Thick Ice Cloud Diurnal Cycle: A Synergetic Approach of Active and Passive MW Sensors

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With special thanks to Frank Evans, Ben Johnson, Stephen Munchak, Ian Adams, Patrick Ericksson and the GPM team in general.

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Why important
to have consistent ice water path (IWP) obs.

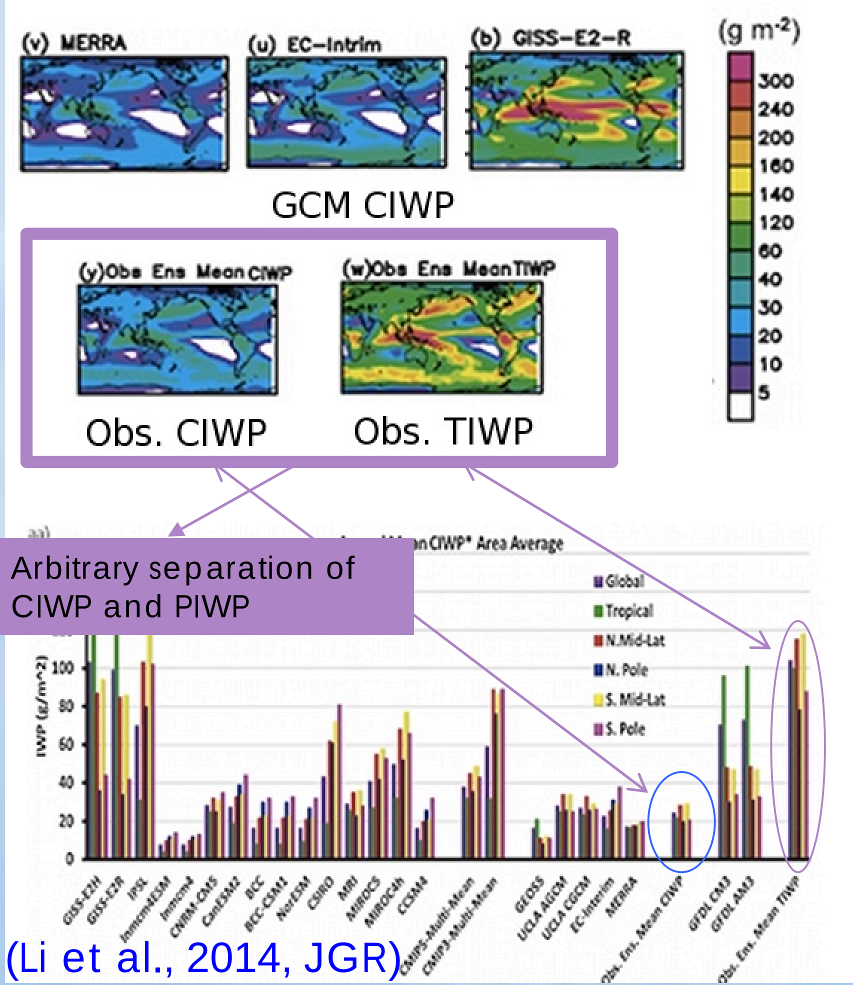
- TIWP = CIWP + PIWP

  total / Ice cloud / Floating snow (precipitating ice)

- GCMs do not have PIWP – radiative effect ~ 5-15 W/m^2 @ TOA (Li et al., 2013)

- Mean CIWP by 1 - 2 folds across CMIP5 models

- Observational constraints are required.



(Li et al., 2014, JGR)

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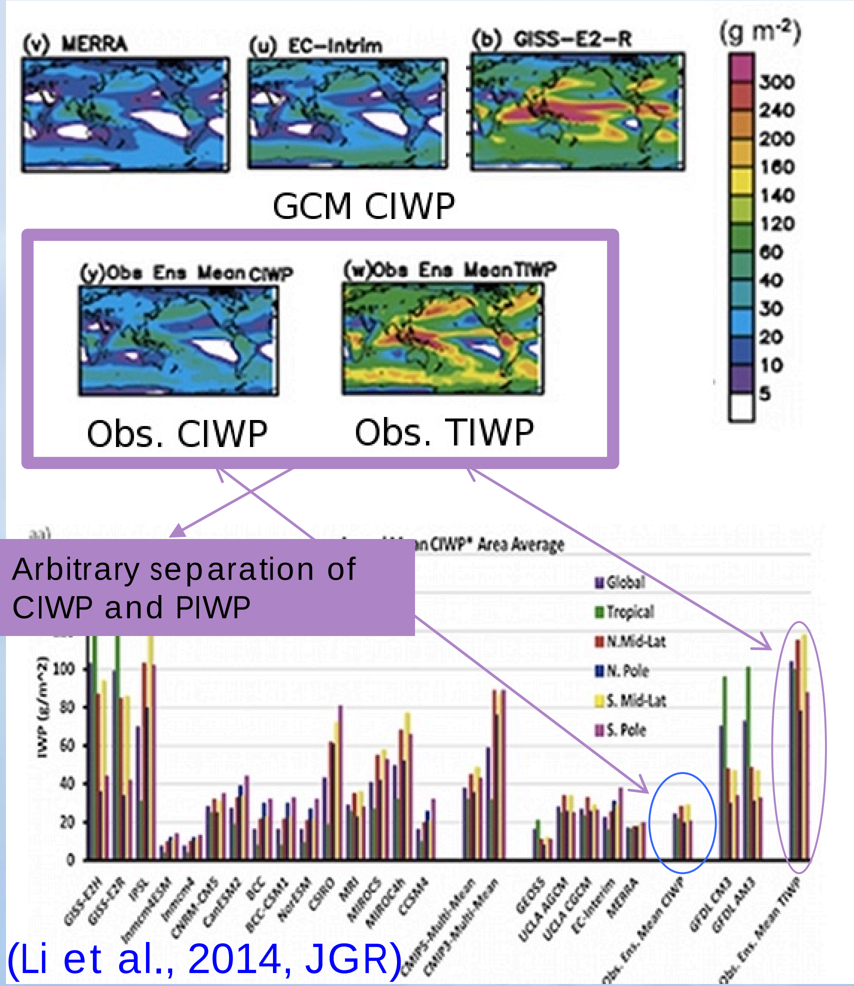

(Li et al., 2014, JGR)

Why important
to have MW ice cloud diurnal cycle?

- VIS/IR ice clouds are the “old” clouds that hang out there;
- MW ice cloud is the origin of VIS/IR ice cloud;
- Large variability of microphysics – ice cloud properties retrieved near the cloud top is not representative of the whole column.
- MW ice cloud also likely precipitates, which means it plays a key role in the hydrological cycle.

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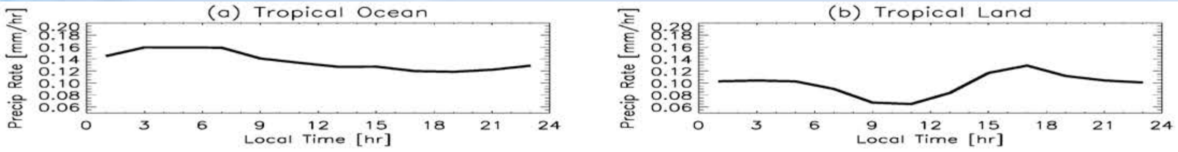
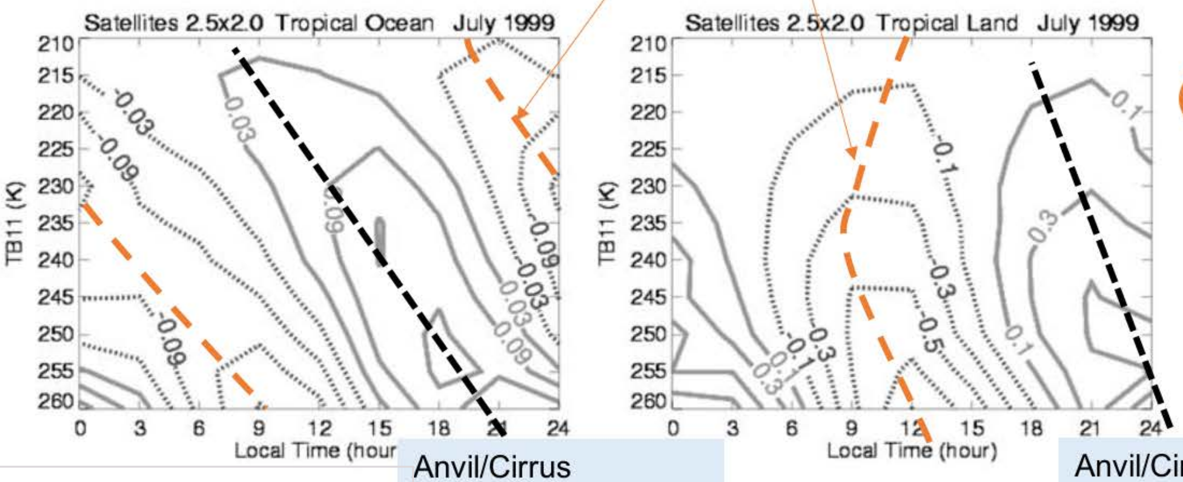


Surface Precip

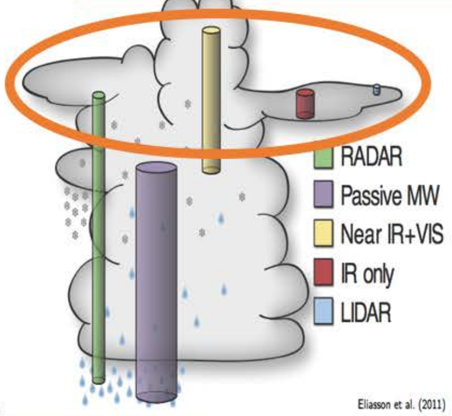
Link Is Missing!

Decay

Geostationary - IR



(f) IR – Anvil/Cirrus

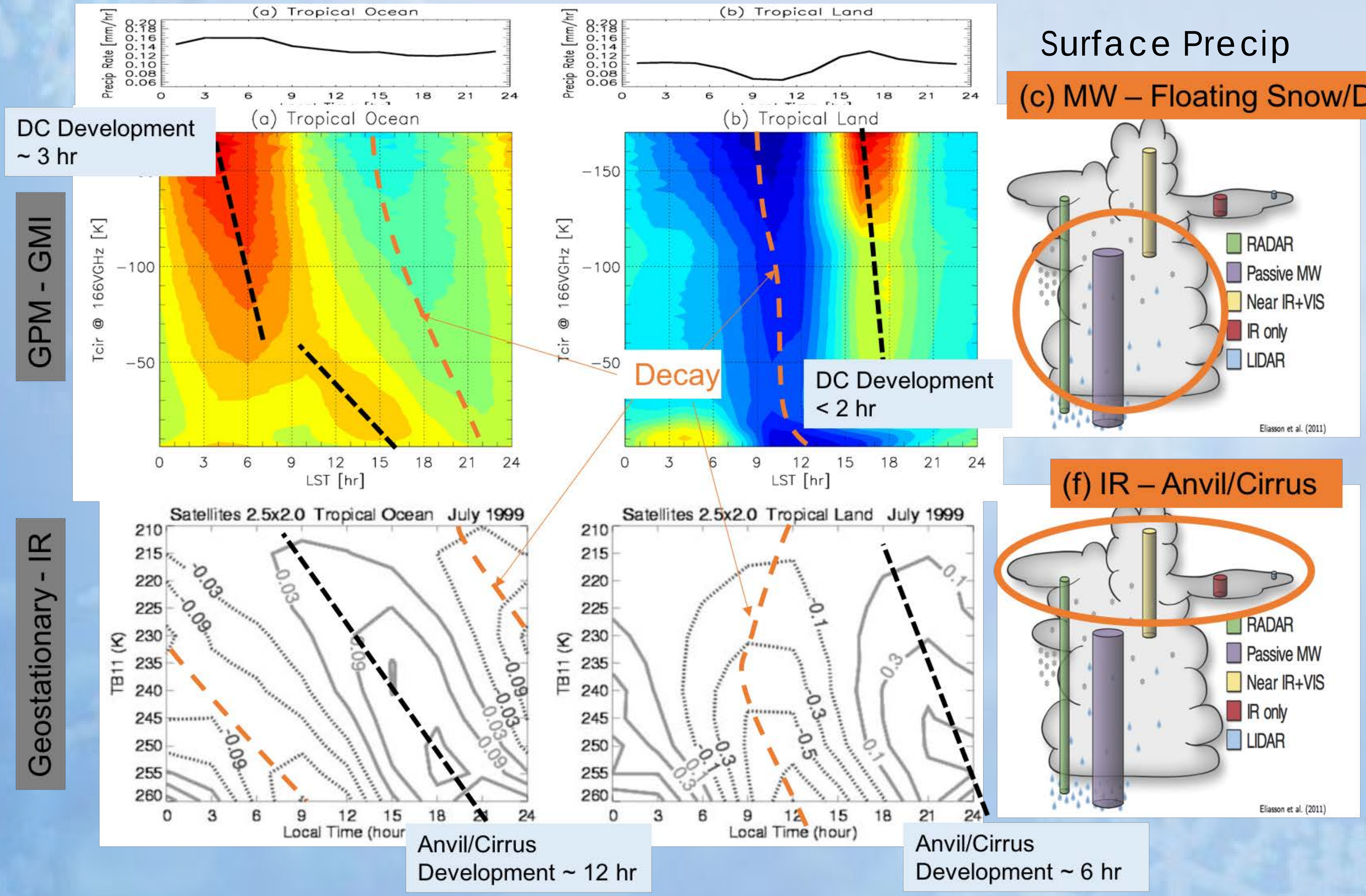


(Tian and Soden, 2004)

Anvil/Cirrus Development ~ 12 hr

Anvil/Cirrus Development ~ 6 hr

Why important
to have MW ice cloud diurnal cycle?



Why important
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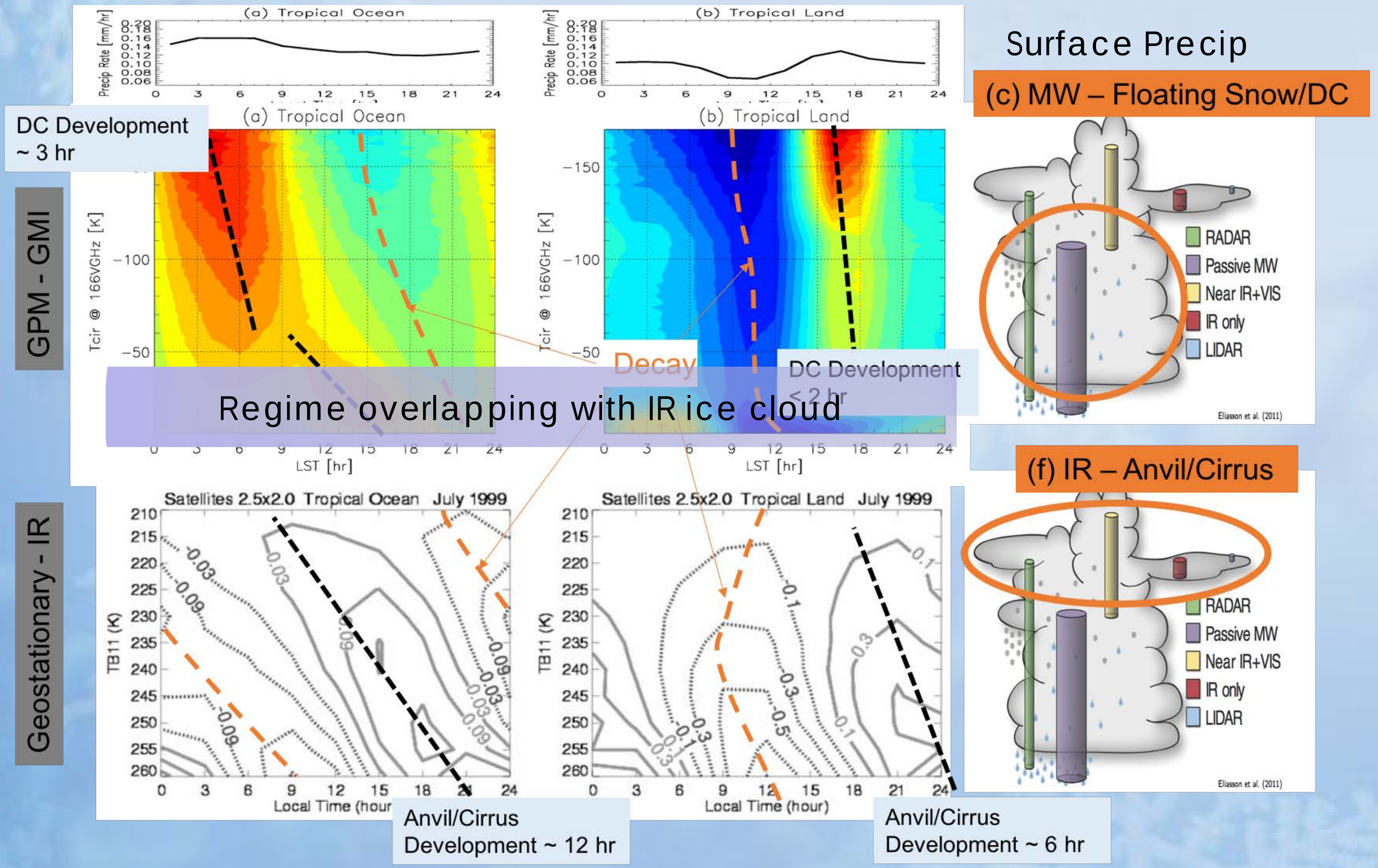


Pros and Cons for MW sensor to study diurnal cycle?

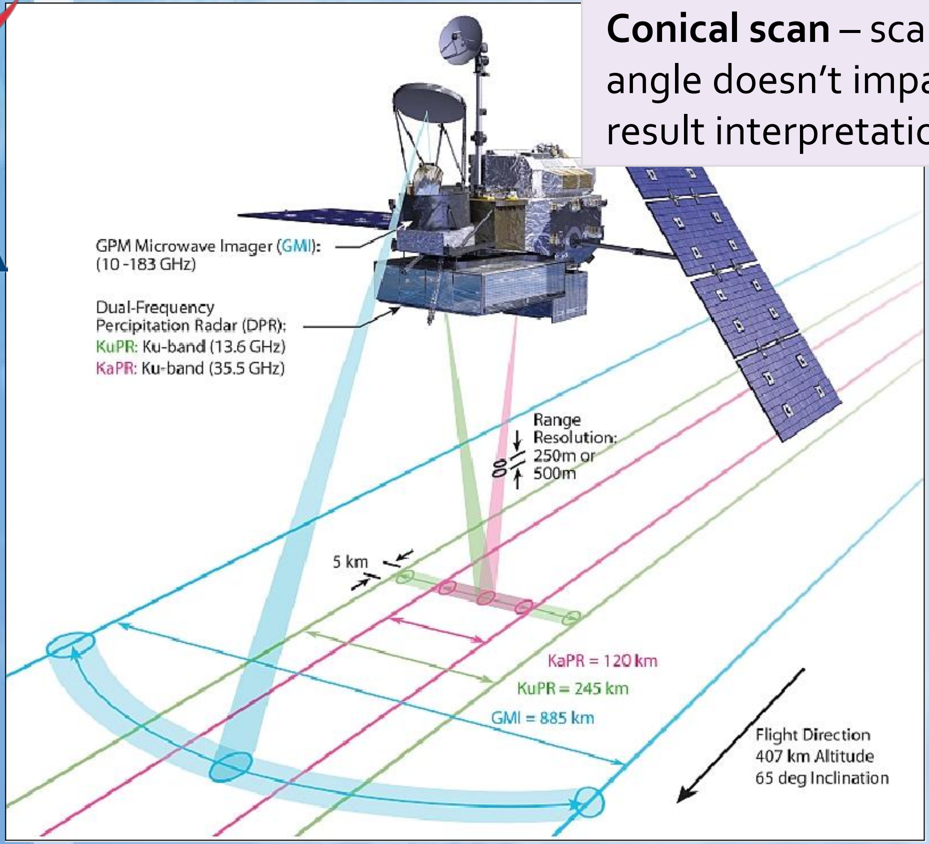
Pros

- Day/Night
- Long-record (30+ years)
- High-frequency (>150 GHz) dominated by near-linear TB-IWP relationship

Cons

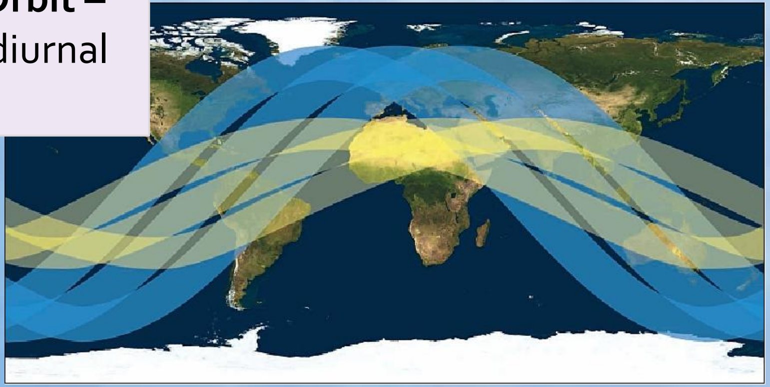
- Not sensitive to thin ice cloud
- No geostationary platform
- TB-IWP relationship hard to be simulated accurately due to complexity of ice microphysics

Global Precipitation Measurement Microwave Imager (GPM-GMI)



Conical scan – scan angle doesn't impact result interpretation

Procession Orbit – Suitable for diurnal study

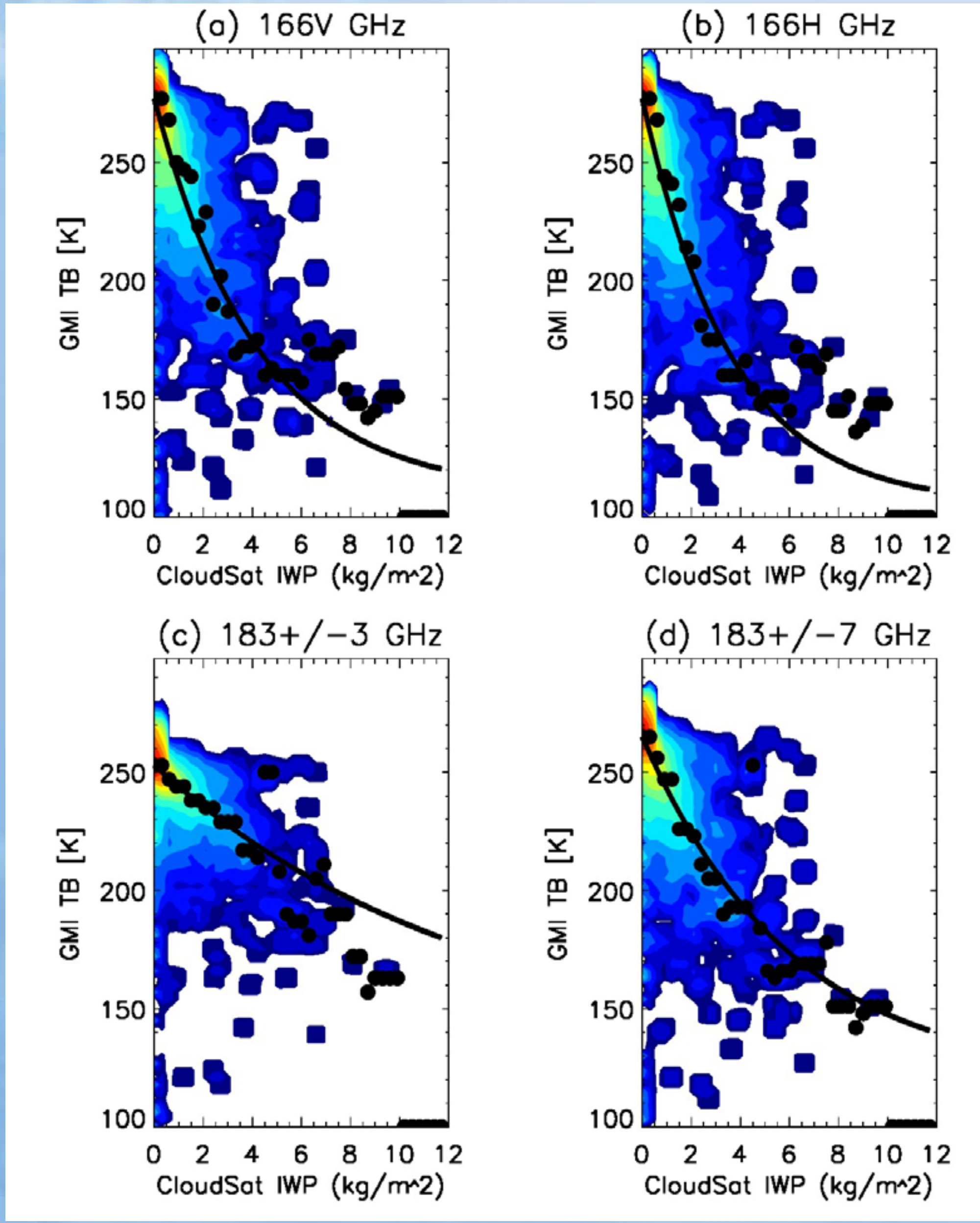


Channel No	Center frequency (GHz)	Ctr. freq. stabilization (±MHz)	Bandwidth (MHz)	Polarization
1	10.65	10	100	V
2	10.65	10	100	H
3	18.70	20	200	V
4	18.70	20	200	H
5	23.80	20	400	V
6	36.50	50	1000	V
7	36.50	50	1000	H
8	89.00	200	6000	V
9	89.00	200	6000	H
10	165.5	200	4000	V
11	165.5	200	4000	H
12	183.31±3	200	2000	V
13	183.31±7	200	2000	V

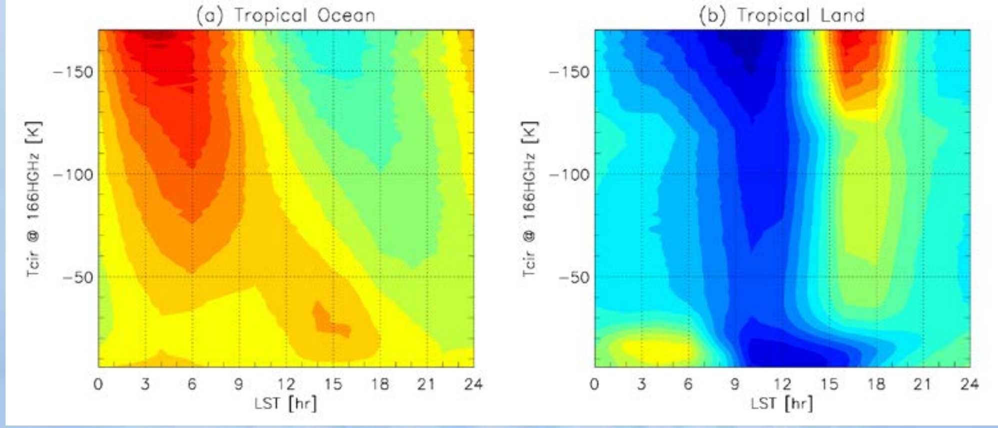
Footprint size: 4.4 km X 7.2 km

High-frequency polarized pairs at 166 and 183 GHz – suitable for this project

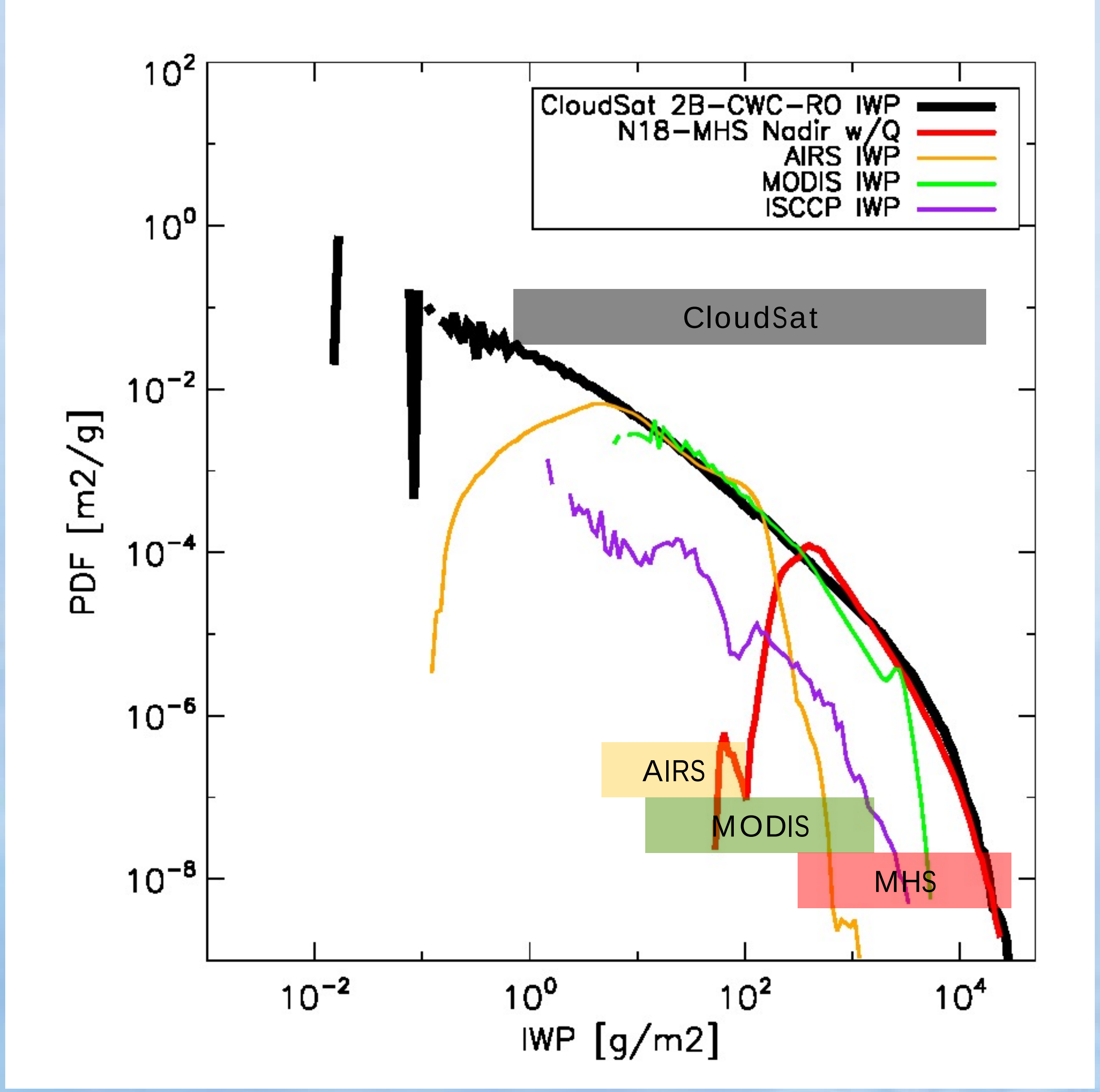
GMI TB-CloudSat IWP relationship



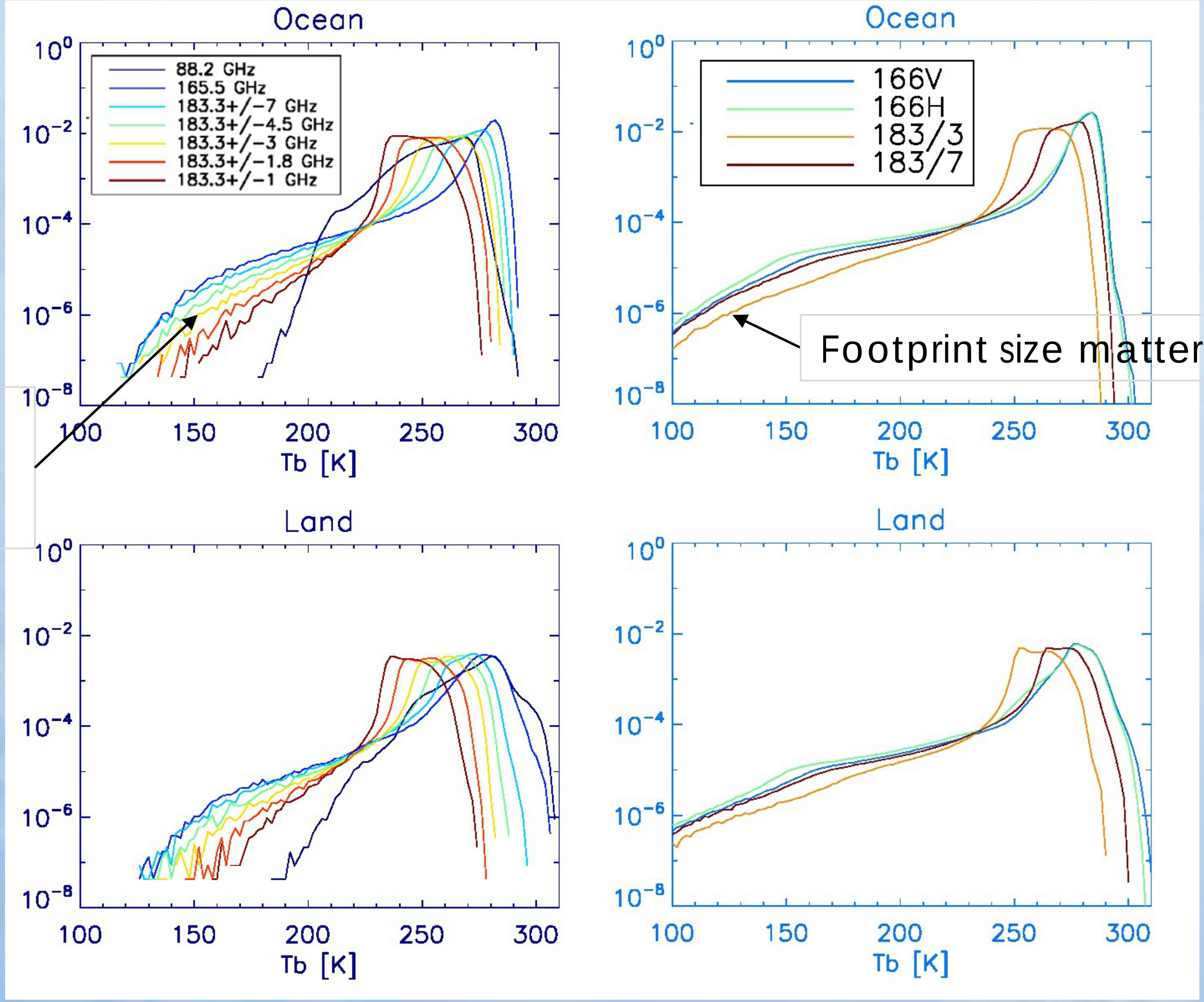
- Tcir = TB – Tccr will be calculated, which will largely remove the clear-sky variability
- This empirical model was built from 3-yr of tropical GMI-CloudSat collocations, which are SPARCE!
- It takes GPM ~ 45 days to cover through one full diurnal cycle for each point on the Earth: seasonal information is blended in.
- For fast convective process, we need **<u>< 2 hr</u>** temporal resolution, especially over land.



Using CloudSat-Calipso as the baseline to construct/validate consistency from passive cloud data record



One month of TB PDFs at near GMI view-angle



183 GHz differentiation in thick-cloudy-sky might be useful for cloud profiling

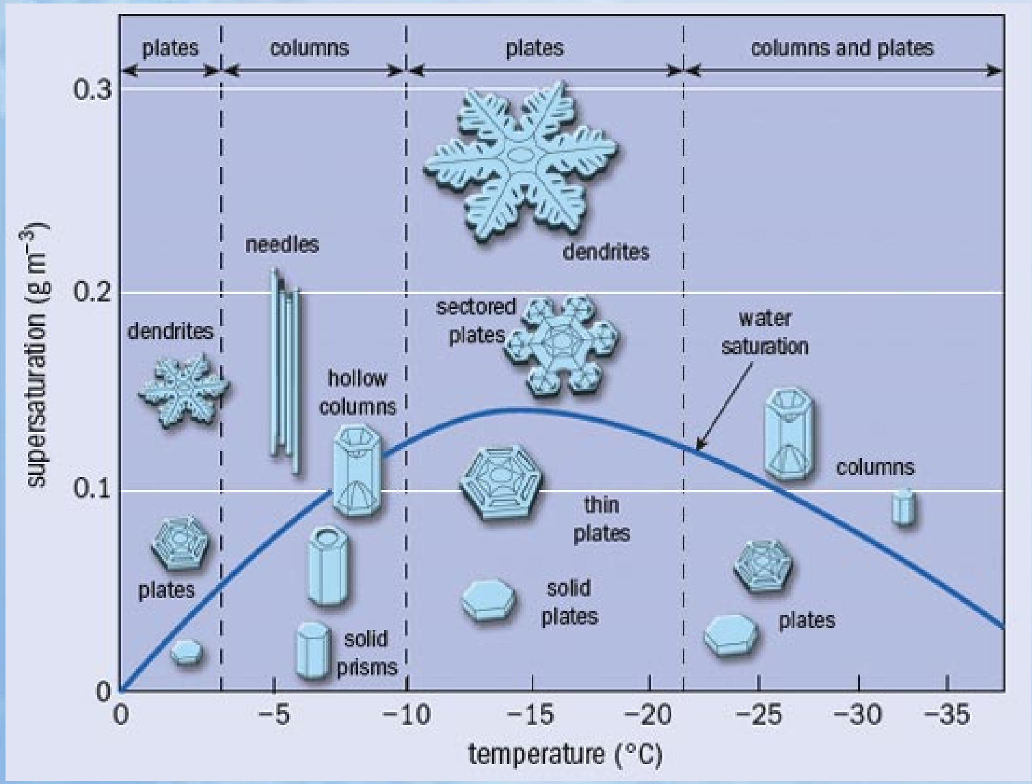
Footprint size matters

NPP-ATMS (15 – 18 km FOV)

GPM-GMI (4.4X7.2 km^2 FOV)

PART2: Diurnal Cycle of Ice Microphysics

In the read world …



In model and satellite retrieval world …

- Ice crystal microphysical properties include **shape, size, density, and orientation**.

- Horizontally aligned ice crystals are observed by CALIPSO lidar and passive sensor at visible spectrum (e.g., POLDER, DSCOVR-EPIC), What about other wavelengths?
- If polarization difference is identified in MW spectrum, does it see the same property as what lidar/passive VIS see?
- What about NIR/FIR?

Previous Studies Shed Some Light on Using Passive High-frequency Microwave Channels

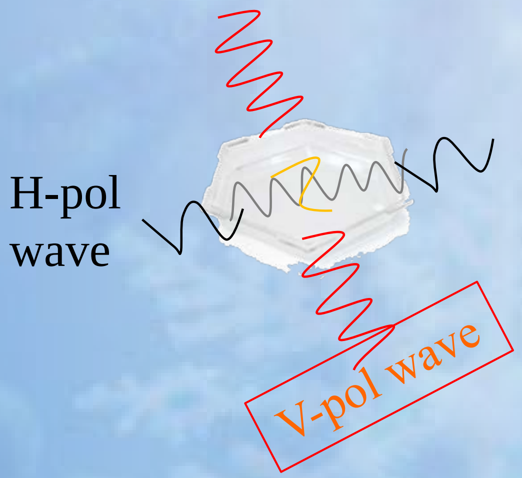
❖ High frequency Microwave (MW) channels (> 85 GHz, or wavelength < 3.3 mm) are particularly suitable for observing ice cloud and frozen hydrometers, as the signals are dominated by ice scattering and not "polluted" by surface emissivity or liquid cloud/rain absorptions.

❖ The higher the MW channel frequency is, the smaller ice crystal it is sensitive to.

❖ Polarimetric MW measurements have been proven to provide a useful view of revealing ice particle's shape and orientation (Czekala 1998; Xie and miao 2011; Prigent et al., 2005; Davis et al., 2007; Homeyer and Kumjian, 2015).

Polarimetric Difference (PD)

› Polarimetric Difference (PD) is defined as radiance difference between the vertically and horizontally polarized channel measurements at the same frequency:



$$PD = TB_v - TB_h$$

- Passing through the same ice cloud/frozen hydrometer layer with frozen particles orient to some degree the same direction, V-pol and H-pol naturally experience different optical thickness.
- $\tau_V < \tau_H$ in this case when the ice plate orients parallel to the H-pol wave, meaning that $TB_v > TB_H$, or $PD > 0$.

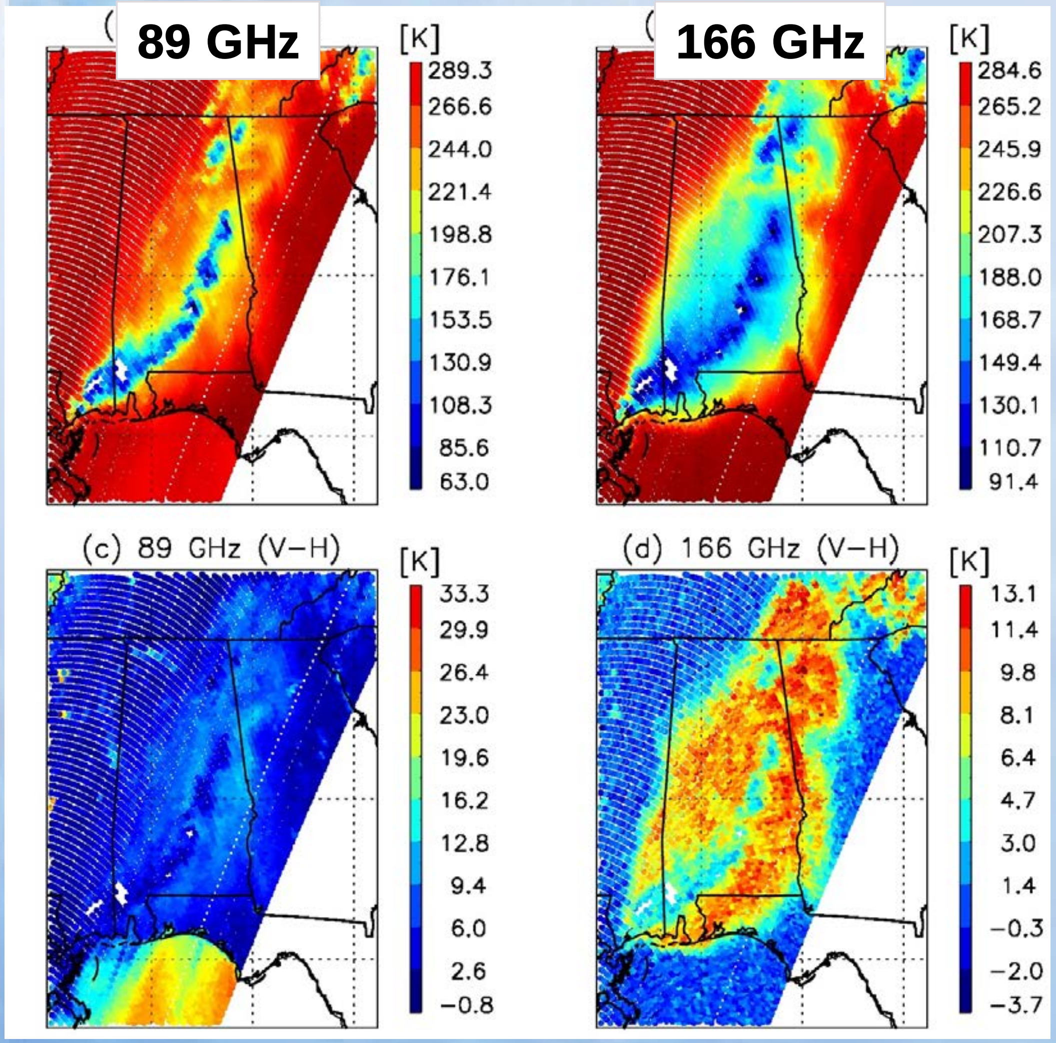
A squall line case

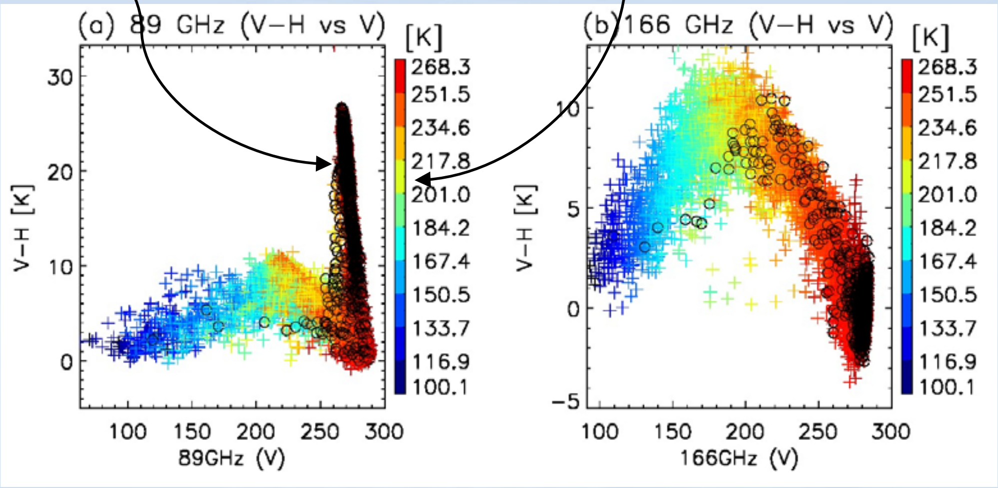
Black circles are over ocean, which is strongly polarized over clear-sky calm surface (like a mirror).

Colorbar: 183+/-3 GHz TB (directly correlate to ice water path)

TBv

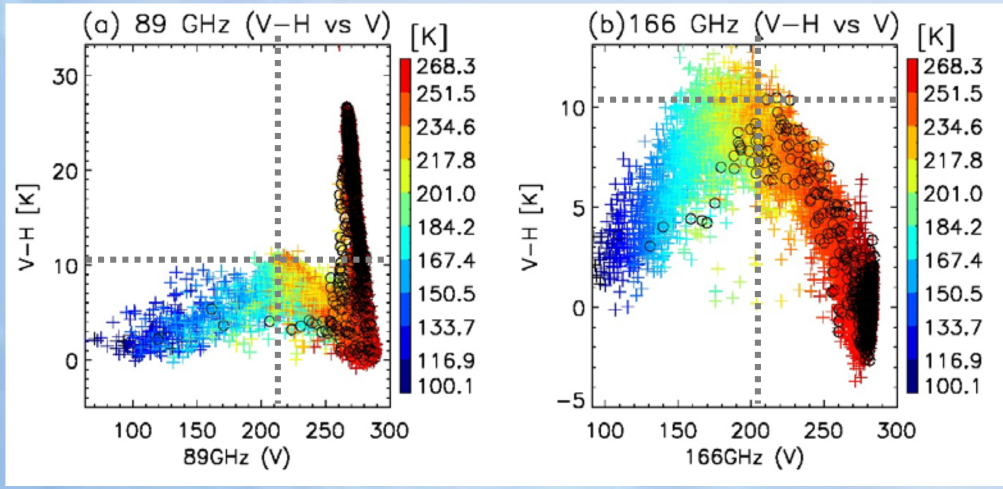
PD



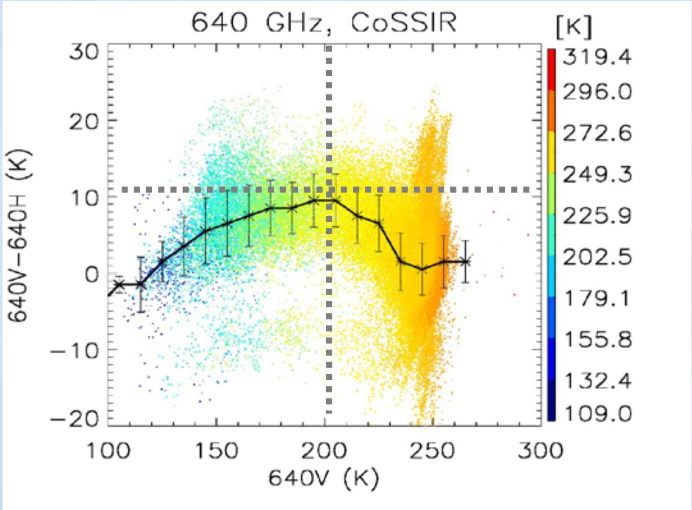


- TB-PD relationship forms the upside down "bell" curve, meaning PD diminishes at both warm (clear-sky) and cold (deep convection) ends, and maximizes for medium cold TB.

This upside down "bell" curve holds for different high-frequency MW measurements



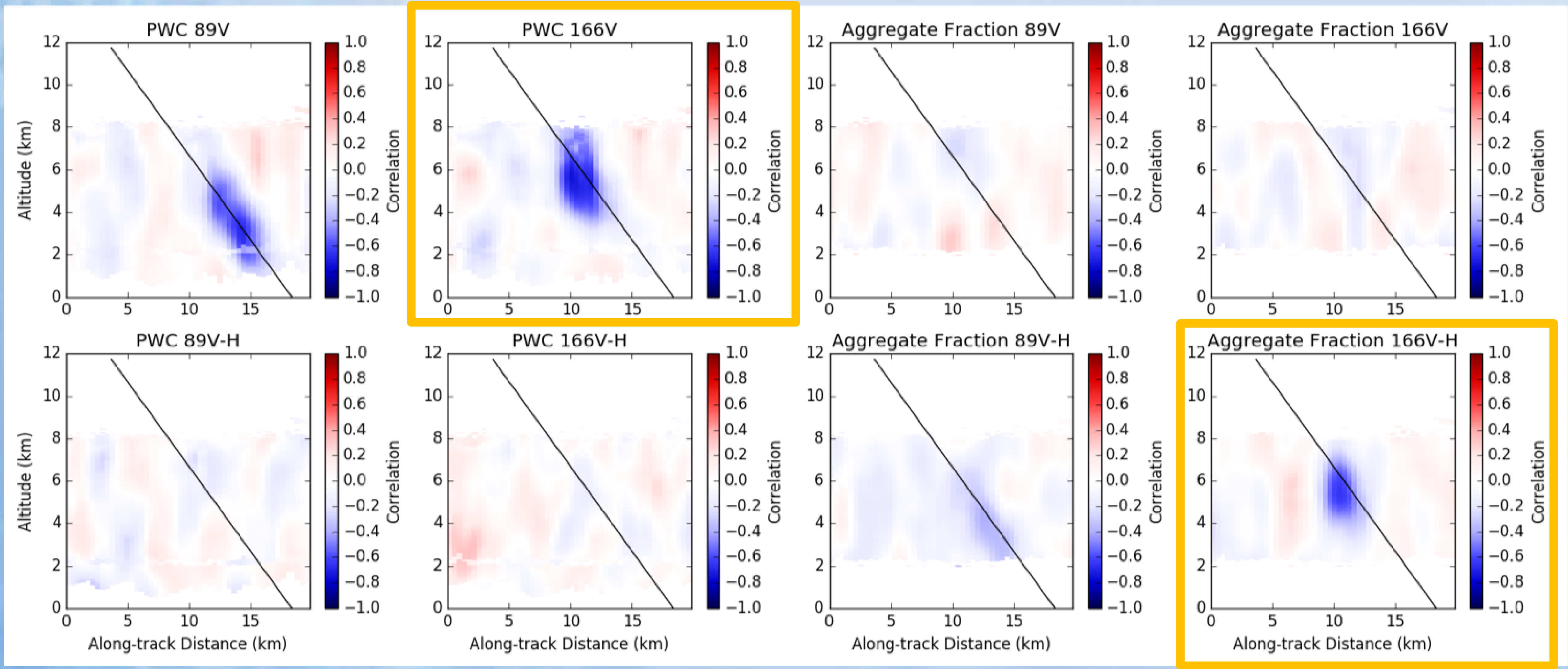
GMI squall line case, 04/29/2014



640 GHz, ER-2 CoSSIR (Compact Scanning Submillimeter-wave Imaging Radiometer) measurements during the TC4 campaign

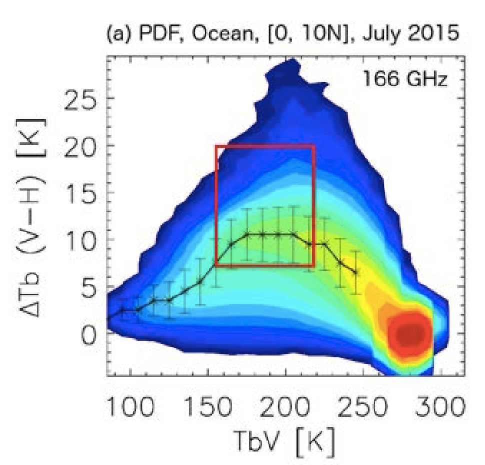
- The peak PD value and the TB value where PD peaks are largely independent of the channel frequency

166 TB sensitive to 4-8 km
“floating snow” cloud

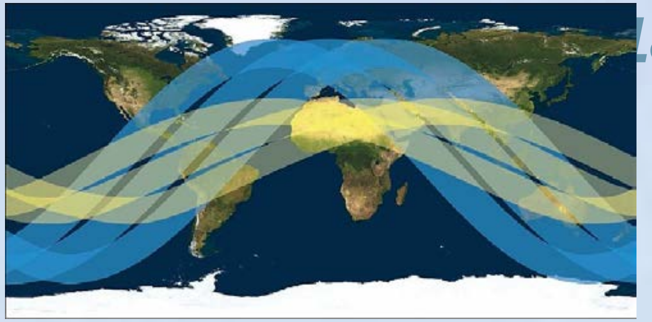


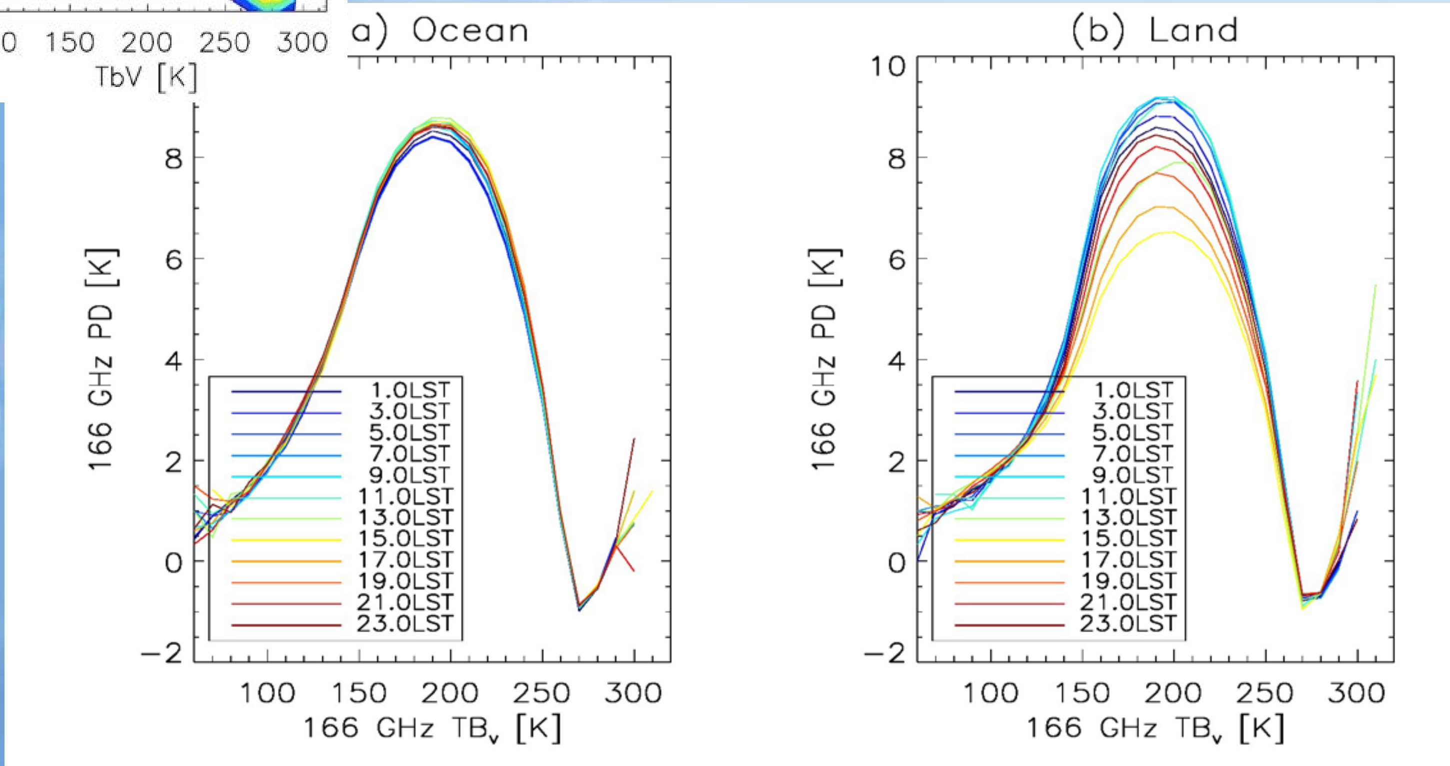
166 PD sensitive to percentage of horizontally oriented ice crystals

Courtesy to Joe Munchak



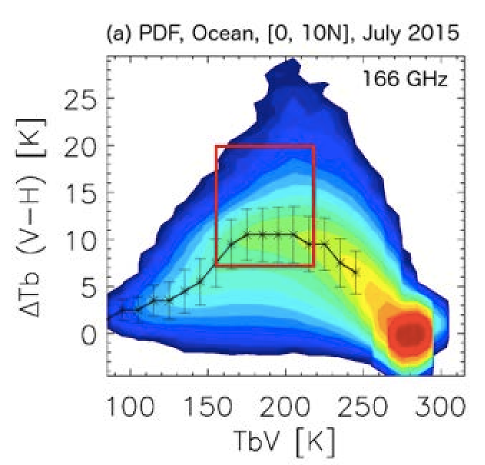
Diurnal Variation of PD





Composite the PD-TB curve for every 2 hours using GMI data between 25°S and 25°N during 2014-2017.

- The PD-TB curves **converge** at both the warm and cold sides, and the peak of PD occurs at ~ same TB.
- So the **peak** of PD becomes the **only metrics** to measure the curvature of the curve.
- PD_{peak} varies **little** (~6%) over tropical **ocean** during a day, but **a lot** (~ 35%) over tropical **land**.



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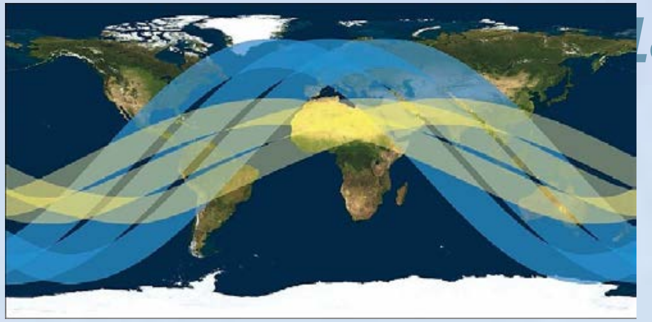

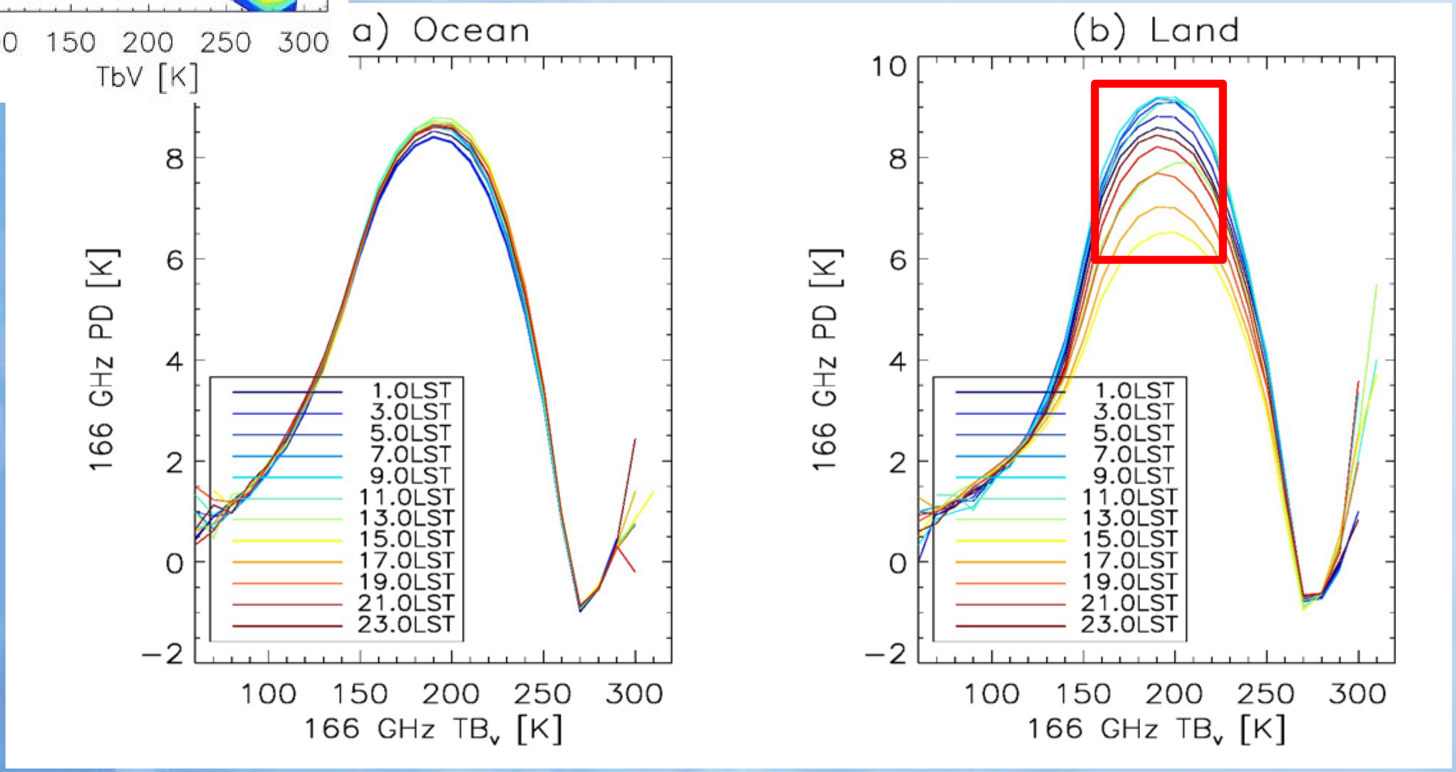

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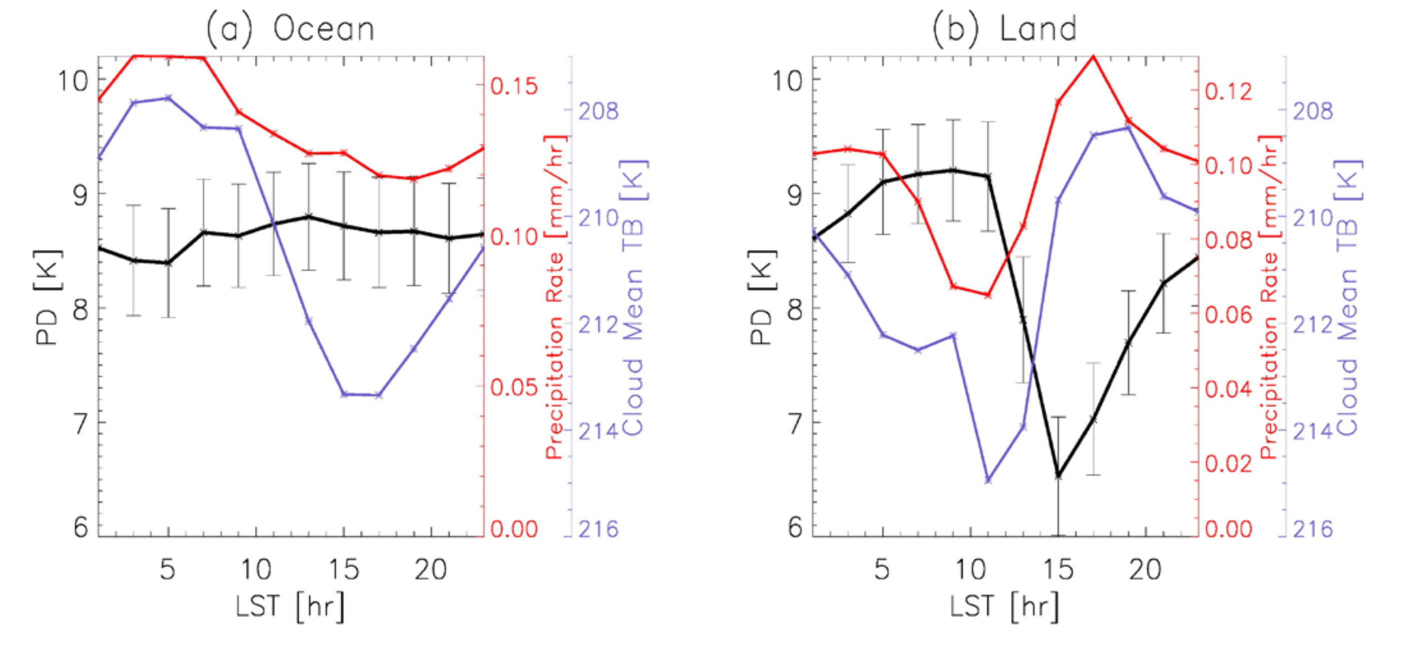
Diurnal Variation of PD

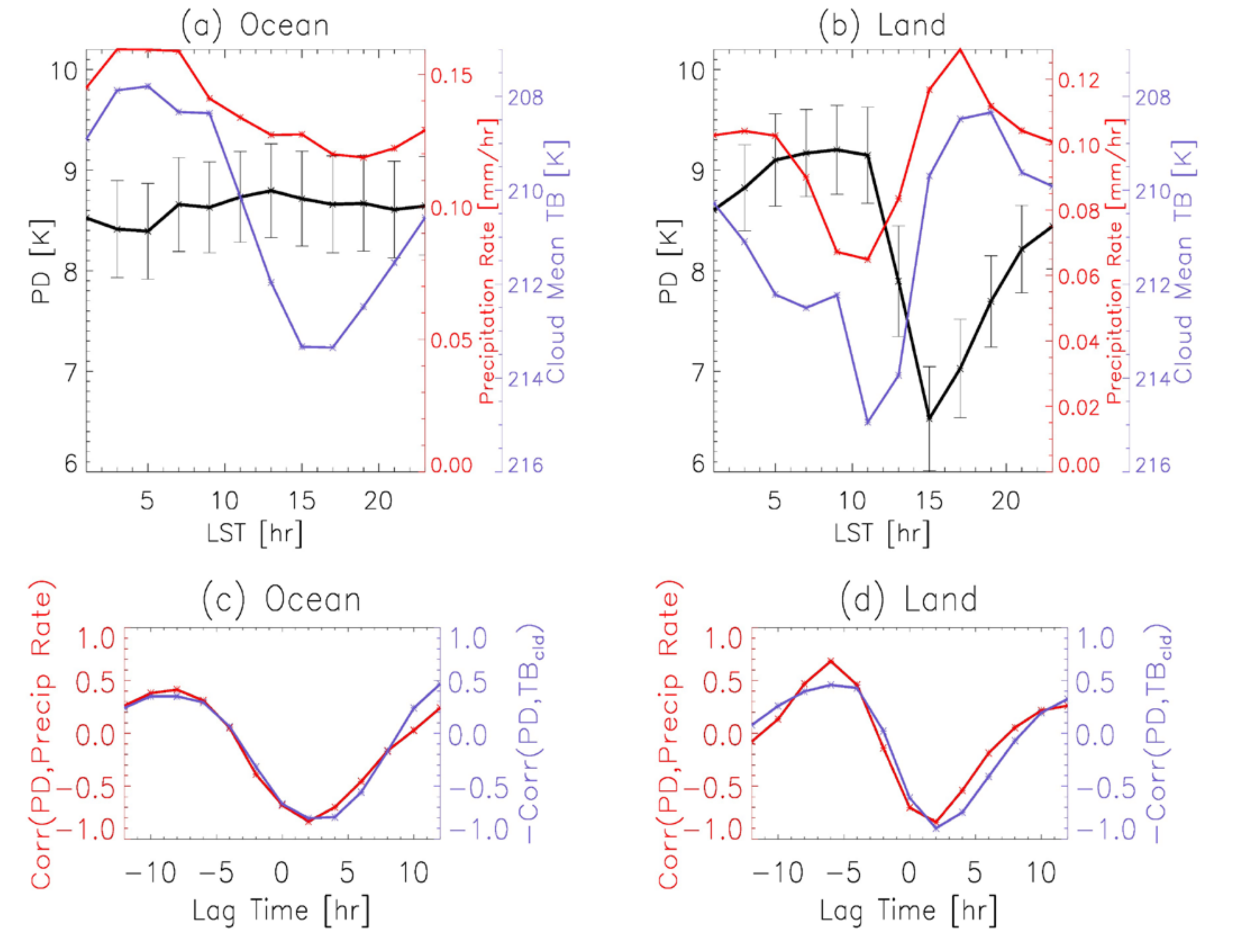


- The largest PD_{peak} over land occurs at local late morning (10:30 am LST) and the minimum occurs at local afternoon (16:30 pm LST).
- Both the peak of cloud IWP and surface precipitation occur at local early evening (17:30-19:30 pm LST).

Black: PD
Blue: $\overline{TB_{cld}}$ (reverse axis)
Red: DPR-Ku Precipitation Rate

Ice crystal microphysics have strong diurnal variation over tropical land. The diurnal cycle of ice microphysics is tied closely with ice cloud and surface precipitation evolvement.

Diurnal Variation of PD

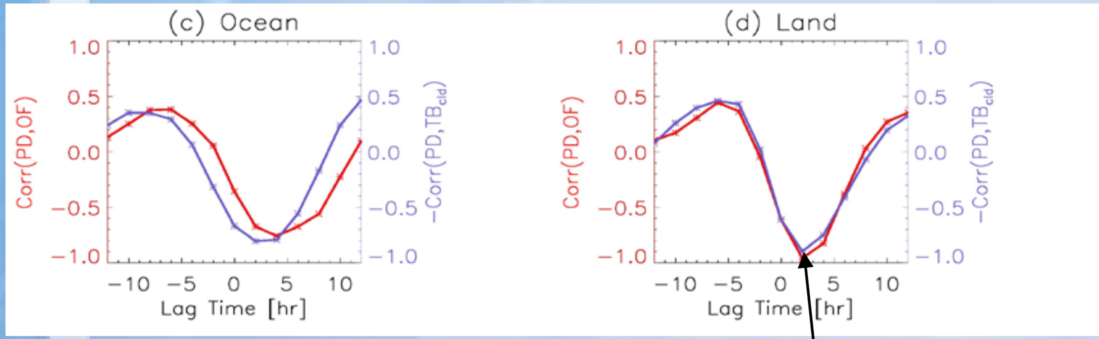


- The lag-correlation suggests that the maximum correlation happens when PD_{peak} leads the ice cloud thickening and surface precipitation by ~ 2 hrs in opposite phase.

The diurnal cycle of ice microphysics is also tied closely with precipitation evolvement.

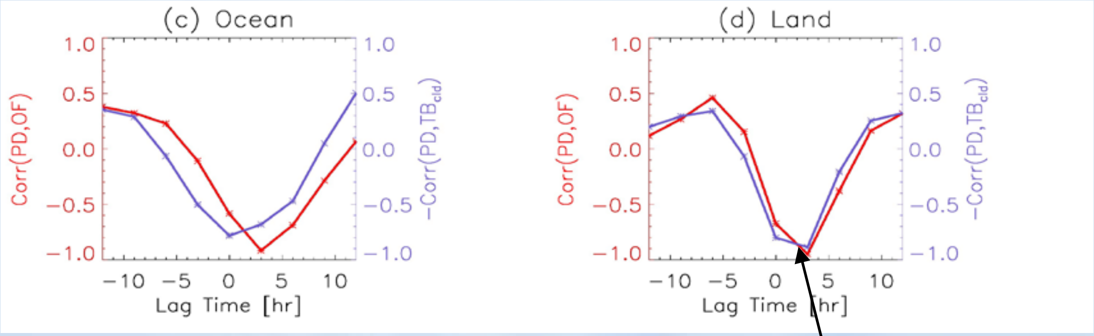
Using coarser temporal resolution may distort the signal. We need more frequent observations!

$\Delta t = 2\ hr$



2 hr

$\Delta t = 3\ hr$



3 hr

- Using $\Delta t = 1\ hr$ also result in $2\ hr$ lag-time, but the time series become more noisy because of lack of enough samples to make statistics robust.

Conclusions

- High-frequency (>150 GHz) passive microwave can retrieve “floating snow” cloud IWP.
- High-frequency MW polarimetric measurements are powerful and full of potentials of inferring ice cloud microphysical properties.
- PD (TB_V-TB_H) is a function of **ice crystal shape, size and orientation**. How to disentangle each contribution requires further fully-polarized 3D radiative transfer model simulations with proper representation of ice scattering properties and ambient air dynamic and thermodynamic conditions.
- Procession orbit design of GPM core satellite endows us an unprecedented opportunity to study the diurnal behavior of ice cloud and its microphysics. We found that it takes less than 2 hrs over tropical land for deep convective cloud to shoot to the upper-troposphere, while thin cloud generated from the outflow takes much slower timescale to develop and dissipate. Ice microphysics vary greatly (up to 35%) over tropical land during a day.
- The diurnal evolution of PD leads that of ice cloud and precipitation macrophysical properties (mean thickness, precipitation rate), which reveals that ***understanding the variations in ice microphysics is necessary to predict, infer and model the bulk properties of the ice clouds and their overall evolution linked to precipitation and radiative processes***.

SPARE

For details, please read:

Atmos. Chem. Phys., 17, 2741–2757, 2017
www.atmos-chem-phys.net/17/2741/2017/
doi:10.5194/acp-17-2741-2017

Atmospheric Chemistry and Physics
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Microphysical properties of frozen particles inferred from Global Precipitation Measurement (GPM) Microwave Imager (GMI) polarimetric measurements

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Research Letter

Diurnal Variation of Tropical Ice Cloud Microphysics: Evidence from Global Precipitation Measurement Microwave Imager Polarimetric Measurements

Jie Gong, Xiping Zeng, Dong L. Wu, Xiaowen Li

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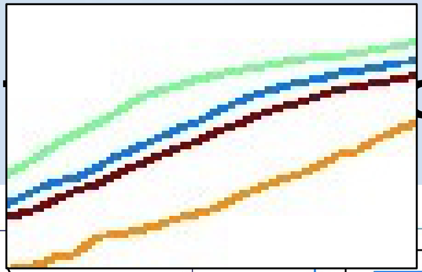
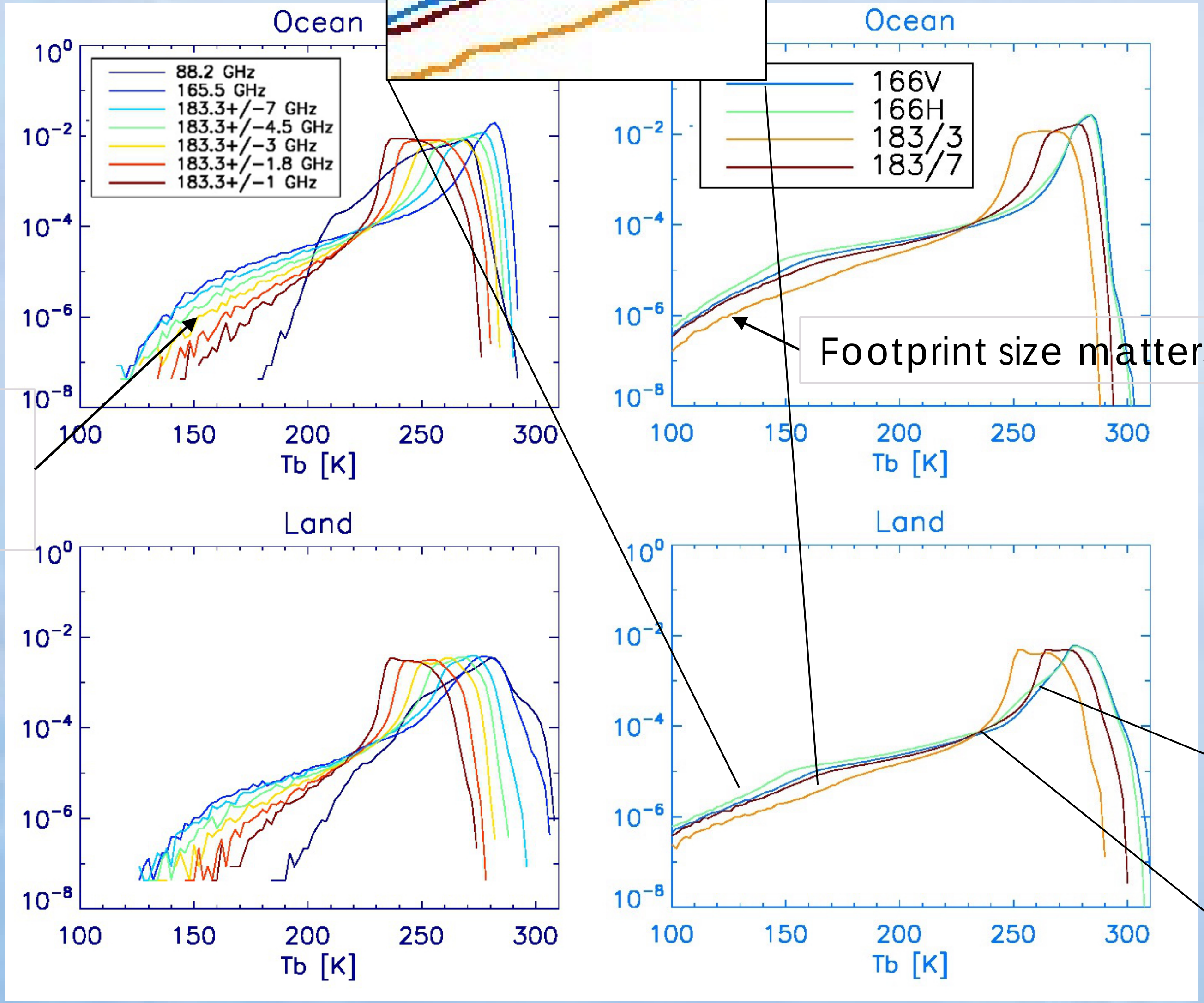
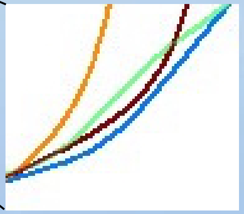
One month of T… GMI view-angle





183 GHz differentiation in thick-cloudy-sky might be useful for cloud profiling

166 V/H differentiation may be useful for small IWP or very large IWP retrievals

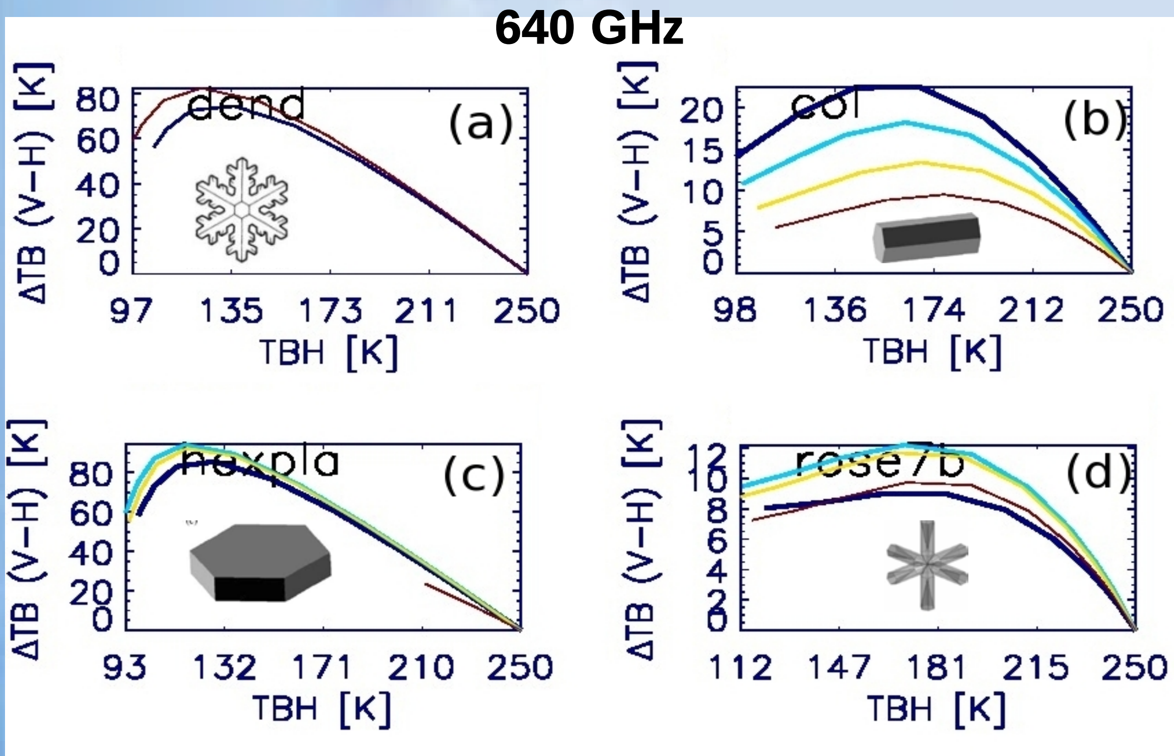


NPP-ATMS
(15 – 18 km FOV)

GPM-GMI
(4.4X7.2 km^2 FOV)

A fully polarized RTM simulation

› PD signal is a function of **ice shape, size, and orientation.**



Radiative transfer cannot explain the entire features. In the real world, dynamics also play a critical role.

- 100% horizontal orientation everywhere is **NOT** a good assumption inside convective core.
- **Turbulence, super-cooled water layer above ice, or irregular-shaped large particles like graupel brought up by vigorous vertical velocities** may all play critical roles on explaining the diminish of PD signal when cloud becomes optically thick.

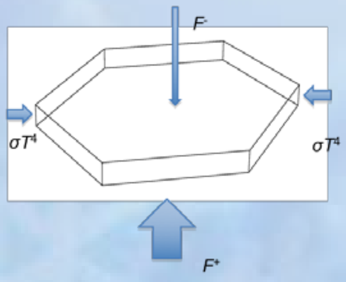
› RT4 of PolTranRad is a fully polarized RTM (Evans and Stephens, 1995, JAS). It assumes 100% horizontal alignment of ice crystals, and computes the [I, Q, U, V] Stoke's parameters layer by layer.

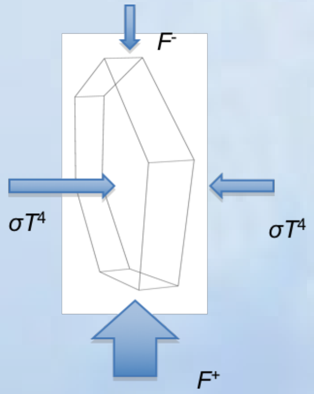
› For this simulation, RT4 is modified to GMI's viewing geometry. Yang et al. (2013, JAS)'s shape parameters were employed (only designed for 0.2-100 um cloud ice crystals but our simulations here run from 100 – 400 um for effective radius). Surface is ideal (Frensnel or Lambertian).

Explanation of the Leading of Ice Microphysical Change to Ice Cloud Coverage/Mass Change

$$\eta_z = \frac{F^+ + F^-}{2\sigma T^4}$$

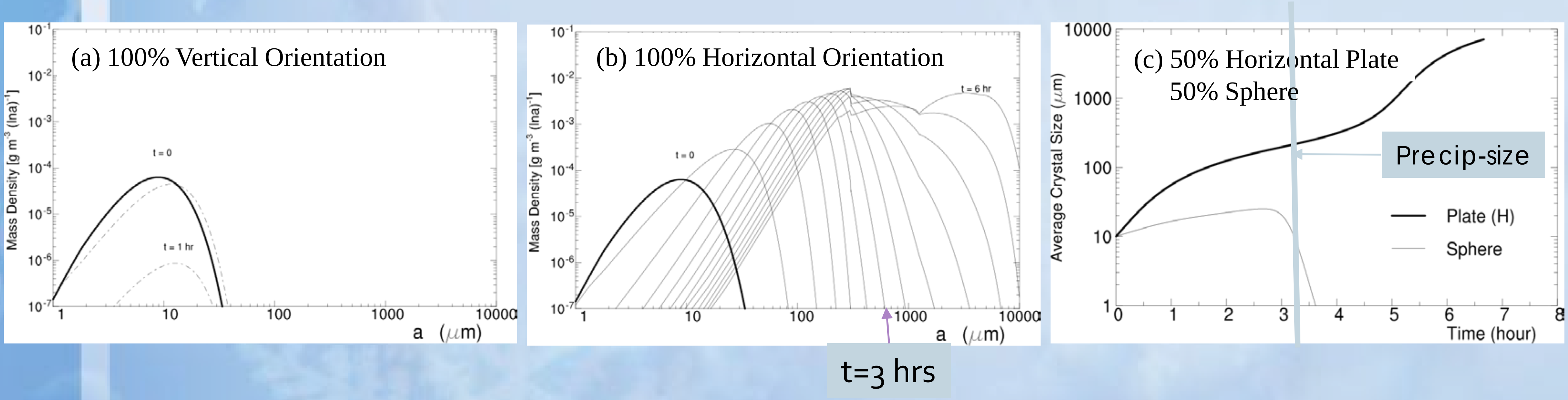
** F^+ and F^- represent the upward and downward fluxes of infrared radiation, respectively; T is atmospheric temperature; σ the Stefan-Boltzman constant.*
**** $\eta_z < 1$ near cloud top**.*





Ice crystals with different orientations/sizes/shapes
- receive different upward and downward radiative fluxes
- Possess different temperatures, and subsequently
- Have different saturation water vapor pressure around them.

Explanation of the Leading of Ice Microphysical Change to Ice Cloud Coverage/Mass Change



After 3 hrs,

- vertically oriented plate barely changes size
- horizontally oriented plates become precipitation, left with less cloud coverage
- Sphere crystals start to dissipate.

(Zeng, 2018; Zeng et al., submitted)

Interpretation by a simple 2-layer conceptual model

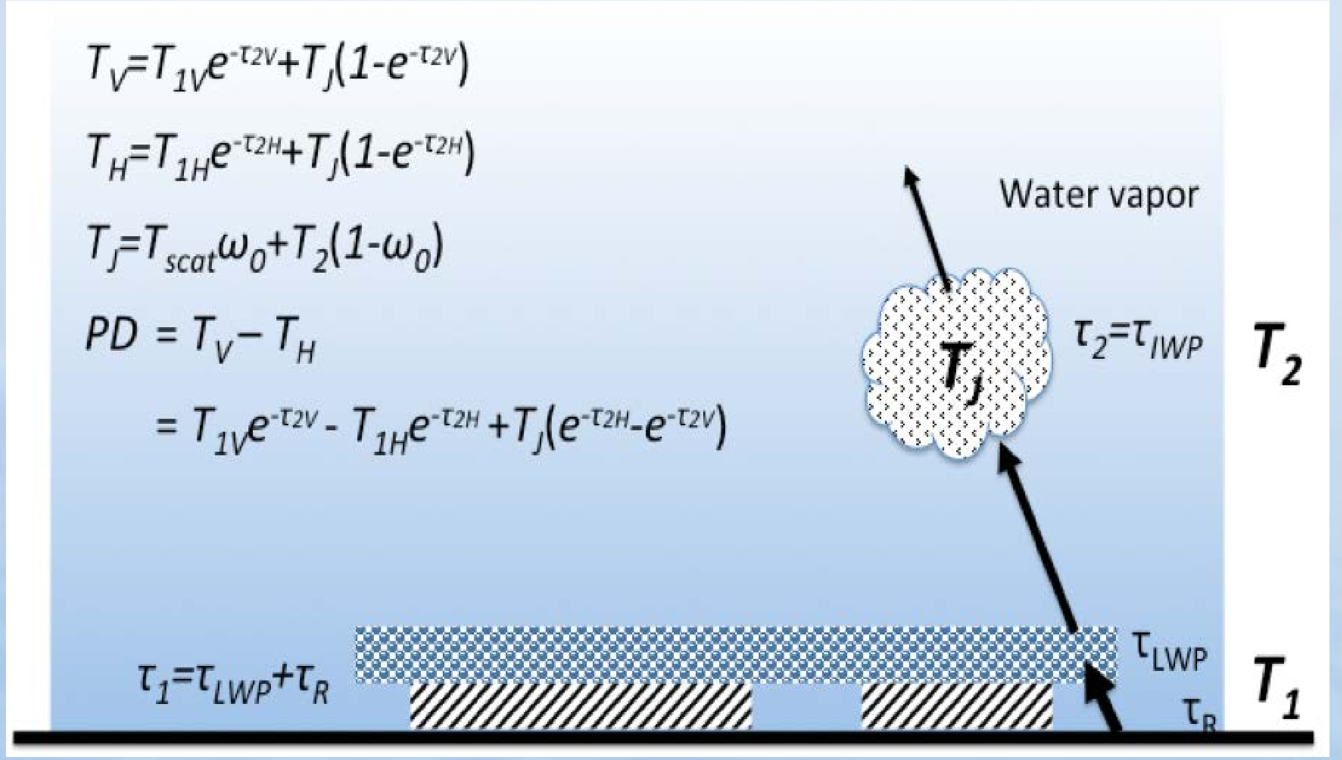
- Assuming all frozen hydrometers are horizontally oriented, naturally V-pol and H-pol pass through the same cloud with different optical depths (τ_v and τ_h)
- If background is unpolarized, $T_{1v} = T_{1h}$, and

$$PD = (T_1 - T_J)(e^{-\tau_{2v}} - e^{-\tau_{2h}})$$

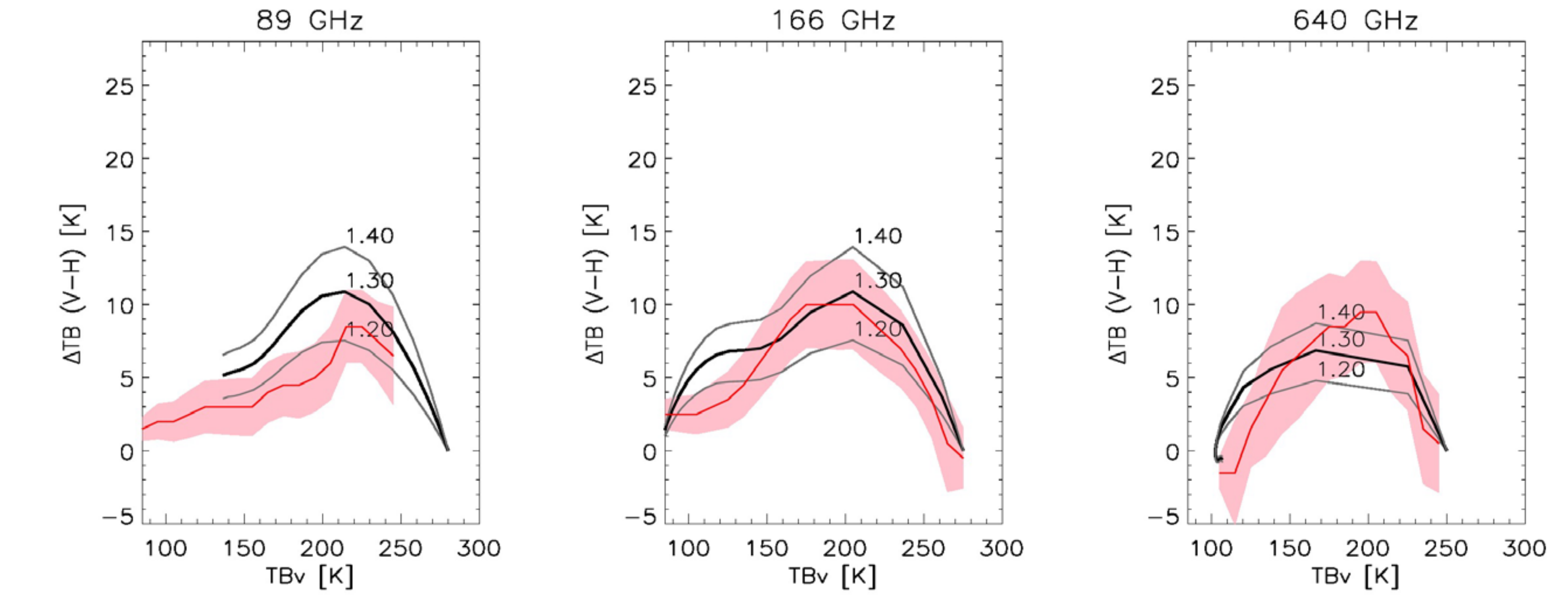
- For cloud with large optical depth, $PD \to 0$
- For thin cloud,

$$PD = (T_1 - T_J)(\tau_{2v} - \tau_{2h})$$

- Define Aspect Ratio ($AR \equiv {}^{\tau_{2v}}/_{\tau_{2h}}$), $PD = (T_1 - T_J)(AR - 1)\,\tau_{2h}$

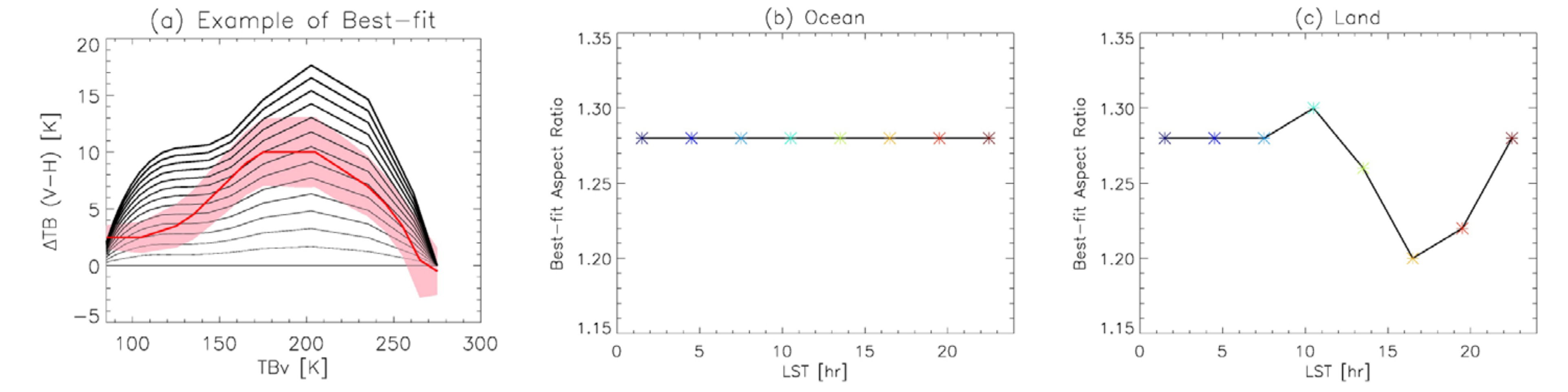


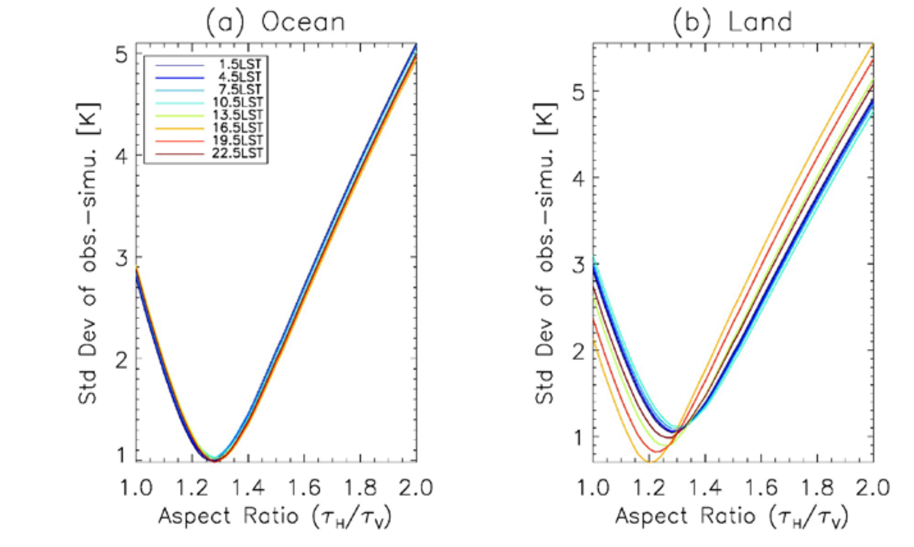
Interpretation by a Radiative Transfer Model (RTM) using the conceptual model



- AR=1.3 overall fits the best with the obs. from 89, 166 and 640 GHz.
- In reality, since these three channels are sensitive to different particle sizes (89 GHz sensitive to frozen hydrometers while 640 GHz only sensitive to small cloud ice crystals), AR is not expected to remain the same for different frequencies.
- There is an indication that AR increases with increase of channel frequency. ⟹ Small crystals are more horizontally oriented? Or small crystals are more flat?

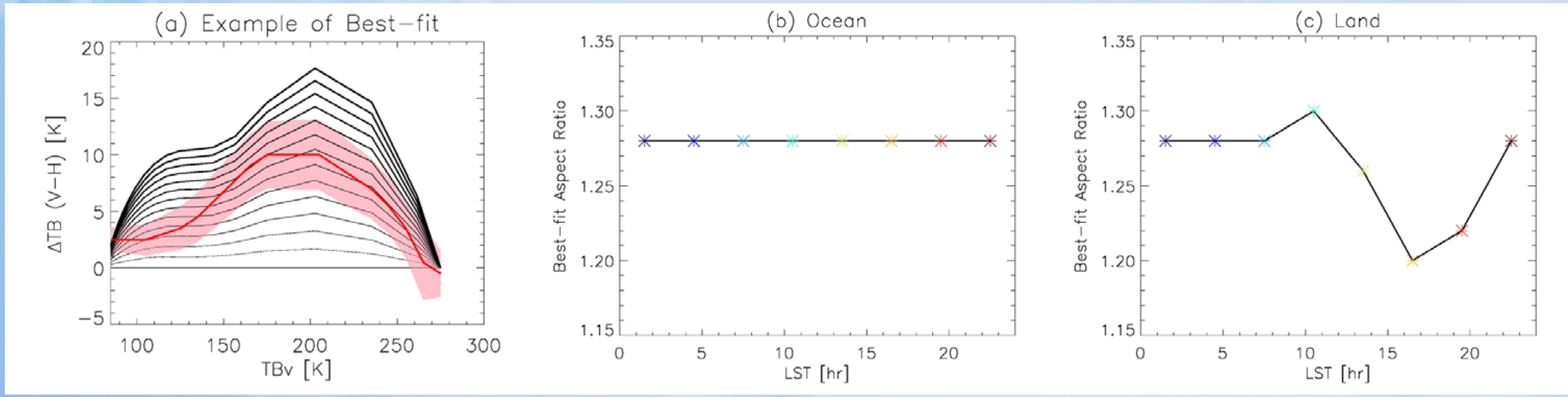
Explanation: Diurnal Variation of Aspect Ratio (AR)





- Varying AR in the simulations can produce different standard deviations. "Best-fit" is defined as where the minimum of standard deviation is achieved.
- The diurnal variation of "best-fit" AR value beats together with PD_{peak}.

Explanation: Diurnal Variation of Aspect Ratio (AR)



- Larger AR corresponds to more percentage of horizontally oriented ice crystals, or flatter ice crystals, or relate to size change (non-monotonic relationship).