Fast Radiative Transfer Algorithms applied in 3-D for multi-spectral visible wavelengths and 1-D with visible and IR for NWP evaluation and Data Assimilation

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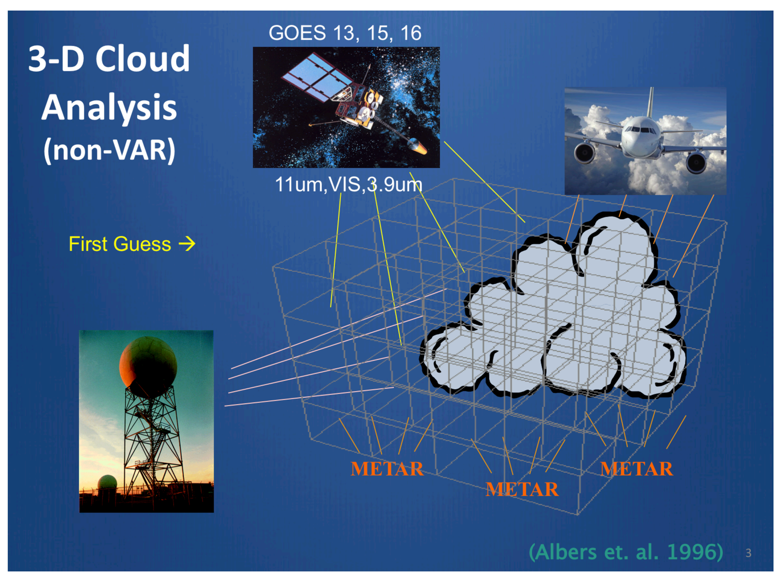
Goals

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

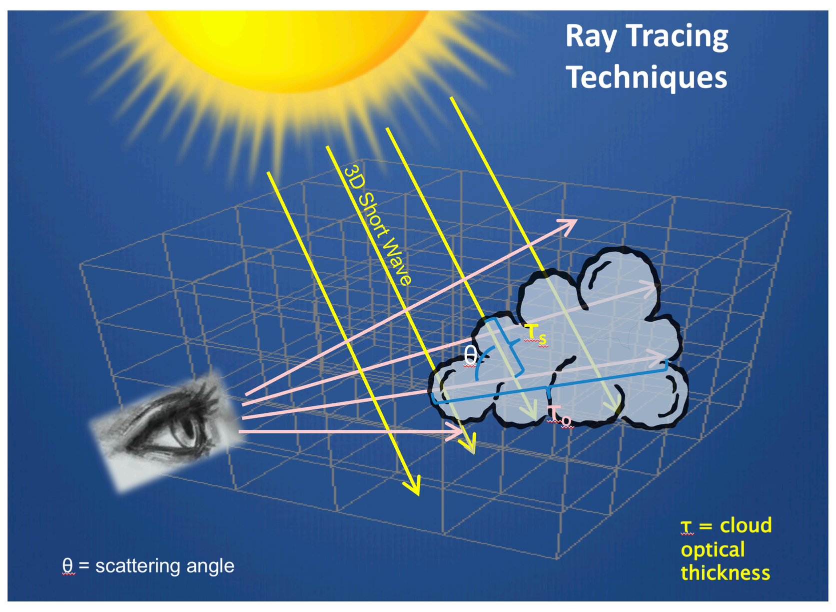
- 3D Simulated Weather Imagery package (SWIm) helps communicate capabilities of high-resolution cloud models, literally "peering inside"
- Display output for scientific and lay audiences
- Visual display conveys a lot of information, providing a **holistic** forecast **visualization**
  - public forecast 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 Components



- 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



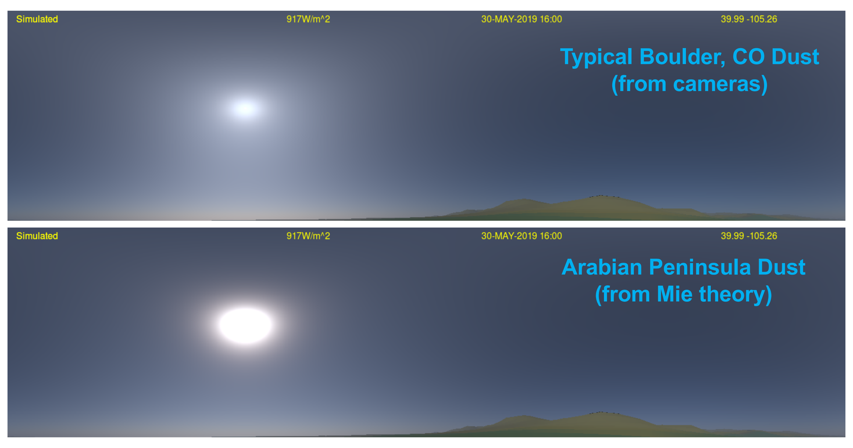
- Physically based fast radiative transfer
  - Simplified **3-D radiative transfer - three visible wavelengths (450, 546, 615nm)**
  - Spectral radiances and reflectances computed
  - RGB images account for color vision and monitor response
- Illumination of clouds, air, and terrain pre-computed
- Forward 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

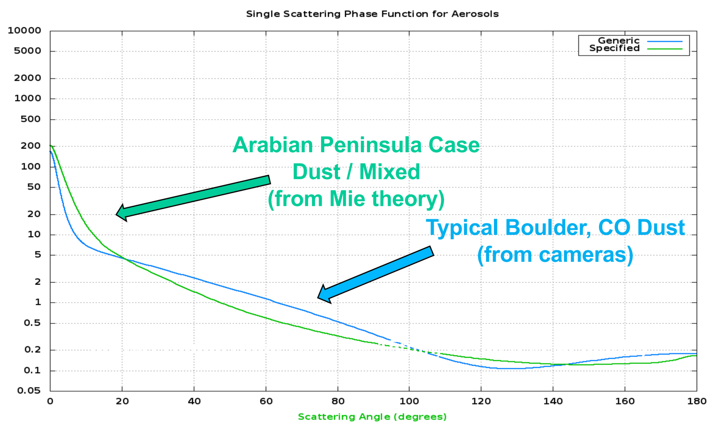
Simulated 3h HRRR Forecast, Seward AK

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

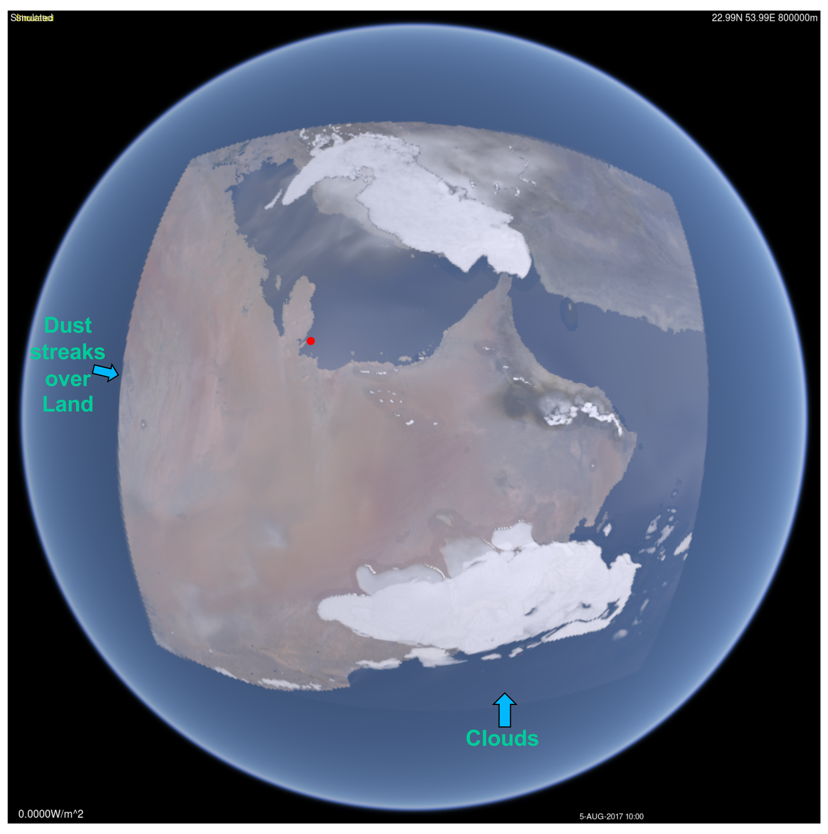
Aerosol Phase Functions



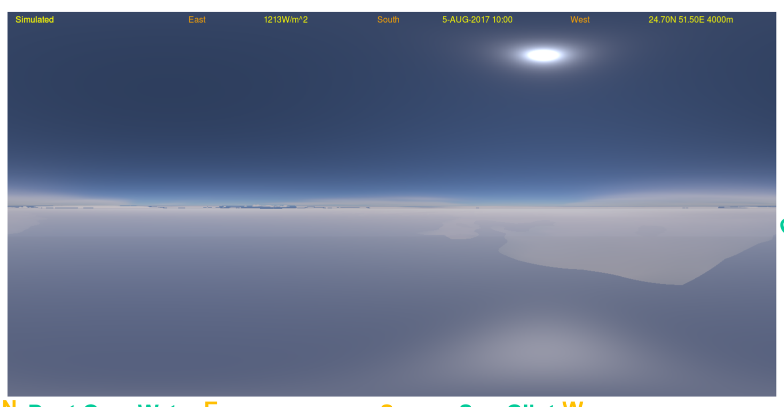


- Double Henyey-Greenstein (DHG) phase functions
  - Two DHG functions combined totalling four parameters

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)

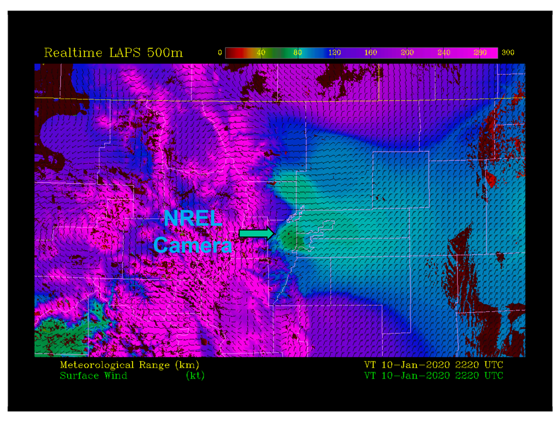


- Panoramic view from 4km AGL (zenith to nadir)

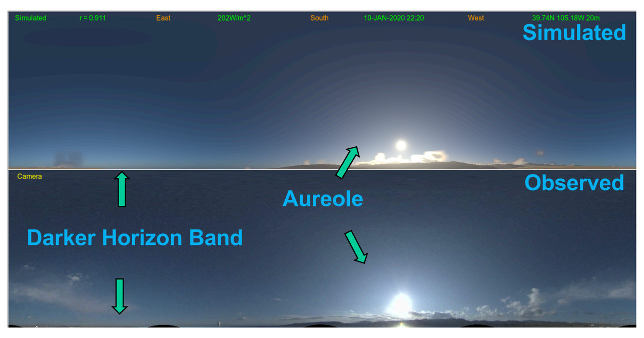
- Panoramic view from 20m AGL
  - Mie scattering from Dust dominates over Rayleigh component

Aerosol Collaborations

- Aerosol analysis using PM2.5 data and/or ECMWF CAMS
- 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

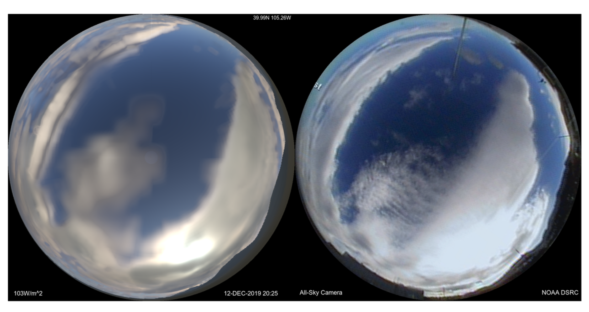
- Mie scattering phase function means thin clouds are brighter near the sun (with "silver lining")
- Thick clouds lit up better when opposite the sun
- Phase function has forward peak with single scattering
  - flattens with multiple scattering parameterization
- Rayleigh scattering by clear air reddens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

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

Simulated Aerial 360 Panoramic View

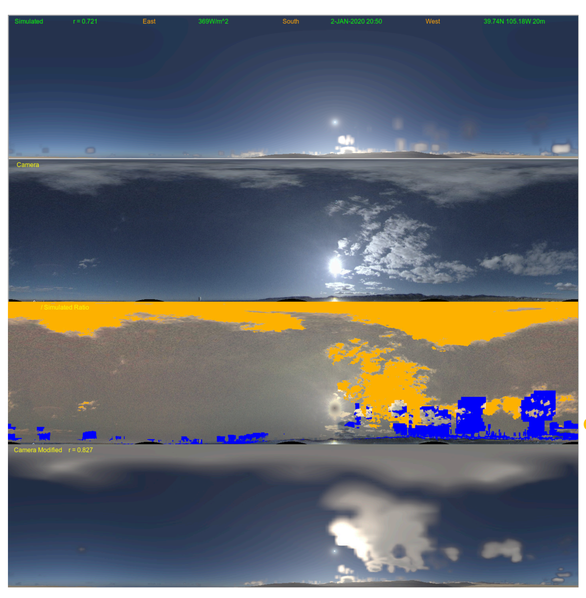
- "Flight Simulator" movie shows airplane landing

Ground-based Camera Validation



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

Ground-based Camera Assimilation



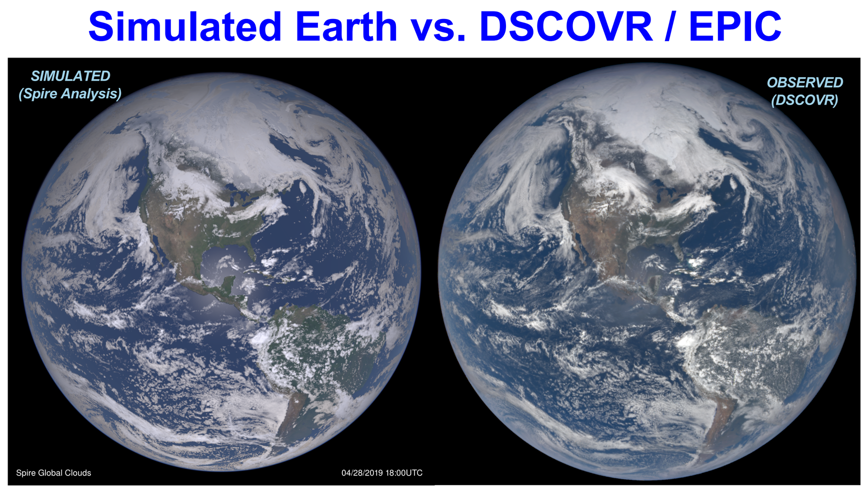
Sky simulation from analysis without camera missed the small-scale clouds (correlation r =.721)

Simultaneous NREL camera image

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

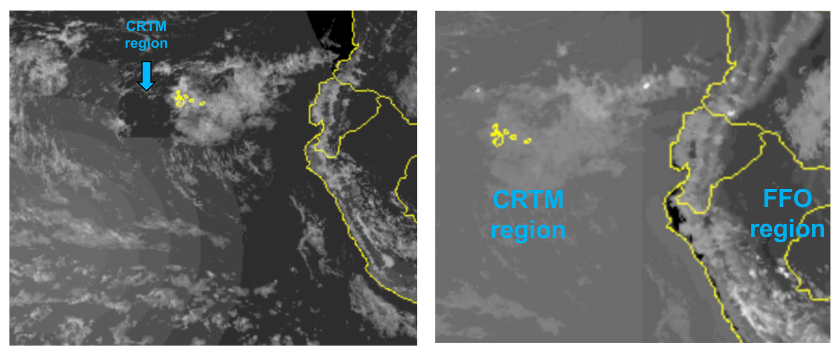
Sky simulation from 3-D hydrometeor analysis with cloud-mask input (r improved to .827)

Simulated Earth vs. DSCOVR / EPIC



Variational Cloud Analysis Development

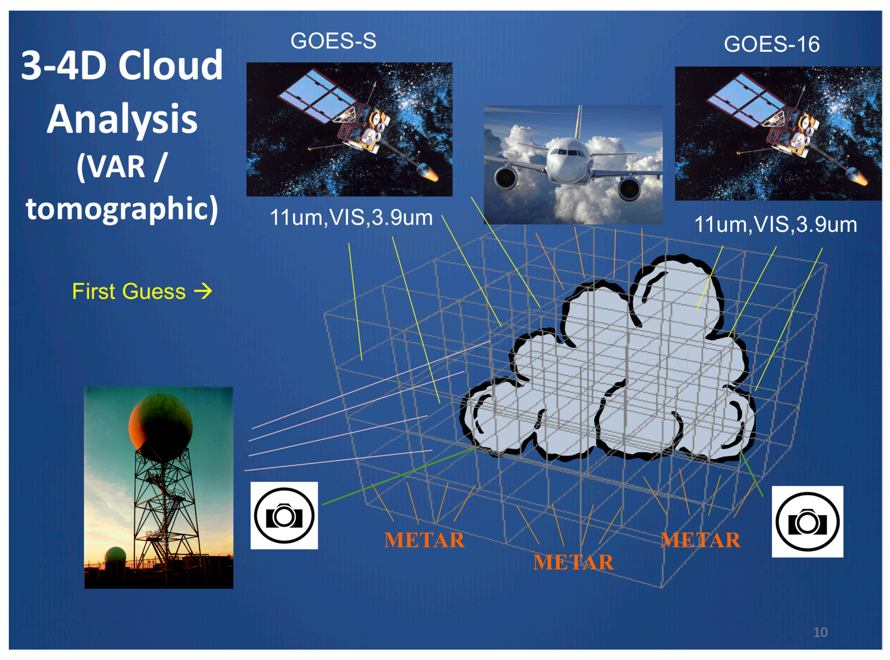
- Tests with simple 1D Fast Forward Operator (FFO) developed for 0.6- and 10.3 micron ABI channels, running ~3 orders of magnitude faster than CRTM.
- Control variables are hydrometeor species
- Additional cost function terms based on analysis innovation and ambient temperature.
- First guess is 3D non-var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



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

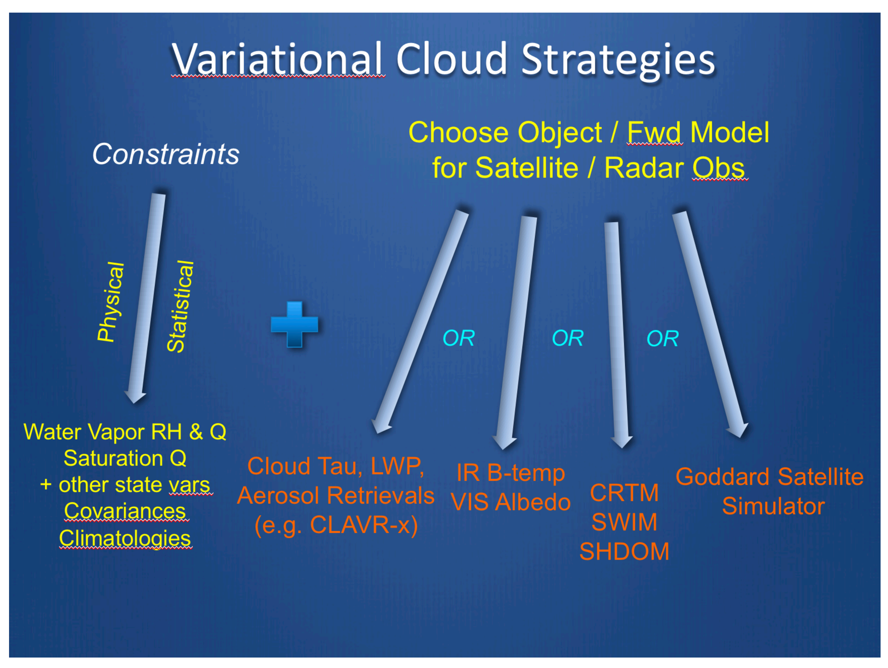
Proposed Tomographic Variational Analysis

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



Modular Software Design

- Forward Models
  - 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



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