate
Microphysics: **Thompson MP +**
Semi-Lagrangian Sedimentation + refined ice microphysics
Deep convection: **saSAS**
Cellular automata convective org scheme.
Positivie definite massflux scheme
Shallow convection: **saMF**
Positivie definite massflux scheme
Radiation: **RRTMG**
Gravity wave drag: **uGWDv0**

HR1

Land: **Noah-MP**
Bug-fixes
PBL: **TKE-EDMF**
Microphysics: **Thompson MP**
Improve radiative fluxes and cloud cover
Deep convection: **saSAS**
Prognostic closure
Shallow convection: **saMF**
Prognostic closure
Radiation: **RRTMG**
Couple convective cloud to radiation
Gravity wave drag: **uGWDv0**

HR2

Land: **Noah-MP**
Bug-fixes
PBL: **TKE-EDMF**
wind shear effect and TKE dependent entrainment.
CONUS CAPE enhancement
Microphysics: **Thompson MP**
Reduce stratus and downwelling rad. fluxes
Deep convection: **saSAS**
wind shear effect and TKE dependent entrainment
Shallow convection: **saMF**
Radiation: **RRTMG**
Gravity wave drag: **uGWDv0**

HR3

Land: **Noah-MP**
PBL: **TKE-EDMF**
Microphysics: **Thompson MP**
Deep convection: **saSAS**
Shallow convection: **saMF**
Radiation: **RRTMG**
Address excessive large net SW net to ocean at low sun angles
Gravity wave drag: **uGWDv1**

UFSR2O physics/dynamics development coordination
Fanglin Yang, Lisa Bengtsson

Acknowledgement to ALL UFS coupled/infrastructure/physics/dynamics/DA developers, application/project leads , and evaluators!

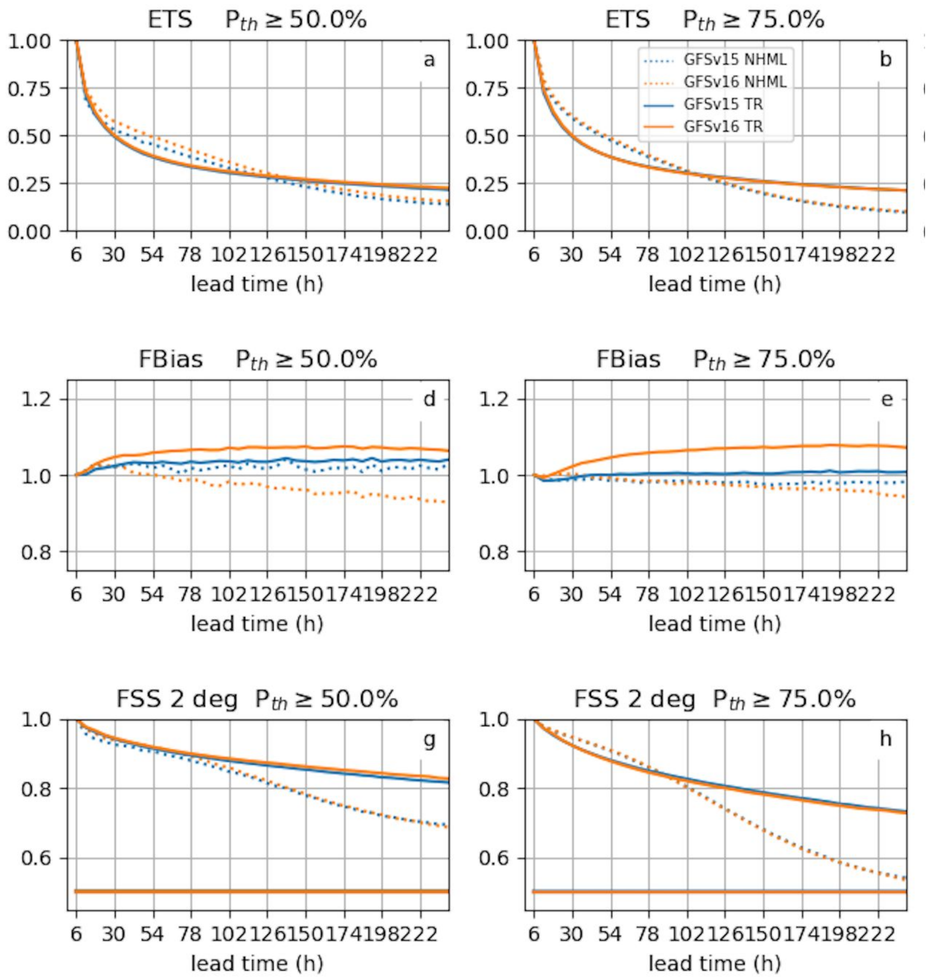
Outline

- Tropical diagnostics capabilities demonstrated using GFSv15, GFSv16 and GFSv17/GEFSv13 prototypes
- Updates to cumulus convection parameterization between GFSv16 and GFSv17/GEFSv13
- A first look at tropical variability the Seasonal Forecast System (SFS) “proof of concept” runs.

Convectively Coupled Equatorial Wave Diagnostics and Skill in the UFS

Maria Gehne (CIRES/NOAA PSL)

Acknowledgement: Brandon Wolding (CIRES), Juliana Dias (PSL), George Kiladis (PSL)



NWP models tend to perform better in mid-latitudes than in the Tropics for lead times <4 days.

- The underlying dynamics are different in the Tropics and mid-latitudes.
- Convection is main driver of precipitation in the Tropics.
- Convective parameterization has a larger impact on precipitation in the Tropics.

There is evidence that better forecast skill in the Tropics can lead to improved forecasts in mid-latitudes.

Evaluating tropical convection in NWP

It is not very well understood which processes in the Tropics are most important to mid-latitude forecast skill.

There are, however, well-known sources of predictability beyond a few days in the tropical atmosphere such as the MJO and Convectively Coupled Equatorial Waves (CCEWs).

Consider metrics and diagnostics specifically for NWP in the Tropics:

- Better understanding of NWP model behavior with respect to tropical convection.
- Identify forecast error sources in the Tropics related to moisture-convection coupling, CCEWs and the MJO.
- We will look at variability and not biases in this presentation, although biases can be substantial at later lead times.

NWP evaluation presents different challenges than climate model evaluation.

- Forecasts are shorter: days-weeks.
- Model versions change frequently.
- It is rare to have long (multi-year) time series of operational model runs.

Consider diagnostics as a function of lead time.

If certain phenomena are initialized correctly, how long is the model able to keep that information?

Model runs

FV3GFS V15 operational (GFSv15) and FV3GFS V16 parallel (GFSv16) runs initialized 6 hourly from April through October 2020 and run out to lead time 240h.

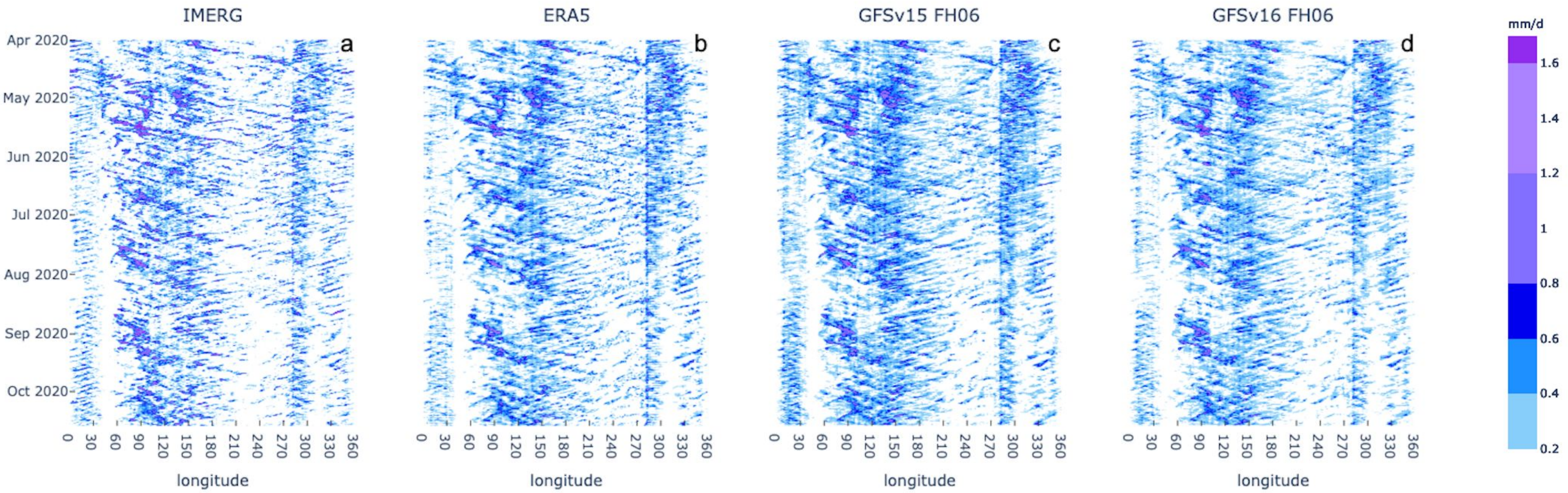
These are uncoupled forecasts.

UFS coupled prototype (P5,7,8) runs - 168 initializations, every 1st and 15th of the month between 20110401 and 20180315.

UFS HR2 runs - initialized every 3 days from December 2019-February 2020 and June - August 2020

More details on the GFS v15 and v16: https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php
More details on the UFS prototypes:
https://registry.opendata.aws/noaa-ufs-s2s/#:~:text=The%20UFS%20prototypes%20are%20the,weather%20prediction%20system%20from%20NWS.

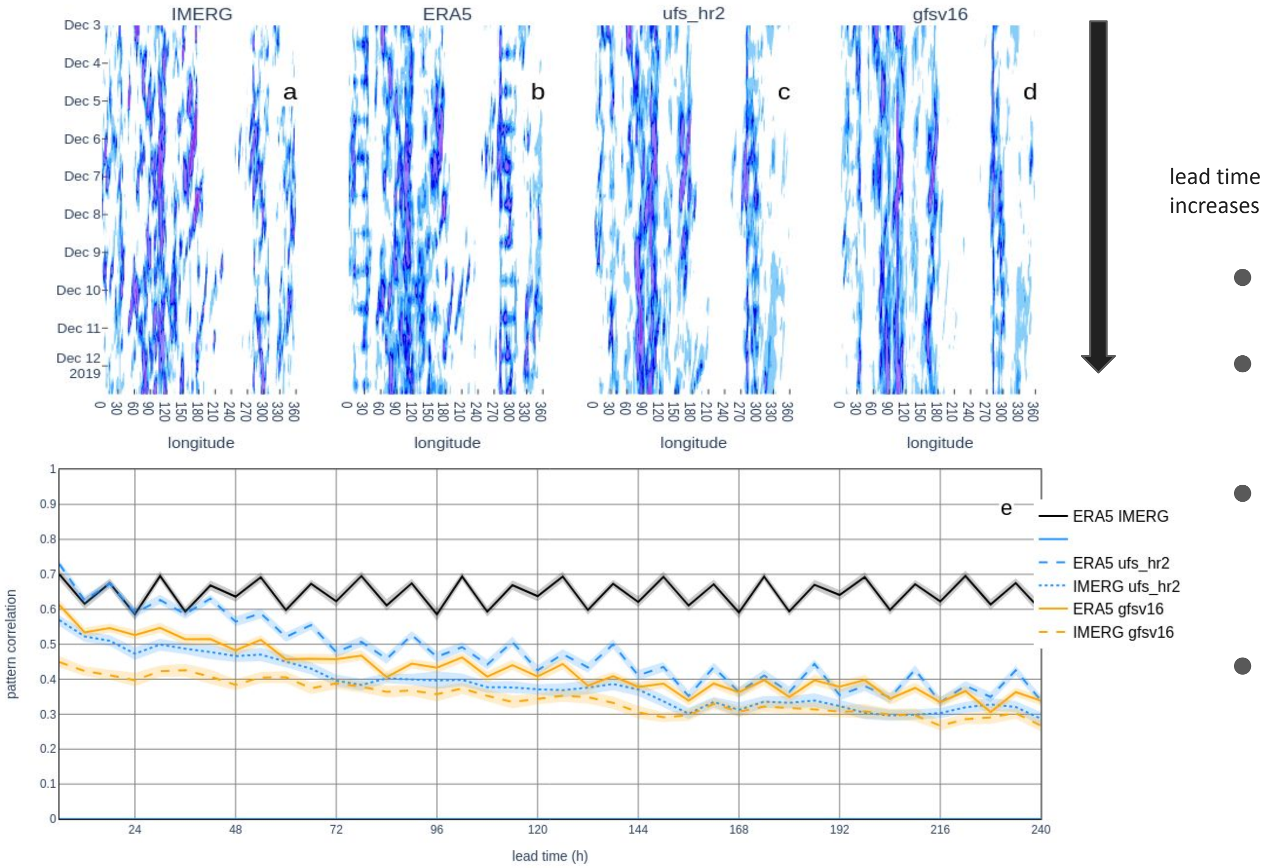
Hovmoeller and Pattern Correlation



Assess the **zonal** propagation of convective features.

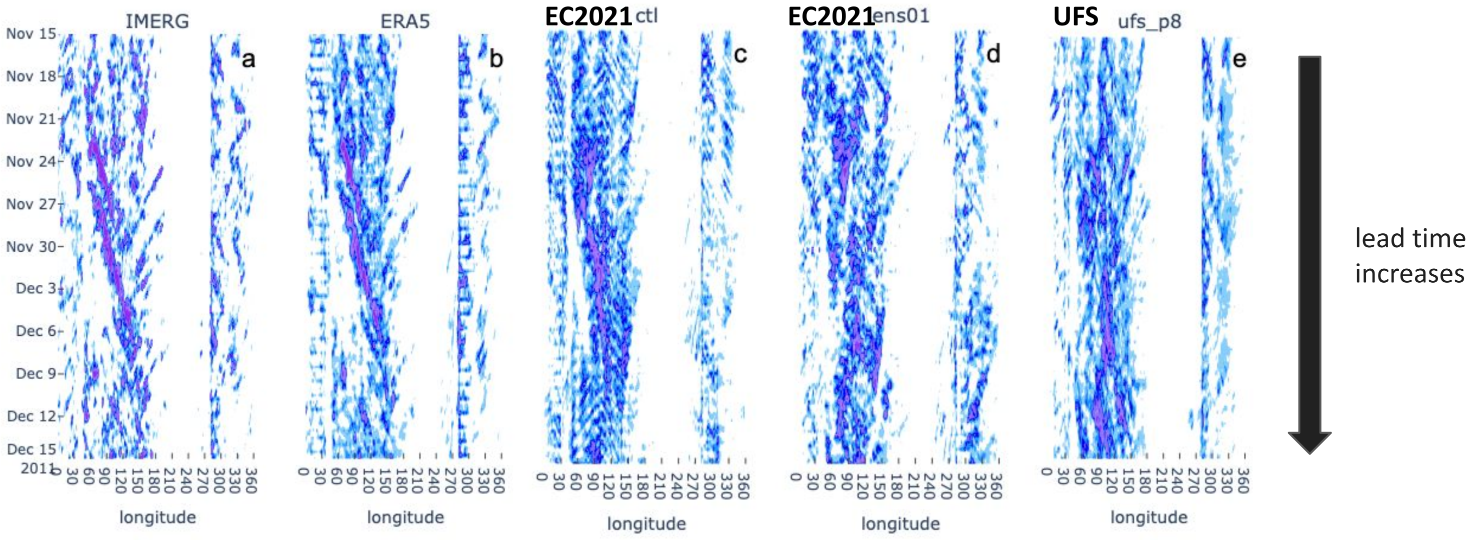
Pattern correlation between forecast and 'truth' can be used as a skill score.

Hovmoeller and Pattern Correlation



- Combined skill for HR2 winter and summer runs.
- HR2 correlation skill improves over GFSv16 by about 0.15 at 6h lead time.
- Skill correlation above 0.5 until 36h lead time for GFSv16, until 72h lead time for HR2 when verification is ERA5.
- Improvement in skill for HR2 is consistent until 72h lead time.

Hovmoeller and Pattern Correlation



30 day period in November - December 2011

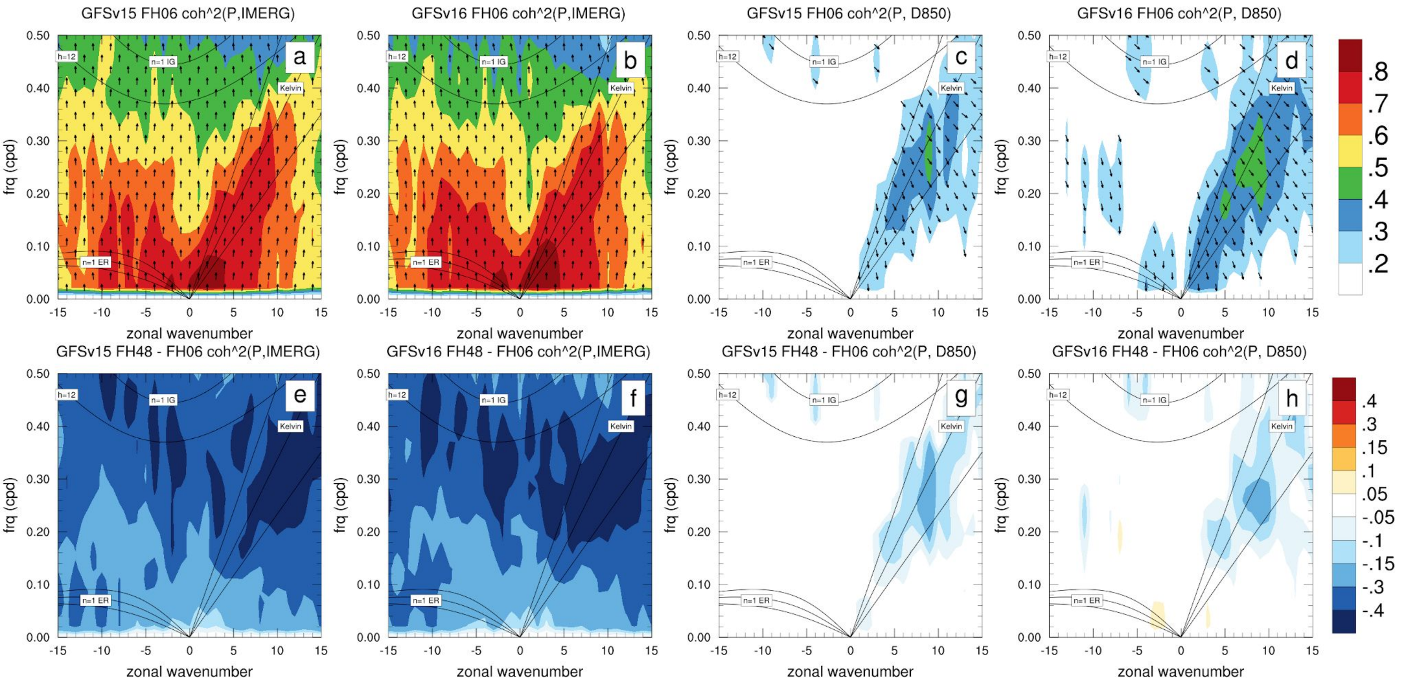
IMERG and ERA5 show the MJO event observed during DYNAMO starting around 11/22.

Model precipitation is plotted along the forecast instead of at a single lead time.

Model forecasts vary widely between models and ensemble members after a few days.

Some forecasts have an indication of enhanced convection during the observed MJO period and others don't.

Space-time coherence-squared spectra

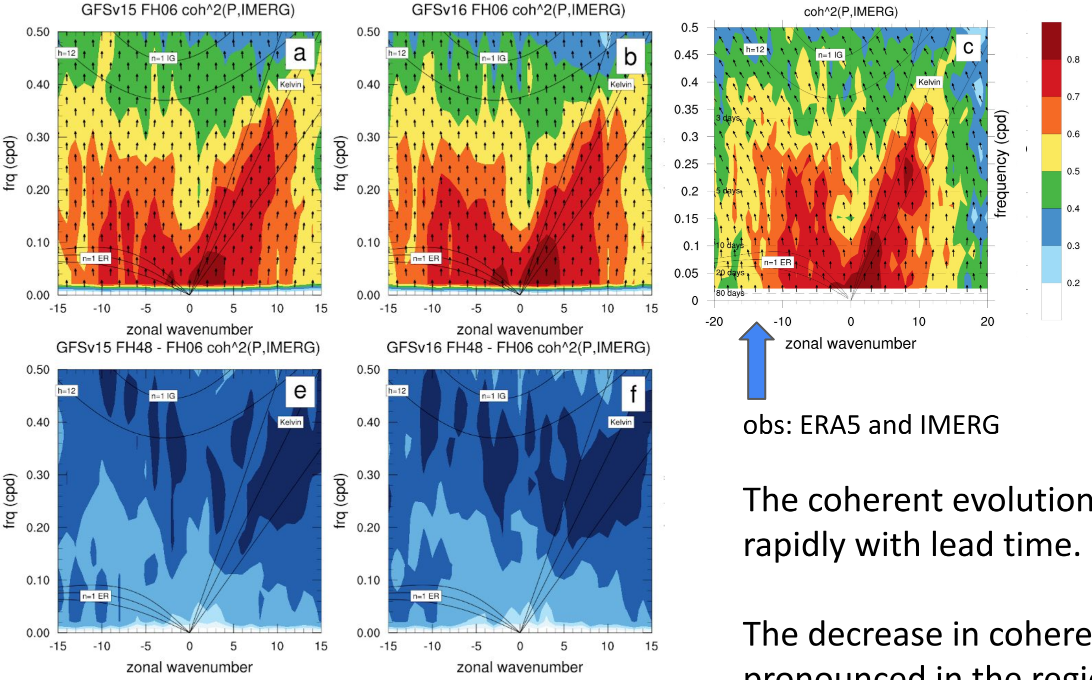


- How well do models initialize and propagate CCEWs?
- Coherence spectra show space-time regions of tropical variability without having to estimate a background.

Evaluate the consistency in variability between modeled and observed precipitation at a range of spatial and temporal scales.

It is possible to evaluate precipitation – dynamics relationship strength and how it changes with lead time.

Space-time coherence spectra



Initially larger coherence values tend to be located near CCEW dispersion curves and at lower frequencies and larger spatial scales.

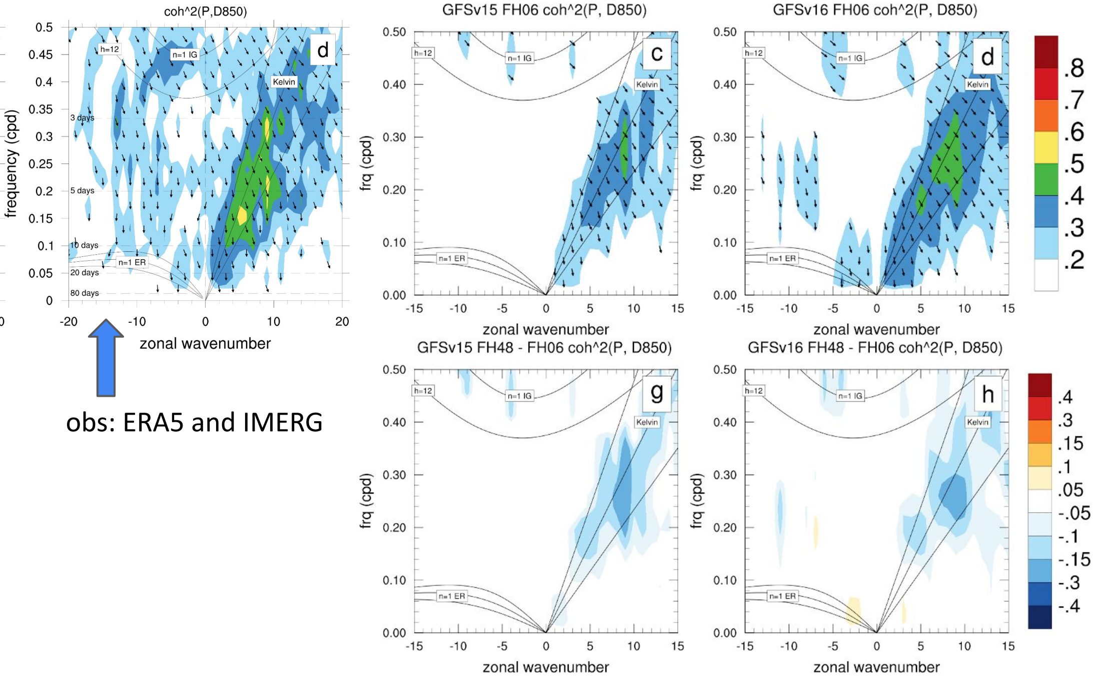
Precipitation in both GFSv15 and GFSv16 in the first 12 - 24h past initialization is largely able to initialize and maintain large scale CCEW events

The coherent evolution of observed and modeled precipitation decreases rapidly with lead time.

The decrease in coherence squared from 6h to 48h lead time is most pronounced in the regions of CCEW dispersion curves and higher frequencies and wavenumbers.

The coherence decay rate is related to the wave lifecycle and the model is able to propagate waves present in the IC, but spontaneous initialization of CCEWs is much harder.

Space-time coherence spectra



obs: ERA5 and IMERG

There are distinct peaks in coherence along CCEW dispersion curves, but overall the model coherence tends to be lower than observed. Models tend to have peaks at slightly higher frequencies than the reanalysis and observations

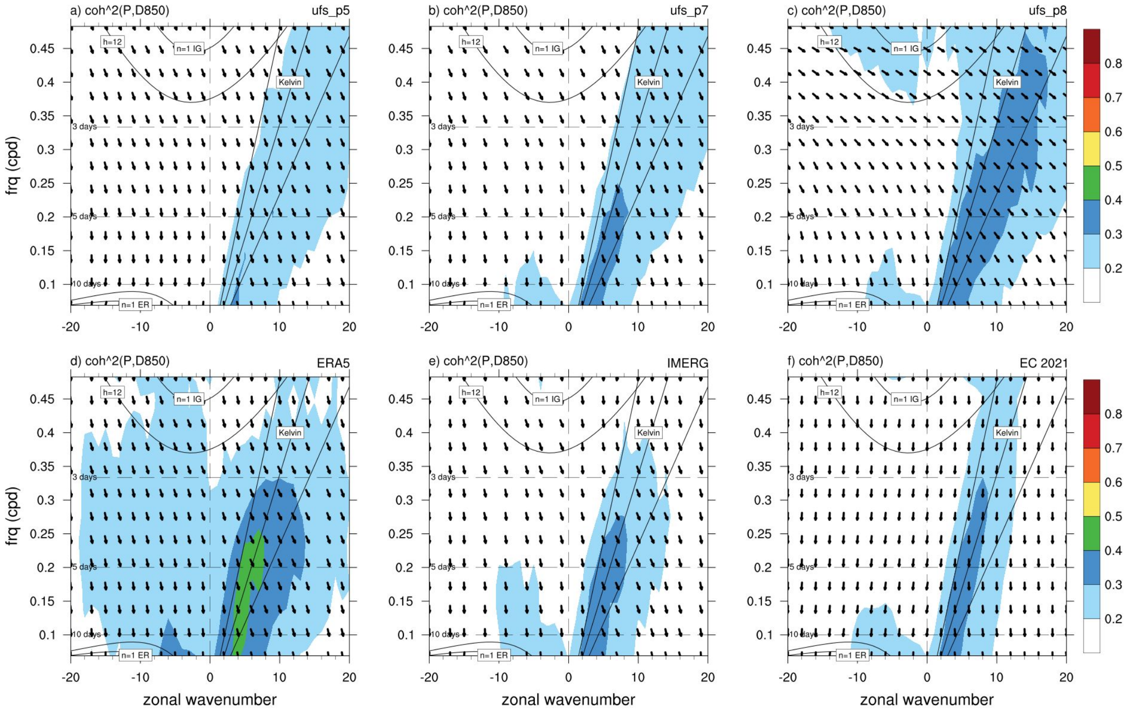
By 48h lead time coherence between precipitation and 850 hPa divergence at the peaks in the Kelvin wave band has decreased by 50-75% (GFSv15) and 30-50% (GFSv16).

Both model versions are able to initialize CCEWs, the coupling between moisture and dynamics is too weak even at initial time.
At longer lead time precipitation is not coupled strongly to the near-surface dynamics, although this is improved in GFSv16.

There is almost no coherence at very high frequencies.

Variability at higher frequencies and wavenumbers does not contribute much to S2S predictability although this activity could still be a source of feedback to the larger scales.

Space-time Coherence Spectra

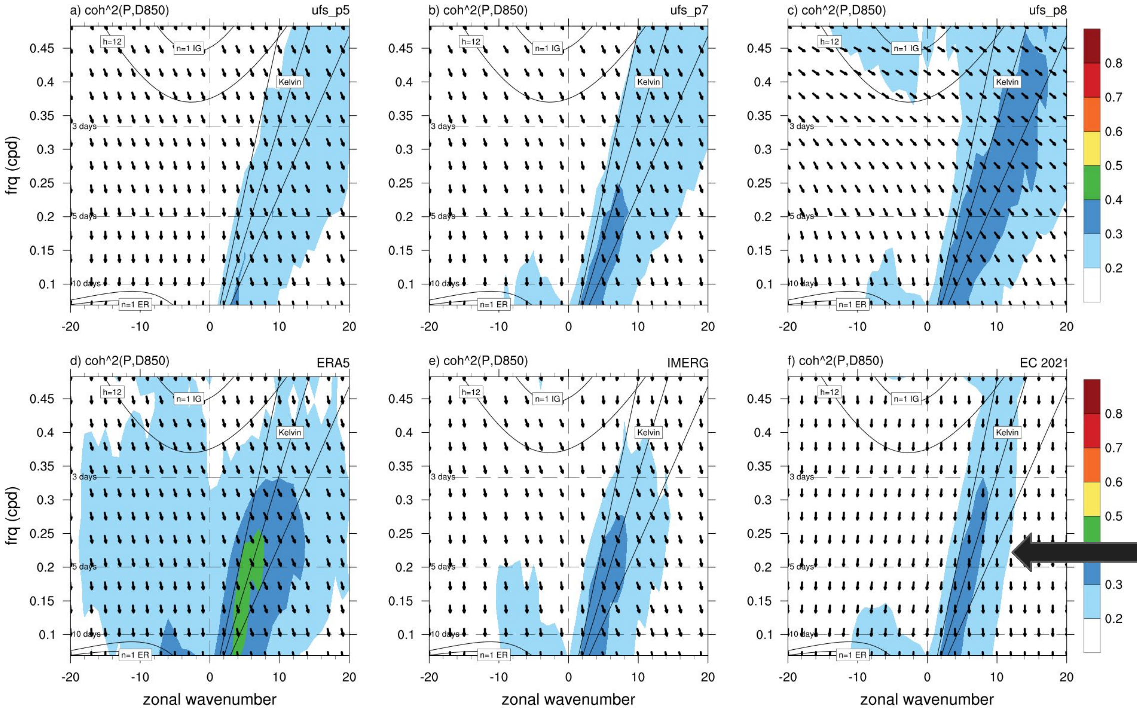


Coherence and phase spectra for precipitation and D850 from different sources for lead time 1- 30 days.

Coherence between low level convergence and precipitation for P7 is more confined.

P8 has stronger coherence and stronger dispersion. Maybe too much coherence at higher frequencies?

Space-time Coherence Spectra



too narrow band of coherence

Coherence and phase spectra for precipitation and D850 from different sources for lead time 1- 30 days.
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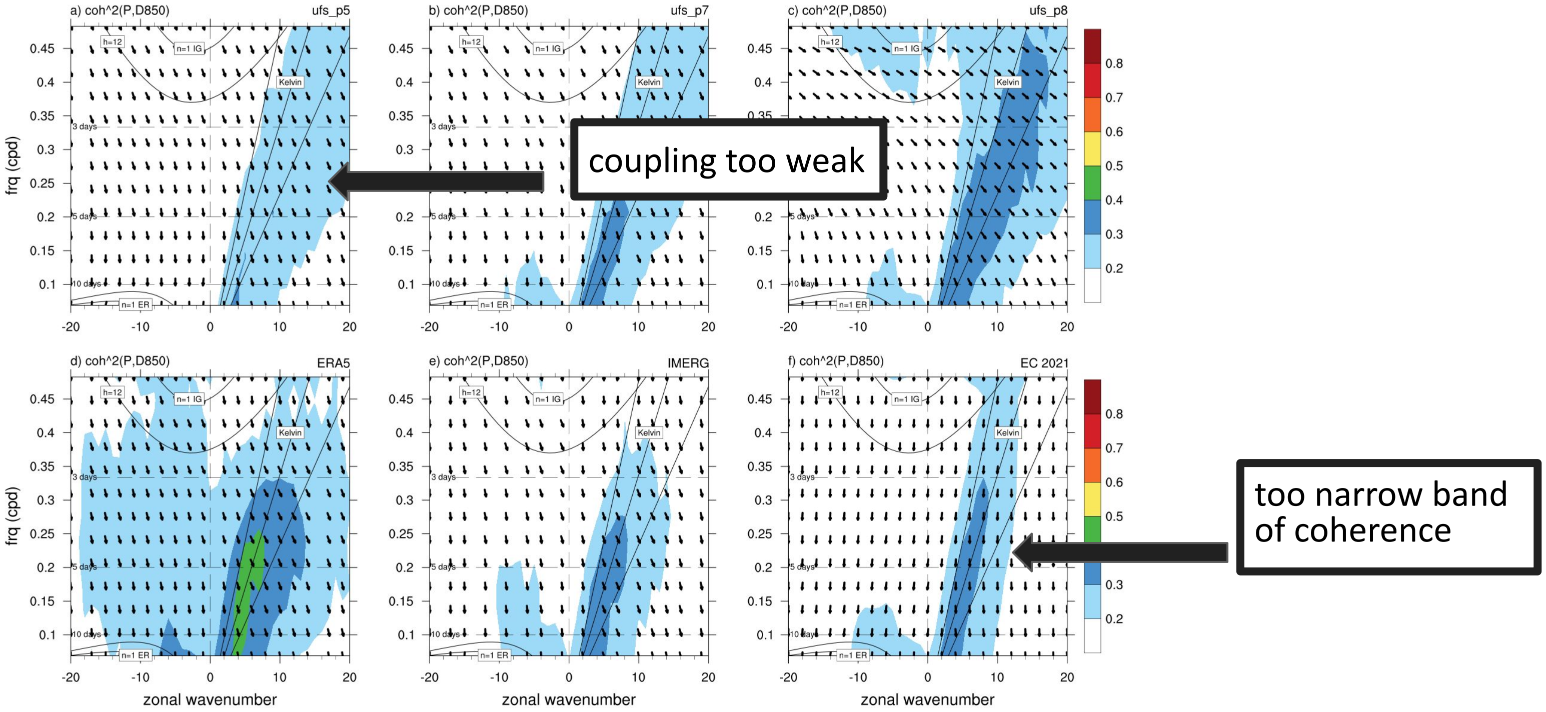
Space-time Coherence Spectra



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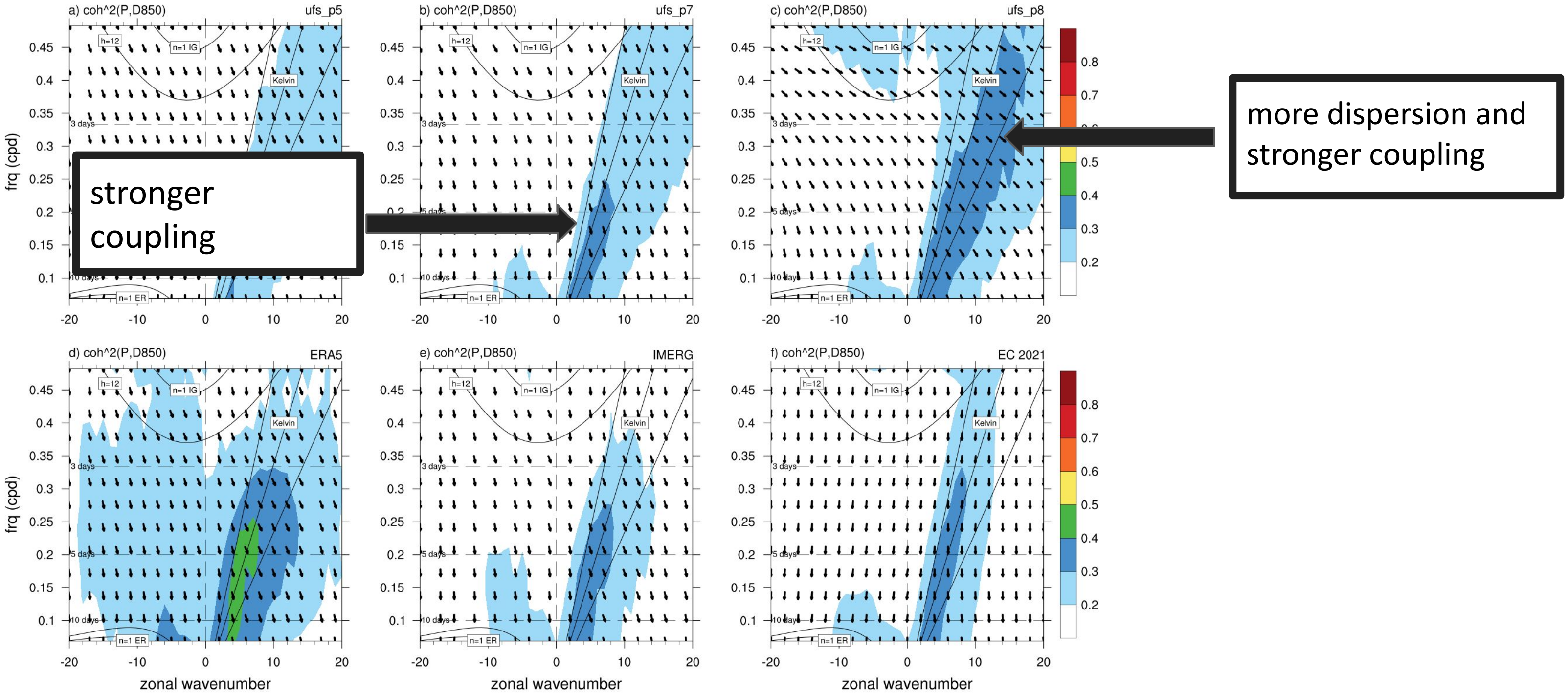


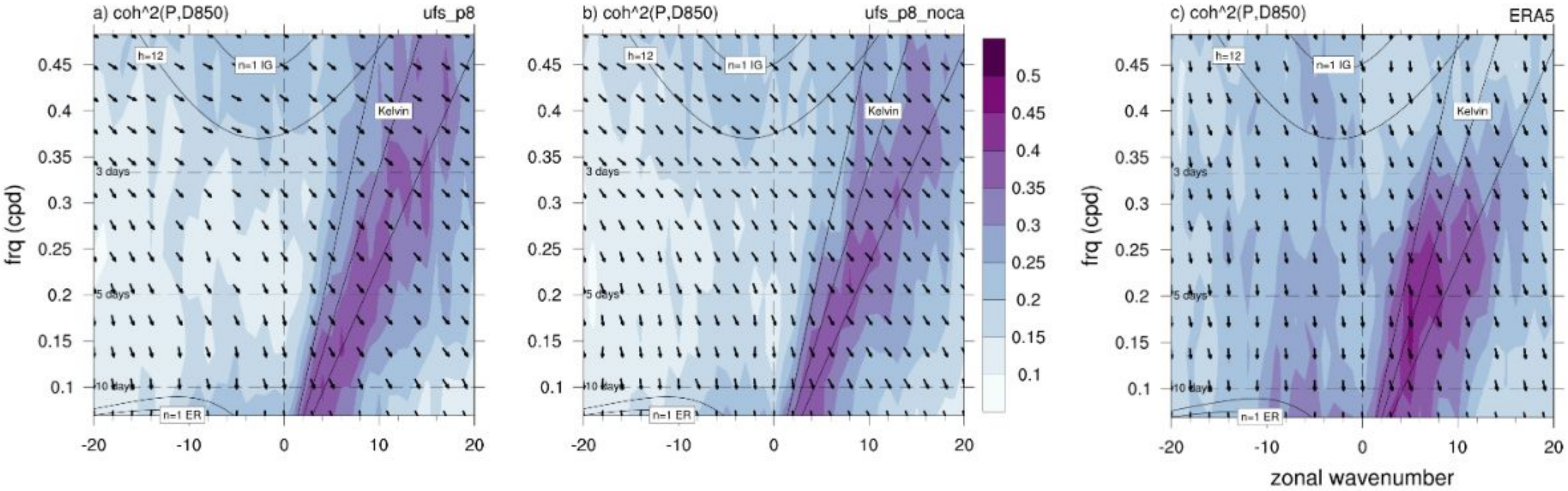
Coherence and phase spectra for precipitation and D850 from different sources for lead time 1- 30 days.

Coherence between low level convergence and precipitation for P7 is more confined.

P8 has stronger coherence and stronger dispersion. Maybe too much coherence at higher frequencies?

Coherence - impact of cellular automata conv. org scheme (CA) only

P8 | P8 - without CA | ERA5



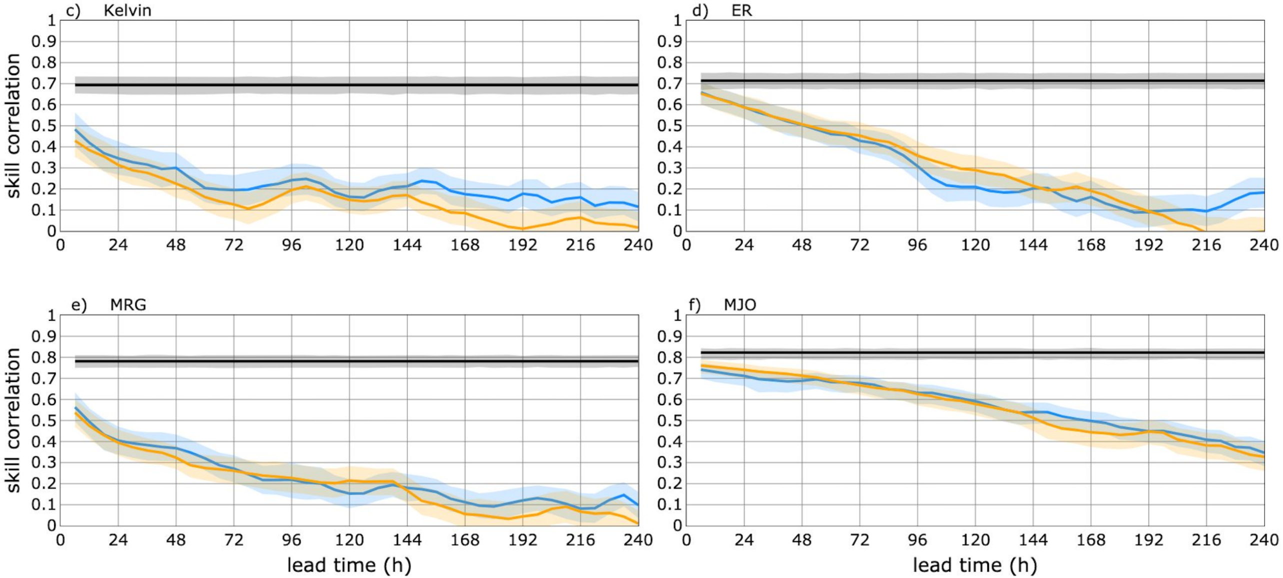
Re-running a subset of cases turning the CA off reveals a slight enhancement in coherence due to the CA conv. org scheme, but it doesn't explain all of the differences between p7 and p8.

Exp from Lisa Bengtsson, PSL

CCEW activity skill in the FV3GFS

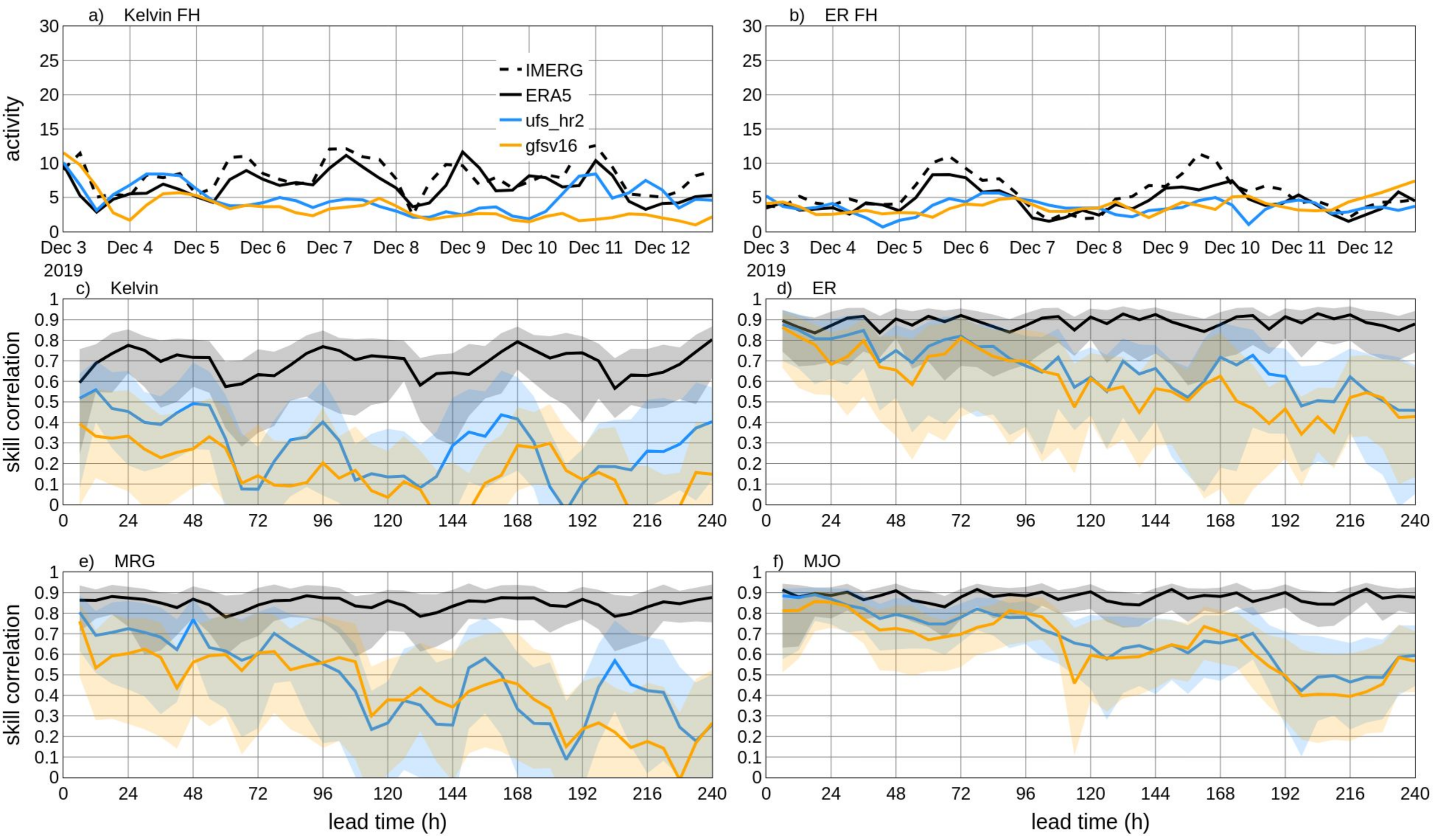
How long and how well can the model predict CCEWs?

1. Use long time series (30+ years) of observed filtered precipitation to compute EOFs describing CCEW signal.
2. Project the model precipitation at each forecast hour onto these EOF patterns and compute a CCEW activity index.
3. Compute anomaly correlation between the observed and model index.



Performance of GFSv16 is slightly improved over GFSv15 for ER and MJO in this diagnostic during the first 48h of the forecast.
Model skill correlation for Kelvin waves drops below 0.5 by 12h lead time, while MJO skill stays above 0.5 past 5 days lead time

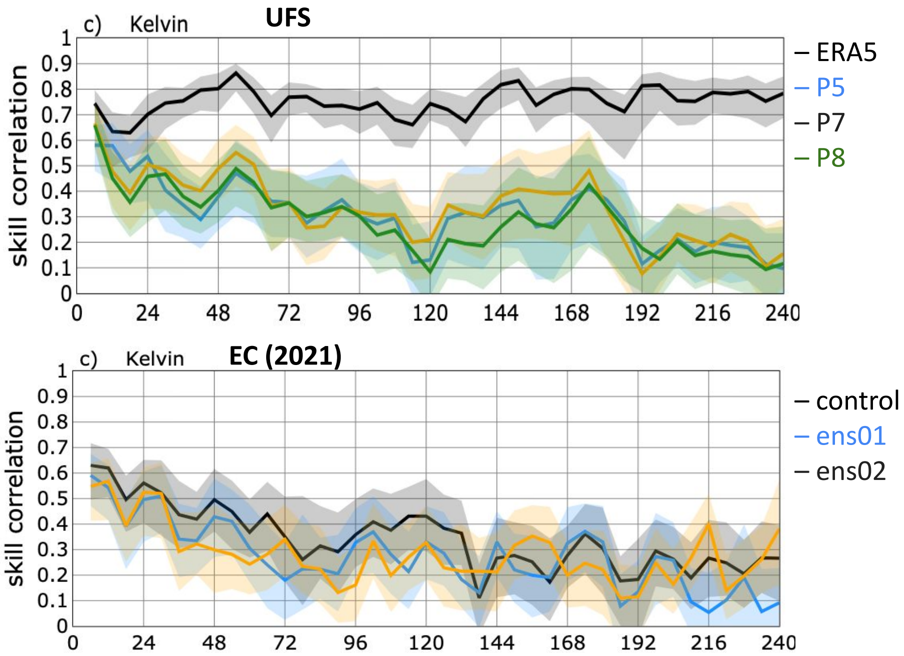
CCEW activity skill in the UFS



Comparing results for the coupled HR2 forecasts with GFSv16, more noise because of smaller sample size.

Overall HR2 skill is higher than GFSv16. The difference is not significant based on the sample size.

CCEW activity skill comparison to EC 2021

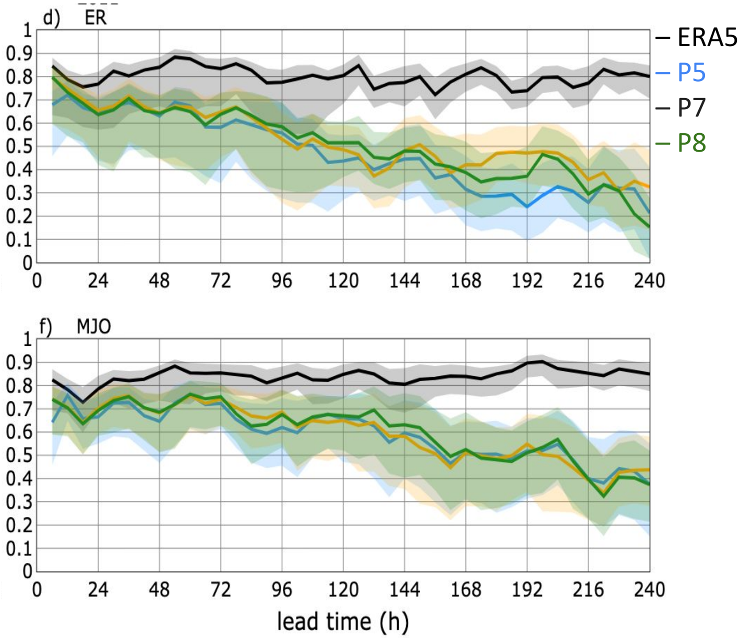


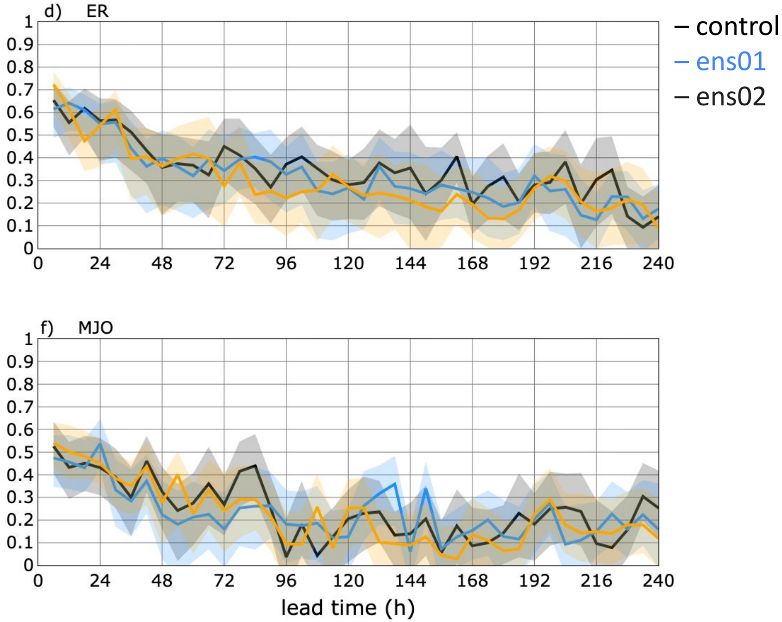
In general, UFS prototypes have comparable skill to the EC S2S ensemble.

UFS initial (at 6h lead time) Kelvin skill for P7 and P8 is slightly higher than in the EC, although difference is not significant.

EC skill at 12h lead time is still above 0.5 correlation while P7 and P8 have dropped below the 0.5 threshold.

CCEW activity skill comparison to EC 2021





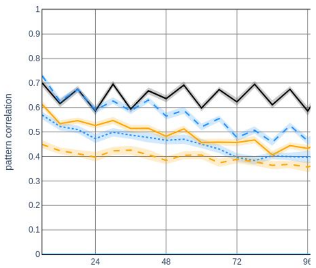
Initial ER skill is comparable between UFS prototypes and EC ensemble forecasts.

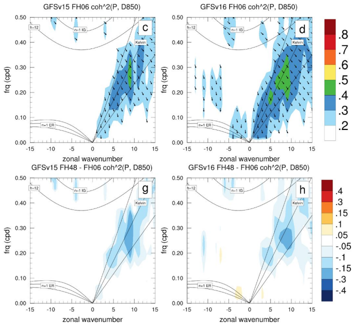
UFS prototypes have ER skill correlation above 0.5 until 96h lead time, while the EC skill correlation drops below 0.5 before 48h lead time.

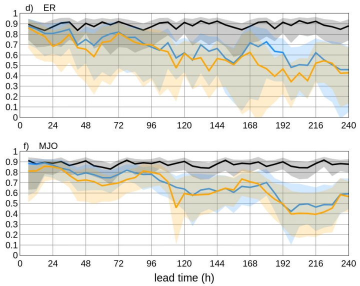
Initial MJO skill is significantly higher in P7 and P8 then the EC forecasts.

EC MJO skill drops below 0.5 in the first 24h, while the UFS MJO skill stays above 0.5 correlation until 144h lead time.

Summary







- Consider skill metrics for tropical convection and in particular for CCEWs.
- Much precipitation skill is lost in the hours immediately following initialization.
- Coupling between convection and the circulation is improved (in terms of scales and strength) in the UFS coupled prototypes, but decreases rapidly with lead time.
- HR2 is an improvement in these precipitation based CCEW skill metrics over GFSv16. Based on similar results for the coupled prototypes we hypothesize that the coupling between atmosphere and ocean is beneficial.
- Several of these diagnostics were included in the November beta release of METplotpy and METcalcpy of [METplus](). A recording of the presentation on METplus Use Cases for UFS P5 and P7 output can be found here (https://dtcenter.org/events/2022/2022-dtc-metplus-workshop/agenda-recordings)

More details on the diagnostics can be found in:
Gehne M., B. Wolding, J. Dias and G. N. Kiladis (2022). Diagnostics of Tropical Variability for Numerical Weather Forecasts, *Weather and Forecasting* (https://doi.org/10.1175/WAF-D-21-0204.1)

Summary

- A stand-alone python GitHub repo for these diagnostics (and more) exists (tropical_diagnostics) and a release is public for testing.

- Several of these diagnostics were included in the November beta release of METplotpy and METcalcpy of METplus. A recording of the presentation on METplus Use Cases for UFS P5 and P7 output can be found here (https://dtcenter.org/events/2022/2022-dtc-metplus-workshop/agenda-recordings)

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METplus GitHub

Updates to NOAA's Unified Forecast System's cumulus convection parameterization between GFSv16 and GFSv17

Lisa Bengtsson (NOAA OAR PSL) and Jongil Han (NCEP EMC)

Acknowledgement: Wei Li, EMC, Maria Gehne, PSL, Juliana Dias, PSL, Fanglin Yang, EMC

Summary of updates to cumulus convection from GFSv16 to GFSv17 (prototype HR2)

1) Implementation of a positive definite mass-flux scheme and a method for removing the negative tracers. (Han et al. 2022)

2) Introduction of a new closure based on a prognostic evolution of the convective updraft area fraction in both shallow and deep convection. (Bengtsson et al. 2022)

3) Introduction of 3D effects of cold-pool dynamics and stochastic initiation using self-organizing cellular automata. (Bengtsson et al. 2021)

4) Introduction of environmental wind shear and TKE dependence in convection, to seek improvements in hurricane forecast prediction. (Han et al. 2023)

5) Stricter convective initiation criteria to allow for more CAPE to build up to address a low CAPE bias in GFSv16 (Han et al 2021).

6) Reduction of convective rain evaporation rate to address a systematic cold bias near the surface in GFSv16 (Han et al 2021).

Experiment design

High resolution HR2 MRW forecast experiment (C768 ~13km):

- **control_hr2**:, HR2: global-workflow and ufs-weather-model HR2 tags (run by EMC).
- **v16_conv** : HR2 with GFSv16 convection: revert all changes in source code and namelist in samfdeepcnv.f and samfshalcnv.f to the GFSv16 version of saSAS.

Summer period of HR2 experiment, 6 day forecasts: June 1st - August 30th, 2020 (3 hour output)

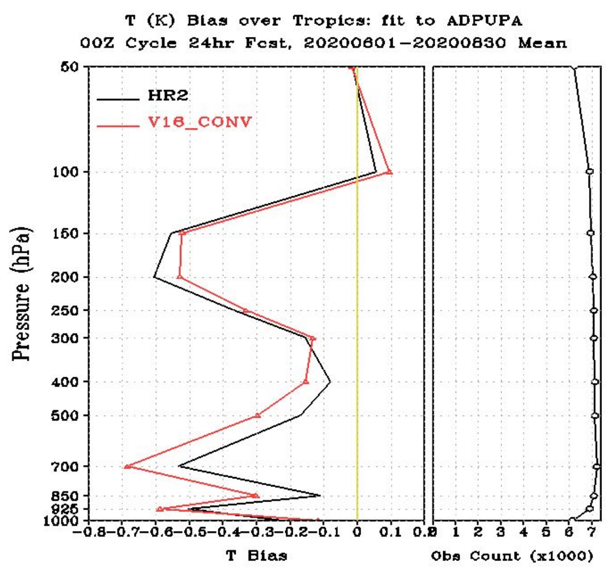
Case study for tropical variablity and MJO:

- Re-ran HR2 and v16_conv out to 25 days for a few cases to have longer leads-times to look at MJO prediction. (6 hour output)
- Second set of experiments same as above, but using un-coupled simulations.

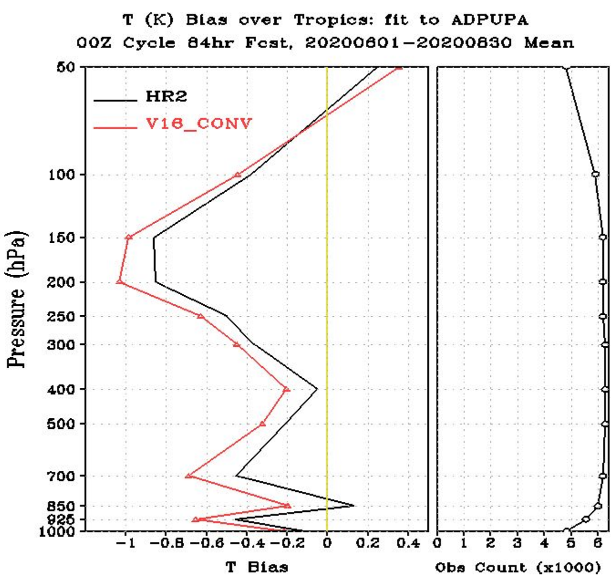
Disclaimer: Note that many physics updates since GFSv16 has been done in tandem, so reverting only the convection could potentially provide unexpected results.

Addressing tropical cold bias

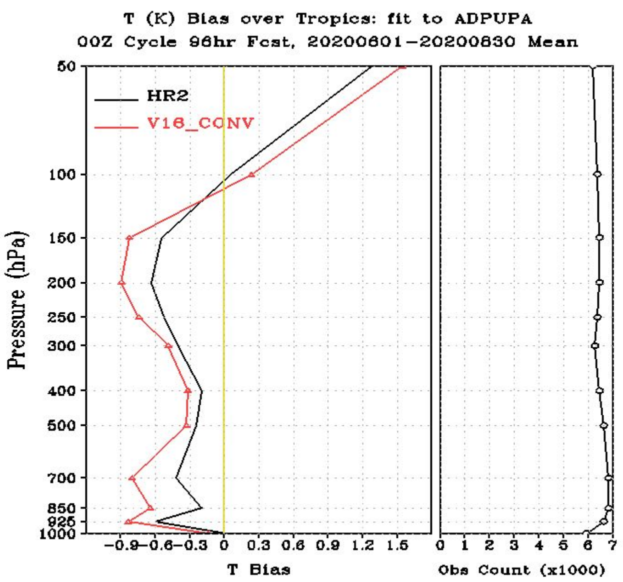
a) 24 hour forecast



b) 84 hour forecast



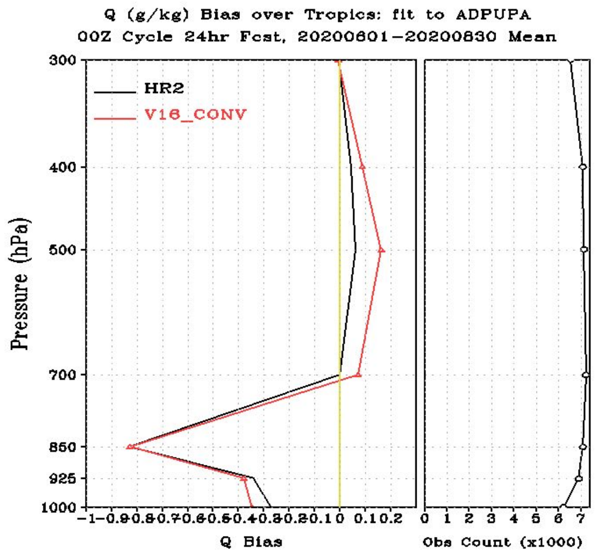
c) 96 hour forecast



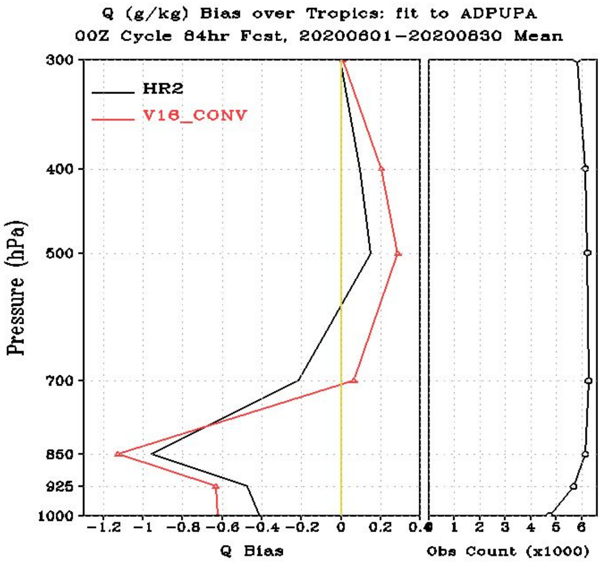
The updates to cumulus convection between GFSv16 and GFSv17 helps reduce the cold-bias over the Tropics. However, there is still a cold bias present.

Specific humidity profiles

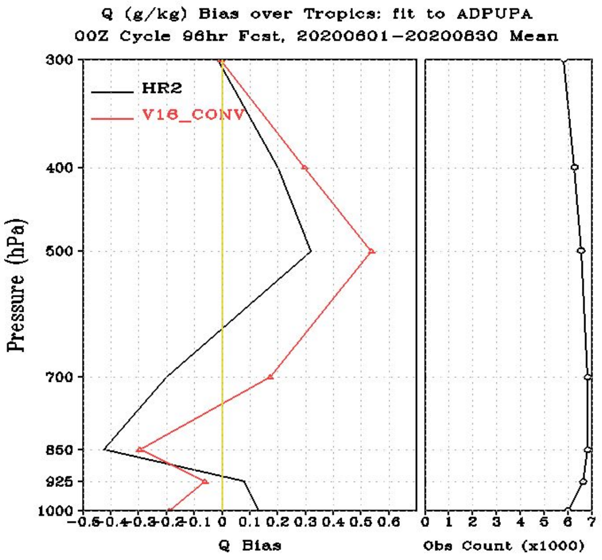
a) 24 hour forecast



b) 84 hour forecast



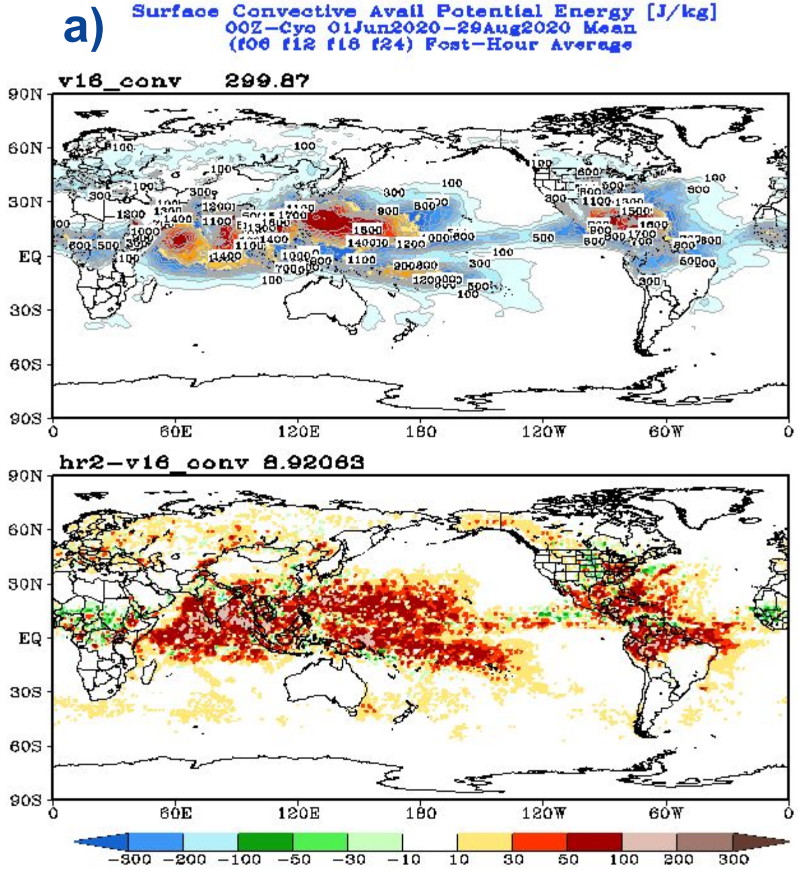
c) 96 hour forecast



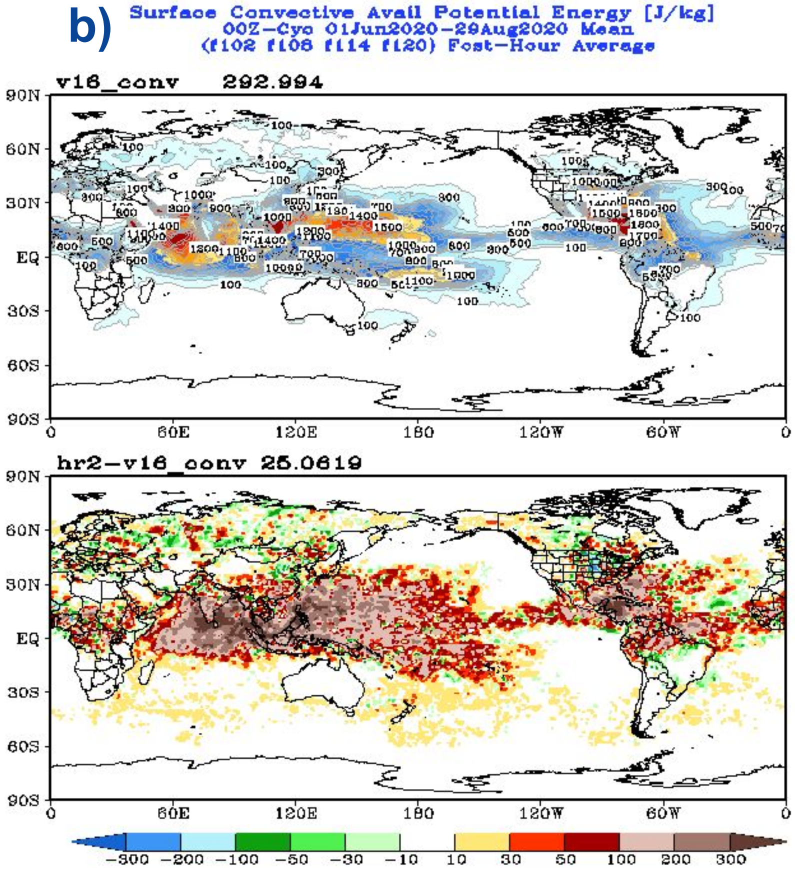
With forecast lead-time, we go from a strong dry bias in the boundary layer, to a slight moist bias in HR2. The model start off dry and cold over the Tropics from the GFSv16 IC’s.

Addressing low CAPE bias

a)



b)

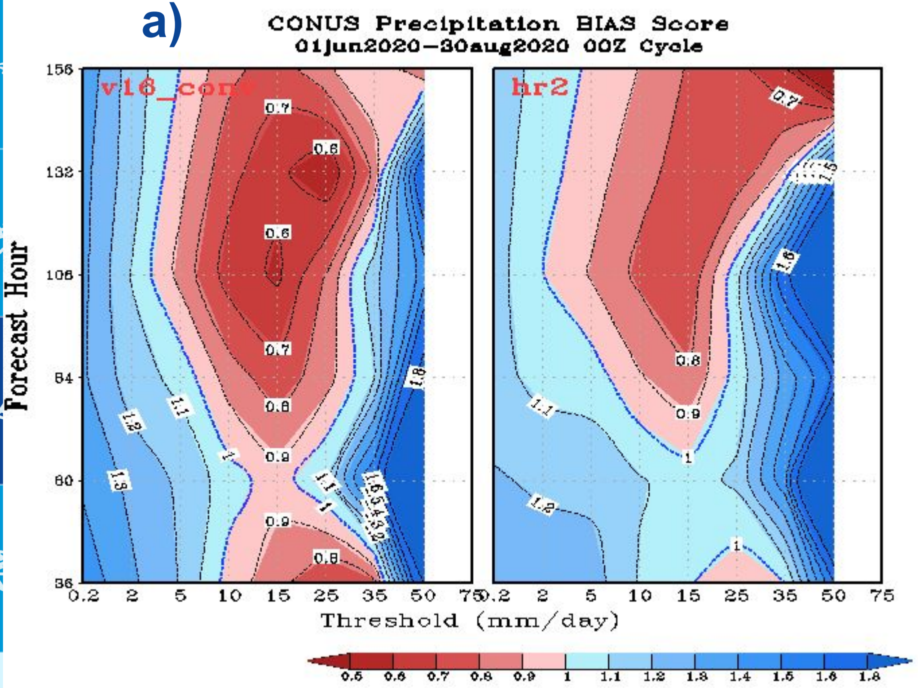


CONUS precipitation

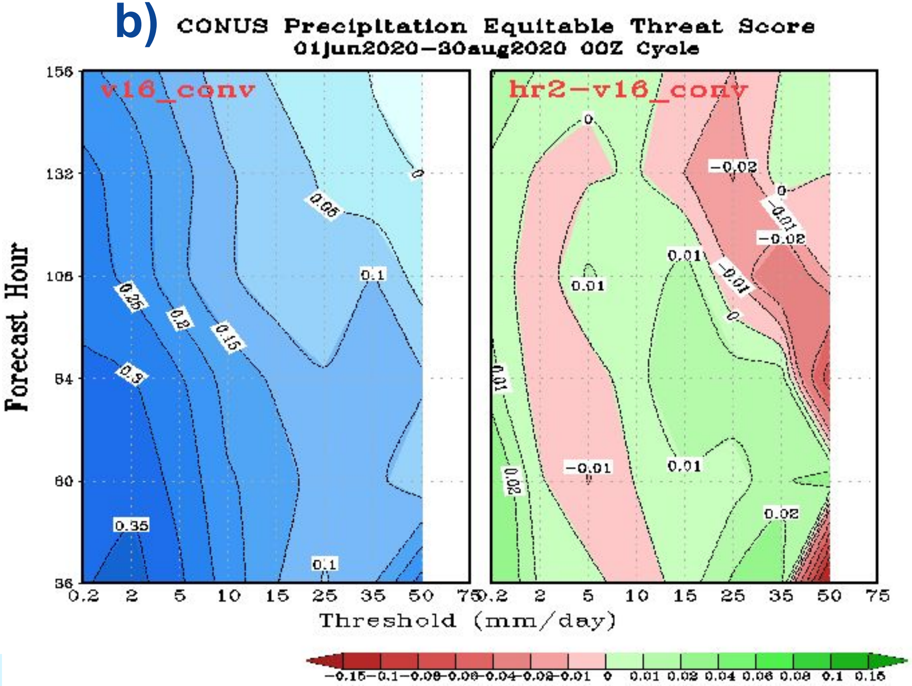
Bias score, 1 is the best. In general, GFSv17 updates to convection is an improvement compared to GFSv16 convection.

ETS score. Second panel shows the difference. Green indicates better score for GFSv17 convection compared to GFSv16 convection.

a)

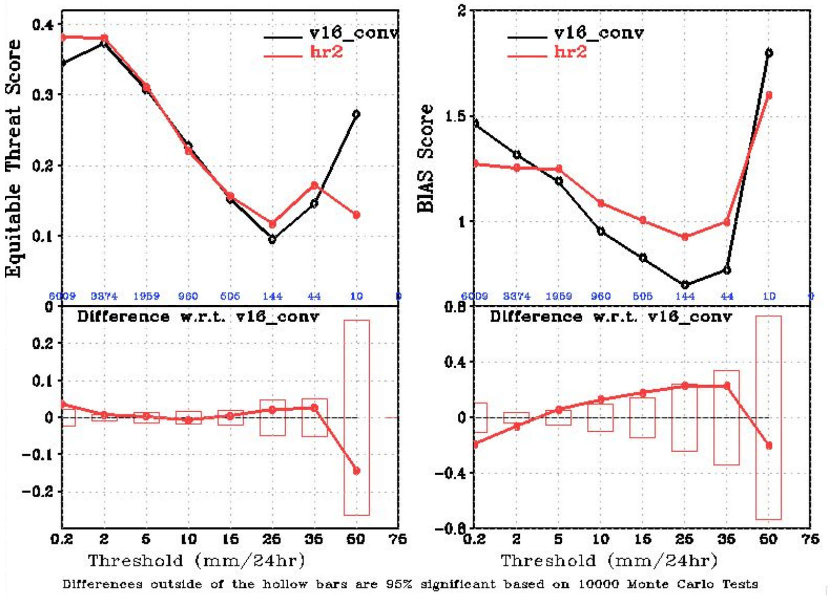


b)

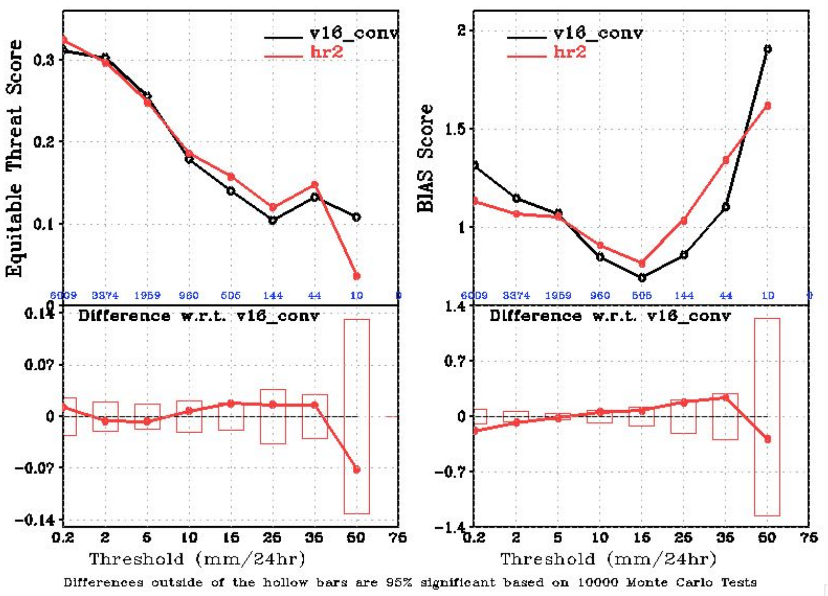


ETS and Bias score, function of threshold

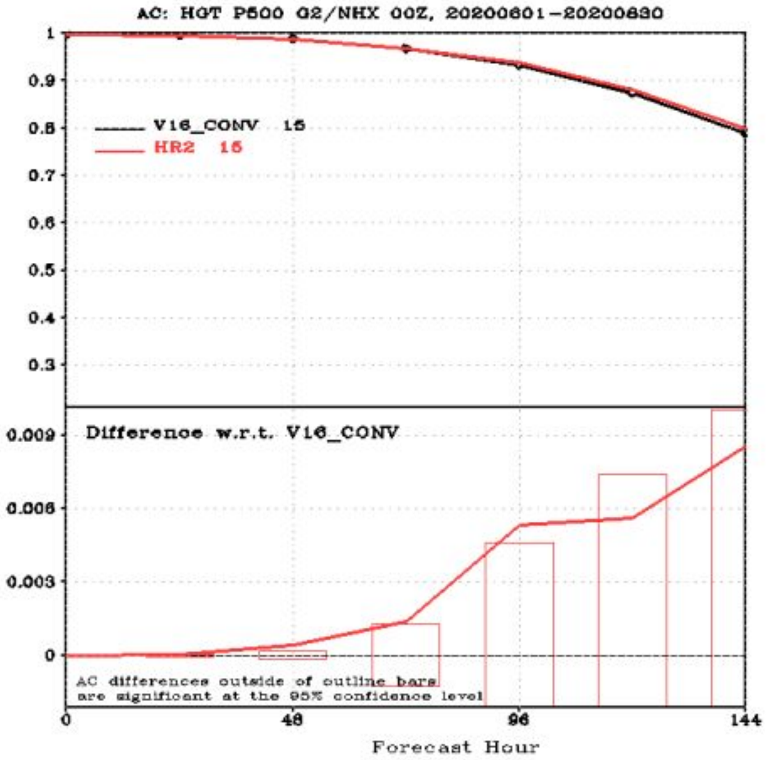
a) CONUS Precip skill scores. 12-36 h lead-time

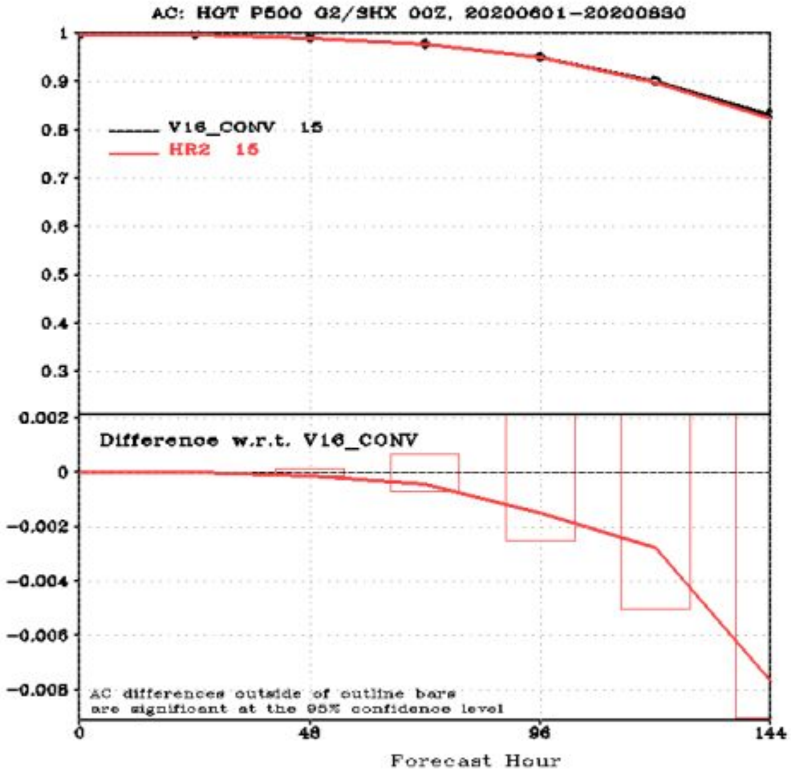


b) CONUS Precip skill scores. 60-84 h lead-time



500 hPa hgt anomaly correlation





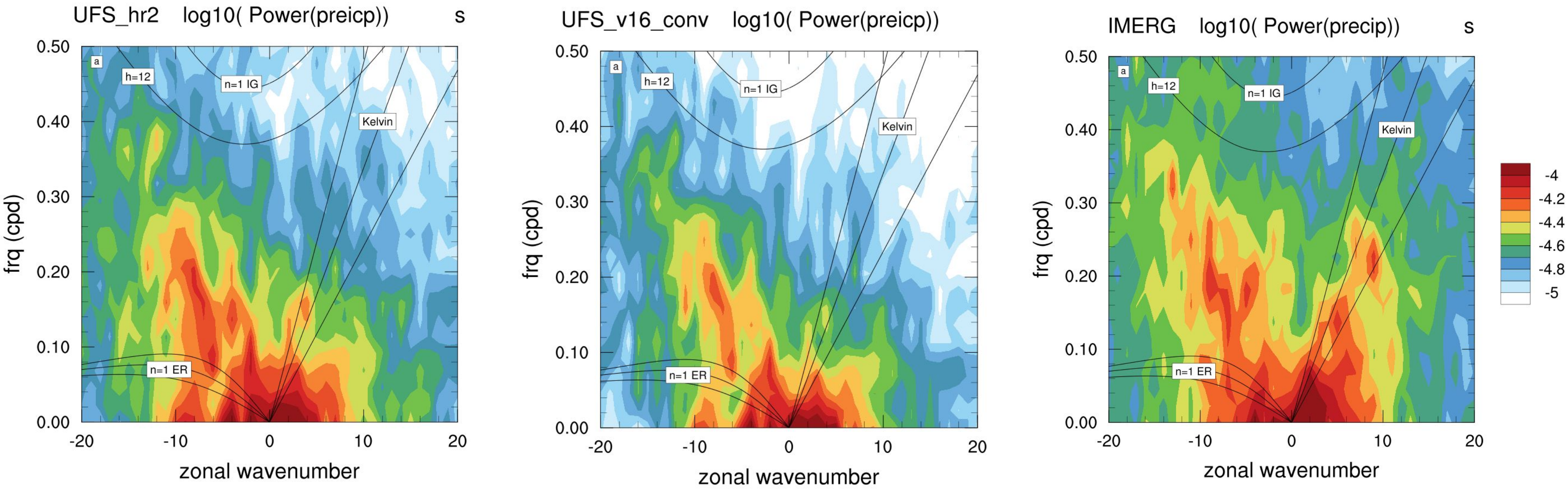
500hPa Geopotential Height anomaly correlation, all wavenumbers

Precipitation power spectra

GFSv17 (prototype HR2)

GFSv17 (prototype HR2) with GFSv16 convection

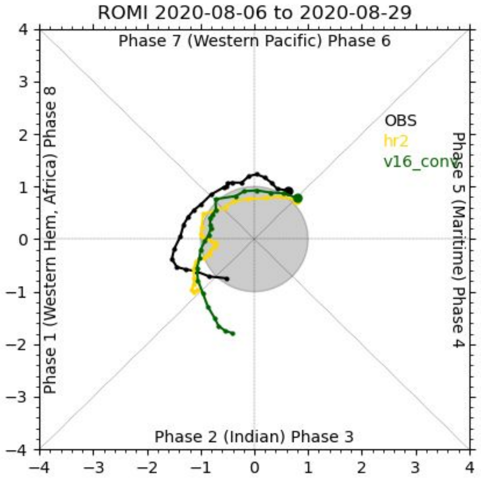
IMERG obs

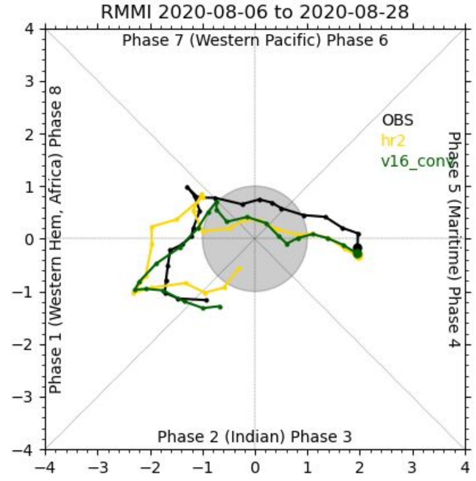


The updates to the convection schemes enhances precipitation power along the space/time spectra. In particularly over higher frequencies (tropical depression) - to some extent also in the Kelvin band. Time-period is short - so spectra look somewhat noisy.

MJO - ROMI and RMMI index

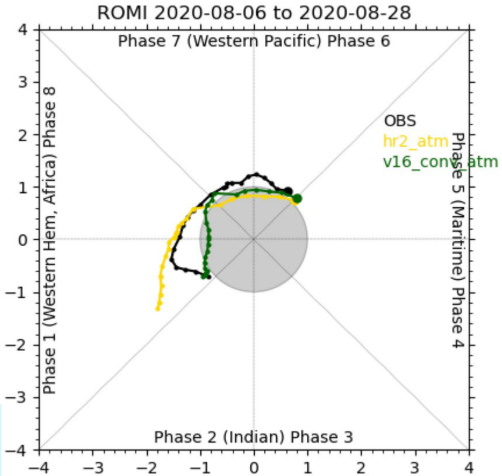
ROMI coupled

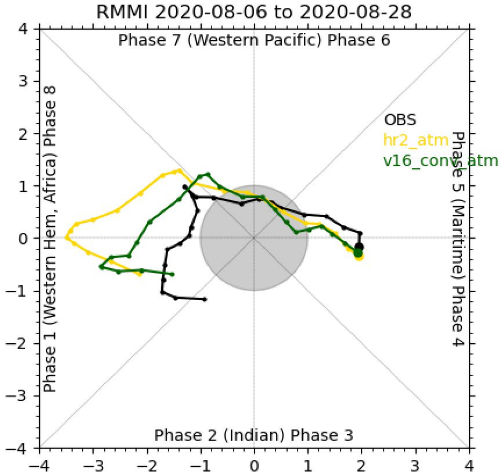




RMMI coupled

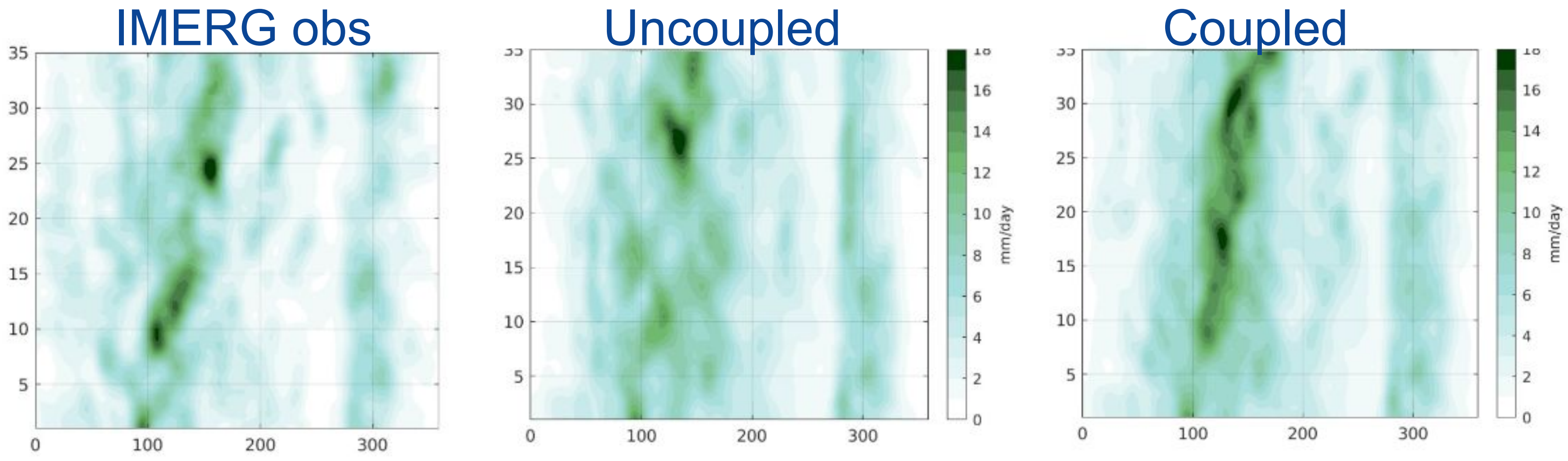
ROMI Un-coupled





RMMI Un-coupled

Impact of ocean coupling on eastward propagation, precip. Hovmöller diagram



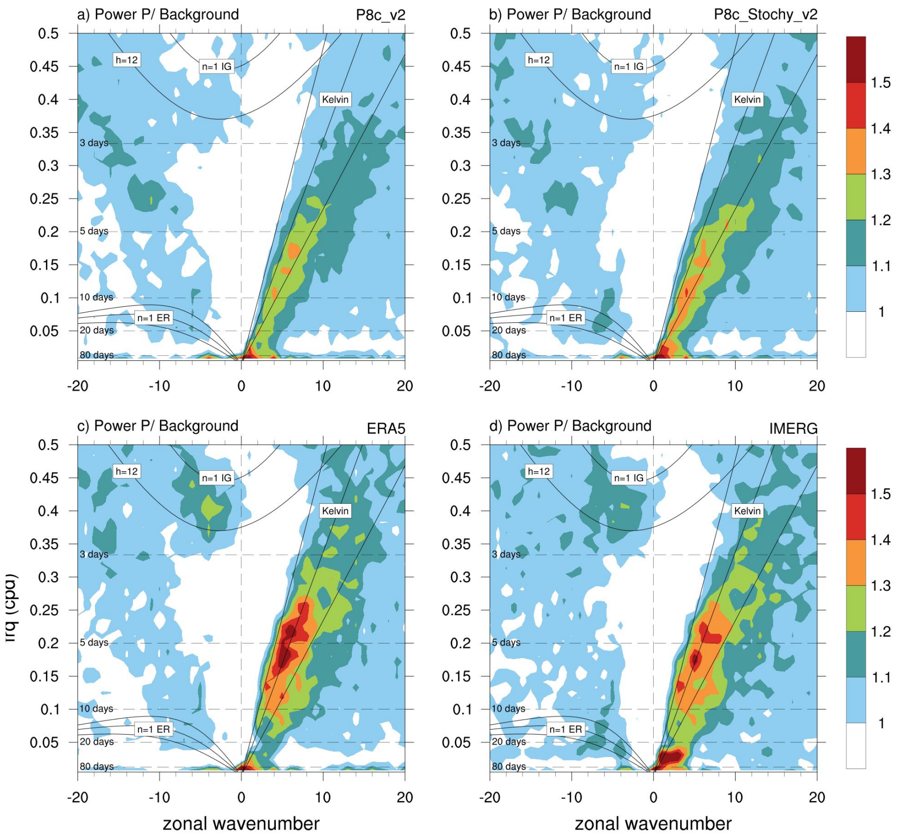
Hovmöller diagram is large scale filtered (using gaussian filter for MJO signal) from Juliana Dias, PSL.

Tropical variability in SFS “proof of concept” runs

Maria Gehne, PSL

Acknowledgement: Phil Pegion (PSL), Xiao-Wei Quan (CIRES), Stefan Tulich (CIRES), Yan Wang (CIRES)

SFS evaluation - spectra



Coupled SFS (C96) 5 member runs initialized 10/01 from 1994-2022.

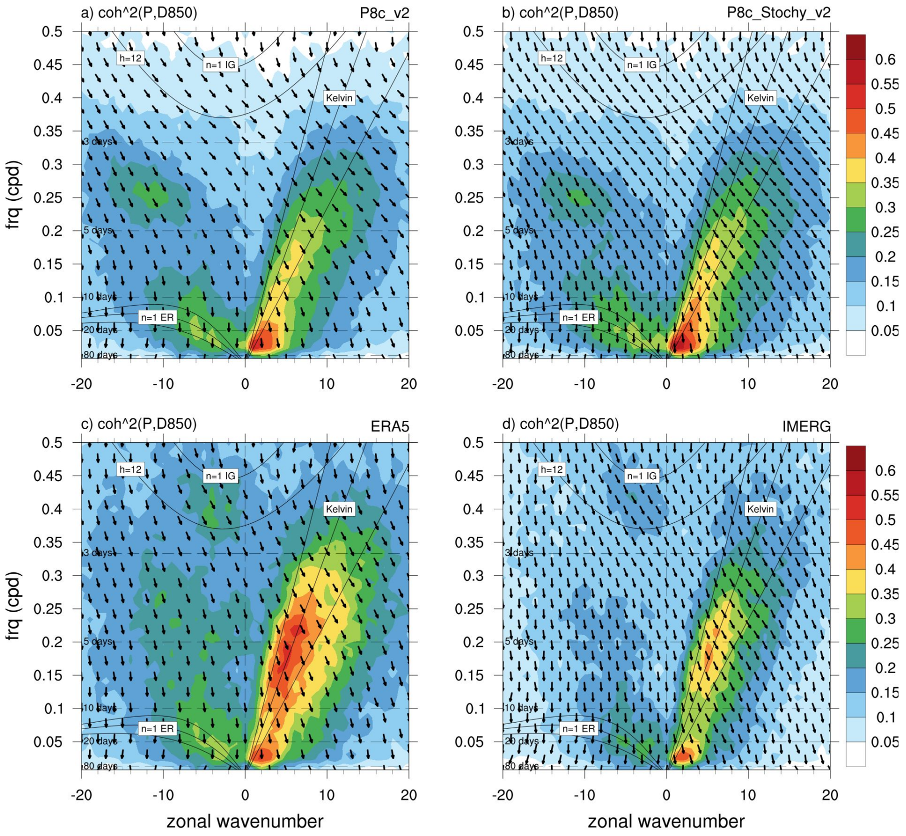
Spectra computed for the first 128 days of the forecasts.

Very active tropical depression type disturbances.

Good CCE Kelvin wave power, but too little total precipitation variance.

Some MJO power in precipitation.

SFS evaluation - spectra



Coupled SFS (C96) 5 member runs initialized 10/01 from 1994-2022.

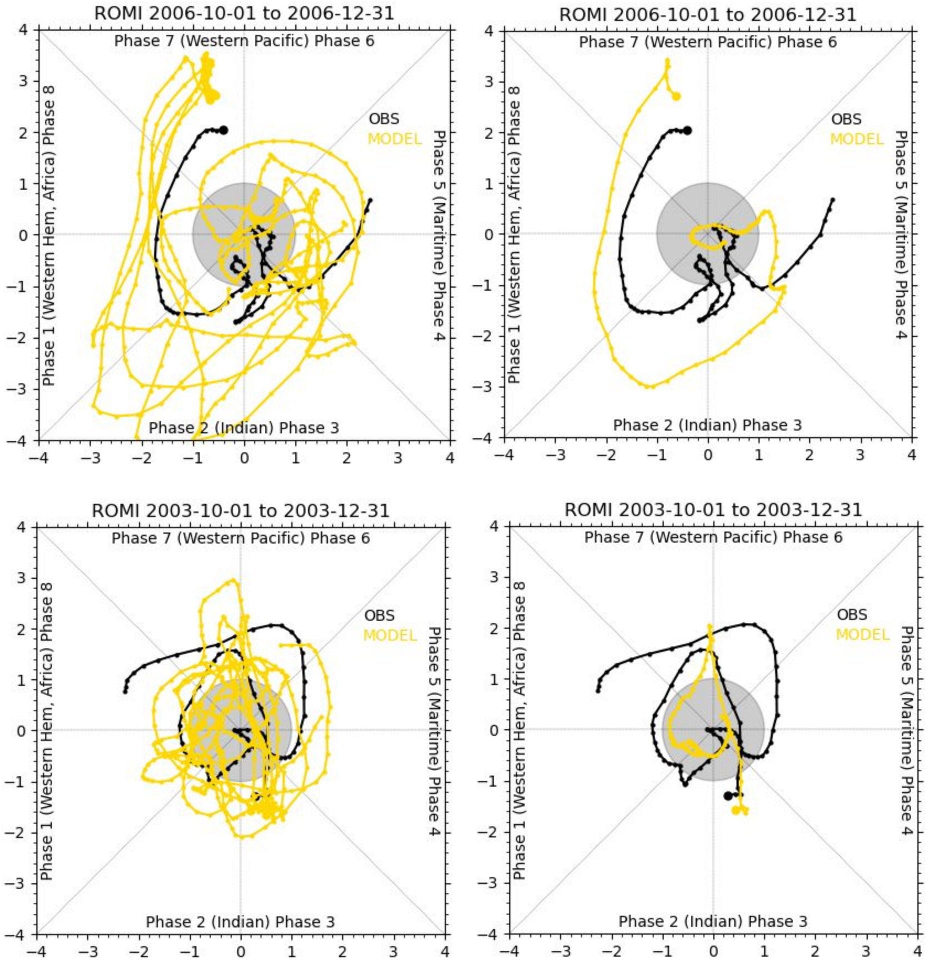
Spectra computed for the first 128 days of the forecasts.

Very active tropical depression type disturbances also visible in P-D850 coherence.

Good CCE Kelvin wave coherence, but coupling not strong enough.

Coupling between precipitation and D850 in the MJO band is visible. SFS shows continuum of coherence between MJO and Kelvin bands.

SFS evaluation - ROMI

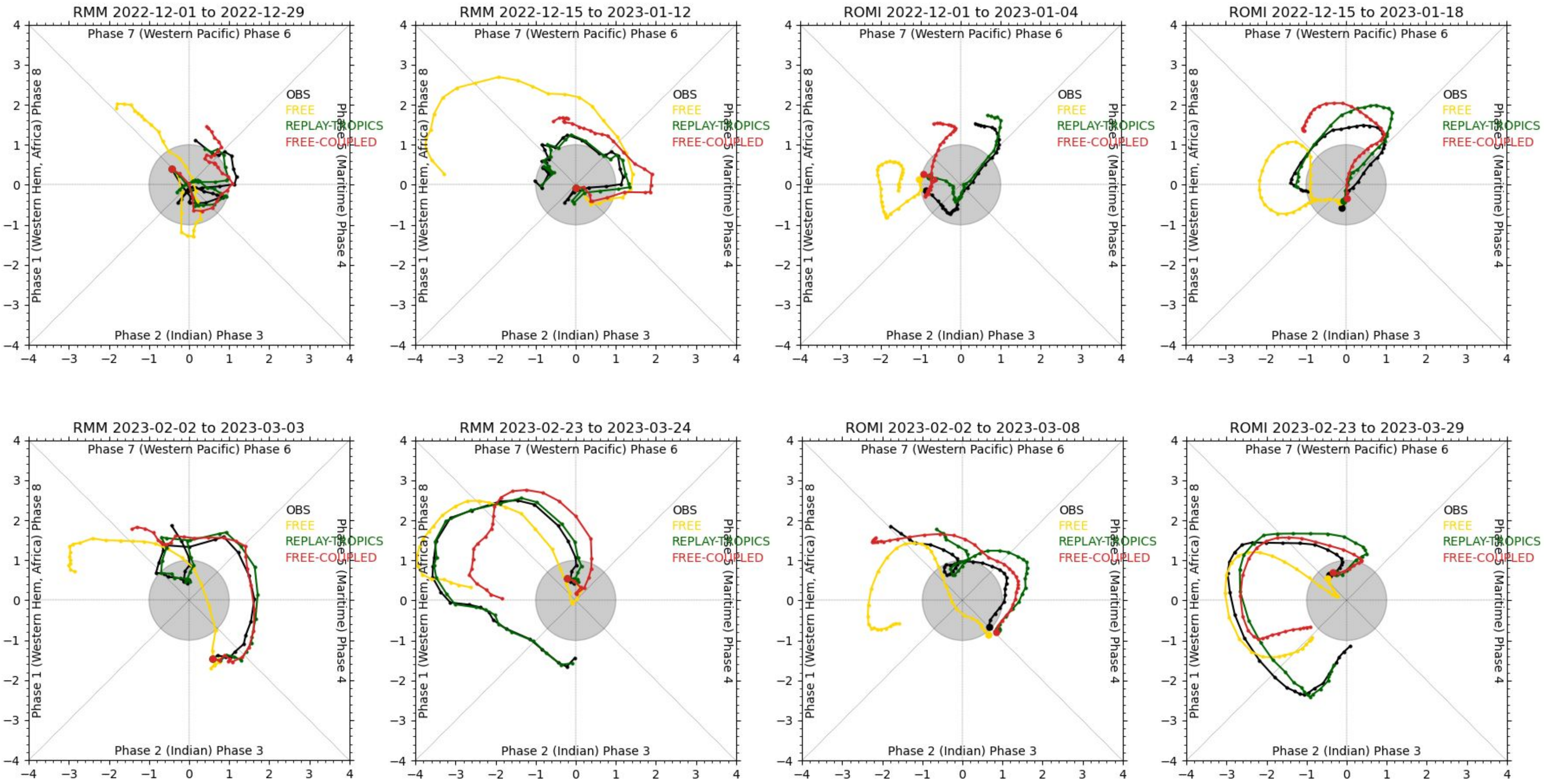


SFS is able to propagate MJO related OLR signal for multiple weeks for some cases.

Sometimes propagation even makes it through the maritime continent, which is a known difficulty for NWP models.

We hypothesize that coupling to the ocean may be helpful for this (see next slide).

Impact of atm-ocean coupling on MJO indices



Summary

- Tropical variability package is available on github (and some aspects has been added to MetPlus): https://github.com/mgehne/tropical_diagnostics

- A manuscript has been submitted to Weather and Forecasting:

  Bengtsson, L and Han, J. (2024): Updates to NOAA's Unified Forecast System's cumulus convection parameterization scheme between GFSv16 and GFSv17. Submitted to Weather and Forecasting.

- Updates to cumulus convection in the prototype process has lead to improvements in reducing temperature and humidity biases, increasing CAPE, and enhancing precipitation power spectra. Evaluation of the MJO reveals a different response of cumulus convection parameterization changes, depending on if the model is run coupled to the ocean or uncoupled.

- Early SFS simulations suggests that the C96 resolution (~100km) is very sensitive to ocean coupling, and we need to understand the poor C96 uncoupled results better.

References

Bengtsson, L., Dias, J., Tulich, S., Gehne, M., & Bao, J.-W. (2021). A stochastic parameterization of organized tropical convection using cellular automata for global forecasts in NOAA's Unified Forecast System. Journal of Advances in Modeling Earth Systems, 13, e2020MS002260. https://doi.org/10.1029/2020MS002260

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Han J., W. Li, F. Yang, E. Strobach, W. Zheng, and R. Sun, 2021: Updates in the NCEP GFS cumulus convection, vertical turbulent mixing, and surface layer physics. NCEP Office Note 505, 18 pp., https://doi.org/10.25923/cybh-w893

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Han et al. 2023: Updates in the NCEP GFS PBL and Convection models with Environmental Wind Shear Effect Parameterization and Modified Entrainment and Detrainment Rates, in preparation for WAF.