Sub/seasonal forecasts with a coupled interactive aerosol model in GEOS-S2S

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Outline:

- **Motivation for interactive aerosol and aerosol-cloud feedback in seasonal prediction**
- **Protocol for WCRP/S2S Aerosol Subproject intercomparison**
- **Seasonal prediction of aerosol/cloud droplet number**
- **(Preliminary) Impact of Interactive aerosol on meteorological forecasts**

GEOS-S2S-2 Used for Aerosol Intercomparison Experiments

Model

- AGCM: ~0.5 deg, recent GMAO NWP (including aerosol model) + two-moment cloud microphysics
- OGCM: MOM5, ~0.5 deg, 40 levels
- Sea Ice: CICE-4.0

- Retrospective forecasts: initialized from weakly coupled data assimilation, no assimilation of aerosol

	Subseasonal	Seasonal
Length of Forecast	45 days	9-12 months
Frequency of forecasts	Every 5 days	Every 5 days
Number of Ensembles	4 per start date	Total of 10 per month
Frequency of submission	Once per week	Once per month
Initial Conditions from	GEOS ODAS	GEOS ODAS
Hindcasts	1999-2016	1980-2016/7

GEOS-S2S-2 was released in November, 2017 (Molod et al., 2020)

Unique to GEOS-S2S: Why Interactive Aerosol Model?

- There may be more useful skill in AOD/PM2.5 seasonal forecasts than from a statistical model or 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)
- May increase seasonal skill in the aftermath of a large volcanic event (eg., Aquila et al 2020).
- May increase subseasonal forecast skill (Benedetti and Vitart, 2018)
- Has a feedback with the MJO and so may effect subseasonal skill (Tian et. Al., 2008, 2011)
- Postulated to have an impact on decadal prediction skill (Bellucci et al., 2015)

Community Activity/Interest in Interactive Aerosol Models

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

GMAO has developed a protocol to use a two-moment cloud microphysics scheme with climatological aerosol and will participate in the intercomparison.

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

A few other groups (ECMWF) have run retrospective forecasts to assess the impact of an interactive aerosol model on sub/seasonal forecasts, but include the direct effect only, no semi- or indirect.

WGNE-S2S-GAW Experiment Protocol

The experiments will consist of a set of runs that include:

- **“Control” – specify observed aerosol amount**
- **“Climatological” – specify climatological aerosol amount**
- **“Interactive” - perform simulations with an interactive aerosol model**
- **“Indirect” – perform simulations with an interactive aerosol model and a two-moment cloud microphysics (Optional)**

Verification: CAMS or MERRA2 for aerosol ERA5 for weather/climate

http://s2sprediction.net/xwiki/bin/view/Phase2/Aerosol#Attachments

WGNE-S2S-GAW Experiment Protocol

Table 2: List of experiments to be conducted in the global domain, for subseasonal prediction purposes, considering the period of simulations, the total number of experiments, the total hours of forecasts, the minimum number of ensemble members and simulation length.

Aerosol events	Re-forecast Period (2016-2019)	Total number of experiments	Effects to be analyzed	Minimum Number of ensemble members	Simulation length (in days)
Dust	May Optional: April and June	2 (3 optional)	Direct Indirect (optional) Climatological	5	32
Smoke	September Optional: August and October		Direct Indirect (optional) Climatological		
Pollution	January Optional: December and February		Direct Indirect (optional) Climatological		

Re-forecast period: 2003–2019
Timeline to deliver model outputs: End of 2021.

http://s2sprediction.net/xwiki/bin/view/Phase2/Aerosol#Attachments

GMAO Experiments with GEOS-S2S-2

Protocol for "Control" simulations using Model with Two-moment cloud microphysics

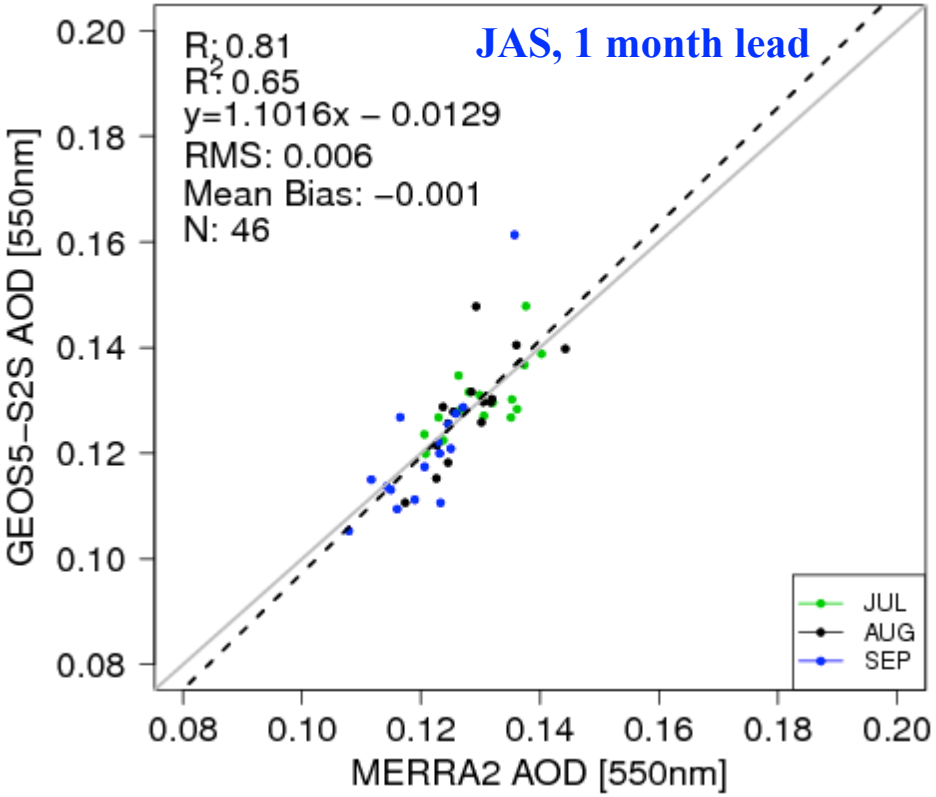
Potential Strategy	Issue
Simply use specified aerosol	"Re-use" of aerosol creates extremely excessive cloud cover
Specify a fixed cloud droplet/ice number concentration	Mean state may differ strongly from Interactive Direct+Indirect
Develop and use a CDNC/INC monthly climatology from forecasts with Interactive, Direct+Indirect	Allows seasonal and geographic variations of CDNC/INC, simulation closer to Interactive, Direct+Indirect

List of Experiments with GEOS-S2S-2

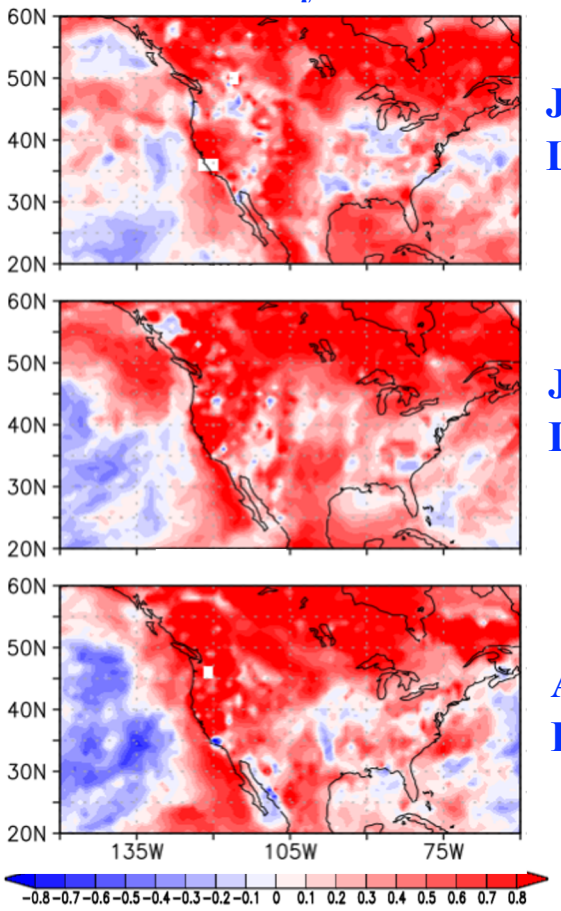
Protocol Name	GEOS-S2S-2 Experiment Name
"Control"	**Observed, Direct (OD)**
"Interactive"	**Interactive, Direct (ID)**
"Indirect"	**Interactive, Direct+Indirect (IDI)**

"Direct+Indirect" Experiment: Seasonal prediction of AOD/PM2.5

Global Mean Aerosol Optical Depth (2000-2015)

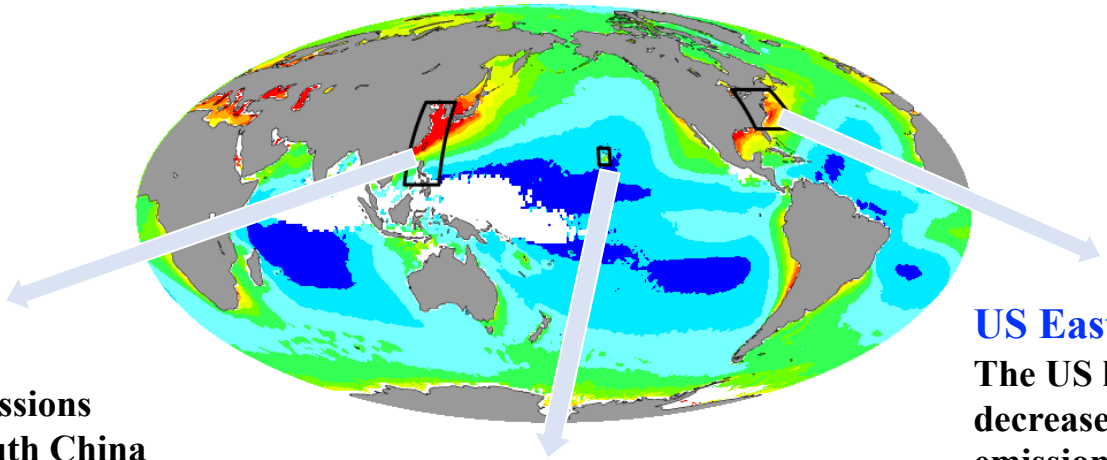


PM2.5 Anomaly Correlation



Result from: Freire et al., 2020; Analysis of Zhao Li

Seasonal prediction of AOD/Droplet Number: Regional



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

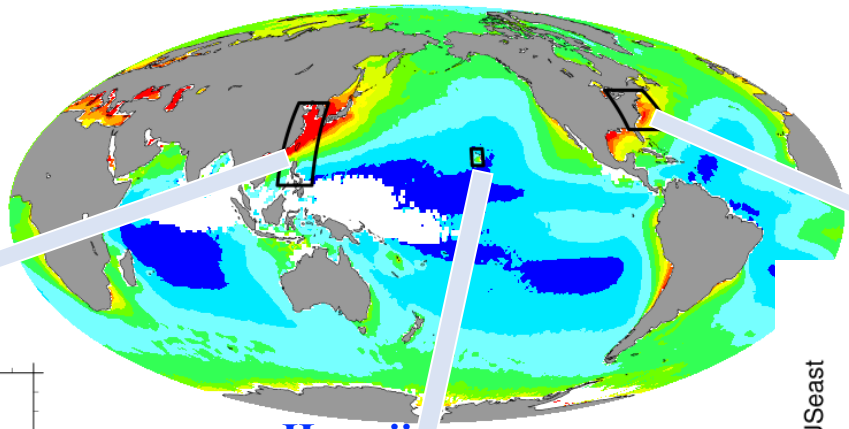
Here the Kilauea crater is a continuous source of sulfate aerosols in an otherwise pristine region. This is typically reflected in modified cloud properties (Yuan et al. 2011, Breen et al. 2020).

US East Coast

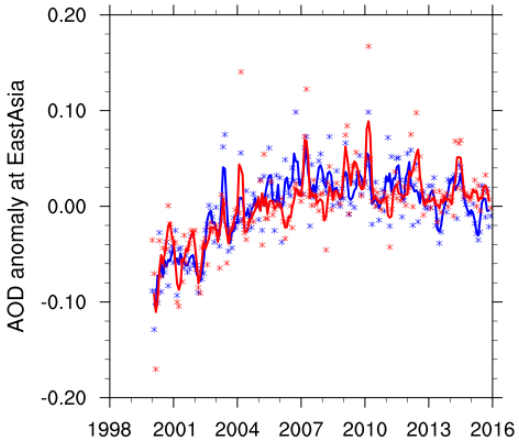
The US has seen a decrease in aerosol emissions during the last decade due to better emission standards and improved technology. CDNC has decreased as a result (McCoy et al. 2018).

Seasonal prediction of AOD Anomaly: Regional

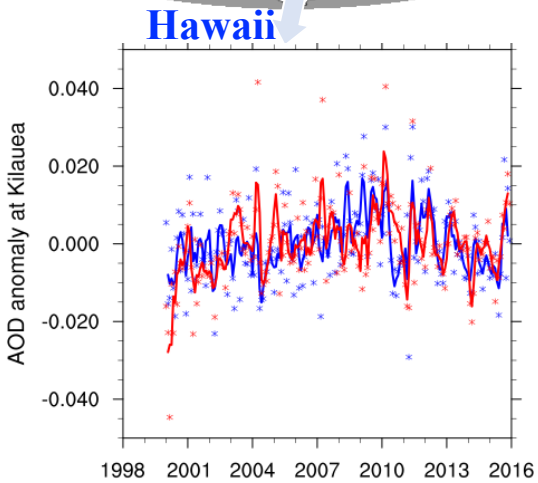
Blue: MERRA-2
Red: GEOS S2S V2-Lead 1



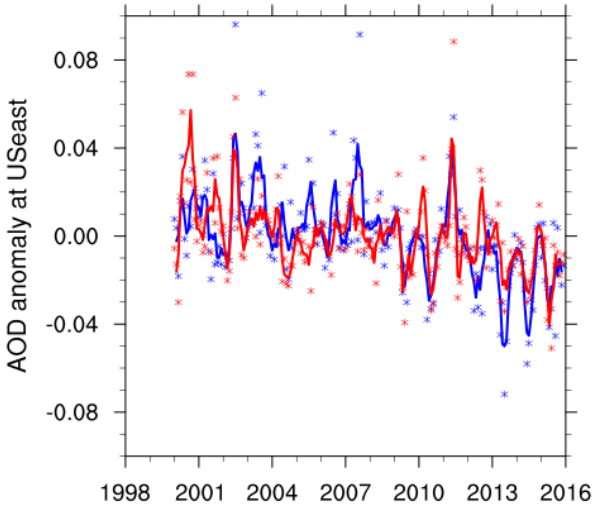
East Asia



Hawaii



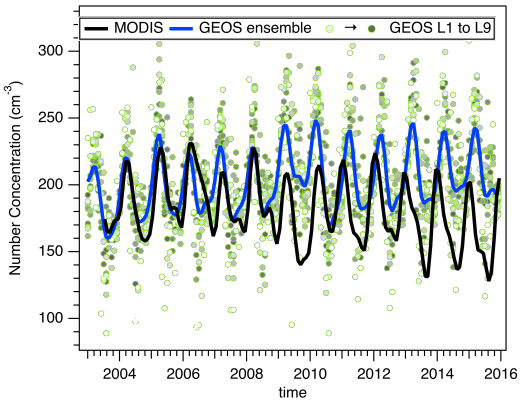
US East Coast



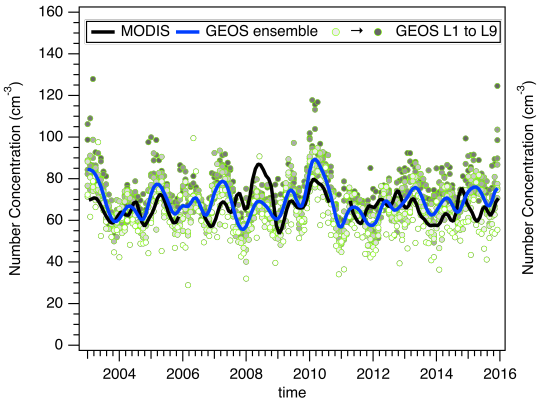
Lines correspond to 3-month running average

Seasonal prediction of CDNC Mean: Regional

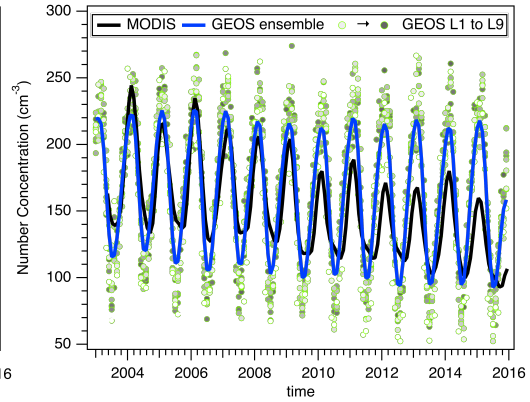
East Asia



Hawaii



US East



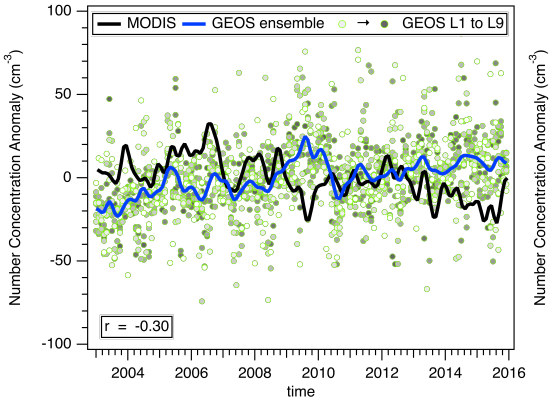
Blue: GEOS S2S V2-Ensemble mean ; Black: MODIS; Green: Individual Members

The GEOS S2S ensemble reasonably reproduces the mean CDNC in each region. The average trend is captured in the US but not in East Asia.

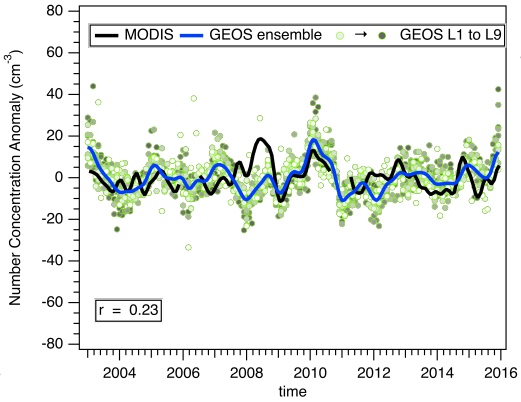
GEOS-S2S also captures the seasonal CDNC cycle in the midlatitudes (East Asia and US, likely driven by anthropogenic SO_2 emissions), however, the variability is high and the amplitude is larger than MODIS, particularly in the US.

Seasonal prediction of CDNC Anomaly: Regional

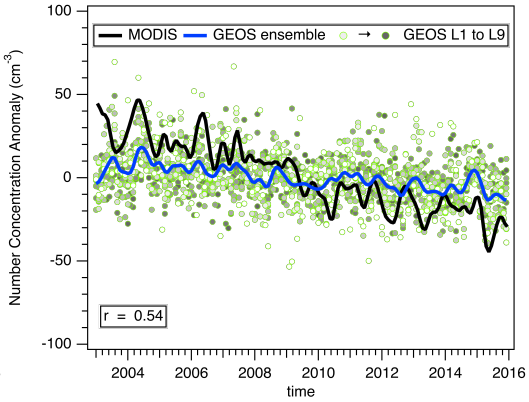
East Asia



Hawaii



US East



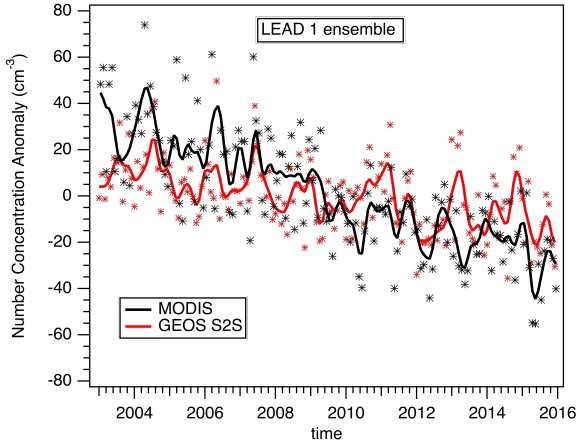
Blue: GEOS S2S V2-Ensemble mean ; Black: MODIS; Green: Individual Members

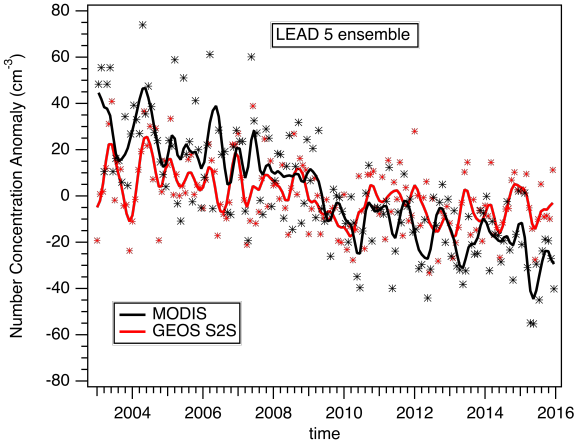
Only in the US does GEOS-S2S capture the (although somehow weaker) trend in CDNC anomaly.

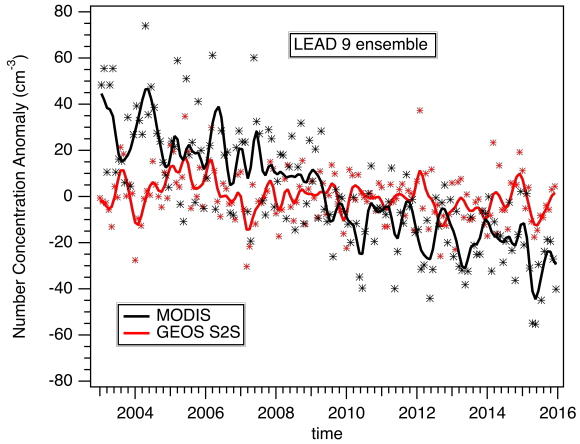
The lack of correlation in East Asia may be due to a larger role of convection in the region.

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.

Seasonal prediction of CDNC Anomaly: Impact of Lead Time



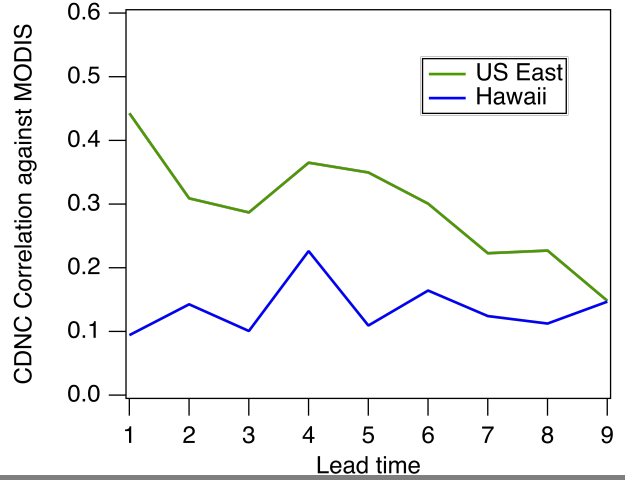




In general skill decreases for longer lead times.

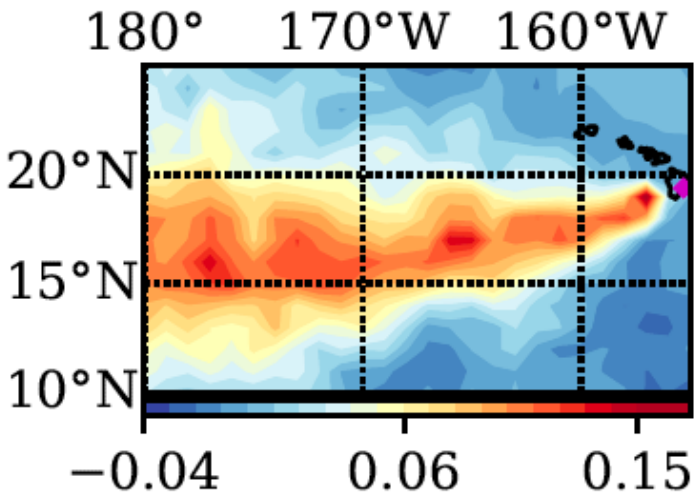
The correlation falling below certain threshold may be a measure of predictability.

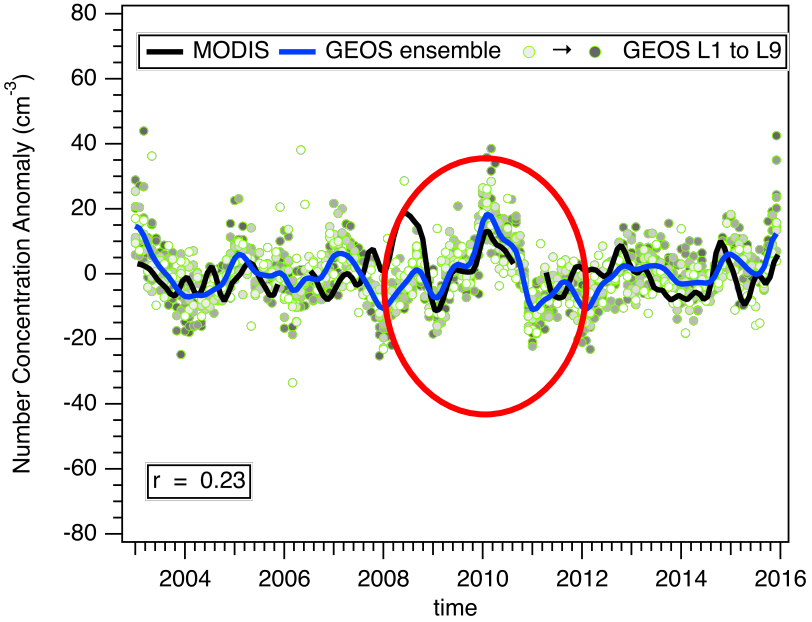
Even for the best case (US East) skill drops quickly after lead 2 (sharp drop at lead 5 may be due to seasonality).



Seasonal prediction of CDNC Anomaly: Forecasts of Opportunity

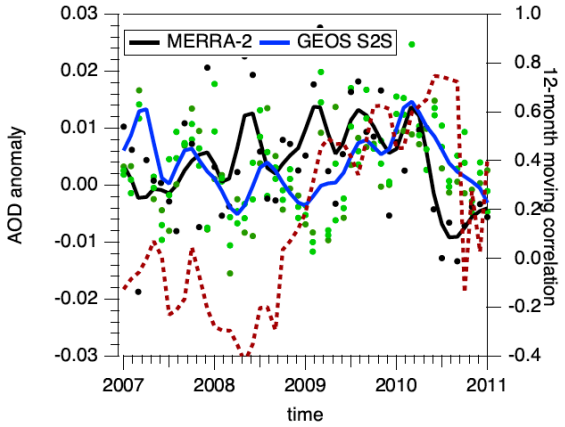
Forecast skill and predictability is not static but dynamic, modulated by certain conditions.
There likely exist aerosol-related forecast of opportunity periods from direct and indirect effects

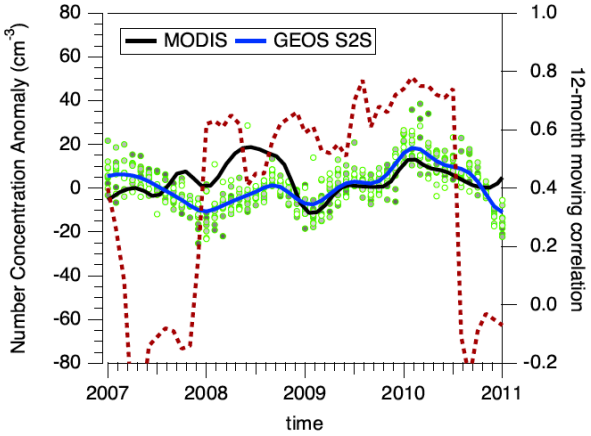


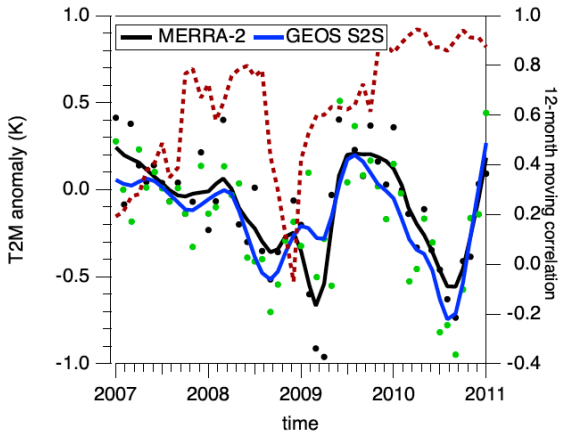


Strong Kilauea degassing event between June 2008 and April 2010: Potential FOO after degassing.

Seasonal prediction of CDNC Anomaly: Forecasts of Opportunity

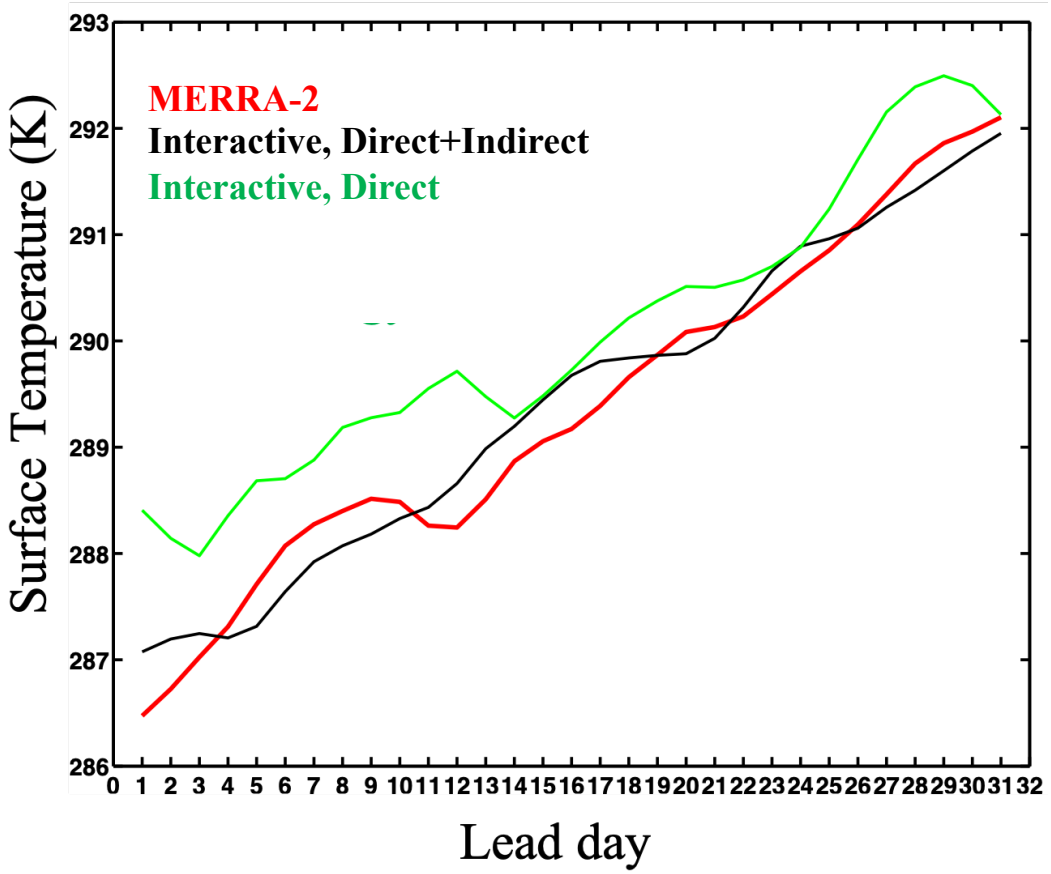






The 2008-2010 event coincides with high correlation (dashed red lines, right vertical axis) of AOD, cloud droplet number and 2m-temperature between the GEOS-S2S ensemble and MODIS/MERRA-2 in the tropical Pacific.

Impact of Aerosol-Cloud Feedback on T2M



Experiments:

1) **Interactive, Direct+Indirect**
2) **Interactive, Direct**
3) **Observed Aerosol, Direct**

Result from comparison of 1) and 2):

The North American surface temperature in the retrospective forecasts with the interactive aerosol and aerosol-cloud interactions is closer to MERRA-2 than the surface temperature in the forecasts without aerosol-cloud interactions at short lead times.

Summary and Outlook

- **Seasonal prediction systems may benefit from inclusion of interactive aerosol and aerosol-cloud interactions – inclusion of both enables prediction of aerosol and may enhance overall skill**

- **The Weather Research Science Working Group (WRSWG) S2S Subgroup and the S2S Prediction Project for the Aerosol subproject encourage participation in the WGNE-S2S-GAW intercomparison! Contact US liaison for help/discussion: andrea.molod@nasa.gov**

- **The GEOS-S2S-2 ensemble shows skill in reproducing observed mean AOD and cloud droplet number concentration (CDNC) both globally and regionally.**

- **GEOS-S2S-2 has some skill in reproducing the CDNC anomaly at the US east coast but lacks skill at Hawaii and East Asia.**

- **Forecasts of opportunity exist where correlations are higher than average.**

- **Preliminary results suggest a positive impact of aerosol-cloud interactions on surface temperature**

- **Complete analysis of the impact of interactive aerosol and aerosol-cloud interactions on forecast skill of important meteorological quantities**