Modeling and Forecasting

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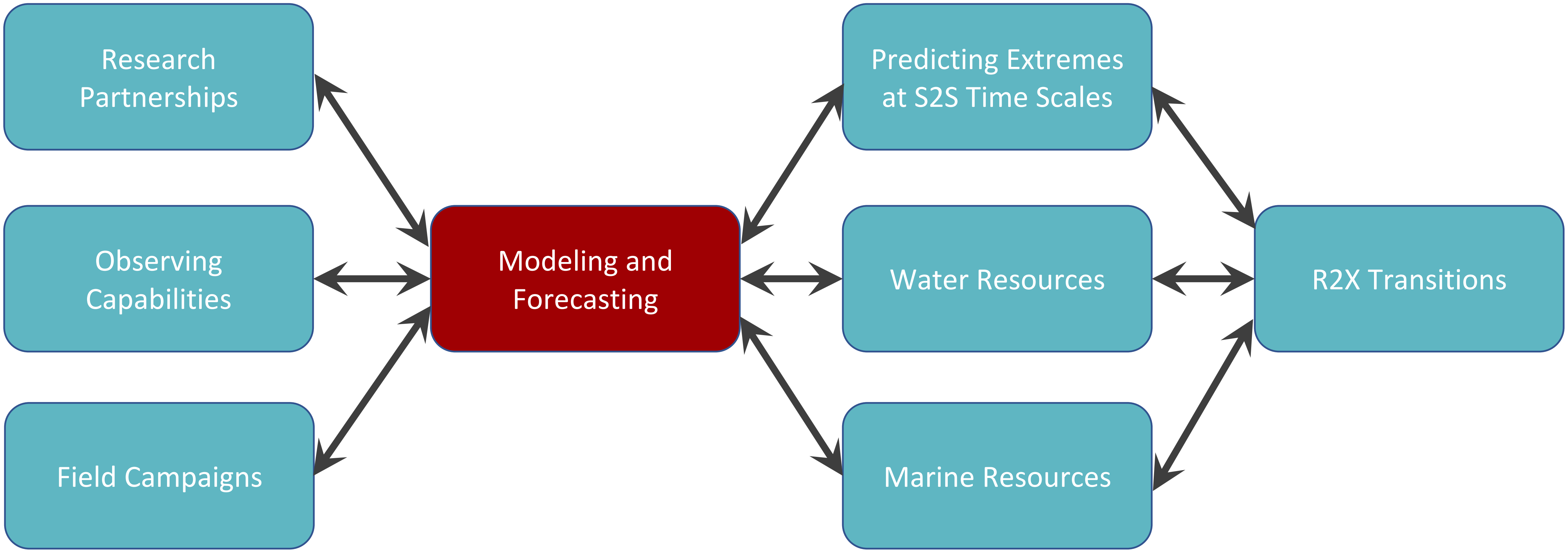
Focus of PSL Modeling and Forecasting Research:

- Use data collected by PSL-lead observational campaigns to evaluate forecast systems and process models
- Investigate key processes in the coupled system, e.g., cloud-microphysics and radiative feedbacks, fluxes between state components, the atmospheric boundary layer, inherently chaotic processes
- Develop physically based numerical weather-climate prediction algorithms that improve state estimates, reduce systematic errors, and improve probabilistic predictions in the UFS
- Produce experimental forecasts to advance process understanding, benchmark operational forecasts, and support stakeholders


Research Partnerships
Observing Capabilities
Field Campaigns
Modeling and Forecasting
Predicting Extremes at S2S Time Scales
Water Resources
Marine Resources
R2X Transitions

Advancing Understanding to Improve NOAA Forecasts

Algorithm Development
(surface flux, stochastic, stratospheric ozone)

Data Assimilation
(land, coupled, 20CR)

Model Evaluation
(UFS-R20, YOPPsiteMIP, NWM, NMME, HRRR/RAP)

Process Studies
(Arctic cyclones, MJO, ENSO, cloud-bl interaction)

Post-Processing
(Reforecasts)

Experimental Forecasts
(LIM, analogs, CAFS)

Advances in **Algorithm Development**

Algorithm Development	Data Assimilation	Model Evaluation
Process Studies	Post-Processing	Experimental Forecasts

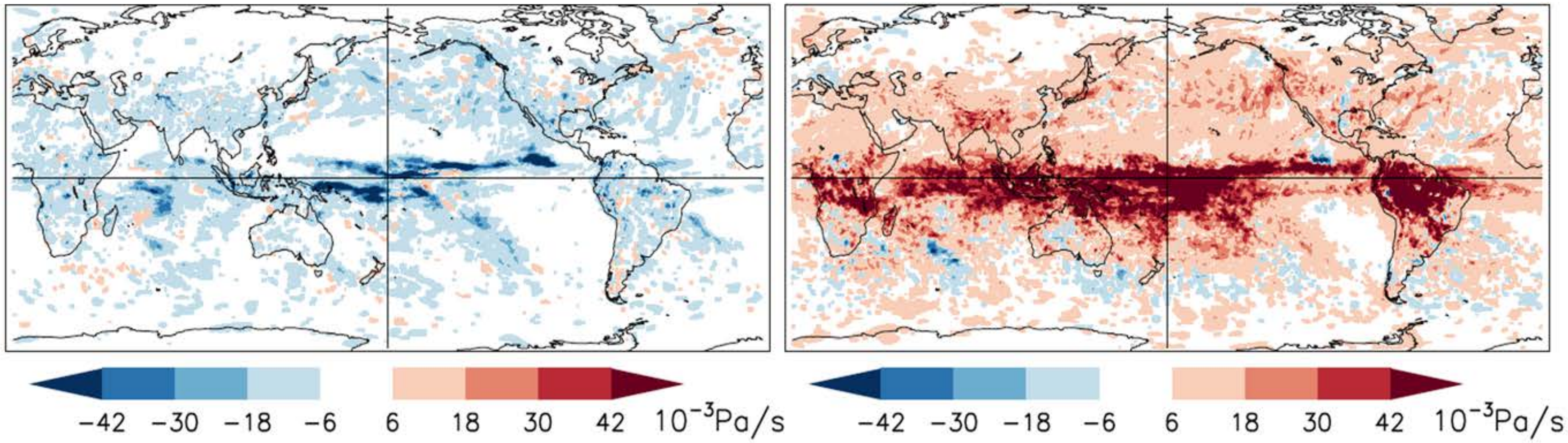
Development at PSL of stochastic physics using rigorous theoretical underpinnings lead to better ensemble mean forecasts and model variability

- **Implemented the widely used SPPT and SKEBS stochastic physics schemes into the UFS and GEFSv12**
- **Developed a process level stochastic deep convection organization scheme using cellular automata**
- Development of consistent uncertainty representation and stochastic perturbations across model component interfaces (ocean/atmosphere/land/ice)

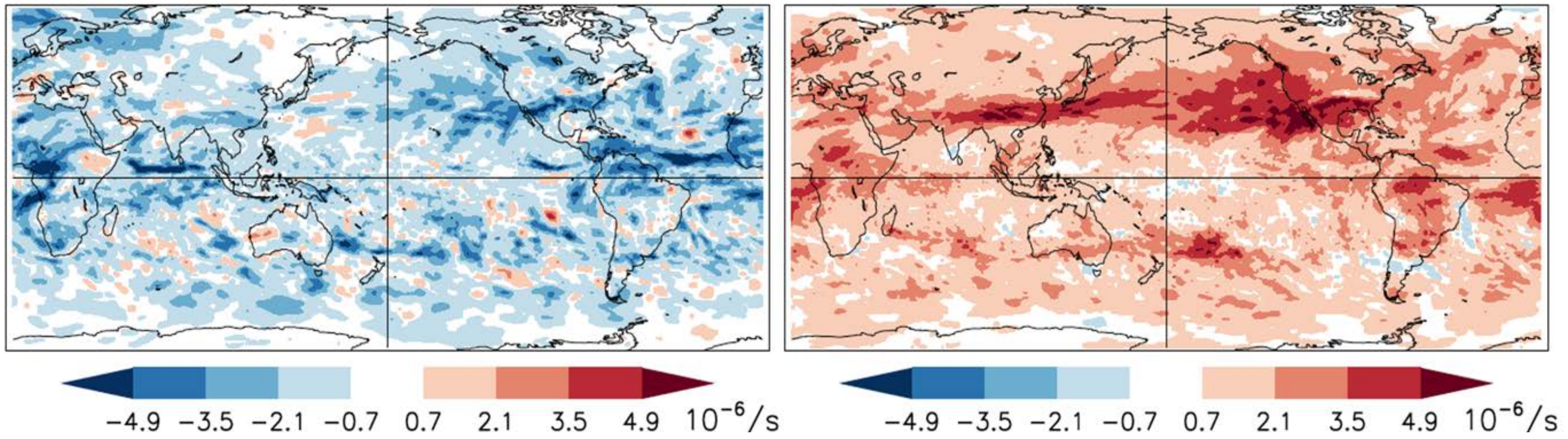
PSL Stochastic Physics Research and Development

Implementing stochastic parameterizations in GFS subseasonal forecasts leads to both a **reduction of the rms error** of the ensemble-mean forecasts and an **increase of the ensemble spread.**

Impact on rms error | **500 mb Omega** | **Impact on ensemble spread**



Impact on rms error | **200 mb Vorticity** | **Impact on ensemble spread**

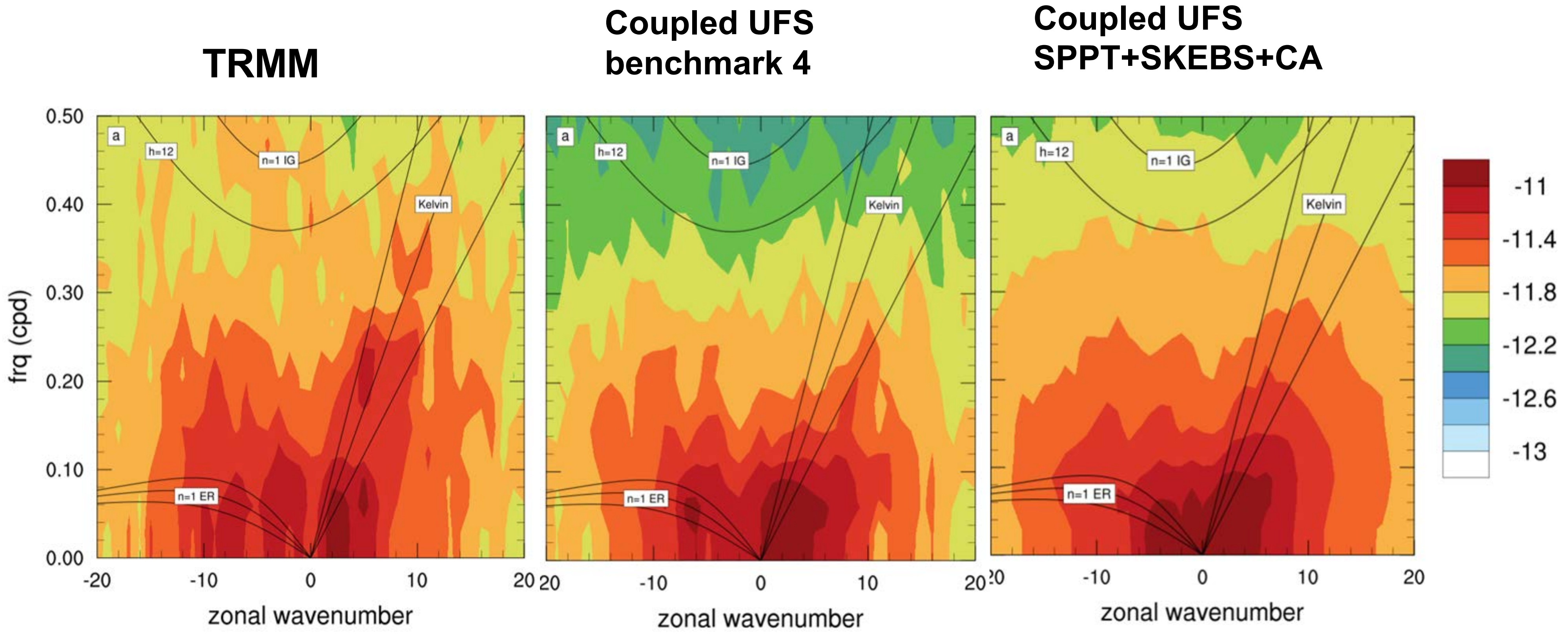


From 80-member GFS 15-day ensemble forecasts for 80 separate forecast cases in Jan-Mar 2016

(ongoing work by Sardeshmukh, Wang, Compo, and Penland)

PSL Stochastic Physics Research and Development

Stochastic physics enhances the variability across the spectra **improving the synoptic scale variability and the Kelvin wave phase speed**



Frequency wavenumber spectra of precipitation power forecasted by the coupled UFS with and without stochastic physics. Results using two initial dates (201201 and 201601) and 35 day forecasts.

(ongoing work by Bengtsson, Bao, Pegion, Whitaker, see Bengtsson et al. 2019)

Advances in **Algorithm Development**

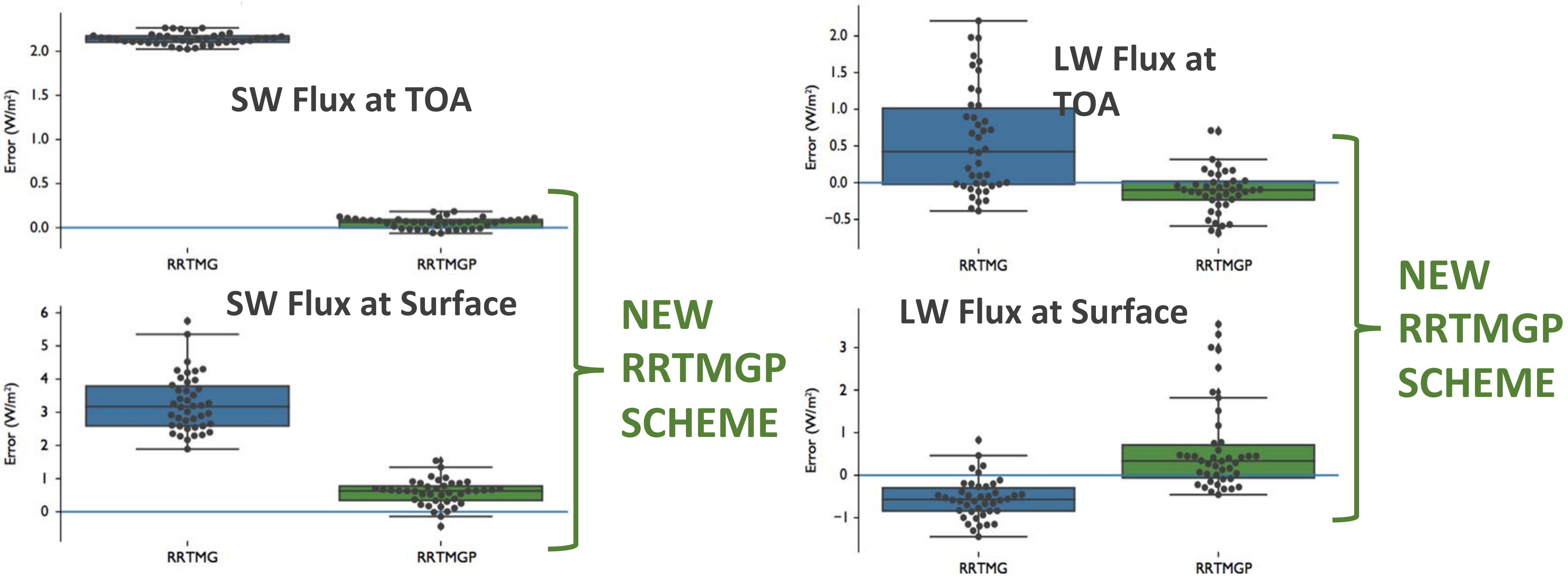
Algorithm Development	Data Assimilation	Model Evaluation
Process Studies	Post-Processing	Experimental Forecasts

Improving physical parameterizations from surface fluxes to cloud microphysics

- Implementation of new stratospheric ozone and water vapor parameterizations in GFS
- Surface flux schemes for stably stratified boundary layers and high wind regimes
- Integration of National Water Model with water agency models to improve simulations of reservoir outflows
- **A modern radiation scheme that improves interactions with cloud microphysics**
- Optimization of the Thompson microphysical parameterization for the UFS
- Updates in deep convection representation including a parameterization for convective subgrid organization and a prognostic closure for representation of cloud life-cycles

PSL Physics Development for the UFS

PSL plays an integral role in the planning and coordination of the model physics development aimed for operations in GFSv17/GEFSv13 under the **UFS R2O physics subproject** in collaboration with EMC, GSL and DTC. For example:



Pincus et al. 2019: Accuracy of new radiation scheme (in green) is improved compared to existing radiation scheme (in blue), for fluxes at the surface and TOA.

(ongoing work by Pincus, Swales, Bengtsson, Bao, Michelson, and Grell)

Advances in **Process Studies**

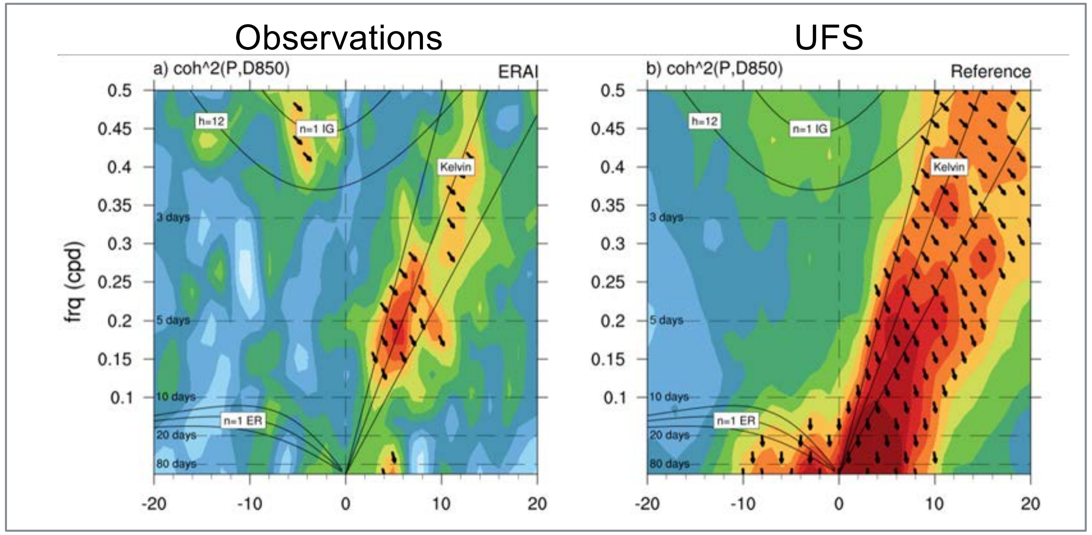
Algorithm Development | Data Assimilation | Model Evaluation
Process Studies | Post-Processing | Experimental Forecasts

Using a hierarchy of model systems to advance the process understanding of the climate system

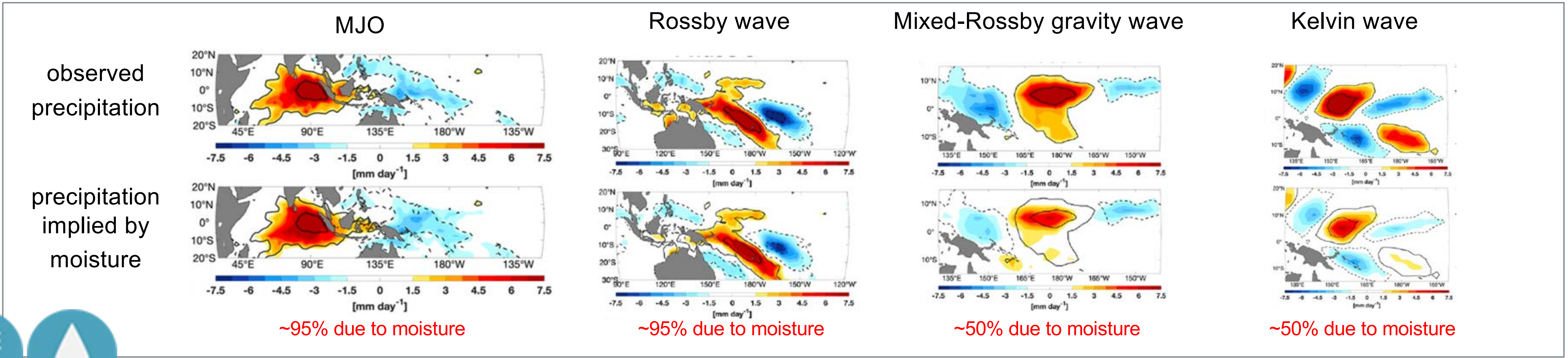
- Tropical forecast error impact on midlatitude precipitation, e.g. US West Coast precipitation
- **Convection-coupling mechanisms in organized tropical convection**
- Ocean-atmosphere coupling mechanisms in organized tropical convection
- Atmospheric transport (water vapor and ozone) over the Pacific-North American basin
- MJO prediction skill dependence on microphysical process representation
- Land-atmosphere coupling on seasonal soil moisture variability and drought predictability
- **Arctic mixed-phase cloud formation**
- Convectively coupled equatorial waves in GFS using ECMWF cumulus convection scheme

Process-Based Studies of Moist Tropical Wave Mechanisms and Prediction

Diagnosis of errors in convection-circulation coupling in the UFS



Investigation of the role of moisture in regulating precipitation in different tropical wave types

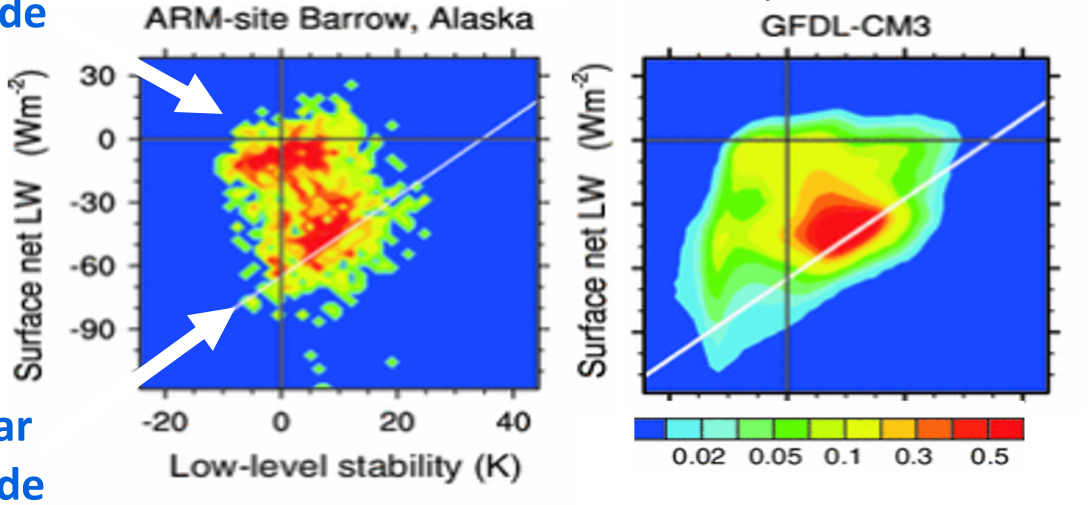


(Wolding et al. 2020)

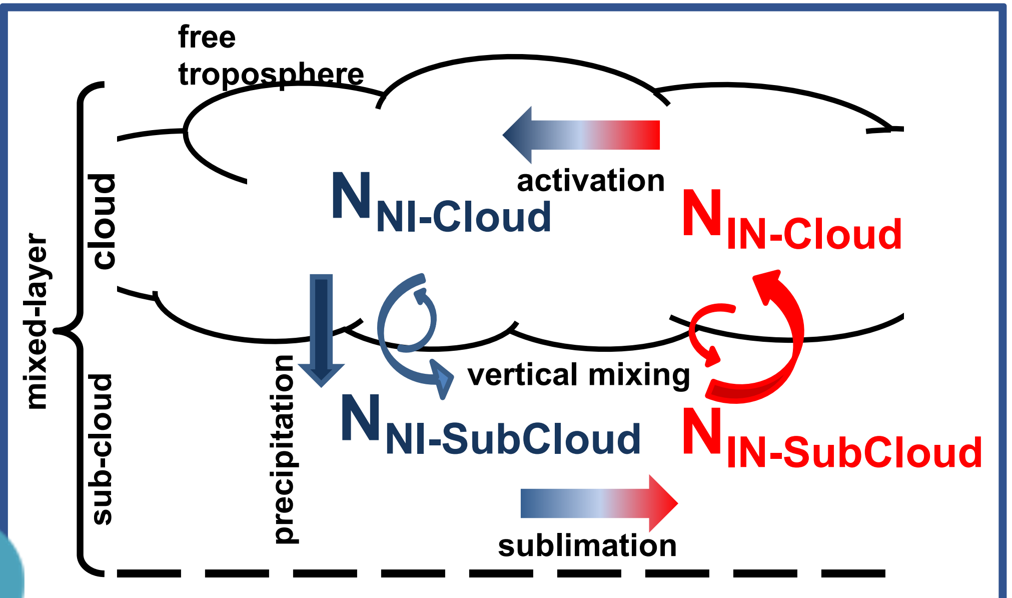
Process Studies to Improve the Representation of Arctic Mixed-Phase Clouds in Forecast Systems

Cloudy mode

Climate models and forecast systems generally miss the observed cloudy mode

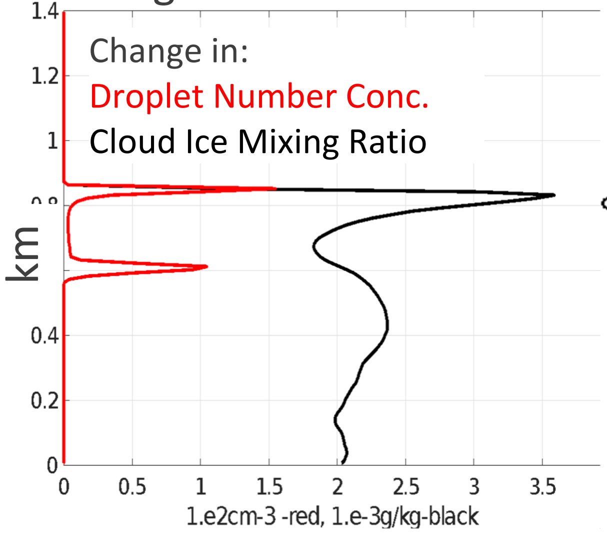


Clear mode

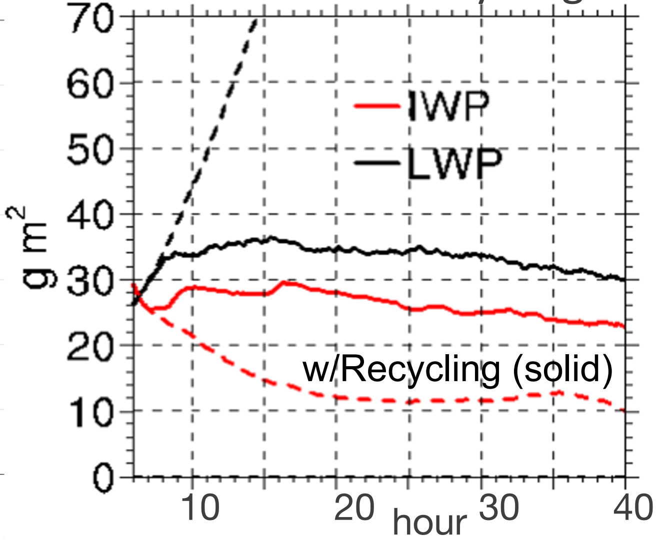


(Solomon, Feingold, Shupe 2015)

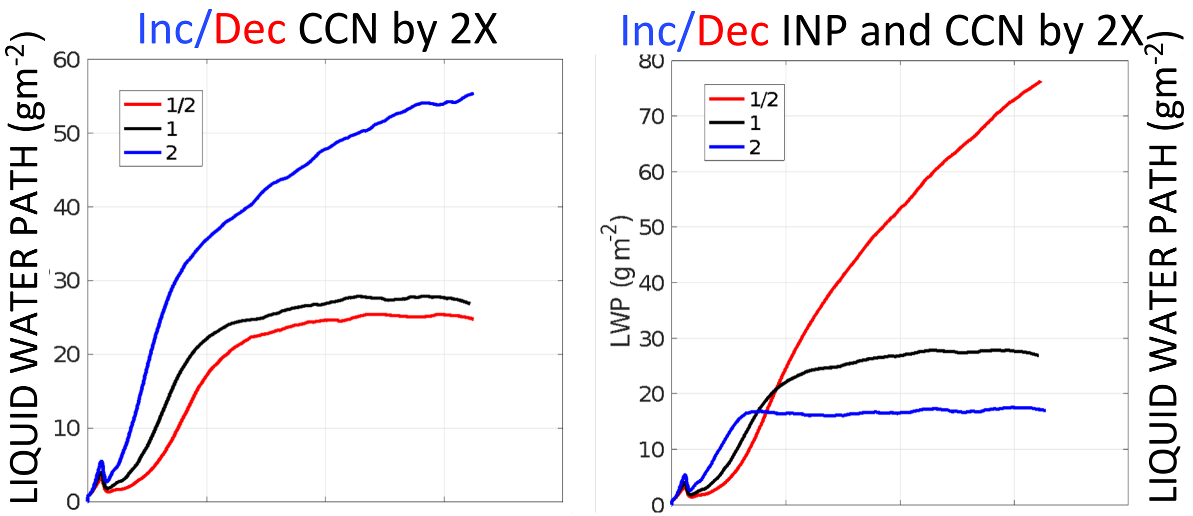
Prognostic vs Fixed CCN



Role of INP Recycling



Relative Impact of CCN/INP



(Solomon et al. 2018)

Advances in **Model Evaluation**

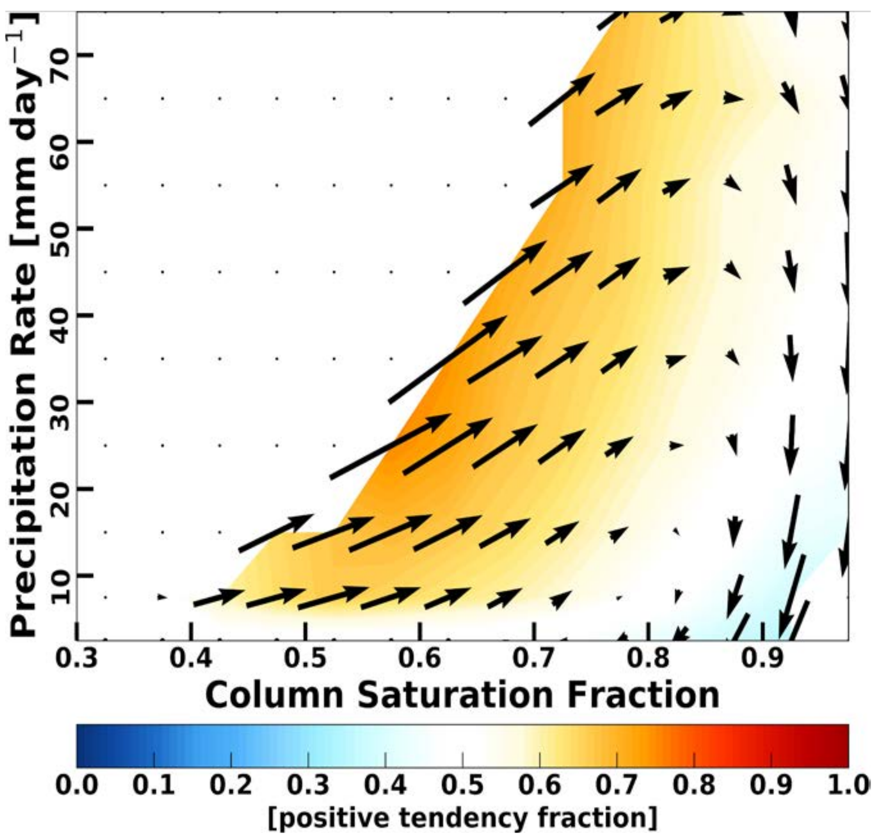
Algorithm Development	Data Assimilation	Model Evaluation
Process Studies	Post-Processing	Experimental Forecasts

Developing new process-oriented diagnostic tools to evaluate forecast systems

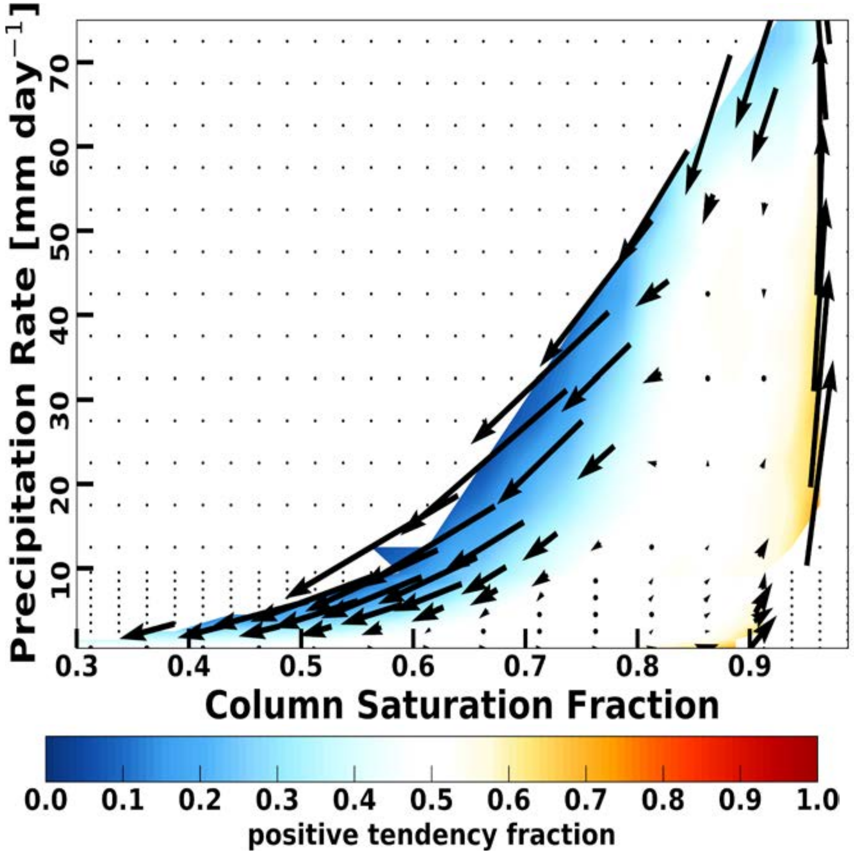
- **Tropical variability in numerical weather prediction and climate modeling**
- Precipitation forecast evaluation in areas of high observational uncertainty
- Diagnostic toolkit to diagnose UFS Arctic and Tropical system biases

Tropical Moisture-Precipitation Coupling Diagnostics

Observations



GFS v15 with FV3



GFS too often excessively dries environment

GFS lacks realistic moisture-convection coupling

Improving moisture-convection coupling is an important step towards improving model representation of the MJO, other equatorial waves, and forecast skill

Arrows show how column moisture and precipitation co-evolve in observations (left) and a recent version of the GFS (right). Shading shows moistening (warm colors) and drying (cool colors)

(Wolding et al. 2020)

Advances in **Model Evaluation**

Algorithm Development	Data Assimilation	Model Evaluation
Process Studies	Post-Processing	Experimental Forecasts

Evaluating model processes and biases with PSL-lead campaign data

- Hydrologic and atmospheric model forecasts for a high impact flood event
- National Water Model streamflow and precipitation forecasts
- Improvement to the HRRR and RAP during WFIP2
- Evaluation of HRRR and RAP forecasts using PSL atmospheric river observatories
- SST/SSH seasonal forecasting skill in NMME in the tropical Pacific and NH coastal regions
- **Evaluation of subseasonal coupled forecast of the Central Arctic over a full annual cycle**
- Evaluation of GFSv16 next generation physics suite against ATOMIC/EURECA observations

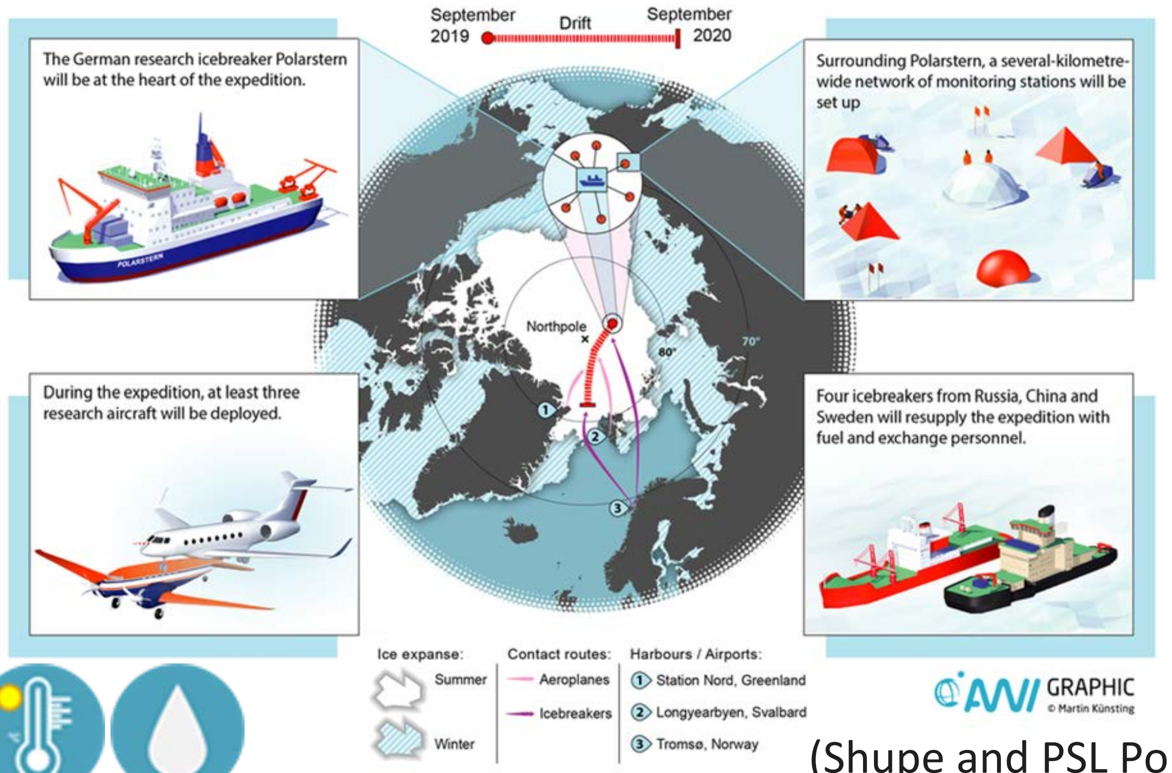
The **M**ultidisciplinary drifting **O**bservatory for the **S**tudy of **A**rctic **C**limate

First Arctic campaign to observe the coupled ocean-ice-atmosphere-ecosystem in the Central Arctic over a full annual-cycle

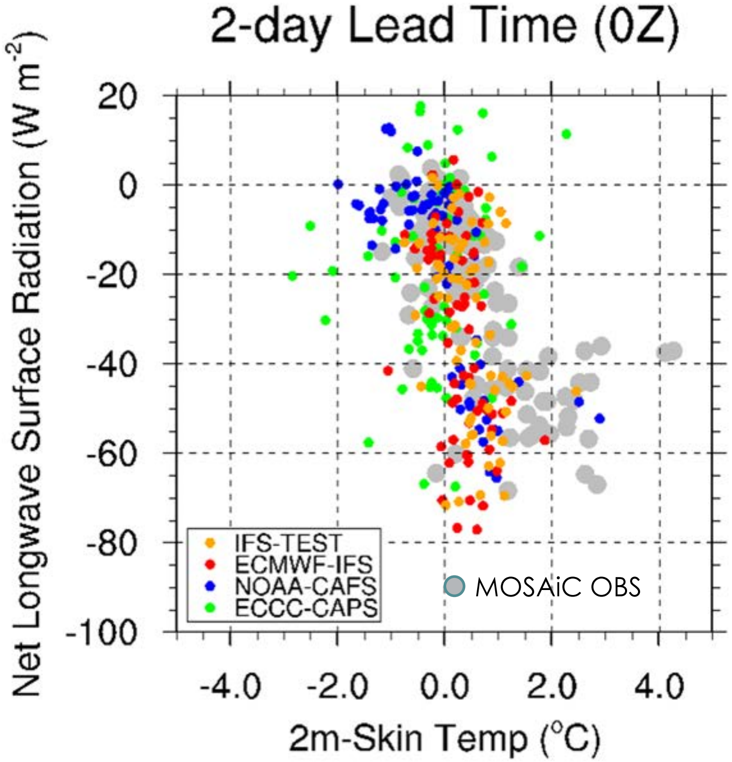
Campaign designed:

--- As a "floating grid box" to evaluate forecast systems and climate models

--- To observe the multi-scale climate system: from synoptic to turbulence scales



PSL is leading the international activities to evaluate forecast systems over the MOSAiC year



(Shupe and PSL Polar Observations and Processes Team, see MOSAiC Science Plan)

Advances in **Data Assimilation**

Improving and implementing new data assimilation schemes

- **Continued development of sparse-input reanalyses (20CR)**
- **Development of EnKF system used in operations (improvements to EnKF, 4DIAU, stochastic physics for improved background-error estimate, JEDI EnKF solver)**
- Developed and tested a scheme to account for land model uncertainty in UFS ensembles
- Evaluated land/atmosphere coupling in UFS to identify targets for land data assimilation
- Developed and implemented a state-of-the-art Optimal Interpolation-based snow data assimilation scheme for the UFS

PSL Ensemble Data Assimilation Research

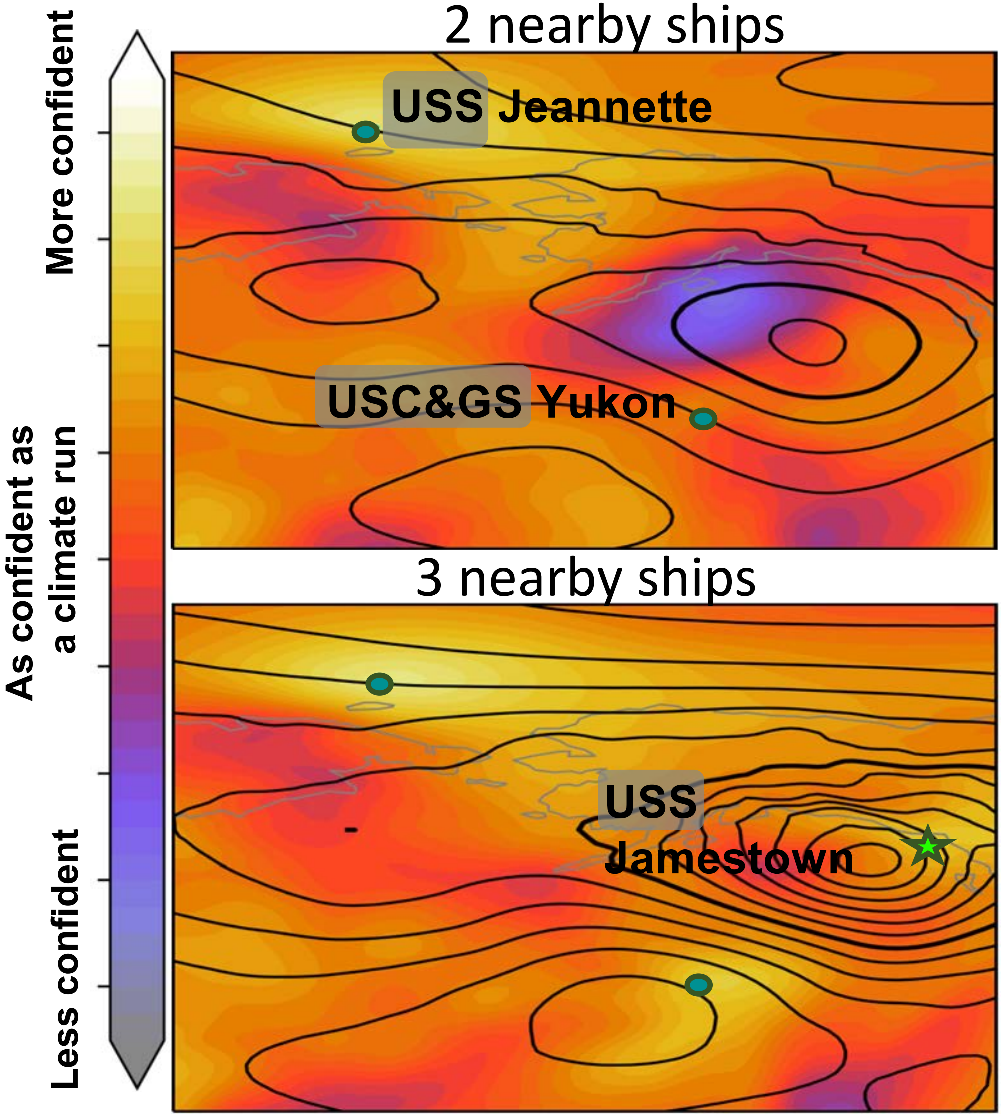
Ensemble-based background-error covariance (B) estimates can be used to extract more information from observations

- PSL developed ensemble Kalman filter (EnKF) code operational for GFS in 2012. Improvements since:
  - Included in regional model DA (HRRR, NAM, RAP, HWRF).
  - GFSv14 - use PSL developed stochastic physics to improve model-uncertainty representation in ***B*** estimate. 3DEnVar -> 4DEnVar for GFS.
  - GFSv15 - updated for new FV3 dycore.
  - GFSv16 - 4DIAU to lessen ‘analysis shock’, model-space vertical localization to improve radiance assimilation.

- Initializing ensemble re-forecasts (just completed GEFS v12 reanalysis/reforecast in collaboration with NCEP/EMC).

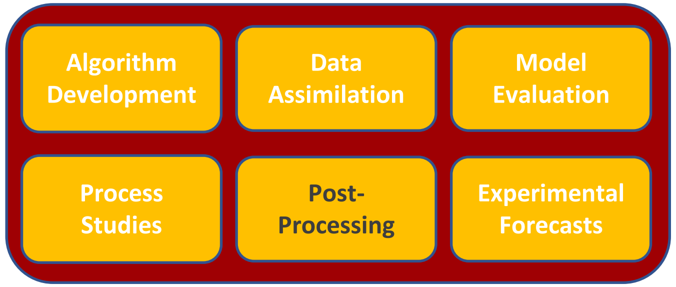
- Migration to JEDI software infrastructure underway, sets stage for ensemble-based coupled DA.

Impact of Adding One Observation in 20CR 1880 Alaska Hurricane



(Whitaker, Frolov, Lei, Shlyaeva, Hamill, Compo, Slivinski,

Advances in **Post-Processing**



Pioneering statistical post-processing techniques to correct forecast errors

- Investigation of the use of artificial intelligence to correct systematic and state-dependent errors in UFS global forecasts
- **Prototype of ensemble, post processed GEFS forcings for National Water Model forecasts**
- **New methods for statistical postprocessing, including precipitation amount, fire-weather, snow fall amount, wind and solar energy production**
- New methods for diagnosis of sources of errors in ensemble predictions
- New methods for benchmarking background forecasts in rapidly cycled data assimilation
- Understanding of characteristics of precipitation analyses used in statistical postprocessing
- Understanding of how changes in analysis characteristics affect reforecasts used for statistical postprocessing

Post-Processed GEFS Forcings for National Water Model Hydrologic Forecasts

Modified Ensemble Copula Coupling (ECC-mQ) method for ensemble forecast fields that are:

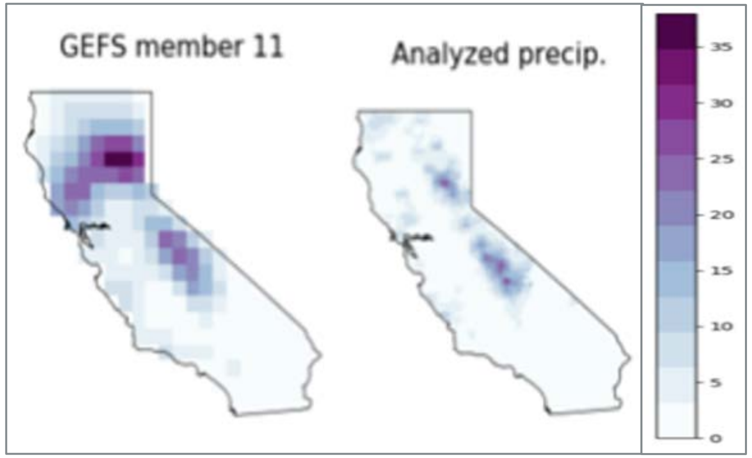
- High-resolution
- Spatially and temporally consistent
- Statistically reliable

Produced on the NLDAS grid and trained using NLDAS forcings from Jan 2010-Jun 2016

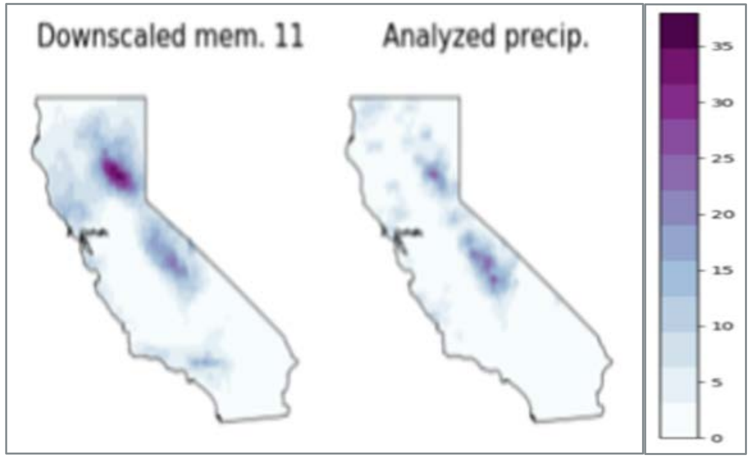
Post-processed meteorological variables:

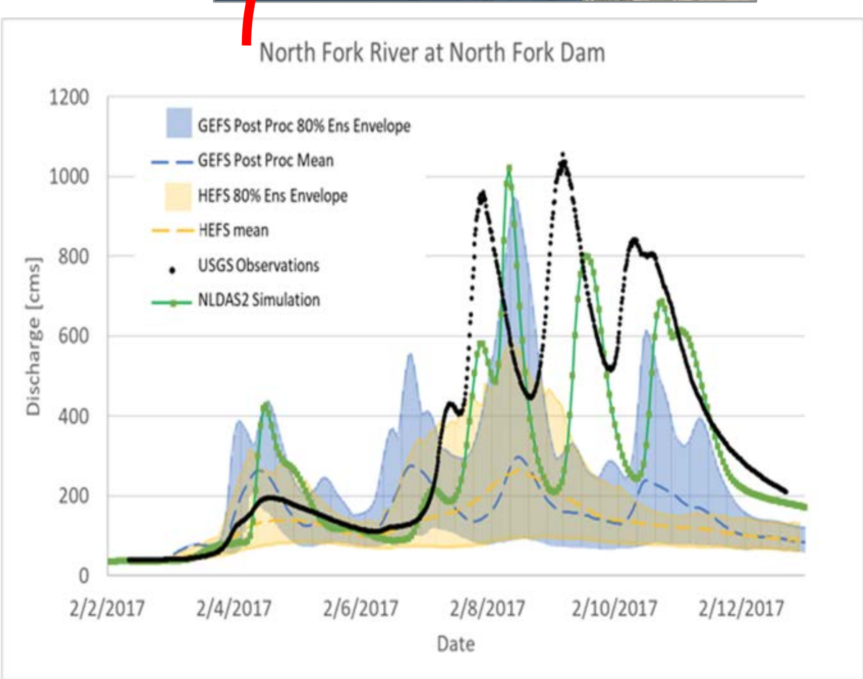
- 2m temp, surface pressure
- U/V wind, precip rate
- QV, long/shortwave radiation

DOWNSCALED PRECIP FORECASTS



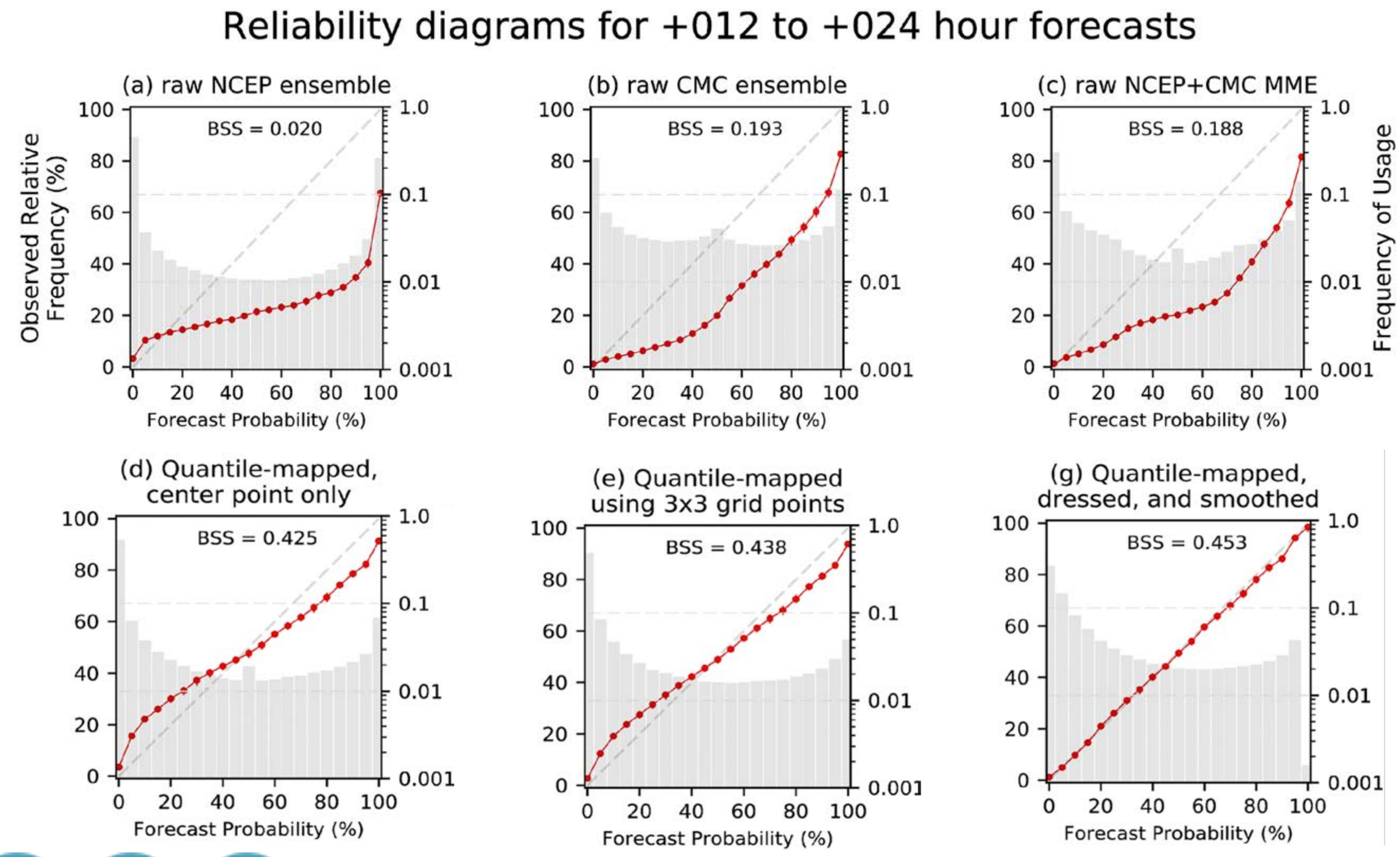
POST-PROCESSED PRECIP FORECASTS





(PSL APA and Hydrometeorology Modeling and Applications Team, see Scheuerer and Hamill 2018)

Statistical Post-Processing of Multi-Center Ensemble Forecasts



PSL developed and provided the NWS Meteorological Development Lab with the precipitation post-processing algorithms for their National Blend of Models, the starting data for the NWS weather forecast process.

Reliability diagrams show pure multi-model combinations not enough to achieve reliability. Through a sequence of steps, reliability and skill are greatly improved.

(Hamill and Scheuerer 2018)

Advances in **Experimental Forecasts**

Algorithm Development	Data Assimilation	Model Evaluation
Process Studies	Post-Processing	Experimental Forecasts

Providing experimental forecasts to benchmark operational forecast systems and provide model guidance to the NWS and CPC

- **Development of LIM for S2S (Weeks 3-4, seasonal) prediction of tropical SST and OLR and benchmarking of operational (IFS and CFS) models**
- Development of model-analogs for seasonal-to-interannual precipitation forecasts
- **Experimental 0-10 day coupled Arctic system forecasts**
- Forecasts based on ESRL/PSL GEFS Reforecasts V2
  - Week 2 probabilistic forecasts
  - Forecasts of 500mb height teleconnection Indices
  - Daily weather forecast maps
  - Precipitation forecast products

Using LIM to Benchmark Operational Forecast Systems

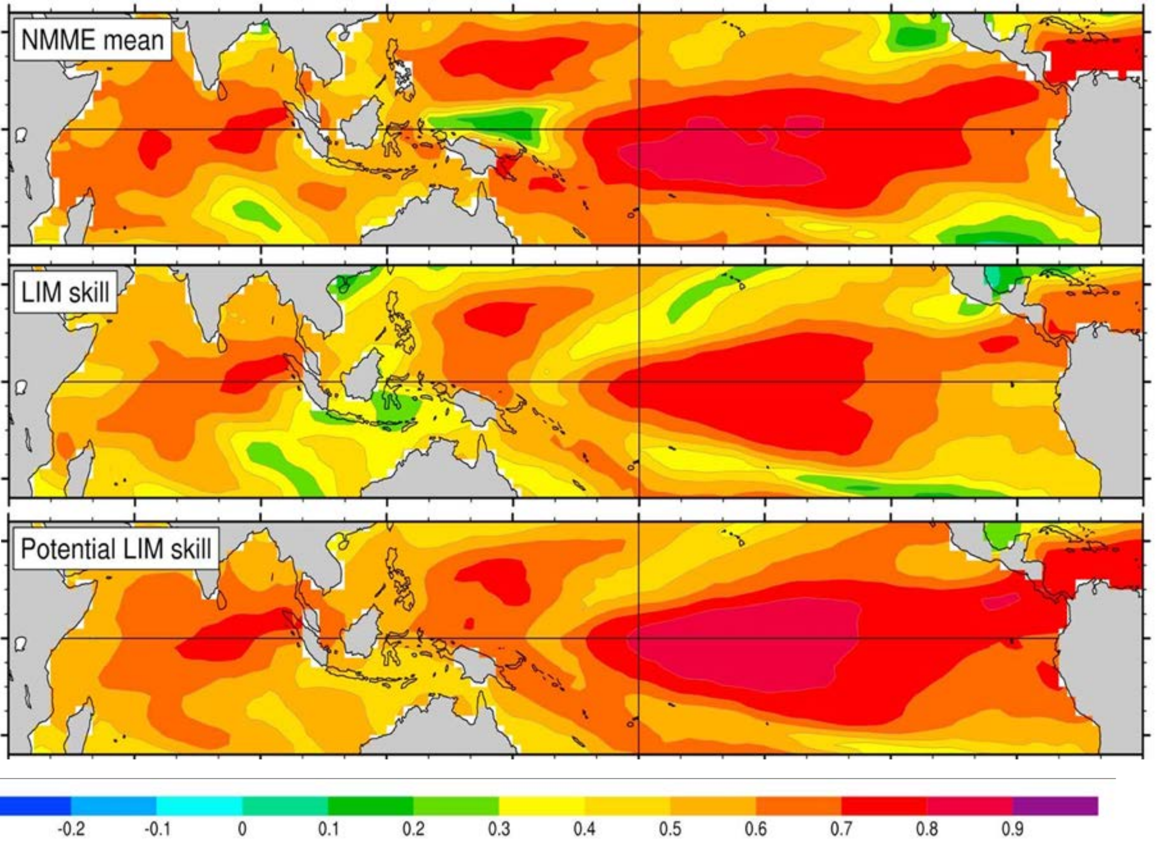
Seasonal tropical SST predictions, a Low-Order (28-component) model estimated through Linear Inverse Modeling (*Penland and Sardeshmukh 1995*) has very similar skill to that of the models used in the operational National Multi-Model Ensemble (NMME) system.

SST anomaly correlation skill at Month 6

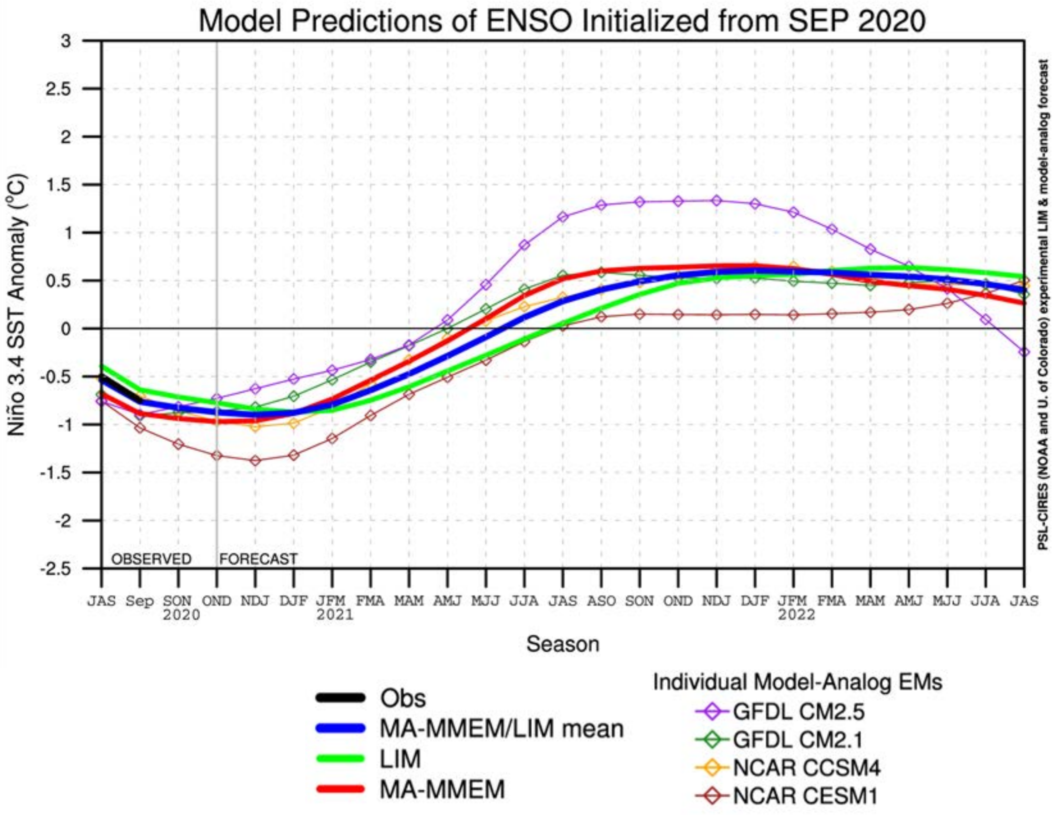
NMME-mean skill

LIM skill

Potential LIM skill ρ_∞



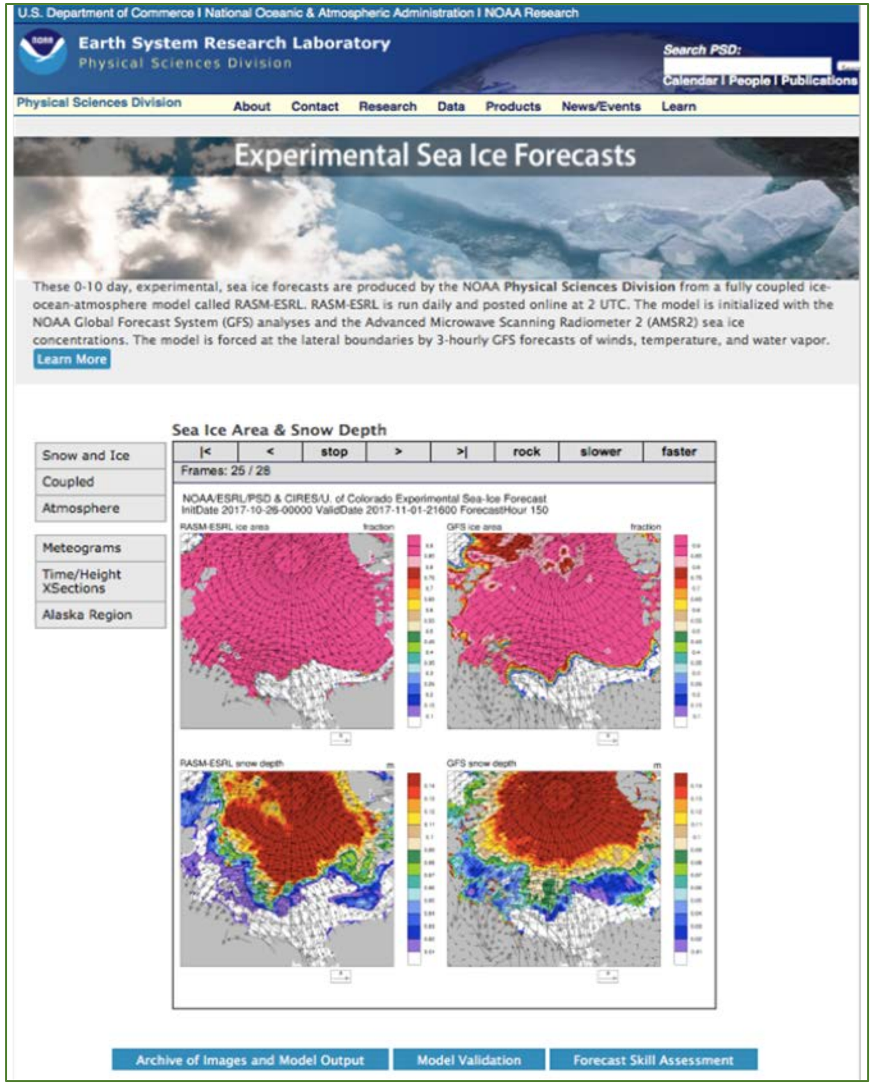
LIM + Model-Analogs



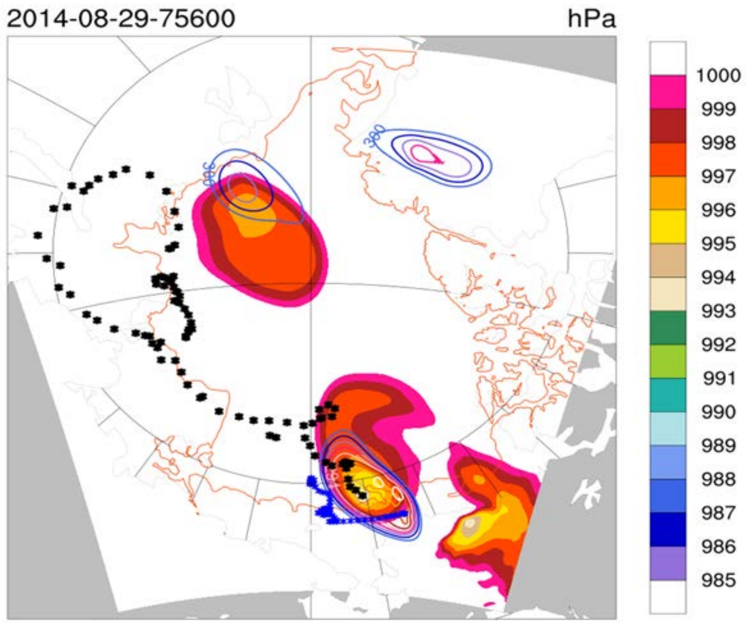
(Newman, Sardeshmukh, Penland, Ding, Alexander, and collaborators)

0-10 Day Coupled Arctic System **Forecasts**

A testbed for improving simulations of ocean-sea ice-atmosphere interactions in the Arctic

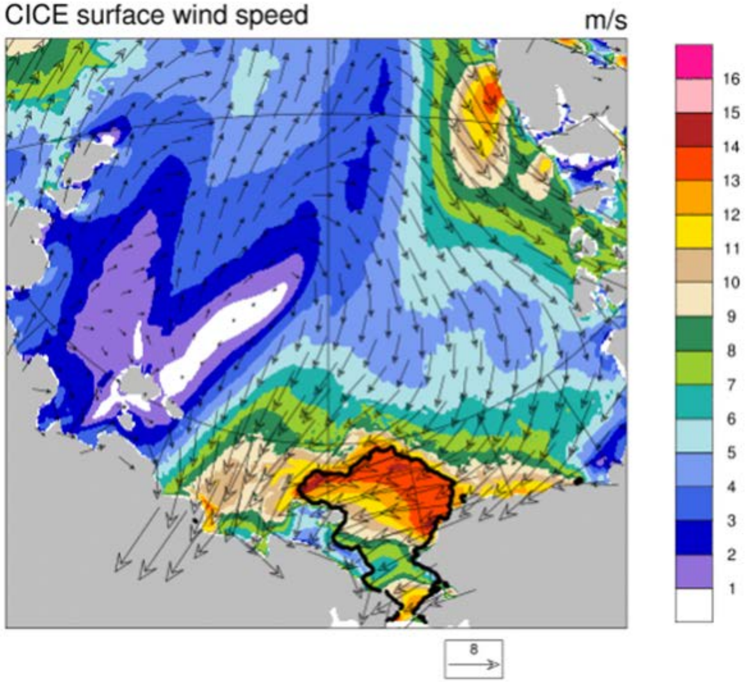


Improving simulations of Arctic extreme events such as rapid ice growth and Arctic cyclones



Simulation of an Arctic Cyclone during the 2014 ACSE campaign

Simulation of rapid ice growth during 2017 freeze-up



To provide model guidance for the NWS, support observational campaigns, and inform UFS development

(Solomon, Intrieri, Persson, Cox, and collaborators, see Intrieri et al. 2020)

PSL – Improving NOAA Forecasts by:

- ✓ Developing stochastic physics using rigorous theoretical underpinnings that lead to better ensemble mean forecasts and model variability
- ✓ Improving physical parameterizations from surface fluxes to cloud microphysics
- ✓ Using a hierarchy of model systems to advance the process understanding of the climate system
- ✓ Developing new process-oriented diagnostic tools to evaluate forecast systems
- ✓ Evaluating model processes and biases with PSL-lead campaign data
- ✓ Improving and implementing new data assimilation schemes
- ✓ Pioneering statistical post-processing techniques to correct forecast errors
- ✓ Providing experimental forecasts to benchmark operational forecast systems and provide model guidance to the NWS, CPC, and observational campaigns

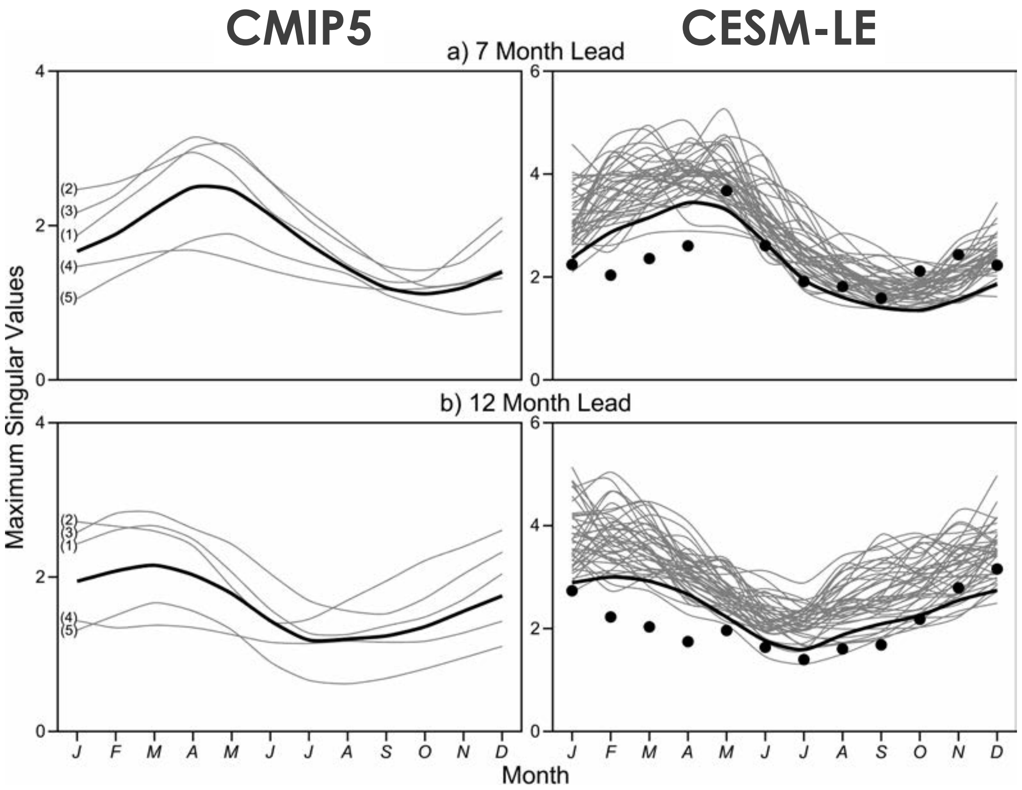
Supplementary Slides

Evaluating the importance of seasonality in ENSO precursor dynamics

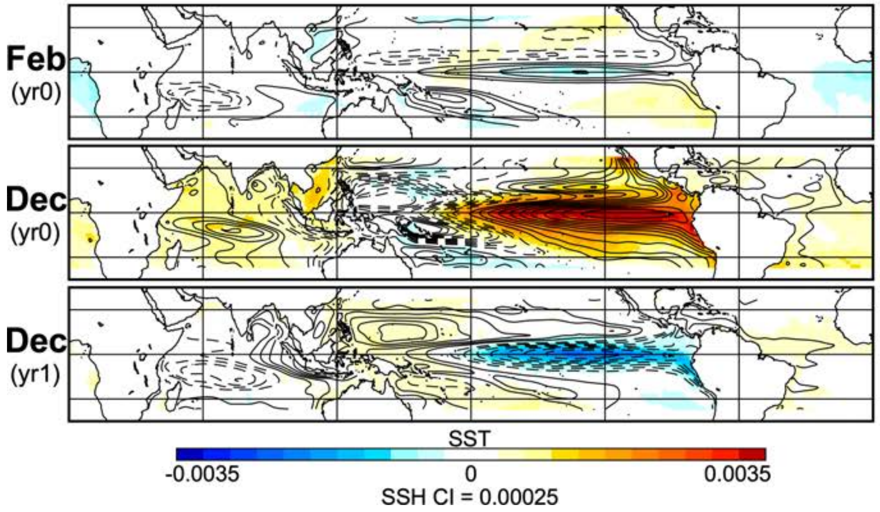
A new "Cyclostationary Linear Inverse Model" (CSLIM), an empirical-dynamical model representing the *chaotic evolution of tropical Pacific upper ocean anomalies as the sum of seasonally-varying predictable linear dynamics and unpredictable noise*, with predictive skill as good as operational numerical prediction models. The CSLIM is then used to diagnose the seasonal dependence of ENSO growth both in nature and in models.

Left: 5 selected CMIP5 models
Right: CESM-LE and observations (heavy dots)

Top: maximum growth over 7-month interval
Bottom: same but over 12-month interval



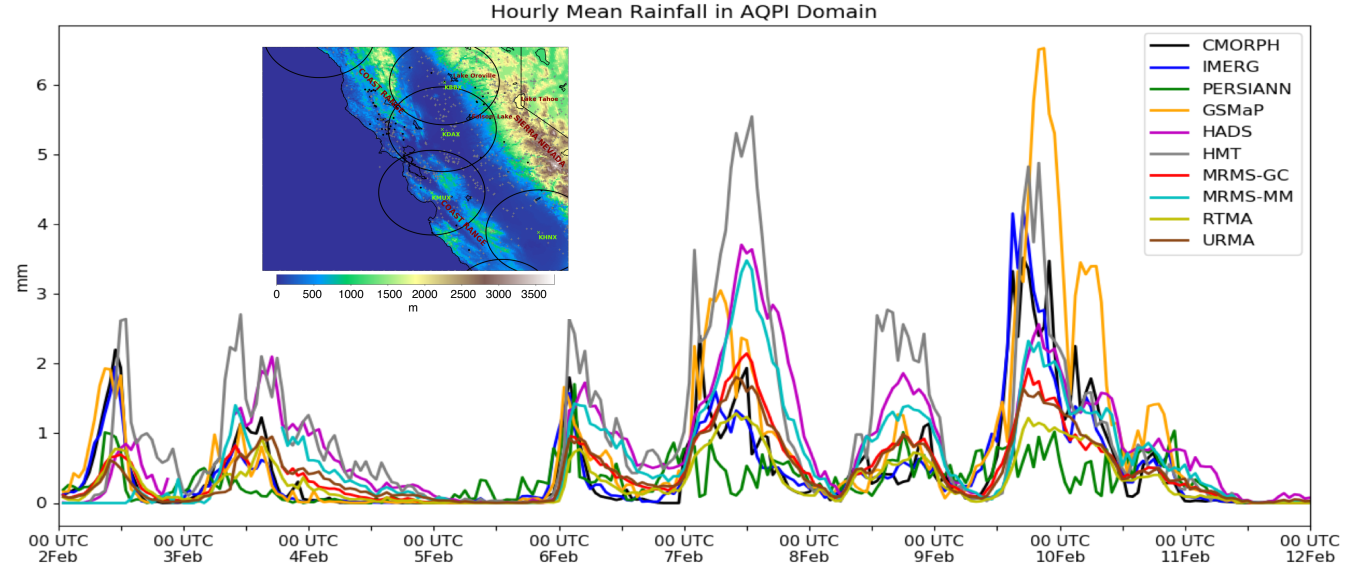
Evolution of February precursor leading to maximum possible December ENSO event



Shading: SST anomaly
Contours: SSH anomaly

Shin, Sardeshmukh, Newman, Penland, and Alexander, 2020: Impact of Annual Cycle on ENSO Variability and Predictability. *J. Climate*, in press.

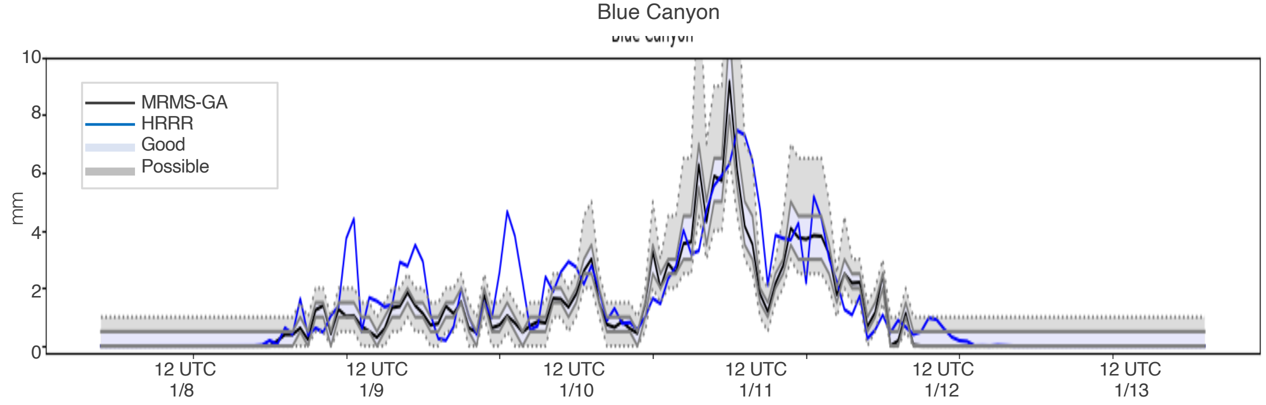
Development of methodology for precipitation forecast evaluation in areas of high observational uncertainty



Problem

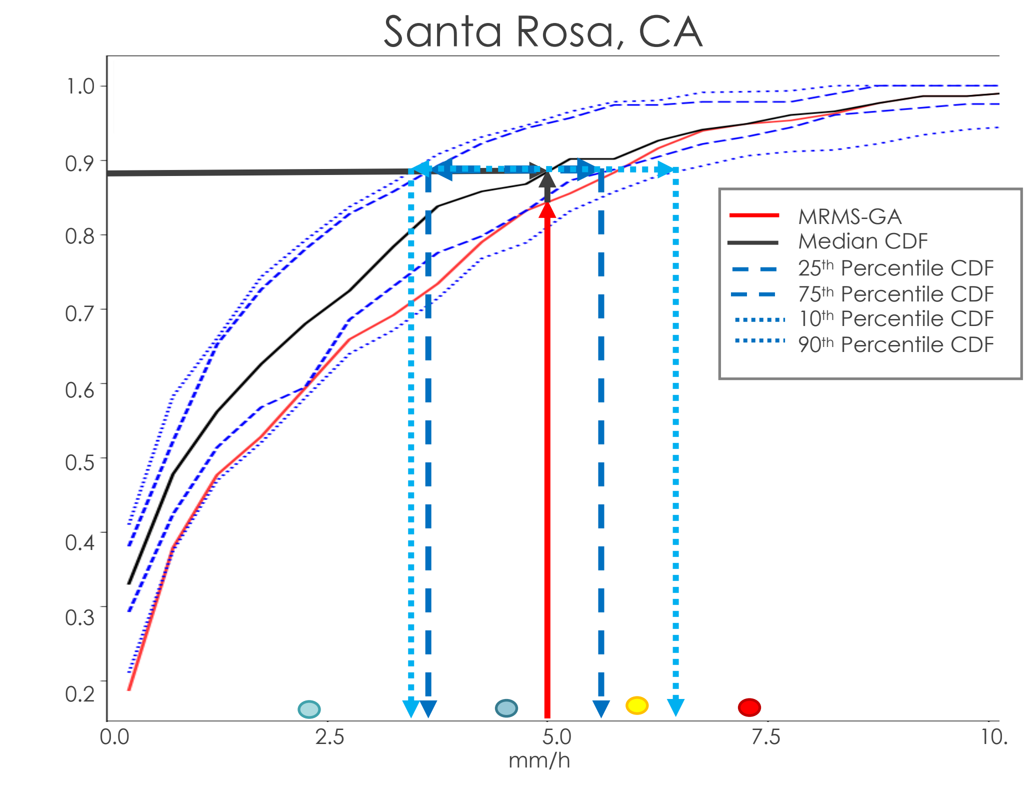
High resolution (hourly, < 10km) QPE is highly uncertain in areas of complex terrain. This makes it difficult to select a reliable reference product for the evaluation of high resolution precipitation forecasts. Bytheway et al. (2020), *J. Hydrometeorology*

Sample Result: January 8-13, 2017



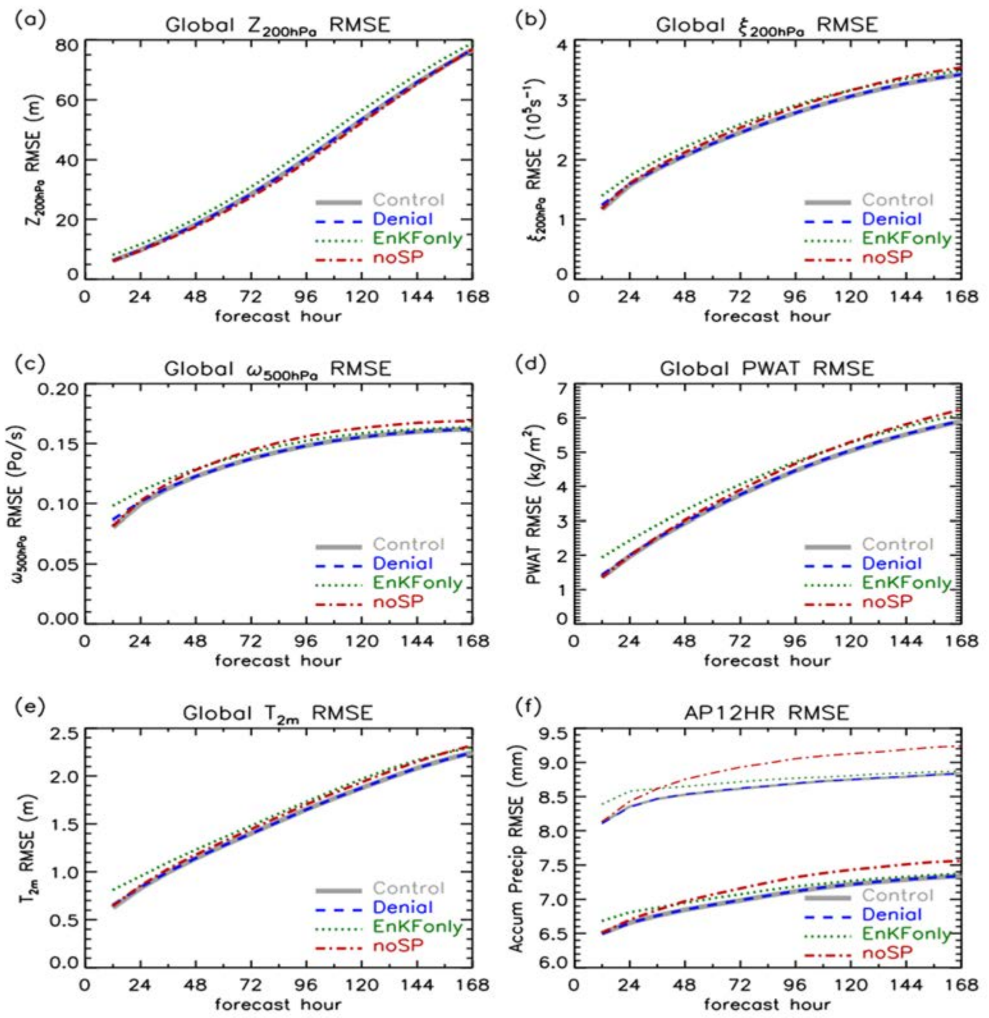
Proposed Solution: "Probabilistic QPE"

- Create monthly CDF of hourly rainfall in each 3km HRRR grid box for each QPE product
- Determine the spread of the CDFs
- At location (x,y) and time (t):
  - Use MRMS-GA as a reference (e.g. 5 mm/h)
  - What is the median CDF at MRMS-GA rain rate?
  - What rain rates correspond to the interquartile range? The 10th and90th percentiles?
  - QPFs within the IQR are considered "good". Those outside the IQR but still within the 10th and 90th percentiles are "possible". Lower than the 10th percentile are underestimates and above 90th percentile overestimate.



Forecast System Evaluation and Sensitivity
(a) Campaign Observations; (b) Data Assimilation; (c) Forecast Model

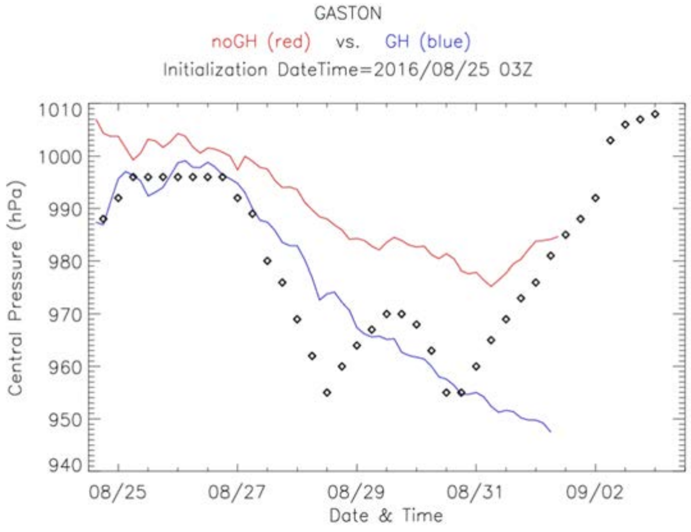
Global forecasts during 2016 El Niño are
1) slightly sensitive to additional dropsonde Observations
2) more sensitive to the Data Assimilation choice
3) most sensitive to the use of model Stochastic Parameterizations

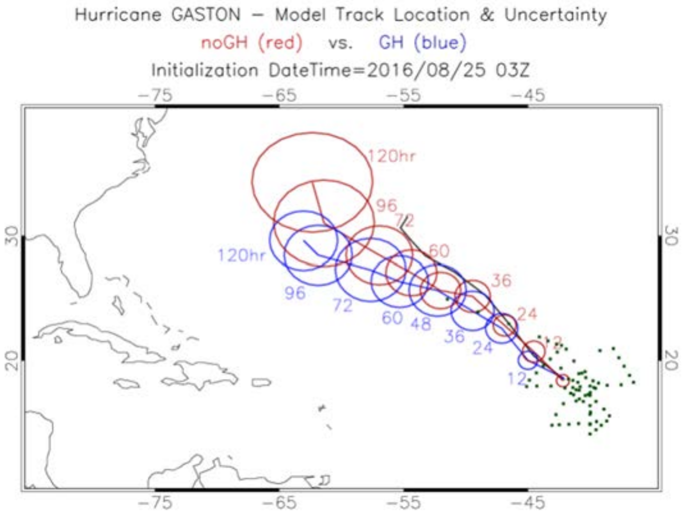


2016 Hurricane GASTON
Model Intensity & Track sensitivity to additional dropsonde Observations

1. Intensity enhanced

2. Model track uncertainty decreased
3. Location error increased



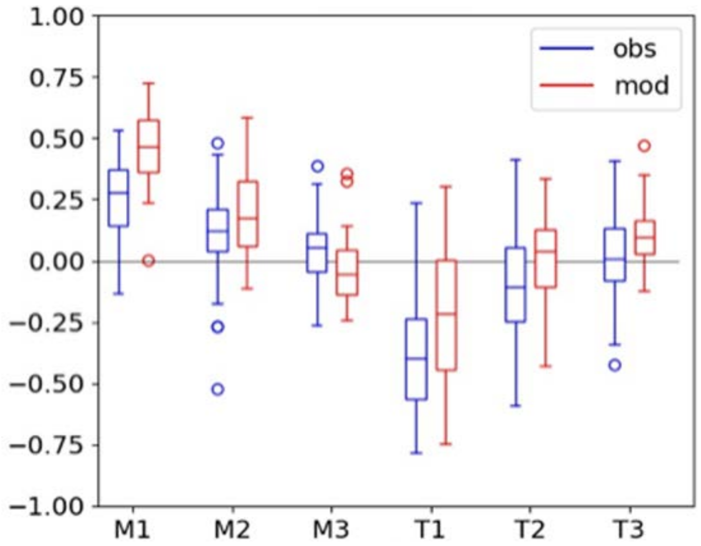


1. Sensitivity of each forecast system component needs testing
2. Benefits of observations are event- and scale-dependent
3. Observation sampling and usage strategy are critical
4. Model sensitivity and uncertainty need attention

Advances in coupled land-atmosphere data assimilation

Understanding the cross-covariances between atmospheric information and land information is a necessary first step in ensuring consistent land and atmospheric states.

How are soil states correlated to 2-m relative humidity?

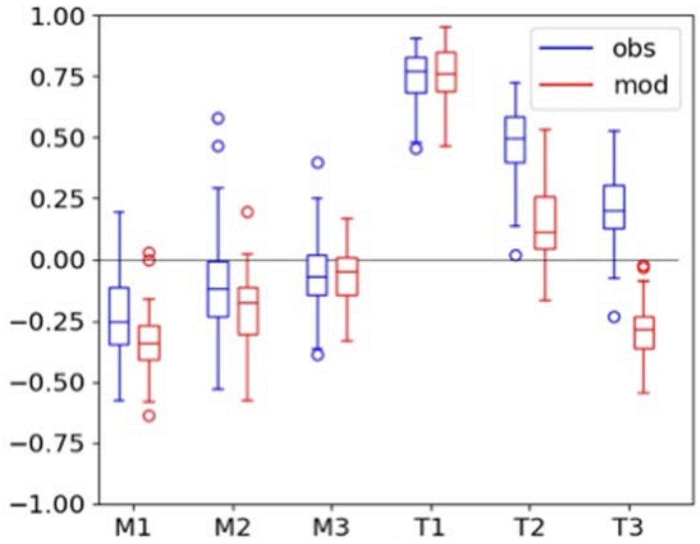


moisture in soil layers, top to bottom

temperature in soil layers, top to bottom

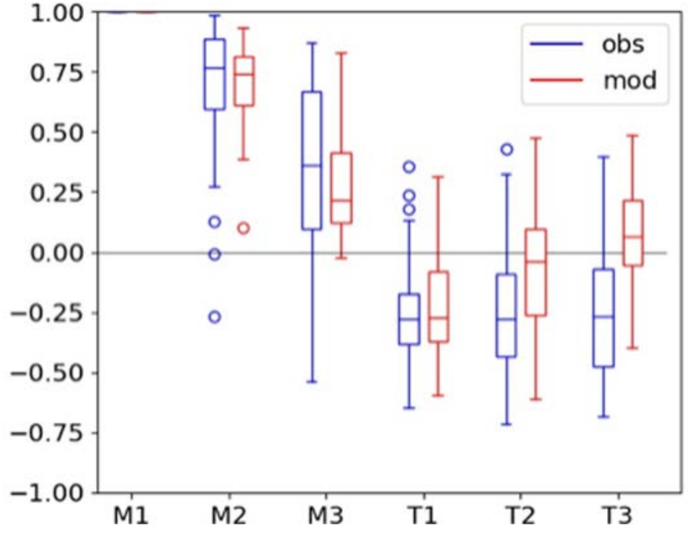
RH may be useful for updating top-level soil moisture and temperature.

How are soil states correlated to 2-m temperature?



2-m temperature is especially helpful for updating the top-level soil temperature.

How are top-level soil-moisture observations correlated with soil moisture and temperature at other levels?



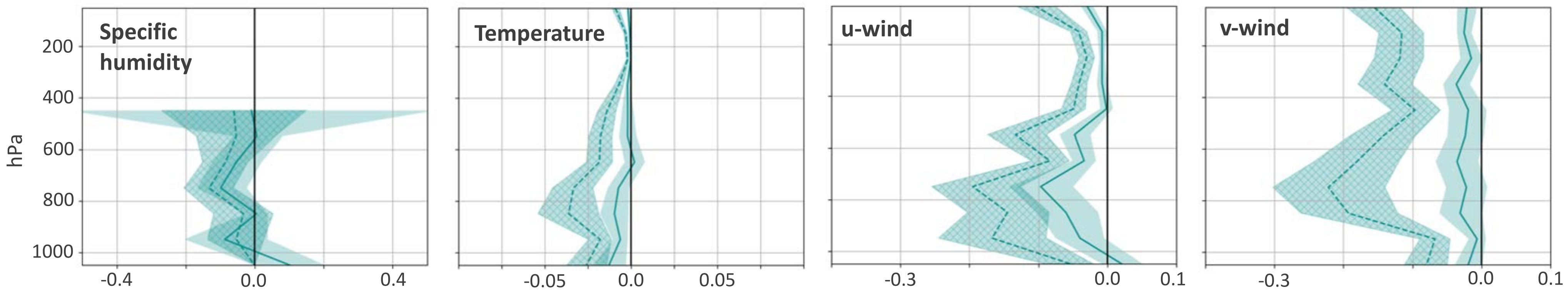
Were observations of top-level soil moisture widely available, they'd provide useful information to update soil moisture at root zone.

(ongoing work by Draper and collaborators)

1) The effects of the ENRR observations are small and localized but significant, demonstrating that these obs. were valuable in the existing, dense obs. network.

$z_{control}$ (resp. z_{denial}) = mean sq. diff. between ENRR obs. and 6-h background (solid lines) or analysis (dashed lines) fields from experiment with ENRR obs (resp. w/o ENRR obs), interpolated to ob. time and location. 95% conf. intervals from paired block bootstrap.

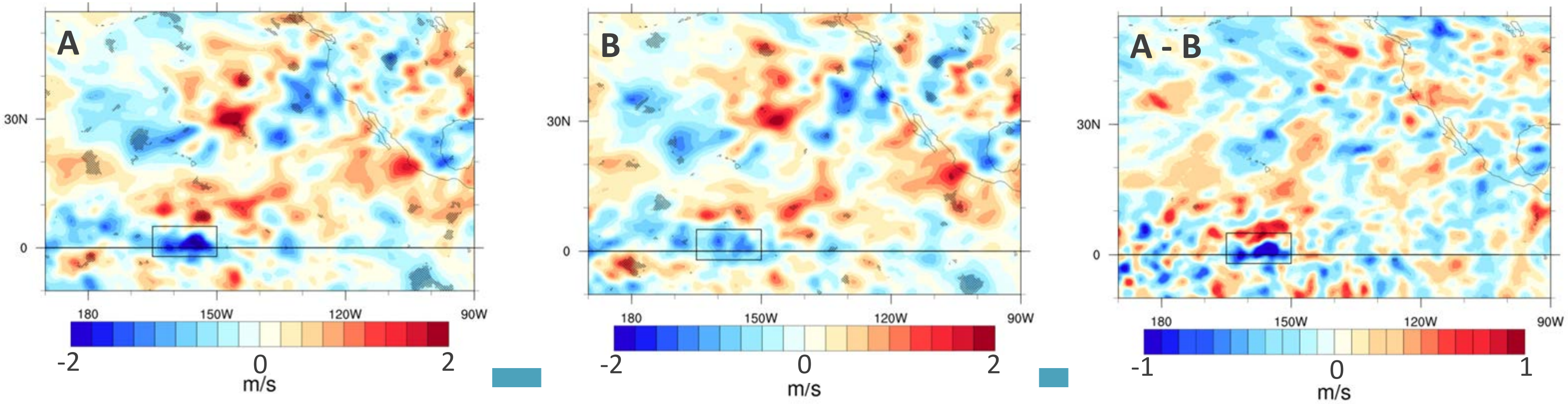
Vertical profiles of normalized RMS difference between $z_{control}$ and z_{denial} *(Feb 14 – Mar 7, all ob times)*



2) The GFS spectral model seems to have a bias in upper level v-wind, which is further corrected by the addition of the ENRR sondes.

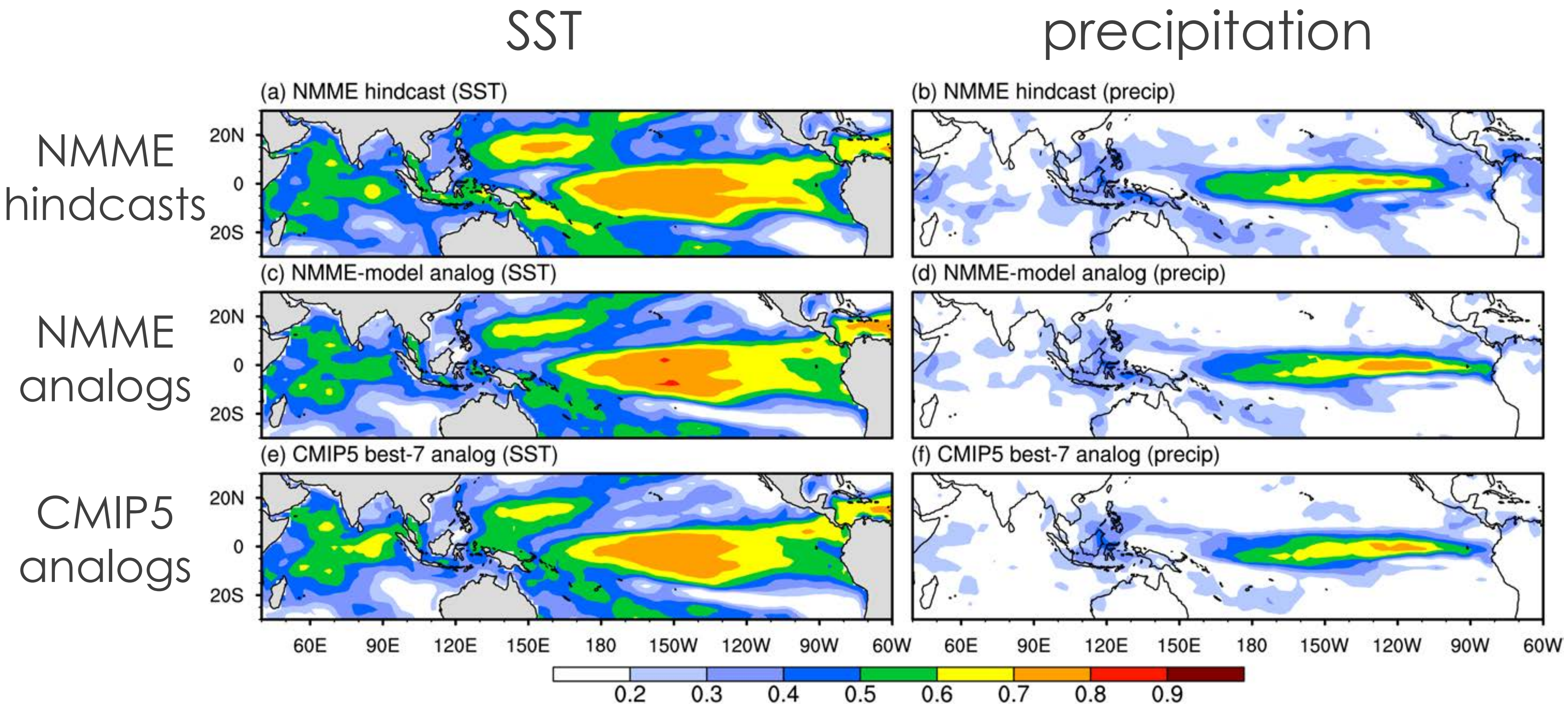
All plots: analysis minus 6-hour background fields, valid at 00Z on the ten "deep tropics" flight days (black box).
Left two plots: crosshatching represents significant differences from respective non-flight days (95% level). Right plot: crosshatching represents significant differences from zero (90% level).

200hPa v-wind update **with** ENRR obs | 200hPa v-wind update **without** ENRR obs | Difference (A minus B)



Model-analog skill matches/exceeds assimilation-initialized CGCM hindcasts

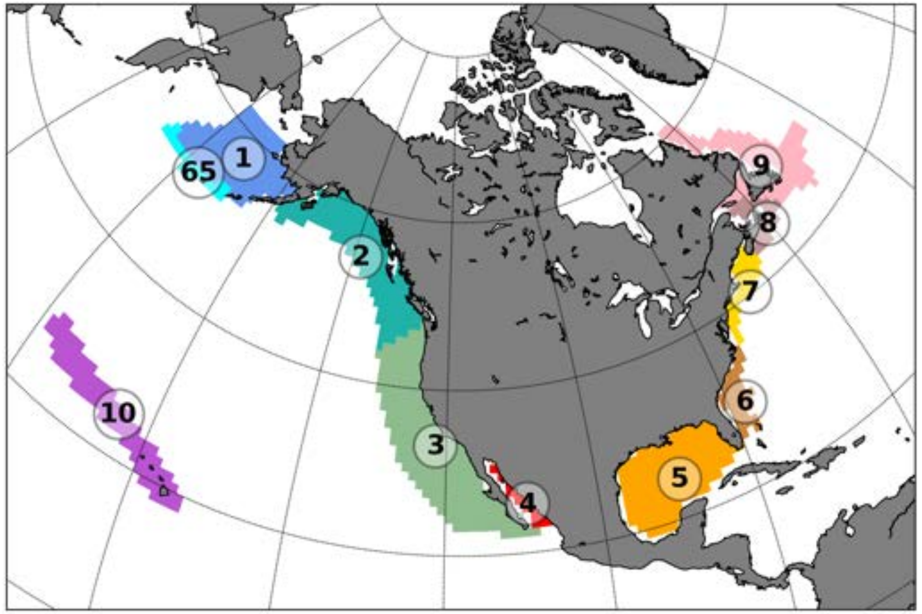
Month 6 hindcast skill, 1982-2009



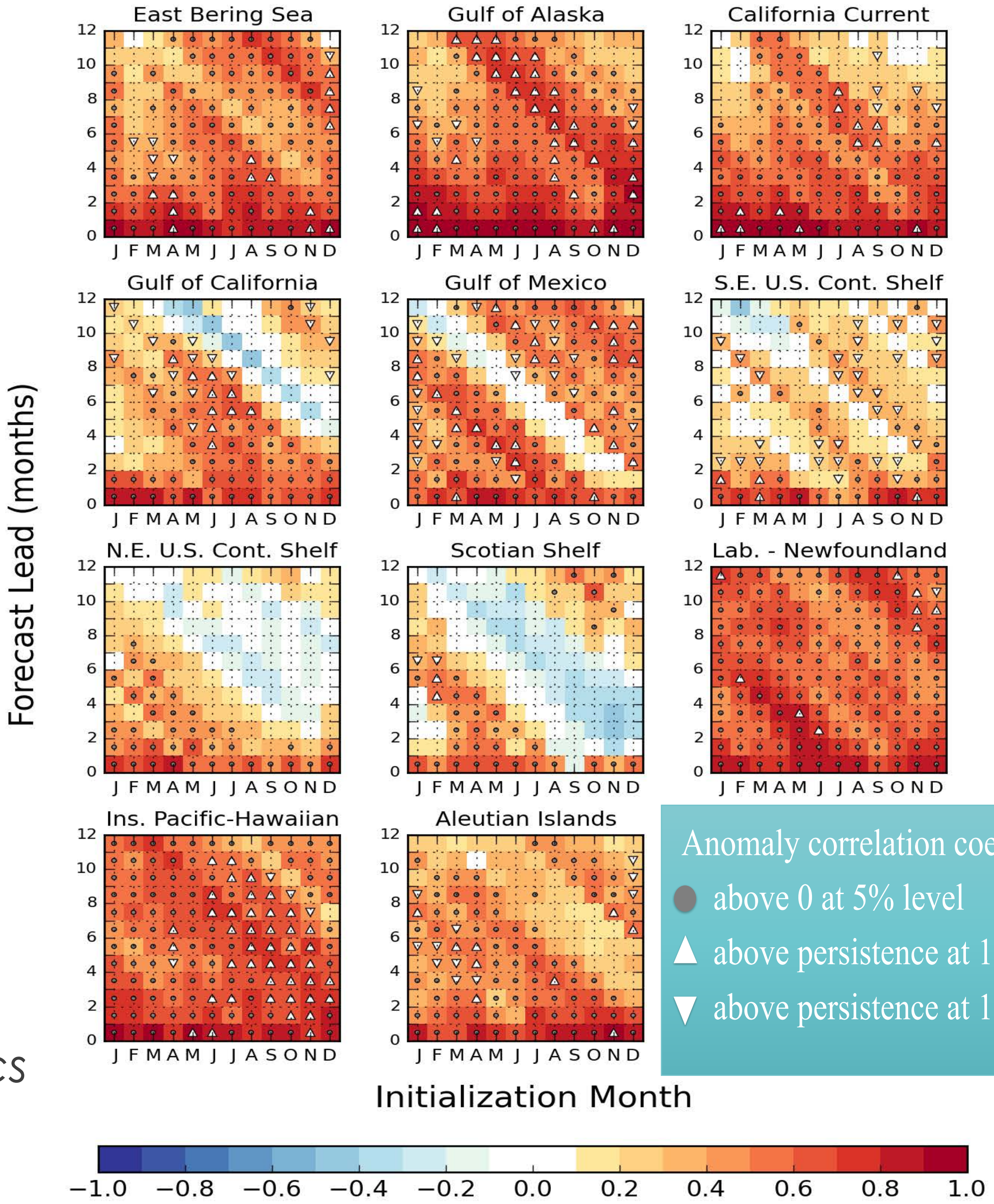
NMME model-analogs for **tropical Indo-Pacific** based on control runs of the same NMME models used for assimilation-initialized hindcasts (NCAR CESM1/CCSM4, GFDL CM2.1/ FLOR)

NMME SST Forecast Skill for US LMEs
(Ensemble of NMME models)

Large Marine Ecosystem Regions



Hervieux et al. 2017 Climate Dynamics



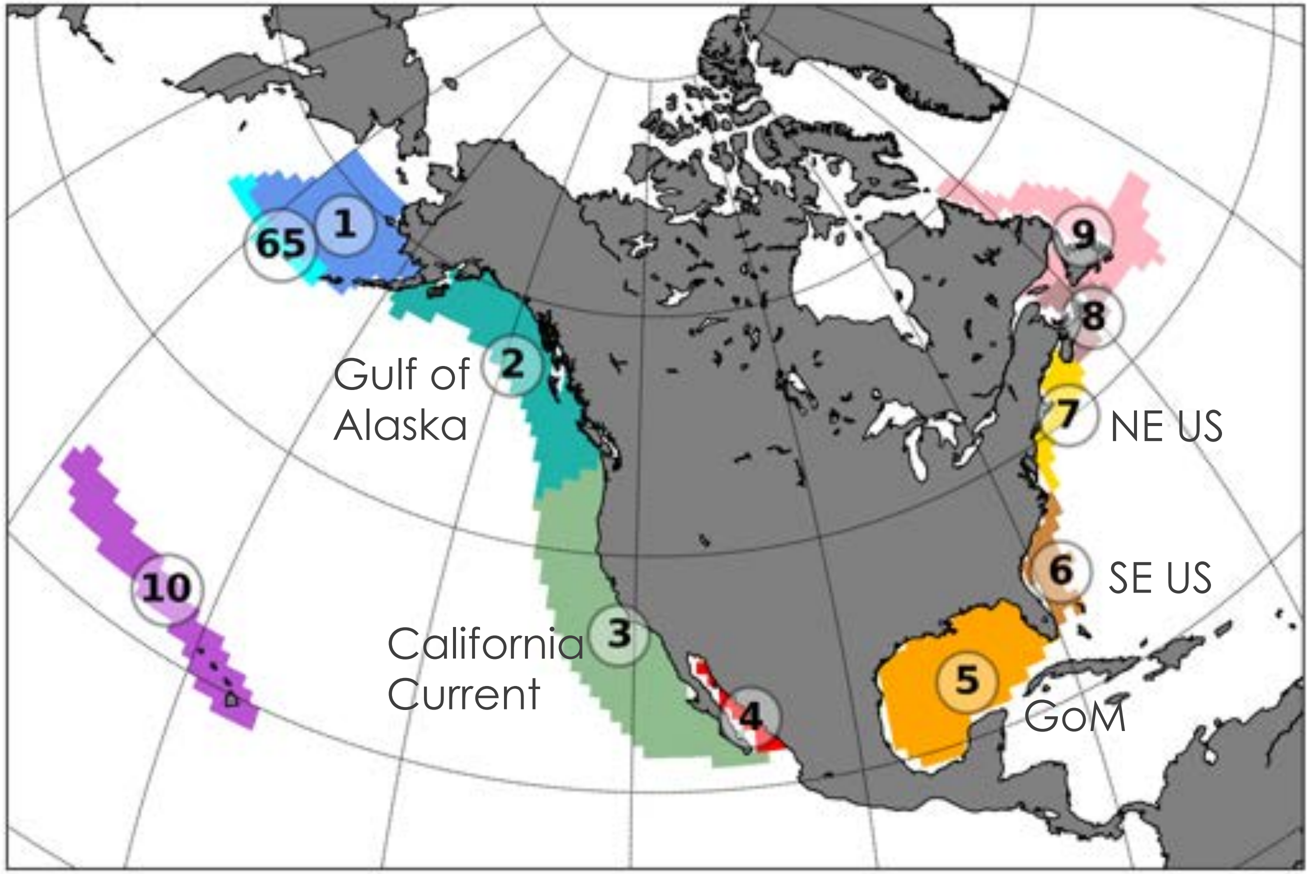
SSTs important for biology as well as physics

Anomaly correlation coefficients:

- ● above 0 at 5% level
- ▲ above persistence at 10% level with ACC > 0.5
- ▼ above persistence at 10% level with ACC < 0.5.

Large Marine Ecosystems (LMEs)

Slide provided for background information



LMEs 1: East Bering Sea (EBS), 2: Gulf of Alaska (GoA), 3: California Current (CC), 5: Gulf of Mexico (GoM), 6: Southeast U.S. Continental Shelf (SEUS), 7: Northeast U.S. Continental Shelf (NEUS), 8: Scotian Shelf (SS), 9: Newfoundland-Labrador Shelf (NL), 10: Insular Pacific Hawaiian (IPH), 65: Aleutian Islands

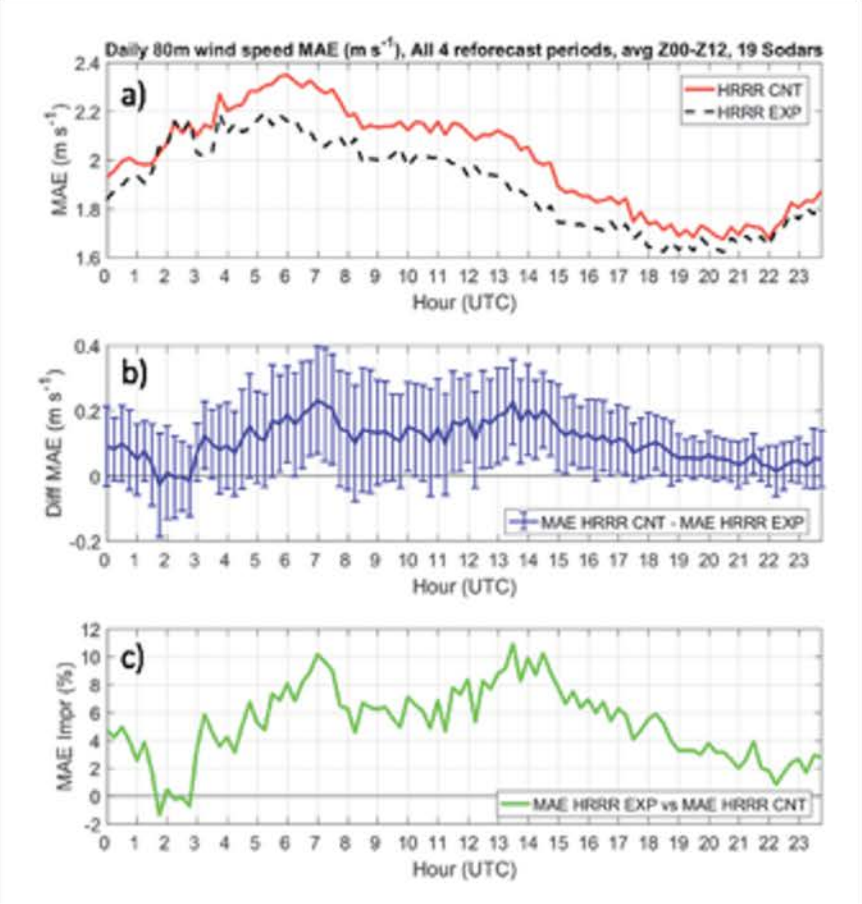
LMEs - coherent ocean areas along continental margins (productive regions).

LMEs have been defined based on ecological criteria, bathymetry, hydrography, productivity and trophic relationships

Improvements to the HRRR and RAP model resulting from the Second Wind Forecast Improvement Program (WFIP2)

Goals:

- Identify weaknesses in HRRR/RAP boundary layer and cloud parameterizations through a field campaign in complex terrain
- Improve our understanding of key physical processes
- Modify or develop new parameterizations that improve the skill of the models, especially for turbine-height winds



Results:

- Cold pools and gap flow winds were identified as being especially difficult to predict well
- Combinations of ground-based remote sensing observations were used to improve our understanding of fundamental physical processes
- PSL collaborated with other ESRL labs (especially GSL) in the development and evaluation of improved parameterizations (PBL mixing, topographic drag, subgrid scale clouds)
- These new parameterizations were implemented in the HRRRv4 that will become operational at NCEP in late 2020

(ongoing work by Wilzcak and collaborators)