RSTAR/WV-CKD

Development of the look-up table of the *k*-distribution in the gas absorption region around 940 nm for the sky-radiometer data analysis

Topic: PWV estimation from the sky-radiometer

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Contents:

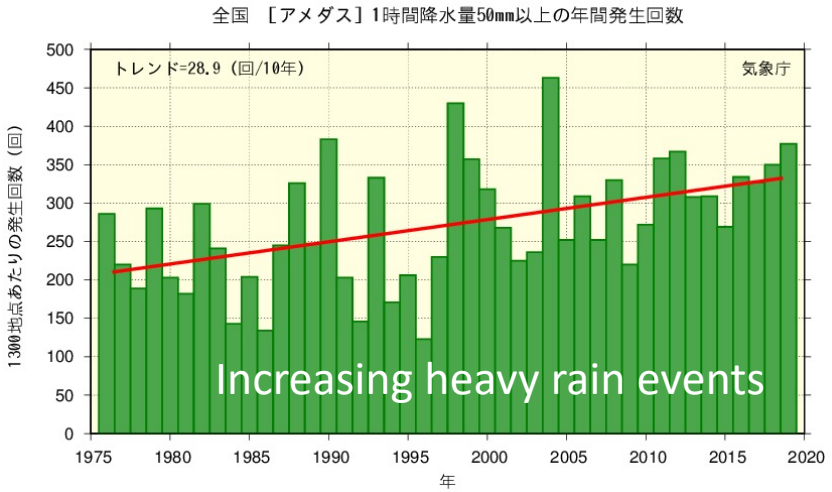
- ✓On-site self-calibration at 940 nm channel from angular distribution [Momoi et al., 2020, AMT]
- ✓Improvement of the gas calculation

Atmospheric water vapor

Meteorological aspects

- To bring rains
- To affect water cycle in Earth system

JMA website

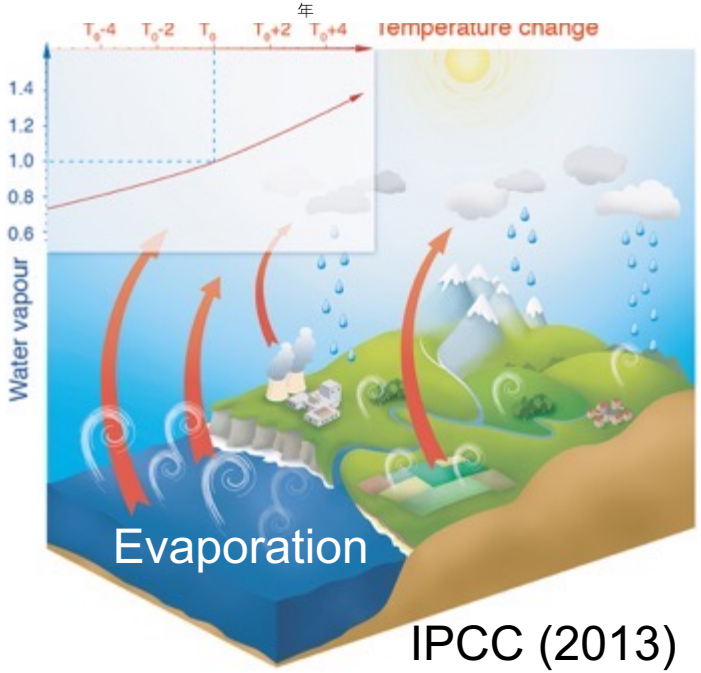


Climatological aspects

Water vapor is specified as an <u>essential climate variable</u>

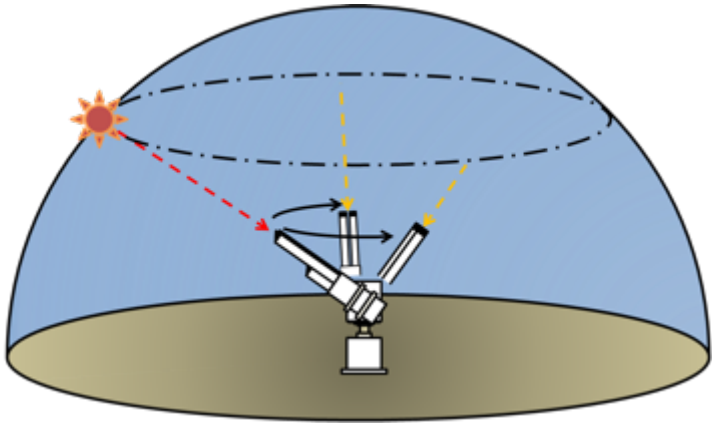
- Water vapor absorbs IR and raises the temperature.
- Rising temperature increases the amount of water vapor in the atmosphere

→ There is a heat-up cycle that accelerates temperature heating



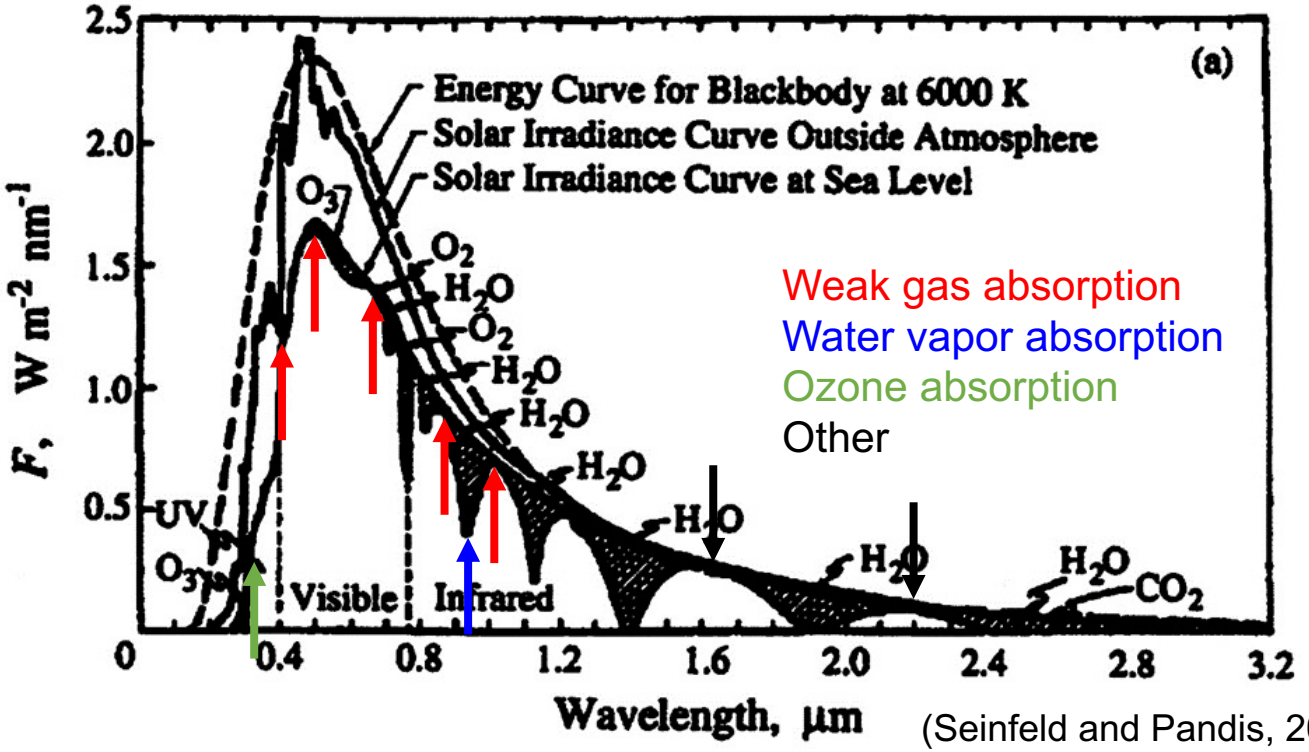
IPCC (2013)

Sky radiance observation



Measurement

- Direct solar irradiance
  : every 1 min.
- Angular distribution of the diffuse radiance
  : every 10 min./ 15 min.



(Seinfeld and Pandis, 2016)

How to estimate PWV from transmittance?

Beer-Lambert's law

: $F = \tilde{F}_0 \tilde{T}_{\mathrm{H_2O}} T_{\mathrm{Ray}} T_{\mathrm{Aer}}$

PROBLEM

⇨ $\tilde{F}_0$ and $\tilde{T}_{H_2O}$ depend on the filter response function (Ψ)

1. $\tilde{F}_0$: Calibration constant of radiometer

: $\tilde{F}_0 = C \int \Psi F_{\mathrm{sol}} \mathrm{d}\lambda$

2. $\tilde{T}_{\mathrm{H_2O}}$: Transmittance of the water vapor

(1) Physics-based approach

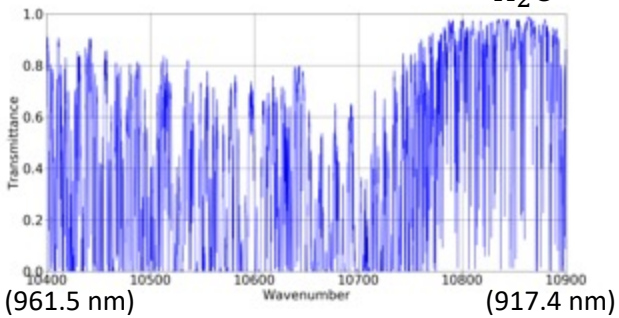
: $\tilde{T}_{\mathrm{H_2O}} = \dfrac{\int \Psi F_{\mathrm{sol}} T_{\mathrm{H_2O}} \mathrm{d}\lambda}{\int \Psi F_{\mathrm{sol}} \mathrm{d}\lambda}$

(2) Empirical equation [Bruegge et al., 1992]

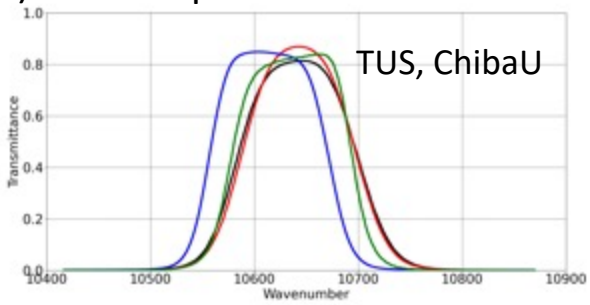
: $\tilde{T}_{\mathrm{H_2O}} \approx \exp[-a(mw)^b]$

(m: optical mass, w: precipitable water vapor)

(a) Water vapor absorption: $T_{\mathrm{H_2O}}$



(b) Filter response function: Ψ



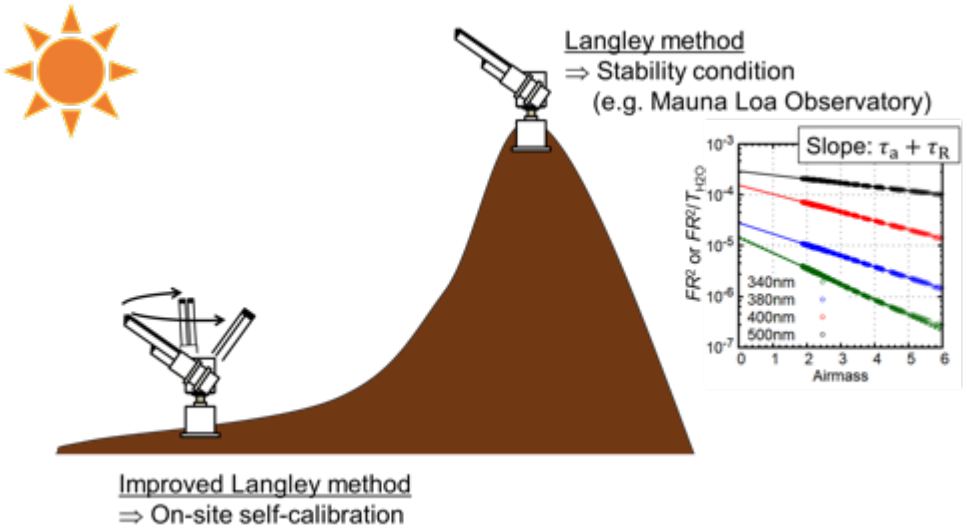
Challenges of PWV estimation from radiometer

Issue of application for international network:
1. Maintaining traceability is costly (it must be calibrated at a stable site).

The calibration techniques at unstable site were developed for the weak gas absorption channel from UV to NIR.

(Nakajima et al., 1996; Campanelli et al., 2007; Mok et al., 2018; Nakajima et al., 2020)

⇨ This techniques made possible to calibrate with on-site.



Approach: We expanded such technology to gas species (water vapor).

2. Adjustment parameters need to be given to each instrument

Approach: we developed the gas calculation in RTM with high speed by correlated *k*-distribution method.

Previous study: calibration of the water vapor channel

Beer-Lambert's law: $F = \tilde{F}_0 \tilde{T}_{\mathrm{H_2O}} T_{\mathrm{Ray}} T_{\mathrm{Aer}}$

Bruegge et al. (1992): $\tilde{T}_{\mathrm{H_2O}} \approx \exp[-a(mw)^b]$

☆Remark: Previous study used empirical equation☆

1. Langley like method (e.g., Uchiyama et al., 2014)
   PWV was inputted from the other instrument.
   Possible to calibrate under stable condition (AOT is constant).
   Adjusting parameters (*a*, *b*) were theoretically estimated.

$$\underbrace{\ln\left(\frac{F}{T_{\mathrm{H_2O}}}\right)}_{\mathbf{y}} = \underbrace{-m(\tau_R + \tau_a)}_{\mathbf{x}} + \ln F_0$$

2. Modified Langley method (e.g., Campanelli et al., 2014)
   Possible to calibrate under stable condition (AOT & PWV are constant).

$$\underbrace{\ln F + m(\tau_R + \tau_a)}_{\mathbf{y}} = -a\underbrace{(mw)^b}_{\mathbf{x}} + \ln F_0$$

Brief of Momoi et al. (2020)

Information on sky radiance around 940 nm

Normalized radiance (Independent of F_0)

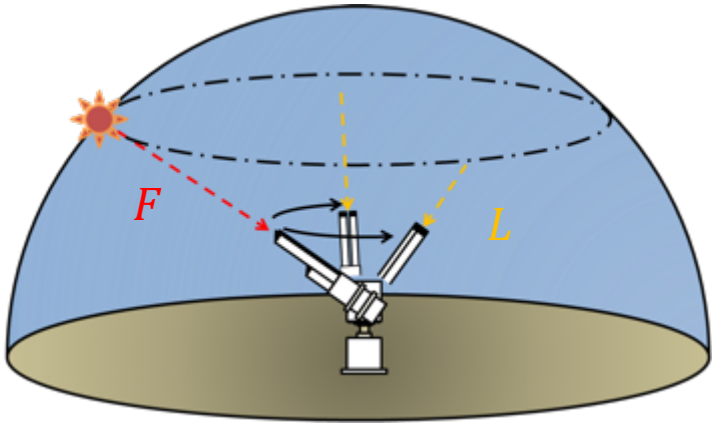
(1) Almucantar plane

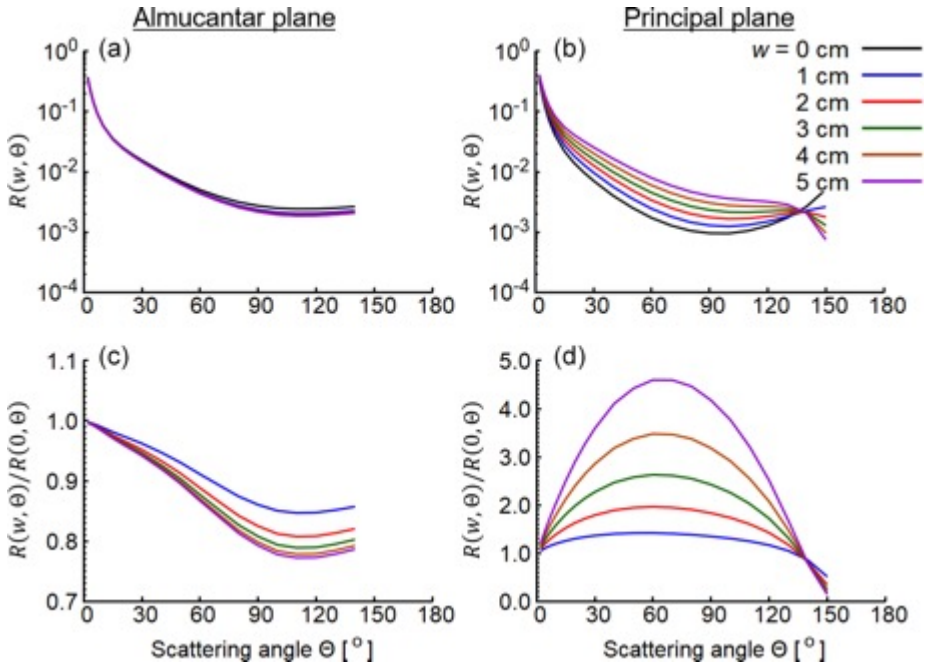
$$R = |\mu|\frac{L}{F} = \omega\tau P(\Theta) + q(\Theta)$$

(2) Principal plane ($\eta \equiv |\mu|^{-1} - |\mu_0|^{-1}$)

$$R = |\mu|\frac{L}{F} = \omega\tau P(\Theta)\frac{e^{-\eta\tau(\lambda)} - 1}{\eta\tau(\lambda)} + q(\Theta)$$

τ : optical thickness
μ: cosine of zenith angle
μ_0: cosine of solar zenith angle
ω : single scattering albedo
Θ : scattering angle
$P(\Theta)$: normalized phase function
$q(\Theta)$: multiple scattering contribution
$\Delta\Omega$: solid view angle





PWV retrieval by SKYMAP/DSRAD procedure

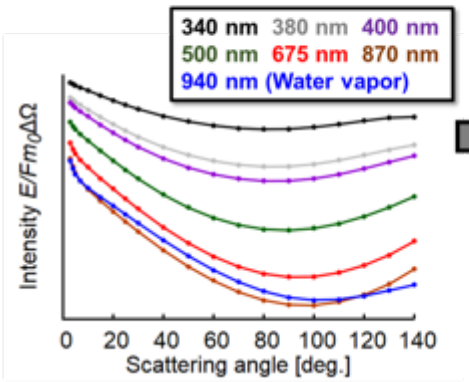
PWV retrieval from the sky-radiometer observation data

- The new on-site self calibration method at water vapor channel (**SKYMAP**)
- The retrieval method of the precipitable water vapor (DSRAD)

Advantage

- The water vapor channel can be calibrated with on-site data.
- The PWV can be estimated without adjusting parameters *a, b*.
  (We consider the filter response function.)

Measurement of angular distribution



SKYMAP

RETRIEVAL PARAMETER

AEROSOL
- Volume size distribution
- Refractive index
- Fraction of the spherical particle

WATER VAPOR
- Precipitable water vapor

OUTPUT PARAMETER

Calibration constant of 940 nm

DSRAD

OUTPUT PARAMETER

AEROSOL
- Aerosol optical thickness
- Angstrom exponent

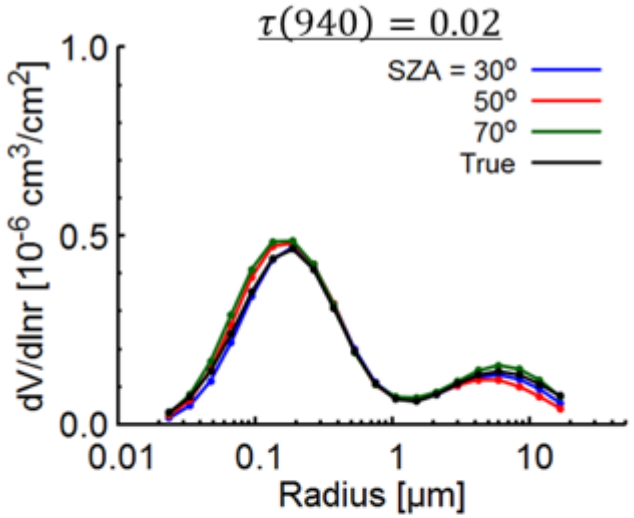
WATER VAPOR
- Precipitable water vapor

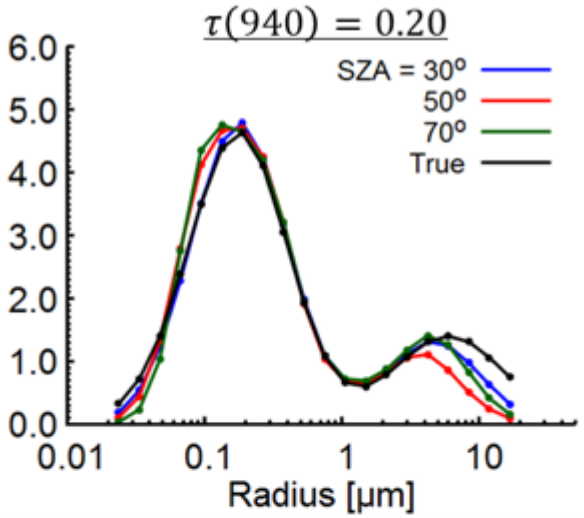
Measurement of direct solar irradiance

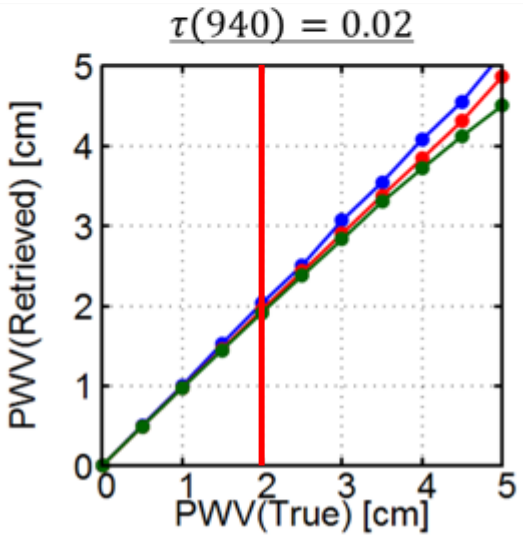
Sensitivity test using simulated data of SKYMAP

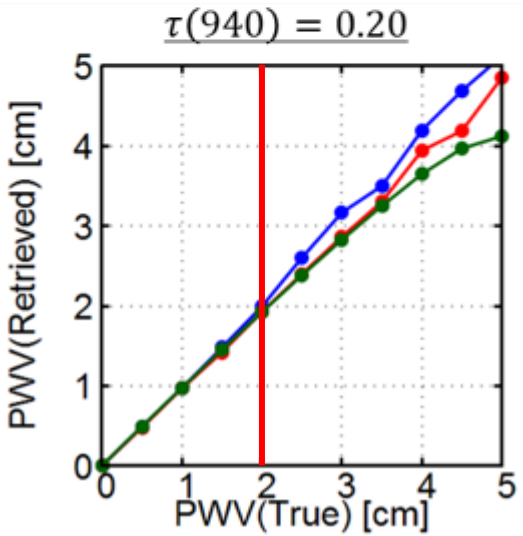
Continental average aerosol

- Water-soluble, Soot, Insoluble









👍 The PWV was retrieved well when the PWV is less than 2 cm.

👎 The PWV can't be retrieved when the PWV is more than 2 cm.

We can calibrate F_0 during dry season???

Challenges of PWV estimation from radiometer

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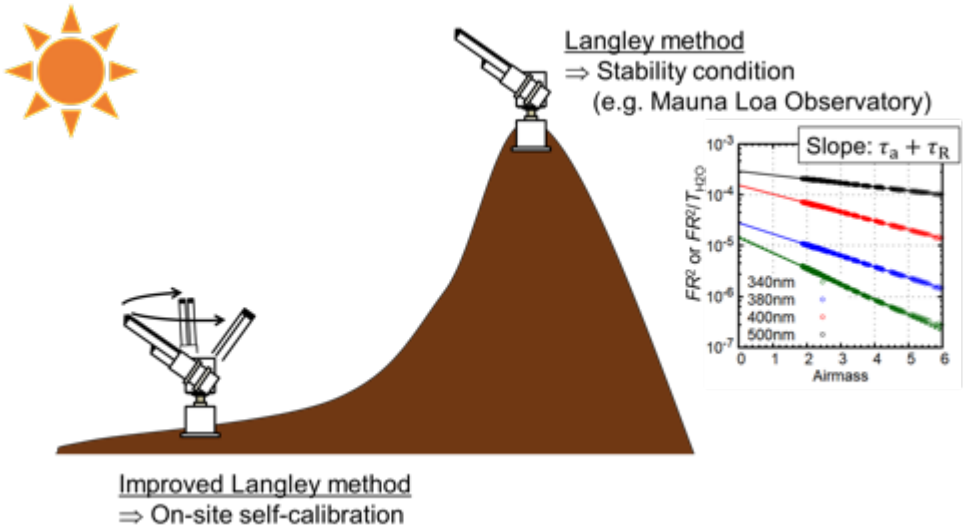

Approach: We expanded such technology to gas species (water vapor).

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Approach: we developed the gas calculation in RTM with high speed by correlated *k*-distribution method.

How to calculate gas absorption rapidly?

$n = 2$: standard CKD tables in RSTAR

Line-by-line method

$$\bar{T} = \int_{\Delta_\lambda} T(\sigma_\lambda)\mathrm{d}\lambda$$

Numerous executions of RTM
(Unsuitable for standard operation)

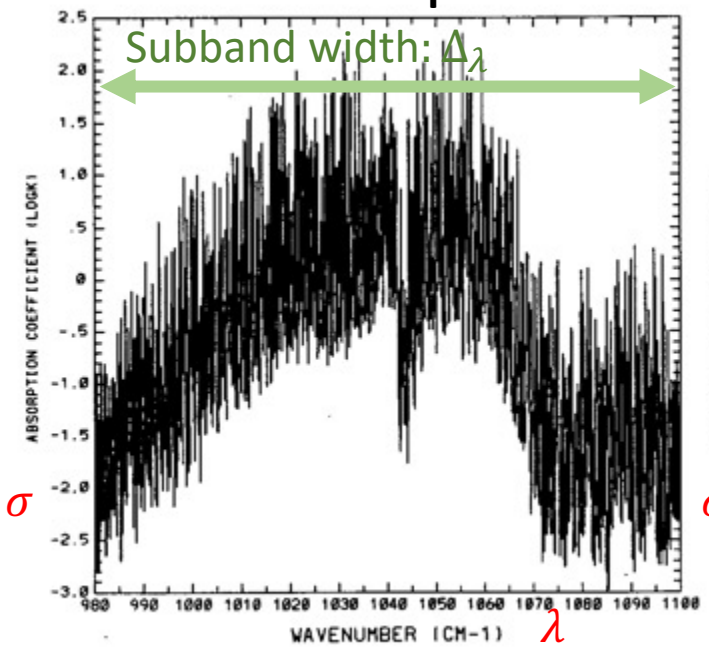
Correlated *k* distribution

$$\bar{T} = \int_0^1 T(\sigma_g)\mathrm{d}g \Rightarrow \sum_i^n T(\sigma_{g_i})w_i$$

e.g. Gaussian quadrature

Only n-times executions of RTM

Line absorption



Probability in Δ_λ

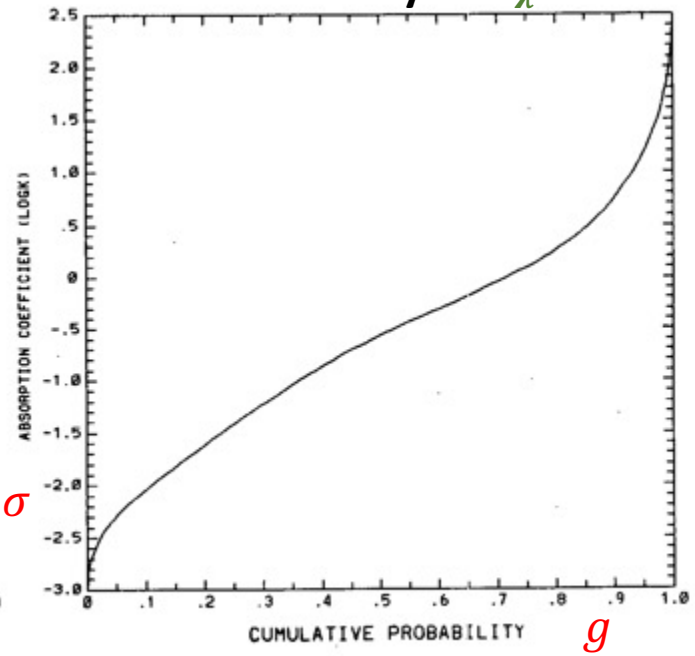
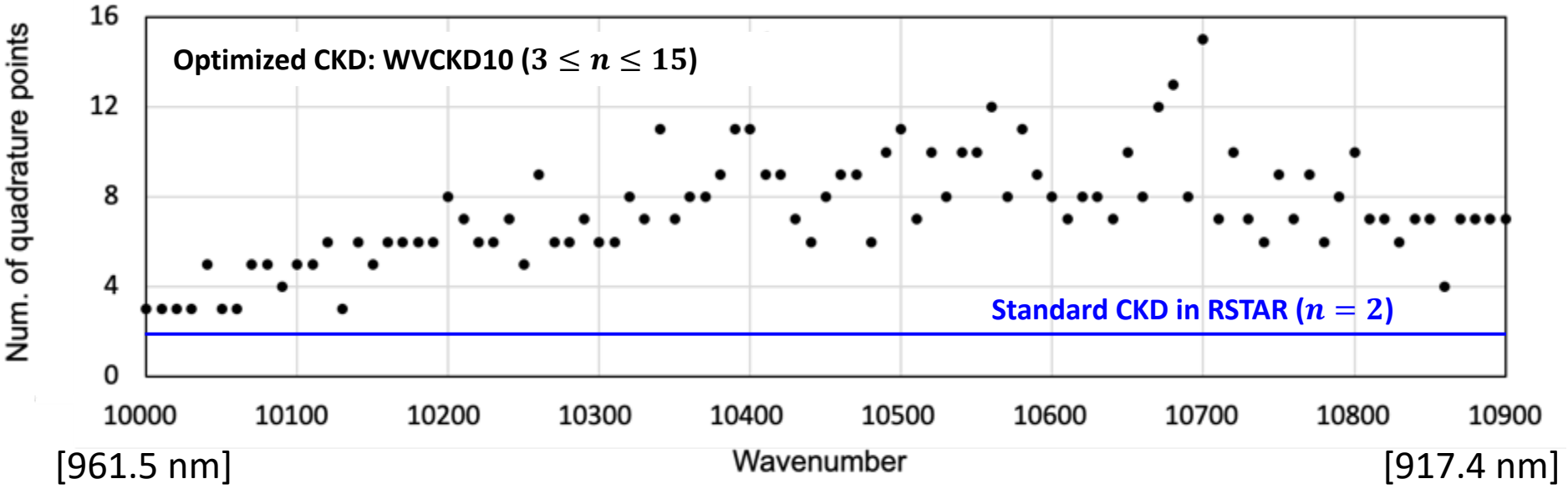


FIG. 1. Absorption coefficient k in (cm atm)$^{-1}$ as a function of (a) wavenumber and (b) cumulative probability for the O_3 9.6-μm band for a pressure of 25 mb and a temperature of 220 K.

[Fu and Liou, 1992]

Optimized quadrature numbers of new CKD tables



	WVCKD2	WVCKD5	WVCKD10	LBL	MODTRAN
	Correlated *k*-distribution method				Band model
Resolution [cm^{-1}]	2	5	10	0.01	0.2
Mean computation times [/cm^{-1}]					
917 – 1000 nm	2.18	1.18	0.734	100	5
920 – 961 nm	2.44	1.33	0.848	100	5

- Finer CKD table needs more quadrature points
- Computation time of WVCKDs are faster than that of LBL and MODTRAN

New LUTs VS previous LUT (SN-CKD)

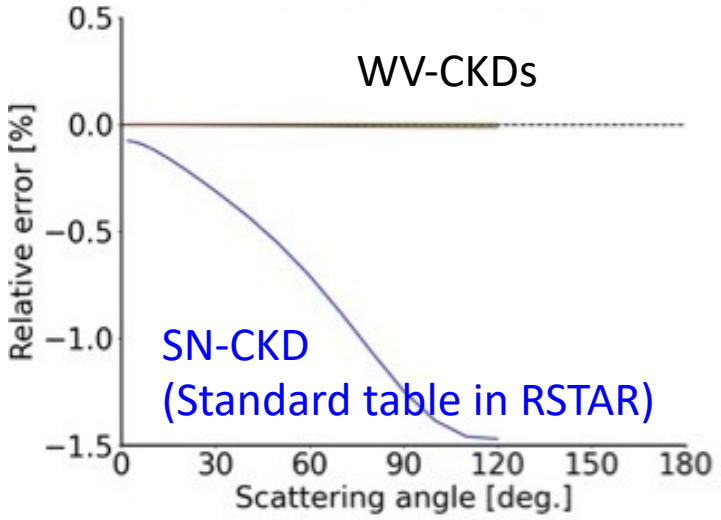
Standard CKD table in RSTAR7 is used by sky-radiometer analysis programs:

- SKYMAP algorithm (Momoi et al., 2020, 2021)
- SKYRAD.pack MRI version 2 (Kudo et al., 2021)

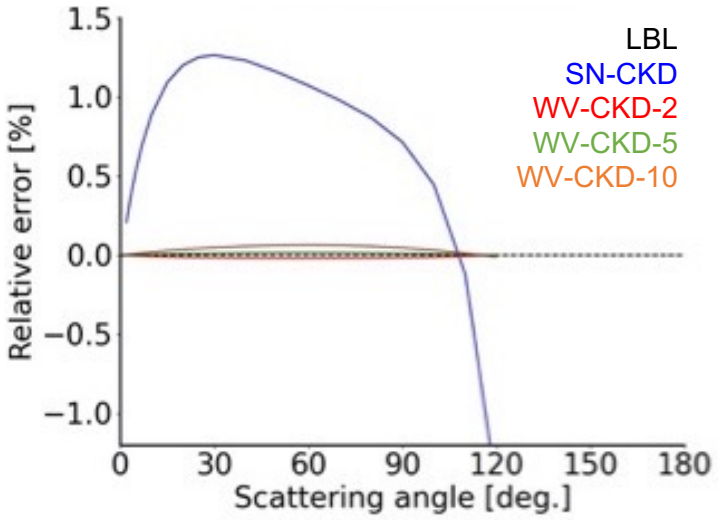
Convolved sky radiances with an FWHM of 10 nm (sky-radiometer specification)

Relative error: $\varepsilon = \frac{F_{\mathrm{df}}^{\mathrm{CKD}} - F_{\mathrm{df}}^{\mathrm{LBL}}}{F_{\mathrm{df}}^{\mathrm{LBL}}}$

Almucantar plane



Principal plane

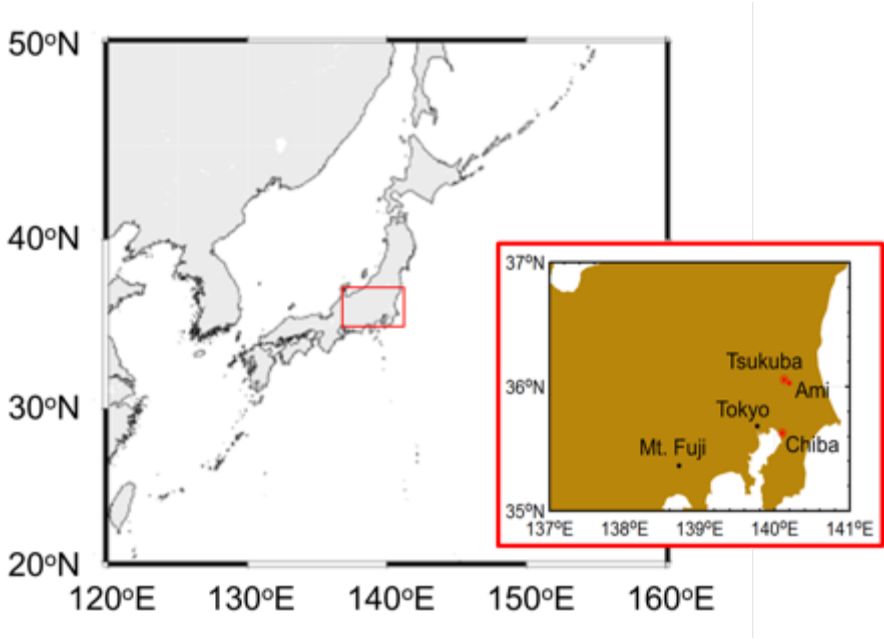


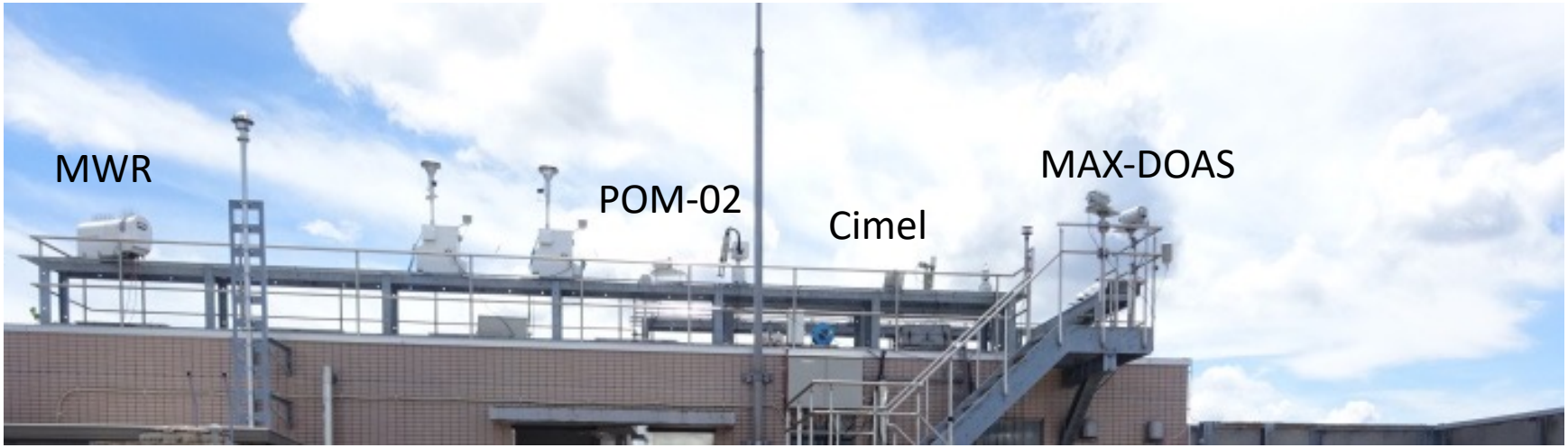
Actual observations with SKYMAP algorithm

SKYNET sites in Japan

Chiba, Japan (140.10E, 35.63N, 2019)

- Sky-radiometer POM-02
- Microwave radiometer (MWR)

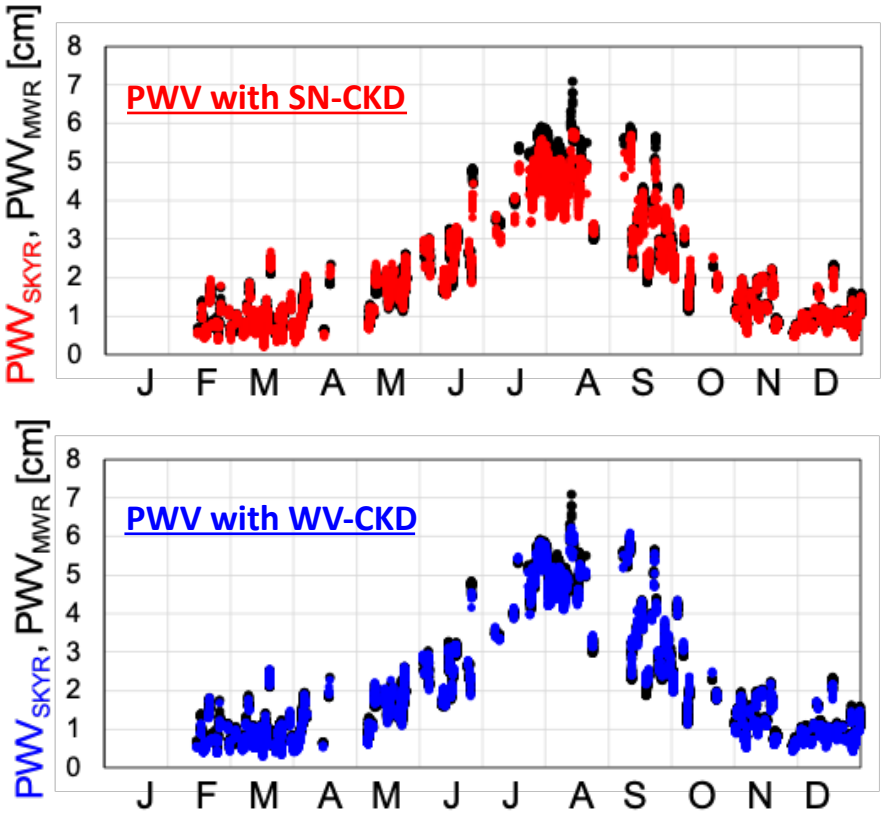




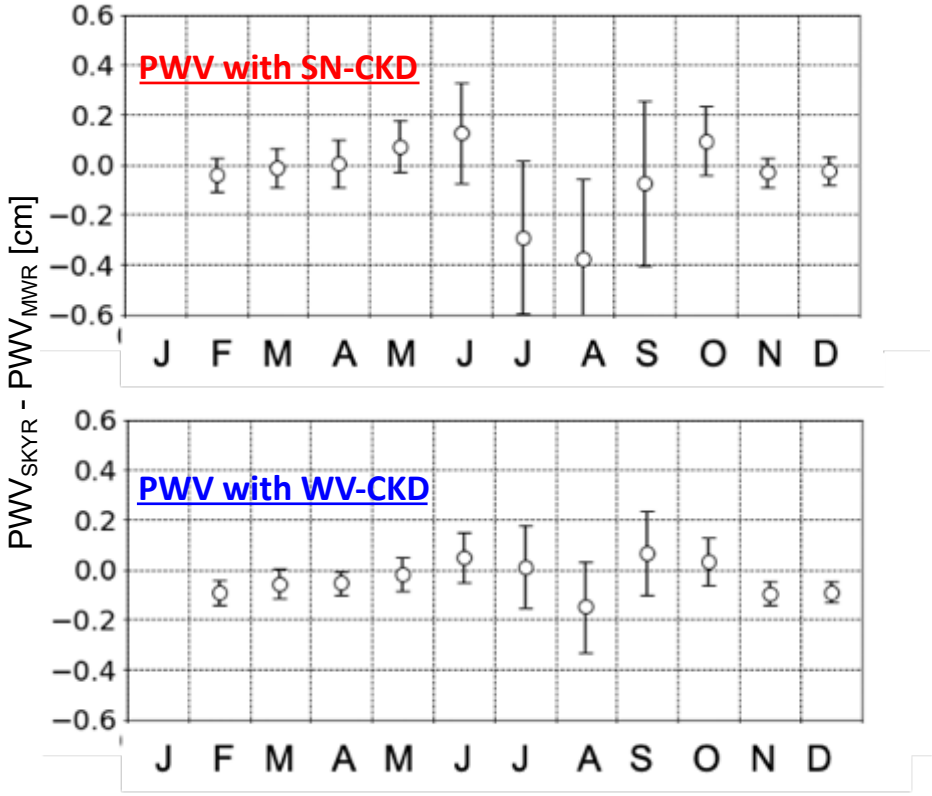
PWV derived with SKYMAP/DSRAD

PWV_{SNCKD} was underestimated!
↔ PWV_{WVCKD} was good agreement with PWV_{MWR}.
⇒ An accurate CKD table is essential for estimating PWV from sky-radiometer observations

Time series



Monthly mean difference



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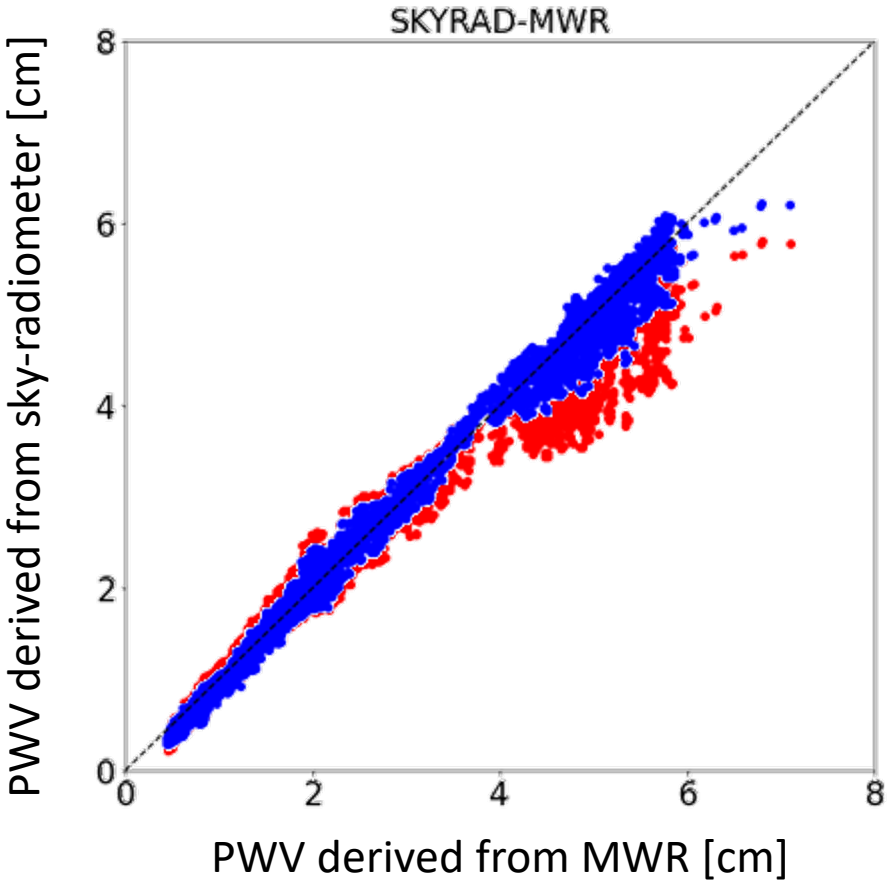

PWV with SN-CKD

Slope: 0.926
Intercept: 0.095 [cm]
RMSE: 0.231 [cm]
Correlation coef.: 0.984

PWV with WV-CKD

Slope: 1.002
Intercept: -0.053 [cm]
RMSE: 0.128 [cm]
Correlation coef.: 0.995

Summary

This study developed

1. New PWV estimation algorithm (SKYMAP algorithm) from sky-radiometer observation without pre- and post-calibration at a specific site (e.g., Mauna Loa Observatory),
2. New CKD tables for effectively reconstructing the sky radiances at 940 nm.

By application for actual SKYNET observation,

1. An accurate CKD table is essential for reconstructing sky radiance and estimating PWV from sky-radiometer observations
2. New PWV retrieval procedure (SKYMAP/DSRAD) is practical

Additional information:

- On-site self-calibration method was published in AMT.
- Physics-based PWV estimation program (DSRAD) are available on request.

For more information, please contact me (m.momoi@biglobe.jp or SLACK).