Navy Aerosol System Science and Development for Operations

http://www.nrlmry.navy.mil/aerosol/

11th ICAP Working Group
Tsukbah Japan
July, 2019

Send comments
Jeffrey S. Reid, US Naval Research Laboratory
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Overview

- Overview of peoples and systems
- Systems update
  - Deterministic
  - Ensemble
  - Reanalysis
- Major projects: CAMP^{2}Ex, PISTON, MURI, C-FOG
- Navy aerosol literature highlights from the last year

Navy Sponsored Aerosol Development for Operations Community

NRL Monterey (Marine Meteorology)

Anthony Bucholtz: Radiation, tactical decision aids
Chris Camacho: Software engineering
James Campbell: Cirrus, lidar studies
Edward Hyer: Satellite data, biomass burning , transitions
Kathleen Kaku (CSRA): Air quality, chemistry
Arunas Kuciauskas: Dust systems
Ming Liu: Inline NAVGEM aerosol
David Peterson: Fire meteorology, biomass burning
Elizabeth Reid: Deployments and analysis
Jeffrey Reid: Applied meteorology & aerosol
Benjamin Ruston: Dust Infrared impacts on DA
Mindy Surratt: Remote sensing
Annette Walker: Mesoscale aerosol & dust sources
Doug Westphal: Emeritus
Peng Xian: ICAP-MME, NAAPS reanalysis

NRL Washington DC (Remote Sensing)

Maggie Anguelova: Microwave retrievals
Josh Cossuth: Remote sensing systems
Juli Rubin: Ensemble systems
Ivan Savelyev: Sea Salt production

Key ONR Programs

HAALE: Littoral zone aerosol prediction S. Miller (CSU, PI), S. Albers (CIRA), R. Holz (SSEC), S. Kreidenweis(CSU), S. van den Heever(CSU), J. Wang(UI), J. Zhang (UND), and M. Zupanasky (CIRA)
C-FOG: Fog prediction: J. Fernando (U. NotreDame) et al.
PISTON: Maritime Continent intraseasonal oscillations

Plus Joint with NASA CAMP^{2}Ex

Aerosol Modeling Roadmap *Short-Range Plan (1-5 years):*
To meet needs of aerosol customers until NEPTUNE ~ 2023

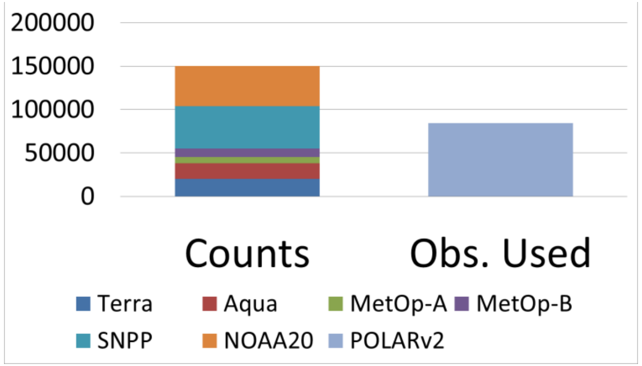
1. **Continue to use NAAPS as operational aerosol forecast method until NEPTUNE**
2. **Upgrade NAAPS:**
   - To handle additional species (investigate needed species)
   - Configure to be NWP-flexible
3. **Freeze Development of NAVGEM In-Line Aerosol at NAVGEM 2.0:**
   - Utilize as testbed to evaluate in-line vs off-line aerosol requirements/capability for NEPTUNE
   - Available for testing/evaluation of aerosol-radiative coupling as needed by ESPC
4. **Further Develop Ensemble Aerosol Forecasting:**
   - Probabilistic modeling and DA technology development: E-NAAPS
   - ICAP consensus
5. **Upgrade COAMPS-Dust to COAMPS-Aerosol (aka COAMPS-Scalar):**
   - Add additional NAAPS species in-line; Initialize using NAAPS
6. **Develop 'Universal FAROP':**
   - To generate needed aerosol optical parameters from any aerosol model

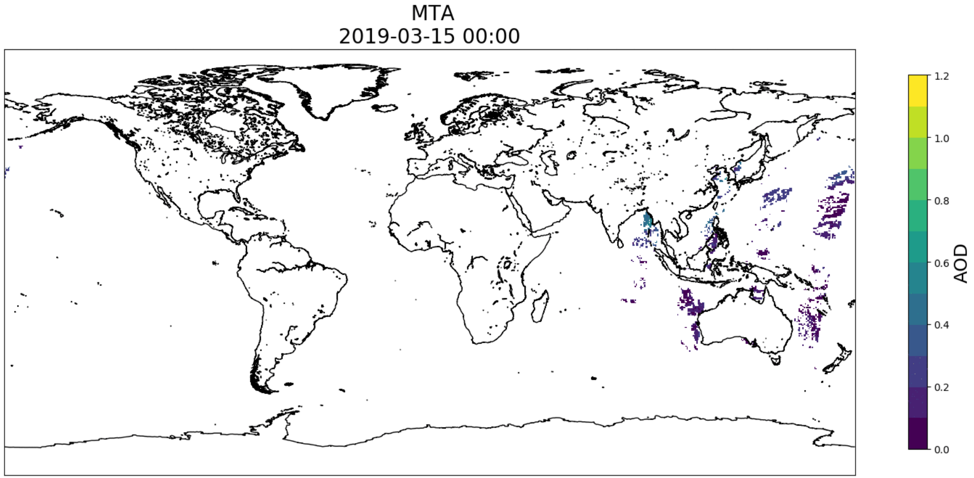
Operational NAAPS Updates

- Currently in BETA testing at FNMOC:
  - Native NetCDF I/O (Aerosol Model Output and Restart Files)
  - 5-satellite polar constellation
    - MODIS x2 (C6.1 Dark Target + Deep Blue w/ NRL-UND pre-processing)
    - AVHRR x2 (ACSPO AOD + NRL pre-processing)
    - SNPP VIIRS (NOAA Enterprise AOD + NRL pre-processing)
      - 6-satellite constellation with NOAA-20 VIIRS AOD now available NRT but cal/val not complete
- Near-term updates in development at NRL:
  - NAVGEM 2.0 including HDF5 IO for NAAPS
  - COAMPS 5.10 includes all NAAPS species
  - Optical calculator refactored as library code (based on FAROP), to facilitate integration across global+mesoscale+nextgen

Polar Constellation Overlap/Redundancy

- Polar constellation nominally has significant redundancy
  - All polar obs are from overpasses between 0930 and 1330 LST (at equator)
  - Obs are collected in 6-hour windows for assimilation
  - 5 sensors in three orbits should be at least 60% redundant
- Statistics show that actual redundancy is less: only about 40% (bar graph at right)
  - This relates to partly cloudy regions: ***Re-sampling, even at a short time separation, increases the odds of a sufficiently cloud-free observation***
  - We saw this with GEO AODs as well





NAVGEM Inline Aerosol Model – A Part of Navy ESPC Project

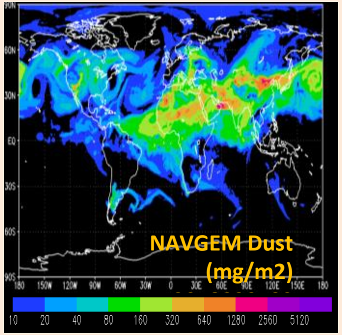
Introduction

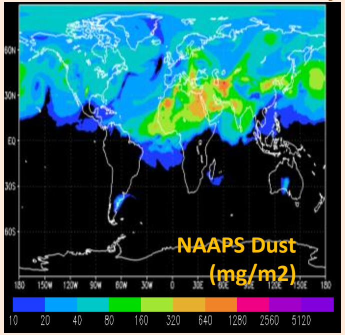
- An inline aerosol forecast capability has been developed in US Navy's Global Weather Forecast System NAVGEM.
- It predicts five aerosols: mineral dust, sea salt, biomass smoke, ABF (anthropogenic and biogenic fine particles), and gas SO2.
- Inline model uses the same source & emission datasets/algorithms as in NAAPS.
- Driven by NAVGEM dynamics and physics at NAVGEM grid point at its time step.
- It will perform aerosol-radiation direct interactions.

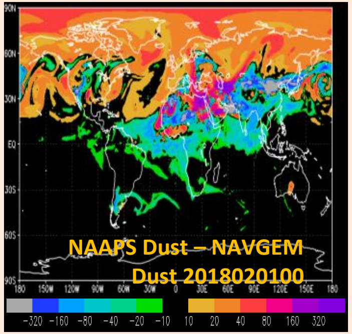
Challenges

- Computational expense in NWP and seasonal prediction.
- Need aerosol assimilation.

An Example of Dust Comparison of NAVGEM with NAAPS after 10-month simulation of successive 6-h analyses without aerosol DA

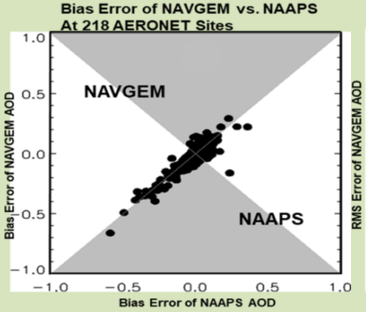


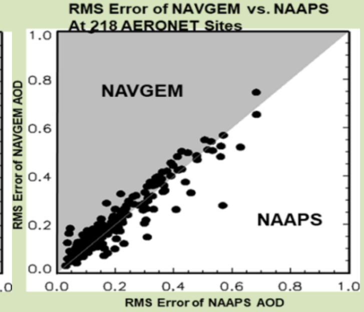




- Stronger gradients are seen in NAVGEM (more realistic).
- NAVGEM predicts more mass from Asian deserts (dynamics effect).
- NAAPS transports lots of mass to N. polar latitudes.
- Impact: different mass distributions result in different radiance corrections of atmospheric DA.

Validation with AERONET Optical Depth (20170801-20180801)

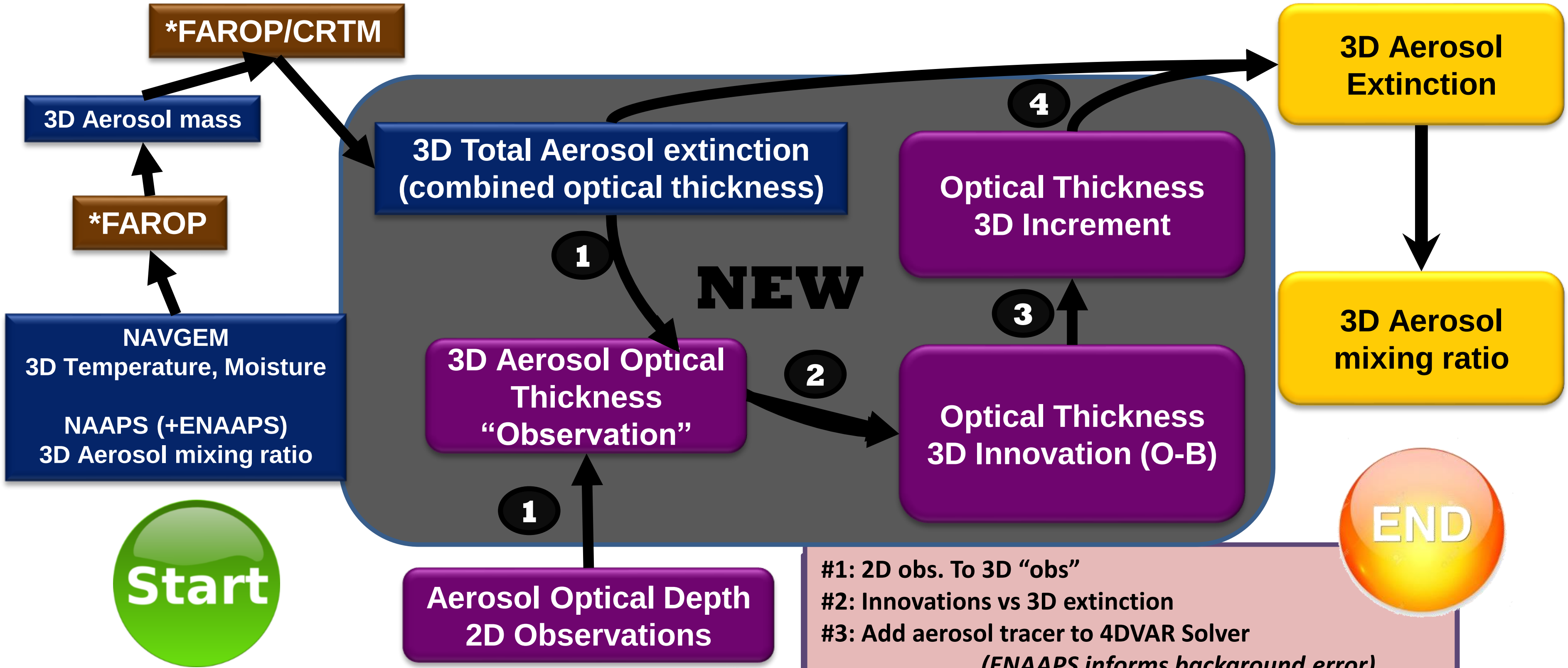




✸NAVGEM outperforms NAAPS over one year average;
✸NAVGEM bias error is similar to NAAPS;
✸NAVGEM RMS error is smaller than NAAPS.

Proposed addition of Aerosol Extinction to Hybrid 4D-Var

Ed Hyer, Juli Rubin, Ben Ruston



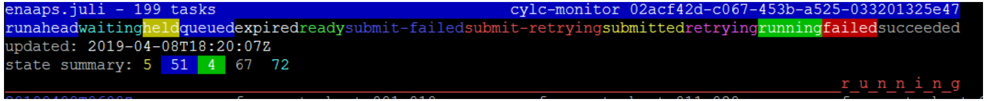
#1: 2D obs. To 3D “obs”
#2: Innovations vs 3D extinction
#3: Add aerosol tracer to 4DVAR Solver
(ENAAPS informs background error)
#4: 3D increment to new initial condition
(ENAAPS informs speciation solution)

*FAROP = Forecast of Aerosol Radiative and Optical Properties
*CRTM = Community Radiative Transfer Model

Global Ensemble Aerosol Prediction System Updates

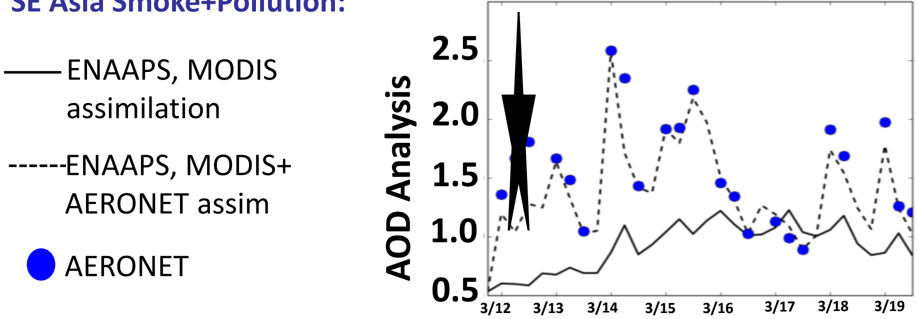
ENAAPS is running in NRT with Cylc:

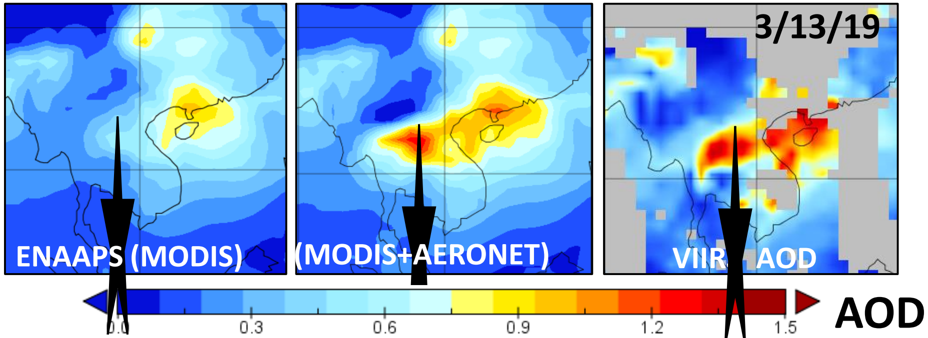
- More efficient task management.
- Coordination with other METOC systems (T. Whitcomb 7532, Ops Modernization Project).



AERONET obs in data assimilation:

SE Asia Smoke+Pollution:

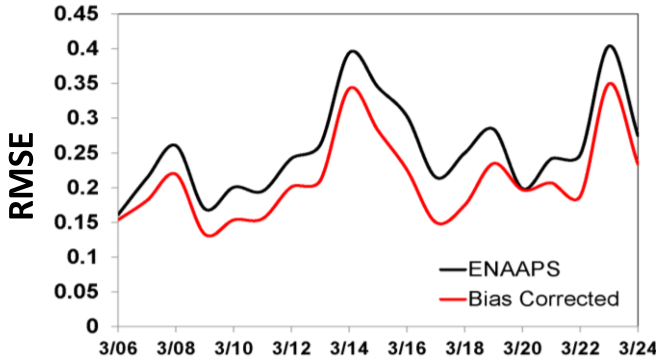




Bias correction for NRT ENAAPS:

- Low bias for high AOD.
- High bias for low AOD.
- Results use a week of archived forecasts/obs.
- Error reduction at all lead times.

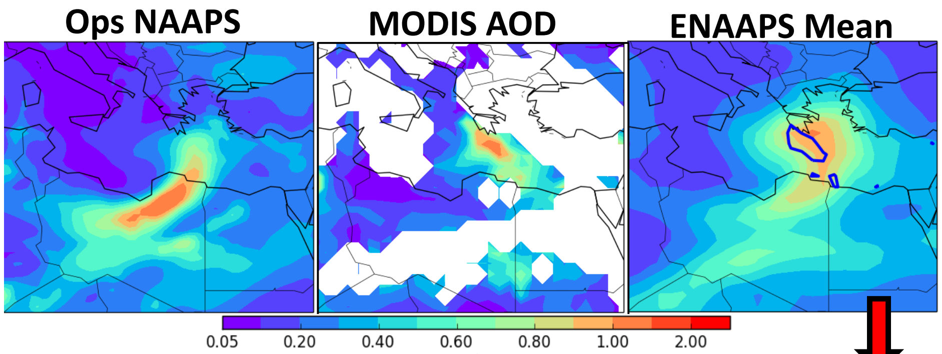
120 Hour Global AOD Forecast Error



Global Ensemble Aerosol Prediction Probabilistic Output

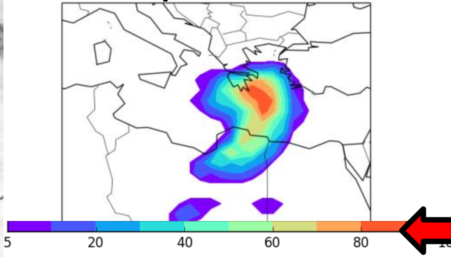
Mediterranean Dust
April 6, 2019 Forecast (t+012):

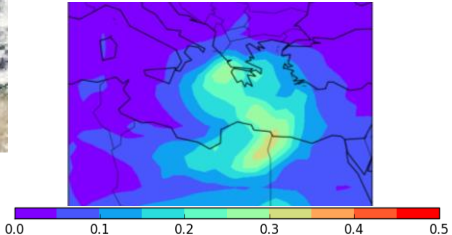
Demonstration of how ENAAPS aerosol ensemble is a valuable complement to operational NAAPS.

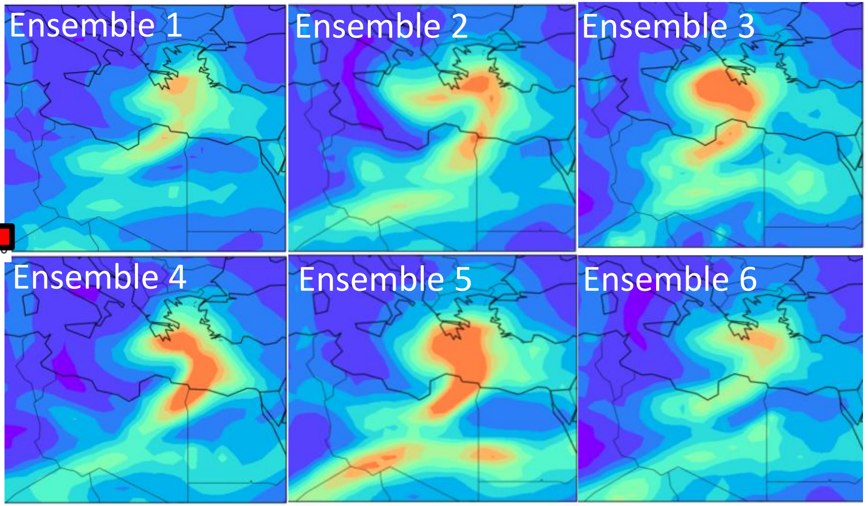


MODIS AOD=0.8 contour

Ensemble shows a range in intensity and position of dust (20 total).







Global Ensemble Aerosol Prediction Verification

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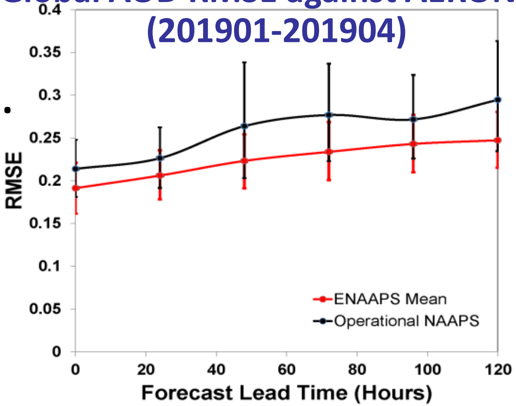
1. ENAAPS mean meets demonstration criteria.

- Criteria: Neutral or better performance.
- ENAAPS/NAAPS RMSE not statistically different.

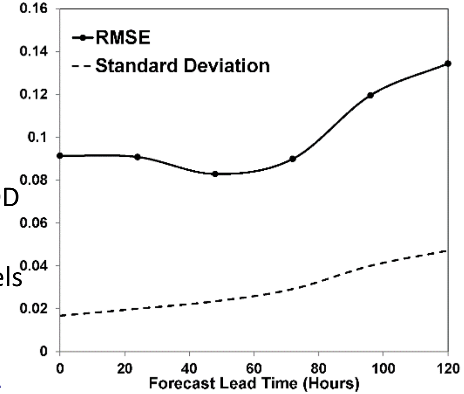
Global AOD RMSE against AERONET (201901-201904)

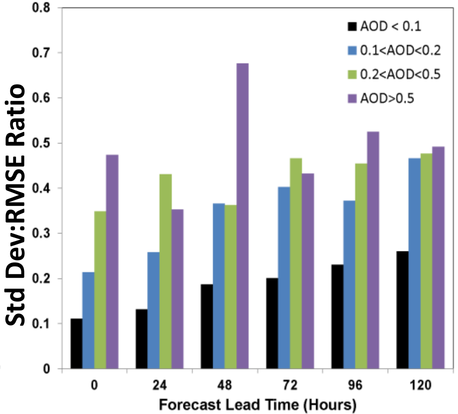


2. ENAAPS forecast uncertainty.

- Ensemble is under dispersive.
- Uncertainty better represented for high AOD events.
- Background aerosol levels are spread deficient (<0.1).

Spread-Skill Evaluation*





* 20190401 Forecast

3. Observations generally fall within the range of the ensemble (AOD above background).

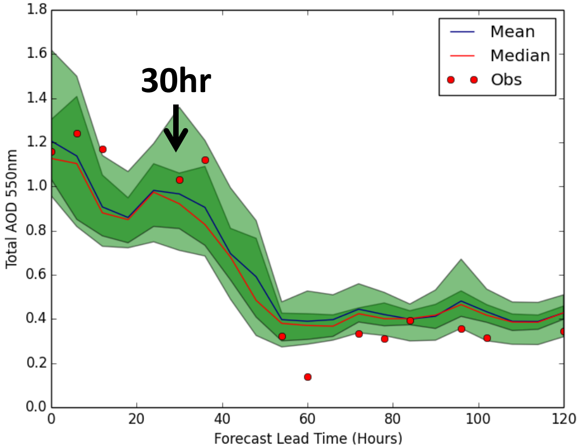
ENAAPS Probabilistic AOD Forecast Evaluation

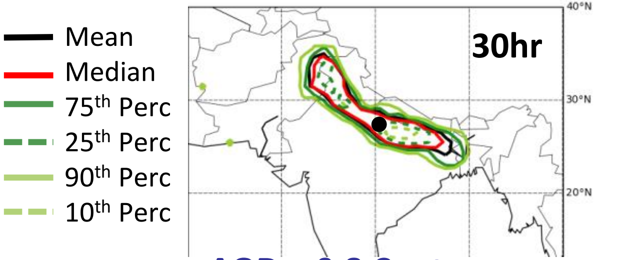
Verification at AERONET site in Kanpur, India (20190206):

Percentile Range:

25th-75th

10th-90th



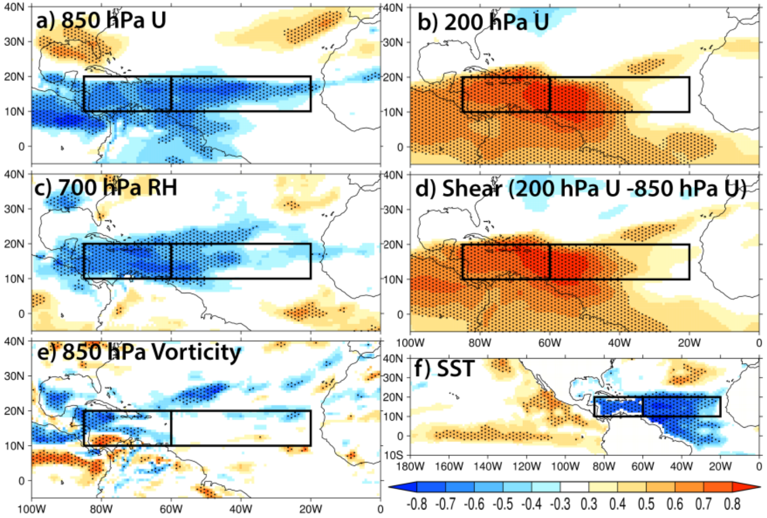


AOD = 0.8 Contour

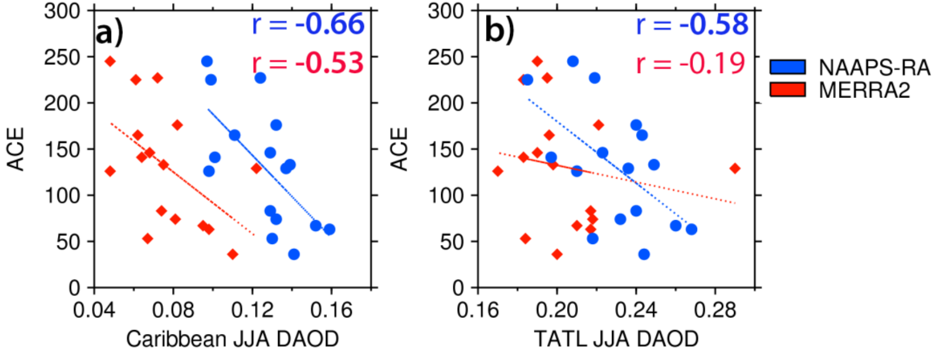
NAAPS Reanalysis and its applications

- A decade-long (2003-2018 and ongoing) global 1x1 degree and 6-hourly 550nm AOD product (Lynch et al., 2016, GMD).
- Species include anthropogenic and biogenic fine (ABF, including sulfate, and primary and secondary organic aerosols), dust, biomass burning smoke and sea salt.
- Assimilation of QA/QCed AOD from MODIS and MISR.
- Driven by the NOGAPS/NAVGEM meteorology analysis, and CMORPH precipitation (a satellite product) within the Tropics.
- It is validated well with AERONET observations and reproduces the decadal AOT trends found using standalone satellite products.
- Data is available publically. https://usgodae.org/cgi-bin/datalist.pl?dset=nrl_naaps_reanalysis&summary=Go

R bwt. JJA Caribbean DAOD and large scale fields



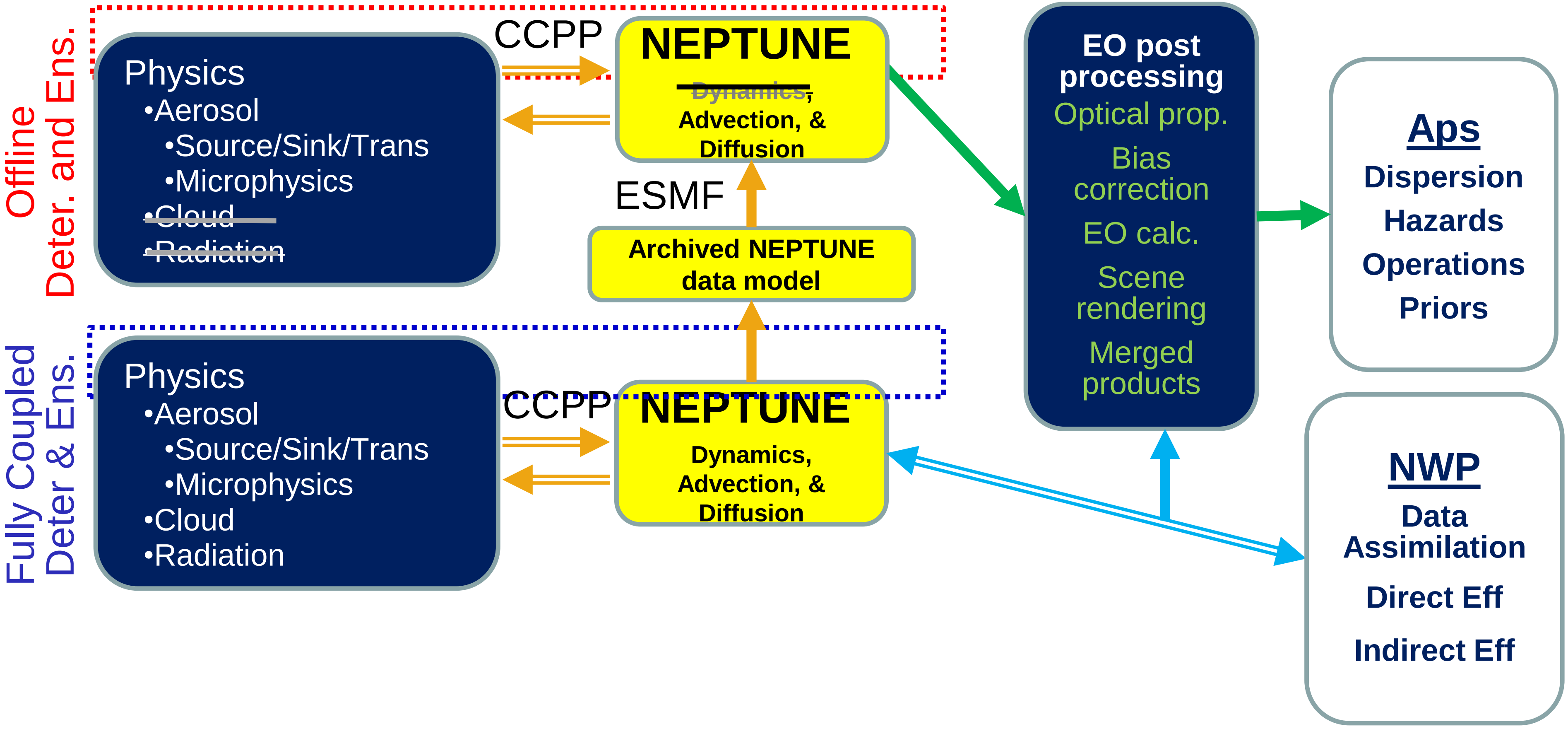
Example application: revisiting African dust and TC relationship



- JJA Caribbean DAOD correlates significantly and negatively with seasonal Atlantic tropical cyclone activity.
- JJA tropical North Atlantic dust level also correlates with Atlantic TC activity, but not as strongly as that in the Caribbean does.
- Large-scale conditions related to TC activity correlate significantly with DAOD, especially in the Caribbean.
- Manuscript under review in JGR-Atmos.

Aerosol Modeling Roadmap-*Long Term Plan (5-10 years)*

Develop NEPTUNE In-Line and Off-Line Aerosol Models



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Overview

- Overview of peoples and systems
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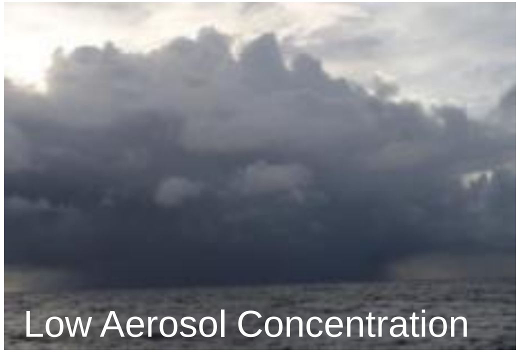
- Major projects: CAMP^{2}Ex, PISTON, MURI, C-FOG
- Navy aerosol literature highlights from the last year

Cloud, Aerosol, Monsoon Processes Philippines (CAMP^{2}Ex)

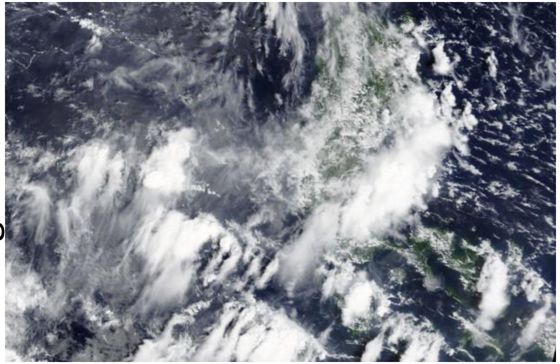
Clark Freeport Philippines, Aug 25-Oct 5, 2019. jeffrey.reid@nrlmry.navy.mil

- NASA, Manila Observatory, NRL will conduct an airborne P3 and Lear 35 campaign out of Subic Bay Philippines Aug 25-Oct 5, 2019.
- Research will focus on these questions
  - Do aerosol particles influence warm/mixed phase precipitation in tropical environments?
  - Do aerosol induced changes in clouds and precipitation feedback into aerosol lifecycle?
  - How does the aerosol and cloud influence on radiation co-vary and interact?
- Manila Observatory is taking a lead on how land use change effects clouds and if this change is a confounder for perceived aerosol impacts.
- ~100 scientist, including ~20 Philippine scientist will conduct ~20 7.5-hour P3 and 8 5-hour Lear 35 flights to measure the cloud and pollution environment around the Philippines.


High Aerosol Concentration


Low Aerosol Concentration

High Shear

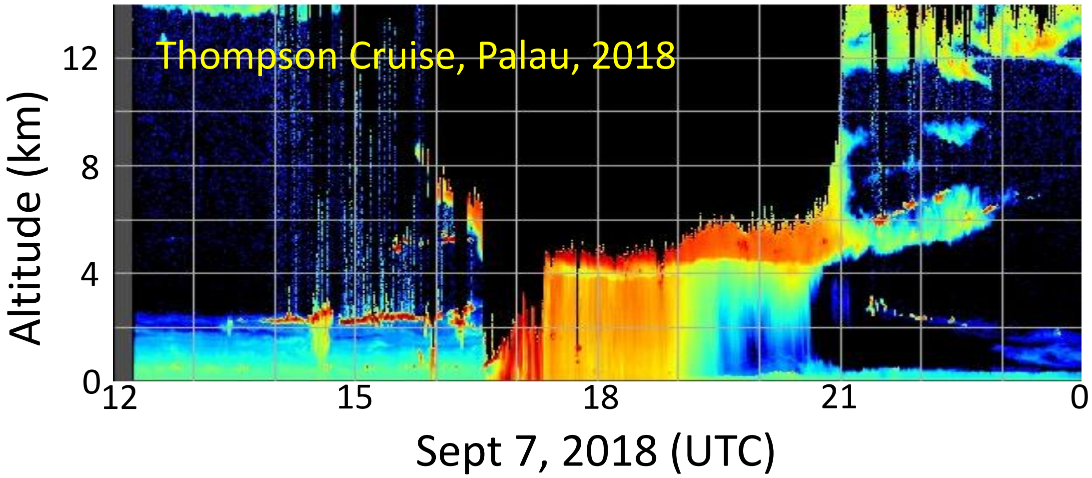


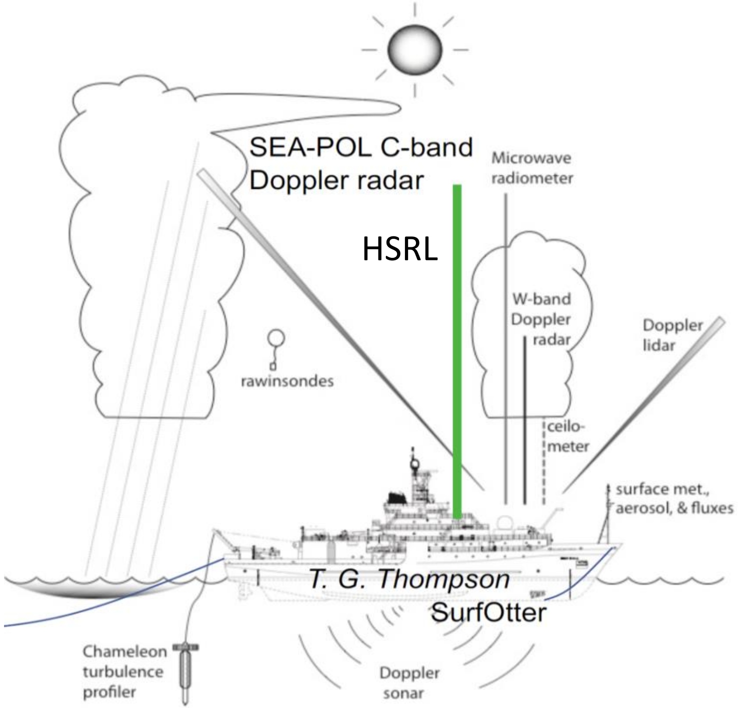
Low Shear

PISTON: Propagation of Intra-seasonal Oscillations

Joint sponsored CALIPSO/ONR deployment of SSEC HSRL to the Thompson

- PISTON is an ONR DRI to assess SE Asian of intraseasonal weather phenomenon across the Maritime Continent, such as the MJO.
- Included is the R/V Thompson cruise mid Aug-Mid Oct, 2018, and Sally Ride Sept 2019 in the WESTPAC to examine diurnal cycle with overlap with CAMP²Ex.
- Included are Air/Sea Flux, C-POL & W radar, and HSRL and (2019) wind lidar.
- Will exercise COAMPS aerosol .



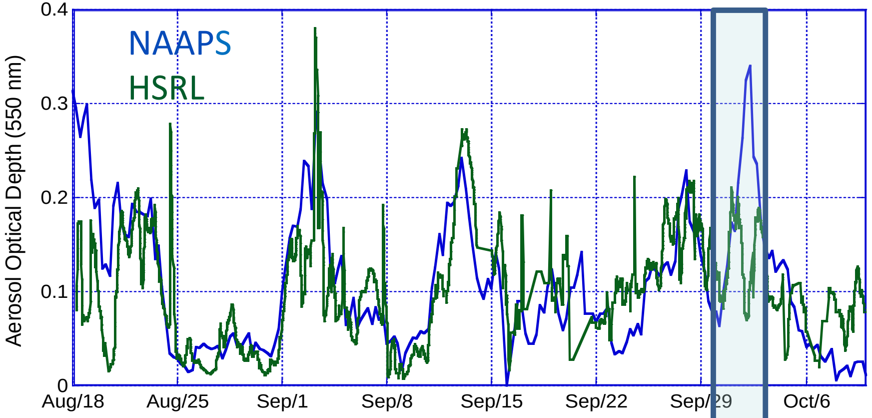


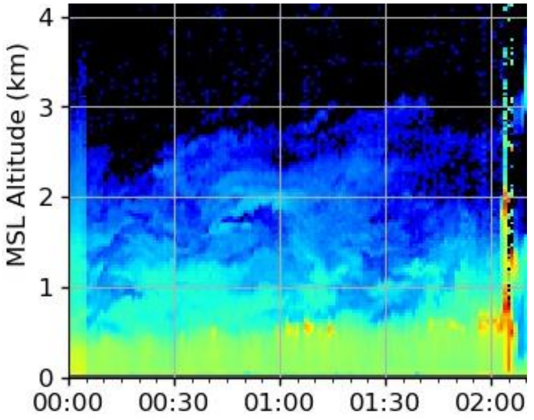
Interested?
Atmos measurements-jeffrey.reid@nrlmry.navy.mil
Meteorology Models- sue.chen@nrlmry.navy.mil
Oceanography-moum@coas.oregonstate.edu

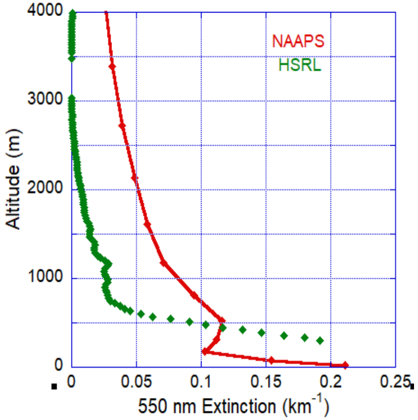
Verification with HSRL

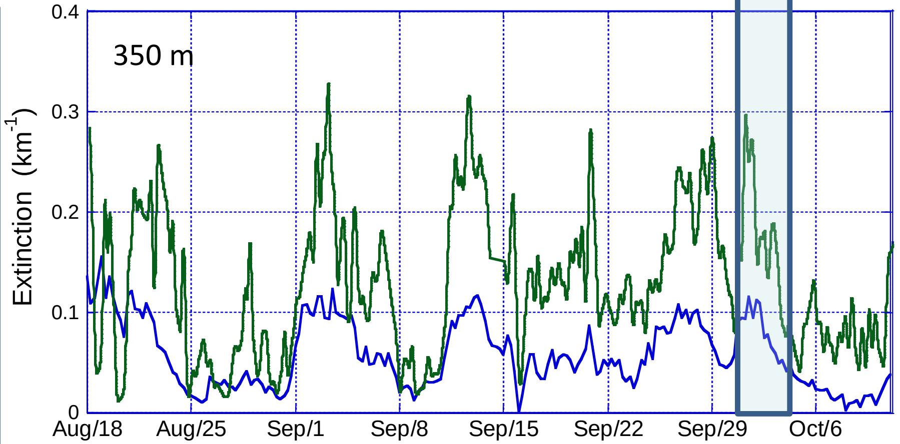
PISTON Cruise to the WESTPAC 2018

- Only 5 sun photometer measurements for PISTON due to clouds.
- But HSRL infers AOD up to cloud base. NAAPS matches well for AOD.
- NAAPS qualitatively gets boundary layer events but has biases due to boundary layer structure and mixing. Here is an extreme event.









MURI: Holistic Analysis of Aerosol in Littoral Environments-HAALE in the 4th year

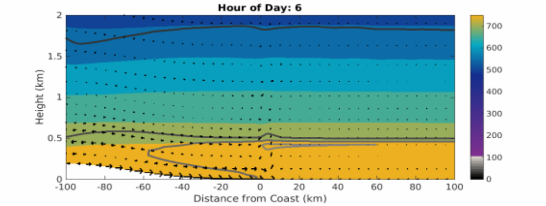
Special sections in ACP and AMT

Interested? Steven.Miller@colostate.edu

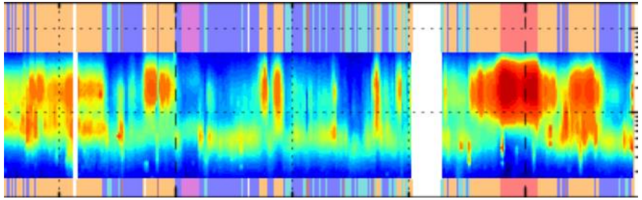
Colorado State University | Wisconsin, University of Wisconsin–Madison | University of North Dakota | The University of Iowa

What are the fundamental environmental factors that govern the spatial distribution and optical properties of littoral zone aerosols at the sub-km scale?

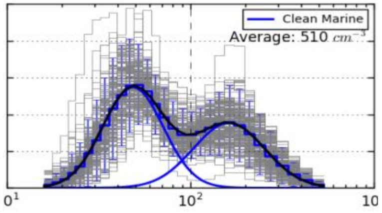
Modeling



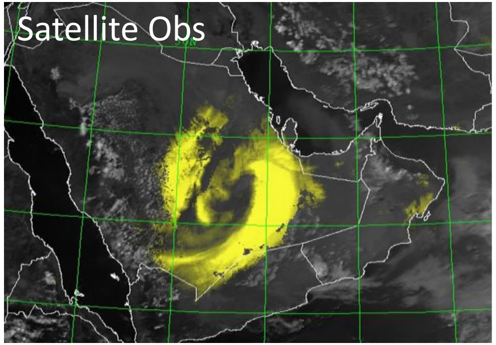
Measurements

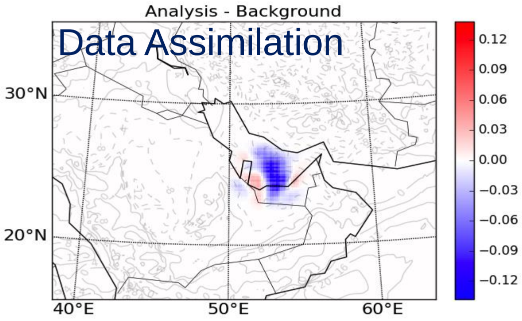


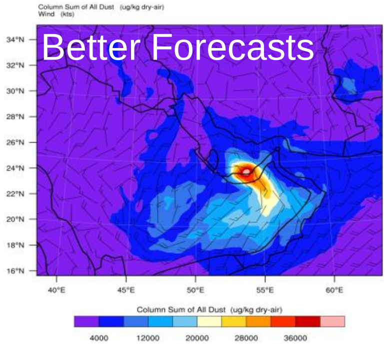
Microphysics



How can we best leverage emergent satellite observing systems and derived products via advanced D/A techniques to optimally inform a high-resolution forecast model's initial aerosol field?







Toward Improving Coastal Fog Prediction (C-FOG)

Interested? Contact Joe Fernando (hfernand@nd.edu)

Science Issues

- Formation, evolution and dissipation mechanisms of different fog types: cold, warm and radiative
- Competing factors (shear instabilities, internal boundary layers, stratification, entrainment, SST and air temperature) determining fog physics
- Microphysical parameterizations controlling fog lifecycle and visibility

Approach

- A comprehensive atmosphere-ocean field campaign (September-October 2018) in Atlantic Canada (coastal stations + RV)
- Studies on coastal fog physics/governing parameters
- Analytical studies on fog dynamics
- Cascading simulations: Mesoscale (NWP), Large eddy & direct numerical simulations

Principal Investigators

- Clive Dorman (Scripts)
- Joseph Fernando (U Notre Dame, PI)
- Ismail Gultepe (ECC Canada)
- Eric Pardyjak (U. Utah)
- Qing Wang (NPS)

Principal Collaborators

- Chris Hocut and Ed Creegan (ARL)
- Will Perrie (Bedford Inst. Oceanogr., Canada)
- Andrew Heymsfield (NCAR)

Wrapping up.

- Motoring along on model development, inline NAAPS into NAVGEM well underway, ENAAPS cycling at DSRC.
- NRL has started planning on the aerosol component in NEPTUNE with inline and offline capability.
- The ONR PISTON/NASA CAMP^{2}Ex big show in 2019, so contact us if you want to join in. Currently analyzing 2018 PISTON cruise and enhanced measurements in Metro Manila.
- Lots of basic research coming out of Navy and partner programs on fundamental aerosol science, in particular on physics relative to associated regional meteorology and remote sensing/assimilation problems.

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Mid-Troposphere Aerosol Detrainment into Altocumulus Layers

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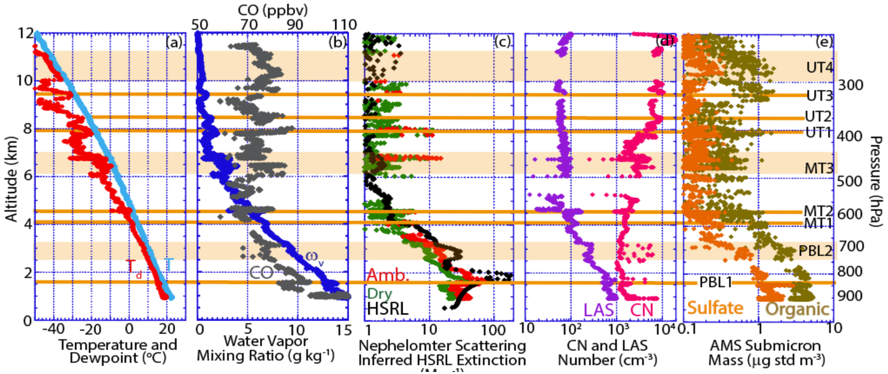
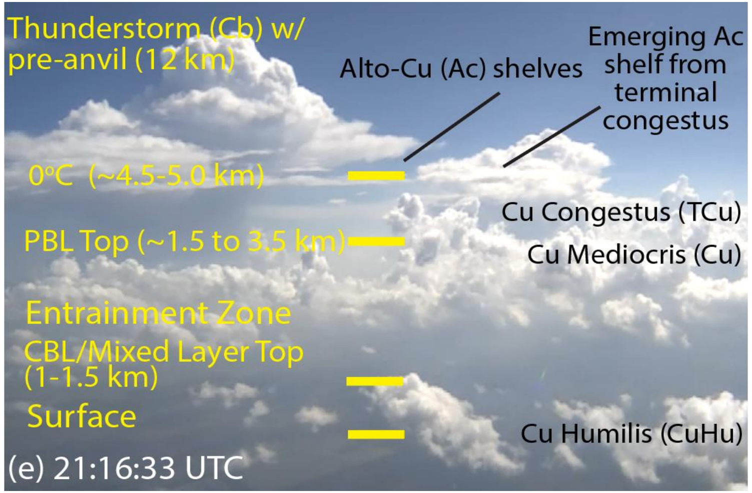
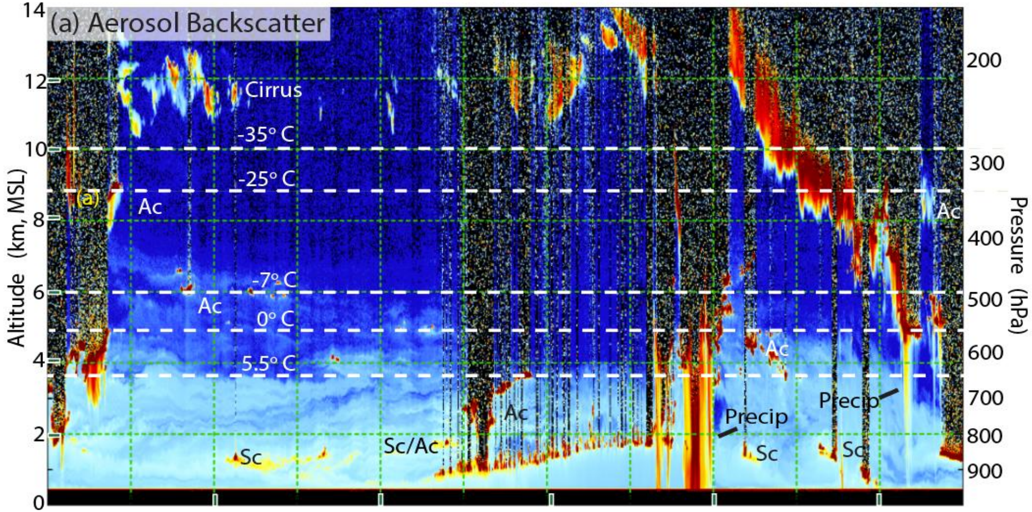
Reid, J. S., D.J. Posselt, K. Kaku, R. A. Holz et al..: Observations and hypotheses related to low to middle free tropospheric aerosol, water vapor and altocumulus cloud layers within convective weather regimes: A SEAC4RS case study, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-179, in press, 2019.

Examined a canonical day from SEAC^{4}RS of aerosol processing and detrainment from an isolated CB.

Particular emphasis on covariability of aerosol, water vapor detrainment with altocumulus cloud formation





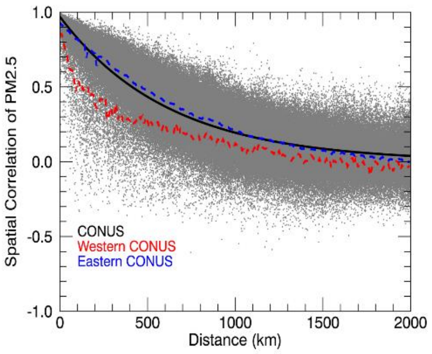


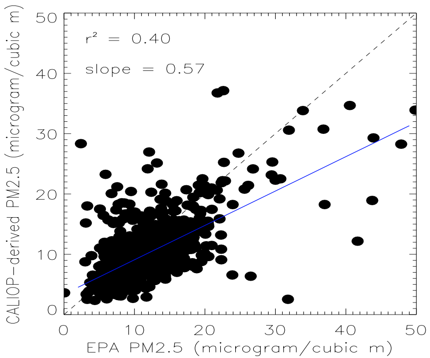
An Innovative Approach for Deriving CALIOP-Based Particulate Matter Concentrations Through a Bulk-Mass-Modeling-Based Method.

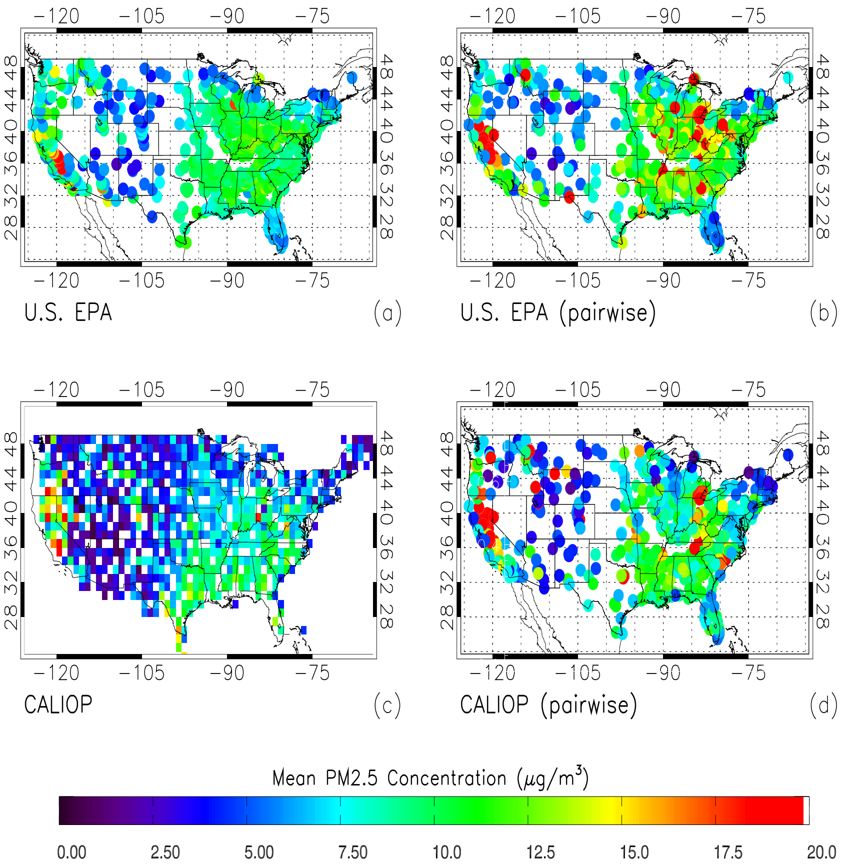
Toth, T. D., Zhang, J., Reid, J. S., and Vaughan, M. A.: A bulk-mass-modeling-based method for retrieving particulate matter pollution using CALIOP observations, Atmos. Meas. Tech., 12, 1739-1754, https://doi.org/10.5194/amt-12-1739-2019, 2019.

Past studies have estimated $PM_{2.5}$ concentrations from AOT from passive satellite sensors (e.g., MODIS, MISR). Yet, $PM_{2.5}$ is surface-based, but AOT is column-integrated. Also, the past studies based upon correlative relationship between unitless parameter and surface aerosol concentration (µg m^{-3}).

A Bulk-Mass-Modeling-based method has been developed to retrieve PM2.5 concentrations using near surface aerosol extinction from CALIOP



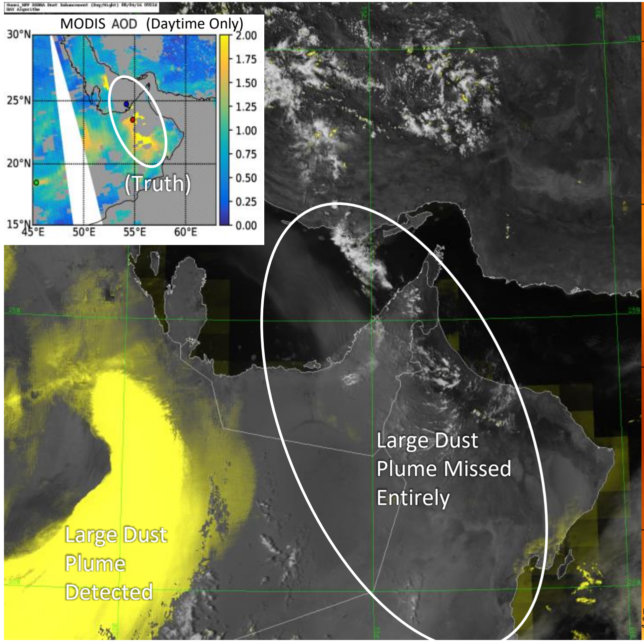




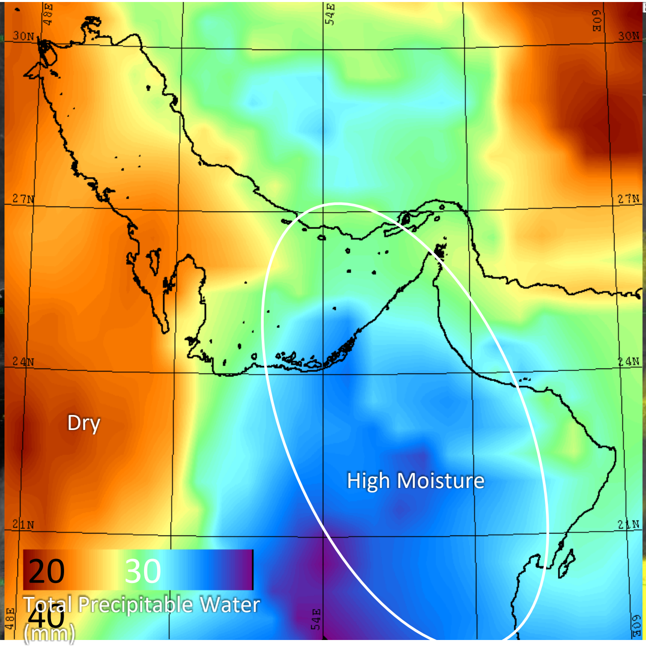
HAALE MURI Special Issue

Mitigating Infrared-Based Limitations in Dust Detection

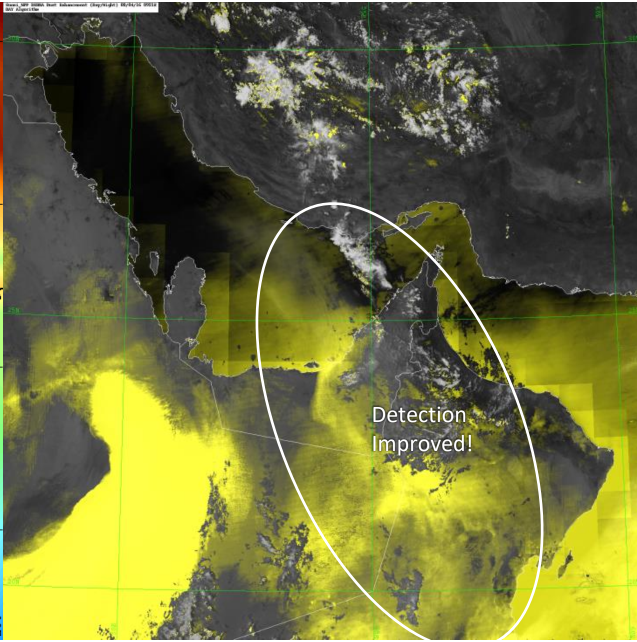
The HAALE-MURI team is working to improve infrared-based mineral dust detection techniques (e.g., the Dynamic Enhancement with Background Reduction—DEBRA) by taking into account the signal masking effects of atmospheric water vapor:



NRL/CIRA "DEBRA" Dust Product (Yellow=Dust)



NUCAPS Moisture (CrIS + ATMS)



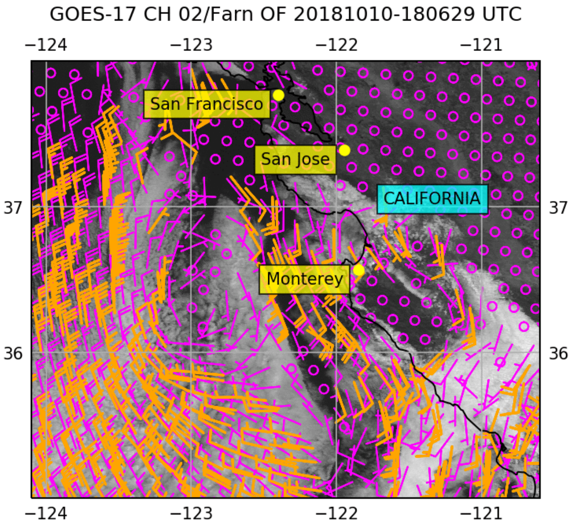
NUCAPS-Adjusted DEBRA

POCs: Steven Miller and Louie Grasso (CSU/CIRA)

Optical Flow for Improved Atmospheric Motion Vectors

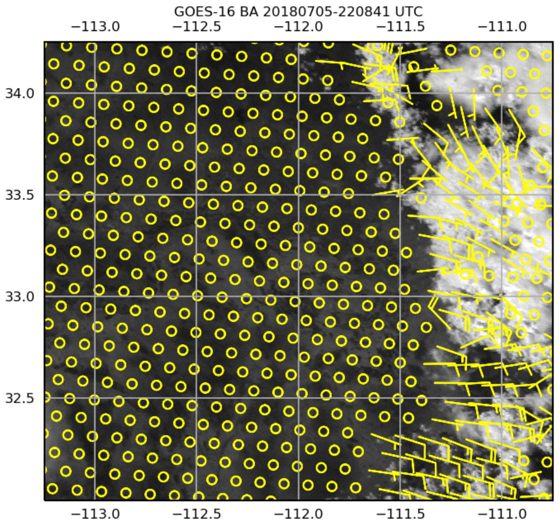
The HAALE-MURI team is refining, developing, and evaluating new optical flow techniques to capture dense vector fields for a variety of meteorological flows and features:

Boundary Layer Clouds



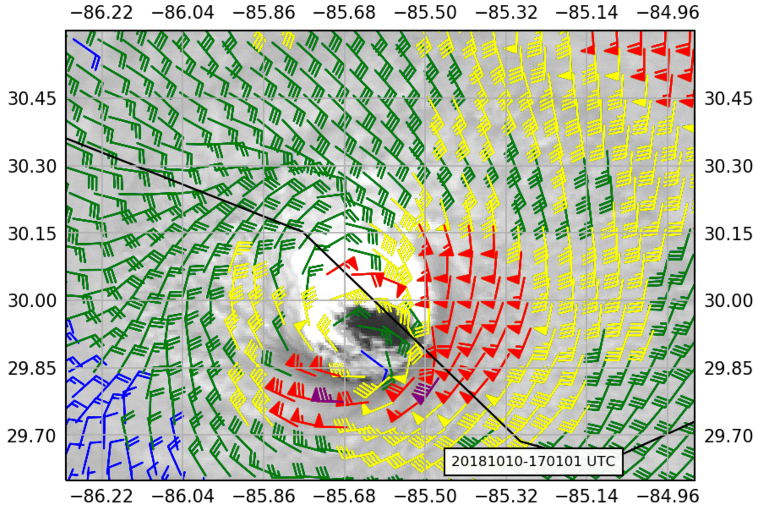
Provides dense motion field vs. traditional differential motion vector techniques.

Outflow Boundaries



Enables tracking of convective outflow boundaries when arcus clouds or dust front is present.

Storm-Top Dynamics



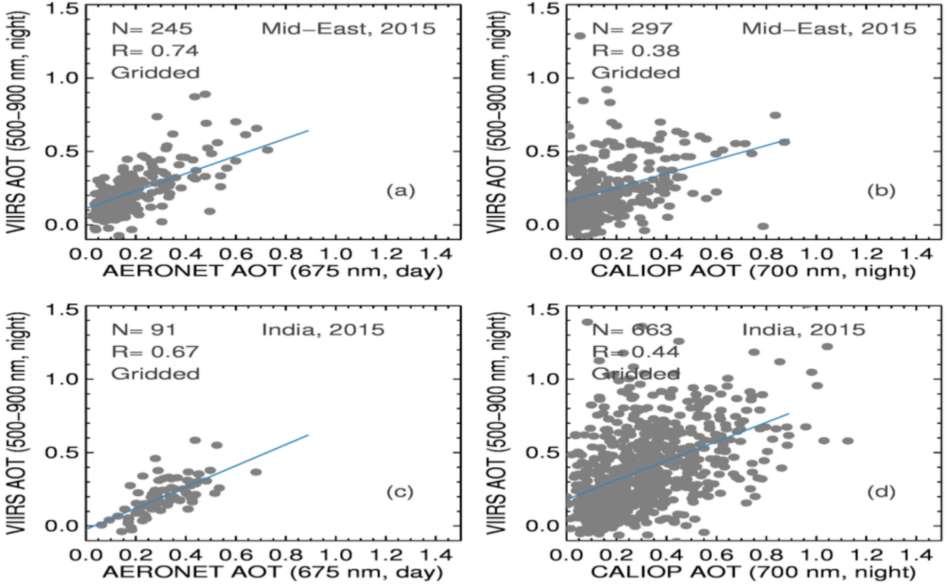
Exploring information content of storm top dense motion vectors in terms of divergence and vorticity fields.

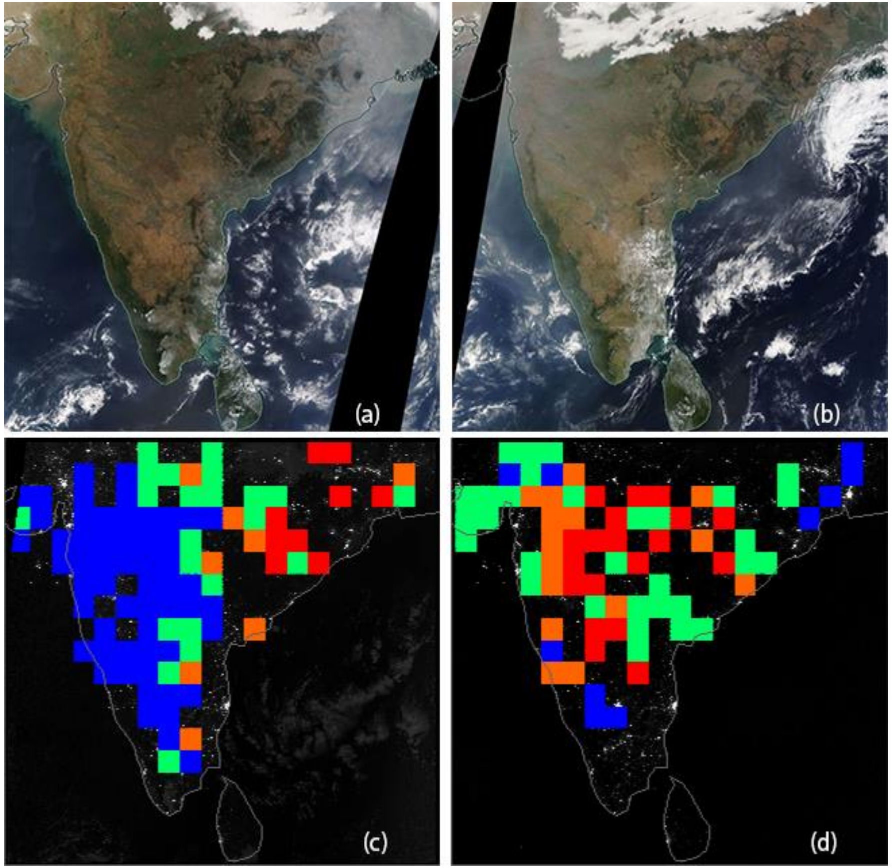
POCs: Jason Apke and Steven Miller (CSU/CIRA)

Aerosol Optical Thickness Retrievals Using Nighttime Observations from VIIRS

Zhang, J., et al.,: Characterization and application of artificial light sources for nighttime aerosol optical depth retrievals using the Visible Infrared Imager Radiometer Suite Day/Night Band, Atmos. Meas. Tech., 12, 3209-3222, https://doi.org/10.5194/amt-12-3209-2019, 2019.

Nighttime aerosol observations are missing in current aerosol DA efforts. A new VIIRS nighttime aerosol retrieval method has been developed utilizing artificially light sources for retrieving night time AOD over both moonless and moon illuminated nights.

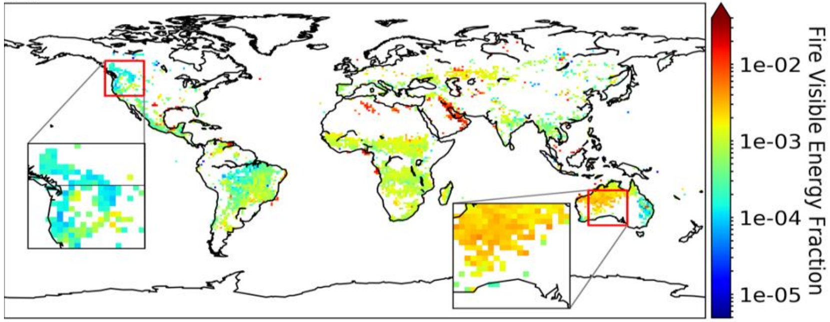




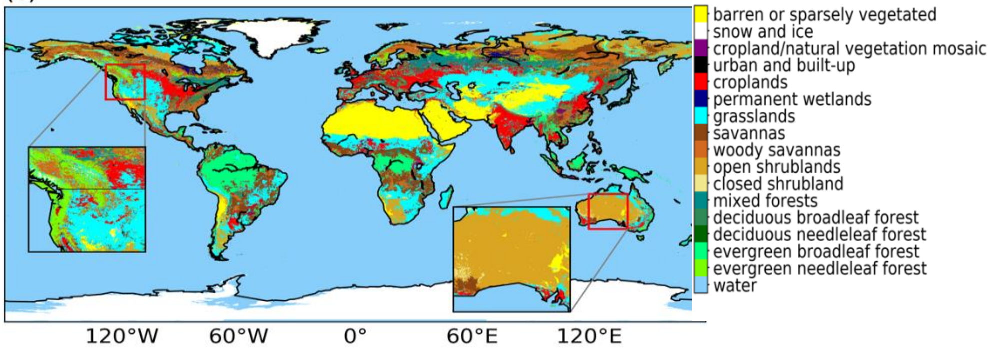
First detection of fire phase at night from space

- An algorithm that combines day-night-band and infrared band on VIIRS is developed to compute Visible Energy Fraction (VEF) w.r.t. FRP.
- We show VEF is superior than FRP to reveal modified combustion effieicy (MCE = $CO_2/[CO+CO_2]$)

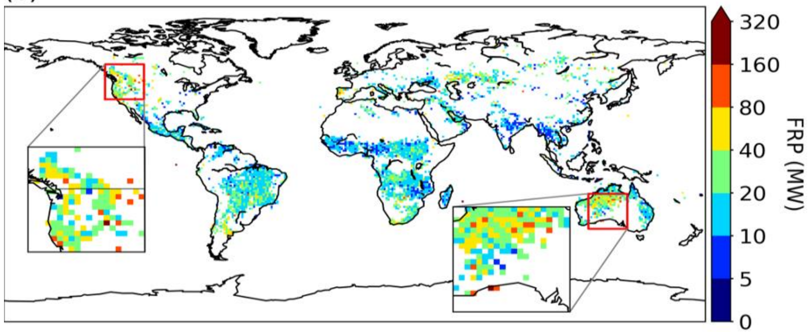
(a)

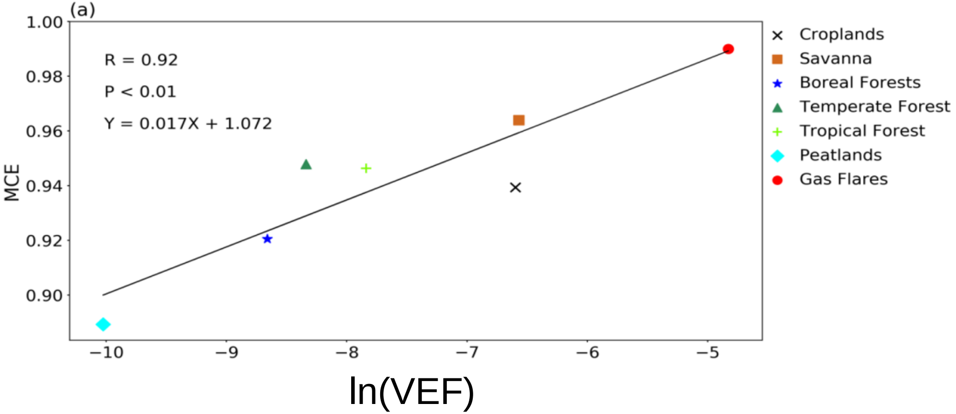


(c)



(b)





Results in review. Please don't cite.

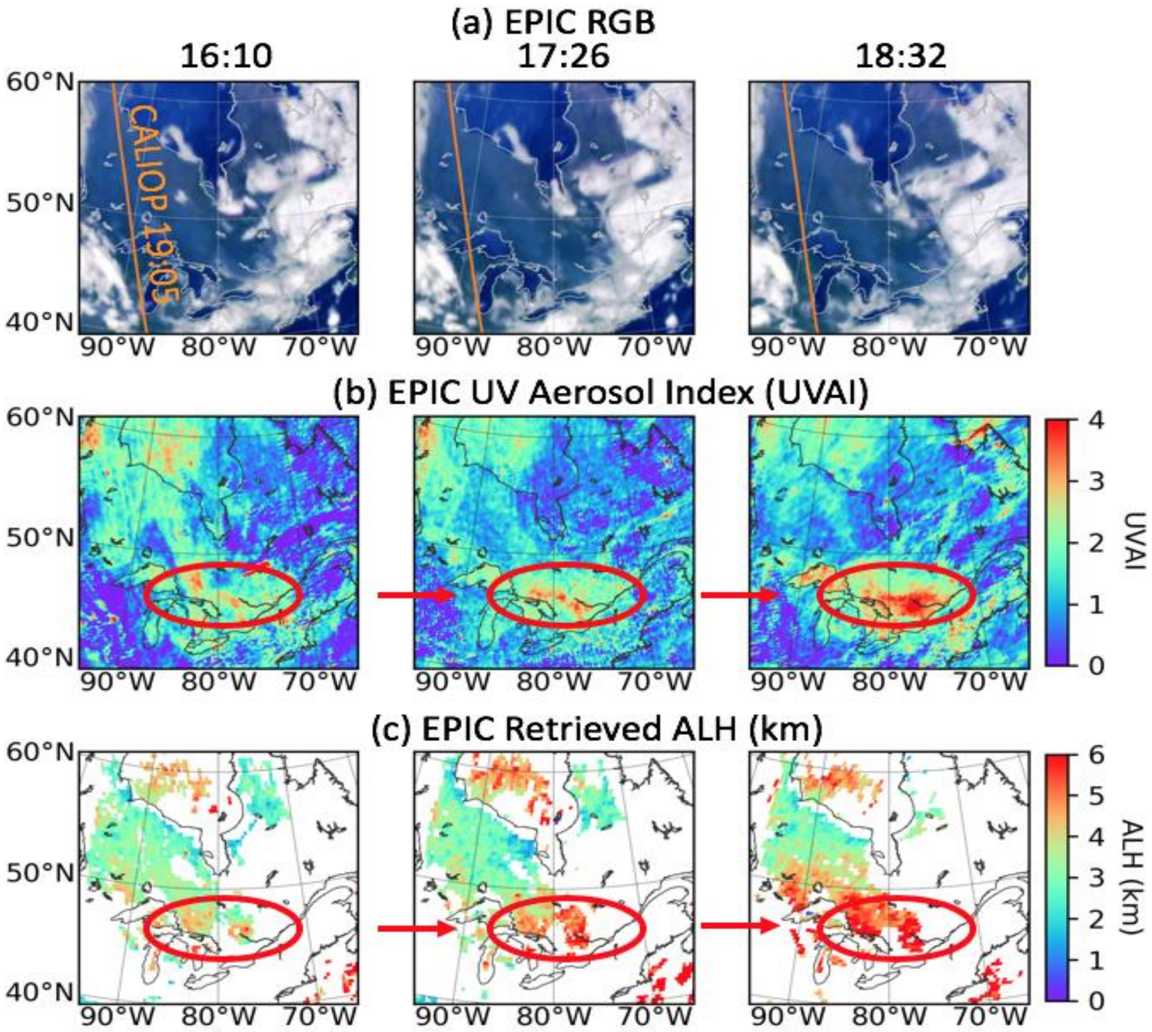
Wang et al., 2019, RSE, in review.

Hourly retrieval of aerosol layer height from EPIC

smoke ALHs over Canada
Case I: Aug-25-2017

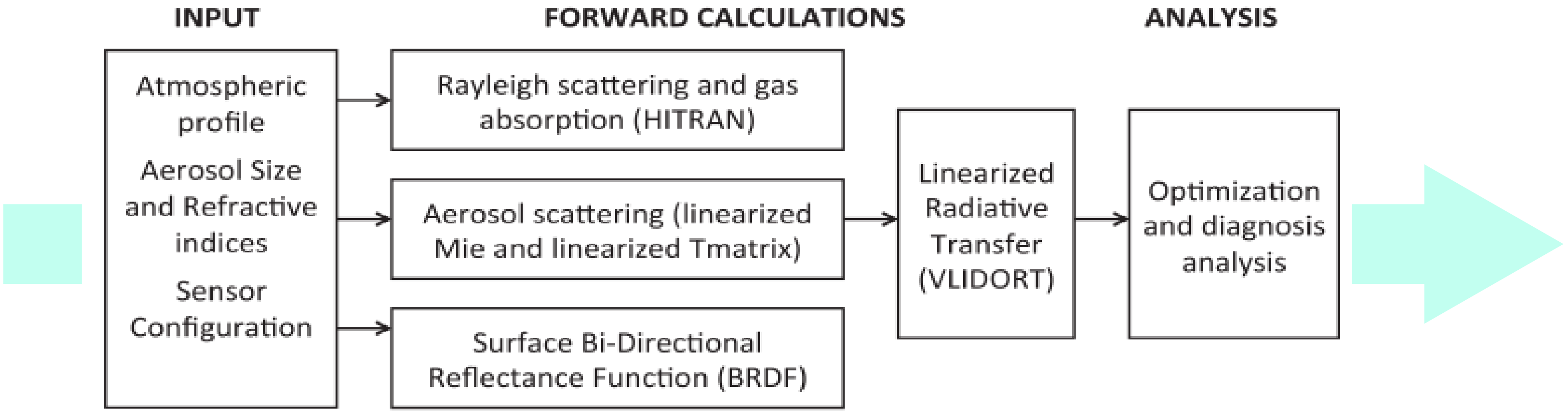
- Smoke layer is 3 – 5 km high over Hudson Bay
- ALHs are 2 – 4 km over land southeast of Hudson bay, increase to 4 – 6 km towards the Great Lakes
- Diurnal changes of UVAI and ALH are likely consistent

Xu et al., AMT, 2019



UNL-VRTM: a versatile tool for radiance data assimilation and satellite retrievals. (line-by-line + Jacobians)

(Wang, Xu, et al., 2014, JQSRT)



Aerosol model

- Particle size distribution (PSD) function
- Aerosol profile
- Refractive index
- Total aerosol concentration and fmf

Surface model

- Lambertian albedo
- BRDF model

Linearized vector RTM

- Input set $\{\Delta_n, \omega_n, \mathbf{B}_{nl}\}$
- Linearized inputs:

$$\phi_\xi = \frac{\xi}{\Delta}\frac{\partial \Delta}{\partial \xi}; \quad \varphi_\xi = \frac{\xi}{\omega}\frac{\partial \omega}{\partial \xi}; \quad \mathbf{\Psi}_{l,\xi} = \frac{\xi}{\mathbf{B}_l}\frac{\partial \mathbf{B}_l}{\partial \xi}$$

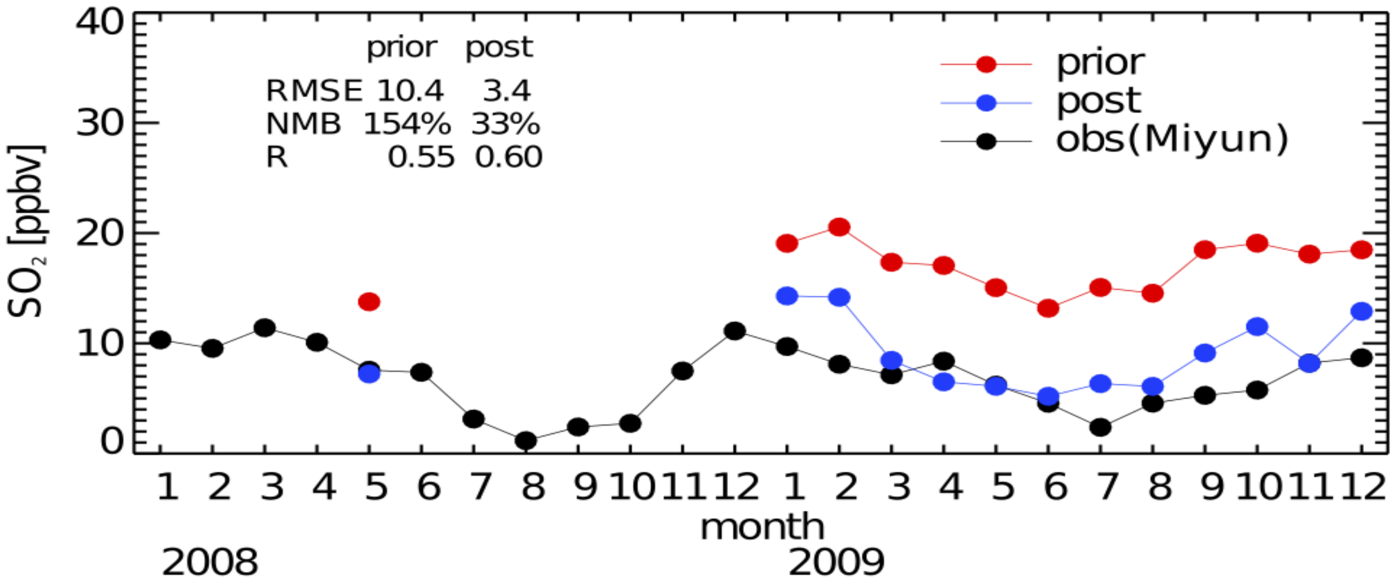
Stokes vector and Jacobians

- Stokes vector: $\{I, Q, U, V\}$
- Weighting functions (Jacobians):

$$\frac{\partial\{I,Q,U,V\}}{\partial \xi}$$

Applying top-down estimate of emission from the past month (of OMI data) to forecast SO_2 for the present month

Prior emission: bottom-up estimates often with time latency of 2 or more years
Posterior emission: top-down estimates from satellite observations with latency of 1 month



A new approach for monthly updates of anthropogenic sulfur dioxide emissions from space: Application to China and implications for air quality forecasts, Wang, Y., et al., Geophys. Res. Lett., 2016

How do diurnally-driven circulations govern convective organization, accumulated precipitation patterns, and aerosol transport in the Maritime Continent?

Idealized Set Up

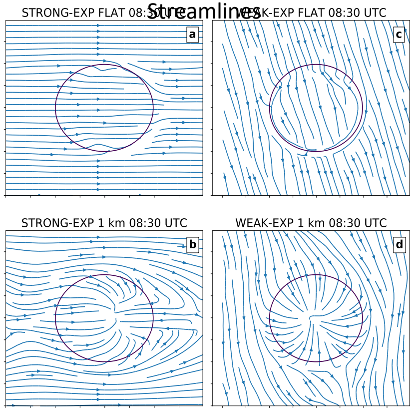
24 Simulations

50 km	100 km	200 km
Flat	Flat	Flat
500 m	500 m	500 m
1 km	1 km	1 km
2 km	2 km	2 km

Strong Meridional Winds (STRONG-EXP)

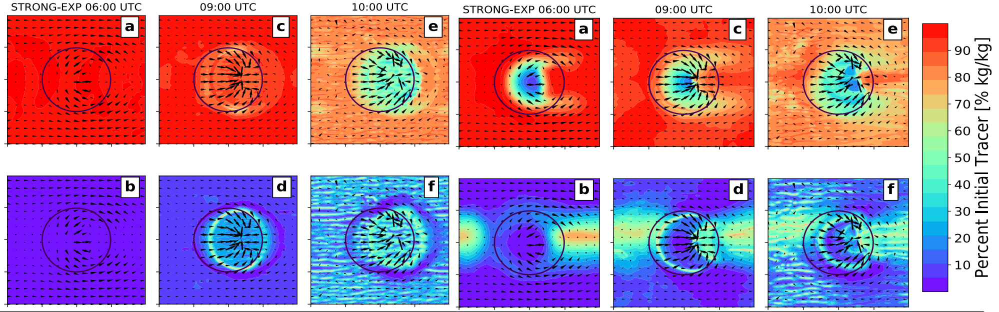
Weak Meridional Winds (WEAK-EXP)

Surface Streamlines



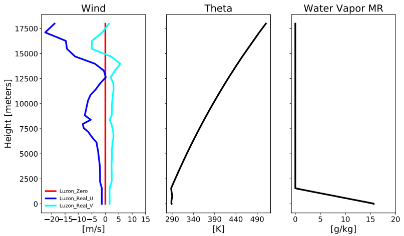
- Orography substantially alters the flow
- STRONG-EXP: the orography induces a reverse flow, lee-vortex formation and a wake
- WEAK-EXP: the orography induces upslope flow around the entire island

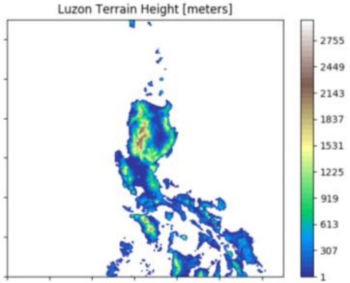
Tracer Redistribution



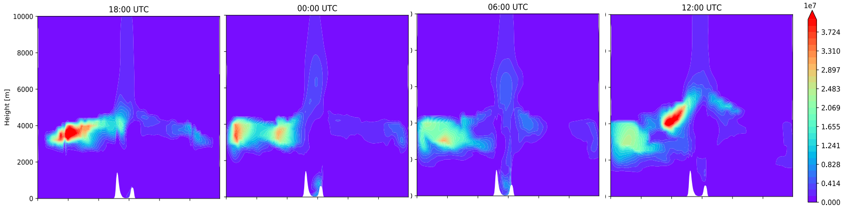
- Flat island (LEFT a-f): Tracers lofted in correlation with moisture flux convergence and cloud formation associated with the sea breeze. (Top panels: 0-500m; bottom: 500-1000m)
- 1 km orography (RIGHT a-f): tracers are lifted from the surface and lofted in the wake, but 80% of original tracer remains in lowest level in the wake

Case Study Set Up





Cross Section Tracers for Zero_Wind 5-km resolution [#/kg dry air]

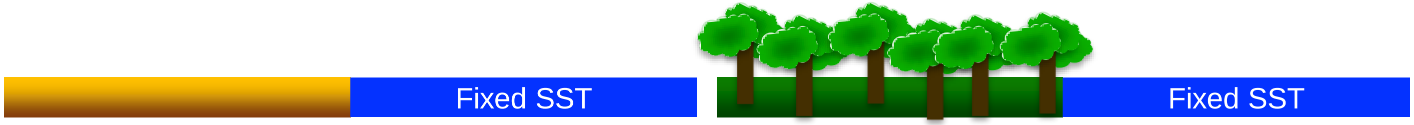


- After 24 hours of simulation (first panel), tracers released from Baguio are being advected westward at about 4 km
- Tracers are advected into the valley region south of Baguio over night and stay through the afternoon, maybe a result from weak horizontal winds in the valley
- By the evening, tracers have advected out of the valley south of Baguio.

(Kawecki and van den Heever, 2019: The roles of island size and orography in the diurnal cycle of tropical convection and aerosol transport. In review Atmospheric Chemistry and Physics)

Vertical Aerosol Redistribution in Two Different Sea Breeze Regimes

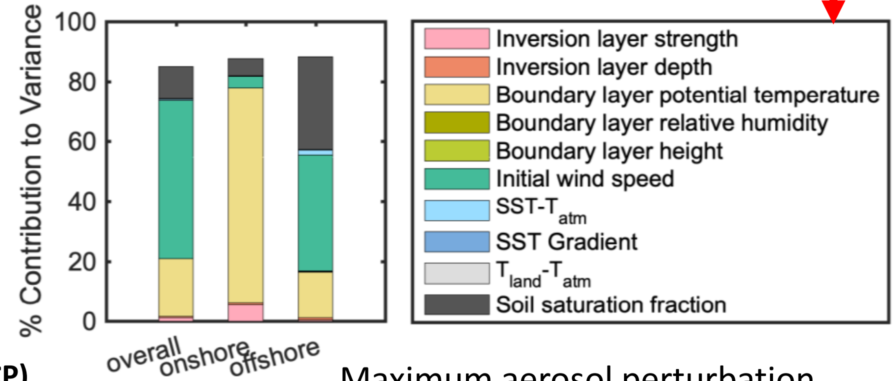
: Dry subtropical desert vs. Moist tropical rainforest



	Dry subtropical desert (Igel et al., 2018)	Moist tropical rainforest (Park et al., 2019)
Vegetation?	No	Yes (evergreen broadleaf tree)
Moist convective processes?	No	Yes (convective clouds and precipitation)
Governing Parameter(s)	Soil saturation fraction	Wind speed, boundary layer potential temperature, and soil saturation fraction (vary depending on the initial wind regime)
Physical processes	Frontal uplift	Sea breeze convergence, convective updraft

In the presence of moist convection ahead of and along the sea breeze front, convective updrafts transport the tracer further aloft than the frontal uplift alone. Therefore, parameters contributing to the updraft strength variability also contribute to the variability in the vertical redistribution of tracer concentrations.

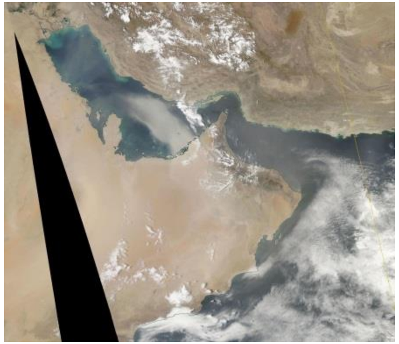
(Park et al, 2019: Environmental Controls on Tropical Sea Breeze Convection and Resulting Aerosol Redistribution. To be submitted to ACP)

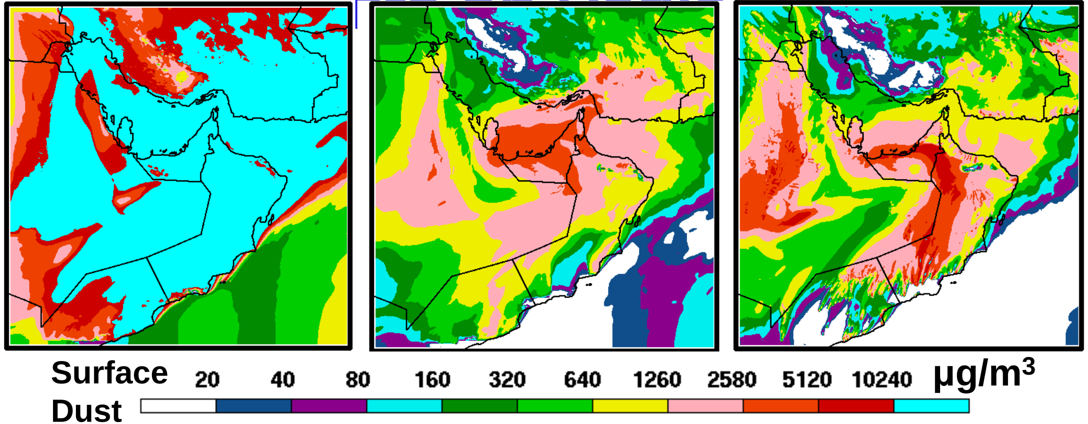


Maximum aerosol perturbation

Variability in Dust Lofting Schemes and

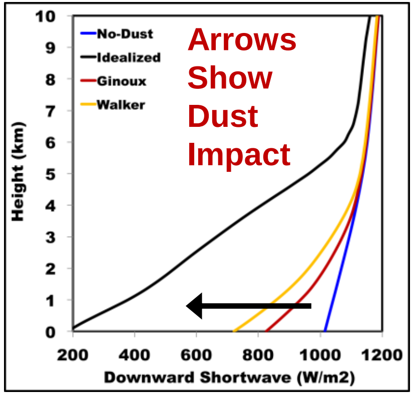
MODIS Visible Imagery | Idealized Dust Lofting | Ginoux Dust Source | Walker/NRL Dust Source



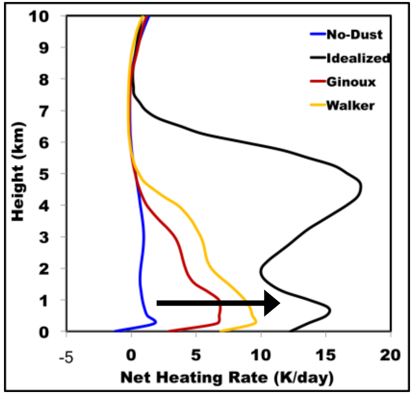


Idealized dust lofting generates far more dust mass than when using databases that constrain lofting potential

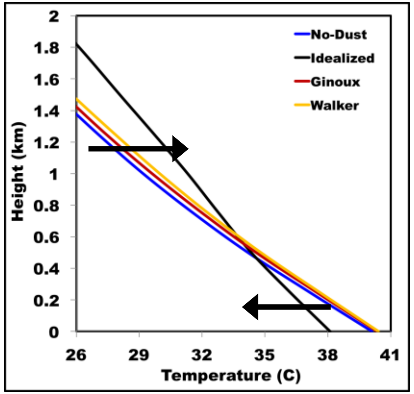
Downward Shortwave



Radiative Heating Rates



Daytime Temperature

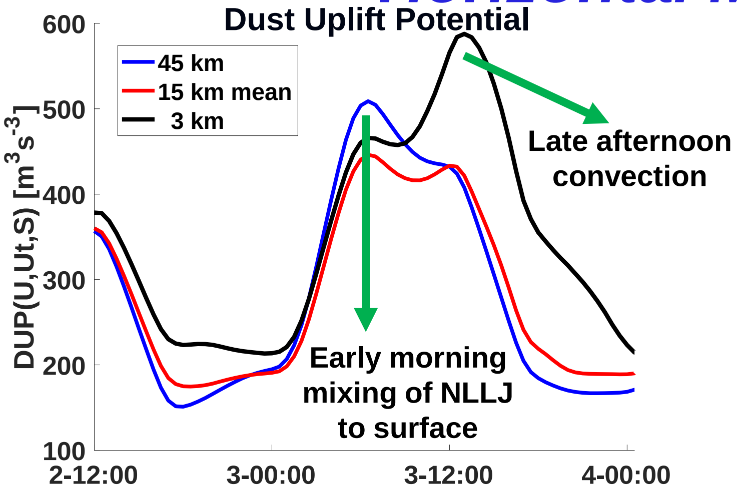


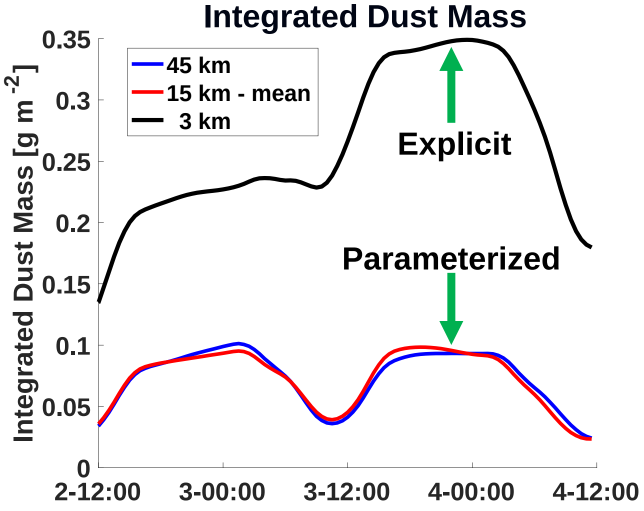
Increased surface dust lofting reduces downwelling shortwave radiation but increases in-situ radiative heating rates.

Competing radiative processes limit the resulting change in temperature except in the case of extreme dust lofting.

(Stephen Saleeby et al. 2019, accepted pending revision at ACP)

Horizontal Model Resolution and Dust Forecasts





Diurnal Effects

Explicit convection simulation has a higher potential for dust uplift during the late afternoon / evening convective maximum

Dust Mass Differences

Difference in dust mass between explicit versus parameterized convection simulations ~100-150%

Radiation Effects

Explicit = SW net cooling effect aloft
Parameterized = LW and SW offset each other aloft

(Bukowski et al. 2019 - in review at ACP)