Upper-air simulator to evaluate the radiation correction and measurement uncertainty of RS41

ICM-13 online

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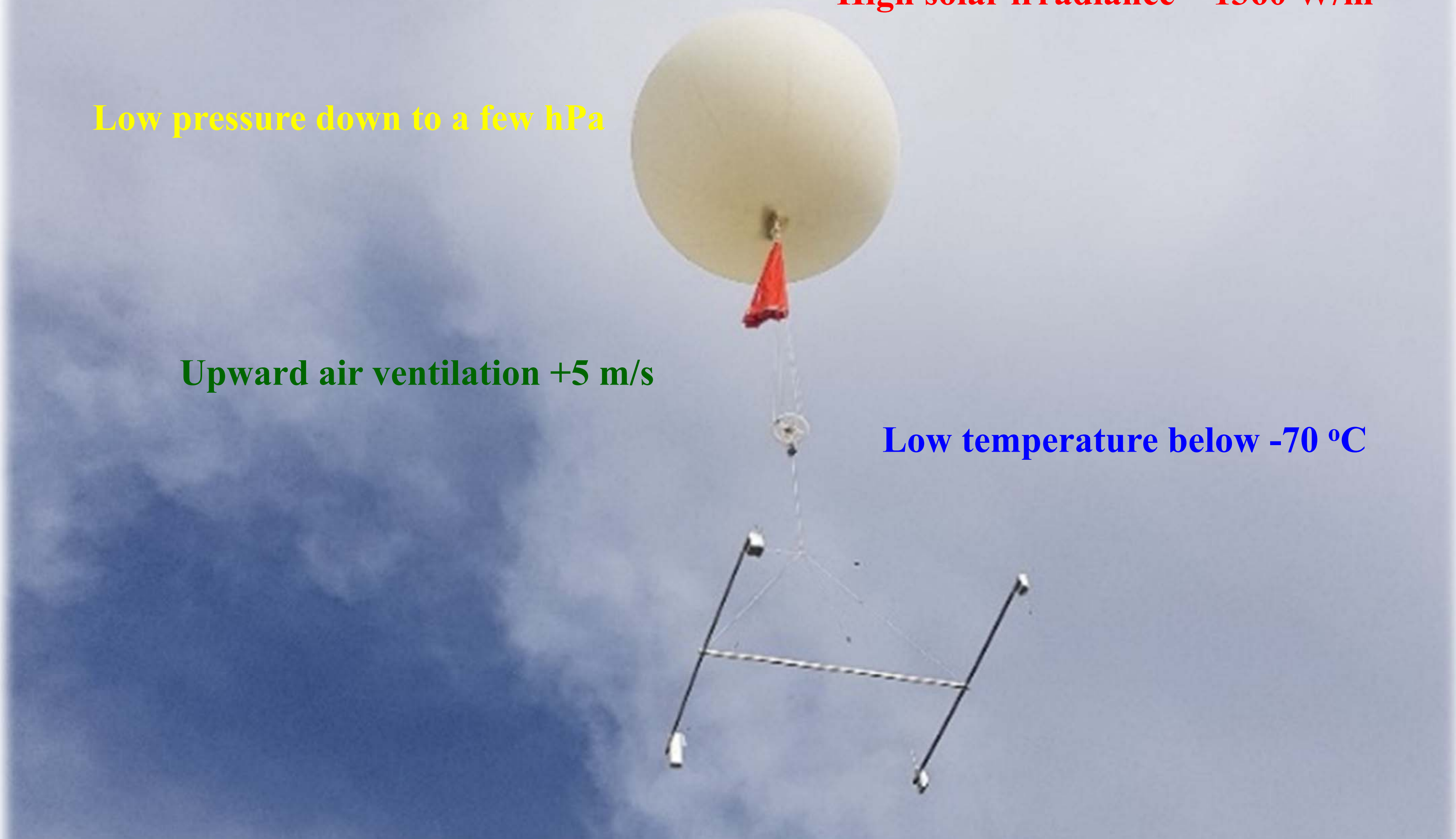
Significance of radiosonde measurement

- Accurate method to monitor the long-term climate change in stratosphere
  - Temperature is the direct index of global warming
- Practical tool to gather climate variables for the weather forecasting in troposphere
- Serve as a Reference to other remote skills such as satellite
- Sounding sites more than 1000 sites
  - National observatories
  - Military bases, etc
  - Institutes & universities for research

Radiosonde meets …



Requiring accurate test method based on international agreement

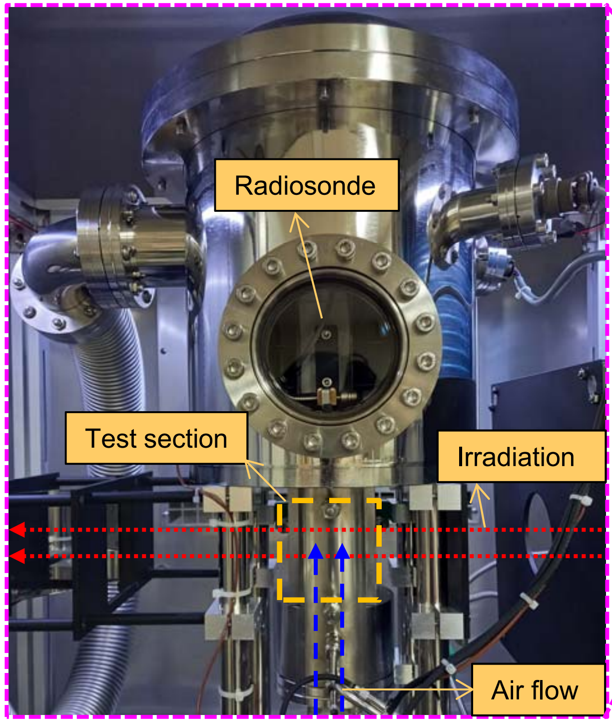
Conditions for test method

- Guide to Meteorological Instruments and Methods of Observation (WMO-No.8)
  - Chapter 12, MEASUREMENT OF UPPER-AIR PRESSURE, TEMPERATURE AND HUMIDITY
    - “The calibration methods used by manufacturers should be identified before purchasing radiosondes.”
    - Stability condition of ±0.2 hPa/min for pressure, ±0.25 K/min for temperature and ±1 relative humidity per minute
    - Errors less than ±0.2 hPa for pressure, ±0.1 K for temperature and ±1% relative humidity

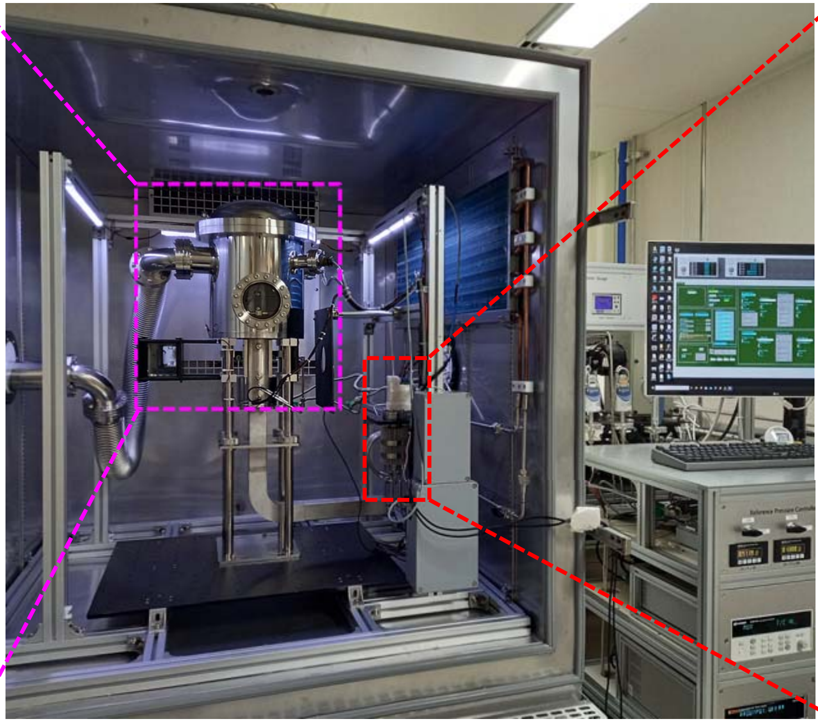
There is no detailed descriptions on the implementation of calibration setups/methods

Upper air simulator (UAS) at KRISS

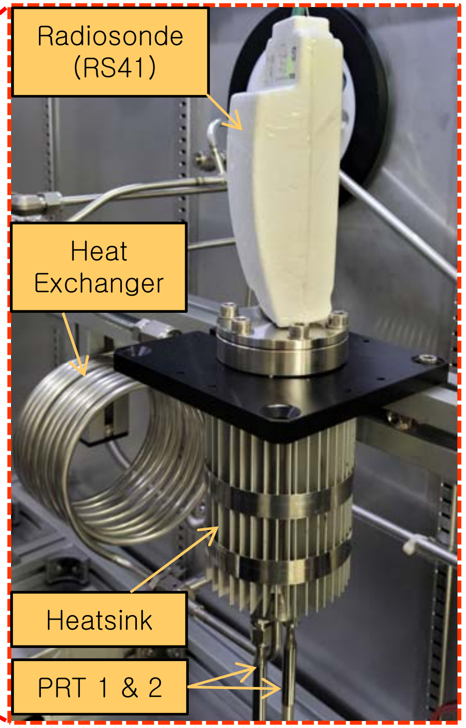
- Radiation correction of temperature sensors
  - Control of temperature, pressure, ventilation, and irradiance
- Calibration of humidity sensors
  - Control of temperature and humidity



<Radiation correction setup>
Lee *et al.* Meteorol. Appl. **27**, e1855 (2020)



<Upper air simulator>

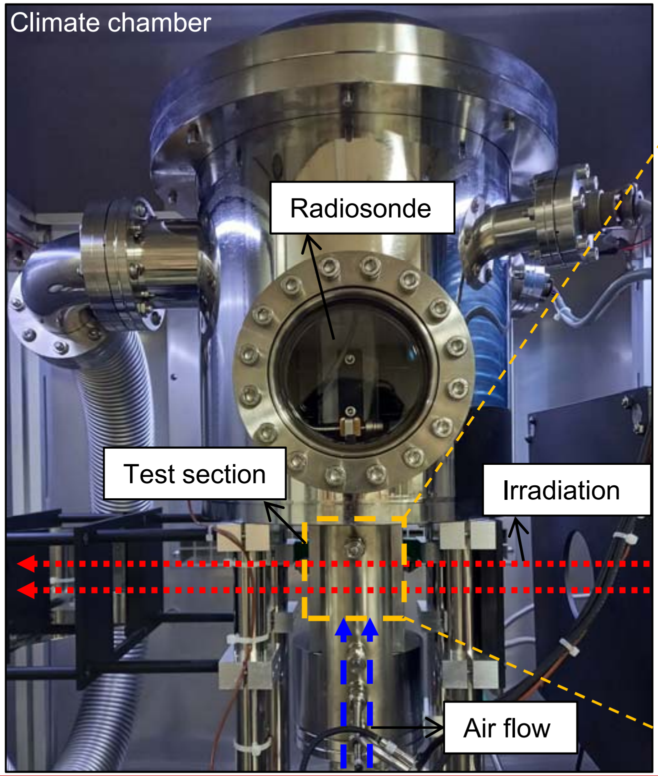


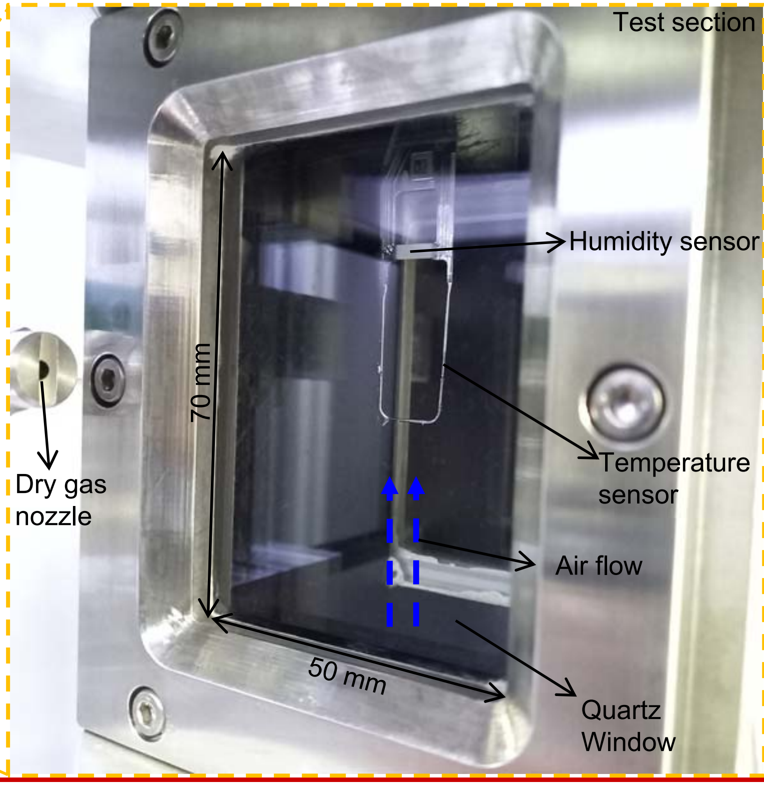
<Humidity calibration setup>
Lee *et al.* Meteorol. Appl. **28**, e2010 (2021)

Radiation correction setup

Environmental factors affecting radiation correction

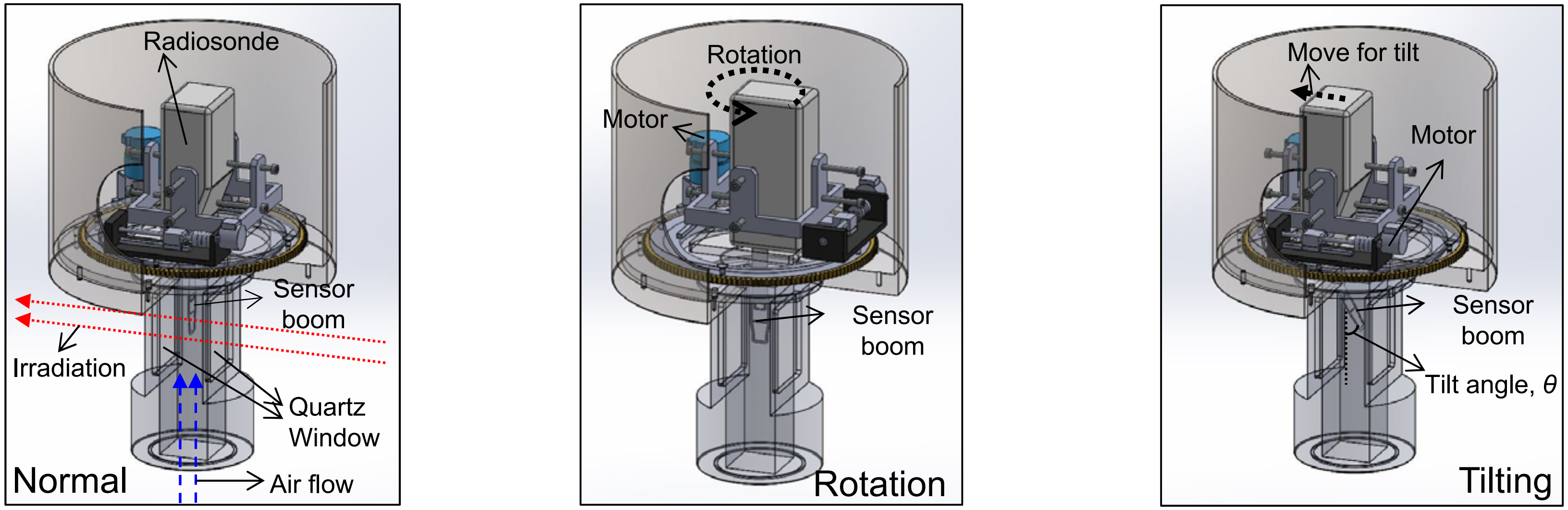
- Temperature (T = -70−20 °C) by climate chamber
- Air pressure (P = 5−500 hPa) & Ventilation (v = 4−7 m/s) by sonic nozzles
- Irradiance (S_0 = 1000 W/m^2) by solar simulator

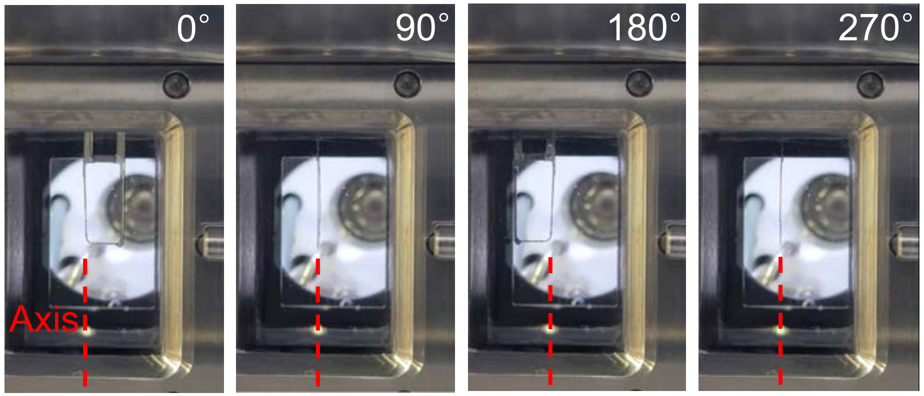




Rotation & Tilting of radiosonde

- Simulation of movement of radiosonde in sounding
  - Rotation (5, 10, 15 s) & Boom tilting (27 °)



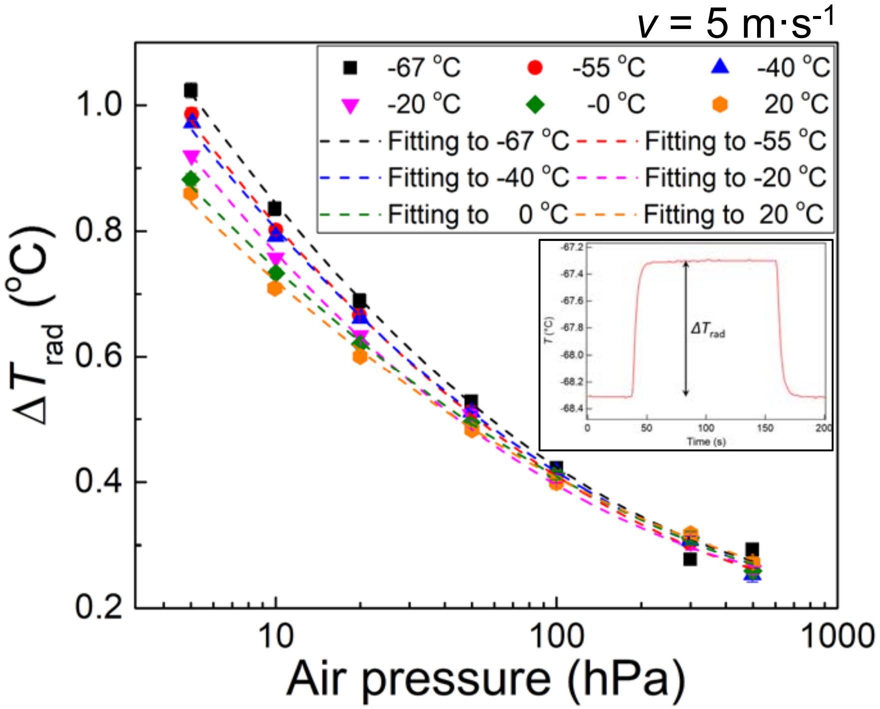


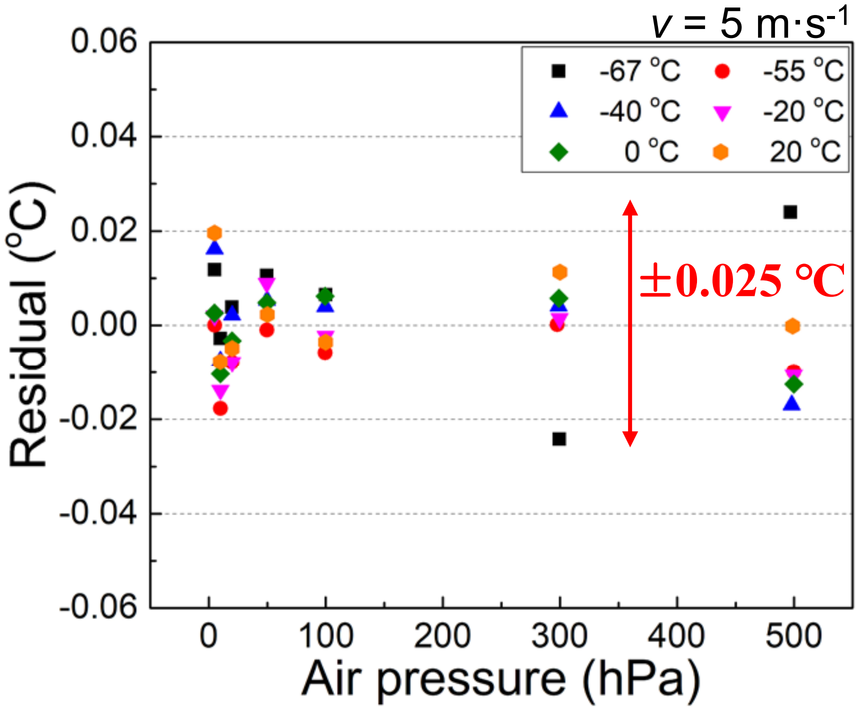
Rotation axis = Temperature sensor

Pressure effect

☐ Convective cooling

- Radiation correction ($\triangle T_{rad}$) decreases as air pressure (P) increases
- Air density ↑ at high P → Convective cooling ↑



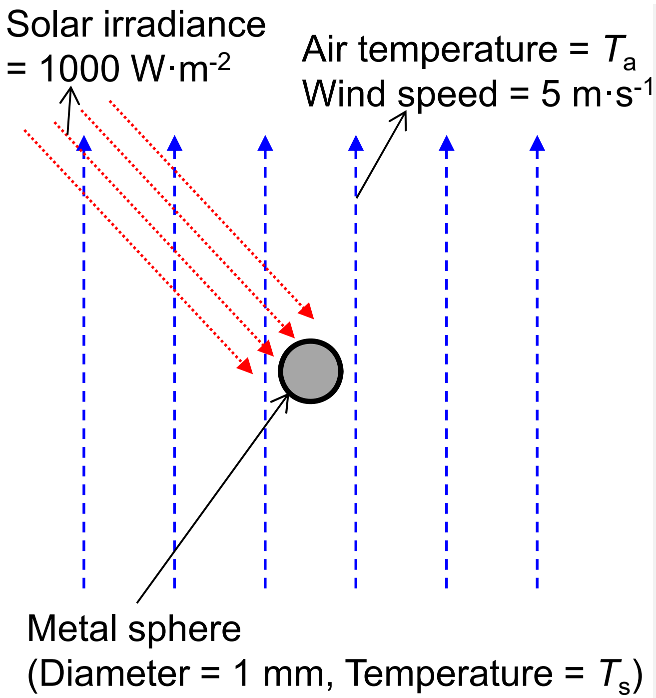


$$\Delta T_{rad} = A_0(T) + B_0(T)\cdot\log(P) + C_0(T)\cdot[\log(P)]^2 \quad \text{for } 5\text{ hPa} \leq P \leq 500\text{ hPa},\ S_0 = 980\ \mathrm{W\cdot m^{-2}}$$

Theoretical understanding

☐ Heat transfer calculation

- Metal sphere is modelled as a temperature sensor



$$\alpha S = h(T_s - T_a)\,,\quad h = \frac{k}{D}\left[2 + \left(0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right)\left(\frac{\mu C_p}{k}\right)^{\frac{2}{5}}\right]$$

α = absorptivity of the metal sphere

S = solar irradiance

***h* = heat transfer coefficient**

D = diameter of the sphere

k = thermal conductivity of air

μ = viscosity of air

C_p = heat capacity of air

Re = Reynolds number ($\rho v D/\mu$)

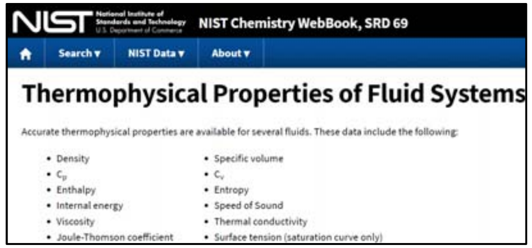
ρ = density of air

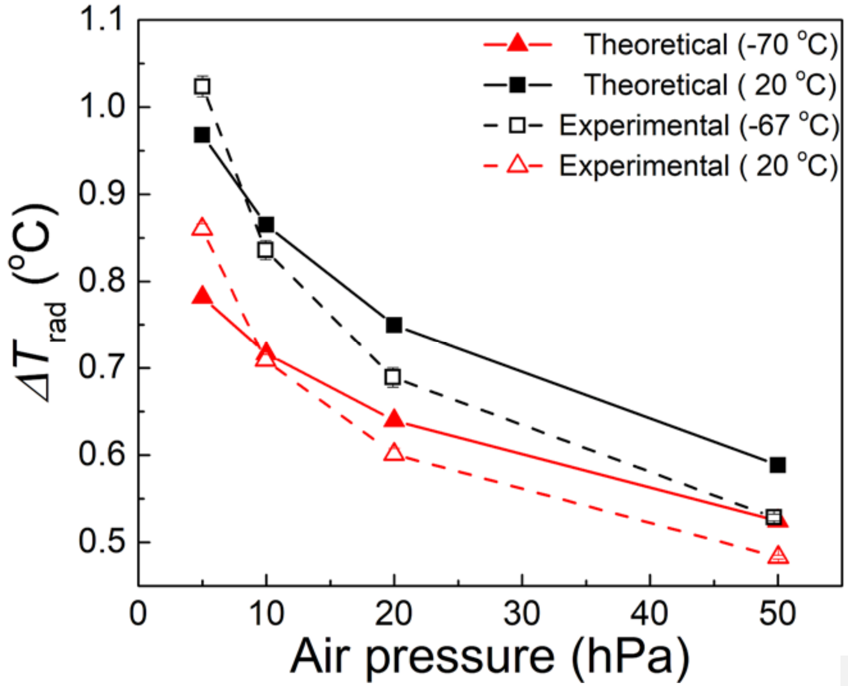
v = wind speed

Properties of air & Sensor geometry

Temperature effect

- Radiation from the sensor
  - $T\downarrow \rightarrow k$ (thermal conductivity) $\downarrow \rightarrow h\downarrow \rightarrow \triangle T_{rad}$



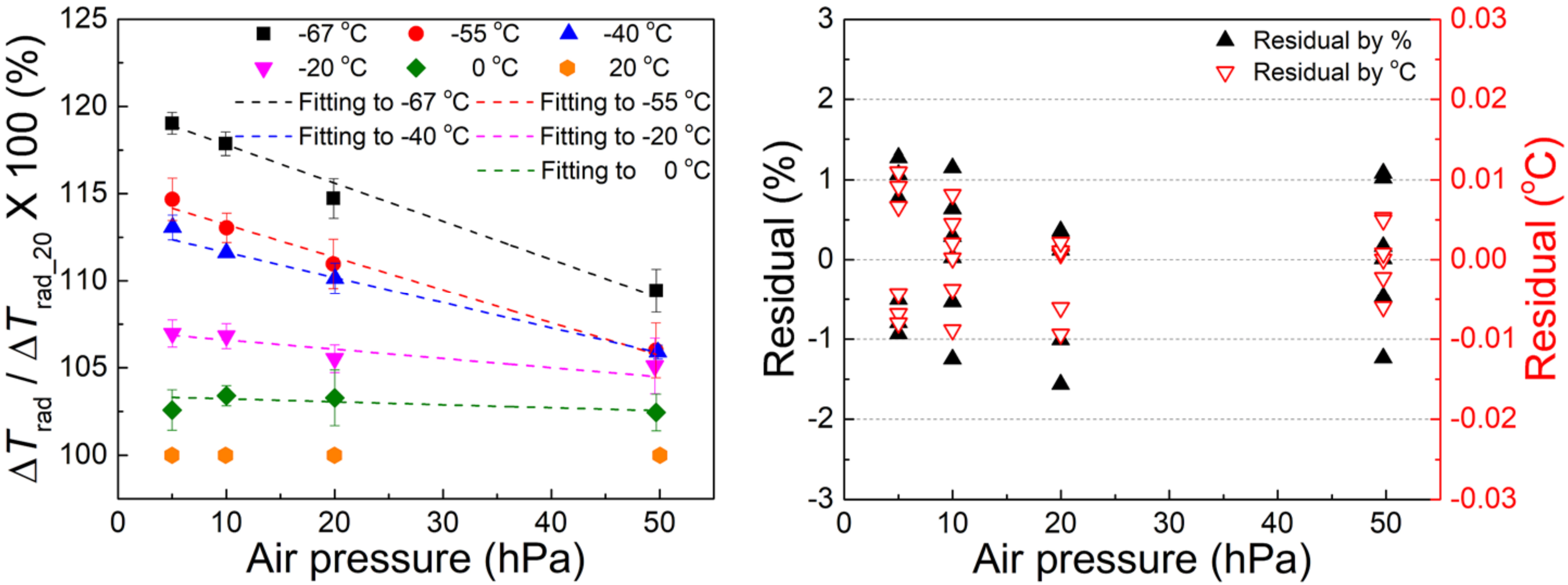


Parameter	Symbol (Unit)	Value (T_a = 20 °C)	Value (T_a = −70 °C)
Diameter	D (m)	0.001	0.001
Air pressure	P_a (hPa)	5	5
Wind speed	v (ms^{-1})	5	5
Viscosity	μ (Pa·s)	0.00001754	0.00001307
Density	ρ (kg·m^{-3})	0.0057466	0.0082925
Thermal conductivity	k (W·m^{-1}·K^{-1})	0.025367	0.018869
Heat capacity	C_p (J·kg^{-1}·K^{-1})	1039.6	1039.1
Reynolds number	Re	1.64	3.17
Heat transfer coefficient	**h (W·m^{-2}·K^{-1})**	**63.97**	**51.67**
Solar irradiance	S (W·m^{-2})	1000	1000
Absorptivity of metal	α	0.2	0.2
Radiation correction	**T_s - T_a (K)**	**0.78**	**0.97**

$$\alpha S = h(T_s - T_a)\,, \quad h = \frac{k}{D}\left[2 + \left(0.4Re^{\frac{1}{2}} + 0.06Re^{\frac{2}{3}}\right)\left(\frac{\mu C_p}{k}\right)^{\frac{2}{5}}\right]$$

Estimation of low temperature effect

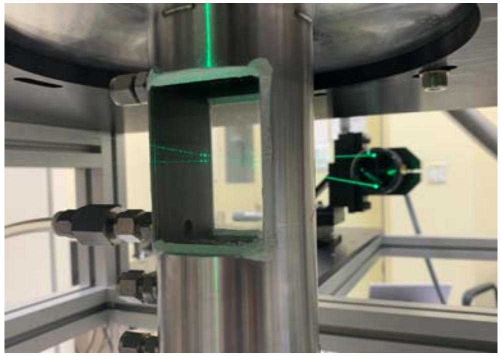
- Empirical formula based on experiment
  - Estimation of $\triangle T_{rad}$ at cold temperatures using $\triangle T_{rad}$ at 20 °C



$$\Delta T_{rad}/\Delta T_{rad\_20} \times 100\ (\%) = D(T)\cdot P + E(T)\ ,\qquad D(T) = d_0\cdot T + d_1\ \&\ E(T) = e_0\cdot T + e_1$$

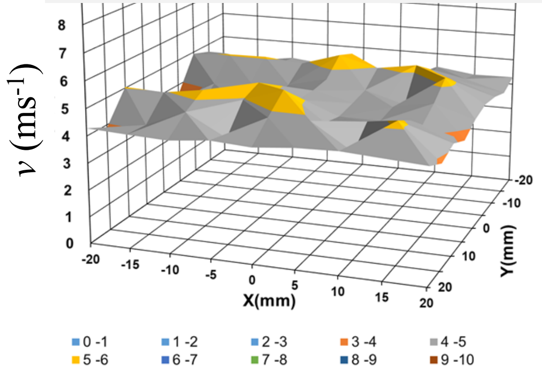
Ventilation effect

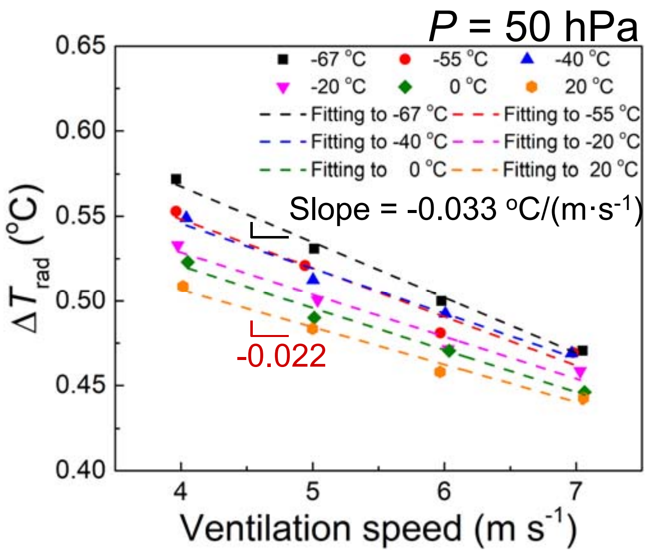
- Convective cooling
  - $v\uparrow \rightarrow \triangle T_{rad}\downarrow$

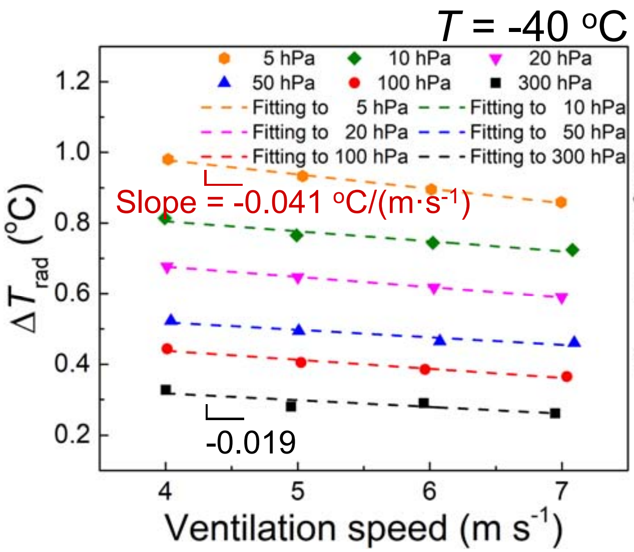


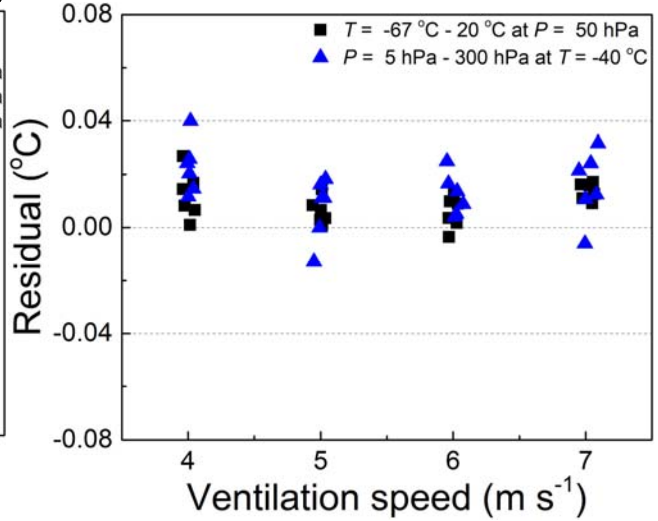
Laser Doppler Velocimetry

Reference: 4.67 ms^{-1} (550 hPa)
Measurement mean: 4.63 ms^{-1}









$$\Delta T_{rad} = A_0(T) + B_0(T)\cdot\log(P) + C_0(T)\cdot[\log(P)]^2 - 0.027\cdot(v\text{-}5)$$

for 5 hPa $\leq P \leq$ 500 hPa, S_0 = 980 W·m^{-2}

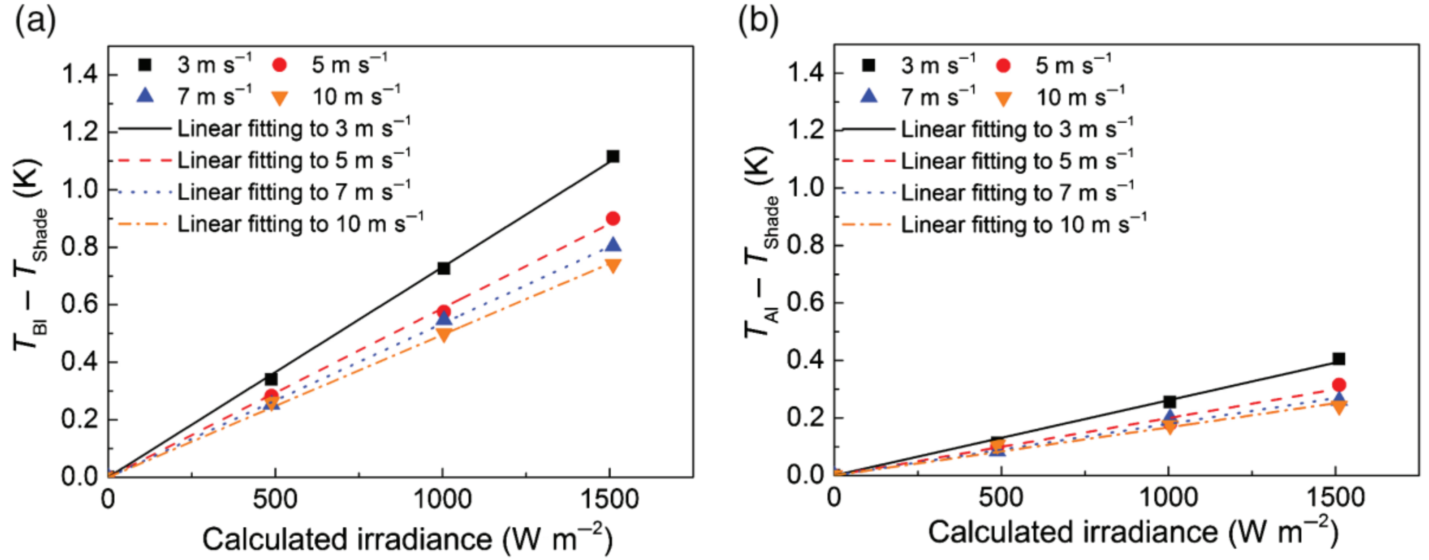
Irradiance effect

Heating by solar irradiance

- $\triangle T_{\mathrm{rad}}$ is proportional to S

$$-h(T_s - T_a) - \sigma\varepsilon(T_s^4 - T_a^4) + \alpha S = 0 \quad \Rightarrow \quad T_s - T_a = \frac{\alpha S}{h}$$

(convection) (sensor radiation) (solar radiation) (Proportional to S)



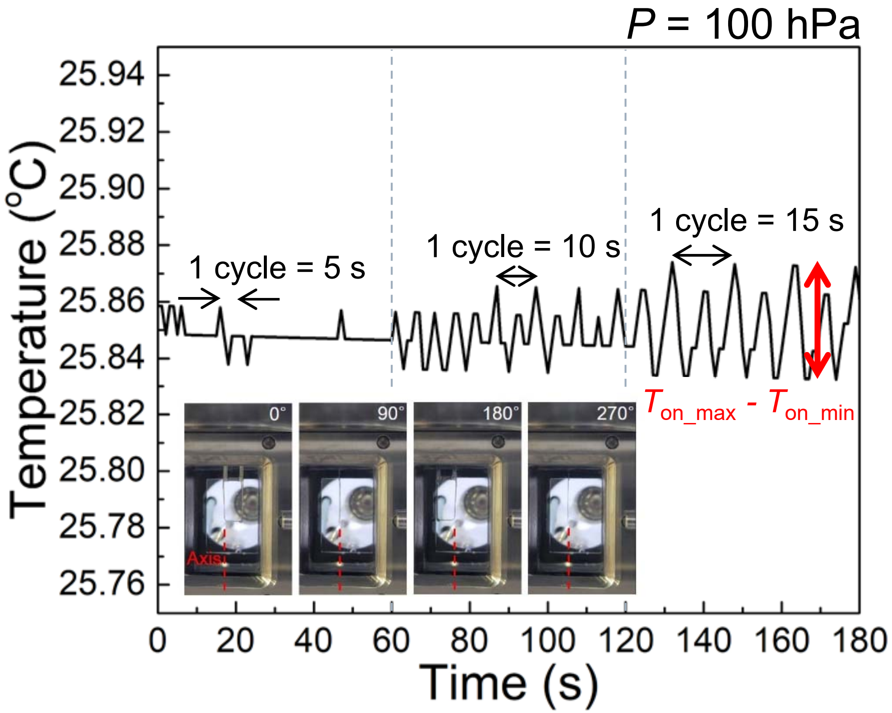
Lee *et al.* Meteorol. Appl. **25**, 209 (2018)

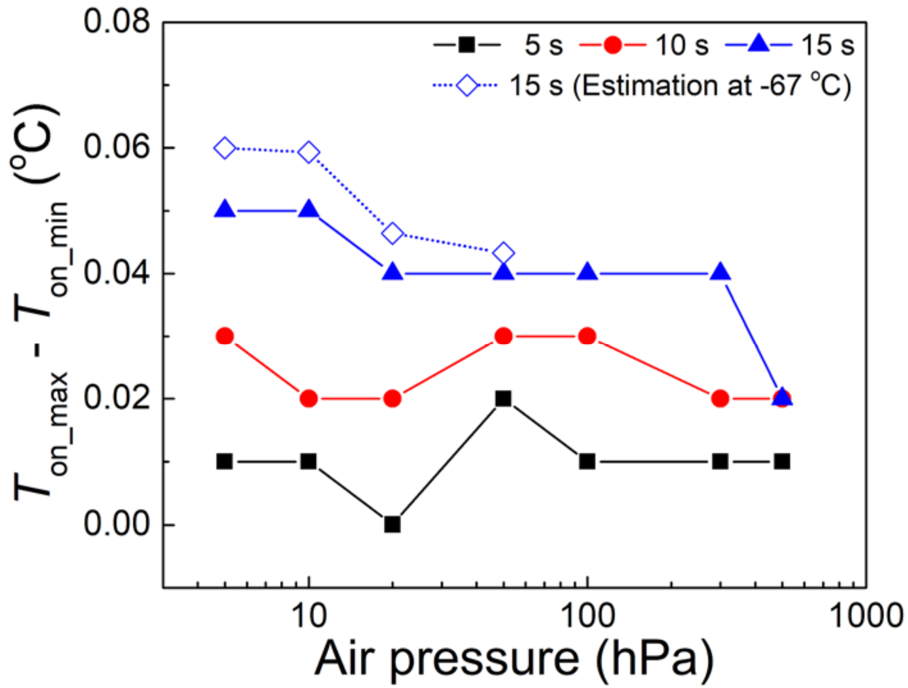
$\Delta T_{\mathrm{rad}} = S/S_0$ x $[A_0(T) + B_0(T)\cdot\log(P) + C_0(T)\cdot[\log(P)]^2 - 0.027\cdot(v\text{-}5)]$

for 5 hPa $\leq P \leq$ 500 hPa, S_0 = 980 W·m^{-2}

Rotation of radiosonde

- Simulating rotation motion of radiosonde in sounding
  - Oscillation of $\triangle T_{rad}$

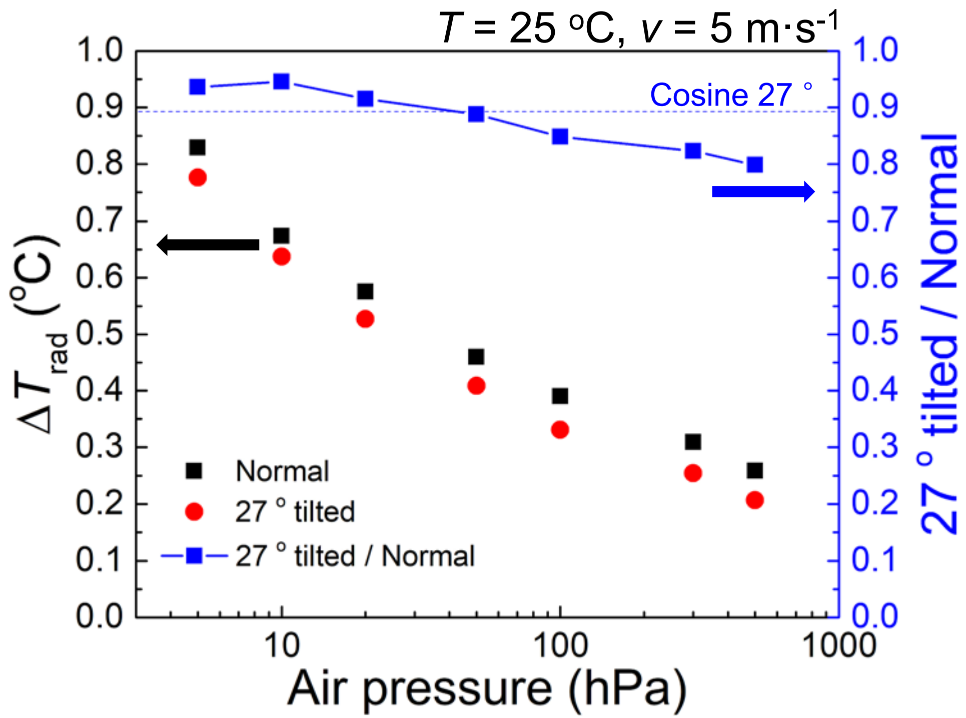


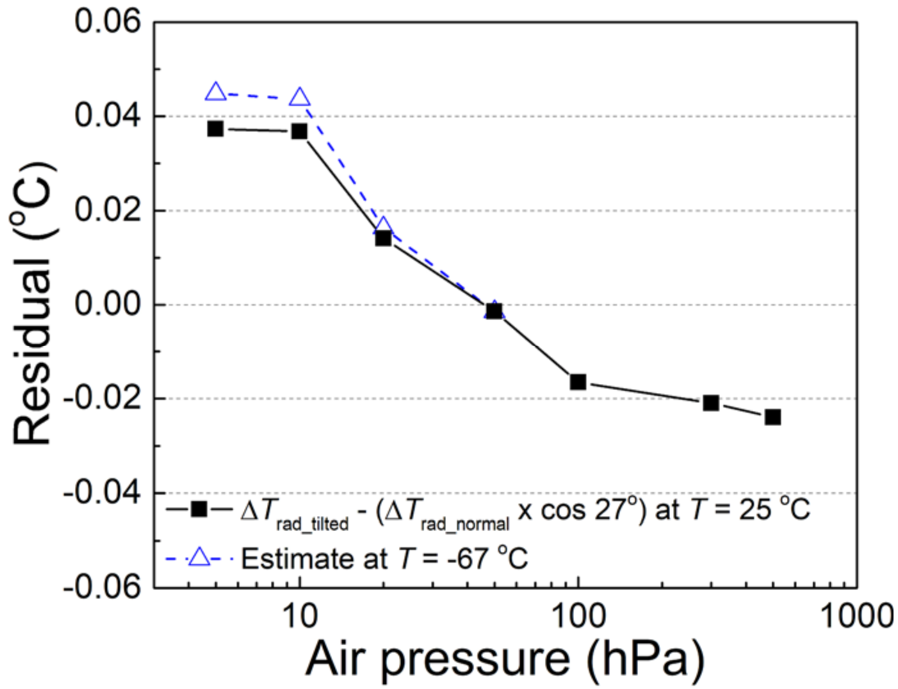


Oscillation of $\triangle T_{rad}$ can be averaged out by fittings or treated as **uncertainty**

Radiosonde tilting

- Simulating solar elevation angle
  - Calculation of $\triangle T_{rad}$ in proportion to effective irradiance



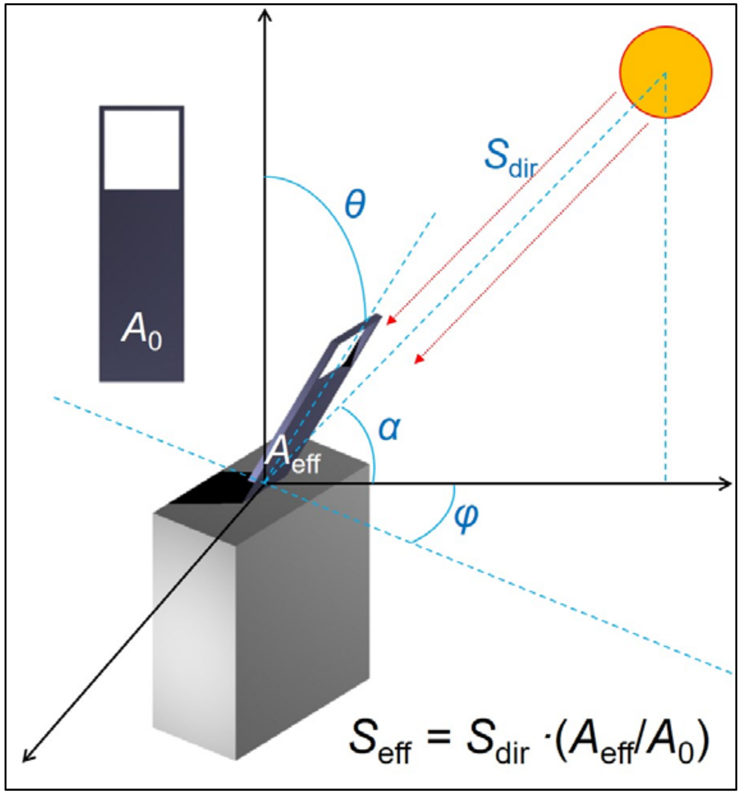


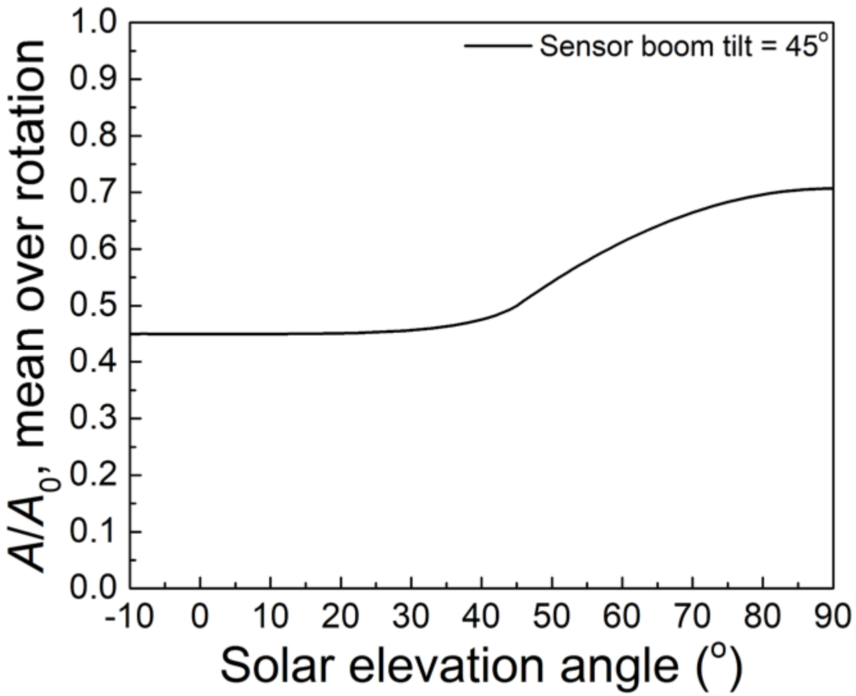
$$\Delta T_{rad} = (S_{eff}/S_0) \times [A_0(T) + B_0(T)\cdot\log(P) + C_0(T)\cdot[\log(P)]^2 - 0.027\cdot(v\text{-}5)]$$

for 5 hPa $\leq P \leq$ 500 hPa, S_0 = 980 W·m^{-2}

Effective irradiance to sensor

- Solar angle α, Azimuthal angle φ, & Boom tilti angle θ
  - Effective irradiance (mean over rotation angle, φ)



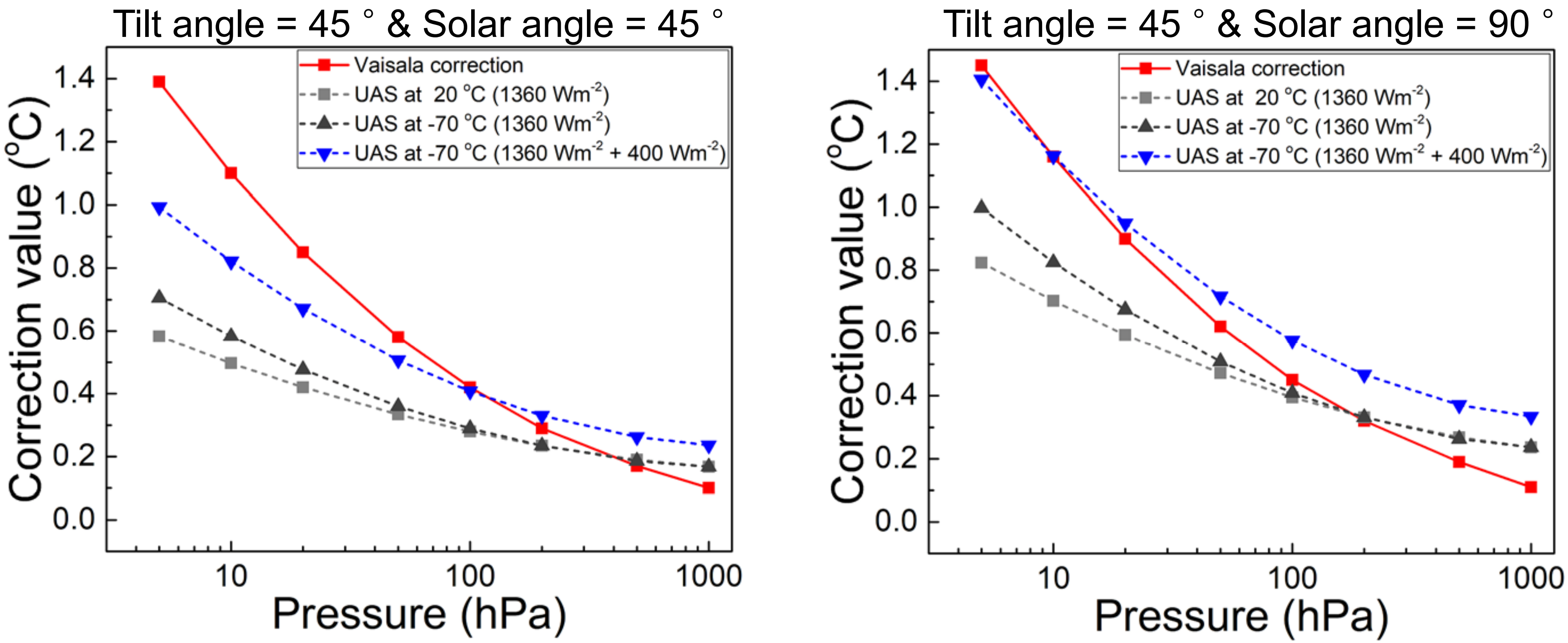


$$S_{eff} = S_{dir} \cdot \left| \cos\alpha \cos\Theta \cos\varphi - \sin\Theta \sin\alpha) \right|$$

Radiation correction

UAS (KRISS) vs. Manufacturer (Vaisala)

- $\triangle T_{rad\_UAS} < \triangle T_{rad\_Vaisala}$



$\Delta T_{rad\_UAS} < \Delta T_{rad\_Vaisala}$ by 0.5−0.7 °C at −70 °C & 5 hPa with S = 1360 W·m^{-2} & α = 45−90 °

$\Delta T_{rad\_UAS} < \Delta T_{rad\_Vaisala}$ by 0.04−0.4 °C at −70 °C & 5 hPa with S = 1360+400 W·m^{-2} & α = 45−90 °

Uncertainty

Uncertainty of radiation correction, $U(\triangle T_{rad})$

Uncertainty factor	Condition	Unit	Standard uncertainty ($k = 1$)	Contribution to uncertainty of radiation correction ($k = 2$)
T	-67	°C	0.028	0.000 °C
P	5	hPa	0.01	0.000 °C
v	5	$m \cdot s^{-1}$	0.058	0.004 °C
S	980	$W \cdot m^{-2}$	30.5	0.062 °C
Rotation	24	$° \cdot s^{-1}$	-	0.035 °C
Tilting	27	°	-	0.052 °C
Fitting error	–0.024 – 0.04	°C	0.023	0.046 °C
Expanded uncertainty of radiation correction ($k = 2$), $U(\Delta T_{rad})$				0.100 °C

Scaled to 1360 $W \cdot m^{-2}$

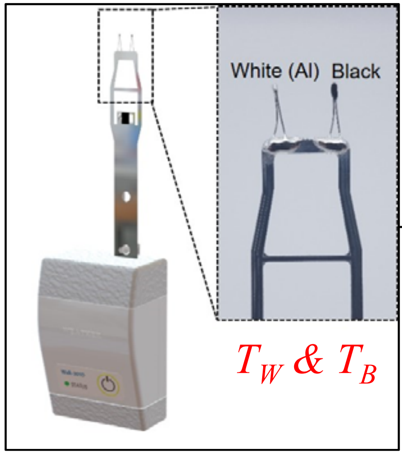
Uncertainty of corrected temperature, $U(T_{cor})$

$$U(T_{cor})^2 = U(T_{raw})^2 + U(\Delta T_{rad})^2$$

Uncertainty factor	Uncertainty ($k = 2$)
Expanded uncertainty for the radiation correction at 1360 $W \cdot m^{-2}$, $U(\Delta T_{rad})$	0.138°C
Calibration of RS41 temperature sensor (Vaisala), $U(T_{raw})$	0.100 °C
Expanded uncertainty in the corrected temperature, $U(T_{cor})$	0.170 °C

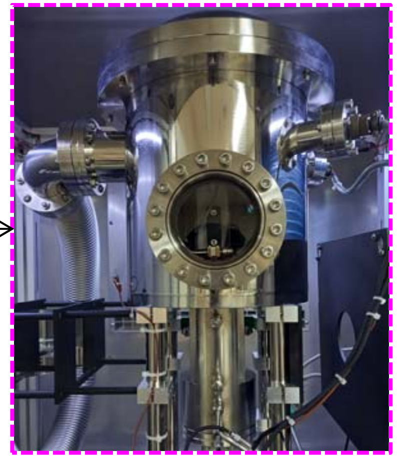
Radiation correction with irradiance measurement

- Dual thermistor radiosonde (DTR)

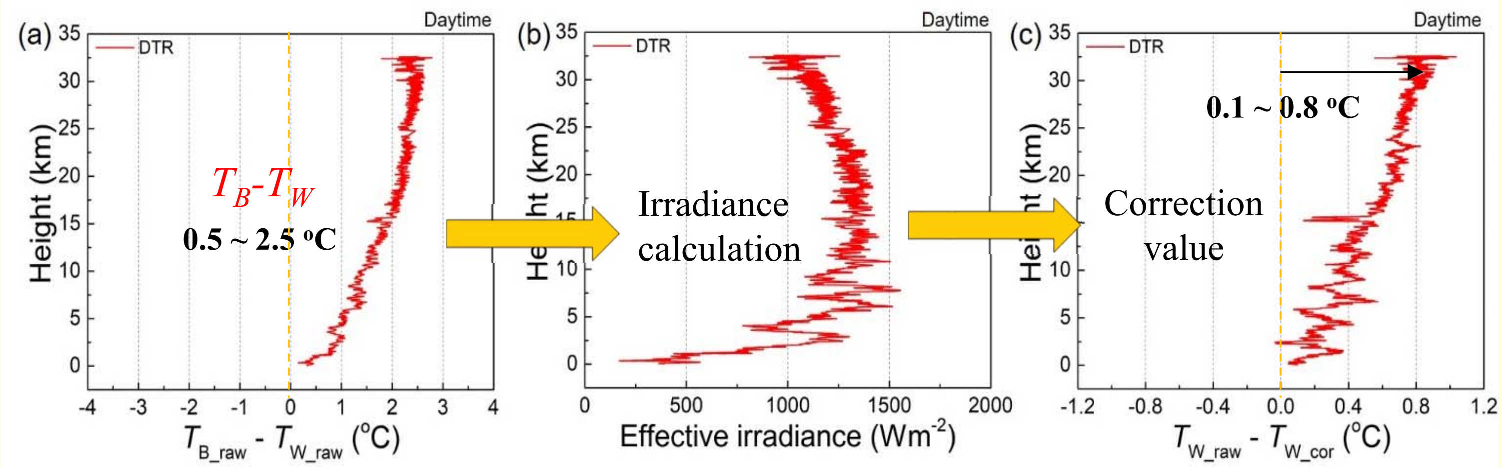


Parameterization of S & $\triangle T_{rad}$

with T_B-T_W, T, P, v in UAS



Daytime



Dual thermistor radiosonde will be presented by Dr. Yong-Gyoo Kim (KRISS)

Summary

Upper air simulator for radiation correction of radiosonde

- Temperature (-70−20 °C), Pressure (5−500 hPa), Ventilation (4−7 m/s), & Irradiance (1000 W/m^2)
- Radiosonde rotation (5, 10, 15 s) & Boom tilting (0−27 °)
- Radiation correction as a function of T, P, v, S and solar angle
- $\triangle T_{\mathrm{rad\_UAS}} < \triangle T_{\mathrm{rad\_Vaisala}}$ by max. 0.04−0.4 °C with $\alpha = 45−90$ °
- Uncertainty of radiation correction, $U(\triangle T_{\mathrm{rad}}) = 0.14$ °C
- Uncertainty of corrected temperature, $U(T_{\mathrm{cor}}) = 0.17$ °C
- Uncertainty of soundings should be added to $U(T_{\mathrm{cor}})$
- Any type of radiosonde can be tested using the UAS at KRISS

Thank you for your attention

More discussions to sangwook@kriss.re.kr