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

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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

\[ WBGT = 0.7 \times WBT + 0.2 \times BGT + 0.1 \times DBT \]

- **10% of Air Temperature**: What your favorite weather app shows.
  - Temperature: 85°

- **70% of Natural Wet Bulb Temperature**: Simulates the cooling effect of sweat.
  - Temperature: 78°

- **20% of Black Globe Temperature**: Simulates how hot it feels in direct sunlight.
  - Temperature: 115°

- **Wet Bulb Globe Temperature**: Includes temperature, humidity, wind speed, and sunlight to measure heat stress on the body.
  - Temperature: 86.1°
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

Study domain

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
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
Results
Model performance

(a) Calipatria/Mulberry

(c) Calipatria/Mulberry
Validation of WBGT

(a) Calipatria/Mulberry (Agricultural)

(b) Seeley (Agricultural)

(c) Westmorland North (Urban-agricultural)

(d) Bombay Beach (Coastal)

(e) Cahuilla (Desert)

(f) Naval Test Base (Coastal)

(g) Niland-English Road (Coastal-agricultural)

(h) Salton City (Urban-coastal)

(i) Sonny Bono (Coastal-agricultural)
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

- Irrigation >> increases humidity >> reduces the humidity bias
- Irrigation >> causes cooling (~2-3°C) >> 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

Heat Stress (WBGT)

Higher
- Wet-bulb temperature
- Increase in humidity
- Air temperature
- Evaporative cooling

Lower
- Wet-bulb temperature
- Increase in humidity
- Air temperature
- Evaporative cooling

Irrigation

Moisture advection

Stronger nighttime winds

Urban/fallow/downwind areas

Crop fields
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!

Questions

Why?

Which?

What?

Who?

Where?

When?
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)
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](image)
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)

<table>
<thead>
<tr>
<th>WBGT(F)</th>
<th>Effects</th>
<th>Precautionary Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80-85</td>
<td>Working or exercising in direct sunlight will stress your body after 45 minutes.</td>
<td>Take at least 15 minutes of breaks each hour if working or exercising in direct sunlight</td>
</tr>
<tr>
<td>85-88</td>
<td>Working or exercising in direct sunlight will stress your body after 30 minutes.</td>
<td>Take at least 30 minutes of breaks each hour if working or exercising in direct sunlight</td>
</tr>
<tr>
<td>88-90</td>
<td>Working or exercising in direct sunlight will stress your body after 20 minutes.</td>
<td>Take at least 40 minutes of breaks each hour if working or exercising in direct sunlight</td>
</tr>
<tr>
<td>&gt;90</td>
<td>Working or exercising in direct sunlight will stress your body after 15 minutes.</td>
<td>Take at least 45 minutes of breaks each hour if working or exercising in direct sunlight</td>
</tr>
</tbody>
</table>

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?

(a) WBGT exceedance greater than 10 hour Apr 2020
(b) WBGT exceedance greater than 25 hours June 2020
(c) WBGT exceedance greater than 100 hours Aug 2020
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

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

\[
WBT = (t_2_c \ast \text{np.arctan}(0.151977 \ast \text{np.sqrt}(rh + 8.313659)) + \text{np.arctan}(t_2_c + rh) - \text{np.arctan}(rh-1.676331) + 0.00391838 \ast (rh) \ast (3 / 2) \ast \text{np.arctan}(0.023101 \ast rh) - 4.686035)
\]

\[
WBG T = 0.1 \ast DB + 0.7 \ast NWB + 0.2 \ast GT
\]
2. Calculation of BGT

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

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

\( h_{cg} \) 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), \( \varepsilon \) is the emissivity of the globe.

\(^1\text{Guo et al. 2018}\)
Calculation of mean radiant temperature (MRT)

- 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,

\[
T_{mrt} = \left\{ \frac{1}{\sigma} \left[ f_a \ strd + f_a \ lur + \frac{\alpha_{ir}}{\varepsilon_p} \left( f_a \ ds w + f_a \ rsw + f_p \ ds rp \right) \right] \right\}^{1/4}
\]

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

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

(Staiger and Matzarakis, 2010)
Daily min. temperature

(a) Transect of Daily Minimum 2-m Air Temp. Apr 2020 - Salton Sea

Sea warming effect (~ 2°C)

(b) Average daily minimum 2-m air temp. (°C) Apr 2020 sensor-indep.

(c) Transect of Daily Minimum 2-m Air Temp. Apr 2020 - Agricultural

Ag. cooling (~ 1°C)

(c) Transect of Daily Minimum 2-m Air Temp. Apr 2020 - Urban

Urban warming (~ 1°C)
Model performance: 10-m wind speed

(a) Bombay Beach

(b) Naval Test Base
Model performance: solar radiation