Thermofeel: a python thermal comfort indices library

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Thermofeel: A python thermal comfort indices library

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ABSTRACT

Here the development of the python library *thermofeel* is described. *thermofeel* was developed so that prominent internationally used thermal indices (i.e. Universal Thermal Climate Index and Wet Bulb Globe Temperature) could be implemented into operational weather forecasting systems (i.e. the European Centre for Medium Range Weather Forecasts) whilst also adhering to open research practices. This library will be of benefit to many sectors including meteorology, sport, health and social care, hygiene, agriculture and building. In addition, it could be used in heat early warning systems which, with the right preparedness measures, has the potential to save lives from thermal extremes.

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Permanent link to code/repository used of this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-21-00124
Legal Code License	*Apache License version 2*
Code versioning system used	*Git*
Software code languages, tools, and services used	*Python*
Compilation requirements, operating environments & dependencies	*Linux and IOS operating systems for some methods indicated in documentation*
If available Link to developer documentation/manual	https://thermofeel.readthedocs.io/en/latest/?
Support email for questions	servicedesk@ecmwf.int

1. Motivation and significance

Extreme heat is an increasing killer hazard and research around heatwaves and heat stress is growing [1–4]. However, there is not a universal definition of heatwaves and this has led to the use of many different heat indices by studies globally [5]. In addition, cold weather continues to cause excess mortality and causes challenges for infrastructure for example Winter in Texas 2021 [6]. Key indices include wet bulb globe temperature [7,8] and the biometerological method of the Universal Thermal Climate Index (UTCI) which brings together meteorological parameters and a body model providing a human centric heat index [9,10].

To date there is no comprehensive library that brings together the most prominent thermal indices, with only **pythermalcomfort** [11] existing for a small selection of indoor thermal comfort indexes, **comfort** [12] not being maintained and undocumented and **ladybug-comfort** [13] which is not developed specifically for numerical weather prediction and does not provide the same methods as *thermofeel*. This makes it difficult to incorporate thermal comfort indices into numerical weather prediction services as well as to adhere to open science best practices, such as reproducibility and transparency, that are widely being adopted [14].

The development of thermofeel as a python library was chosen due to the popularity of the language for scientific applications,

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Nomenclature

t2 m	2 m temperature (K)
td	dew point temperature (K)
va	wind speed at 10 metres height (m/s)
rh	relative humidity (%)
svp/e_hPa	saturation vapour pressure (hPa)
mrt	mean radiant temperature (K)
mrtgt	mean radiant temperature from globe temperature (K)
ssrd	surface solar radiation downwards (J/m^2)
ssr	surface net solar radiation (J/m^2)
fdir	total sky direct solar radiation (J/m^2)
strd	surface thermal radiation downwards (J/m^2)
strr	surface net thermal radiation (J/m^2)
lat	latitude
lon	longitude
y	year
m	month
d	day
h	hour
tbegin	time step beginning
tend	time step end
cossza	cosine of the solar zenith angle (°)
utci	universal thermal climate index (°C)
wbt	wet bulb temperature (°C)
bgt	globe temperature (°C)
wbgt	wet bulb globe temperature (°C)
wbgts	wet bulb globe temperature simple/approximation (°C)
hi	heat index (°C)
net	normal effective temperature (°C)
C	Celsius
K	Kelvin
m	metres
J	Joules
Pa	pascal

usually with faster run-time on a given system than that of R, a comparable language [15]. It also has a range of free learning courses associated with it, making it easier to learn than other common scientific languages such as C, C++ or Fortran [16]. In addition, it has a constantly growing catalogue of libraries that aid testing and documentation but complement the methods presented in *thermofeel* [17].

thermofeel allows the user to reproduce the methods used in the development of the ERA-5 HEAT dataset which provides historical world-wide data records for mean radiant temperature and universal thermal climate index [10]. In addition, it extends this dataset by giving users methods to easily calculate the most prominent heat indexes, with a current focus on outdoor thermal comfort. Users can use the methods on a range of different data types by making use of existing python libraries.

Most notably this library presents the first operational method of calculating the wet bulb globe temperature from mean radiant temperature [18,19]. Furthermore, *thermofeel* is developed by the European Centre for Medium Range Weather Forecasts (ECMWF) following well established development procedures for time-critical operational software and contains methods that are currently being tested and integrated into ECMWF's weather forecasting product generation systems.

2. Software description

2.1. Software architecture

The library thermofeel contains a main module with the calculation methods and a helper module which is called in the background for auxiliary functions. The functional design of this library allows for easier maintenance and, since each calculation method is implemented as a *pure function* guaranteeing no side-effects, the library can be easily used in parallel and concurrent environments such as Dask [20]. Moreover, this also allows each calculation method to simultaneously support scalars and numpy arrays as input, performing the calculations elementwise where appropriate and thus returning a compatible result (scalar or arrays) as output. This design was intentional to ease the integration with ECMWF's parallel computing environment. This library was developed and tested on the Linux and Mac OSX operating systems, and we believe it is fully compatible with any POSIX system supporting Python 3.

2.2. Software functionalities

thermofeel provides methods to calculate the most prominent indices which currently focuses on outdoor thermal comfort. Ahead we discuss the methods and present some of the relevant literature describing them in more detail, with more depth provided in the *thermofeel* documentation (https://thermofeel.readthedocs.io/en/latest/?). Table 1 shows the different thermofeel index calculation methods

2.3. Software exceptions and validation

We filter the data as is indicated by the original method documentation where appropriate. For example, the UTCI is set to −9999 when its input parameters – temperature, wind speed, relative humidity and mean radiant temperature – fall outside specific validity ranges [10]. In addition, adjustments are calculated for set thresholds for solar zenith angle integrated and heat index adjusted.

2.4. Software validation

The thermofeel library also contains unit tests for all provided calculation methods and based on the pytest library. The inputs for the tests are based upon the average hourly data from ERA5 reanalysis [31] for the 2nd November 1996 and the 2nd August 2003. An example of the inputs can be seen in Table 2 and the outputs in Table 3. We implemented further tests on some methods, e.g. on the cosine of the solar zenith angle method, and these can be found on the software repository.

3. Illustrative examples

To test how a user might apply the methods presented in Section 2.2, Table 1 to meteorological data, we produced visual maps of all the indices using data from ERA-5 [31] reanalysis for 06UTC on the 8th June 2020 which is shown in Fig. 1. These figures can be easily produced from our library and the existing **netCDF4, matplotlib** and **cartopy** libraries using source code 1. We also provide examples using other python libraries developed by ECMWF such as magics and eccodes these can be seen in the GitHub examples directory (https://github.com/ecmwf-projects/thermofeel/tree/master/examples).

Table 1
Showing thermofeel index calculation methods.

Name	Function	Description	Reference
Solar declination angle	solar_declination_angle(jd,h)	Returns declination angle in degrees and time correction in hours	
Relative humidity	calculate_relative_humidity_percent(t2 m,td)	Returns relative humidity as a percentage	
Saturation vapour pressure	calculate_saturation_vapour_pressure(t2 m)	Returns relative humidity as water vapour pressure units hPa	
Cosine of the solar zenith angle instant	calculate_cos_solar_zenith_angle(lat,lon,y,m,d,h)	Returns the cosine of the solar zenith angle which is used to calculate mean radiant temperature	[21]
Cosine of the solar zenith angle integrated	calculate_cos_solar_zenith_angle_integrated(lat,lon,y,m,d,h,tbegin,tend,intervals_per_hour=1, integration_order=3,):	Returns the cosine of the solar zenith angle which is needed to calculate mean radiant temperature from solar radiation, based upon an integration over forecast steps	[21]
Mean radiant temperature	calculate_mean_radiant_temperature(ssrd, ssr, fdir, strd, strr, cossza)	Returns mean radiant temperature (mrt) in kelvin, incidence of radiation on the body which is used in the utci and wbgt calculations	[22]
Universal Thermal Climate Index (UTCI)	calculate_utci(t2 m, va, mrt, ehPa)	Returns the biometeorology index the universal thermal climate index (utci) in °C	[9,10]
Wet bulb globe temperature simple	calculate_wbgts(t2 m)	Returns an approximation of wet bulb globe temperature known as wet bulb globe temperature simple in this library °C	[23]
Wet bulb temperature	calculate_wbt(t2 m,rh)	Returns wet bulb temperature calculated using an empirical expression from temperature and relative humidity percent	[24]
Globe temperature	calculate_bgt(t2 m, mrt, va)	Returns globe temperature calculated from temperature mean radiant temperature and 10 metre wind speed in °C (Method not tested for windows operating system)	[18,19]
Wet bulb globe temperature	calculate_wbgt(t2 m,mrt,va,td)	Returns wbgt using the wet bulb temperature and globe temperature methods as components into the wbgt equation	[25]
Mean radiant temperature from globe temperature	calculate_mrt_from_bgt(t2 m, bgt, va)	Returns mean radiant temperature using the inverse method to calculate_bgt in °C	[18,19]
Humidex	calculate_humidex(t2 m, td)	Returns humidex a heat index that incorporates relative humidity with temperature in °C	[26]
Normal Effective Temperature (NET)	calculate_net_effective_temperature(t2 m, rh, va)	Returns normal effective temperature (NET) which is a model of how a human responds to meteorological parameters in °C	[27]
Apparent temperature	calculate_apparent_temperature(t2 m,rh,va):	Returns apparent temperature a heat index modelled on wet bulb globe temperature in °C	[28]
Wind chill	calculate_wind_chill(t2 m,rh,va)	Returns wind chill is designed to emulate how cold it feels in a very windy environment in °C	[29]
Heat index simplified	calculate_heat_index_simplified(t2 m, rh=None)	Returns heat index simplified the original method for heat index in °C	[30]
Heat index adjusted	calculate_heat_index_adjusted(t2 m, td)	Returns heat index that is adjusted between different thresholds to be more accurate in the tropics in °C	[30]

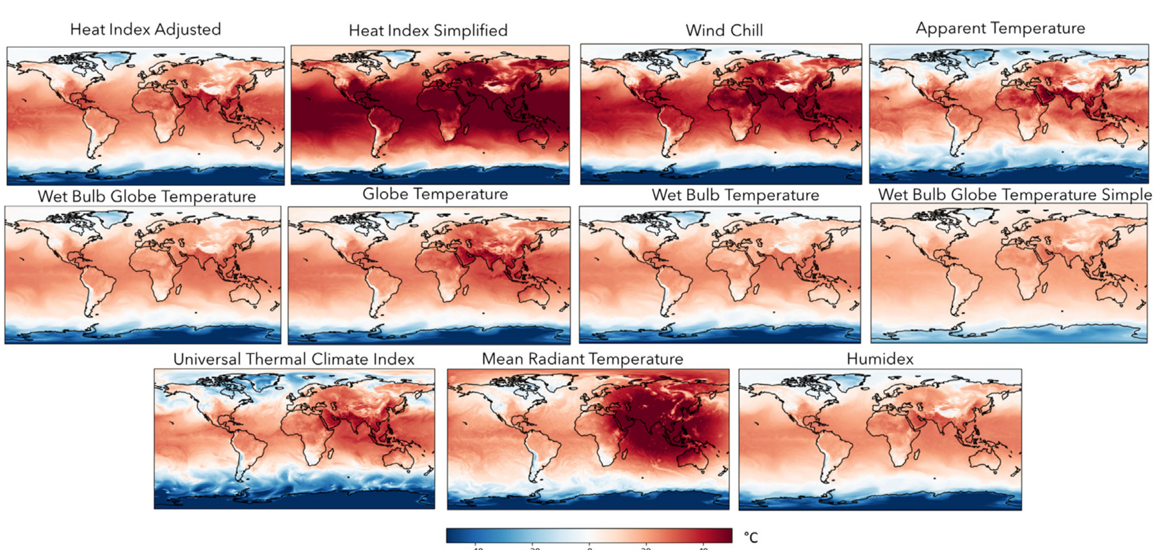

Fig. 1. Global maps of thermal indexes for 06UTC on the 8th June 2020 as described in Section 2.2, Table 1.

In addition, in Fig. 2, we present two approaches to calculating the cosine of the solar zenith angle [21]. A method which is integrated over forecast steps and is specialised for a forecasting system with a beginning and end time, where radiation values are

Table 2
The test variable values for thermofeel.

t2m K	td K	va m/s	mrt K	ssrd W/m^2	ssr W/m^2	fdir W/m^2	strd W/m^2	strr W/m^2	cossza °
310	280	2.00	300	604146	471818	374150	1061213	−182697	0.5
300	290	0.02	310	604135	467182	377084	1061000	−183218	0.5
277	273	0.59	286	607954	464531	383763	1061090	−184536	0.5
277	273	0.59	286	613806	463360	391216	1061362	−186295	0.5
277	273.	0.60	286	619349	462326	398038	1062483	−187558	0.5
277	273	0.59	286	626611	463422	406661	1063639	−189544	0.5
277	273	0.59	286	634958	465688	416602	1064458	−192353	0.5
277	273	0.59	287	638089	463850	418866	1066043	−194661	0.5
277	273	0.59	287	640019	462945	42167	1066746	−196444	0.5

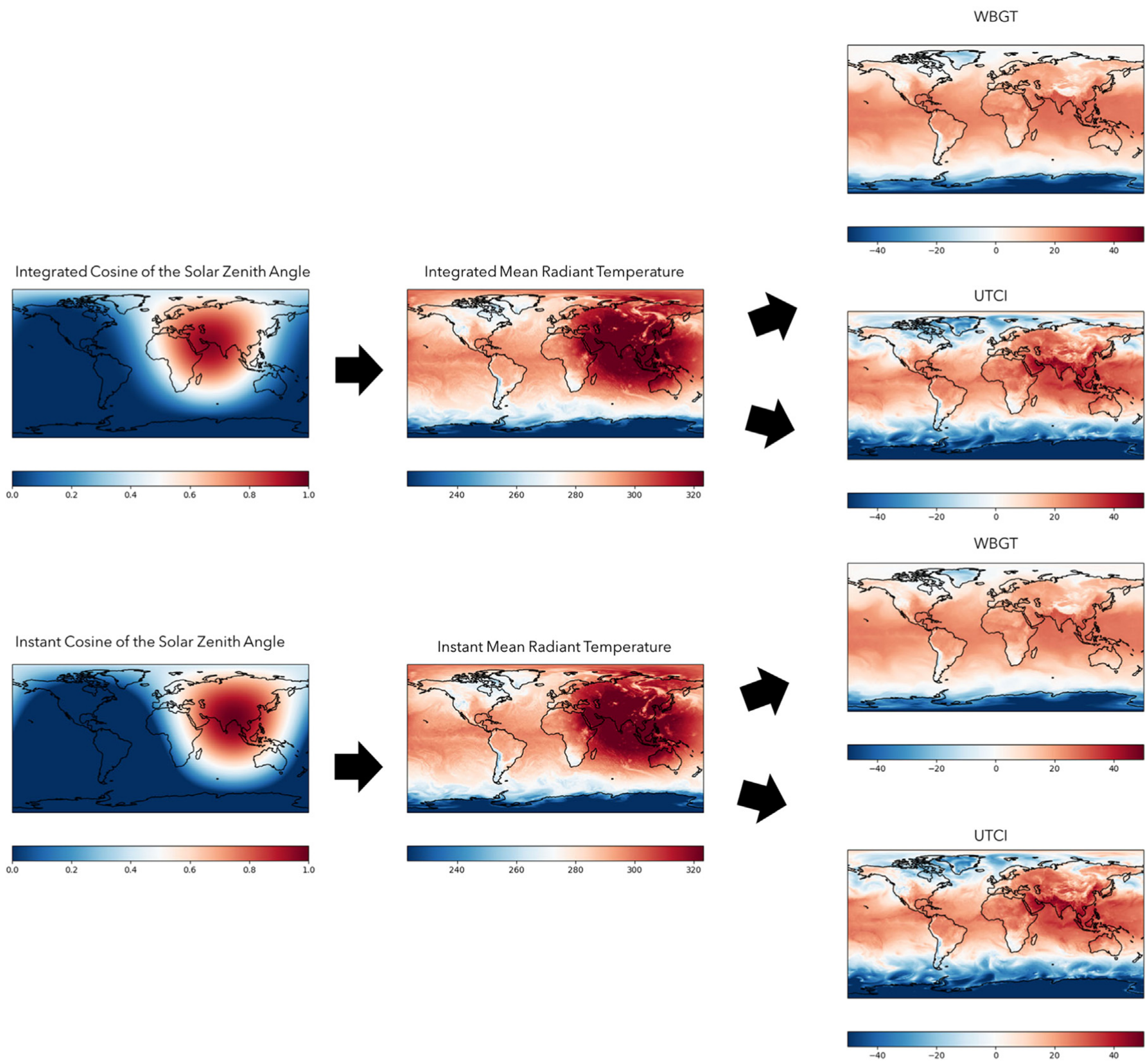

Fig. 2. Methods for using the two cosine of the solar zenith angle calculations.

accumulations, as well as an instantaneous method which only needs the UTC (Universal Time Zone) hour to calculate the cosine of solar zenith angle. Cosine of the solar zenith angle is a key component of mean radiant temperature [22] which is used to calculate the thermal indexes the UTCI and WBGT [10,19].

The difference between these two approaches (mean value) is tiny at 1×10^{-8} for the UTCI and 2×10^{-9} WBGT final output, and this allows for an accurate cosine solar zenith angle to be calculated with a simpler method that requires less parameters.

Source Code 1: Showing an example of the methods for 06UTC on the 8th *June 2020, run on a Linux operating system.*

4. Impact

Heat stress is a growing impact of climate change, with heatwaves increasing in intensity, frequency and duration [1]. In addition, cold stress is continuing to have an impact [32]. It is therefore important to have a robust set of methods to aid research and the development of early warning systems in this field [33]. We anticipate *thermofeel* will have a large impact on the research of heat stress, heatwaves and thermal comfort as a whole. It allows for open science practices [14] to be more readily applied to the extreme thermal research area in a way not available before. We also expect this library to be easily extendable

Table 3
The test outputs for thermofeel calculated using the inputs from Table 2.

rhp %	svp hPa	Heat index °C	Heat index adjusted °C	Humidex °C	mrt K	net °C	utci °C	wbgt °C	wbgts °C	Wind chill °C
15.93	62.31	68.27	34.59	31.82	286.04	40.75	33.50	35.61	26.72	60.09
54.31	35.37	52.14	27.53	23.12	286.11	31.49	29.93	25.78	19.99	50.75
74.75	8.19	16.82	2.51	1.07	286.29	3.41	8.63	3.27	6.02	9.30
74.77	8.20	16.86	2.53	1.09	286.54	3.43	8.64	3.29	6.03	9.32
74.74	8.23	16.93	2.58	1.14	286.81	3.50	8.76	3.34	6.06	9.41
74.47	8.27	17.07	2.67	1.21	287.11	3.60	8.93	3.42	6.11	9.56
74.32	8.31	17.17	2.73	1.27	287.42	3.68	9.10	3.48	6.15	9.66
73.80	8.40	17.40	2.88	1.40	287.70	3.85	9.28	3.63	6.23	9.90
73.41	8.44	17.53	2.95	1.47	287.85	3.94	9.37	3.71	6.28	10.01

by the research and operational weather forecast communities, as well as those in the humanitarian sector.

In addition, it allows for easy integration of thermal comfort indexes into operational weather forecasting. Further, we envision that cross-sectional users will benefit from our library, from researchers and operational meteorologists [10] to health professionals [5] and those in engineering and urban planning [34].

Thermofeel calculation methods are being tested and integrated into the operational weather forecasting systems at ECMWF. On a global scale this will be the first time these methods will be forecasted, and lead to practical applications. For example, with the right preparedness measures *thermofeel* methods could save lives and build heat resilience [33]. The library has also the potential to be commercialised and applied to the growing area of climate services [35,36] through the development of a mobile app for health services.

5. Conclusions

Here we have set out the key information of the python library *thermofeel*. This library has been designed so that thermal indexes can easily be incorporated into numerical weather prediction and operational forecasting systems. In addition, it adheres to open source development and robust operational testing and acceptance procedures. We have produced comprehensive documentation and provided examples of how to use this library to further aid users. We envision that this library will be of benefit to a wide range of users across sectors and could aid in the further development of early warning systems for thermal extremes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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