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California Institute of Technology
Pasadena, California

Observing Cloud Properties and Processes from the A-Train and Future Sensors

Dong L. Wu

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Outline

- High clouds
  - Water budget and uncertainties of cloud ice in the upper troposphere
  - Aura MLS 240 and 640 GHz
    - Cloud-induced radiance (Tcir) and IWC morphology
  - CALIOP 532nm backscatter (β_{532}) and MLS-path integral (γ_{532})
    - Derived γ_{532}-Tcir and β_{532}-IWC relation
- Low clouds
  - Blind side of the curtain and nadir views -> Multi-angular views
  - MISR high-res cloud height and cloud motion
  - A-Train and future sensors for observing cloud processes
- What is cloud?

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High Clouds

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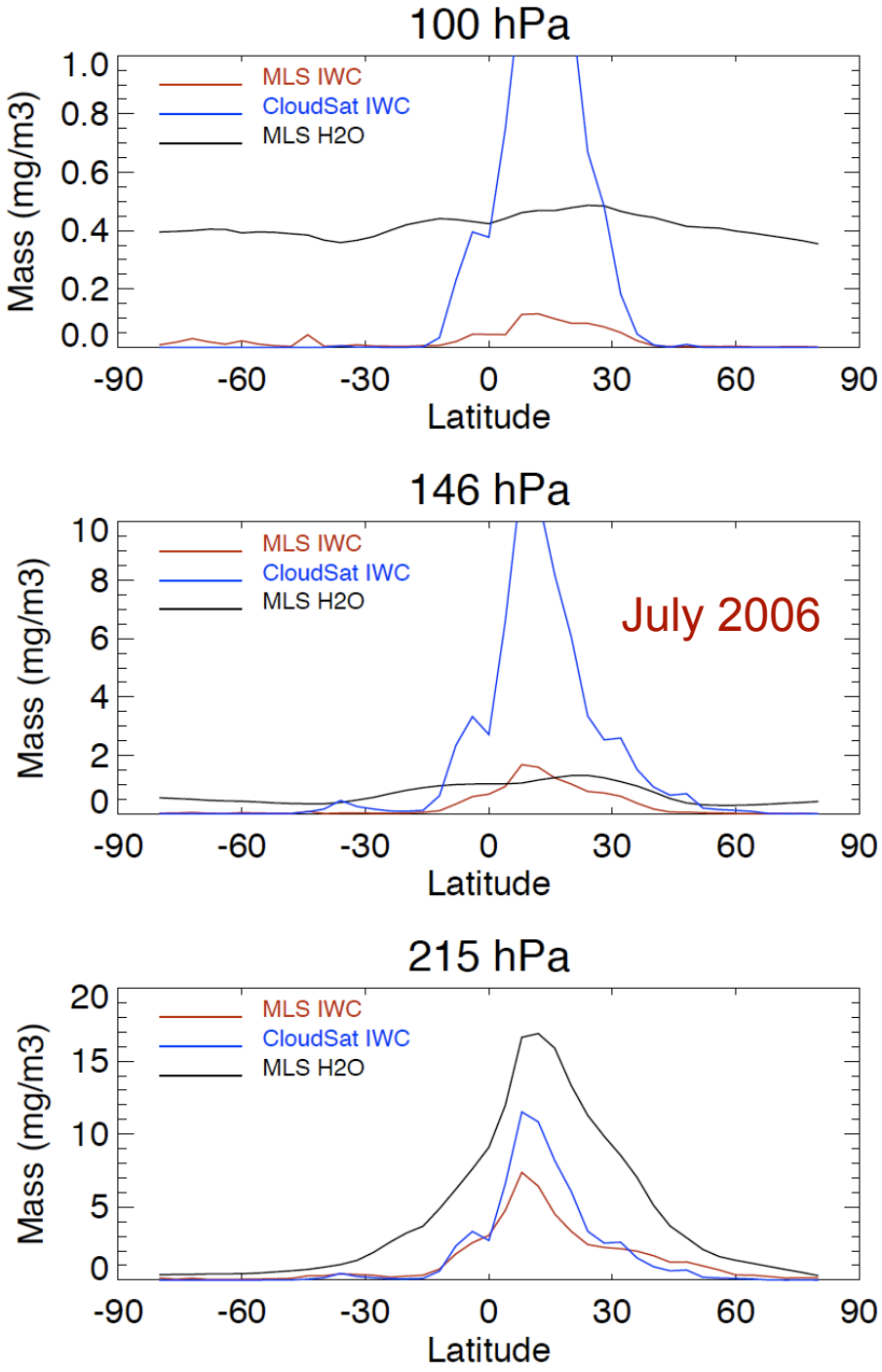
Water Mass Budget in the Upper Troposphere

- 1 mg/m^3 in IWC

  ≈ 10 ppmv in H_2O
- Deep convection as source of the UT H_2O and cloud ice
- Cloud ice vs precipitating ice



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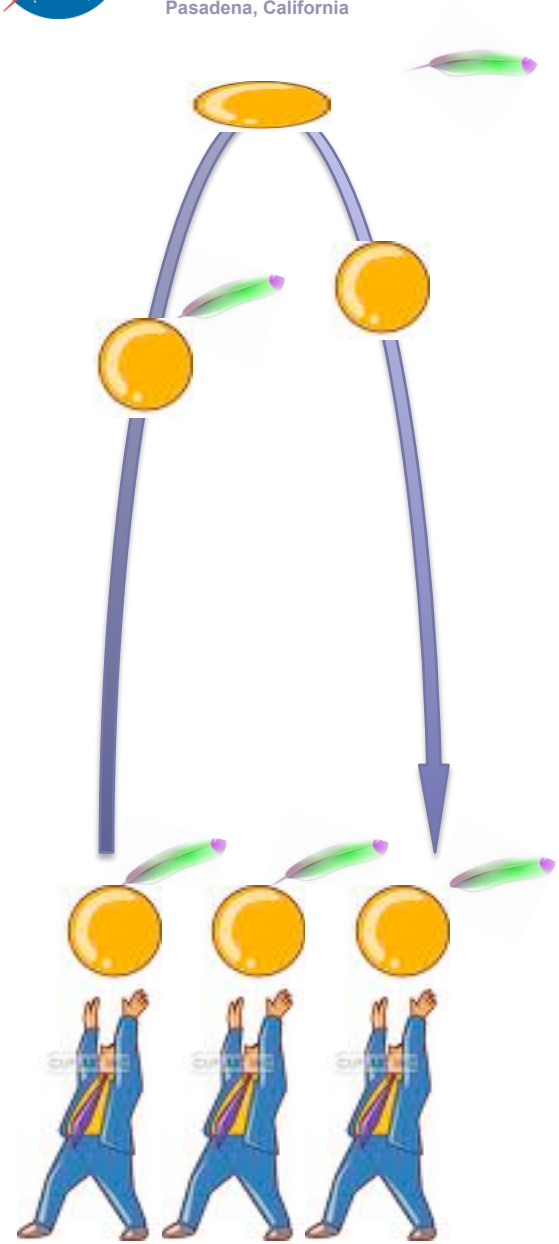
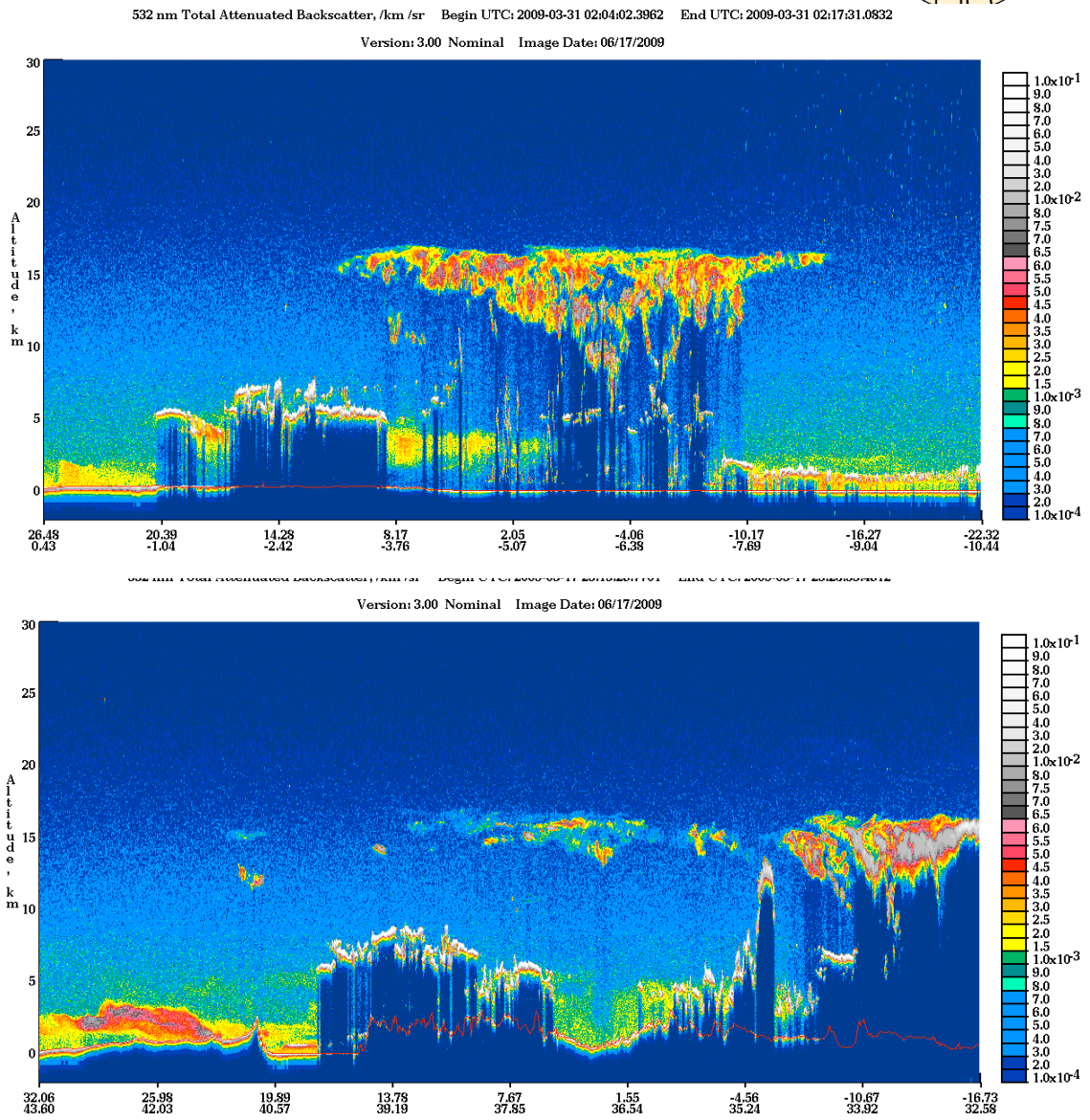
CALIPSO 532nm Backscatters





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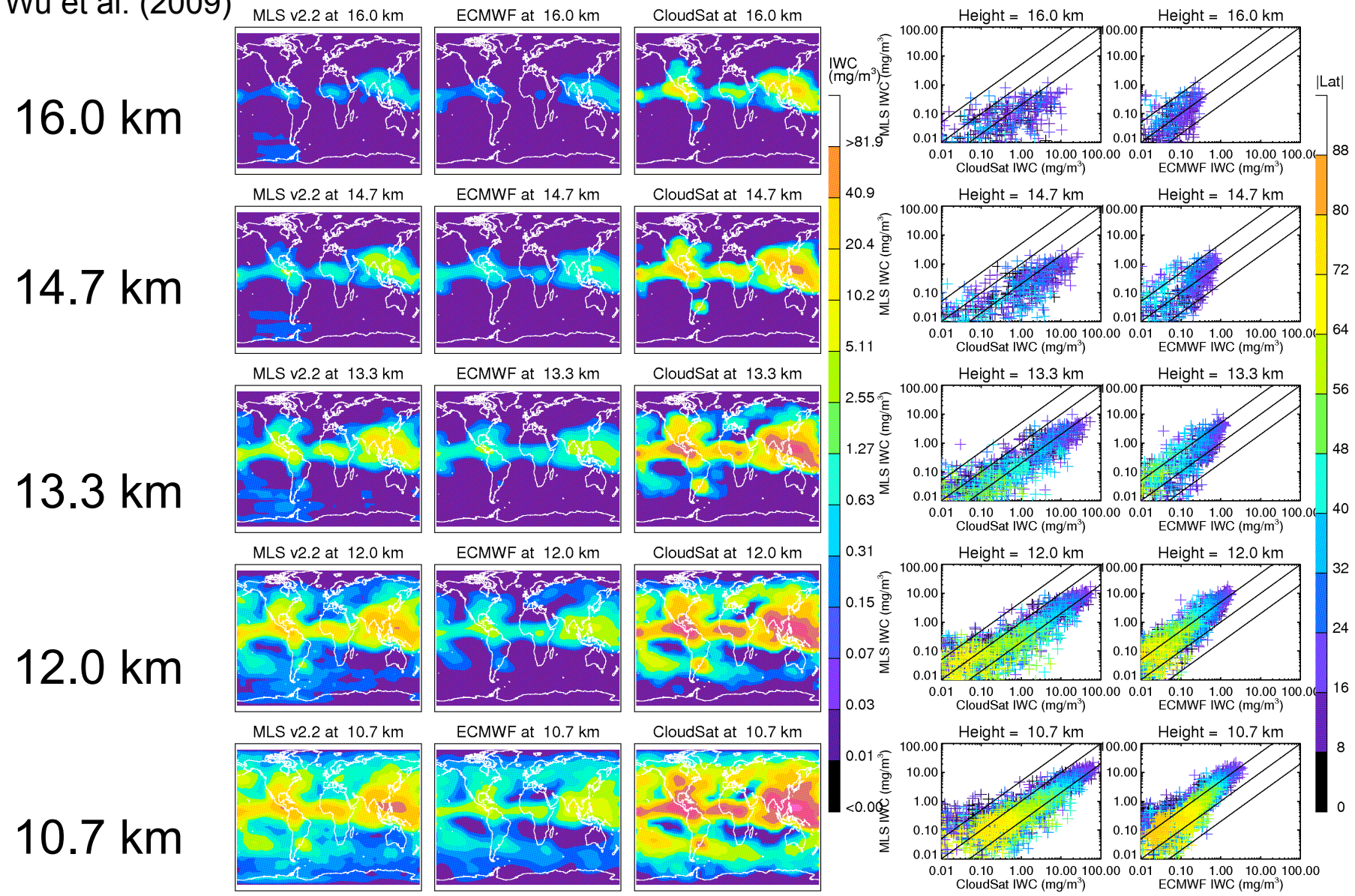
IWC from MLS, CloudSat, ECMWF

Wu et al. (2009)



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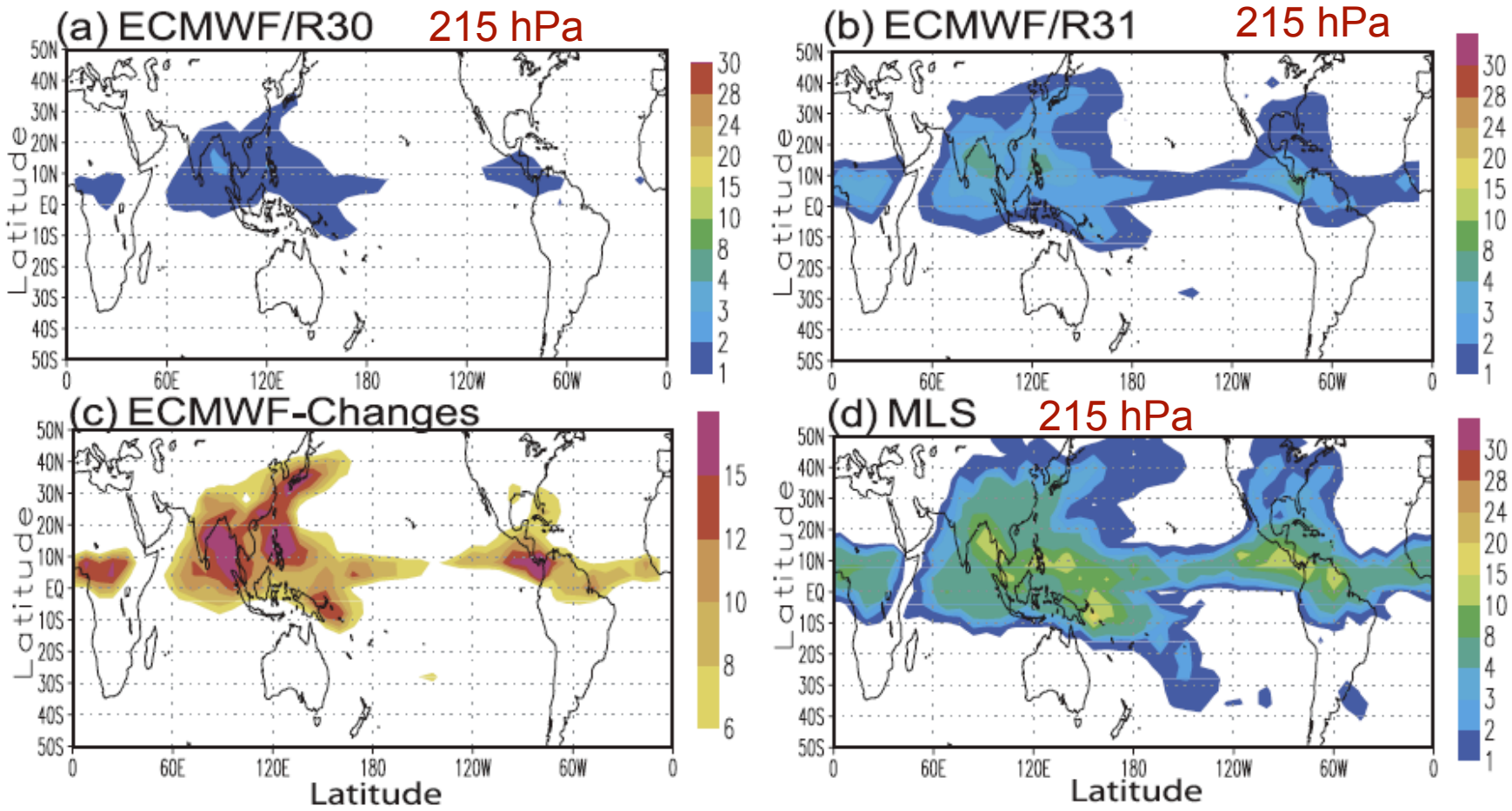
Sensitivity to Cloud Microphysics in Models

- Ice-phase supersaturation allowed
- New scheme for crystal sedimentation
- New scheme for snow autoconversion rate

Tompkins et al. (2007)

Waliser et a. (2009)



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MLS, CloudSat, and CALIOP and on A-Train

MLS IWC

Volume average

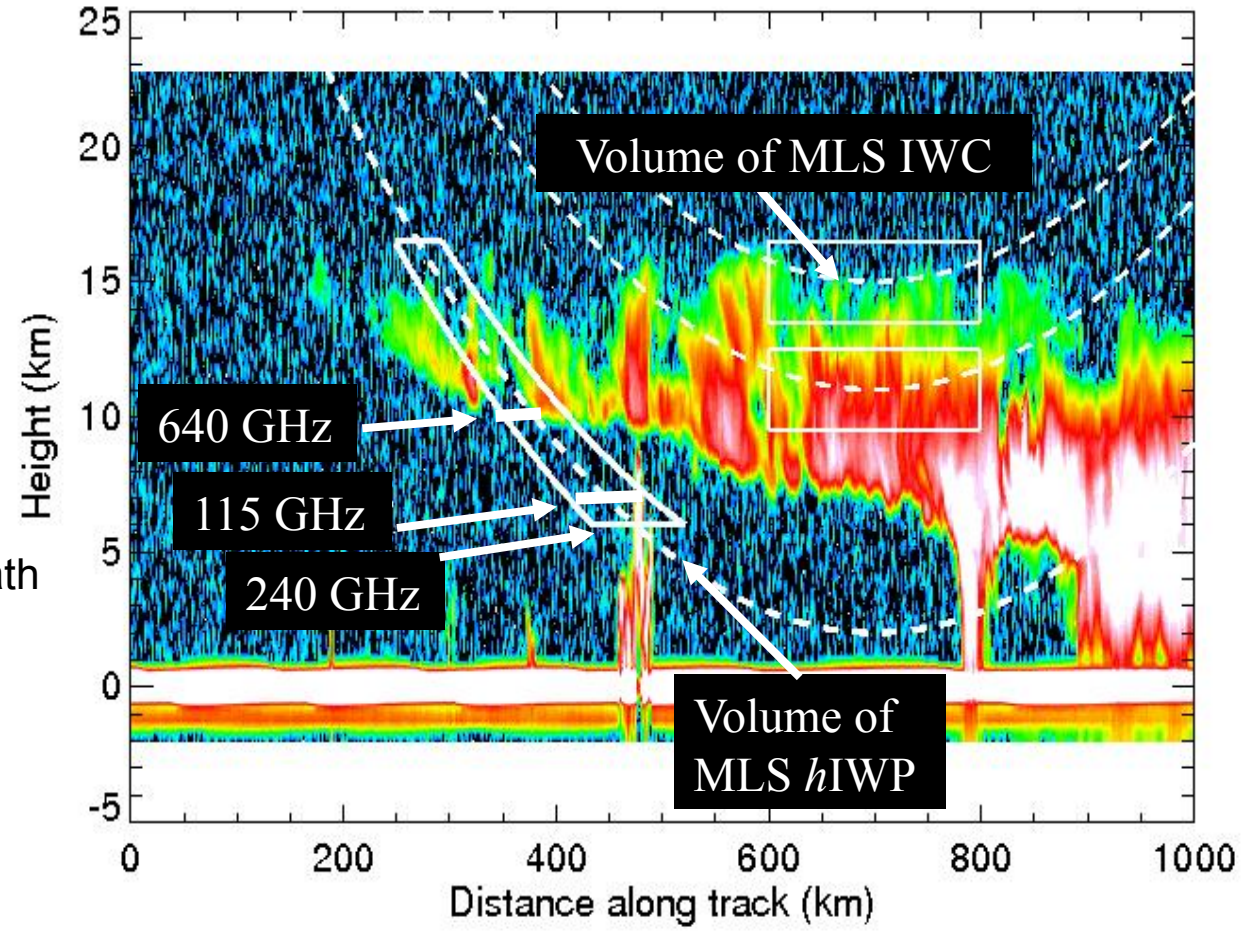
- 200-300 km along track
- 4 km vertically

MLS *h*IWP

A partial column with 3°slant path

Approximate column

Freq, (GHz)	bottom, (km)	cross (km)
118	8	12
190	7	8
240	6	6
640	11	3



$$\beta_{532} \approx 0.4 \bullet IWC \qquad \text{km}^{-1}$$

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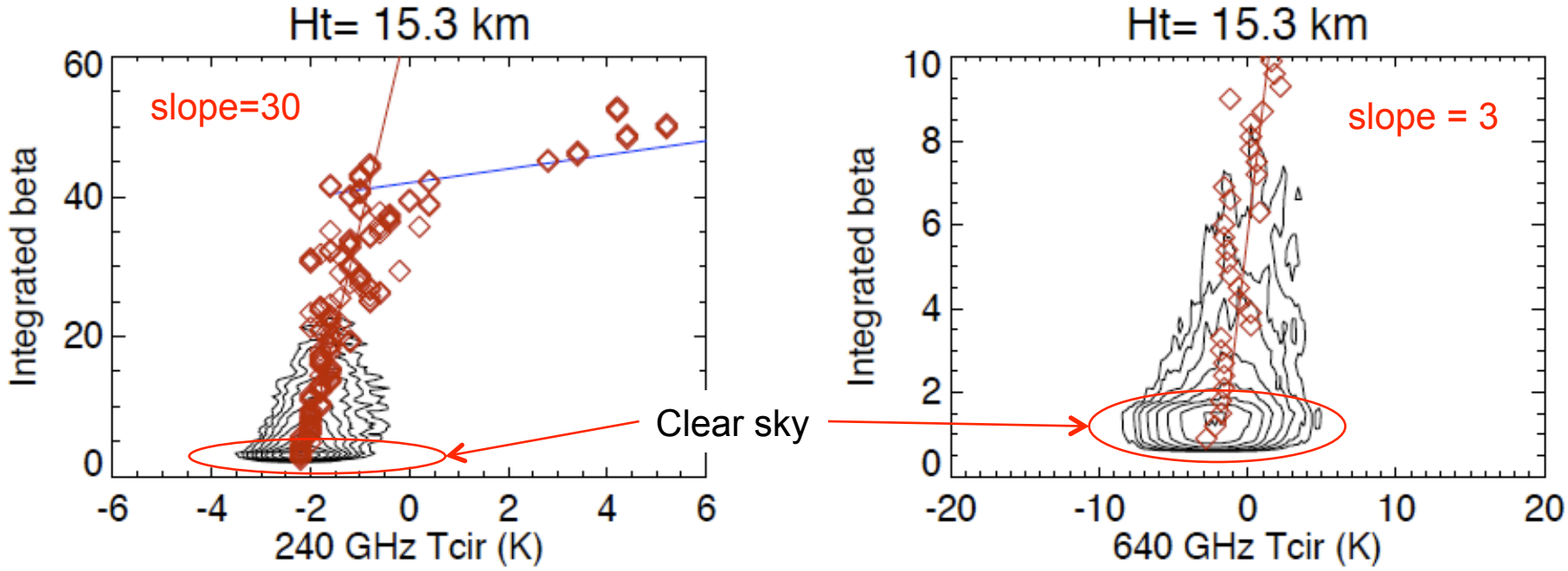
CALIOP-MLS: γ_{532} –T_{cir} Relations

Monthly Statistics



240 GHz

$\gamma_{532} = 30 \bullet Tcir$

640 GHz

$\gamma_{532} = 3 \bullet Tcir$ sr^{-1}

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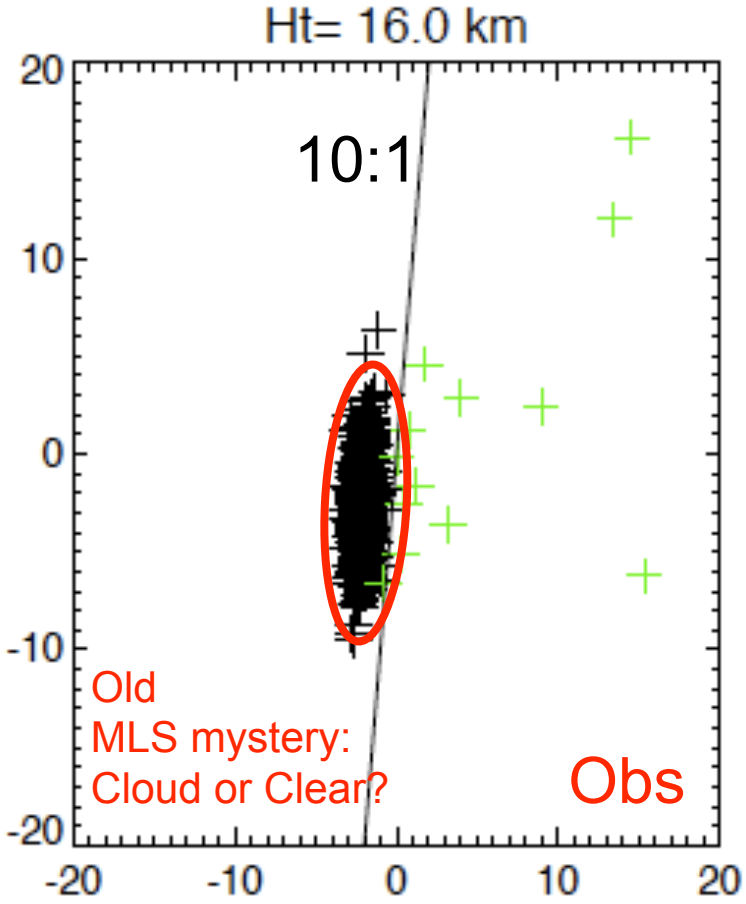
MLS Forward Model (ice cloud emission radiation)

MLS ATBD



$$\beta_{c\_e} \approx \beta_{c\_a} = \int_0^\infty \pi r^2 N(r)(\xi_e - \xi_s)dr$$

$$= \frac{6\pi \,\mathrm{Im}(-K)}{\lambda} \int_0^\infty N(r)\frac{4}{3}\pi r^3 dr$$

$$= 6\pi \frac{\mathrm{Im}(-K)}{\lambda}\frac{IWC}{\rho_i}$$

Courtesy of
Joe Waters

$$= 2.1\frac{IWC}{\lambda}\frac{3\varepsilon''}{(\varepsilon'+2)^2+\varepsilon''^2} \qquad (\mathrm{km}^{-1})$$

$$\varepsilon''_{240} = 0.0081$$

$$\varepsilon''_{640} = 0.0243$$

$$\frac{\beta_{c\_e}(640)}{\beta_{c\_e}(240)} = \frac{\lambda_{240}}{\lambda_{640}}\frac{\varepsilon''_{640}}{\varepsilon''_{240}} \approx 8:1$$

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β_{532}–IWC Relation

$$\Delta T_{cir} = T_0 \Delta \tau_{cir} = \beta_{c\_e} \Delta s = 2.1 \frac{IWC}{\lambda} \frac{3\varepsilon''}{(\varepsilon' + 2)^2 + \varepsilon''^2} \Delta s$$

$$\Delta T_{cir}(240) = 0.015 \bullet IWC \bullet \Delta s$$

$$\gamma_{532} = \beta_{532} \bullet \Delta s = 30 \bullet T_{cir}(240)$$

$\beta_{532} = 0.45 \bullet IWC$ km^{-1}

$$\Delta T_{cir}(640) = 0.12 \bullet IWC \bullet \Delta s$$

$$\gamma_{532} = \beta_{532} \bullet \Delta s = 3 \bullet T_{cir}(640)$$

$\beta_{532} = 0.36 \bullet IWC$ km^{-1}

$$\beta_{532} \approx 0.4 \bullet IWC \quad \text{km}^{-1}$$

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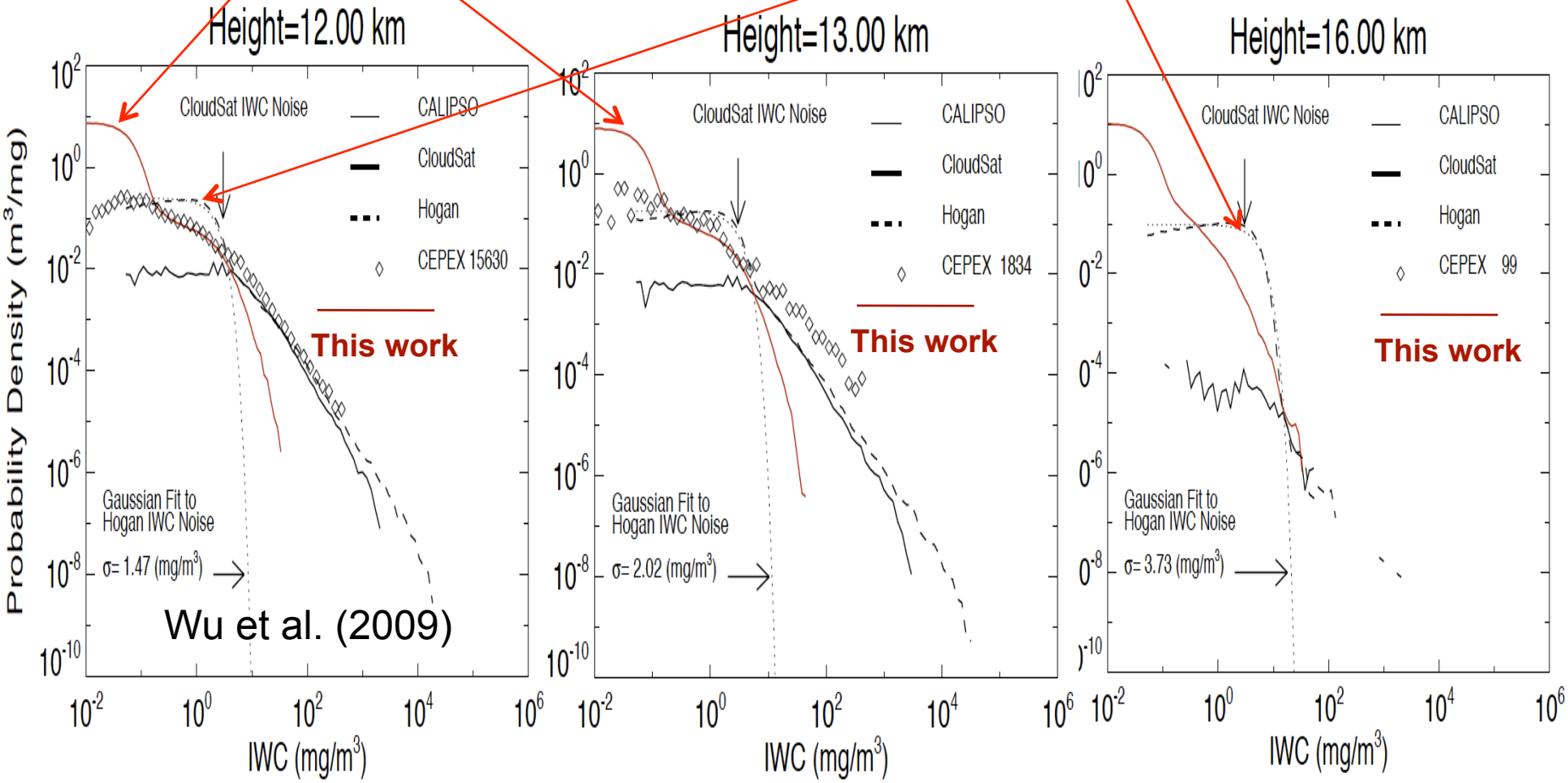
CloudSat and CALIOP IWC

CALIOP noise: ~0.1 mg/m^3

CloudSat noise: 1-4 mg/m^3



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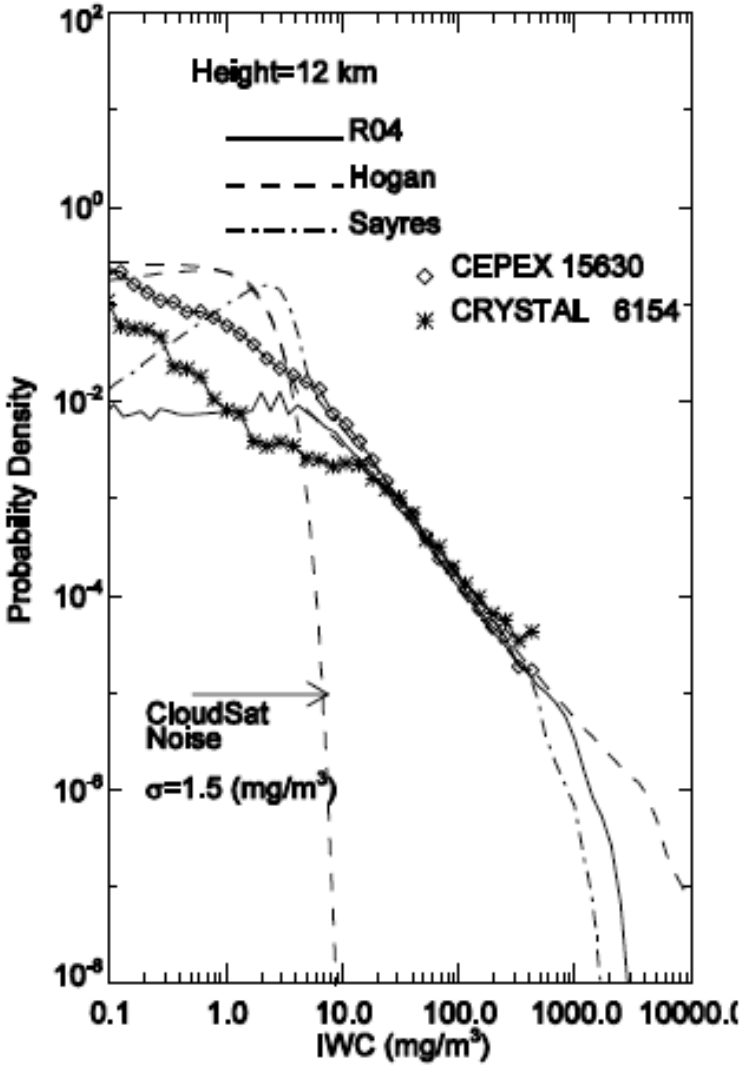
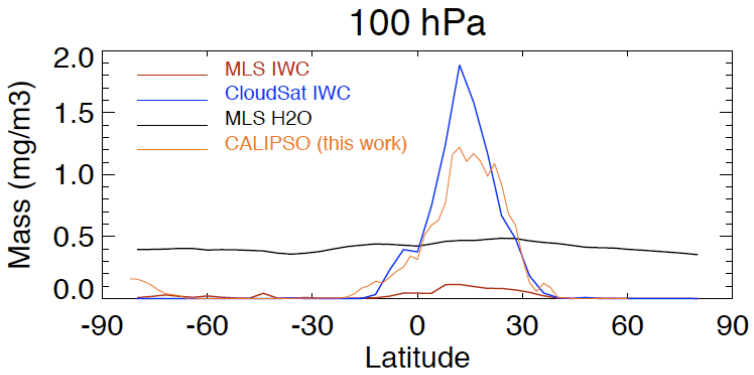
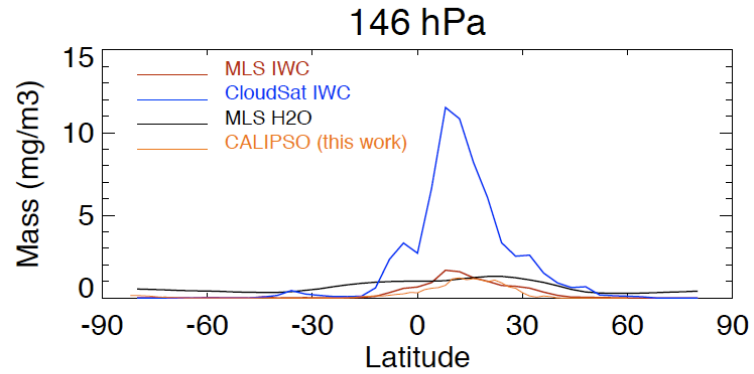
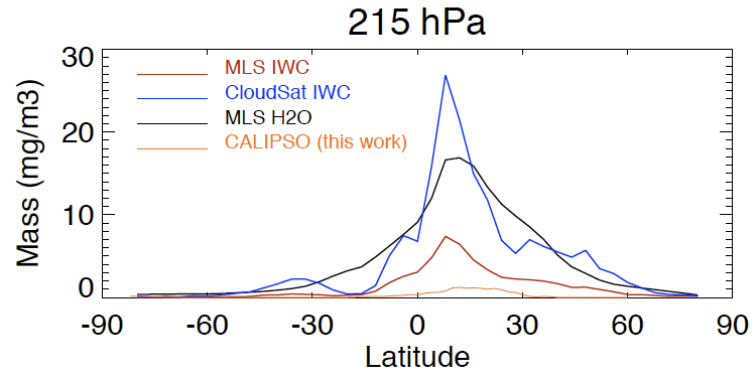
UT Ice Mass Probability Distribution









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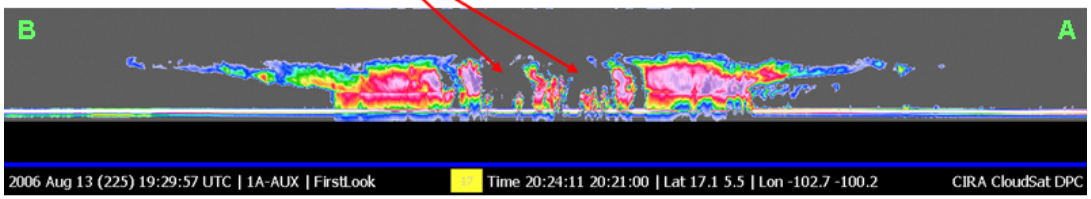
Limitations of Curtain and Nadir Views

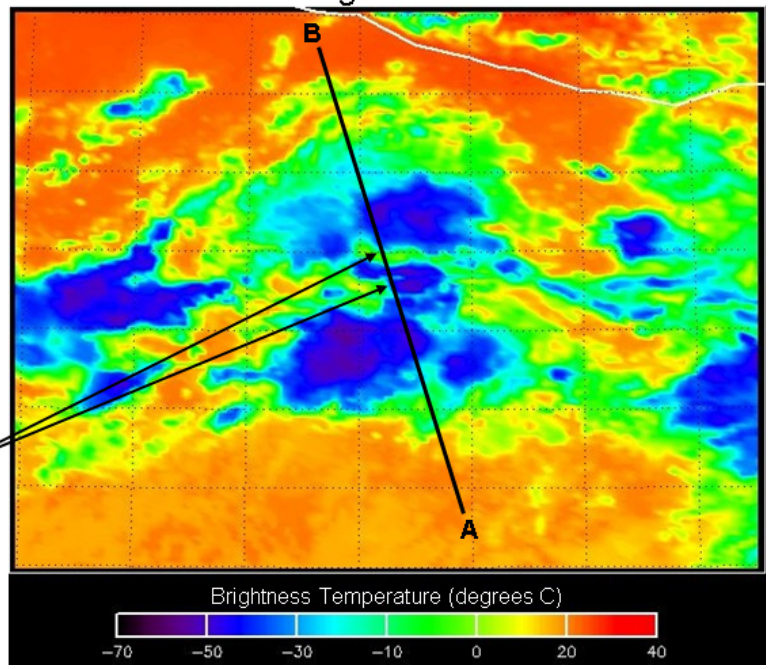
- Cloud and Precipitation Processes:
  - 3D
  - 10s m – 100s km
  - Inhomogeneous
  - Dynamic
- Other dimensions
  - Doppler lidar/radar
  - Advanced vis/IR multi -angle imagers
  - High-frequency μ-wave radiometers

No, this is not a hurricane. Although the two sides of this storm are symmetrical, the cloud-free zone in the center is far too large to be the eye of a hurricane.



By comparing the Quicklook image above with the GOES-11 satellite image below, we see that CloudSat is viewing a vertical slice of a tropical convection off the Southwest coast of Mexico, a product of the Inter-Tropical Convergence Zone (ITCZ) near the equator.

Notice that the cloud-free zones can be seen on the GOES-11 image as well.



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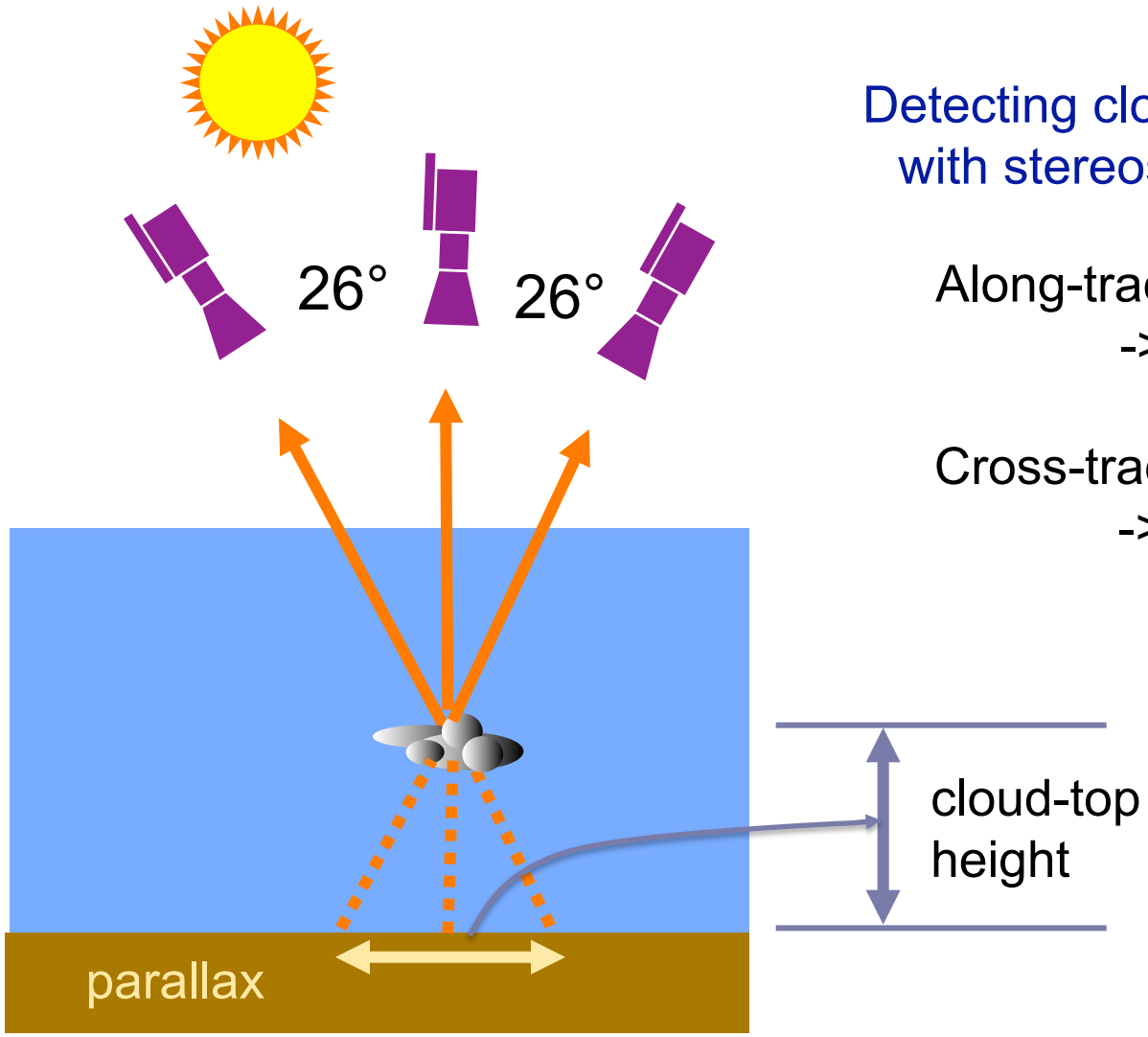
Multiangle Imaging SpectroRadiometer (MISR)



Detecting cloud height and wind with stereoscopic techniques:

Along-track parallax:
-> cloud height

Cross-track displacement:
-> cloud motion

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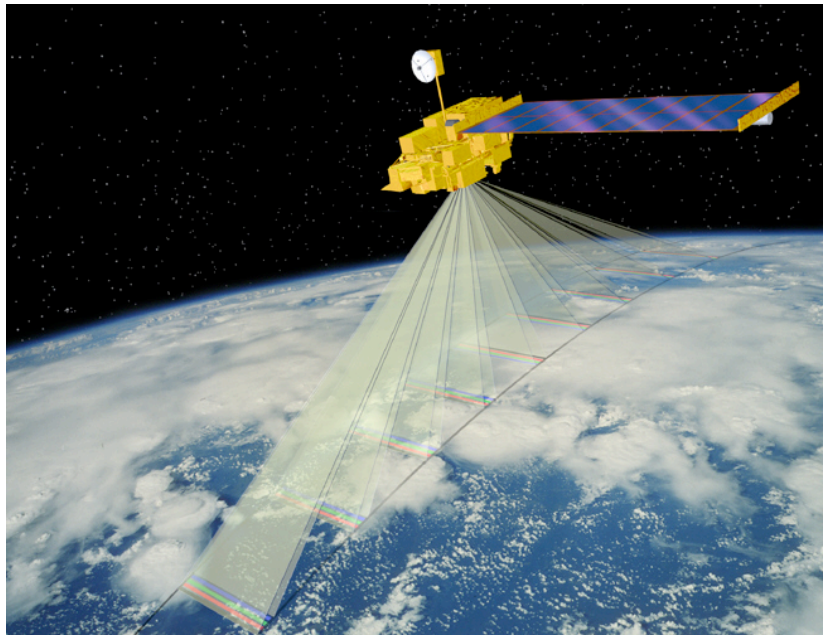
Multi-Angular Views

- MISR
  - Nadir ±26º, ±46º,±60º, ±70º
  - 446, 558, 672, 866 nm
  - 400-km swath
  - 275 m - 1.1 km resolution

movies



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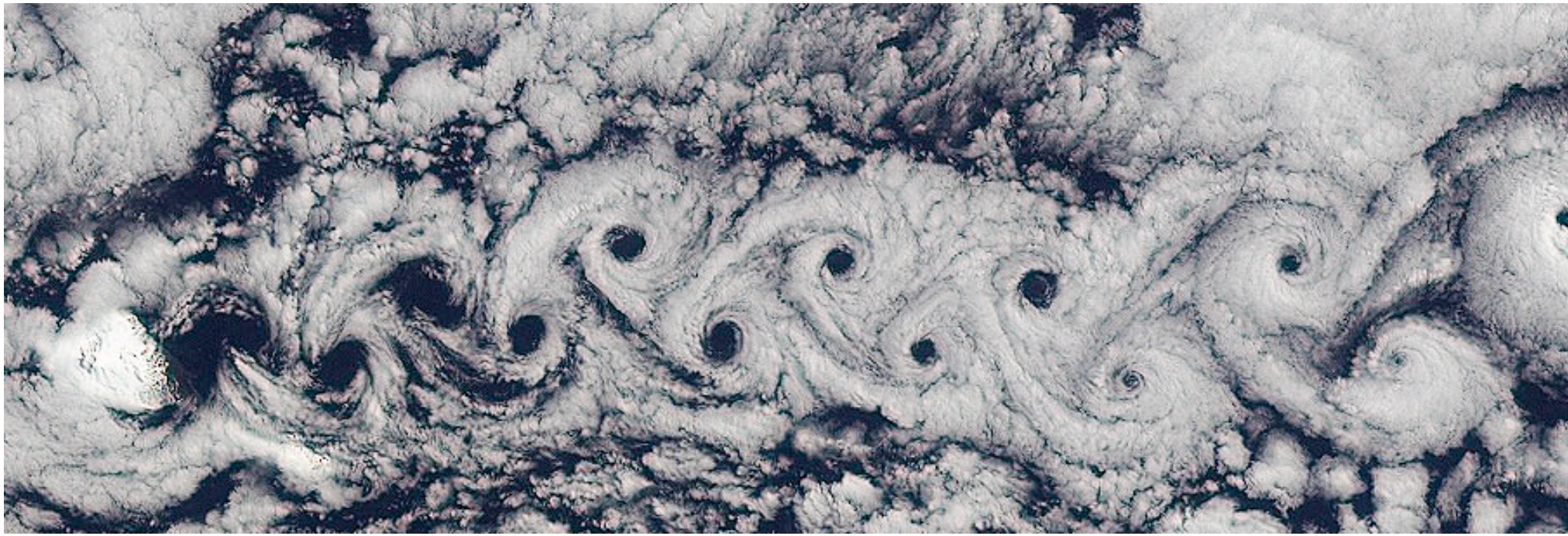
Von Karman vortex street near Jan Mayen Island



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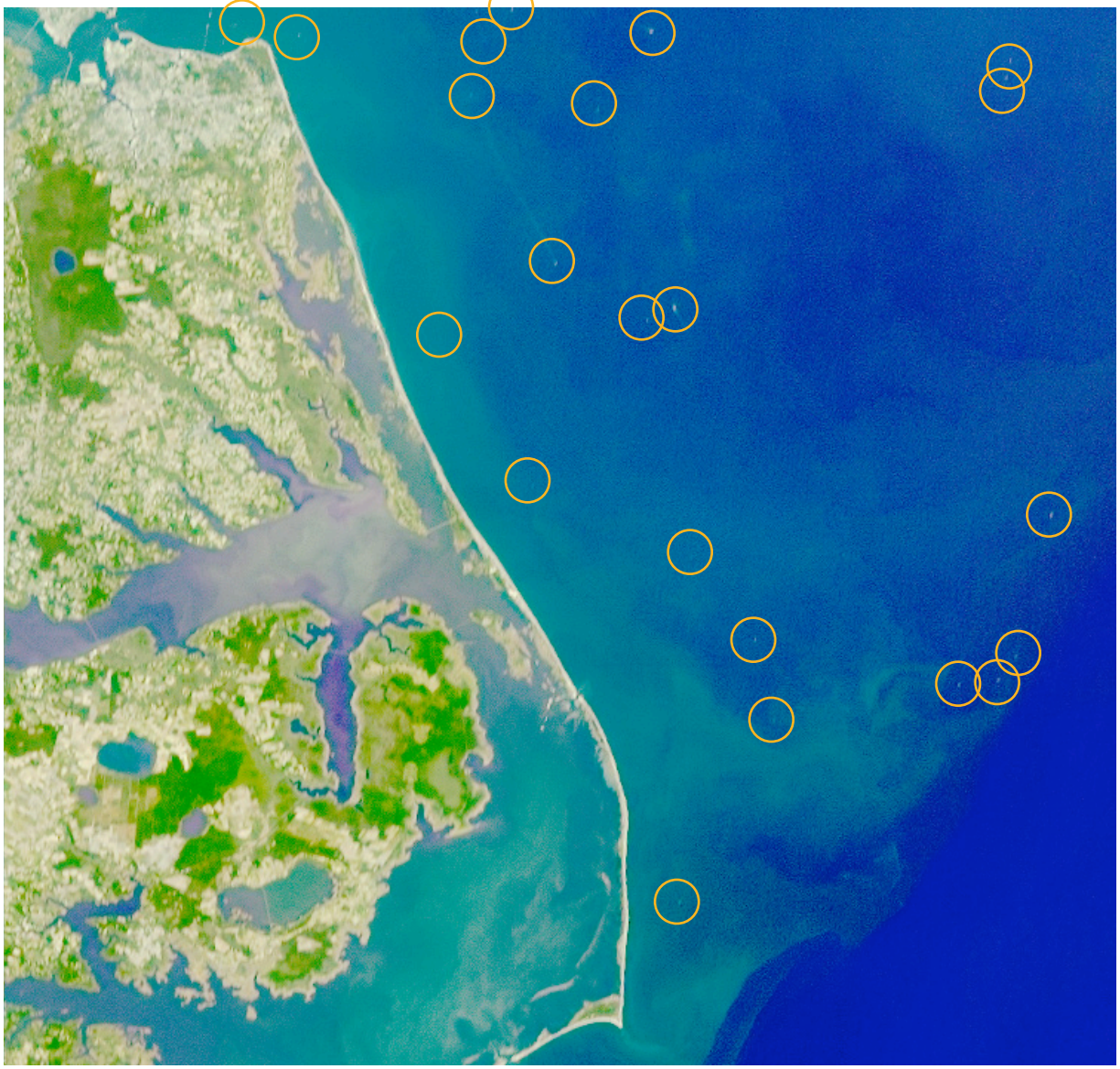
Time lapse: moving boats off N. Carolina coast



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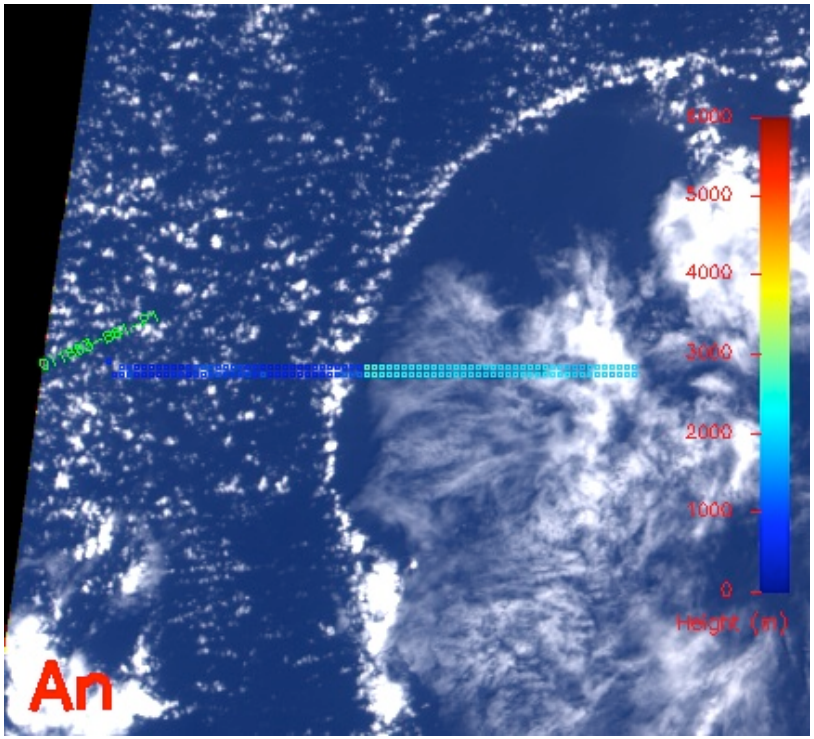
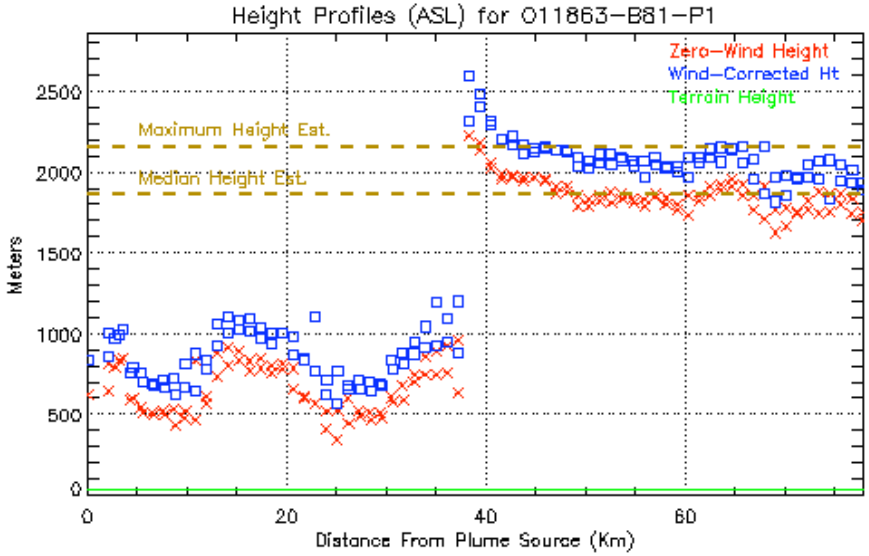
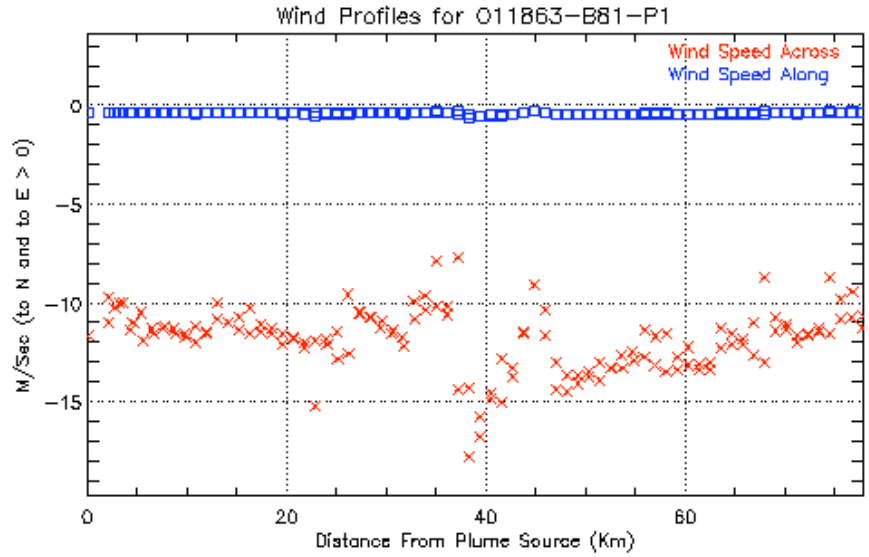
Dynamics and Cloud Processes







Resolution: 1.1 km

Precision:

height: ~100 m

wind: ~0.3-1 m/s

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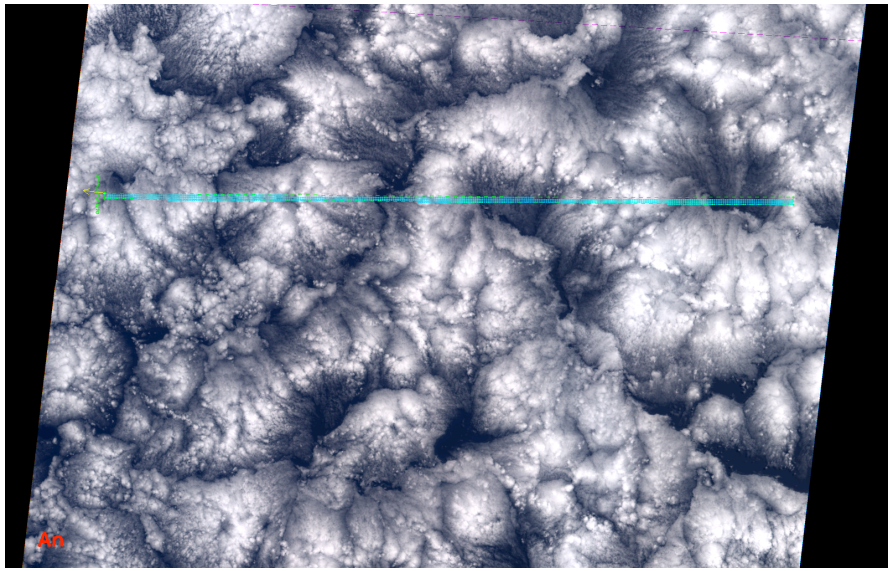
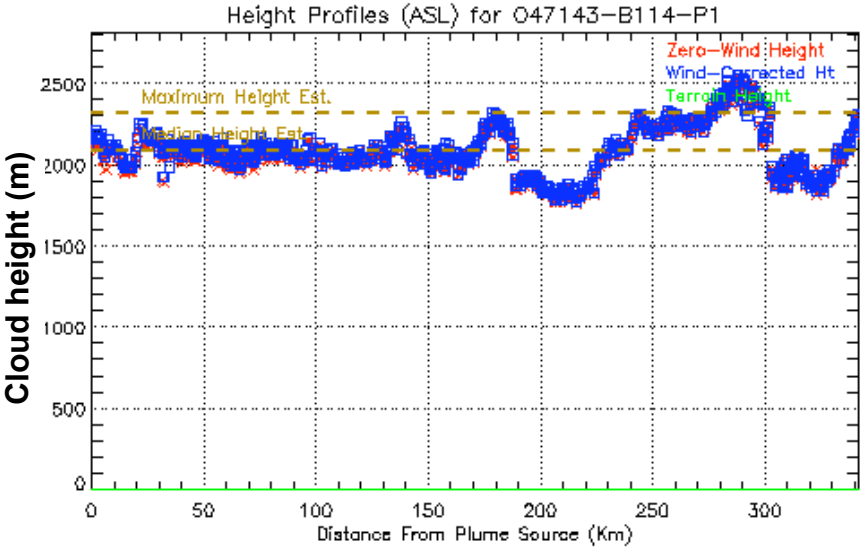
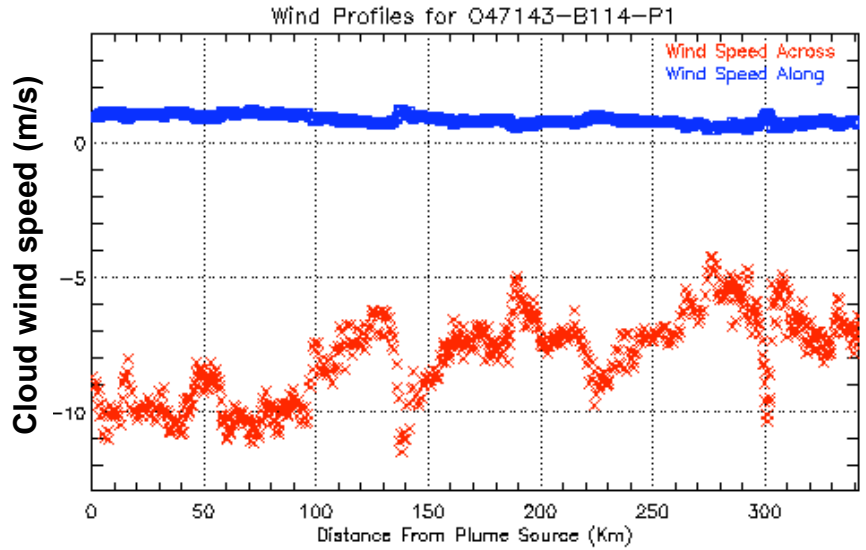
Dynamics and Cloud Processes (2)







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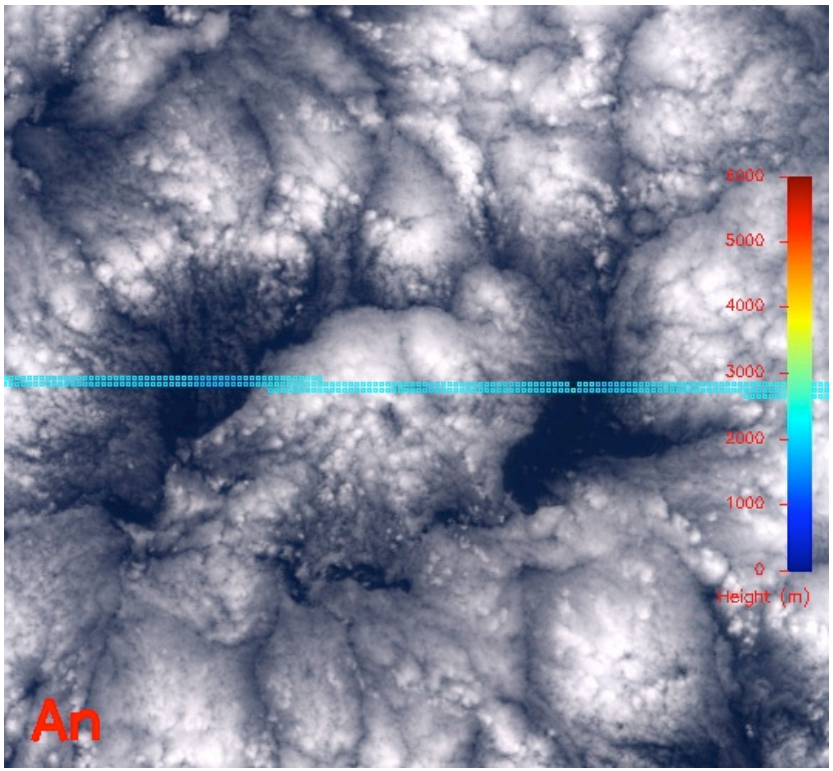
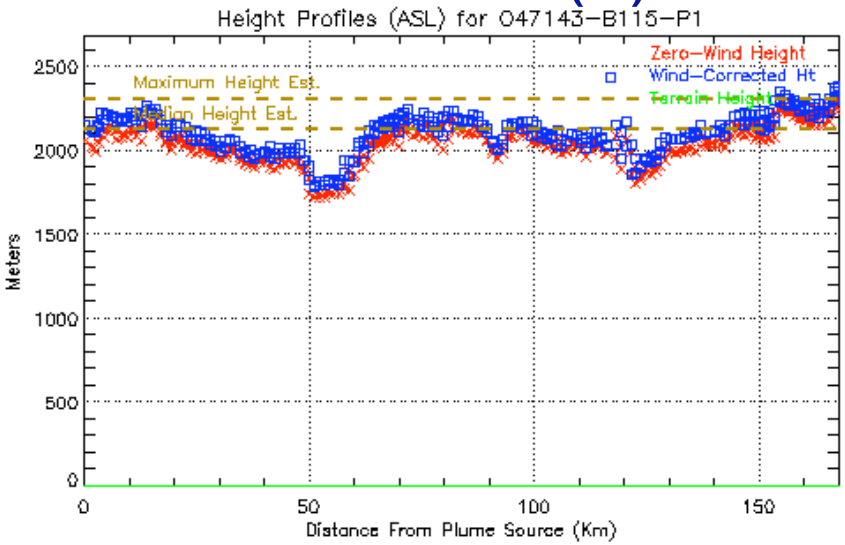
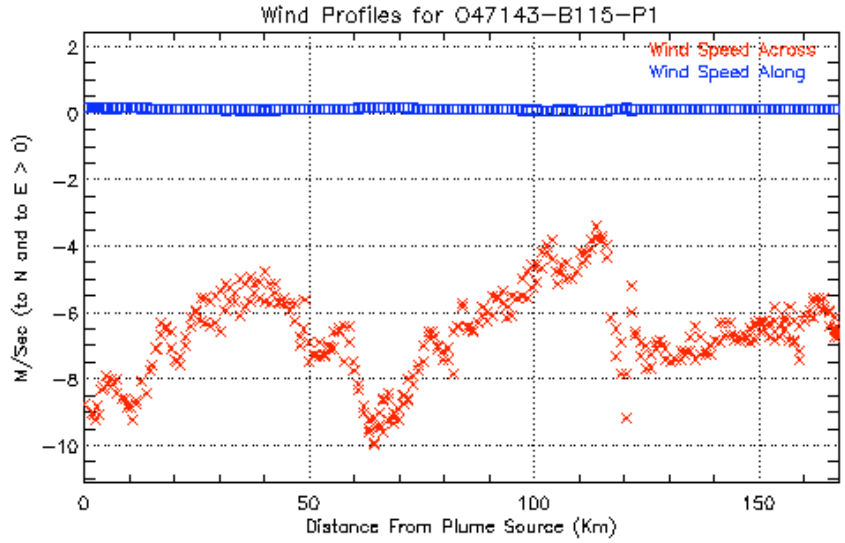
Dynamics and Cloud Processes (3)







Resolution: 1.1 km

Precision:

height: ~100 m

wind: ~0.3 m/s

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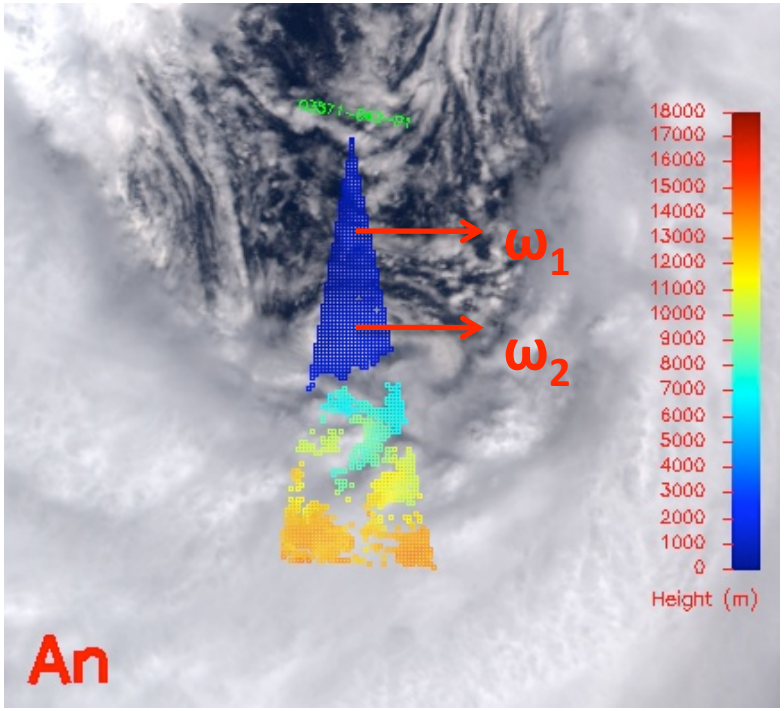
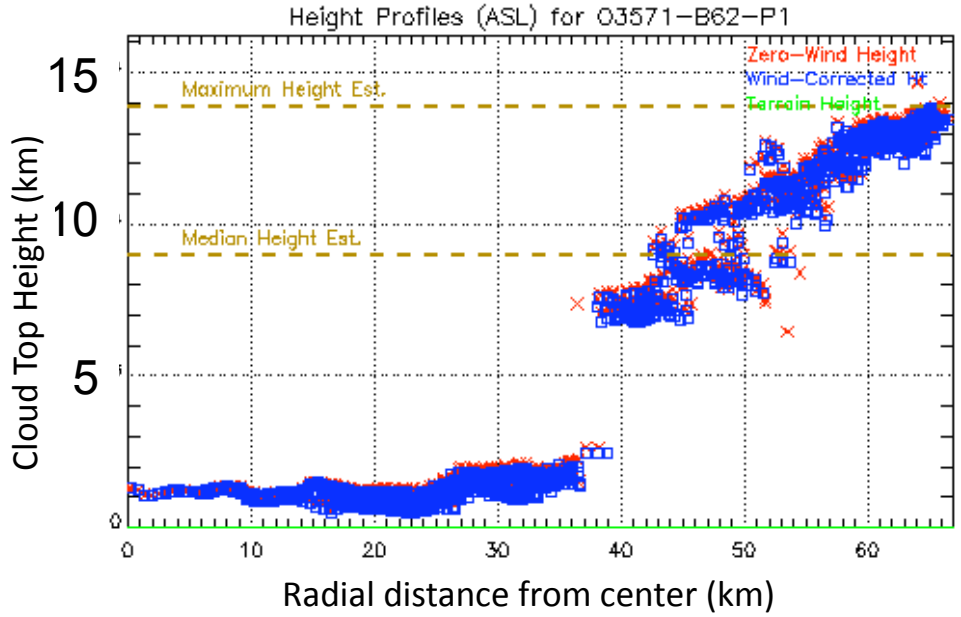
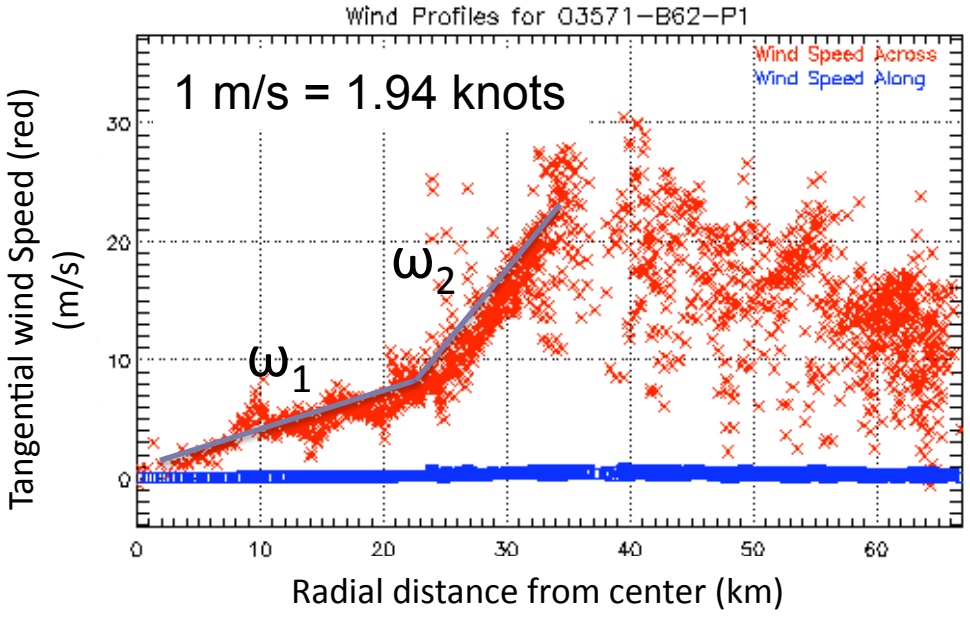
Inner-Core Dynamics of Hurricanes

- Non-uniform rotation revealed in MISR 1.1 km cross-track wind speed
- Higher rotation associated with the mesovortex
- Asymmetric rotations between southern and northern sides of Alberto's eye







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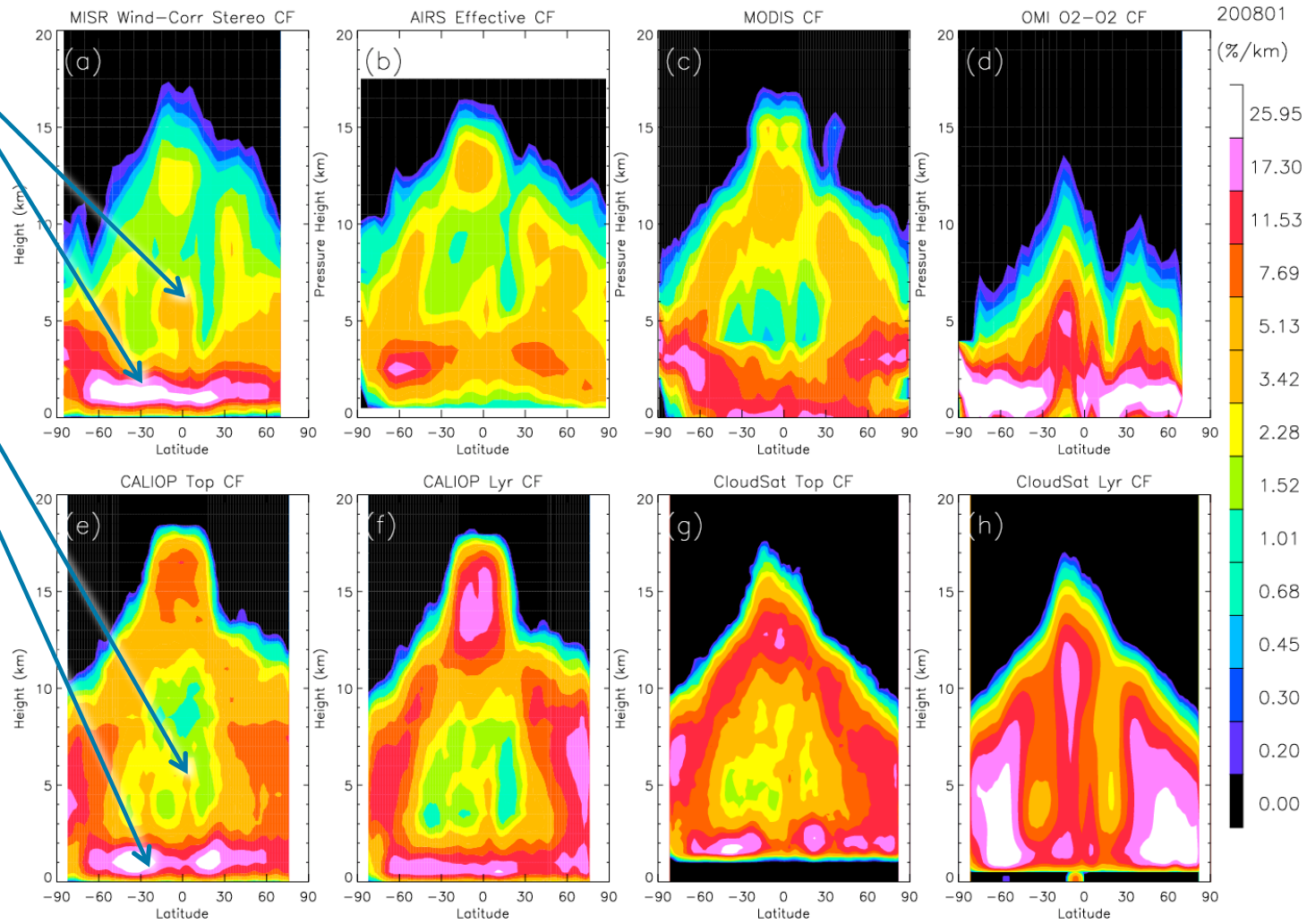
Vertical Distribution of Clouds

MISR
mid-level clouds
boundary-layer clouds

CALIPSO
mid-level clouds
boundary-layer clouds



Wu et al. (2009)

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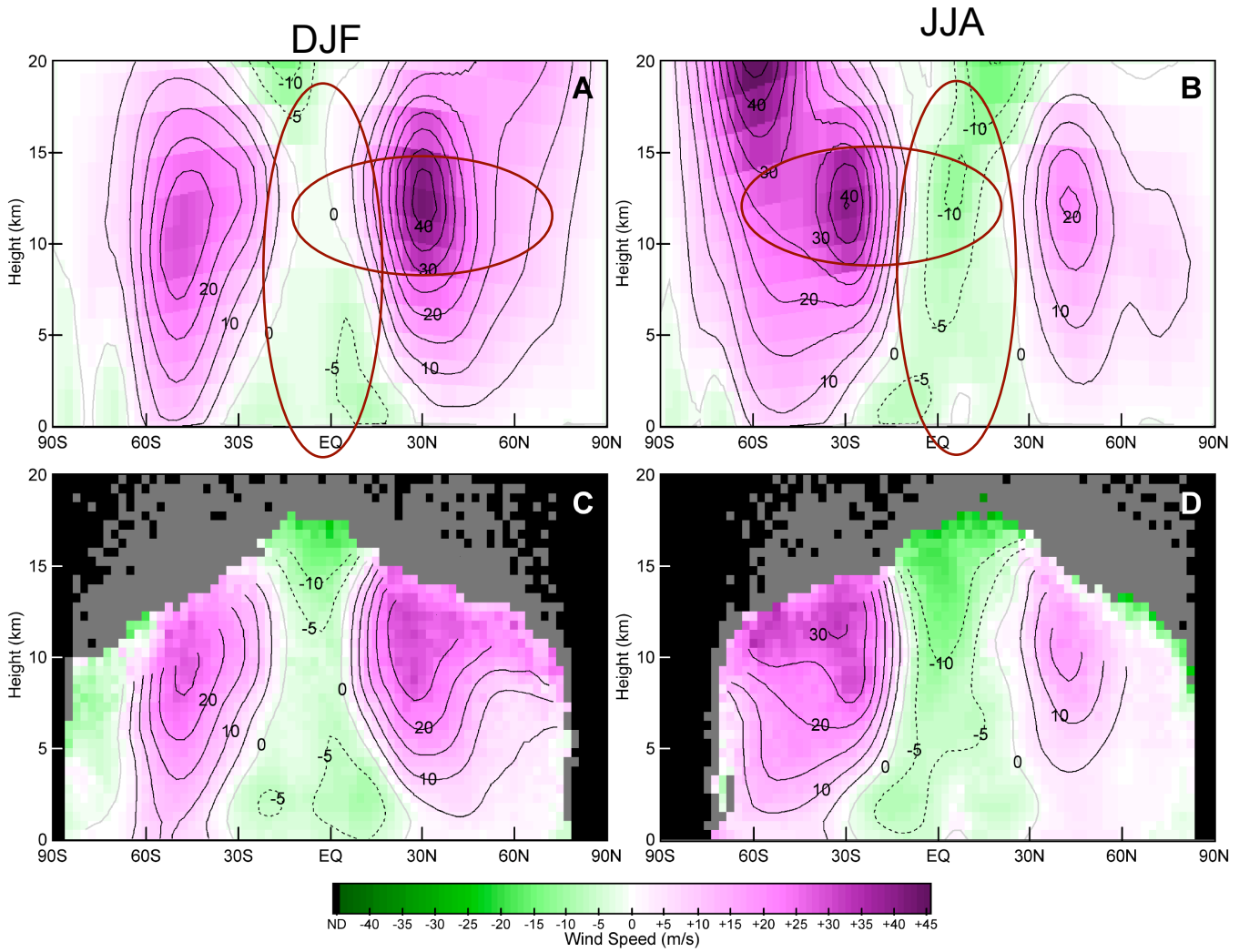
Vertical Profile of Winds

NCEP-DOE
Reanalysis 2

MISR
Height-Resolved
Cloud-Track
Zonal Winds



(Courtesy of Michael Garay)

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Future Cloud Observations from Space

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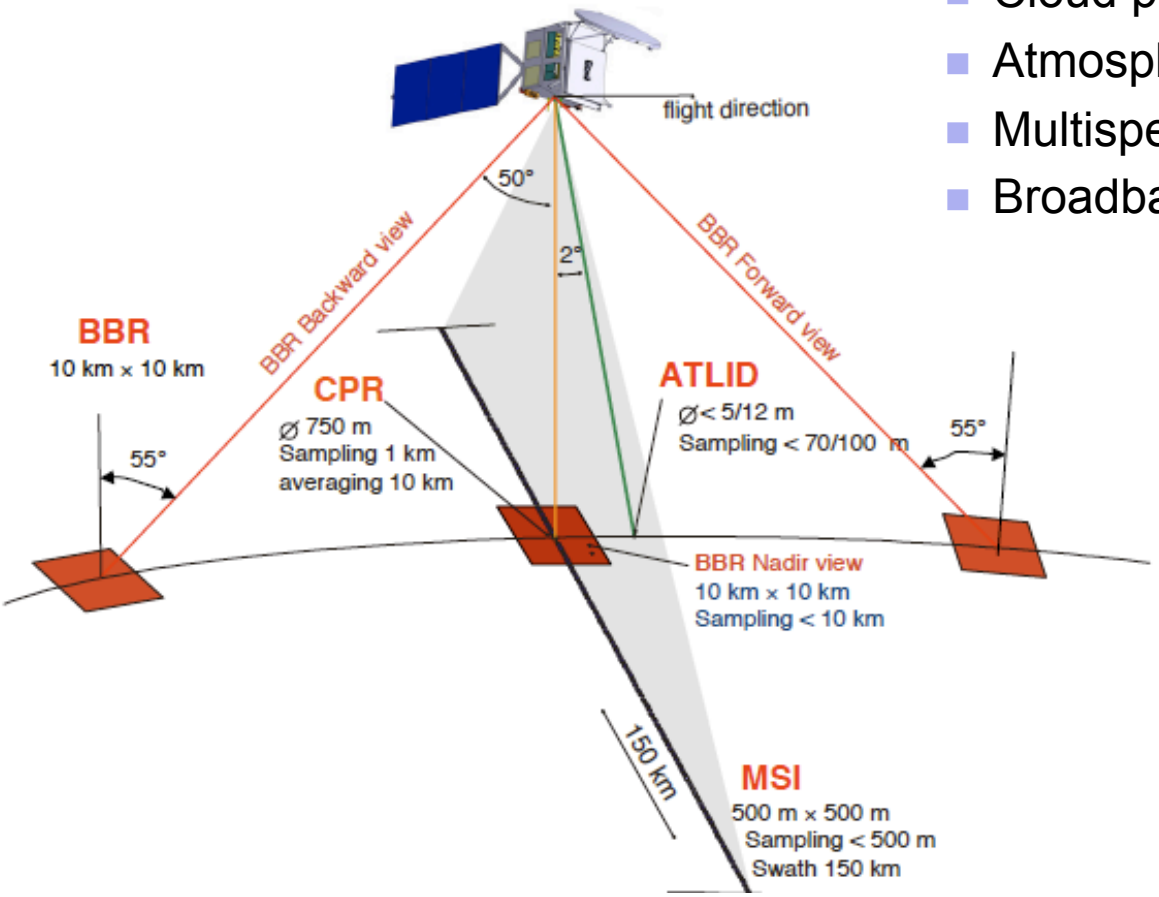
ESA-JAXA

The Earth Clouds, Aerosol, and Radiation Explorer (EarthCARE)

- Science objectives
  - Cloud properties
  - Aerosol properties
  - Cloud vertical velocities
  - Drizzle rain rate
- Technologies
  - Cloud profile radar (JAXA)
  - Atmospheric lidar
  - Multispectral imager
  - Broadband Radiometer



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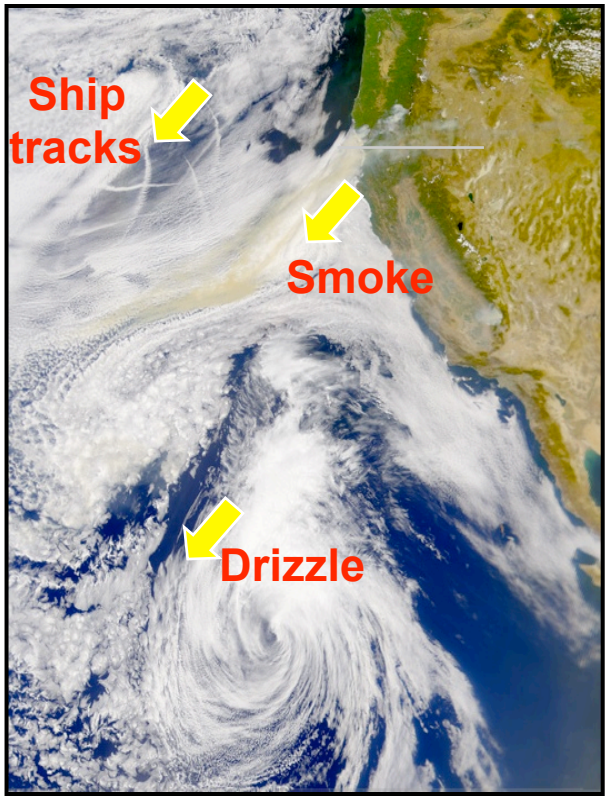
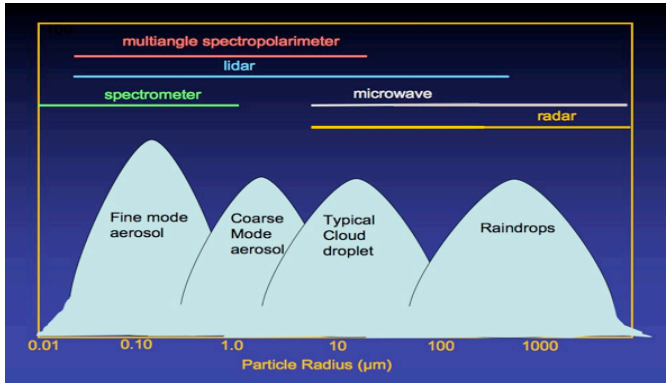
NASA

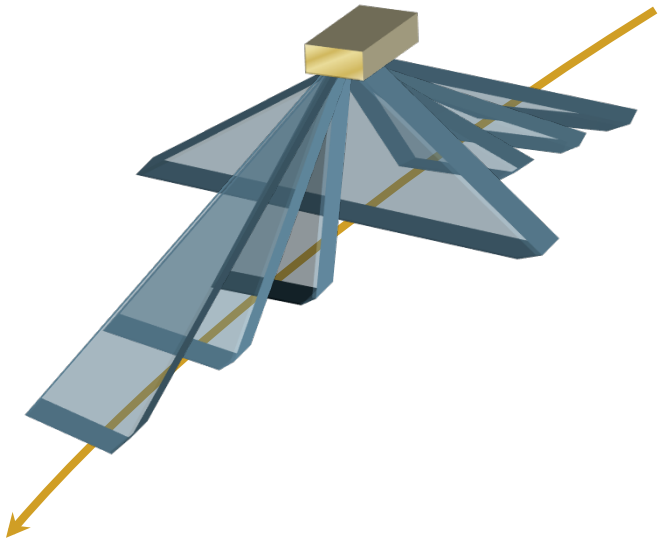
Aerosol, Cloud, and Ecosystems (ACE)

- Science objectives
  - 3D cloud structure and occurrence
  - Microphysical and macrophysical cloud and aerosol properties
  - Cloud vertical velocities
  - Aerosol-cloud interactions
  - Cloud-precipitation interactions
  - Cloud-radiation interactions
- Technologies
  - Dual-Freq (94 and 35 GHz) radar
  - Lidar
  - Multiangle spectropolarimeter
  - Multiband spectrometer
  - Microwave radiometers
  - Others



What is cloud?





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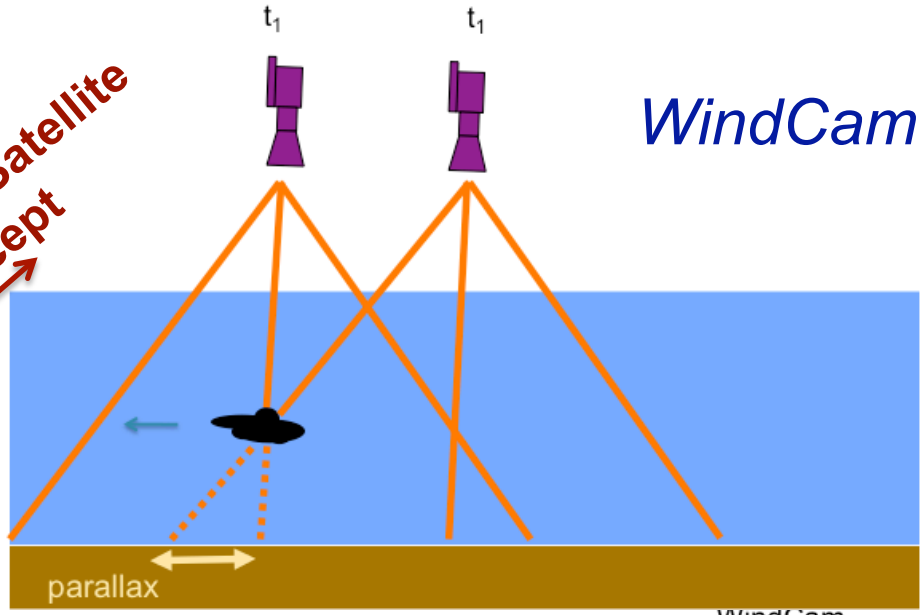
Future Cloud Observations from Space

- GOES-R
- Doppler dual-frequency cloud/precip radars
- Doppler lidars
- Advanced vis/IR multi-angle imagers (winds and clouds)
- High-frequency μ-wave radiometers
- GPS radio occultation of BL clouds

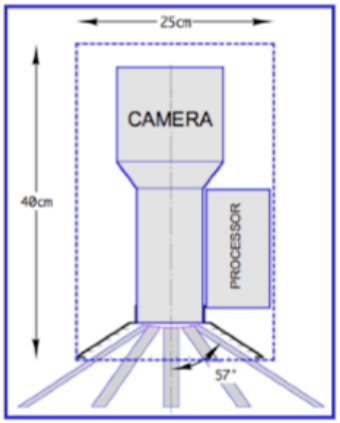
Small Satellite Concept



WindCam

MISR	WindCam
9 narrow angle cameras, 4 VNIR bands	1 wide angle camera, 1 red band
View angles: Nadir, 26°, 46°, 60°, 70°	View angles: Nadir, 40°, 60°, 70°
Resolution preserved by varying the camera focal lengths vs. angle	Resolution preserved by varying the detector sizes vs. angle
Mass: 150 kg Power: 75 W Data rate: 7 Mbps	Mass: 17 kg Power: 23 W Data rate: <3 Mbps
Spatial resolution: 275 m 400 km swath Global coverage - 9 days	Spatial resolution: 250 m 1000 km swath Daily global coverage from 3 platforms

WindCam



(Courtesy of David Diner)

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

spares

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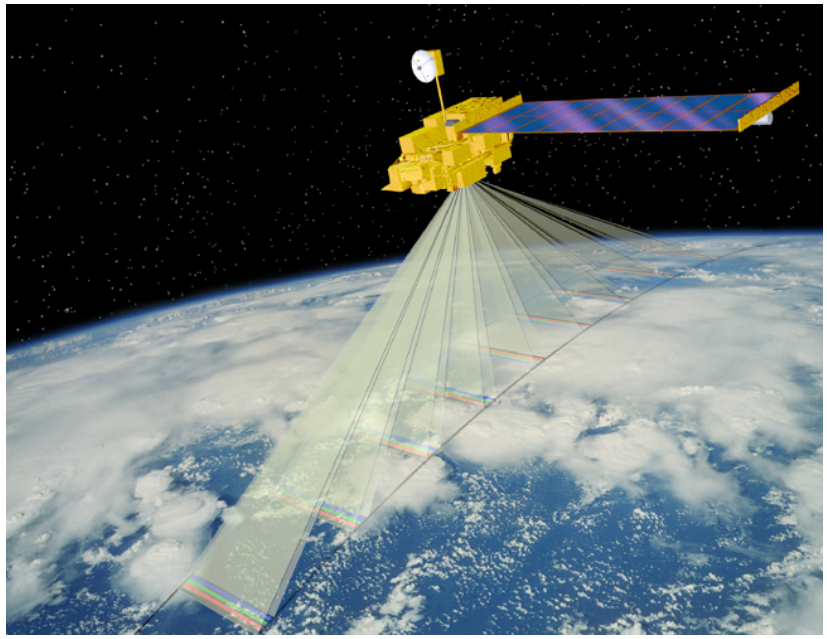
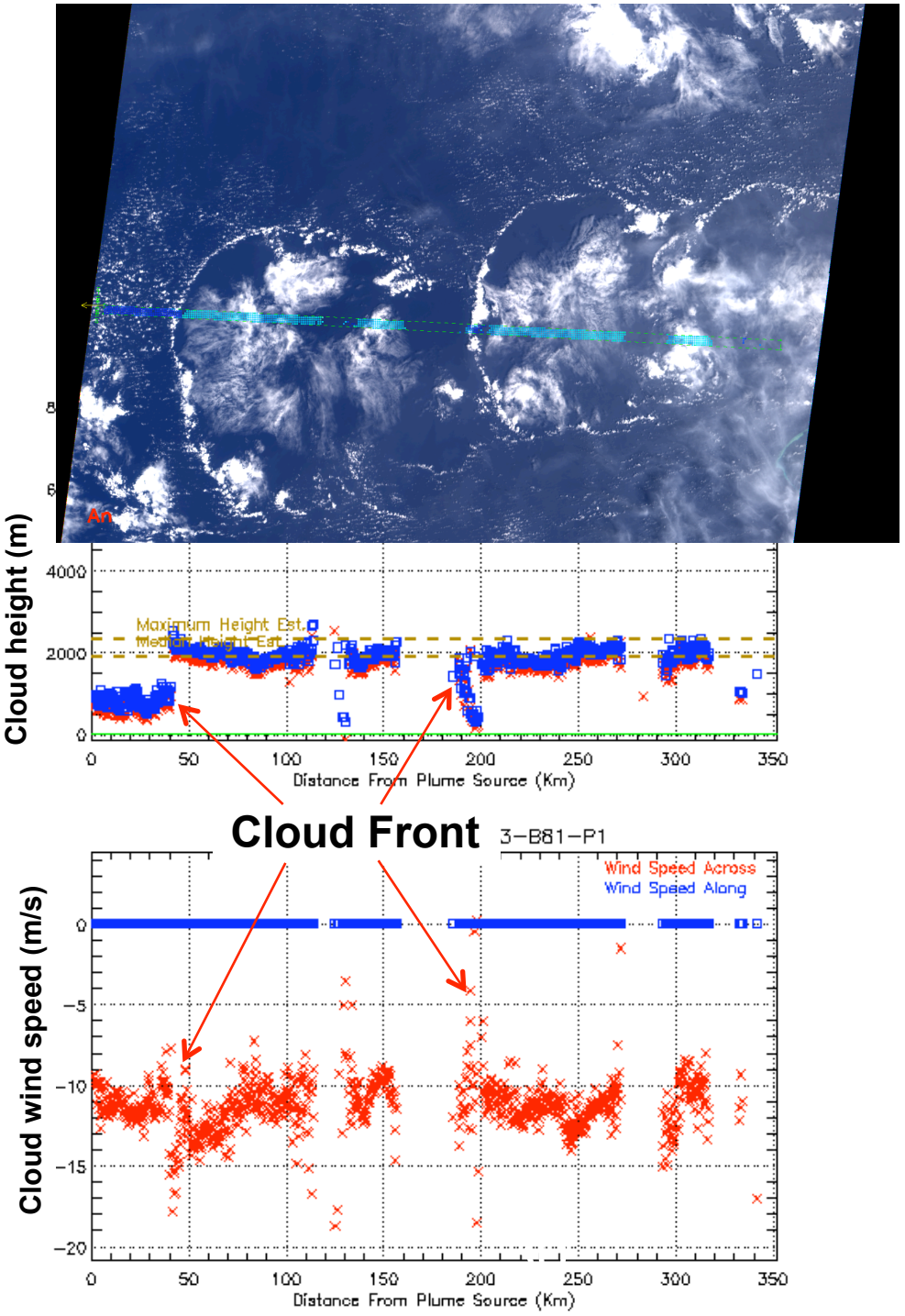
Multi-Angular Views

- MISR
  - Nadir ±26º, ±46º,±60º, ±70º
  - 446, 558, 672, 866 nm
  - 400-km swath
  - 275 m - 1.1 km resolution





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Dynamics and Cloud Processes (4)