Observation Operators using Fast Radiative Transfer Algorithms for Cloud Analysis, Visualization, and Assimilation

Steve Albers[1]

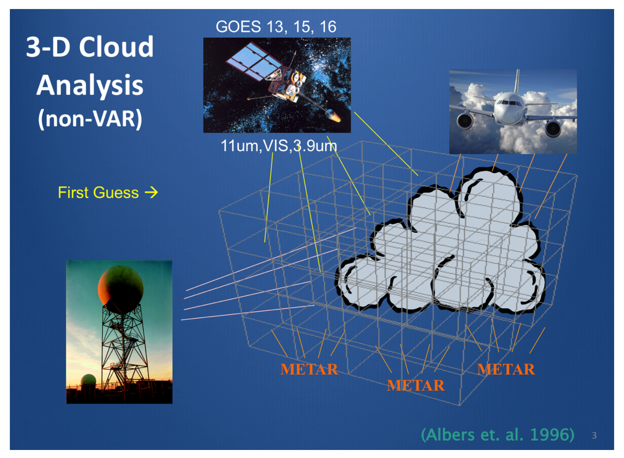
[1]Spire Global, Inc. (steve.albers@spire.com)

Goals

Use fast 3D radiative transfer (RT) package for NWP evaluation with visually & physically realistic simulated image. Develop 1D fast RT package as an observation operator in a variational cloud analysis.

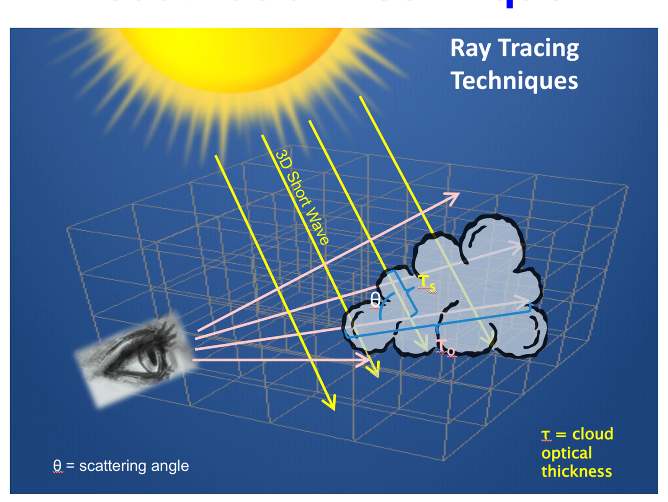
- 3D Simulated Weather Imagery package (SWIm) helps communicate capabilities of high-resolution cloud models, literally "peering inside"
- Display output for scientific and lay audiences
- Visual display conveys a lot of information, providing a **holistic** forecast **visualization**
  - public forecast dissemination via web, media
- Sensitive **independent validation**
  - cloud microphysics, aerosols, land surface, short wave radiation
- Cameras are a potential data source for model data **assimilation,** while the sky simulation package can be used as a forward model to translate the model variables into camera-like images
- 1D package can speed up radiance-based variational cloud analysis.

SWIm Sky Simulation



- Sun and other light sources (moon, planets, stars, artificial lights for day / night use)
- Various models (analyses / forecasts)
  - LAPS, HRRR, FIM, NAVGEM, RAMS
  - 3-D Gridded Cloud / Hydrometeor Fields (cloud liquid, ice, rain, snow)
  - Aerosols (3-D extinction coefficient + optical properties)
  - Atmospheric Gases
- Vantage points can be ground-, air-, or space-based

Visualization Technique



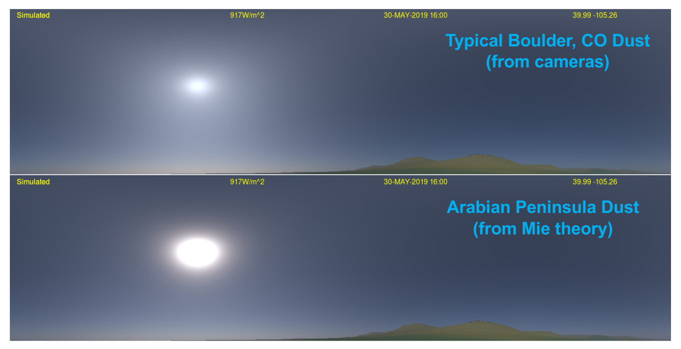
- Physically based fast radiative transfer
  - Simplified **3-D radiative transfer - three visible wavelengths (450, 546, 615nm)**
  - Spectral radiances and reflectances computed
  - RGB images account for color vision and monitor response
- Illumination of clouds, air, and terrain pre-computed
- Forward Ray Tracing from sun and other light sources
- Backward Ray Tracing from vantage point to each sky location
- Scattering by intervening clouds, aerosols, gas (via effective particle radius and optical thickness)
- Terrain included where present along sight lines

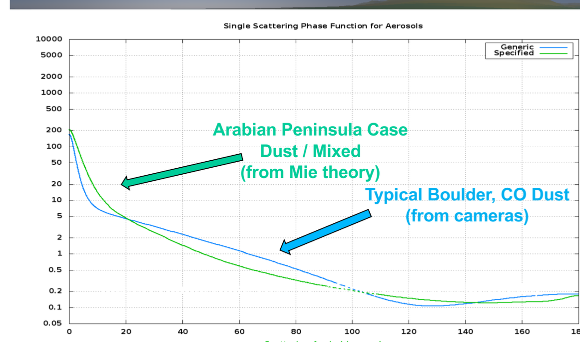
Simulated 3h HRRR Forecast, Seward AK

Clear Air (Gas/Aerosol) Sky Brightness

- Source can be sun or moon
- Rayleigh Scattering by N_2,O_2 Molecules (blue sky)
- Ozone (O_3) absorption
  - Contributes to blue zenithal sky with low sun or twilight
- Mie Scattering by Aerosols
- Cloud/Terrain shadows can show crepuscular rays
- Night-time sky brightness from other light sources
  - Planets, stars, airglow, surface lighting
- Earth shadow geometry considered during twilight

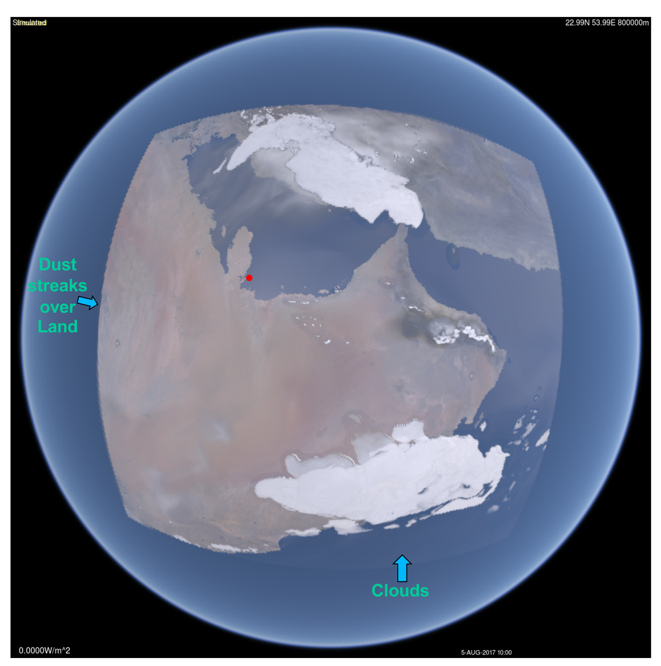
Aerosol Phase Functions





- Double Henyey-Greenstein (DHG) phase functions
  - Two DHG functions combined totalling four parameters

Arabian Peninsula RAMS Simulation



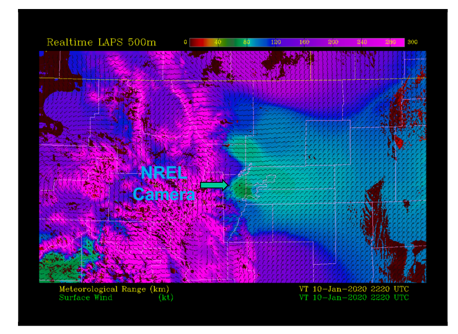
- Viewing perspective at 800km altitude
  - Mixed Dust / Thin Clouds over NW Persian Gulf
  - Light-Moderate Dust over S Persian Gulf and Gulf of Oman
  - Locations below near Qatar in Persian Gulf (red dot above)

- Panoramic view from 4km AGL (zenith to nadir)

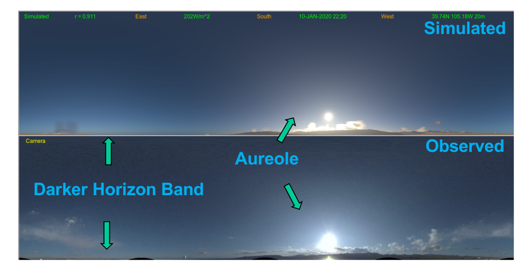
- Panoramic view from 20m AGL
  - Mie scattering from Dust dominates over Rayleigh component

Aerosol Specification

- Global analysis using PM2.5 data and/or ECMWF CAMS
  - Regional version uses HRRR-Smoke in place of CAMS
  - 3D extinction coefficient field is determined
- Visual effect of aerosol / relative humidity dependence
  - Sky brightness
  - Feature Contrast
  - Land / Sky contrast at horizon
- Case studies using Colorado camera testbed
  - Compare simulated sky image from aerosol analysis with camera images
  - Correlation coefficient used as a metric
  - Constrain Optical Properties / Aerosol Fields



Visibility derived from PM2.5 data and 3D aerosol extinction coefficient analysis.



Corresponding Sky simulation / camera comparison

Cloud / Precip Scattering

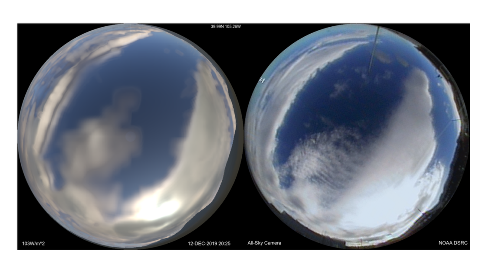
- Mie scattering phase function means thin clouds are brighter near the sun (with "silver lining")
- Thick clouds lit up better when opposite the sun
- Phase function has forward peak with single scattering
  - flattens with multiple scattering parameterization
- Rayleigh scattering by clear air reddens distant clouds
- Rainbows included in scattering phase function

- SWIm visualizing a NOAA HRRR forecast (above)
- Examples below use LAPS cloud analysis

Simulated Aerial 360 Degree View

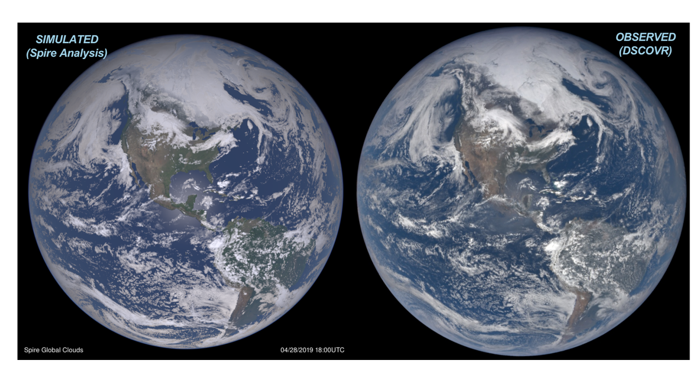
- "Flight Simulator" movie shows airplane landing

Ground-based Camera Validation



Sky simulation (left) from 3-D analysis has relatively good agreement with independent camera

Simulated Earth vs. DSCOVR

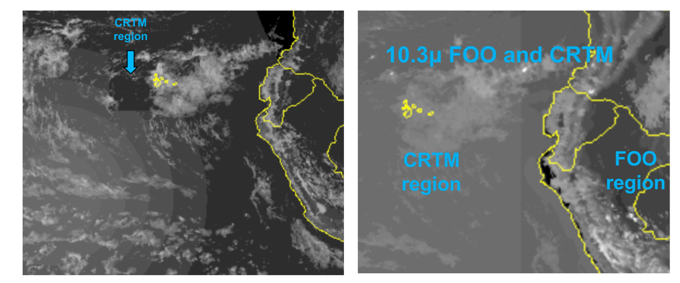


- DSCOVR / EPIC imagery independent of global analysis
  - See next section for cloud analysis procedure
- Holistic validation of Earth System variables
  - Hydrometeors
  - Aerosols
  - Multispectral surface albedo
  - Snow and Ice cover
  - Ocean waves (via sun-glint)

Variational Cloud Analysis

- Developed with simple 1D Fast Observation Operator (FOO) developed for 0.6- and 10.3 micron ABI channels, running ~3 orders of magnitude faster than CRTM (v2.3).
- Control variables are hydrometeor species
- Additional cost function terms planned based on analysis innovation and ambient temperature.
- First guess is 3D non-var LAPS cloud analysis

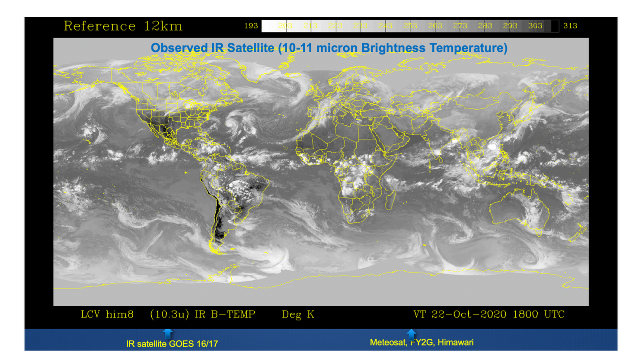
0.6µ FOO and CRTM

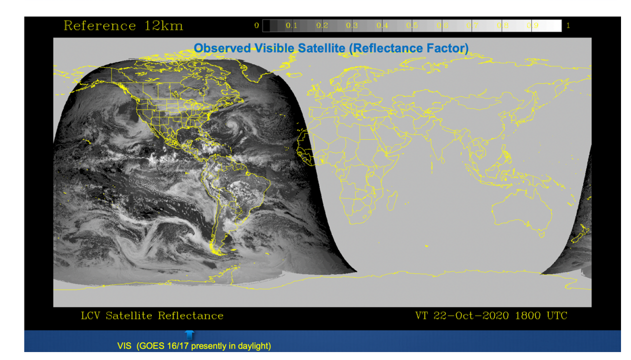


- FOO and CRTM applied to non-var cloud analysis
- IR comparison slightly warmer in clear areas in FOO
- IR RMSE comparison CRTM vs FOO ~2.5K
- Visible less sun-glint from ocean in CRTM
- Both operators give similar cloud appearance comparing in visible and IR

Global Domain Implementation

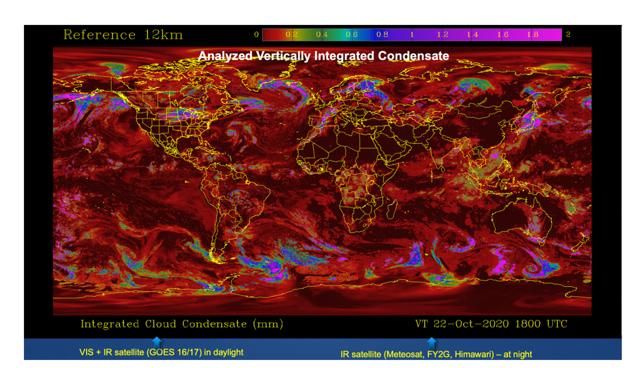
- Run with hourly frequency in real-time
- Utilizes 5 geosychronous satellites spaced in longitude around the world (GOES 16/17, Meteosat, Feng-Yun 2G, Himawari)





Solve for vertical hydrometeor profiles

- Inputs
  - Vertical profiles of cloud liquid, cloud ice, aerosol extinction coefficient
  - Estimated skin temperature, emissivity, snow/ice cover, visible albedo, total column ozone
  - Profiles are processed at every model grid-point without any observation thinning, allowing full-resolution of satellite data to be utilized
- Outputs
  - Simulated 10.3 micron IR brightness temperature
  - Simulated 0.6 micron visible reflectance factor (usually between 0 and 1)

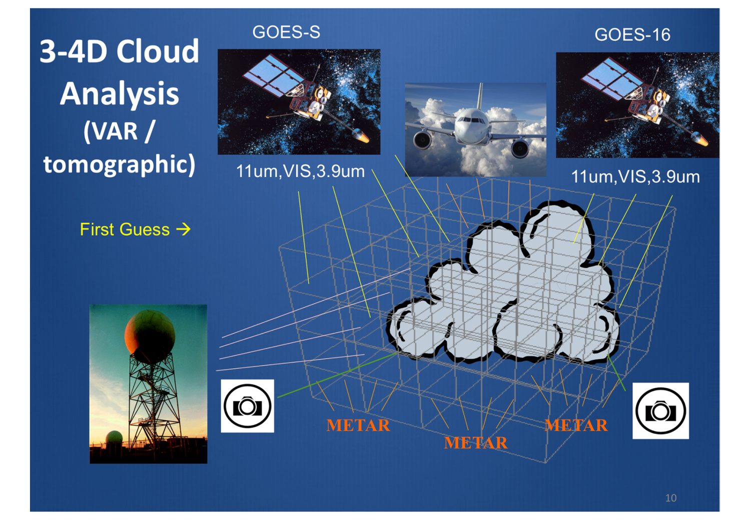


Minimization constraints and strategy

- Specify shape of vertical hydrometeor profile
  - "Correction vectors" (strategic line search directions) utilized since problem is underdetermined
  - One or two search directions based on whether both IR and Visible are available
- Match simulated and observed VIS/IR satellite
  - Satellite 10.3 micron IR brightness temperatures derived from analysis agrees with input satellite within 3K RMSE. Compares with available GFS agreement of 14K.
  - Satellite visible reflectance factor agrees within 3% RMSE. Compares with available GFS agreement of 15%.
- Validate by comparing vertically integrated condensate with independent IMERG precip
  - Useful correlation found despite being "apples" and "oranges"
  - Clouds analysis has improved IMERG agreement vs GFS clouds, with ETS typically increased from .13 to .22

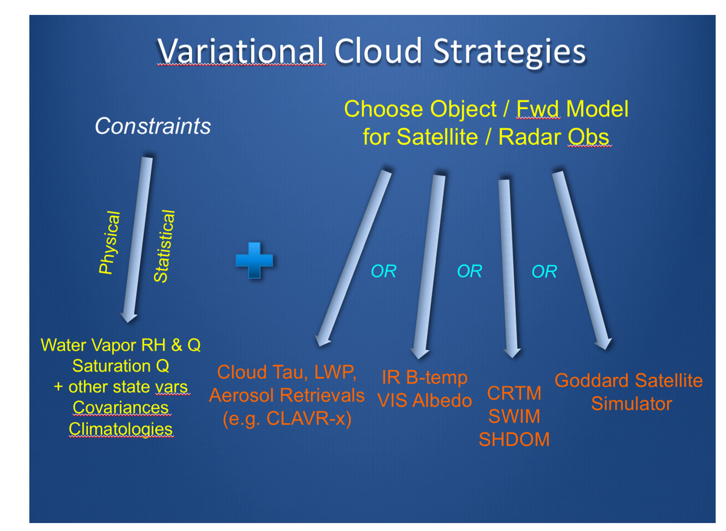
Proposed Tomographic Analysis

- Use **multiple vantage points** to help constrain 3-D cloud structure
- Considers **multiple scattering** in visible light, along with IR channels to variationally diagnose optical and microphysical properties deep within clouds

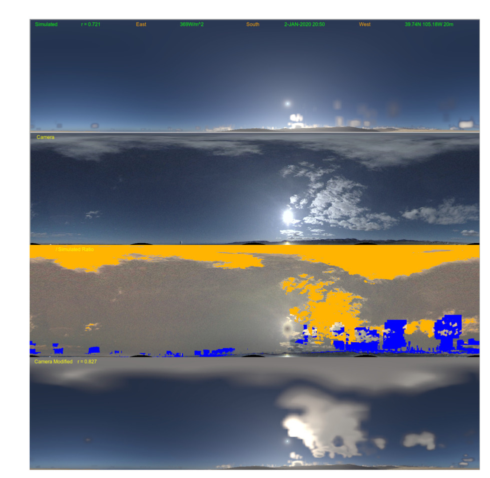


Modular Software Design

- Observation Operators
  - CRTM (mainly for IR – in 2D)
  - SWIm and SHDOM can augment CRTM in 3-D (particularly for visible light)
- Physical and Statistical Constraints added in a modular manner
  - Temperature vs hydrometeor type
  - RH vs hydrometeor content
  - Covariances with state variables
- Applications (incorporating **modular components** into **JEDI** variational framework for minimization and model interfacing)
  - Pre-convective environment (Cu fields)
  - Active convection (Thunderstorm evolution)
  - Solar Energy – detailed cloud and irradiance forecasting



Ground-based Camera Assimilation



Sky simulation from analysis without camera missed the small-scale clouds (correlation r =.721)

Simultaneous NREL camera image

2-D cloud mask derived from camera image (orange - add clouds, blue – subtract clouds)

Sky simulation from 3-D hydrometeor analysis with cloud-mask input (r improved to .827)

References

- S. Albers et. al. 2020: A Fast Visible Wavelength 3-D Radiative Transfer Procedure for NWP Visualization and Forward Modeling (Atmospheric Measurement Techniques)
- Levis et. al. 2015: Airborne Three Dimensional Cloud Tomography.
- H. Jiang et. al. 2015: Real-Time Applications of the Variational Version of the Local Analysis and Prediction System (vLAPS)
- J. Zhou et. al. 2014: A Fast Inverse Algorithm Based on the Multigrid Technique for Cloud Tomography
- T. Vukicevic et. al. 2004: Mesoscale Cloud State Estimation from Visible and Infrared Satellite Radiances
- R. Polkinghorne 2010: Data Assimilation of Radiances in a Cloud Resolving Model
- S. Albers et. al. 1996: The Local Analysis and Prediction System (LAPS): Analyses of clouds, precipitation, and temperature.

Acknowledgements

- NOAA/ESRL LAPS group (including Zoltan Toth) – provided base version of LAPS software and advice with SWIm and cloud analysis development
- Cooperative Institute for Research in the Atmosphere (CIRA) – provided RAMS runs and other support with SWIm development
- NOAA/ESRL HRRR modeling group (including Ravan Ahmadov) – provided HRRR-Smoke fields