Aerosol-Cloud Interactions in Seasonal Prediction

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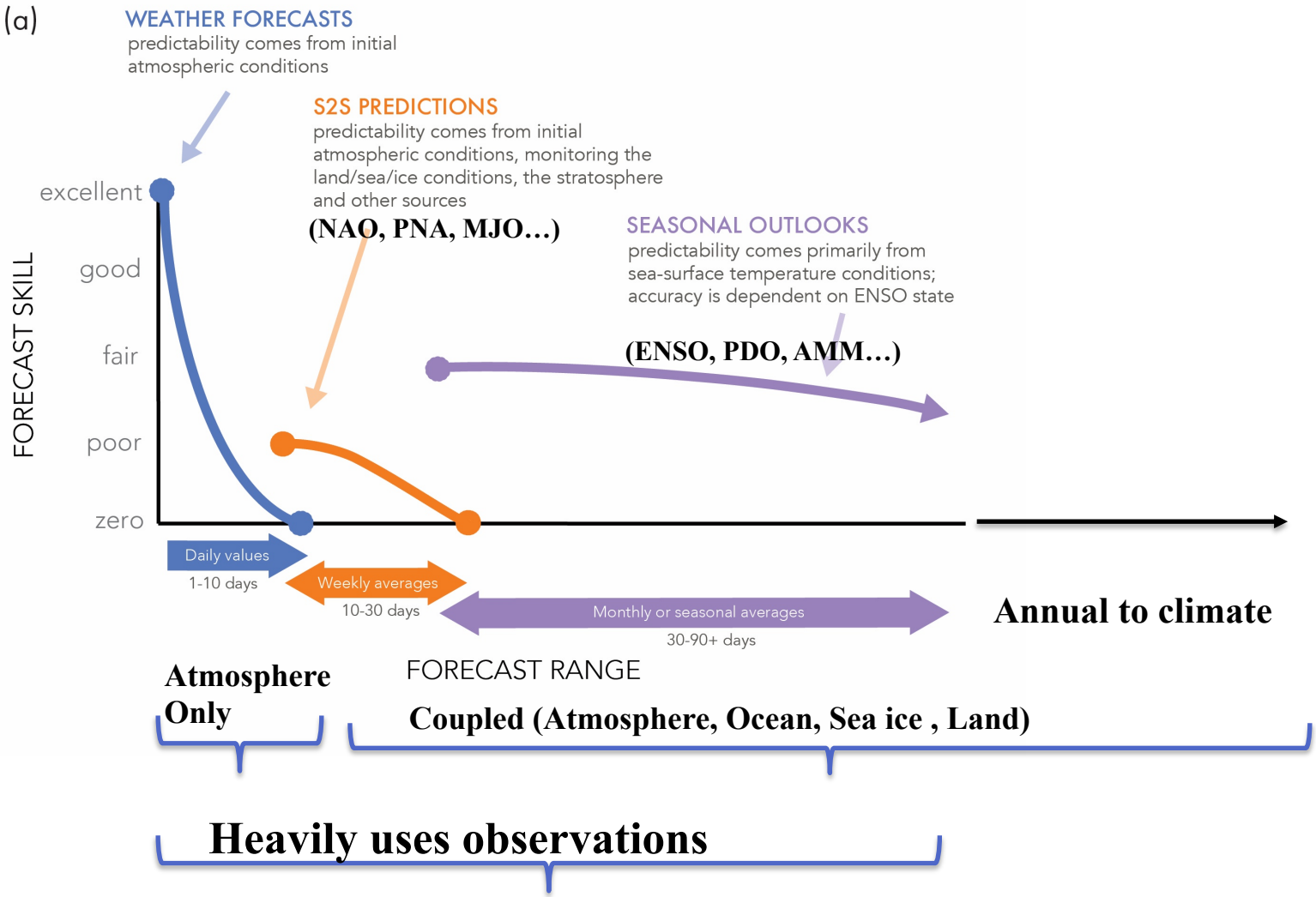
Outline

1. Interactive aerosol and seasonal prediction

2. Predictability of cloud droplet number concentration

3. Effect of aerosol-cloud interactions on prediction skill

Prediction Scales



Seasonal Prediction

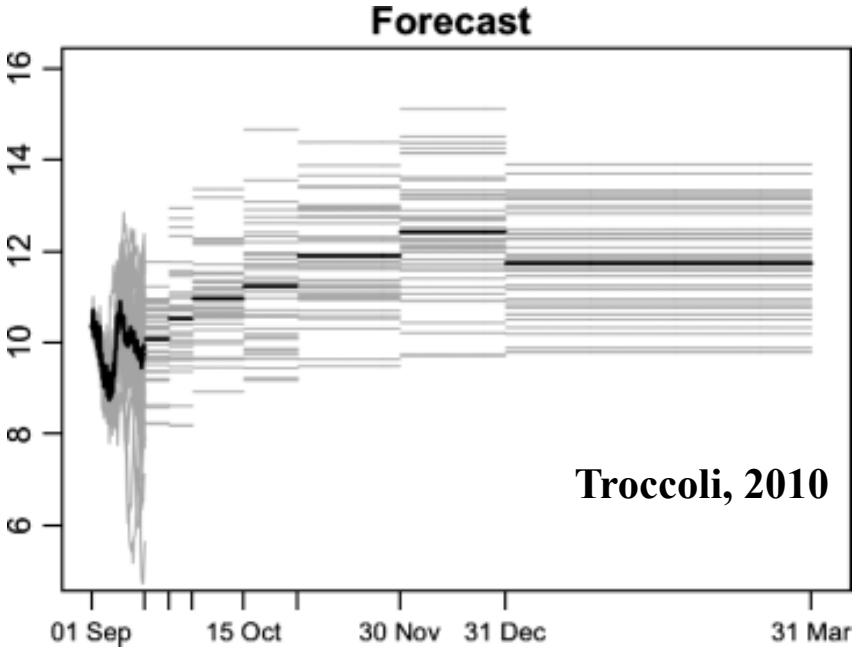
What is predictable at Seasonal Lead Times?

- **Time averages**
- **Spatial averages**
- **Probabilistic Measures (PDFs)**

Ensemble forecasts needed to predict PDFs, must assess reliability

Forecasts require calibration, or removal of mean bias or of mean bias and variance (standardization). For this we need reforecasts. Calibrated forecasts are more reliable.

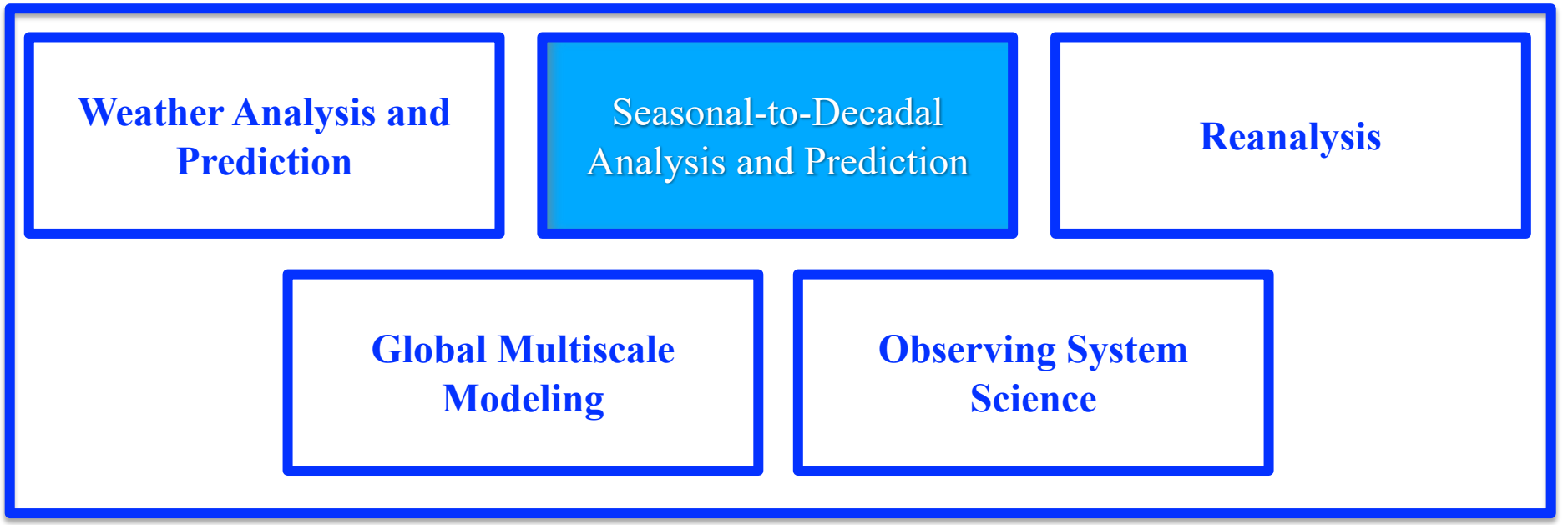
Multi model ensembles help (Krishnamurti et al., 1999; Palmer et al., 2004) skill, but not clear why. It does reduce overconfidence.



The longer the lead time, the longer the period of time average needed. This increases the signal to noise ratio enough to obtain reliable forecasts.

Slide adapted from Andrea Molod

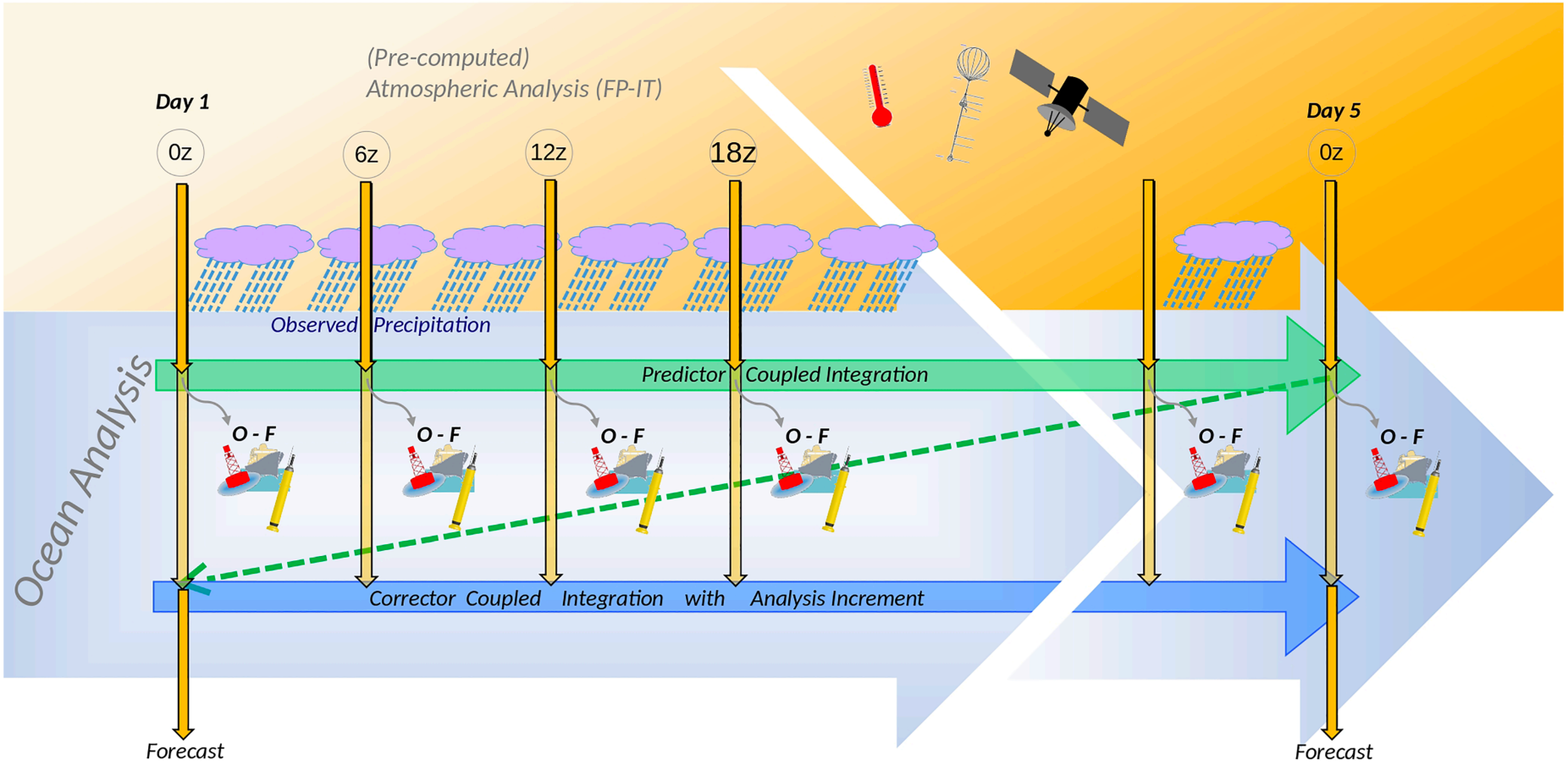
Major Activities in GMAO: from Research to Products



- These (non-orthogonal) themes span GMAO's main activities
- Guiding principle: NASA's Earth Observations (use, support, planning).
- Overall intent: to demonstrate added value of NASA's unique observations for weather analysis and prediction, reanalysis, and subseasonal-to-seasonal prediction.
- All themes include multiple elements of the Earth System

Slide adapted from Steven Pawson

Data Assimilation in Seasonal Forecasting



Molod et al., *JGR*, 2020.

GEOS S2S from Version 1 to Version 2

Table 2
Highlight of the Differences Between the Setup for the S2S-v1 (Middle Column) Versus GEOS-S2S-2 (Right Column)

Component	GEOS-S2S-1	GEOS-S2S-2
Atmosphere	Pre-MERRA-2 version, 1°, 72 vertical levels	Post-MERRA-2 version, 0.5°, 72 vertical levels
Ocean/sea ice model	MOM4.1, 0.5°, 40 layers down to 4,500-m depth, CICE 4.0	MOM5.0, 0.5°, 40 layers down to 4,500-m depth, CICE 4.0
Assimilation technique	SAFE/EnOI, 5-day IAU	LETKF, 18-hr IAU
Forecast error	Prespecified static forecast error covariance from leading EOFs of an ensemble of forecast anomalies (with respect to climate drift) from AOGCM	Estimate evolving errors using monthly averaged anomalies from 20 freely coupled AOGCMs recentered about analysis
Data	10-day window, binned to model level, reject if > 6σ from WOA09, observational error prescribed to observation and type, decor-relation scales x, y, z, t function of variable, unique vertical localization factors applied for each observation and type	5-day window, binned to model level, reject if > 6σ from WOA13, observational error from $\frac{dT,S}{dz}$ or $\frac{dADT}{d(alongtrackdist.)}$, horizontal location applied $\propto$ Rossby deformation radius, no vertical localization applied
Assimilation sequence	Tz, Sz Clim (SAFE) SSS Clim (SAFE) SST (SAFE) Tz (EnOI) Sz (EnOI) AICE	Tz, Sz, ADT
Relaxation Vars	None	SST (1-day), AICE (insertion)
Replay forcing	MERRA corrected using GPCP) (< Sep 2009), CMAP (Sep 2009 to present	"MERRA-2 like" (FPIT) corrected using CMAP precipitation

	GEOS-S2S-1	GEOS-S2S-2
Aerosol	Climatological	Interactive Single-moment (GOCART)
Cloud Microphysics	Single moment	Two-moment for Convective (B14) and Stratiform (MG08)

GEOS-S2S is an atmosphere-ocean coupled system used operationally for seasonal prediction at the spatial resolution of 0.5° (atmosphere and ocean).

The latest version GEOS-S2S system implements interactive aerosol transport as well as a two-moment cloud microphysics scheme (Barahona et al. 2014) therefore it is suitable for studying the effect of aerosol-cloud interactions on climate.

Molod et al., *JGR*, 2020.

Interactive Aerosol in Seasonal Prediction

- **Reasons for interactive aerosol:**
  - Increase skill in AOD/PM2.5 seasonal forecasts than a climatology (Benedetti and Vitart, 2018 for AOD)
  - May increase weather/subseasonal skill under certain conditions (forecasts of opportunity) such as the impact of dust on tropical cyclone development. (eg., Reale et al., 2011, Nowotttnick et al. 2017, both using GMAO NWP system)
  - May increase seasonal skill in the aftermath of a large volcanic event (eg., Aquila et al 2019 using GMAO-S2S-2 system)
  - May increase subseasonal forecast skill (Benedetti and Vitart, 2018)
  - May have an impact on decadal prediction skill (Bellucci et al., 2015)

GMAO S2S version-2 is the only model participating in either NMME or SubX or WCRP S2S (i.e., near real-time forecasts on sub/seasonal scale) that has been running with interactive aerosol model and 2-moment microphysics that includes the direct, semi-direct and indirect aerosol effect.

Slide adapted from Andrea Molod

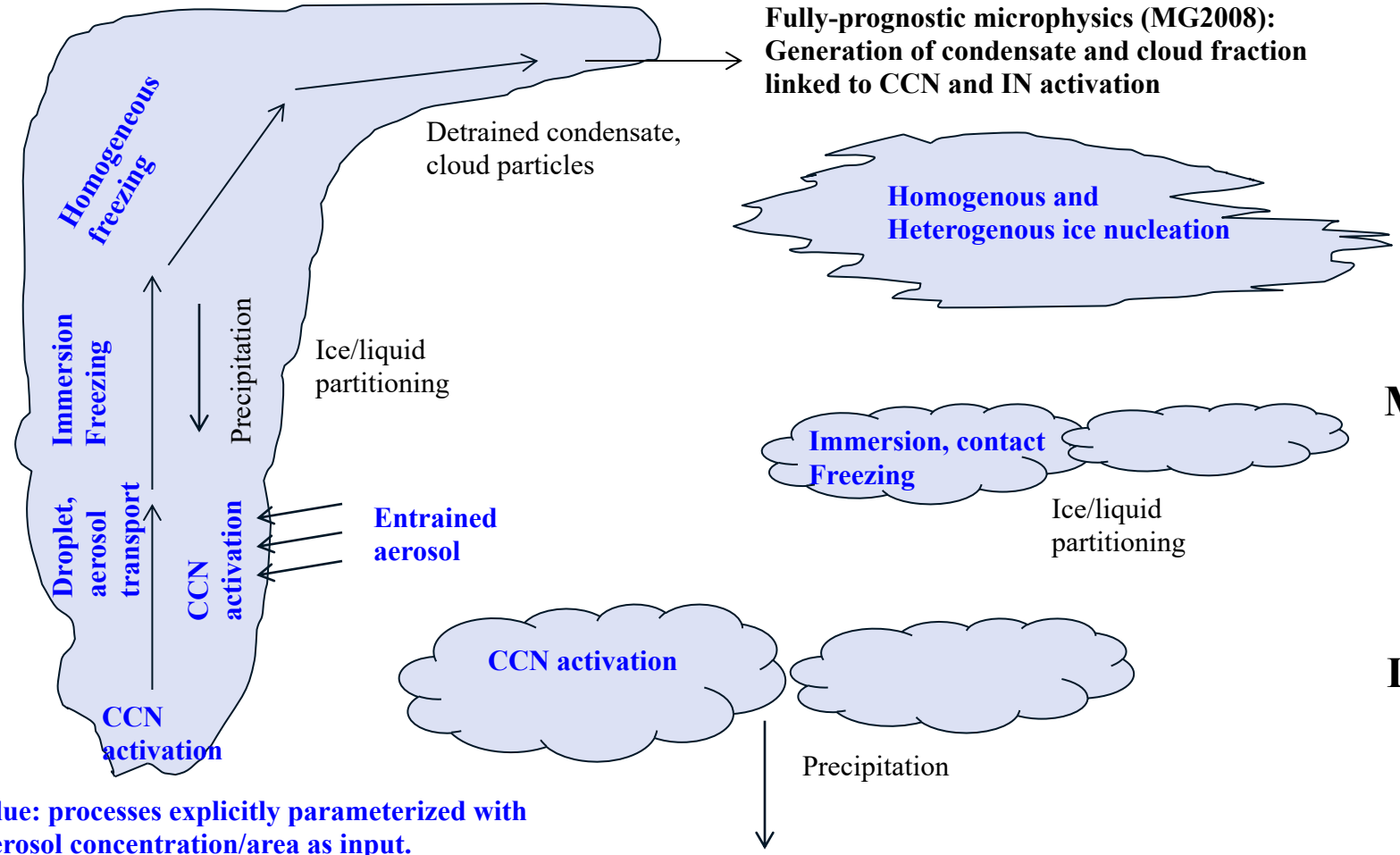
Aerosol-Cloud Interactions in GEOS-5

Convective

Semi-prognostic microphysics: Aerosol affects Rain formation and phase partitioning. Linked to CCN and IN activation.

Stratiform

Fully-prognostic microphysics (MG2008): Generation of condensate and cloud fraction linked to CCN and IN activation



Blue: processes explicitly parameterized with aerosol concentration/area as input.

Bias: Aerosol Optical Depth (2000-2015)

GEOS-S2S-2 (1-month lead ensemble)

Bias against MERRA-2

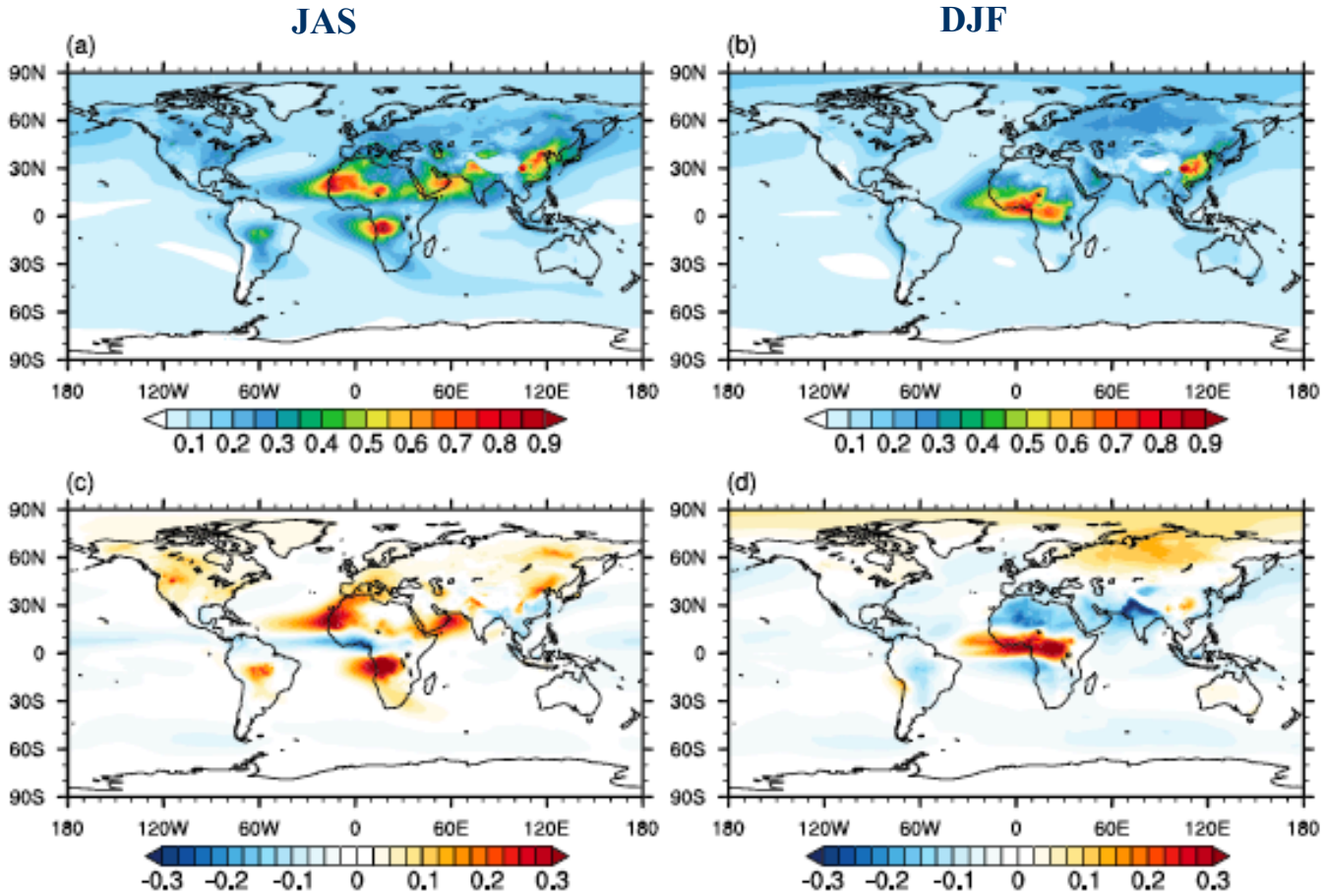


Figure 20. (a) Spatial distribution of aerosol optical depth (AOD) at 550 nm in July-August-September and (b) December-January-February, averaged for the period 2000–2015 from the GEOS-S2S-2 ensemble mean. (c) Like (a) but GEOS-S2S-2 minus MERRA-2 AOD; (d) like (b) but GEOS-S2S-2 minus MERRA-2 AOD. Global mean difference from MERRA-2 in JAS is 0.11 and in DJF is −0.05.

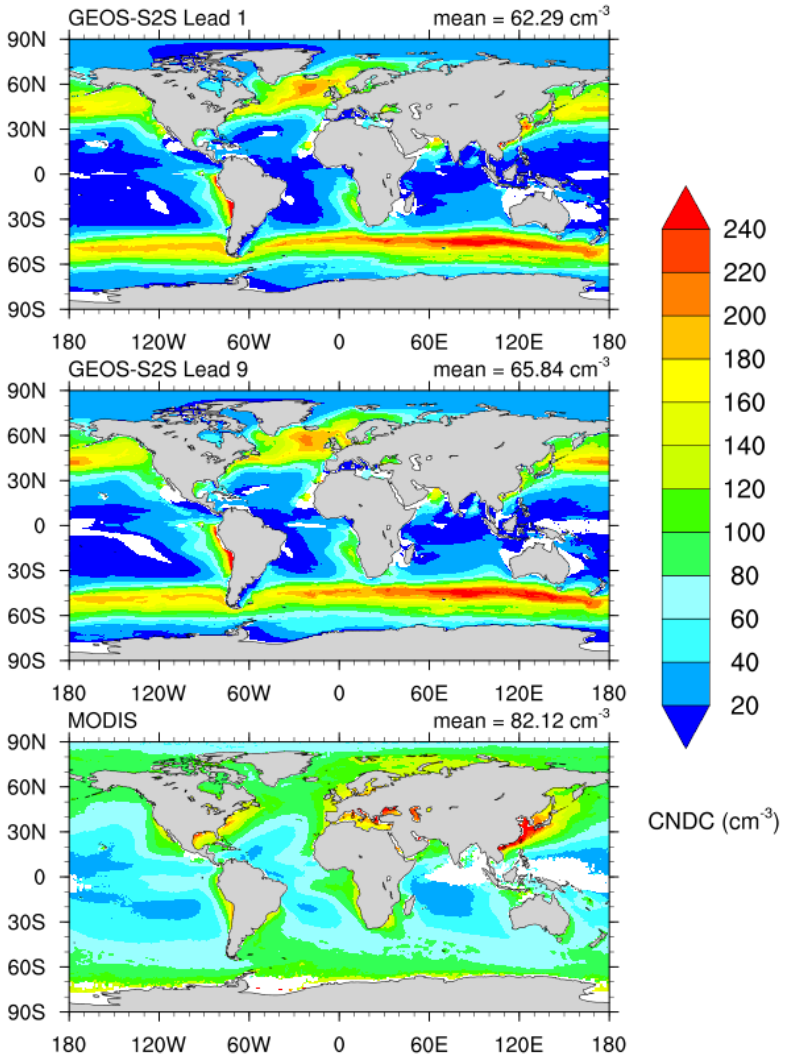
Molod et al., *JGR*, 2020.

Cloud Droplet Number Concentration (2003-2015)

GEOS-S2S-2 (1-month lead ensemble)

GEOS-S2S-2 (9-month lead ensemble)

MODIS (Bennartz et al. 2017)



Comparison against MODIS-retrieved CDNC (Bennartz, et al. 2017) suggest a reasonable skill of the model in reproducing the global mean CDNC with notable exceptions at the high latitudes of both hemispheres.

Some small changes in global mean CDNC between time leads 1 and 9, although with important local differences.

Sampling of the model may bias the satellite-model comparison since only adiabatic extended stratocumulus are included in the retrieval.

Barahona, Molod and Borovikov. 2020, *in prep.*

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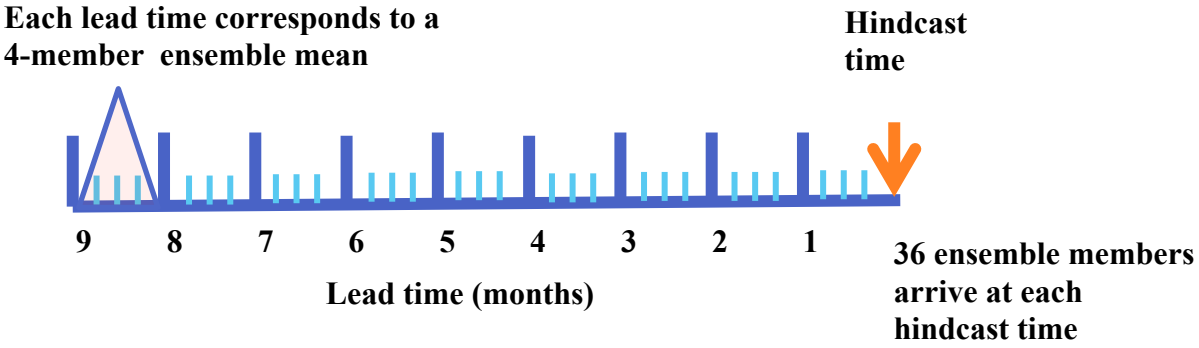
3. Effect of aerosol-cloud interactions on prediction skill

Droplet Number Concentration Predictability

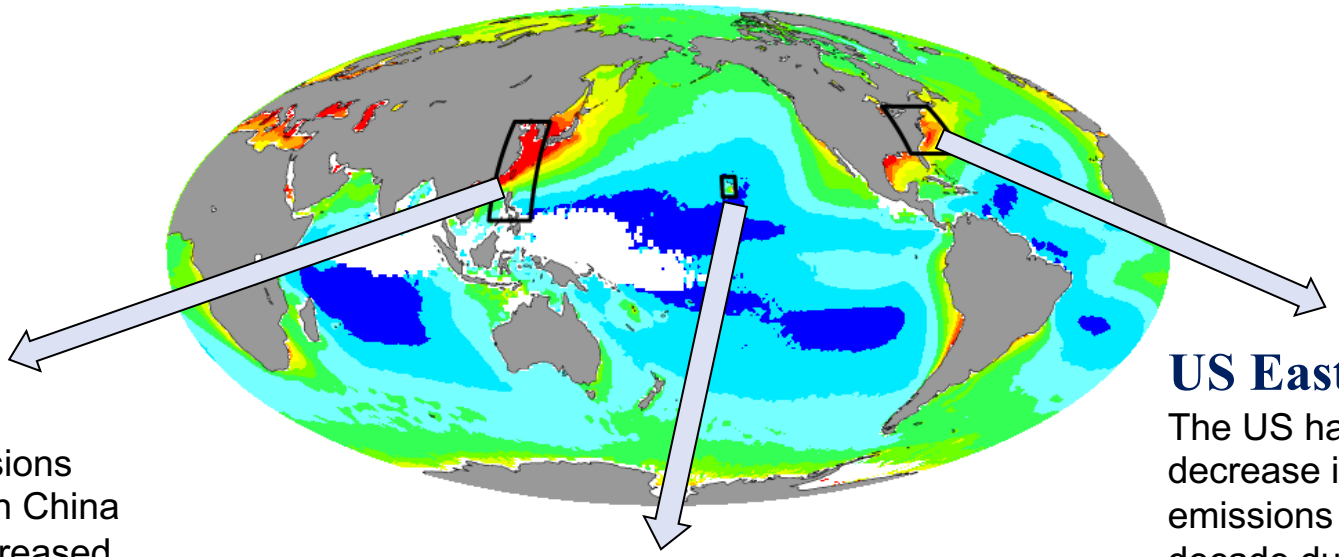
What does our seasonal prediction system tell about the predictability of droplet number concentration in warm stratocumulus?

Method:

We use a set of 35 year (1980-2015), four ensemble member, 9 month lead retrospective forecasts (initialized using MERRA-2 and GEOS-S2S-V1, Gelaro et al. 2016) simulations of the NASA GEOS seasonal prediction system (GEOS-S2S-V2), to study the evolution of CDNC in in different regions where aerosol emissions may exert significant control on cloud properties.



Droplet Number Predictability – Regional Analysis



East Asia

Aerosol emissions over the South China Sea have decreased over the past decade, and it may be reflected in reported CDNC trends.

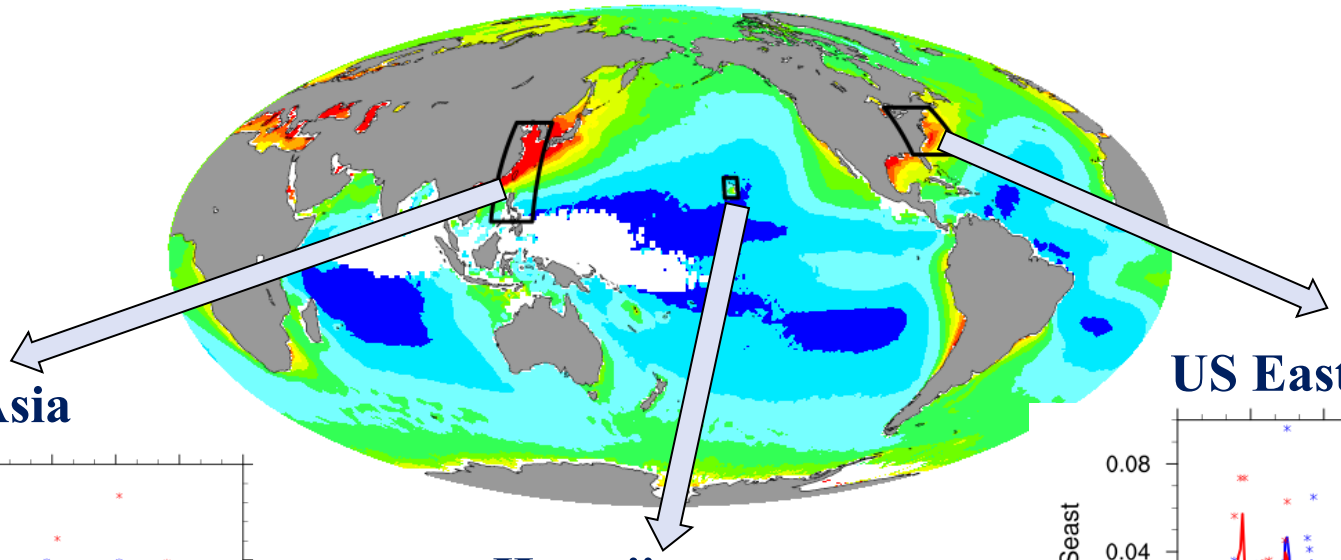
Hawaii

Here the Kilauea crater is a continuous source of sulfate aerosols in an otherwise pristine region. This is typically reflected in modified cloud properties (Yuan et al. 2011, Breen et al. 2020).

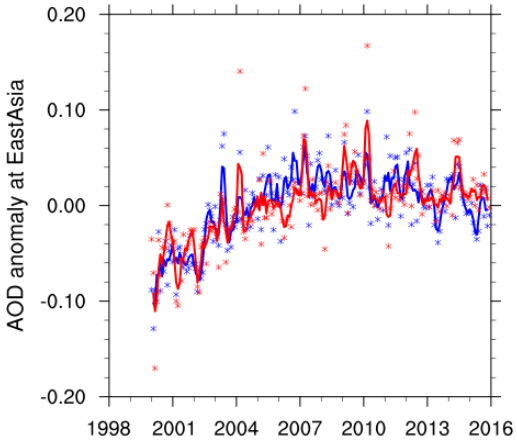
US East Coast

The US has seen a decrease in aerosol emissions during the last decade due to better emission standards and improved technology. CDNC has decreased as a result (McCoy et al. 2018).

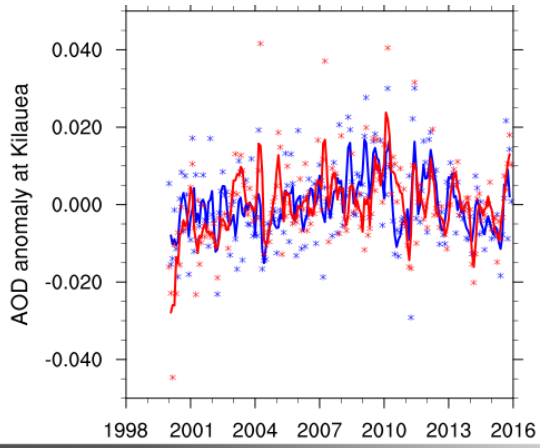
AOD Anomaly



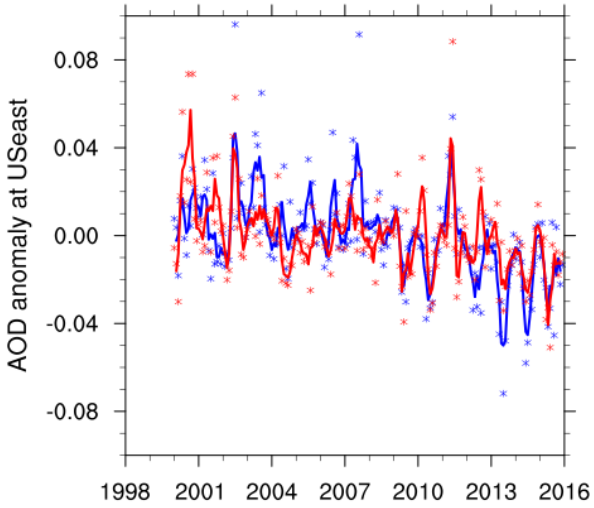
East Asia



Hawaii



US East Coast

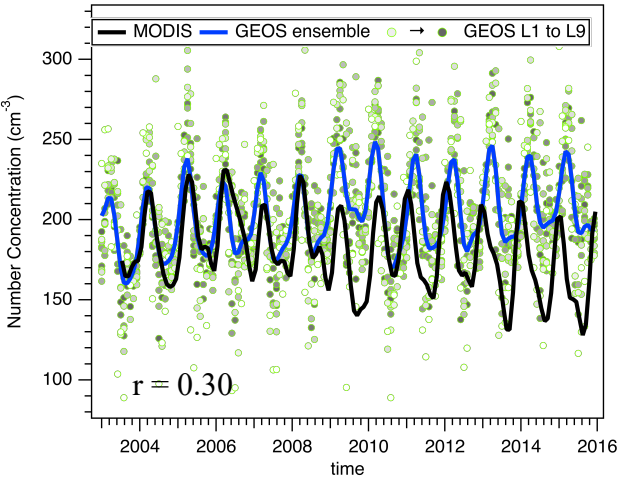


Blue: MERRA-2
Red: GEOS S2S V2-Lead 1

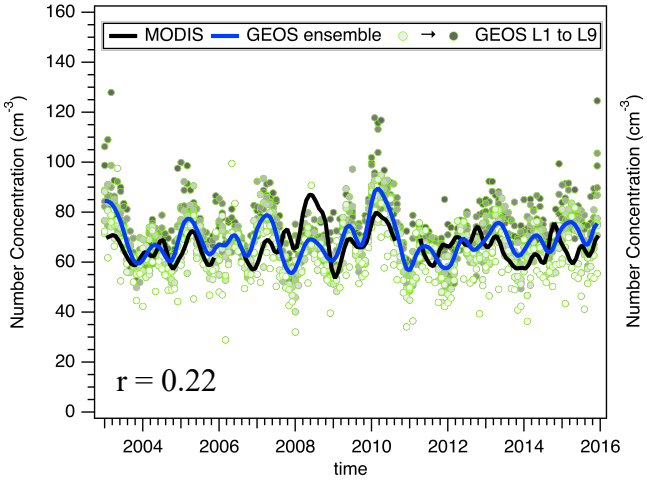
Lines correspond to 3-month running average

CDNC in GEOS Reforecast Ensemble

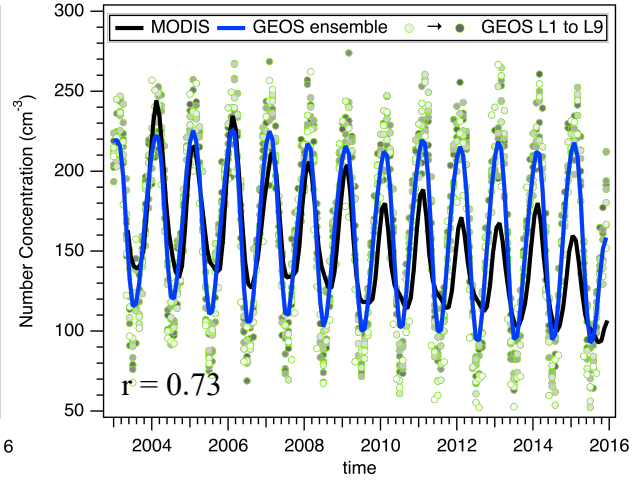
East Asia



Hawaii



US East



Black: MODIS (Bennartz et al., 2017). Lines correspond to 3-month moving average.
Blue: GEOS S2S V2-Ensemble mean
Green: individual ensemble members (darker color correspond to longer lead times)

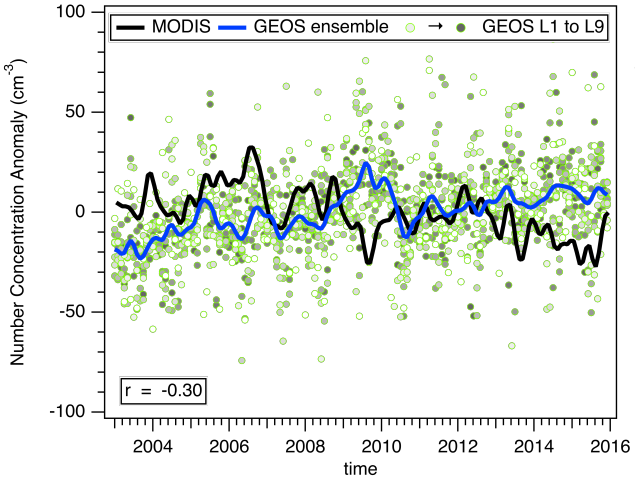
The GEOS S2S ensemble reasonable reproduces the mean CDNC in each region. Average trend seems to be captured only in the US.

It also captures the seasonal CDNC cycle in the midlatitudes (East Asia and US, likely driven by anthropogenic SO_2 emissions), however variability is high and the amplitude is larger than MODIS, particularly in the US.

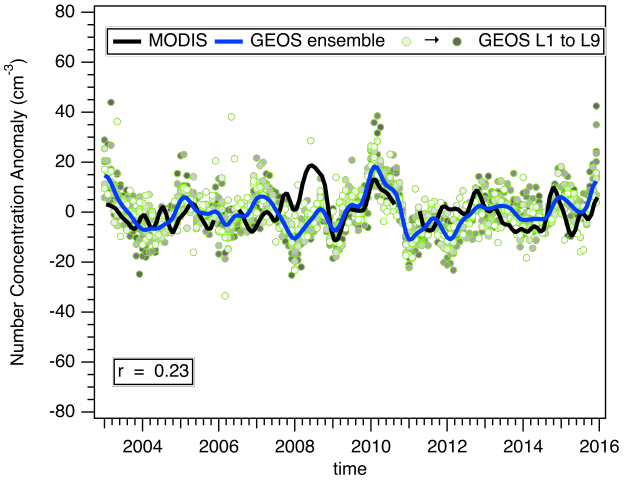
Barahona, Molod and Borovikov. 2020, *in prep.*

CDNC Anomaly

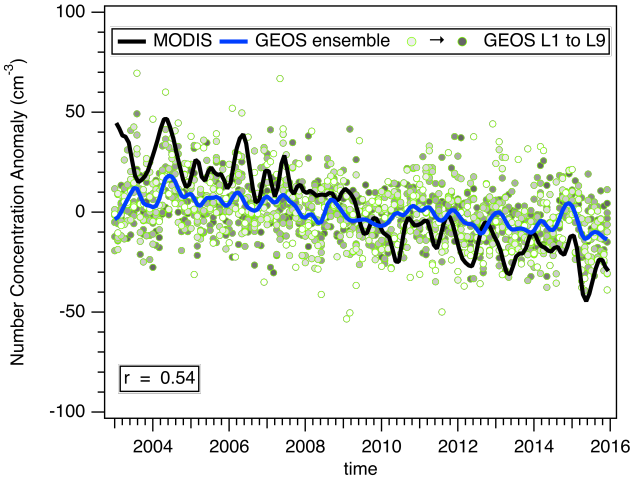
East Asia



Hawaii



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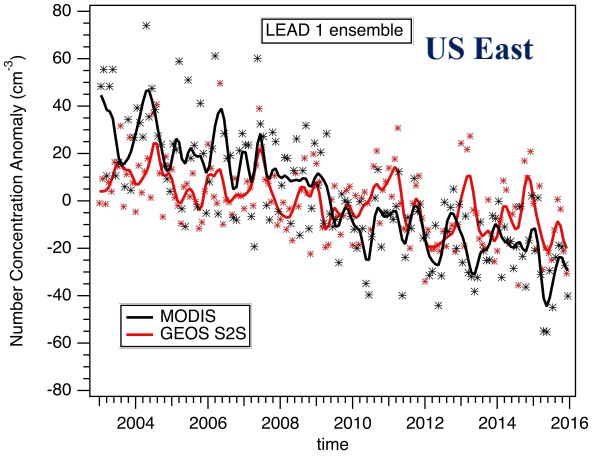
Only in the US the GEOS S2S ensemble captures the average (although somehow weaker) trend in CDNC anomaly.

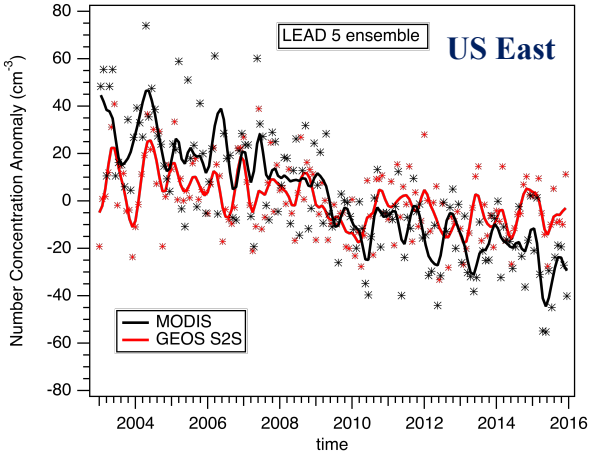
The lack of correlation in East Asia may be due to a larger role of convection in the region.

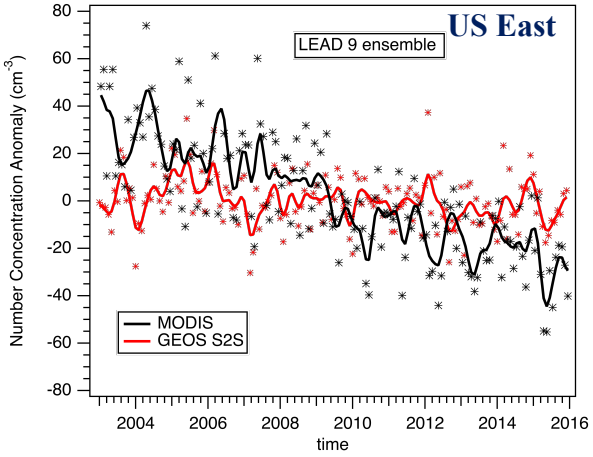
Surprisingly, some positive correlation is retained in Hawaii. This may be due to the long-lasting effect of volcanic emissions (see the 2008 event that shows up in 2009) and may be important for ENSO.

Barahona, Molod and Borovikov. 2020, *in prep.*

Anomaly vs. Lead Time (US East)





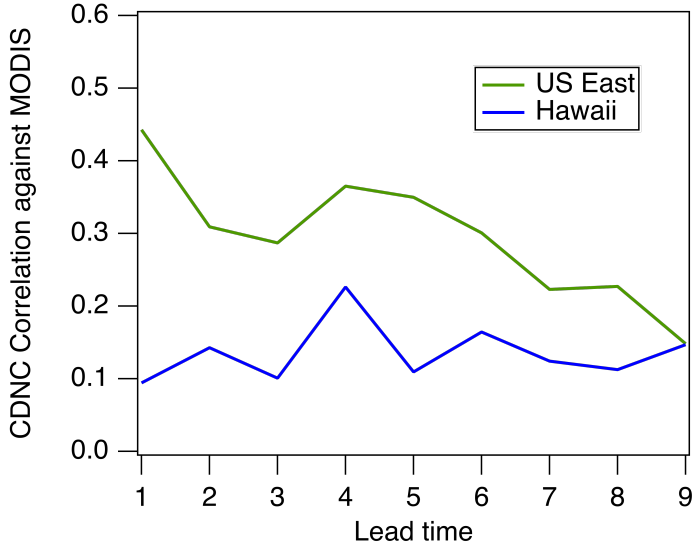


In general skill decreases for longer lead times.

The correlation falling below certain threshold may be a measure of predictability.

Even for the best case (US East) skill drops quickly after lead 2 (bump at lead 5 may be due to seasonality).

This indicates that emissions should be updated every month.



Barahona, Molod and Borovikov. 2020, *in prep.*

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What about Forecast Skill?

Does including aerosol-cloud interactions in the GEOS S2S impact/improve seasonal prediction skill?

WGNE-S2S-GAW (WCRP Working Group on Numerical Experimentation-Subseasonal to Seasonal Project-Global Atmospheric Watch) Phase 2 will ask models to run retrospective forecasts with interactive aerosols. GMAO will participate.

Problem: Elucidate an appropriate, no aerosol-cloud interactions, control run. Model can't run without ACI.

Strategy	Issue
Fixed aerosol climatology	ACI corresponds to climatology.
Use a fixed number concentration	Mean state may differ strongly from control. Other processes not considered.
Develop a climatology from full model	Although mean state is closer to control, cloud fraction and ice/liquid partitioning must be prescribed.

Conclusions and Outlook

- Seasonal predictions systems may benefit from explicit inclusion of interactive aerosol and aerosol-cloud interactions (ACI).
- The GEOS-S2S-v2 ensemble shows skill in reproducing observed mean cloud droplet number both globally and regionally.
- GEOS-S2S-v2 has some skill in reproducing the CDNC anomaly at the US east coast but lacks skill at Hawaii and East Asia.
- It is likely that CDNC is not predictable beyond lead 1, indicating the need for almost real time emissions and/or predictive approaches.
- Question remain on the effect of ACI on forecast skill. Comparison between retrieved CDNC and model output is ambiguous, and statistical significance must be assessed.