High-resolution modeling of Farmers' heat stress over intensely irrigated lands of California

Noah-MP workshop 2024

National Center for Atmospheric Research
06/04/2024

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Layout

- Introduce heat stress
- Study area: Imperial Valley, California
- Quantification of heat stress (WBGT)
- Why use a regional climate model (WRF) to map heat stress?
- Irrigation effect on heat stress

Introduction

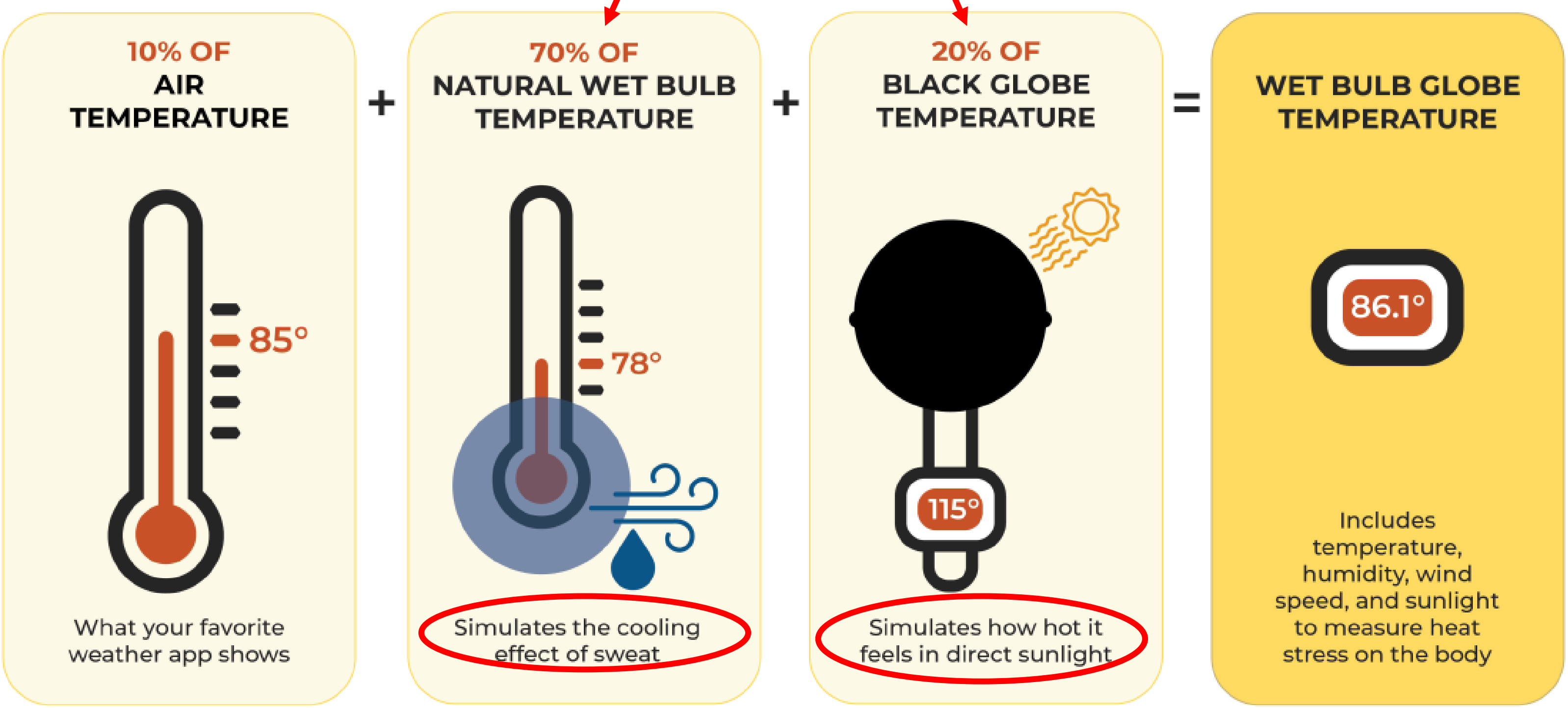
- Farmworkers are the frontline workers of our food system, who are often exposed to heat stress that is likely to increase in frequency and severity due to climate change.
- Irrigation can worsen heat stress, quantification of which is crucial in intensely irrigated agricultural lands such as the Imperial Valley (IV) in California.

Imperial Valley (IV)

- IV produces over 2/3 of the winter vegetables (e.g., lettuces) and 1/3 of the fruits/nuts consumed in the entire US
- Irrigation is heavily applied in the IV crop fields, ~ 5 ft >>>> average annual rainfall in the region (~ 2.9 inches).

Quantification of heat stress

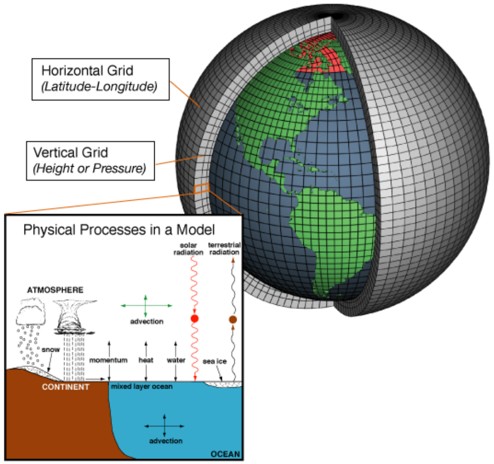
$$WBGT = 0.7 * WBT + 0.2 * BGT + 0.1 * DBT$$



Duke NICHOLAS INSTITUTE *for* ENERGY, ENVIRONMENT & SUSTAINABILITY

Adopting WBGT for the farmworkers

- US military and large scale sports organizations use WBGT to monitor heat stress in their training or playing fields
- Installing WBGT instruments in agricultural fields may not be feasible
- Regional climate models (RCMs) can help →

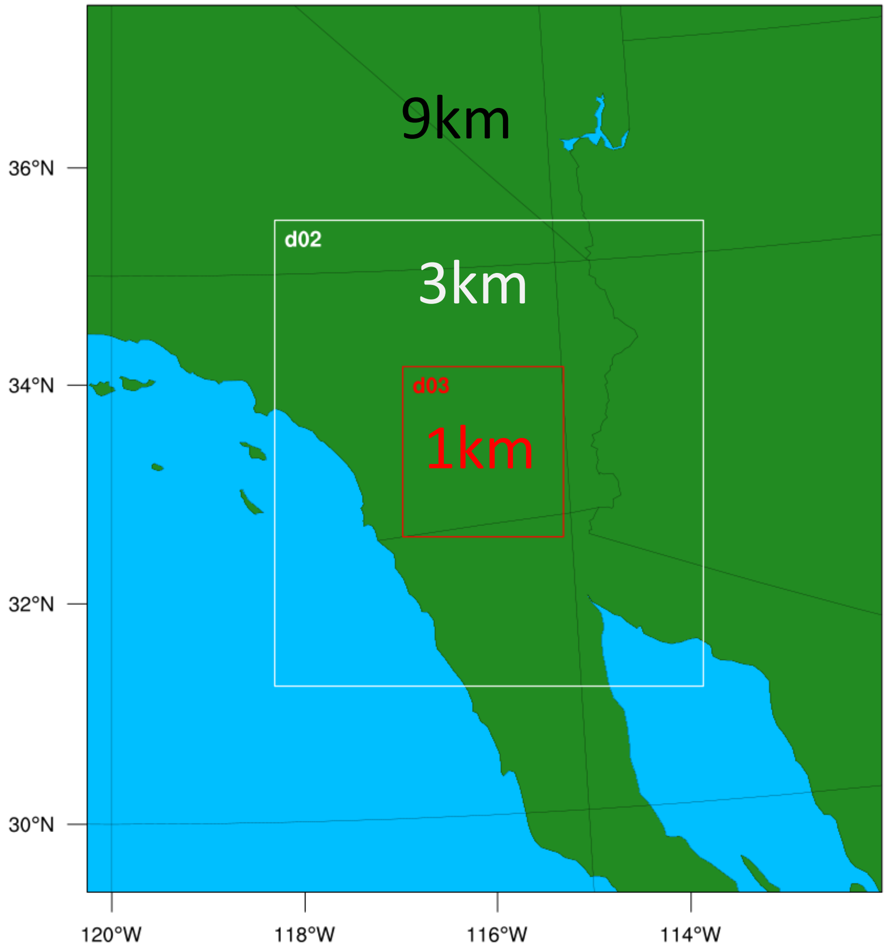


- RCMs can simulate surface temperature, winds, humidity, and radiation fields at high spatial (~1 km) and temporal (hourly) resolution
- Allows to calculate heat exposure at a specific time and location in different crop and land use environments (including night)
- Allows forecasting

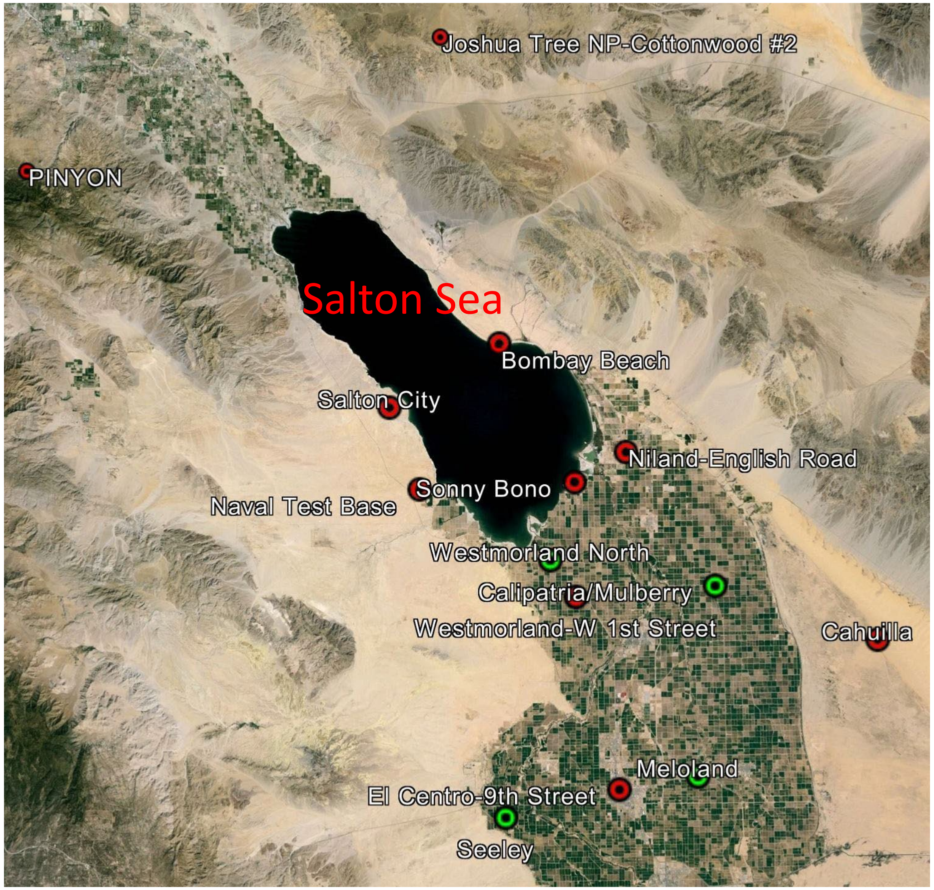
https://www.agriculture.com/crops/corn/how-extreme-heat-affects-corn-and-soybeans

Study domain

WPS Domain Configuration



Stations used for model validation



Simulation period: Apr, June, Aug, 2020

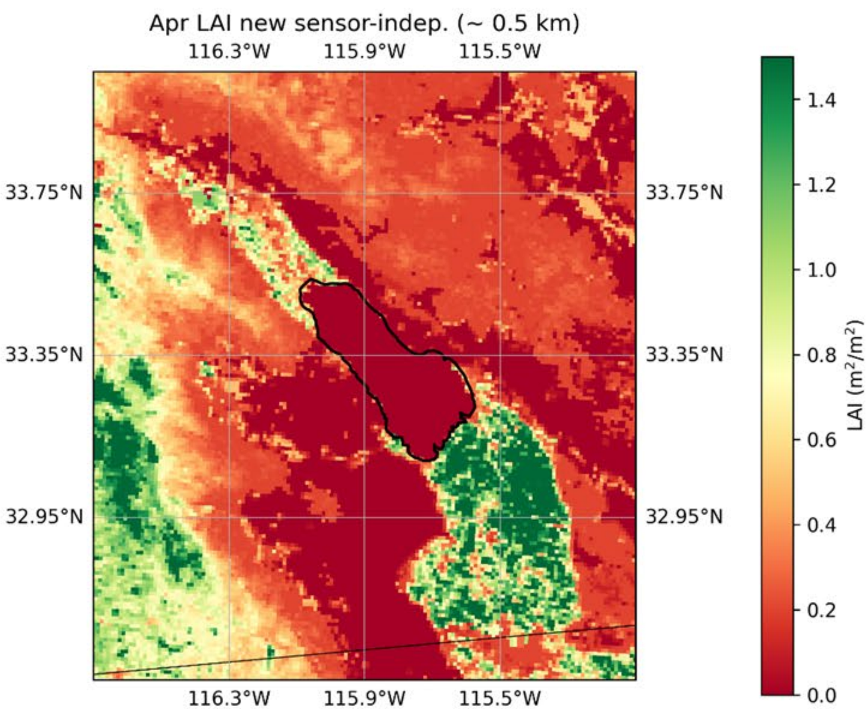
High-resolution inputs

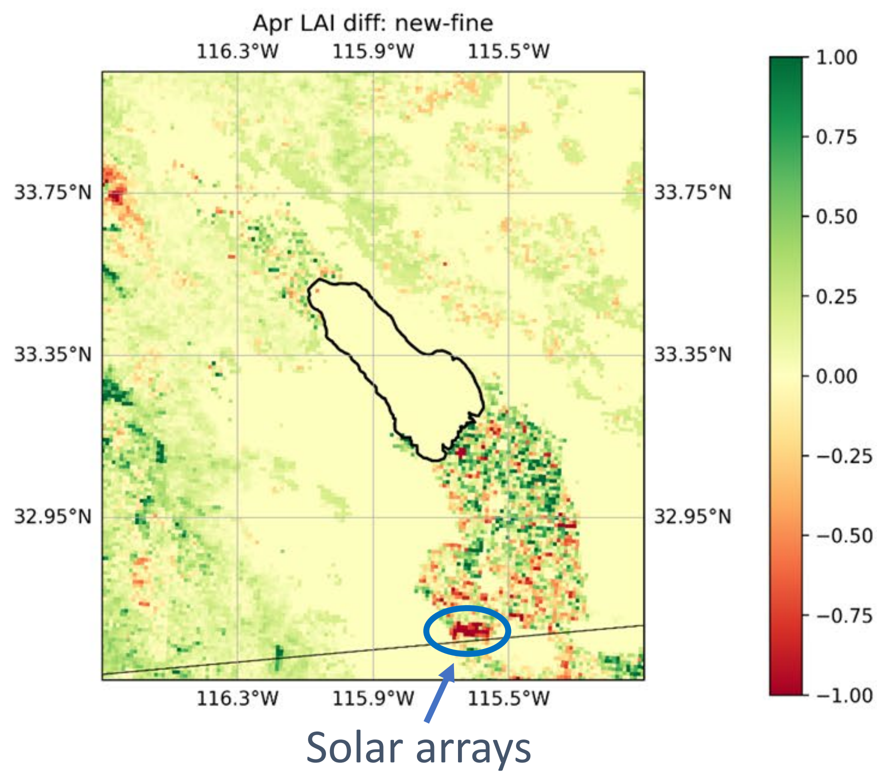
- High-resolution simulation requires high-resolution inputs
- WRF uses monthly climatological average LAI/FPAR data (2001-2010) (~ 0.9 km)
- We use high-resolution data (~0.5 km) developed recently at Boston University

Sensor-independent LAI/FPAR CDR: reconstructing a global sensor-independent climate data record of MODIS and VIIRS LAI/FPAR from 2000 to 2022

Jiabin Pu[1], Kai Yan[2], Samapriya Roy[3], Zaichun Zhu[4], Miina Rautiainen[5], Yuri Knyazikhin[1], and Ranga B. Myneni[1]

[1]Department of Earth and Environment, Boston University, Boston, MA 02215, USA





Calculation of WBGT

- We calculate WBGT using outputs from WRF model simulations
- We use Thermofeel python library to calculate WBGT
- Thermofeel is developed by ECMWF, a trusted provider of climate data

SoftwareX
Volume 18, June 2022, 101005

Original software publication

Thermofeel: A python thermal comfort indices library

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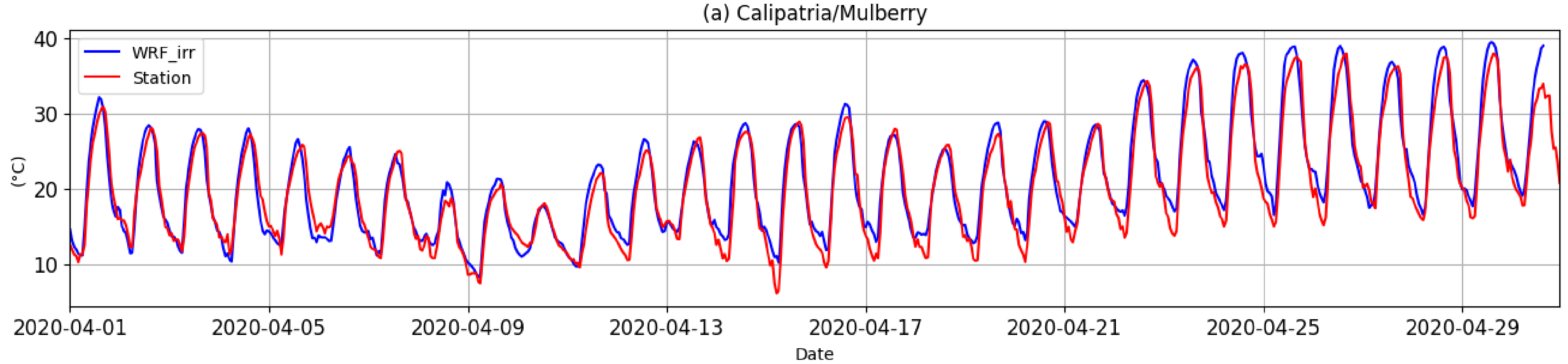
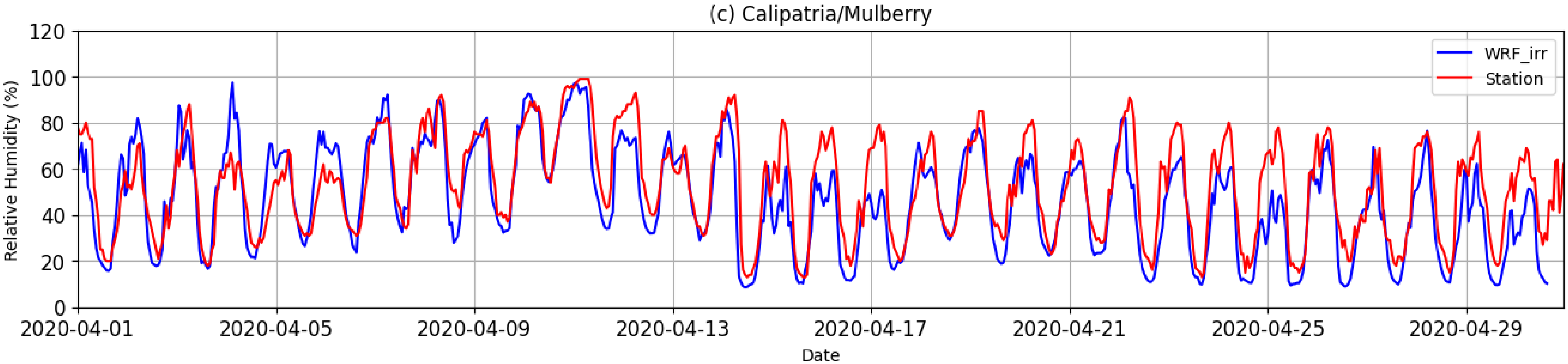
[a] Department of Geography and Environmental Science, University of Reading, Reading, RG6 6AB, UK
[b] European Centre for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, Reading, RG2 9AX, UK

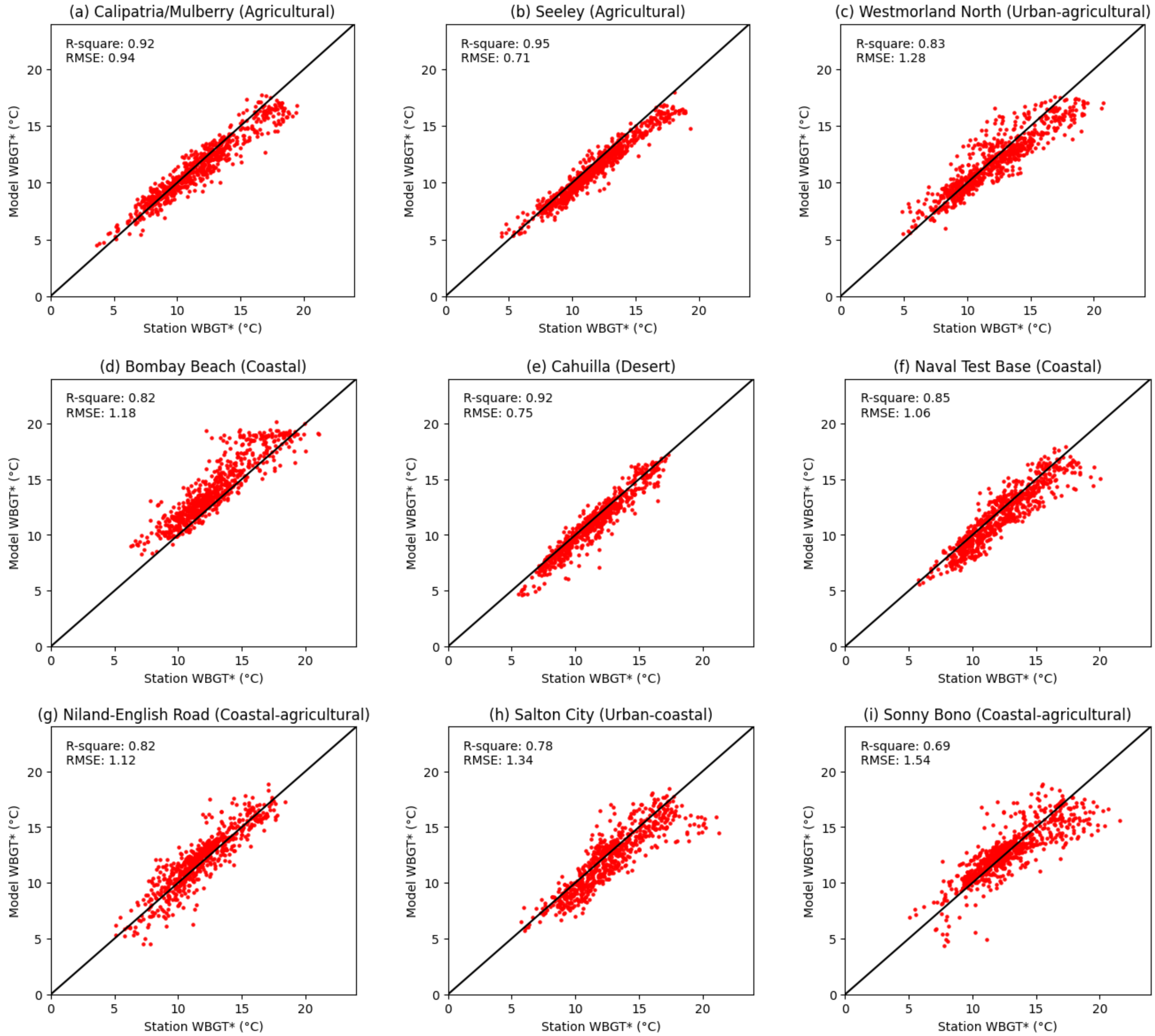
Results

Model performance



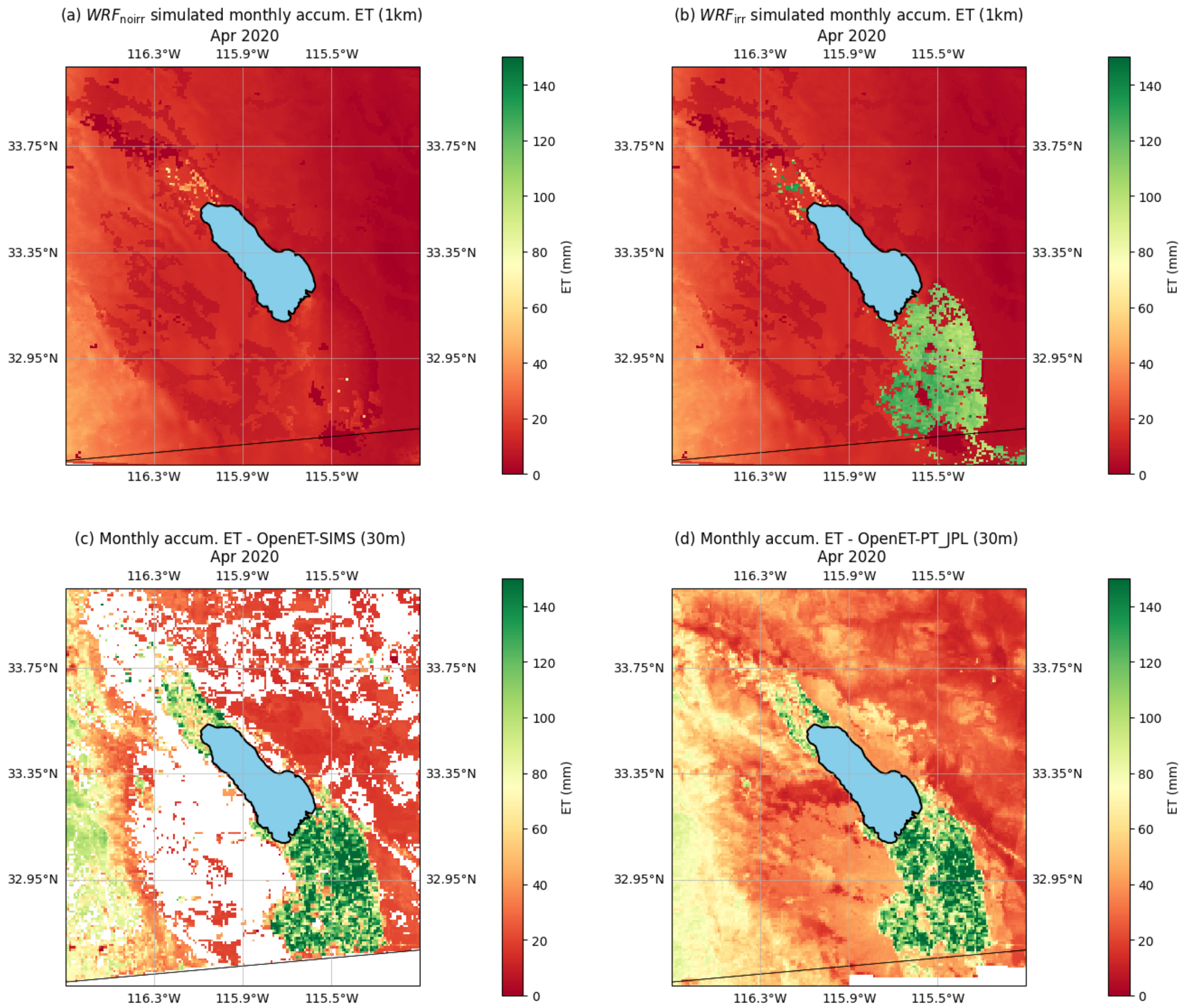


Validation of WBGT



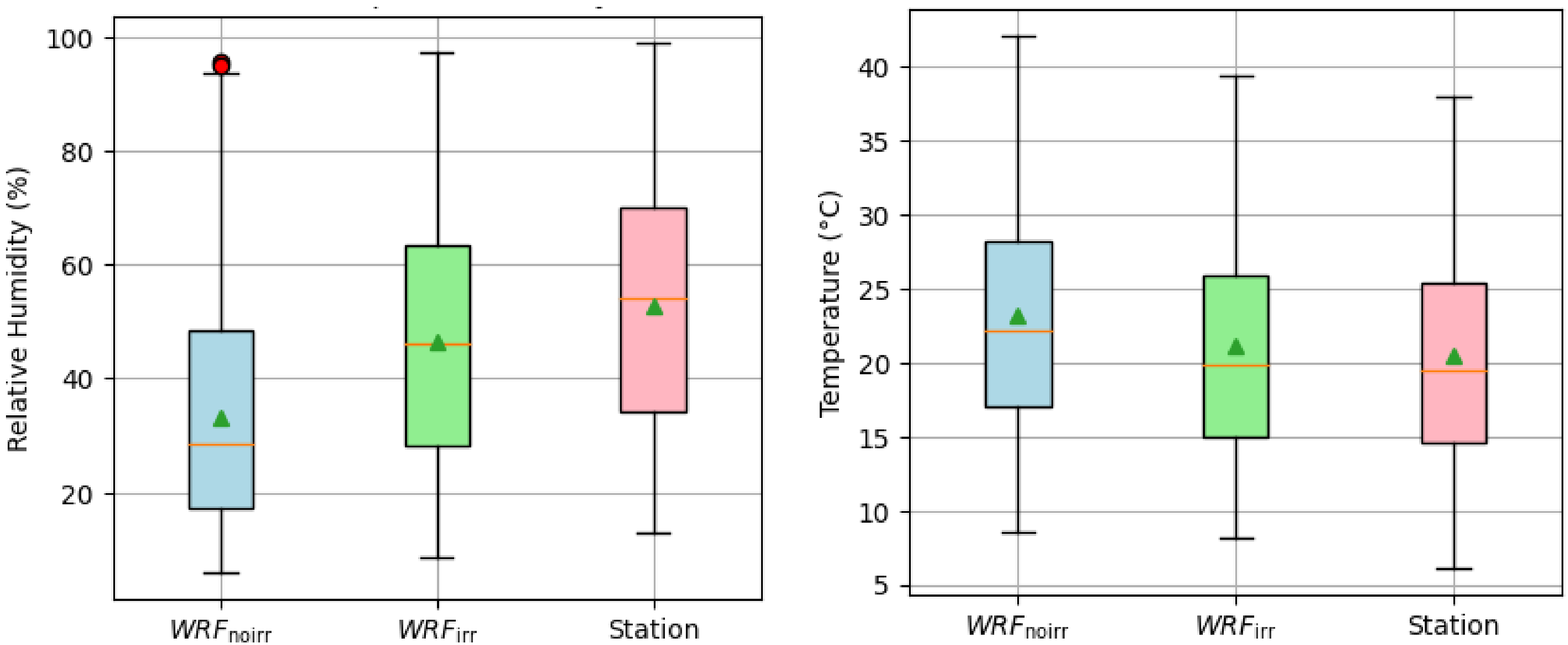
Irrigation effect on ET

- The model without irrigation greatly underestimates the ET in the cropped areas
- Application of irrigation increases ET remarkably and brings it closer to the satellite-derived ET estimates



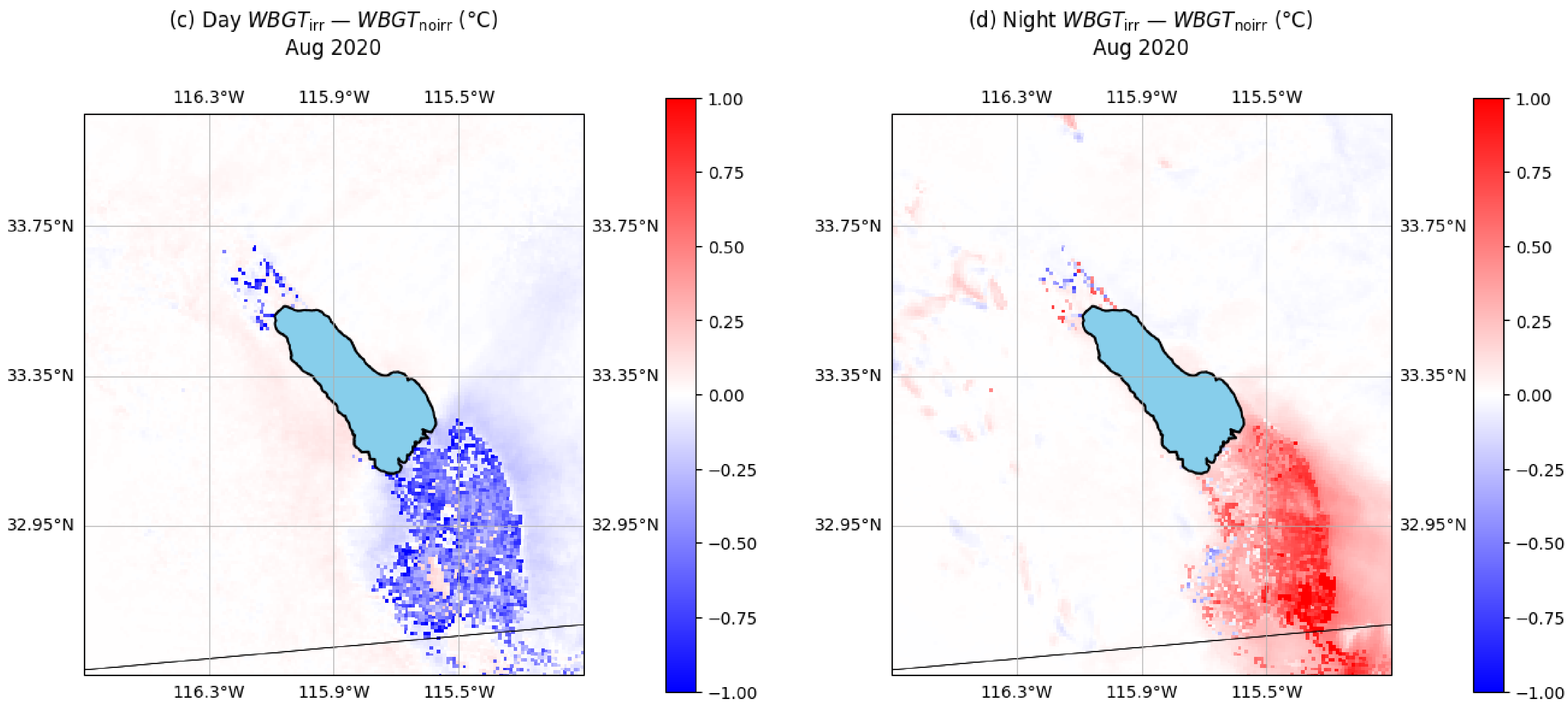
Irrigation effect on air temp. and humidity

Calipatria/Mulberry (Agricultural site)



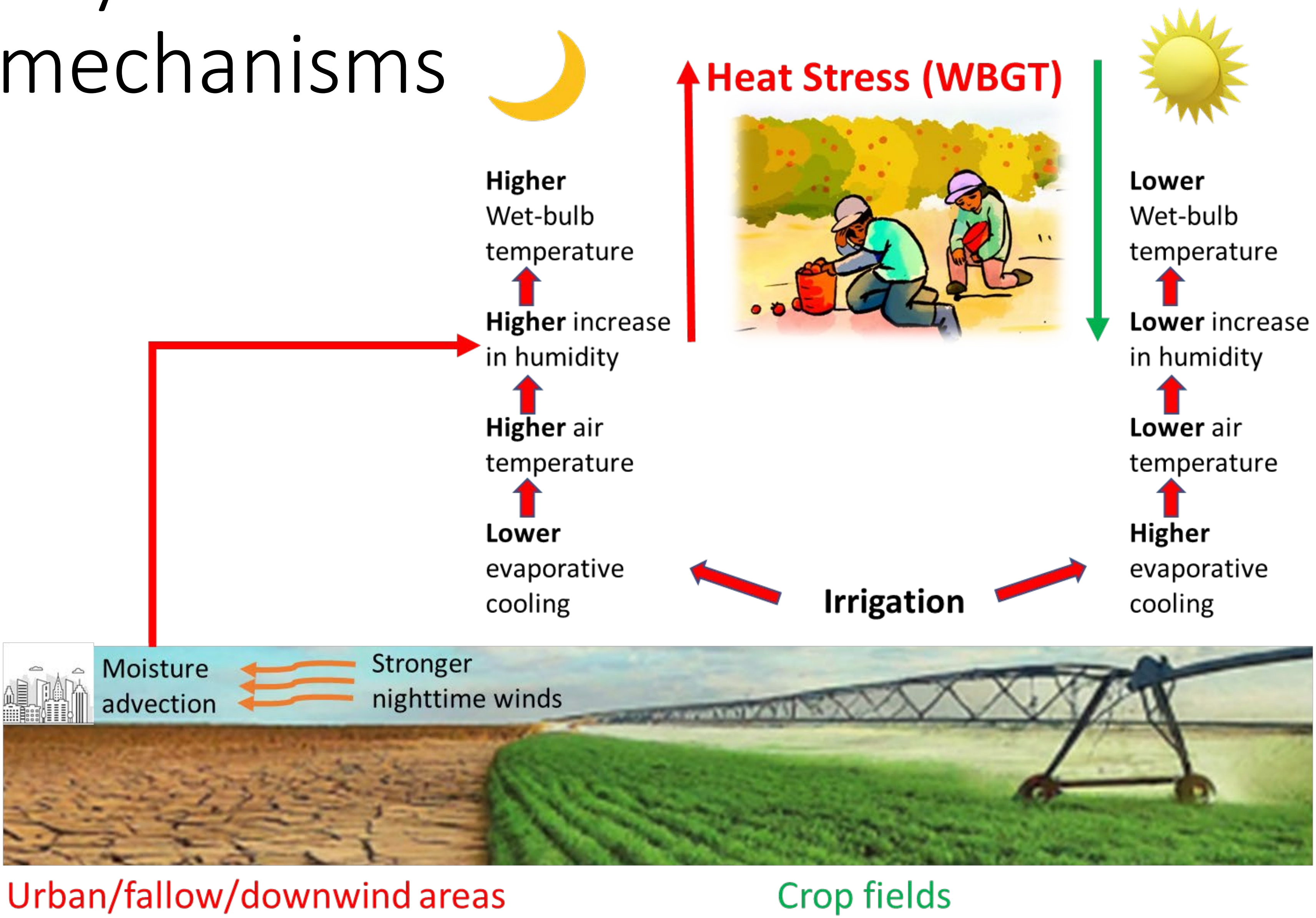
- Irrigation >> increases humidity >> reduces the humidity bias
- Irrigation >> causes cooling (~2-3℃) >> reduces the temperature bias

Irrigation effect on WBGT



- Irrigation reduces heat stress during daytime by 0.3-1.3 °C WBGT but urban and fallow areas experience increased heat stress
- During summer nights, irrigation increases WBGT by 0.4-1.3 °C

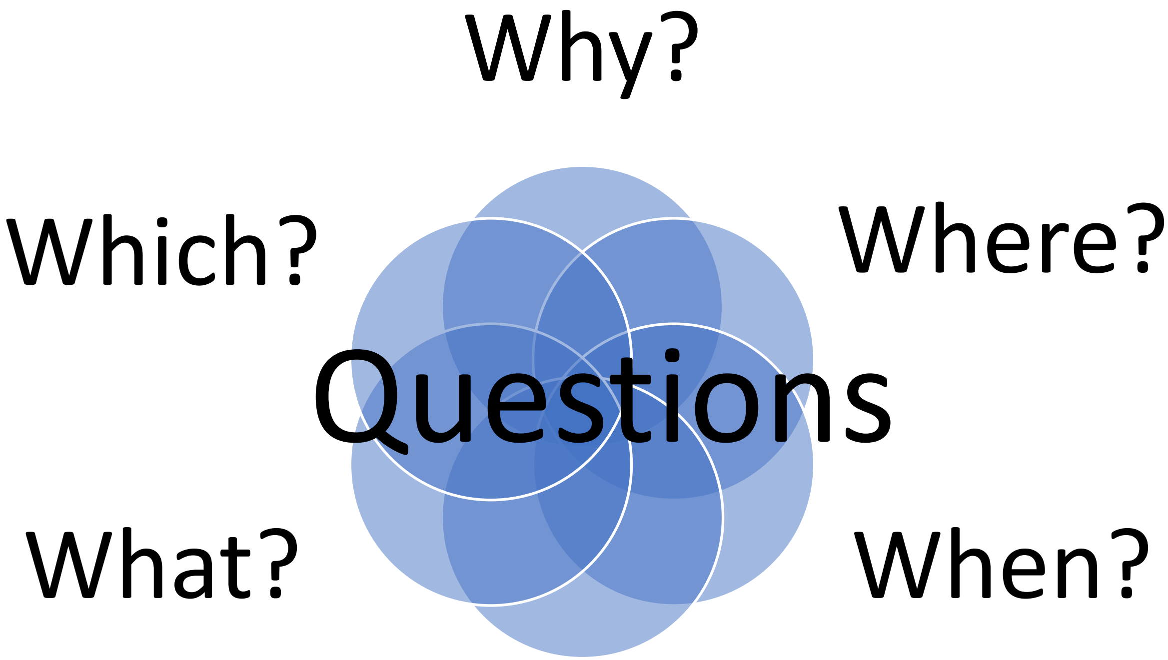
Physical mechanisms



Take-home messages

1. Irrigation reduces heat stress in the crop fields during daytime by 0.3-1.3 °C WBGT.
2. Heat stress is higher in the urban and fallow areas adjacent to the crop fields.
3. During nighttime, irrigation increases WBGT by 0.4-1.3 °C
4. Modeled WBGT frequently exceeds the regulatory threshold in the crop fields during key harvest seasons
5. The heat stress modeling framework >> prototype to develop climate change adaptation strategies for the agricultural regions and can inform labor and environmental policies in California and elsewhere.

Thank you!



The beginning

- The WBGT was first used in 1960 for addressing heat casualties in Marine Corps Trainees
- 600 heat casualties in Marine Corps Recruit Depot (MCRD), Parris Island (South Carolina) in the summer of 1952
- After WBGT adoption, the heat casualties were reduced by five to tenfold (Minard, 1960)

Prevention of Heat Casualties in Marine Corps Recruits*

Period of 1955-60, With Comparative Incidence Rates And Climatic Heat Stresses in Other Training Categories

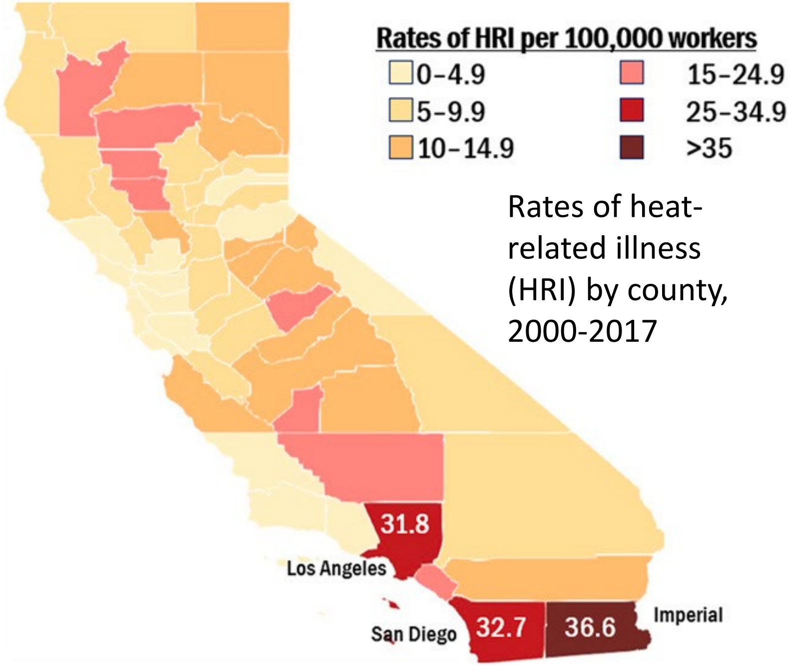
By

CAPTAIN DAVID MINARD, MC., *U. S. Navy*†


Alina Thackray/U.S. Marine Corps

Why model heat stress in the IV?

- Generally, heat-related deaths are remarkably higher in construction and agriculture sector
- Heat Illness rates highest in Imperial County in California
- Labor of estimated 829,000 individual farmworkers in California



Rates of heat-related illness (HRI) by county, 2000-2017

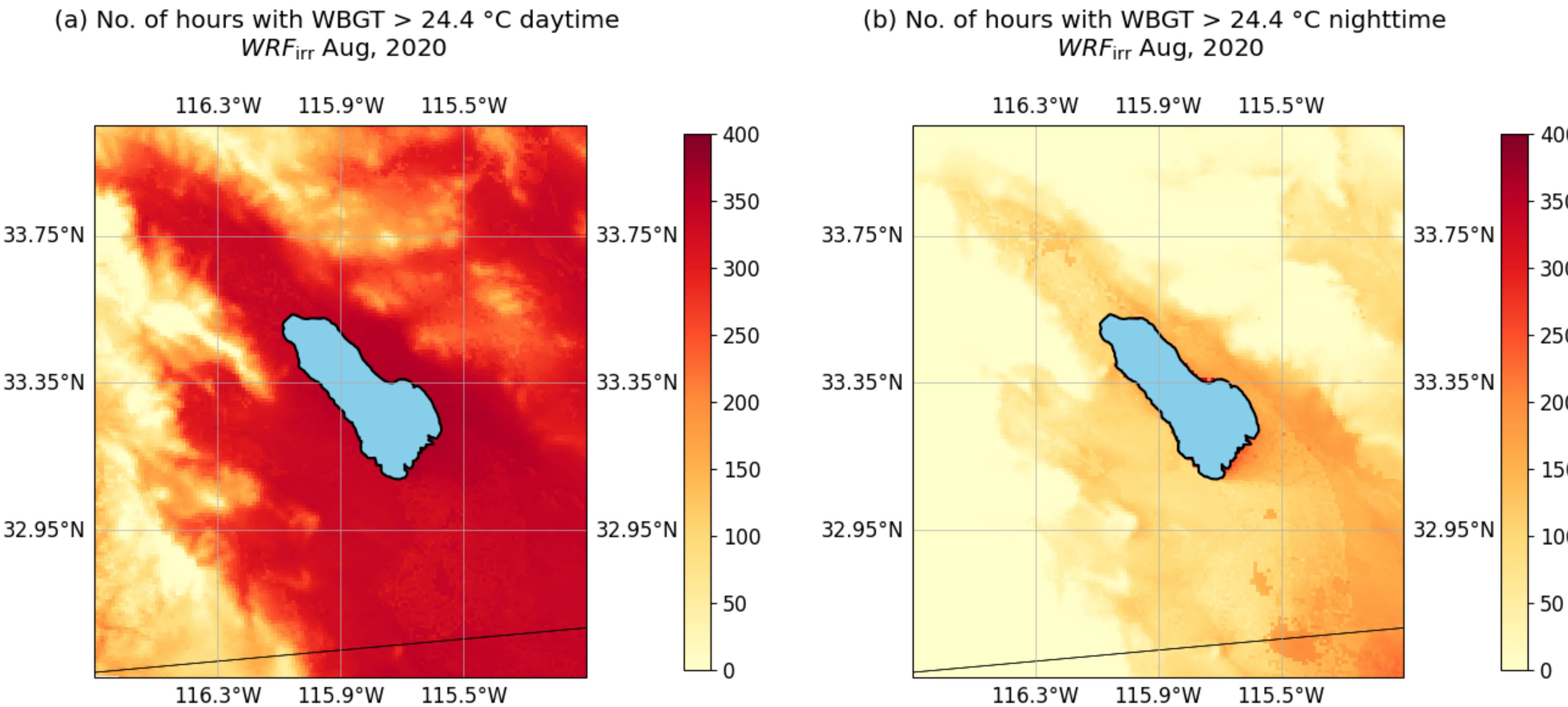
Quantification of heat stress

- **Wet Bulb Globe Temperature (WBGT)** is a standard heat index for measuring heat stress in outdoor environment
- Why? The normal air temperature (measured in a shade), does not take into account the evaporative cooling (sweating) and heat load by direct sun
- Heat stress also depends upon metabolic rate (physical activity level) and clothing (effective WBGT)

Suggested Actions and Impact Prevention		
WBGT(F)	**Effects**	**Precautionary Actions**
< 80		
80-85	**Working or exercising in direct sunlight will stress your body after 45 minutes.**	**Take at least 15 minutes of breaks each hour if working or exercising in direct sunlight**
85-88	**Working or exercising in direct sunlight will stress your body after 30 minutes.**	**Take at least 30 minutes of breaks each hour if working or exercising in direct sunlight**
88-90	**Working or exercising in direct sunlight will stress your body after 20 minutes.**	**Take at least 40 minutes of breaks each hour if working or exercising in direct sunlight**
>90	**Working or exercising in direct sunlight will stress your body after 15 minutes.**	**Take at least 45 minutes of breaks each hour if working or exercising in direct sunlight**

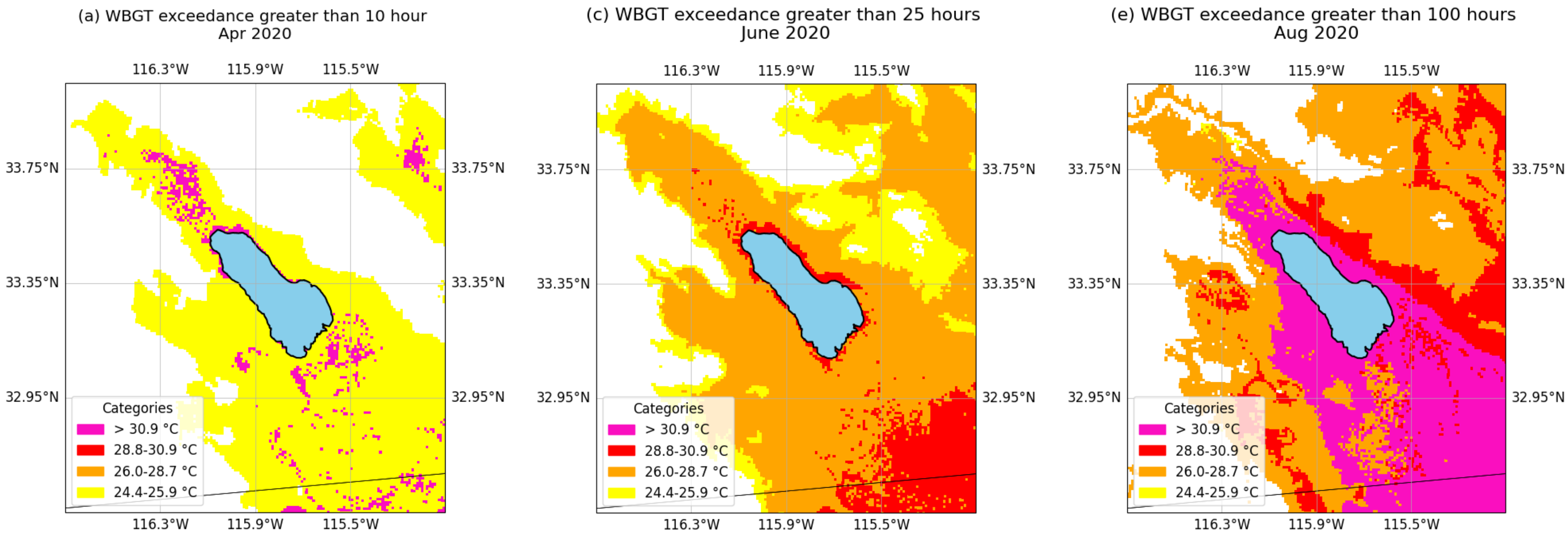
https://www.weather.gov/car/WBGT

How often is WBGT exceeded in day and night?



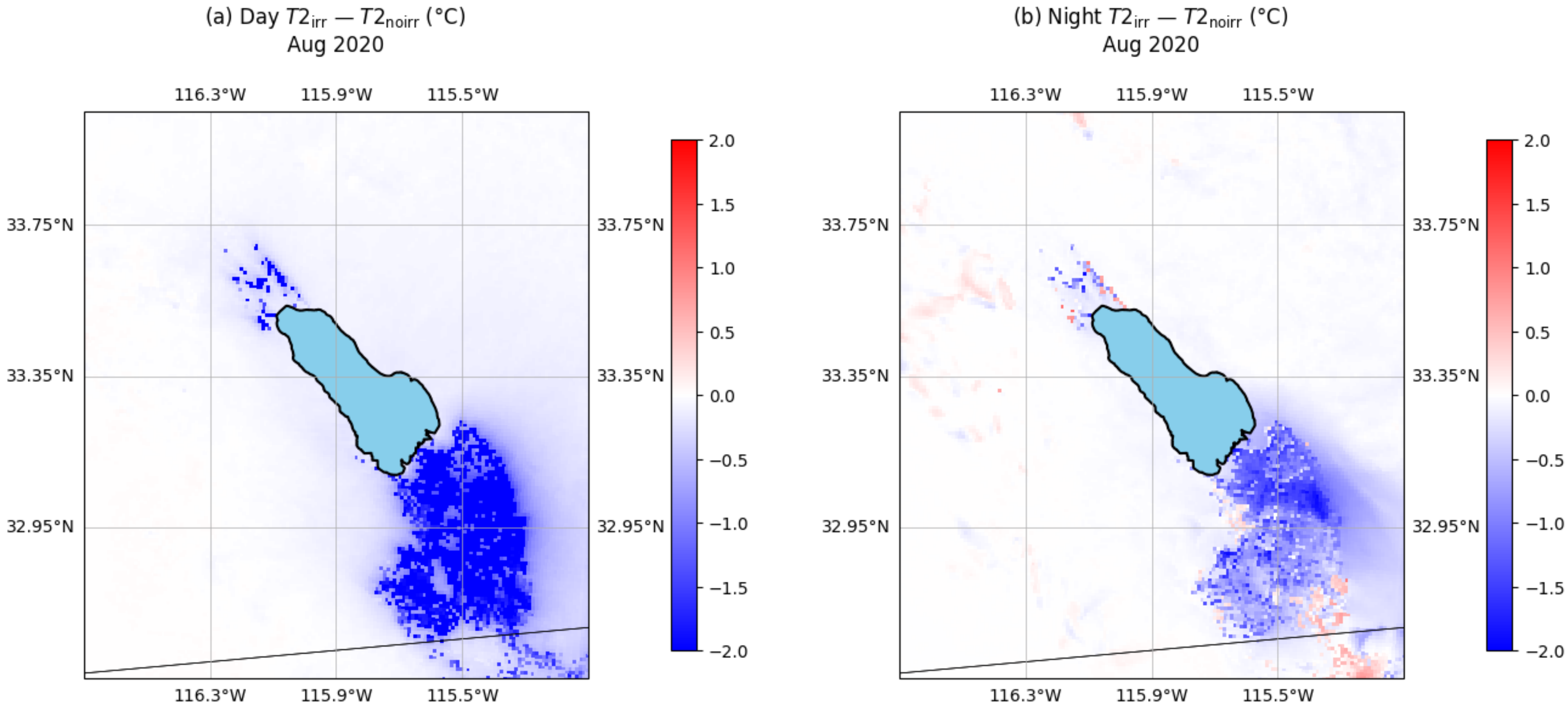
- Heat stress exceeds suggested thresholds even at night
- Working in the nighttime could become more common in the future to avoid the daytime heat
- Many farmworkers live in cities and lack a/c, exposing them to heat during sleeping hours

How often is WBGT exceeded during major harvest seasons?



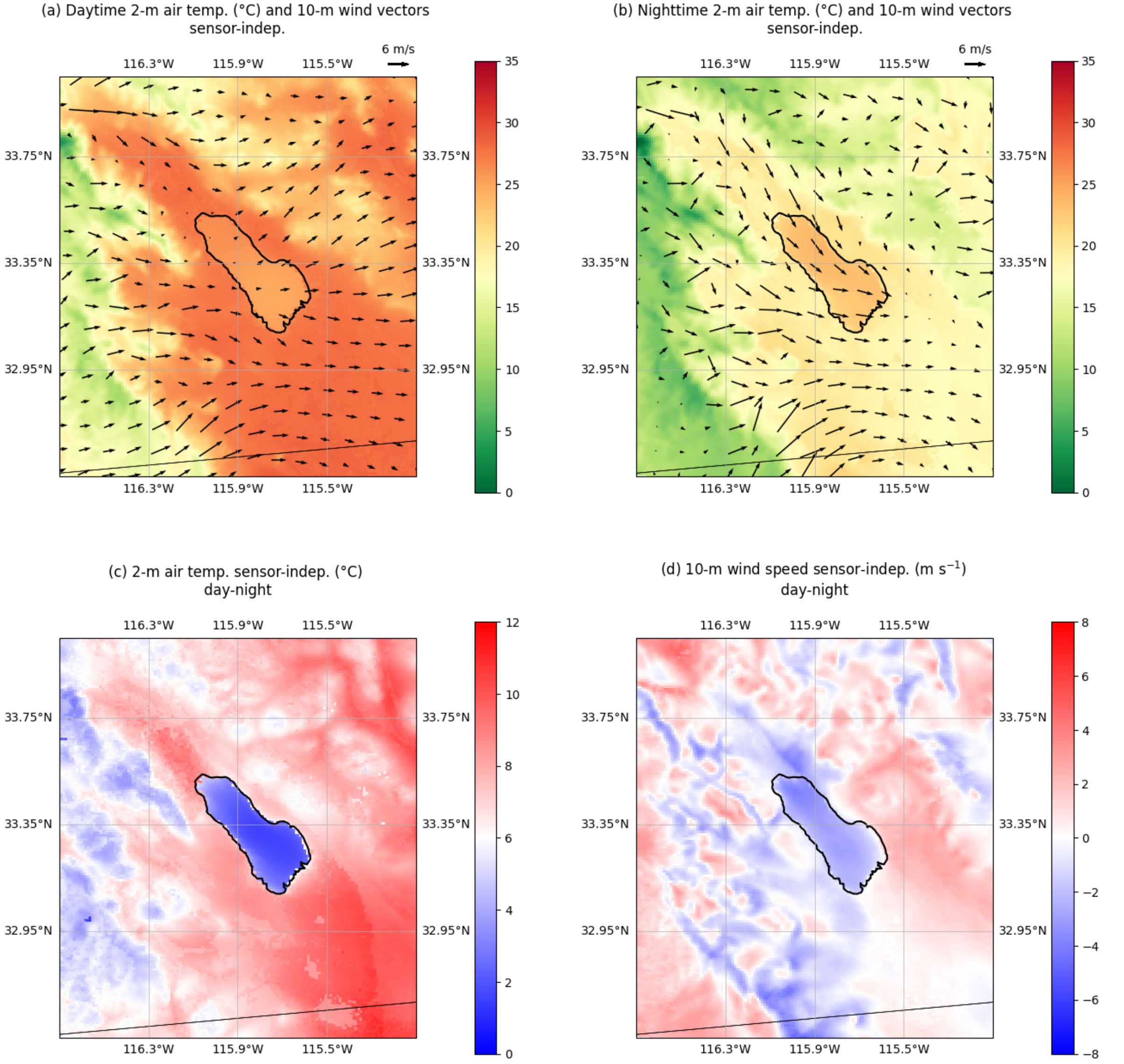
Irrigation effect on Air Temperature

- Irrigation reduces air temperature through evaporative cooling, more strongly in daytime than at night
- Temperature increase in some areas through increase in soil heat capacity

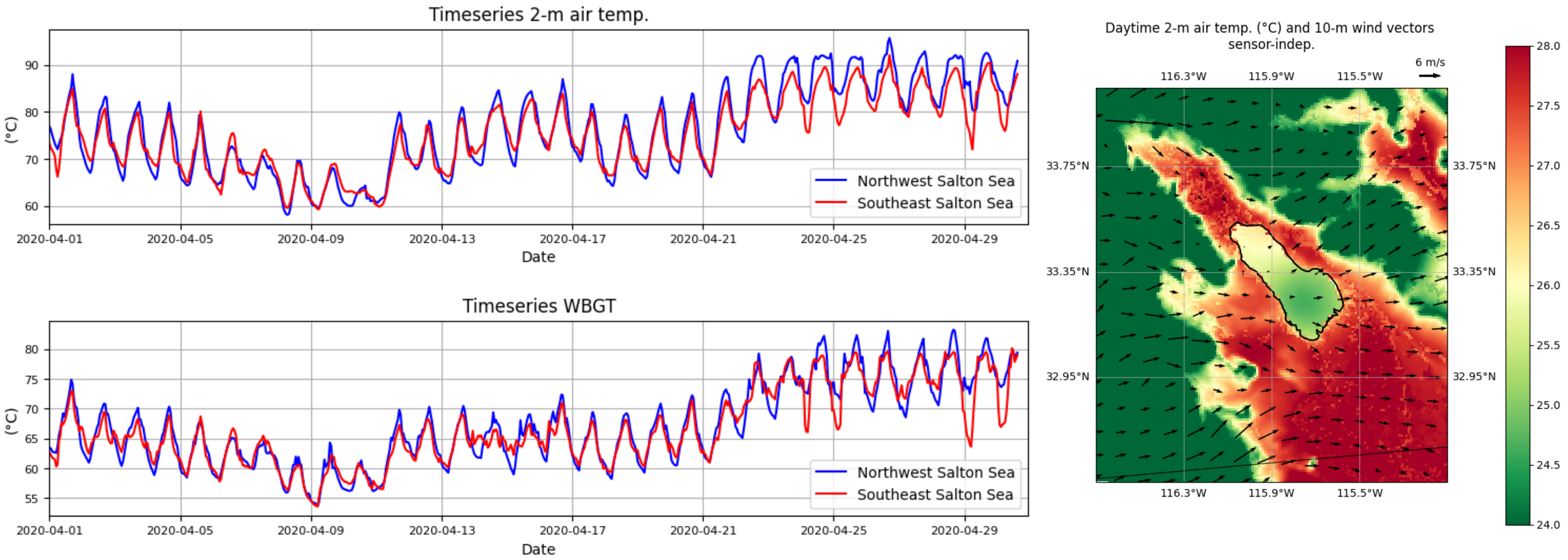


Day-night variability of winds and temperature

- Two prominent wind patterns: moderate northwesterly winds along the Coachella Valley/Salton Sea (local), and the stronger west-southwesterly (WSW) (synoptic)
- Nighttime winds are stronger at the Salton Sea (local effect)
- The difference between day and nighttime temp. is ~10C in agricultural area, ~ 5C in urban centers (remains warmer in the night), nearly zero in the Salton Sea (Fig c).



What causes high WBGT over northern half of the Salton Sea?



Imperial Valley (IV) — an oasis in the desert

- Located in the south of the Salton Sea lying mostly below sea level.
- North part drains to Salton Sea and the southern area drains to the Gulf of California
- The area is heavily cultivated partly because of the good irrigation infrastructure – thanks to the All-American canal built in the 1930s.

WRF equivalent output parameters used for Thermofeel

Parameters	Thermofeel variable	Equivalent WRF output variable name	Remarks
Dewpoint temperature at 2m	td_k (K)	Td_2m (K)	Calculated with the NCAR NCL script wrfout_to_cf
Air temperature at 2m	t2_k (K)	T2 (K)	Standard wrf output
Relative humidity at 2m	rh (%)	rh_2m (%)	Calculated with the NCAR NCL script wrfout_to_cf
Wind speed at 10m height	va (m/s)	U10, V10 (m/s)	Calculated from standard WRF output U10 and V10
Cosine of solar zenith angle	cossza (°)	COSZEN Cosine of solar zenith angle	Standard wrf output
Solar elevation angle	γ (°) = 90-cossza	-	-
Total sky direct solar radiation at surface (downward on a horizontal plane)	fdir (W/m2)	SWDDIR (w/m2) Shortwave surface downward direct irradiance	Not a standard WRF output, added in myoutfields.txt
Surface solar radiation downwards	ssrd (W/m2)	SWDOWN (W/m2) Downward short-wave flux at ground surface (W/m2)	Standard wrf output
Surface thermal radiation downwards	strd (W/m2)	GLW (W/m2) Downward long wave flux at ground surface	Standard wrf output
Surface solar radiation upwards	rsw = ssrd-ssr	SWUPB (W/m2) Instantaneous upwelling shortwave flux at bottom	Standard wrf output
Surface thermal radiation upwards	lur = strd-strr	LWUPB (W/m2) Instantaneous upwelling longwave flux at bottom	Standard wrf output
Surface net solar radiation	ssr (W/m2)	SWDOWN-SWUPB	Required for calculating mean radiant temperature
Surface net thermal radiation	strr (W/m2)	GLW-LWUPB	Required for calculating mean radiant temperature
Direct solar radiation (at surface) on a plane perpendicular to the direction of the Sun	dsrp (W/m2)	SWDDNI (W/m2) Shortwave surface downward direct normal irradiance	Not a standard WRF output, added in myoutfields.txt
Diffuse solar radiation	dsw = ssrd-fdir	SWDDIF (W/m2) Shortwave surface downward diffuse irradiance	Not a standard WRF output, added in myoutfields.txt

Initial and boundary conditions (IC/BC)

Most commonly used data for IC/BC

- GFS (~ 27 km) developed by National Centers for Environmental Prediction (NCEP)
- ERA5 (~ 31 km) by European Centre for Medium-Range Weather Forecasts (ECMWF)
- We use ERA5

1. Calculation of WBT

- WBT is calculated using a psychrometric equation developed by Stull (2011)

WBT = (t2_c * np.arctan (0.151977 * np.sqrt(rh + 8.313659)) + np.arctan (t2_c + rh) - np.arctan (rh-1.676331) + 0.00391838 * (rh) ** (3 / 2) * np.arctan(0.023101 * rh) - 4.686035)

$$WBGT = 0.1 * DB + 0.7 * NWB + 0.2 * GT$$

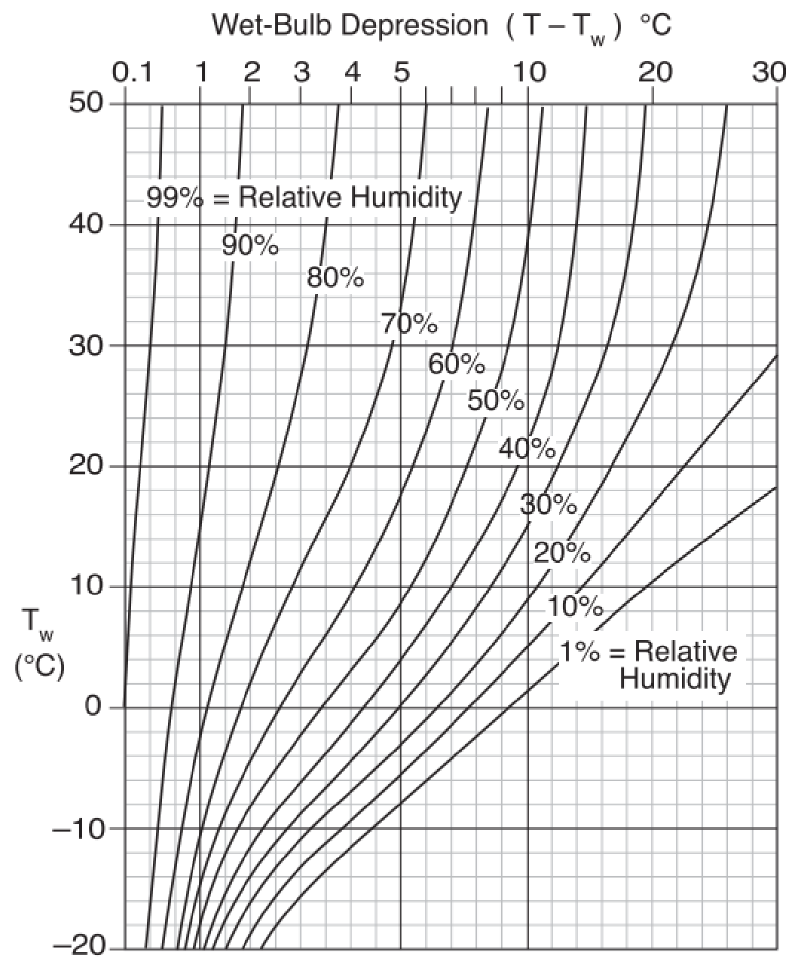


FIG. 1. Psychrometric graph for standard sea level pressure of 101.325 kPa. The abscissa changes scale at the dark vertical lines. In the saturation calculation to determine relative humidity, Teten's equation was used to account for variations in latent heat of vaporization (Stull 2011).

2. Calculation of BGT

- BGT needs to be directly measured
- Alternatively, BGT can be calculated from mean radiant temperature (MRT)

$$^{1}T_{mrt} = \sqrt[4]{T_g^4 + \frac{h_{cg}}{\varepsilon\, D^{-0.4}}\,(T_g - T_a)}$$

h_{cg} is the globe's mean convection coefficient equal to $1.1 \times 10^8 \times v_a^{0.6}$, where v_a is the wind speed at the globe level (1.1 m), ε is the emissivity of the globe.

[1]Guo et al. 2018

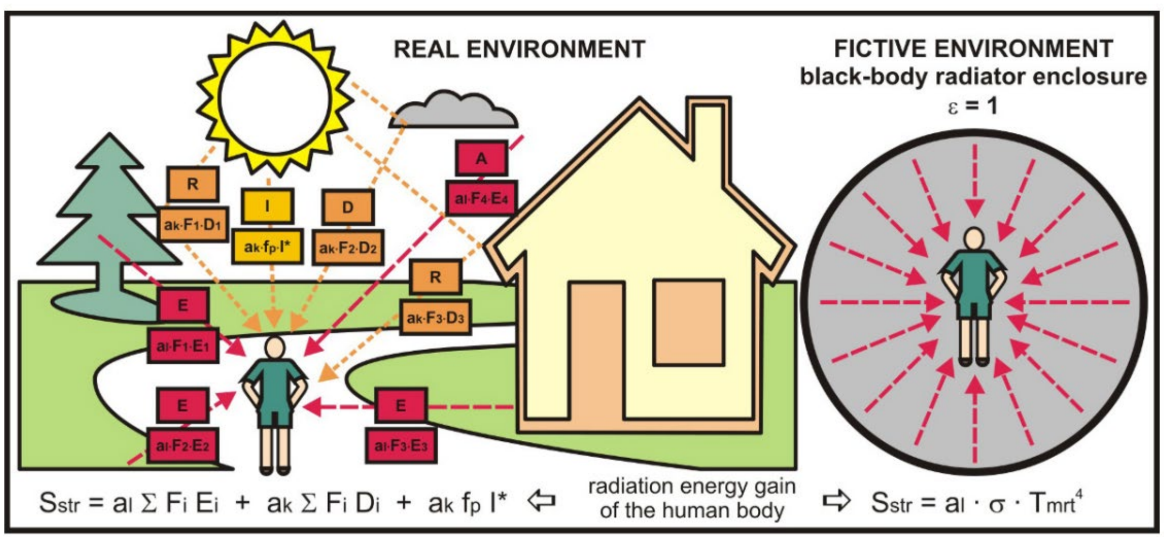
```
calculate_mean_radiant_temperature(ssrd, ssr, dsrp, strd, fdir, strr, cossza)
    MRT - Mean Radiant Temperature
        :param ssrd: (float array) surface solar radiation downwards [W m-2]
        :param ssr: (float array) surface net solar radiation [W m-2]
        :param dsrp: (float array) direct solar radiation [W m-2]
        :param strd: (float array) surface thermal radiation downwards [W m-2]
        :param fdir: (float array) total sky direct solar radiation at surface [W m-2]
        :param strr: (float array) surface net thermal radiation [W m-2]
        :param cossza: (float array) cosine of solar zenith angle [dimentionless]
        returns mean radiant temperature [K]
    Reference: Di Napoli et al. (2020)
    https://link.springer.com/article/10.1007/s00484-020-01900-5

Help on function calculate_wbgt in module thermofeel.thermofeel:

calculate_wbgt(t2_k, mrt, va, td_k)
    WBGT - Wet Bulb Globe Temperature
        :param t2_k: (float array) 2m temperature [K]
        :param mrt: (float array) mean radiant temperature [K]
        :param va: (float array) wind speed at 10 meters [m/s]
        :param td_k: (float array) dew point temperature [K]
        returns wet bulb globe temperature [K]
    Reference: Stull (2011)
    https://doi.org/10.1175/JAMC-D-11-0143.1
    See also: http://www.bom.gov.au/info/thermal_stress/

Help on function calculate_bgt in module thermofeel.thermofeel:

calculate_bgt(t2_k, mrt, va)
    Globe temperature
        :param t2_k: (float array) 2m temperature [K]
        :param mrt: (float array) mean radiant temperature [K]
        :param va: (float array) wind speed at 10 meters [m/s]
        returns globe temperature [K]
    Reference: Guo et al. 2018
    https://doi.org/10.1016/j.enbuild.2018.08.029
```

Calculation of mean radiant temperature (MRT)

MRT is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure

- MRT is used to reduce various sources of heat falling on a human body to a one convenient dimension (temperature)
- MRT can be obtained by equating the radiant heat absorbed by a human body to the radiation emitted by a fictive black-body emitter ($\sigma \, T_{mrt}{}^4$) solving which we get,

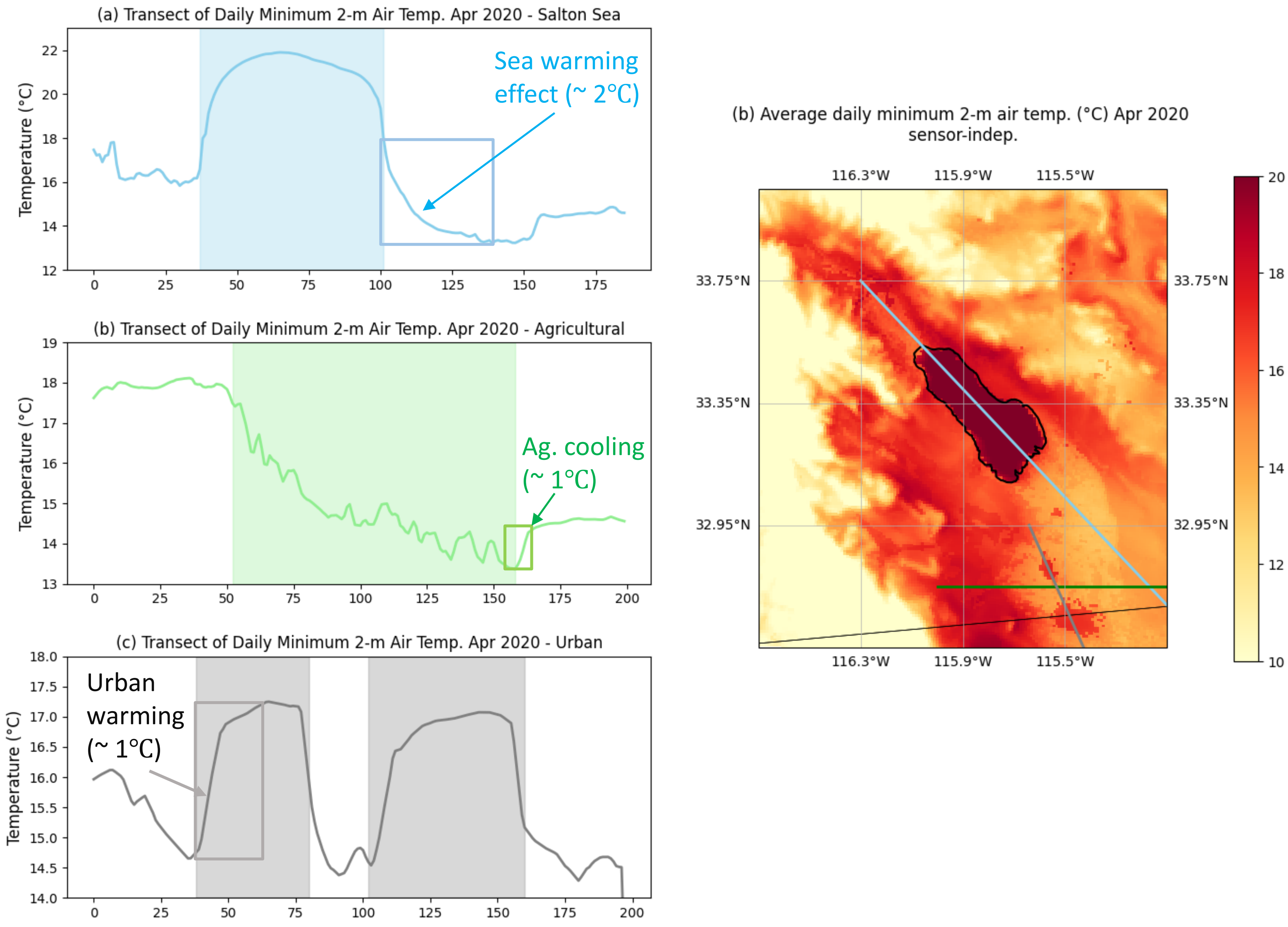
$$T_{mrt} = \left\{ \frac{1}{\sigma} \left[f_a \, strd + f_a \, lur + \frac{\alpha_{ir}}{\varepsilon_p} (f_a \, dsw + f_a \, rsw + f_p \, dsrp) \right] \right\}^{1/4}$$



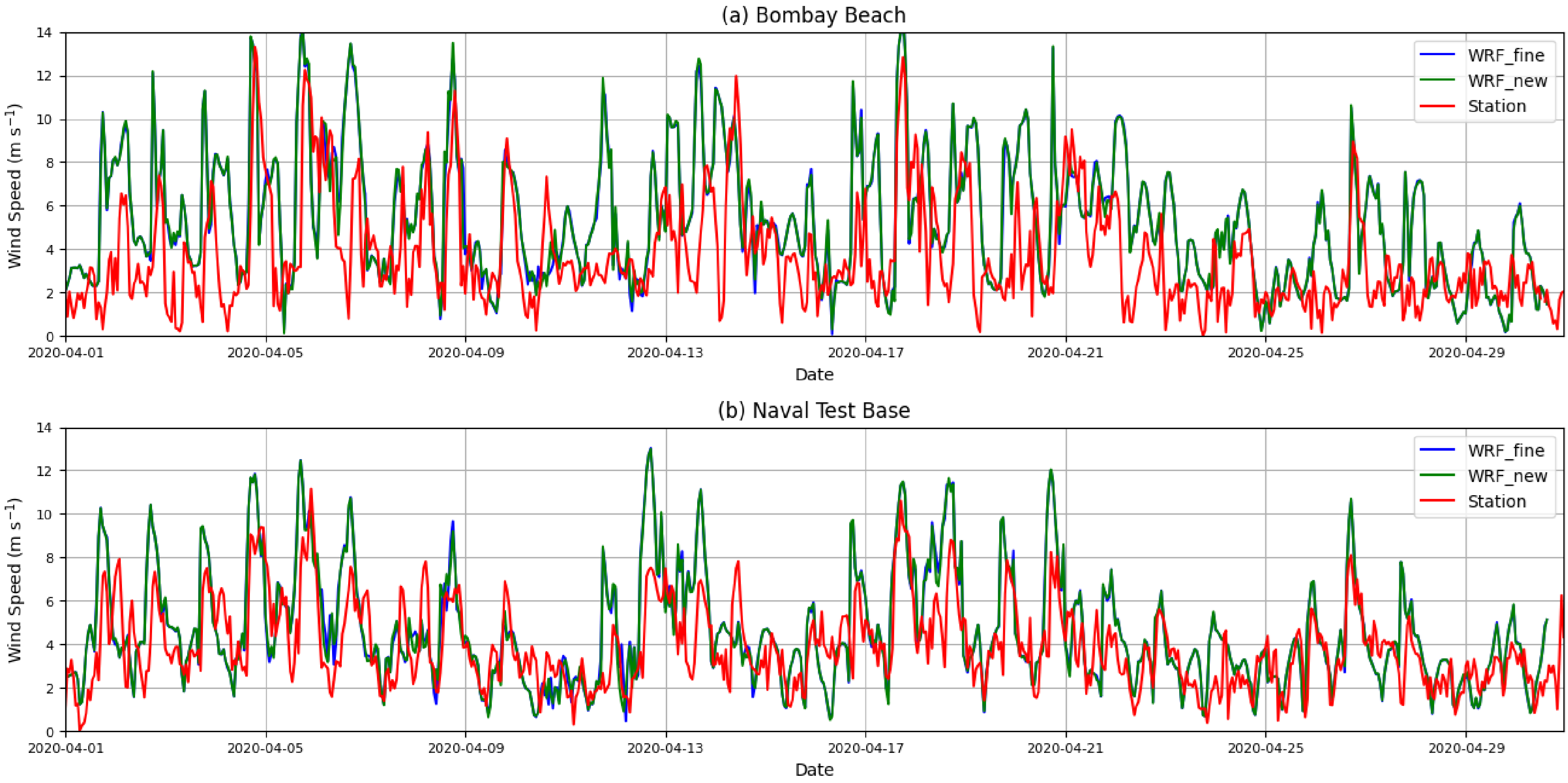
Multiple sources of heat in an outdoor environment
So a regional climate model is ideal

(Staiger and Matzarakis, 2010)

Daily min. temperature



Model performance: 10-m wind speed



Model performance: solar radiation