WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

Calibration of Thermometers for Marine Applications

Carmen García Izquierdo
CEM

WMO OMM

World Meteorological Organization
Organisation météorologique mondiale

15th December 2021

Thermometers for marine applications are usually based on thermistors:

temperature-sensitive **semiconducting** ceramic devices

Advantages:

- 1. very high sensitivity (typically ten times that of PRT)
- 2. small size (some smaller than 0.2 mm)
- 3. fast time constants (some as short as a few milliseconds)
- 4. High resistance values

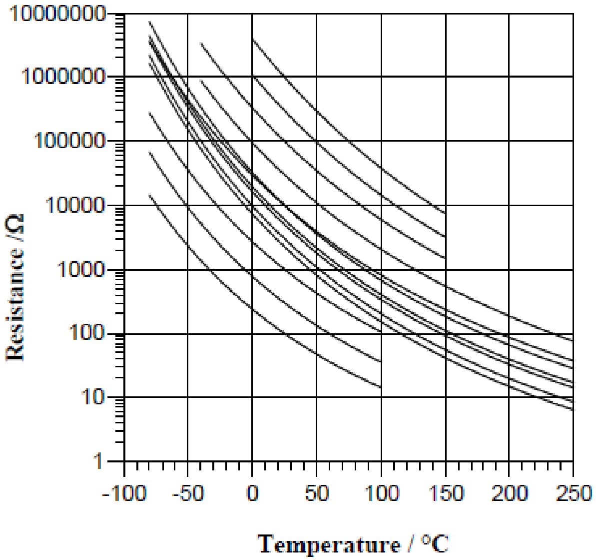
Disadvantages:

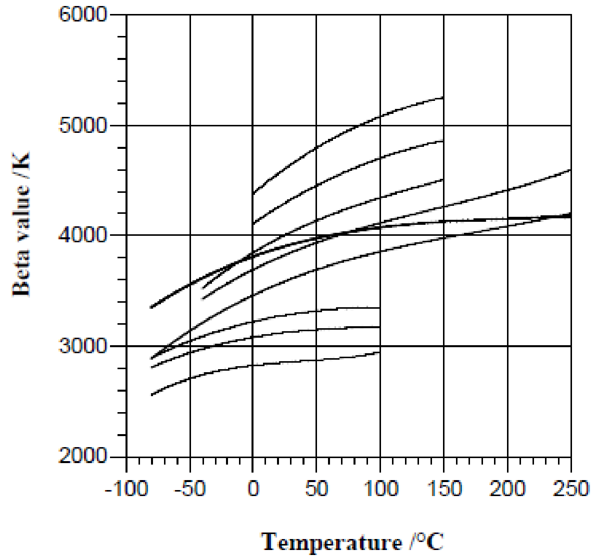
- very high non-linearity,
- a limited temperature range,
- a risk of high self-heating due to the sensing current

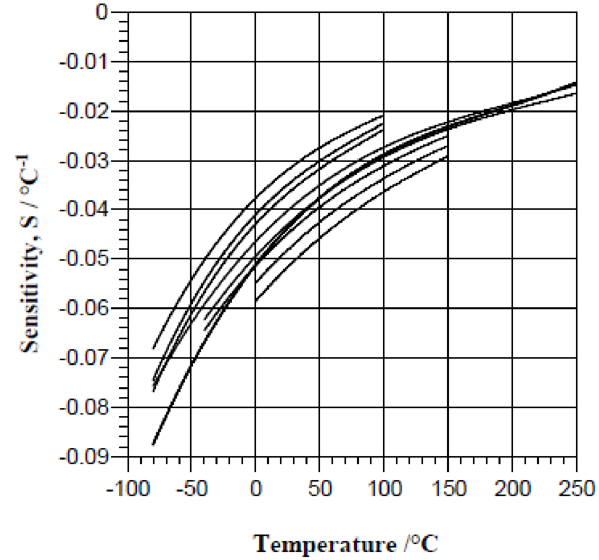
$$R(T) = R(T_0)\exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

$$S = \frac{1}{R}\frac{dR}{dT} = \frac{d\ln(R)}{dT} = -\frac{\beta}{T^2}.$$

$T_{0:}$ is a reference temperature, often 25 ºC
β: is a characteristic of the thermistor material





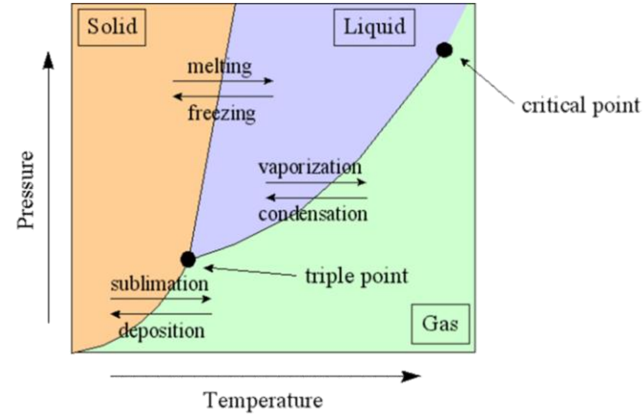


We measure $R \rightarrow T$??

By the calibration of the thermistors at different temperatures

Calibration of Sea-Bird 35 in fixed points:

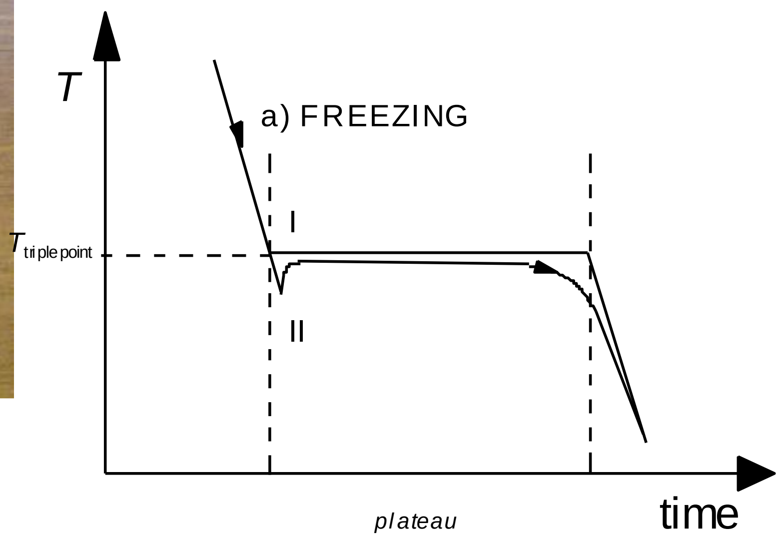
H_2O: 0.01 ºC
Ga: 29.7646 ºC

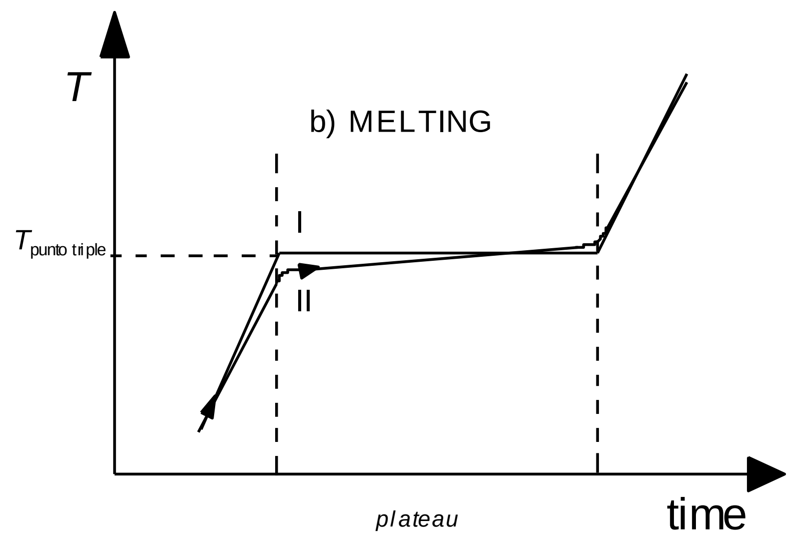


Melting and freezing plateaus

The phase transition plateaus are the period of time in which a substance experience a phase transition:

- From liquid to solid: freezing plateau
- From solid to liquid: melting plateau





The objective is to get as much **flat** plateaus and as much **longer** plateaus as possible

ITS-90. Defining Fixed points

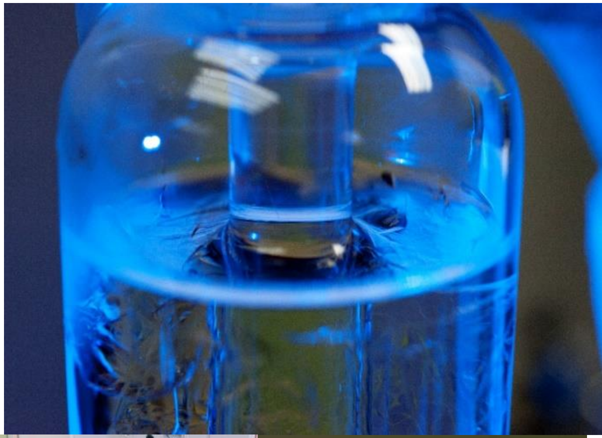
The Triple Point of Water

A triple point of water cell contains ice, water and water vapour.

In practice the thermometer needs to be immersed in a place at the triple point temperature. This is achieved with an ice mantle surrounding the thermometer well, with a thin water interface between the ice and the well. This allows the water-ice interface to be in close thermal contact with the thermometer.

To prepare the triple point:

1. the thermometric well is filled with a refrigerant (dry ice, cold nitrogen gas, metal rod cooled in liquid nitrogen…).
2. Once the ice mantle is large enough, the refrigerant is removed and the cell is maintained in an appropriate isothermal enclosure (i.e. water bath).
3. The thin water interface between the ice and the thermometric well by inserting a metal rod at ambient temperature in the thermometric well.



ITS-90. Fixed points

Metal Fixed Points

Open cells

In most cases, the metal sample is contained in a high purity **graphite crucible**, being the thermometric well also made in graphite.

A volume of 100 ml to 250 ml is usually required. **An immersion** of the thermometer of at least 20 cm is needed for optimal realizations.

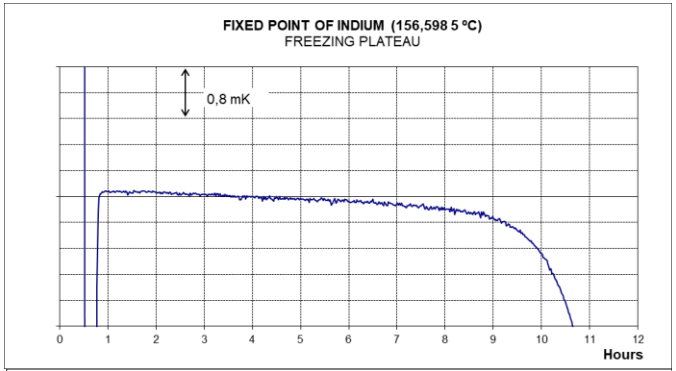
The graphite crucible is assembled in a **glass or quartz tube** (depending on the temperature), and a second thermometric well made of glass or quartz is also inserted in the graphite crucible.

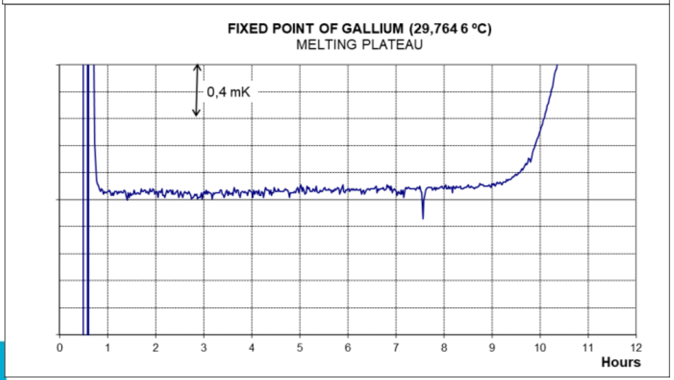
In the case of the Ga cell, the crucibles are made of PFTE and Stainless Steel or glass is used for mercury.

WMO OMM

ITS-90. Defining Fixed points

Metal Fixed Points. Realization.





The fixed point cell is inserted into a **furnace** to induce the phase transition.

The typical furnace is a tube of around 400 mm to 600 mm long.

The essential furnace requirements are the **temperature uniformity and stability**.

Furnaces: three zone furnaces and heat pipe furnaces

The usual realization procedure of a freezing plateau is, roughly:

- The cell is placed in the furnace with a thermometer in the thermometric well. Then, the temperature of the furnace is raised to about 5 K above the melting point to assure a complete melt.
- Once the melt is completed the furnace is set to about 1 K or 2 K below the freezing point.
- Once the thermometer indicates that a freezing plateau is reached, a cold glass or quartz rod (depending on the temperature) should be inserted in the thermometric well to create a thin solid layer between the melted metal and the thermometric well.

Calibration of a thermistor:

A thermistor resistance measurement usually involves a voltage measurement, then the accuracy is limited by the resolution of the voltmeter

Self-heating: $$\Delta T_{sh} = I^2 R(T)(\rho_{int} + \rho_{ext}) = \frac{V^2}{R(T)}(\rho_{int} + \rho_{ext}),$$

Depending on the temperature range is better to work at *V* constant or *I* constant

Reducing the error due to self-heating by the calibration at the same conditions of use

Influence of environmental conditions (*T*): conduction of the leads

	H2O, mK	Ga, mK	
UNCERTAINTIES DUE TO THE REFERENCE SYSTEM			
	0.041 28	0.098 47	
UNCERTAINTY COMPONENTS DUE TO THE SB 35			
Resolution	0.016 79	0.119 67	average of the noise in measurements
Repeatability	0.084 86	0.034 12	maximum of the reading's difference at several fixed points plateaus
Environmental conditions (conduction effect)	0.946 20	0.287 97	Maximum variation of the readings in a fixed point with changed environamental conditions (*T*)
Standard uncertainty *u* =	1.0	0.3	mK
Expanded uncertainty, *U*(*k* =2) =	1.9	0.7	mK

Calibration of a thermistor:

High sensitivity implies high non-linearity:

Calibration curve:

$$R(T) = R(T_0)\exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right],$$

$$\frac{1}{T} = A + B\ln(R/R_0) + C\left[\ln(R/R_0)\right]^2 + D\left[\ln(R/R_0)\right]^3 + \dots, \qquad \ln(R/R_0) = A + \frac{B}{T} + \frac{C}{T^2} + \frac{D}{T^3} + \dots,$$

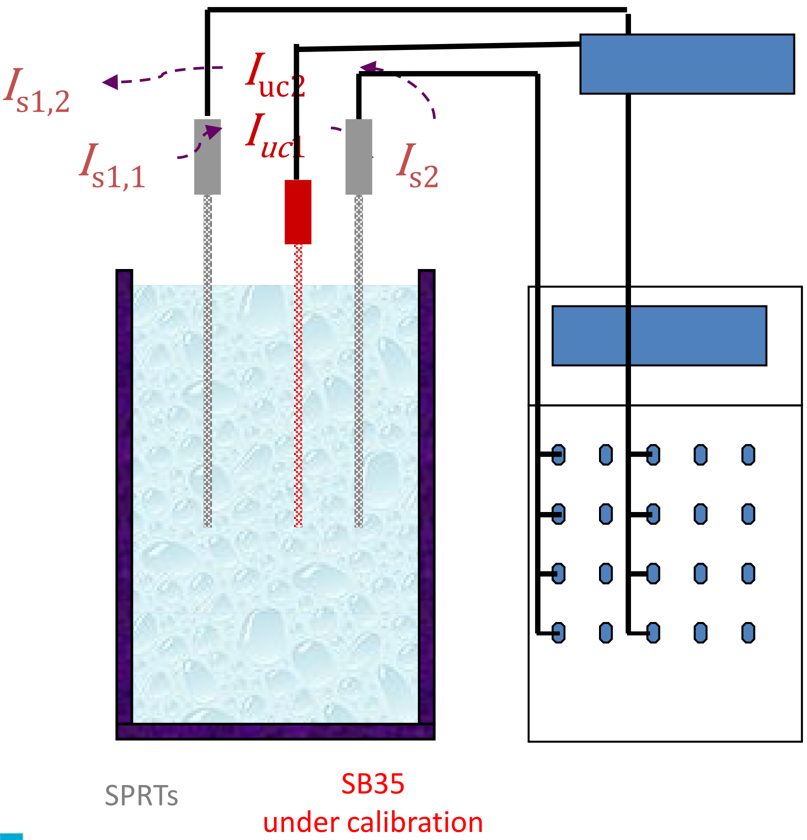
With only two calibration points, (H_2O and Ga) the uncertainty of the calibration curve is high

$$u_T^2 = \sum_{i=1}^{N}\left[l_i^2(T)\left(\frac{T}{T_i}\right)^{6-2N}\left(u_{T_i}^2 + \frac{T_i^4}{\beta^2}\frac{u_{R_i}^2}{R_i^2}\right)\right] + \frac{T^4}{\beta^2}\frac{u_R^2}{R^2},$$

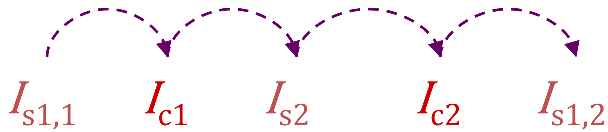
so more calibration points are needed: **Calibration by comparison in baths**

WMO OMM

Calibration by Comparison. Two reference thermometers.



Reading cycle for each calibration point:



The use of two standards and this reading cycle allows to check the stability and uniformity in temperature of the isothermal enclosure in each calibration point by using the readings the standards:

Stability check:

$I_{s1,1} - I_{s1,2}$ < stability of isothermal enclosure (previously determined)

Uniformity check:

$(I_{s2} - (I_{s1,1} + I_{s1,2})/2)$ < uniformity of isothermal enclosure (previously determined)

These checks allow a better assurance of the calibration quality. Uniformity is usually the dominant uncertainty component

	values/mK	probability distribution	Contribution to the combined uncertainty/ mK	
UNCERTAINTIES DUE TO THE REFERENCE SYSTEM				
Reference thermometers calibration	1.5	normal	0.75	
Resistance bridge	1.0	normal	0.50	
UNCERTAINTIES DUE TO THE CALIBRATION BATH				
stability	2.0	normal	1.15	
homogeneity	2.8	recatngular	1.62	
UNCERTAINTY COMPONENTS DUE TO THE SB 35				
Resolution	1.0	rectangular	0.58	average of the noise in measurements
Repeatability	0.2	rectangular	0.10	maximum of the reading's difference at several fixed points plateaus
Environmental conditions (conduction effect)	1.6	rectangular	0.90	Maximum variation of the readings in a fixed point with changed environamental conditions (*T*)
Standard uncertainty *u* =			2.43	mK
Expanded uncertainty, *U* (*k* =2) =			4.9	mK

Reference temperature, ºC	Reading SB35, ºC	Correction SB35, ºC	Expanded Uncertainty (k =2), ºC
-0.003	-0.003	0.000	0.005
5.092	5.094	-0.002	0.017
10.091	10.090	0.001	0.005
15.215	15.217	-0.002	0.005
18.150	18.148	0.002	0.005
20.146	20.145	0.001	0.005
22.164	22.164	0.000	0.005
25.124	25.124	0.000	0.005
28.096	28.093	0.002	0.005
30.077	30.076	0.001	0.005
-0.003	-0.003	0.000	0.005

References:

- [1] International vocabulary of metrology – Basic and general concepts and associated terms (VIM) 3rd edition. https://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf
- [2] Evaluation of measurement data — Guide to the expression of uncertainty in measurement. https://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf
- [3] *The Internacional System of Units* , 8th edition 2006 Organisation intergouvernementale de la Convention du Mètre. http://www.bipm.org/en/publications/si-brochure/
- [4]*Traceable Temperatures*, J.V. Nicholas and D.R. White, 2001, 2nd edition, John Wiley & Sons.
- [5] *Temperatura*, T.J. Quinn , 1990, 2nd edition, Academic press
- [6] *Principles and Methods of Temperature Measurement*, T.D. McGee, 1988, John Wiley & Sons
- [7] *Thermodynamics and an introduction to thermostatics*, Herbert B. Callen, 1985, 2nd edition, John Wiley & Sons.
- [8]. Definition of kelvin. https://www.bipm.org/metrology/thermometry/units.html
- [9] The International Temperature Scale of 1990 (ITS-90), *Metrologia* 27, 3-10 (1990). https://www.bipm.org/utils/common/pdf/ITS-90/ITS-90_metrologia.pdf
- [10] Guide to the Realization of the ITS-90. https://www.bipm.org/en/committees/cc/cct/guide-its90.html
- [11] Guide to the Realization of the ITS-90. Metal fixed points for contact thermometry. https://www.bipm.org/utils/common/pdf/ITS-90/Guide_ITS-90_2_4_MetalFixedPoints_2018.pdf.
- [12] D.J. Curtis, in Temperature Its Measurement and Control in Science and Industry, vol 5, ed. by J.F. Schooley (AIP, New York, 1982), pp. 803-812.
- [13] C. García Izquierdo et al, "*Evaluation of the self-heating effect in a group of thermometers used in meteorological and climate applications*" , October 2018 Meteorological Applications 26(1). DOI:10.1002/met.1746.
- [14] C. García Izquierdo, D. del Campo, F. Raso, "Measurement of AC and DC Insulation Leakage in Platinum Resistance Thermometers up to 960 °C", (2011), International Journal of Thermophysics, 32, 1399-1408. DOI: 10.1007/s10765-011-0949-3
- [15] Guide to the Realization of the ITS-90. Platinum Resistance Thermometry. https://www.bipm.org/utils/common/pdf/ITS-90/Guide_ITS-90_5_SPRT_2018.pdf

References:

- [16] IEC 60751 (2008).
- [17] Guide on Secondary Thermometry: Thermistor Thermometry. https://www.bipm.org/utils/common/pdf/ITS-90/Guide-SecTh-Thermistor-Thermometry.pdf
- [18] E.H. McLaren y E.G. Murdock; *"Properties of some noble and base metal thermocouples at fixed points in the range 0-1 100 ºC "*; 1982; Temperature: Its Measurement and Control in Science and Industry; **Vol 5** AIP Conf. Proc :pag 953-974.
- [19] F.Edler and P. Ederer, "*Thermoelectric homogeneity and stability of platinum-rhodium alloyed thermoelements of different compositions"* 2013; Temperature: Its Measurement and Control in Science and Industry; **Vol 8** AIP Conf. Proc : 1552, 532-537.
- [20] McLaren, E.H. & Murdock, E.G., "*The Au/Pt thermocouple, Part I: Essential Performance, PartII: Preparatpry Heat Treatment, Wire Comparisons and Provisional Scale"*, National Research Council Canada, Publication NRCC/27703.
- [21] Burns G.W., Strouse, G.F., Liu, B.M., and Magnum, B.W. *"Gold versus platinum thermocouples: performance data and an ITS-90 reference function"*. 1992, Temperature: Its Measurement and Control in Science and Industry, **Vol 6**, pp. 531-536.
- [22] F. Edler, H. Lehmann, *"Mechanical stability of Pt/Pd thermocouples*", In: Tempmeko 04, The 9th International Symposium on Temperature and Thermal Measurements in Industry and Science, Zagreb, Croatia, Editor in chief Davor Zvizdic, Published: LPM/FSB 2005, pp 625-630.
- [23] K. D. Hill."*An investigation of palladium oxidation in the platinum/palladium thermocouple system*", Metrología, 2002, **39**, 51-58.
- [24] Yong-Gyoo Kim, Kee Sool Gam and Jeong Hoon Lee 1997 "*The thermoelectric inhomogeneity of palladium wire*" Meas. Sci. Technol. **8** 317-321.
- [25] G.W. Burns, D.C. Ripple and M. Battuello. *"Platinum versus palladium thermocouples: and emf-temperature reference function for the range 0 ºC to 1500 ºC"* Metrología, 1998, **35**, 761-780.
- [26] EURAMET No. 8 | Guidelines on the Calibration of Thermocouples | TC-T | Version 3.0, 02/2019
- [27] EURAMET **No. 13 | Guidelines on the Calibration of Temperature Block Calibrators | TC-T | Version 4.0, 09/2017**
- [28] BIPM-CCT Guide to realization of the ITS-90. Platinum Resistance Thermometry.
- [30] Mise en practique for the realization of the kelvin. https://www.bipm.org/en/publications/mises-en-pratique
- [31] Temperature scales and the kelvin. https://www.bipm.org/en/publications/mises-en-pratique

WMO OMM

Thank you
Merci

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

WMO OMM

World Meteorological Organization
Organisation météorologique mondiale