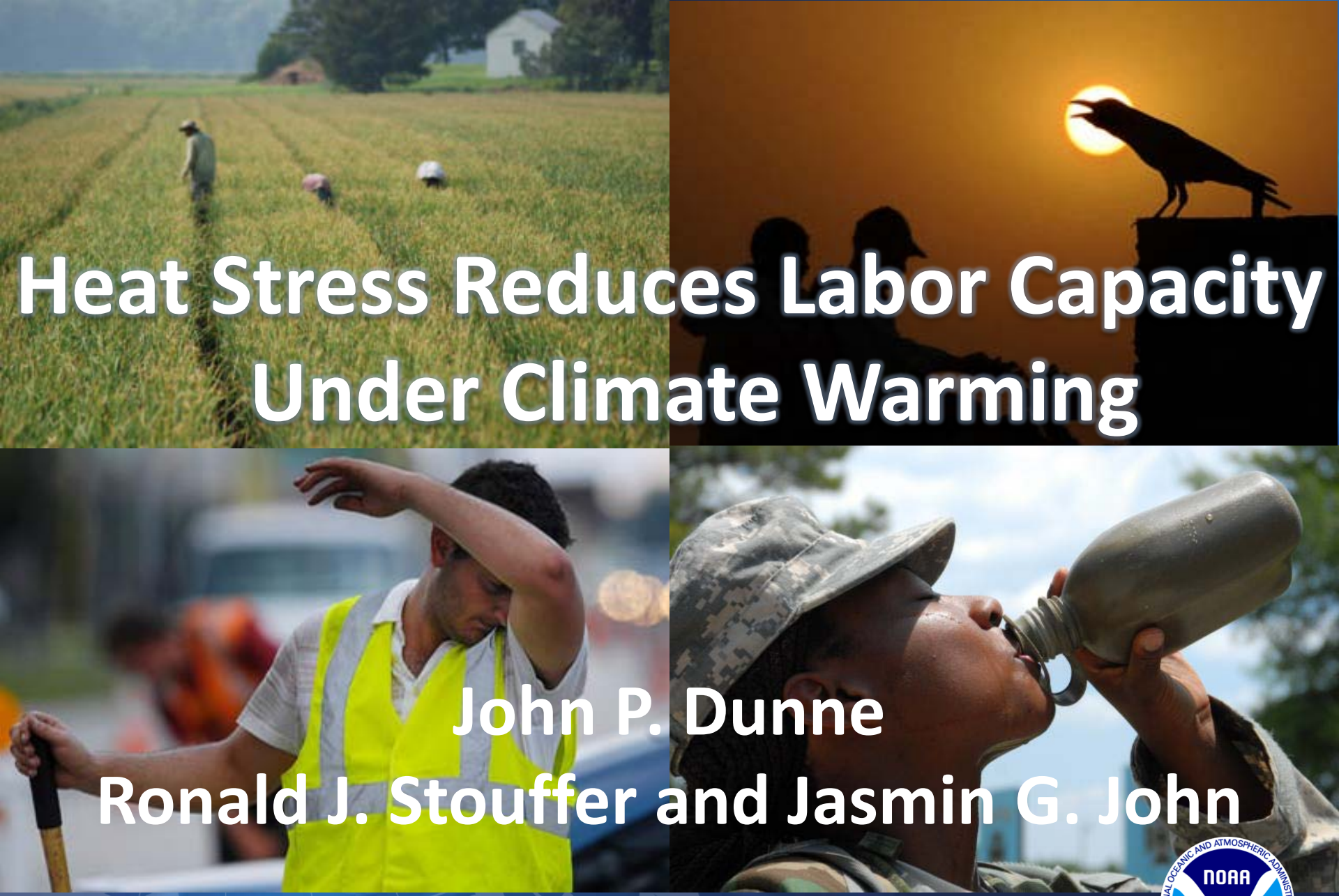


# Heat Stress Reduces Labor Capacity Under Climate Warming


John P. Dunne

Ronald J. Stouffer and Jasmin G. John

Geophysical Fluid Dynamics Laboratory

# Outline

- **Background**
  - **Heat Stress Metrics**
  - Heat Stress under Climate Change
  - Applicability of Heat Stress Metrics
- ESM2M Response
  - Wet Bulb Globe Temperature
  - Labor Capacity
- Exploration of Uncertainties
  - Model Biases
  - Population Change
  - Model Construction
  - Emissions Projection
- Conclusions

# What is Heat Stress?

Humans dissipate heat radiatively, sensibly and evaporatively to sustain a **skin temperature** of **~35°C** and **core temperature** of **37°C**.

**Heat stress** is the combined buildup of heat by working muscles and the environment.

**Hyperthermia, heat exhaustion** and **heat stroke** result when the body is subjected to more heat than it can dissipate.

# Some Factors Involved in Heat Stress

- **Environmental**
  - Temperature and Humidity
  - Solar and Ambient Radiation
  - Wind
- **Physiological**
  - Magnitude and Duration of Exertion
  - Health/Age
  - Acclimation
- **Sociological**
  - Clothing
  - Social and Occupational Adaptation
  - Buildings and Other Structures

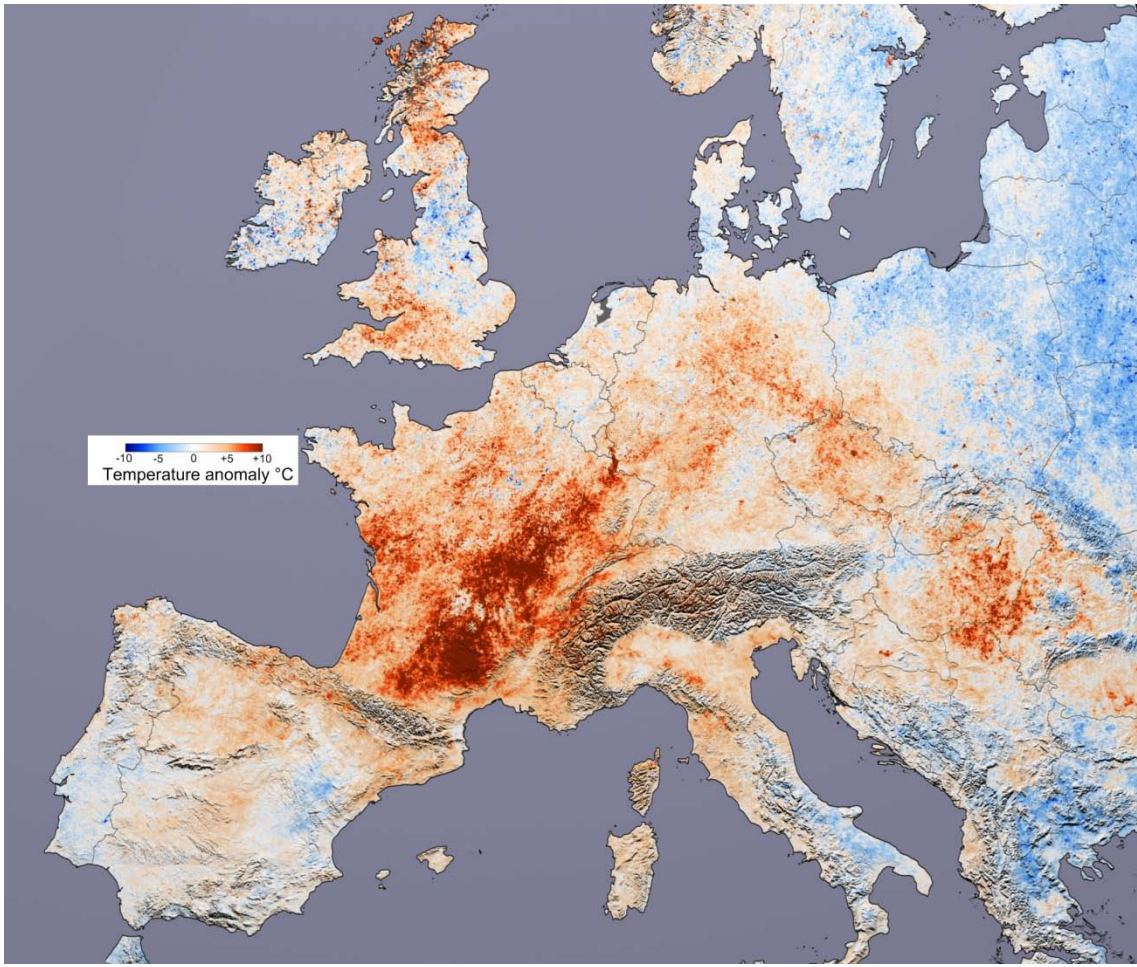
# Various Metrics of Moist Temperature

- **Dry Bulb Temperature** ($T_A$) – Common value
- **Steadman Heat Index** – Common temperature and humidity based metric for heat waves
- **Wet Bulb Temperature** ($T_W$) – empirical value to which a wetted thermometer will drop under evaporation
- **Dew Point Temperature** ($T_{Dew}$) – theoretical value that would be required to drop to reach 100% humidity ($T_W \geq T_{Dew}$)
- **Black Globe Temperature** ($T_G$) – empirical value of globe in ambient radiative equilibrium
- **Wet Bulb Globe Temperature** (WBGT) – Several empirical combinations of $T_W$, $T_A$, and $T_G$ to suit various purposes

# Uncertain Heat Waves Impacts under Climate Change

## >70,000 deaths from 2003 European Heat Wave*

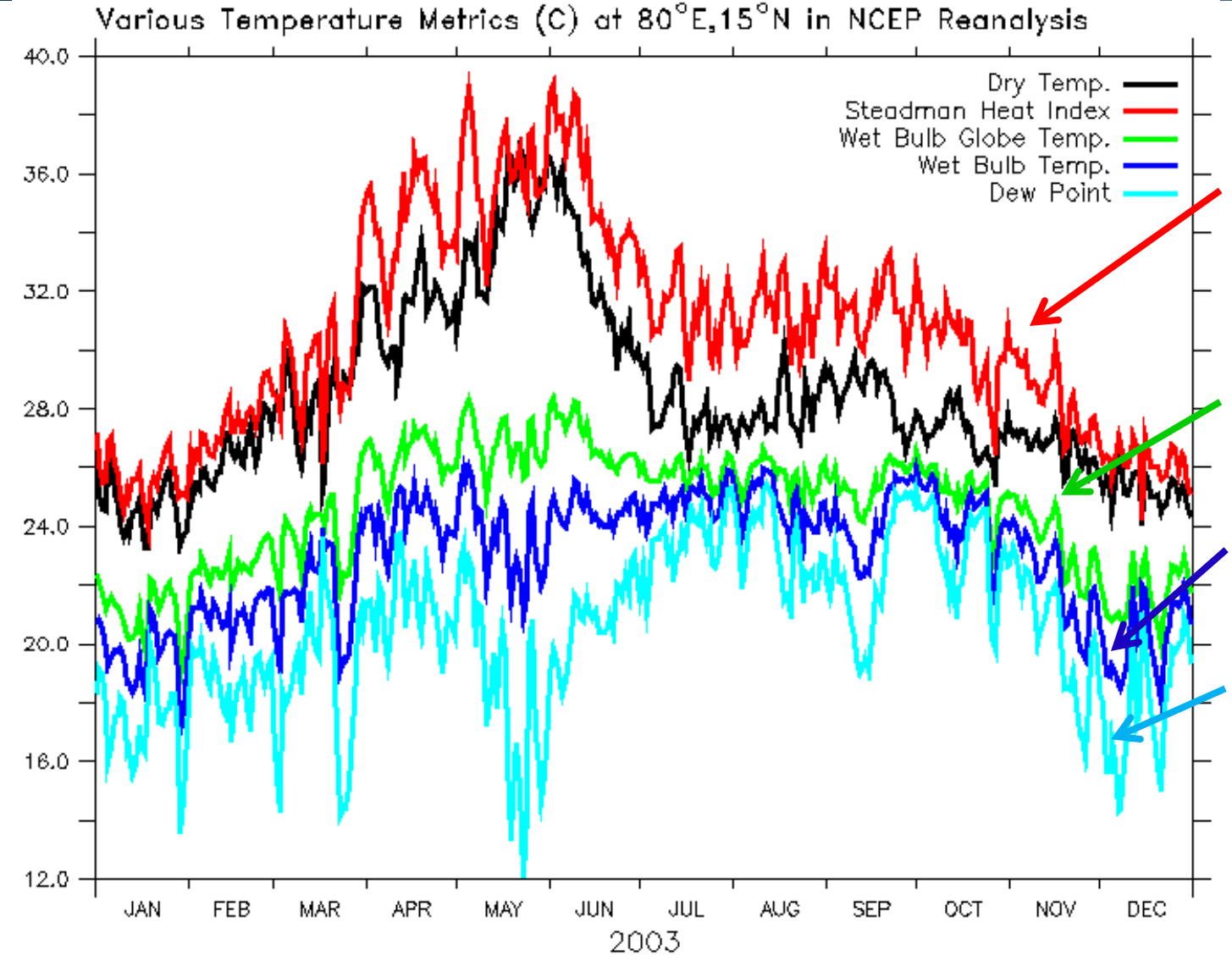
- **Certainly catastrophic, but…**
- **Not extreme in relation to global climate**
- **Attribution is complex**
- **Skewed to elderly and otherwise vulnerable**
- **No physiological acclimation opportunity**
- **No societal adaptation opportunity**
- **Uncertain societal adaptation implications**




http://upload.wikimedia.org/wikipedia/commons/7/7e/Canicule_Europe_2003.jpg

*Robine, J.-M., et al., Death toll exceeded 70,000 in Europe during the summer of 2003, *Comptes Rendus Biologies*, **331**, 171-178 (2008)

# 2003 Indian Heat Waves (>3000 Dead)




**With high variance, Steadman shows when people died**

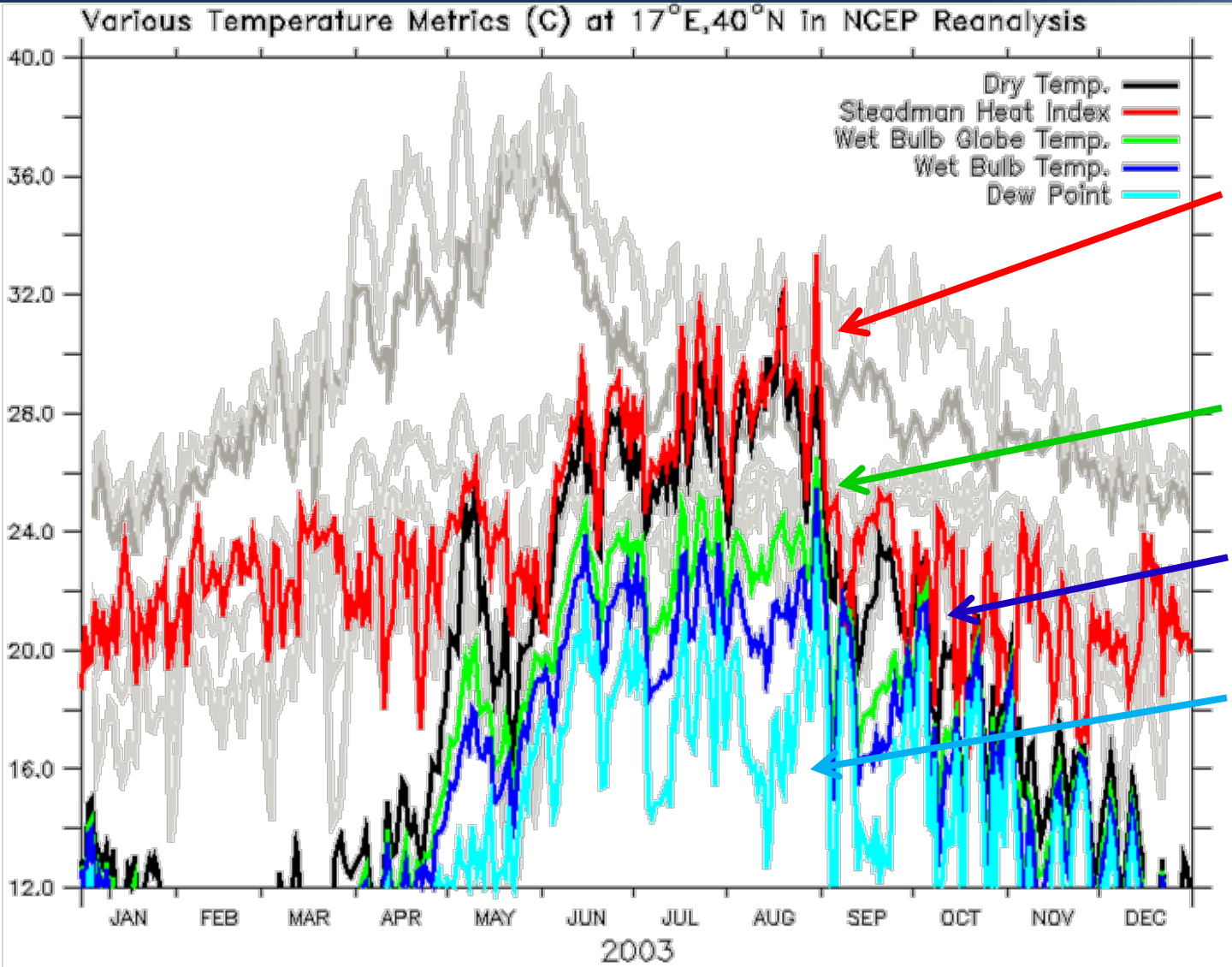
**With muted variance, WBGT shows when the stage was set**

**$T_W$ doesn't correlate well with heat stress**

**$T_{Dew}$ can be inversely correlated with heat stress**

Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# 2003 European Heat Wave (>70K Dead)

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# 5th Coupled Model Intercomparison Project (CMIP5)

**Previous Special Report on Emission Scenarios (SRES): 6 Families and 40 Scenarios**

**Present Representative Concentration Pathways (RCP): Reduces to 4 main scenarios**

| | Radiative Forcing | Concentration | Pathway | RCP Model | Reference |
|---|---|---|---|---|---|
| RCP8.5 | >8.5 W $m^{-2}$ in 2100 | >1370 $CO_2$-eq in 2100 | Rising | MESSAGE | Rao and Riahi (2006), Riahi et al. (2007) |
| RCP6.0 | ~6 W $m^{-2}$ in 2100 | ~850 $CO_2$-eq (stabilization after 2100) | Stabilization without overshoot | AIM | Fujino et al. (2006), Hijioka et al. (2008) |
| RCP4.5 | ~4.5 W $m^{-2}$ in 2100 | ~650 $CO_2$-eq (stabilization after 2100) | Stabilization without overshoot | MiniCAM | Smith and Wigley (2006), Clarke et al. (2007) |
| RCP2.6 | Peak at ~3 W $m^{-2}$ before 2100 and then decline | ~490 $CO_2$-eq before 2100 and then decline | Peak and decline | IMAGE | van Vuuren et al. (2006, 2007) |

# Emissions thus far outstrip projections

Peters et al., 2012: The challenge to keep global warming below 2°C. *Nat. Clim. Change*, **3**, 4-6.

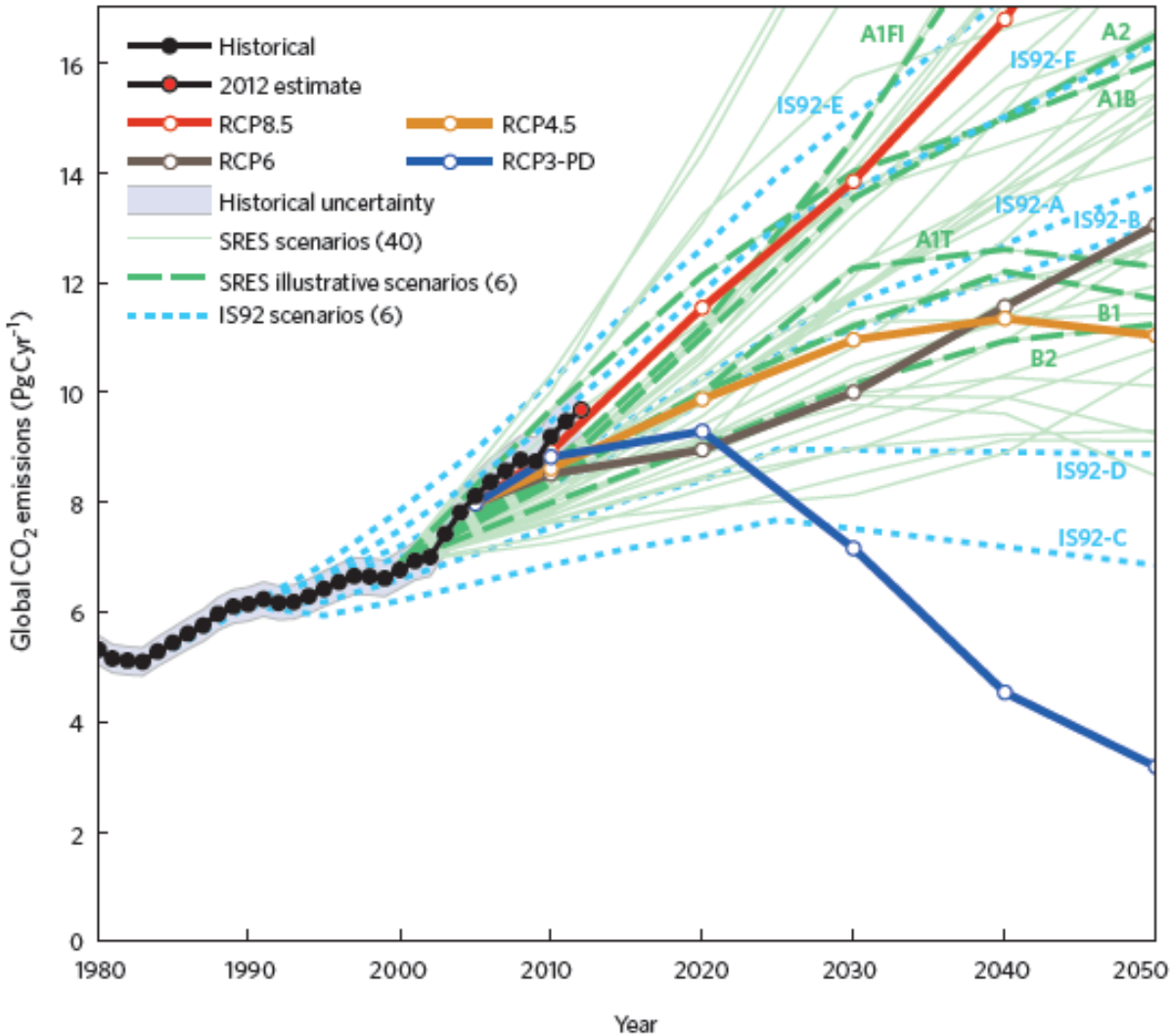
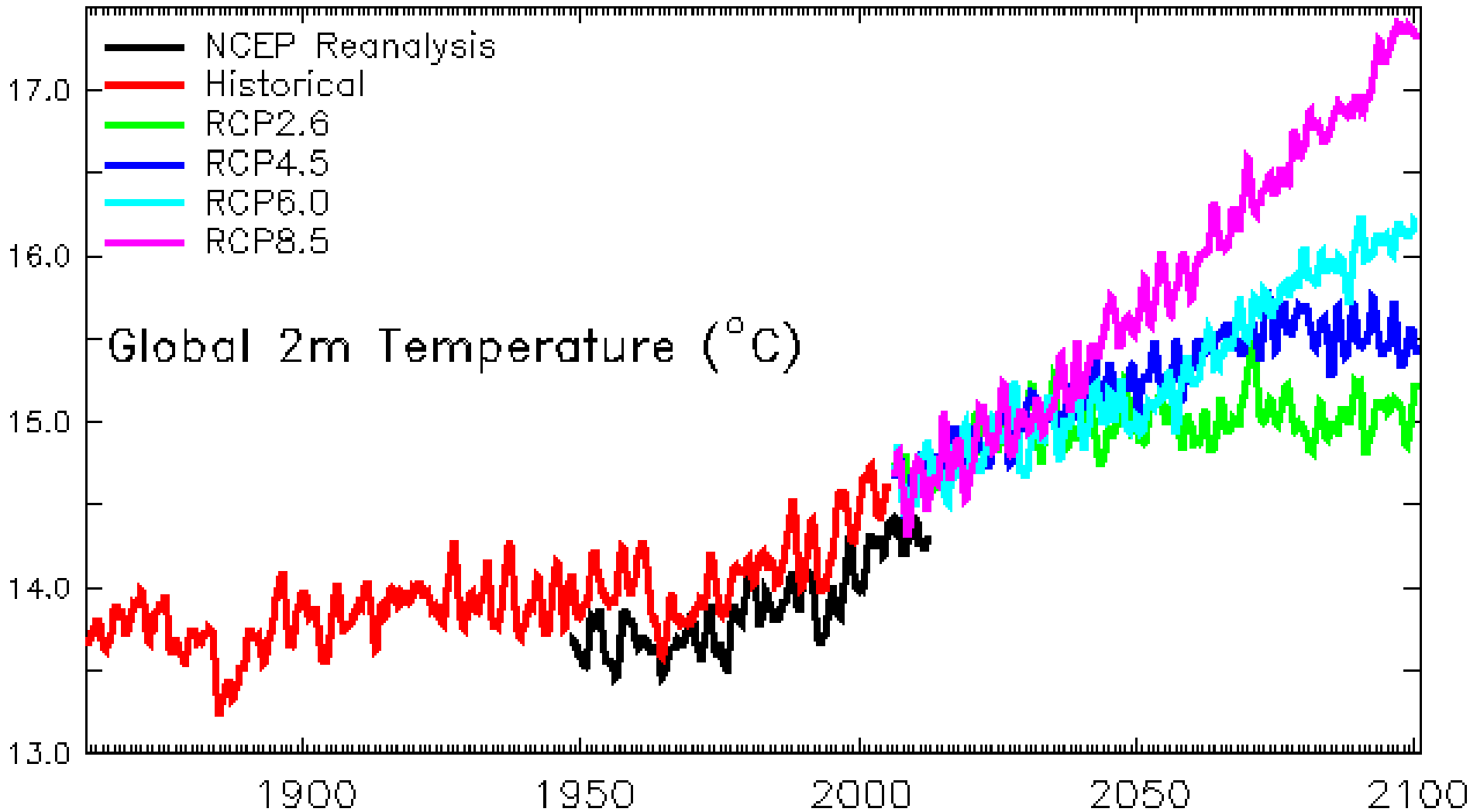



**Figure 1 |** Estimated $CO_2$ emissions over the past three decades compared with the IS92, SRES and the RCPs. The SA90 data are not shown, but the most relevant (SA90-A) is similar to IS92-A and IS92-F. The uncertainty in historical emissions is ±5% (one standard deviation). Scenario data is generally reported at decadal intervals and we use linear interpolation for intermediate years.

# Global Temperature in GFDL ESM2M Under Hist/RCPs



# Climate Warming is a Moist Response

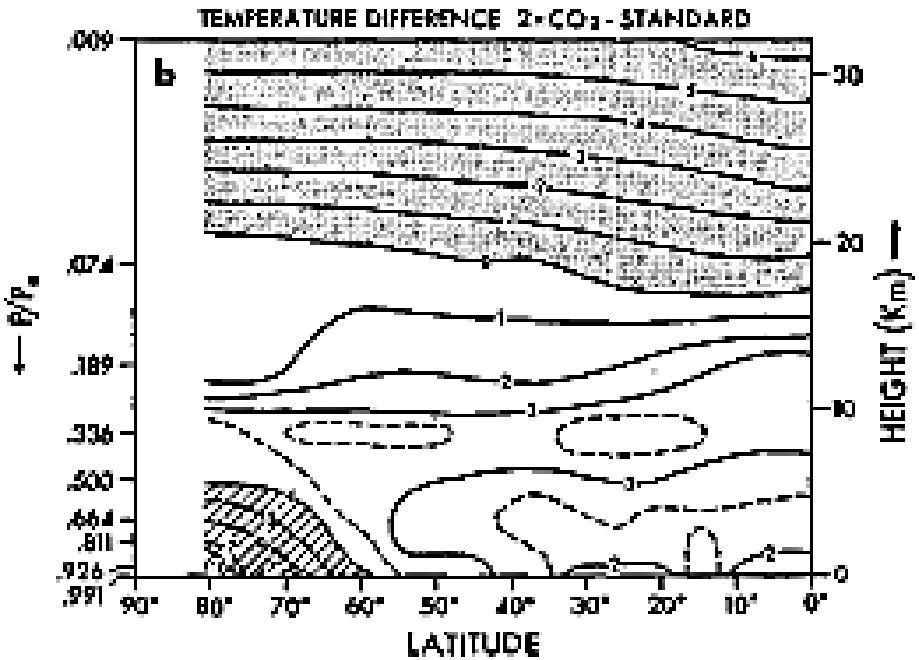



FIG. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of $CO_2$ concentration (b). Stippling indicates a decrease in temperature.

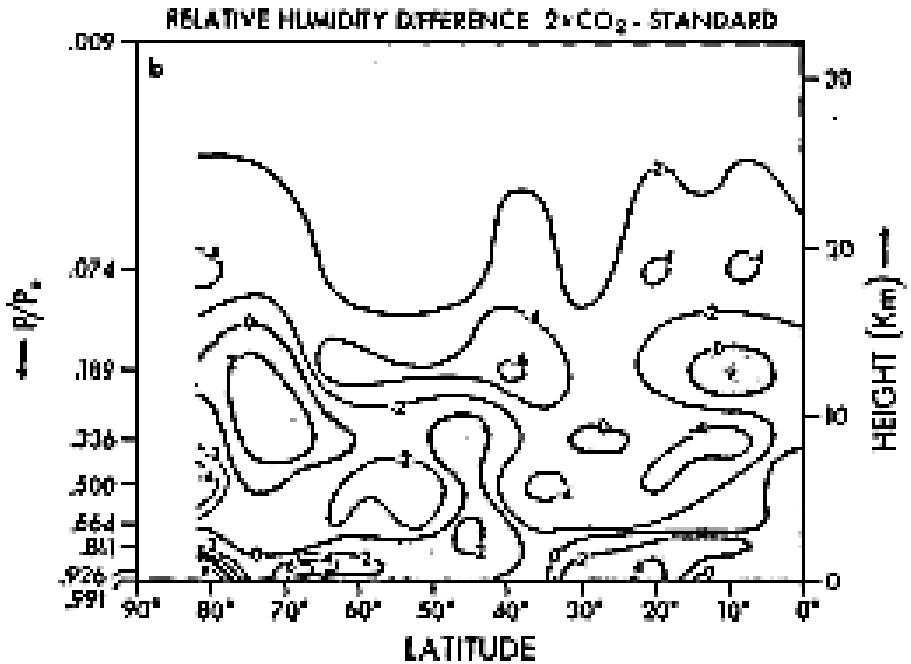
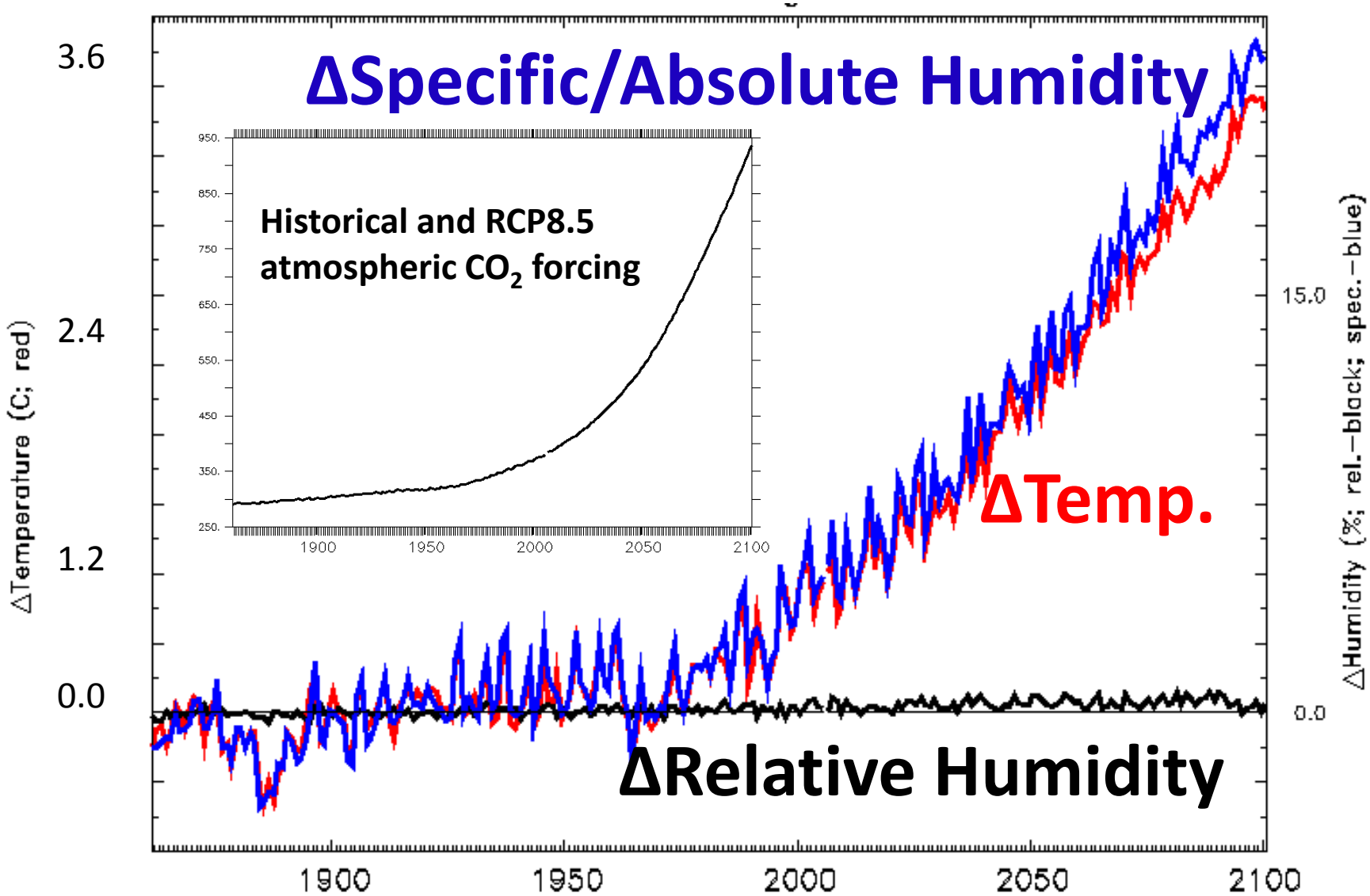



FIG. 6. Latitude-height distribution of zonal mean relative humidity (%) for standard case (a) and of the increase in zonal mean relative humidity resulting from the doubling of $CO_2$ concentration (b). Stippling indicates an increase of relative humidity.

Manabe, S. and R. T. Wetherald, 1975: The effects of doubling $CO_2$ concentration on the climate of a general circulation model. *Journal of the Atmospheric Sciences*, **32**, 3-15.

# ESM2M Surface Water Vapor Response



# Climate Warming is a Moist Response

- In contrast to depictions of climate warming as a desert…
- Climate warming increases absolute humidity.
- Experientially, this makes climate warming…

Unlike a desert or the diurnal cycle (i.e. hotter feels drier),

but more like the Eastern US seasonal cycle (i.e. hotter feels wetter)

# Across Hot Extremes, ΔTemperature and ΔHumidity Roughly Counterbalance

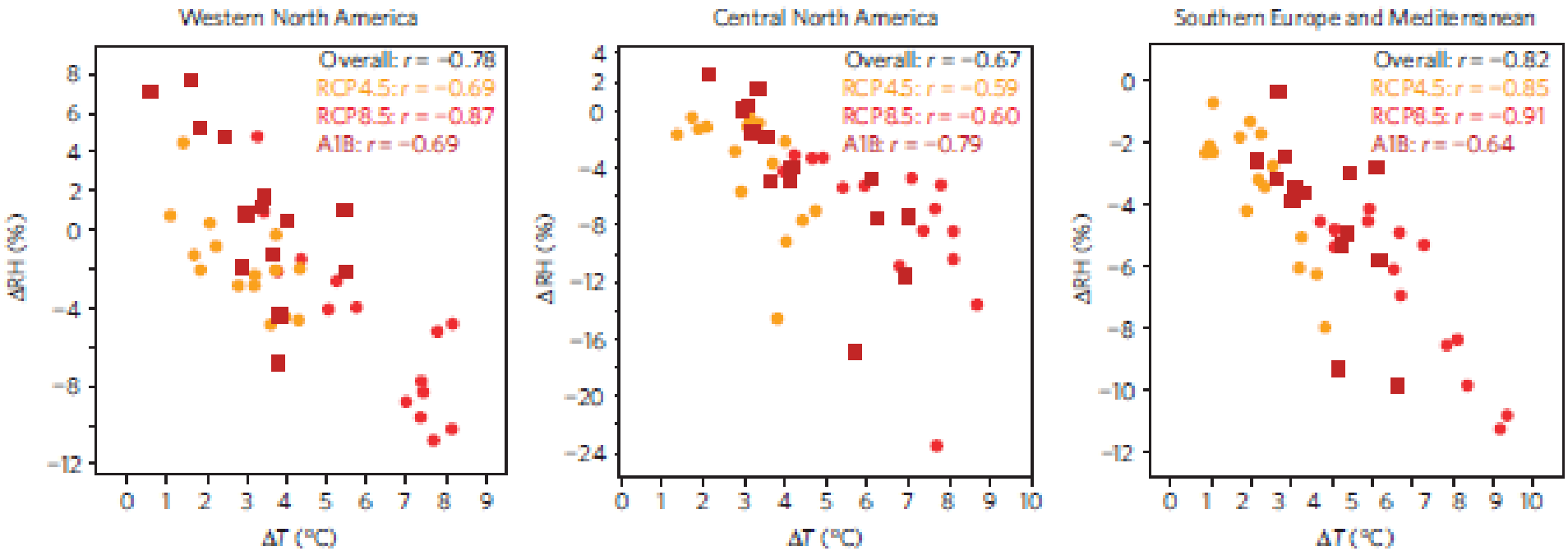



**Figure 3 | Joint projections in hot extremes and humidity.** Change in regional average temperature and relative humidity on the hottest 1% of days ($T_{x1\%}$ and $RH_{x1\%}$) averaged across the three regions western North America (103°–130° W and 30°–60° N), CNA (85°–103° W and 30°–50° N), Southern Europe and the Mediterranean (10° W–40° E and 30°–48° N). The circles mark the 15 GCMs of the CMIP5 experiment (red for RCP8.5, orange for RCP4.5) and the brown squares mark the 14 GCMs from the CMIP3 experiment (for A1B scenario). Changes are shown for the period 2081–2100 relative to 1986–2005 for the CMIP5 models and relative to 1981–2000 for the CMIP3 models. 2 m temperatures and relative humidity are shown for CMIP5, whereas for CMIP3 the values are shown at the 925 hPa level owing to a lack of daily model output at surface levels.

Fischer, E. M., and Knutti, R. Robust projections of combined humidity and temperature extremes. *Nat. Clim. Change*, doi:10.1038/nclimate1682 (2012).

# Summer Heat Index Under Climate Change

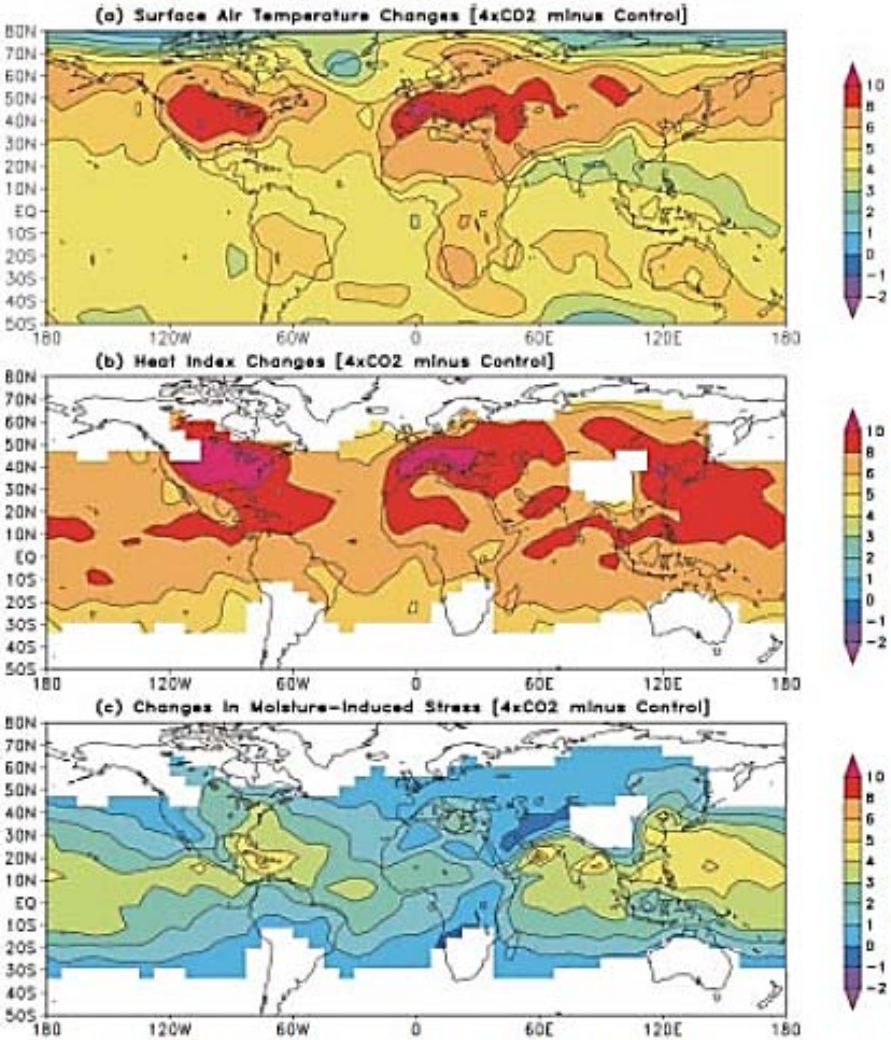



*Figure 7.* Same as Figure 6 except using differences between experiment 4 × $CO_2$ (years 141–170) and the Control. Note the change in the color shading levels versus Figure 6.

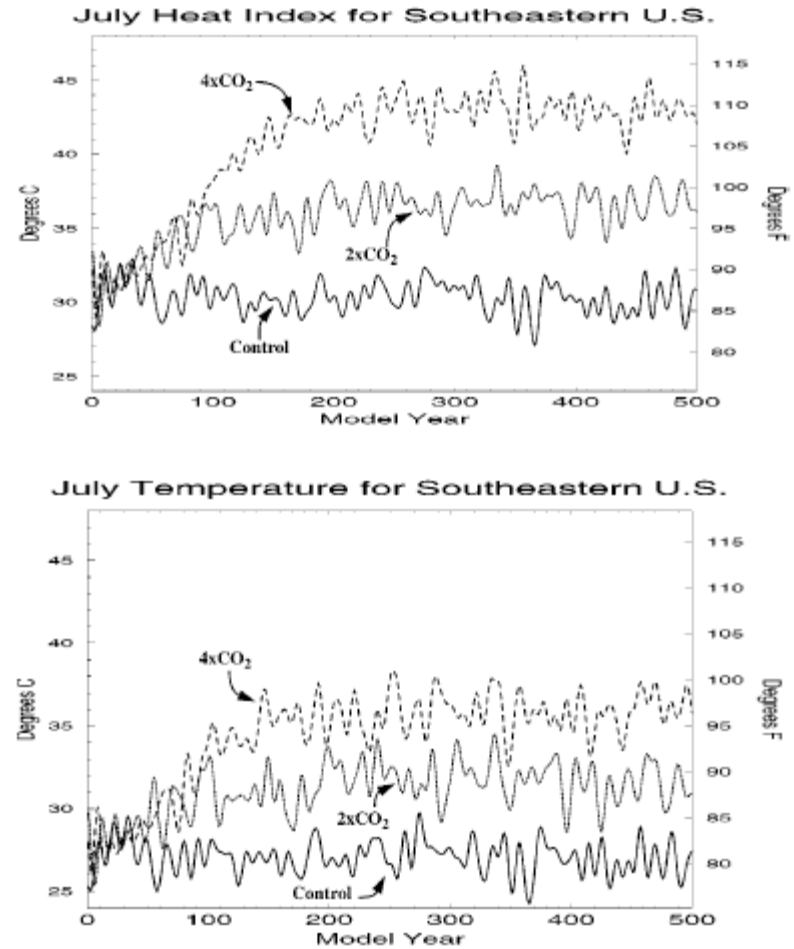



*Figure 8.* (a) Time series of surface temperature averaged over the southeastern United States for the three experiments. Only values from July are plotted. Prior to plotting, a 10 year low pass filter was applied to the time series. (b) Same as (a) for Heat Index. In the 4 × $CO_2$ experiment the combination of temperature and humidity is occasionally so large that Heat Index values are not defined (see text for discussion). In such cases, the spatial mean is computed using only those spatial locations with defined Heat Index values.

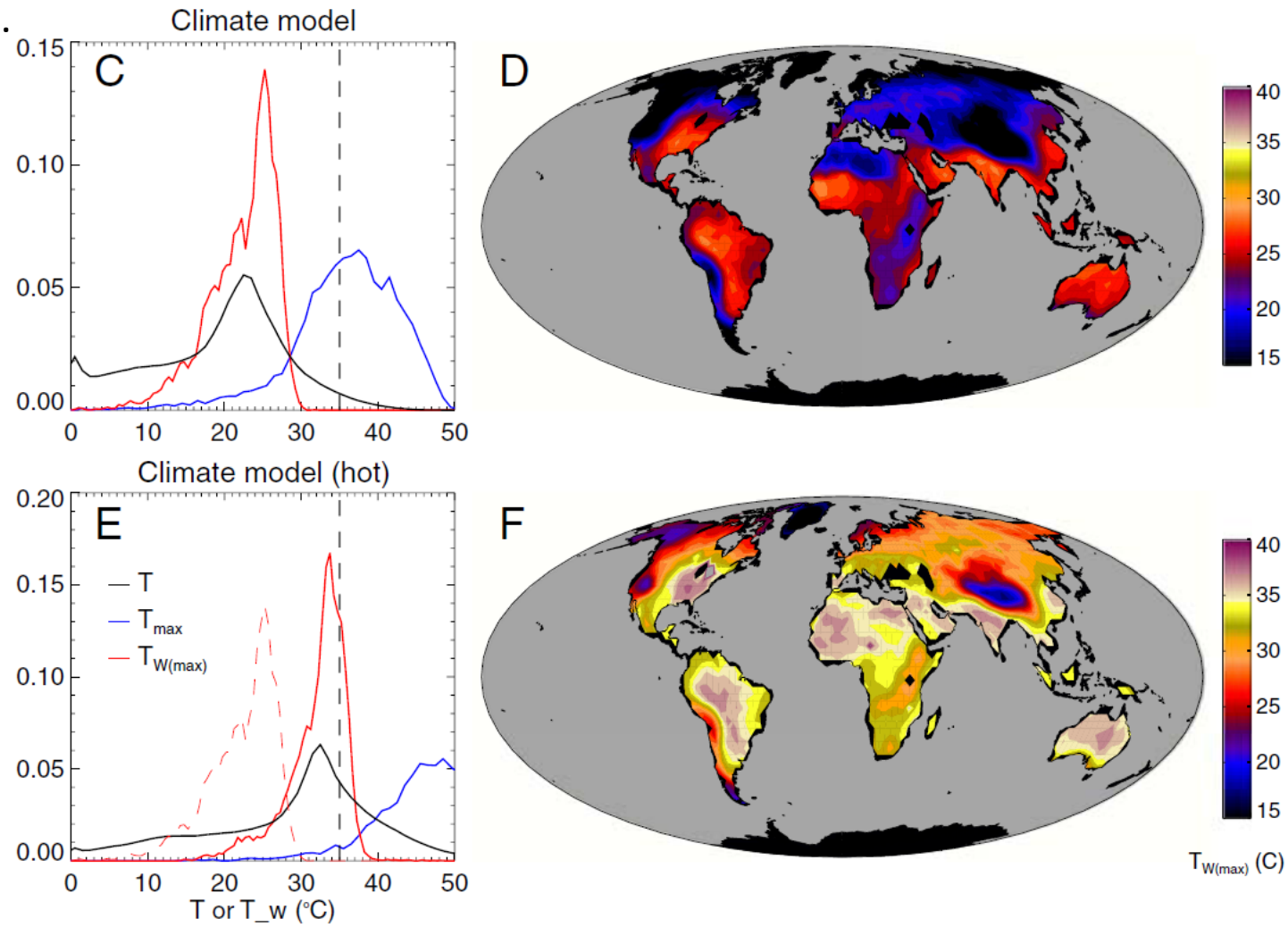
Delworth, T. L., Mahlman, J. D. and Knutson, T. R. Changes in heat index associated with $CO_2$-induced global warming. *Climatic Change*, **43**, 369-386 (1999).

# Recent WBGT, Physiology, and Climate Studies

- Diffenbaugh, N. S., Pal, J. S. Giorgi, F. and Gao, X. Heat stress intensification in the Mediterranean climate change hotspot, *Geophys. Res. Lett.*, **34**, L11706, doi:10.1029/2007GL030000 (2007).
  - **Regional analysis of changing extremes**
- Kjellstrom, T. Climate change, direct heat exposure, health and well-being in low and middle-income countries. *Global Health Action*, **2**, (2009).
  - **Advocates for adaptation of the WBGT metric**
- Kjellstrom, T., Holmer, I. and Lemke, B. Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, **2**, (2009).
  - **Lists WBGT thresholds and the projected warming trajectories for various cities**
- Jendritzky, G. and Tinz, B. The thermal environment of the human being on the global scale. *Global Health Action*, **2** (2009).
  - **Develops physiological hot and cold discomfort thresholds and exceedance frequency**
- Dash, S. K. and T. Kjellstrom Workplace heat stress in the context of rising temperature in India. *Current Science*, **101**, 496-503 (2011).
  - **Regional analysis applying thresholds**
- Willett, K. M., and Sherwood, S. C. Exceedance of heat index thresholds for 15 regions under a warming climate using the wet-bulb globe temperature, *Int. J. Climatol.*, **32**, 161-177, (2012).
  - **Regional analysis applying thresholds and exceedance frequencies**
- **…and many others…**

# The Mortality Limit: 12°C Warming Gives $T_W$ > 37°C

**Based on $T_W$=35°C as a 'Critical Thermal Maximum'** (Bynum et al. Induced hyperthermia in sedated humans and the concept of critical thermal maximum. *Am J. Physiol.*, **235**, R228-R236, 1978).




Sherwood, S.C. and Huber, M. An adaptability limit to climate change due to heat stress. *Proc. Nat. Acad. Sci.*, **107**, 9552-9555 (2010).

# Human Physiological Limits Cast Climate Change in a Fundamentally Different Impact Scope

- Not a relative linear departure from current adaptation as a measure of risk
- Casts warming as an approach to a fixed physiological limit
- However:
  - With present day $T_W$ always ≤ 30°C, does not resemble present day environments
  - Ignores human ability to survive hyperthermia
- Here, we make use of commonplace applications rather than an ultimate mortality limit…

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- Conclusions

# Wet Bulb and Globe Temperature Measurement

- A Sling Psychrometer measures both Wet and Dry Bulb Temperature

http://en.wikipedia.org/wiki/File:Sling_psychrometer.JPG

http://upload.wikimedia.org/wikipedia/commons/0/03/US_Navy_100524-N-5328N-671_Cryptologic_Technician_(Technical)_Seaman_Antron_Johnson-Gray_checks_the_wet_bulb_globe_temperature_meter.jpg

- Globe temperature measures the radiative component
- We approximate $T_W$ with a function of $T_{ref}$, $rh_{ref}$, and $P_s$

# Wet Bulb Globe Temperature Metrics

- Original US Navy "Corrected Effective Temperature" (Vernon and Warner, 1932):
  $WBGT = 0.7 \cdot T_W + 0.1 \cdot T_A + 0.2 \cdot T_G$
- Modern definition: $WBGT = 0.7 \cdot T_W + 0.2 \cdot T_A + 0.1 \cdot T_G$
- 'Indoor, shade, night' approximation ($T_G \approx T_A$): $\mathbf{WBGT = 0.7 \cdot T_W + 0.3 \cdot T_A}$
- Many variants for different metabolic states (labor, resting, sleeping), including:

| Index | Formula |
|---|---|
| Oxford index (WD)[34] | $0.85T_w+0.15T_a$ |
| Discomfort index (DI)[36] | $0.4T_w+0.4T_a+8.3$ |
| Discomfort index (DI)[39] | $0.5T_w+0.5T_a$ |
| Fighter index of thermal stress (FITS)[71] | $0.83T_w+0.35T_a+5.08$ |
| Modified discomfort index (MDI)[77] | $0.75T_w+0.3T_a$ |
| Wet-bulb dry temperature (WBDT)[79] | $0.4T_w+0.6T_a$ |

Epstein, Y. and Moran, D. S. Thermal comfort and the heat stress indices. *Industrial Health*, **44**, 388-398 (2006).

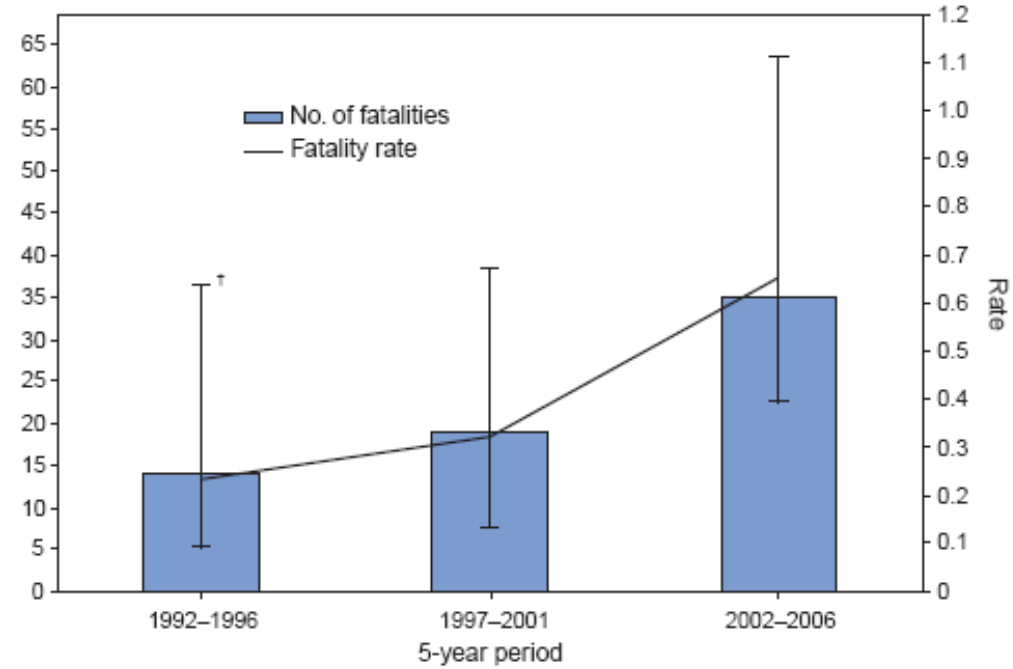
# Notes on Monthly 'Indoor, Shade, Night' WBGT

- Focuses at the granularity climate models are most robust
- Among the various heat stress indicators, gives an indication of the climate-scale heat stress.
- High level of physiological understanding and calibration
- Diurnal or weather-scale heat stress should be treated separately (not included in present work)
  - Internal variability within the month adds about 2°C.
  - Daytime radiation can add 4°C
  - Wind can reduce heat stress
- Assumes Physiological Acclimation and Social Adaptation:
  - Avoid direct sunlight
  - Optimize clothing and structures to mute the diurnal signal
  - Avoid activity during weather-scale heat waves

# Heat Stress Concerns in Occupational Health

- All history includes heat-related illness and death in physically intensive and confined occupations, e.g.
  - Agriculture
  - Landscaping
  - Mining
  - Construction
  - Iron/Steel/Smelting
  - Brick/Ceramic firing
  - Kitchens/bakeries
  - Laundries
  - Electrical
  - Boilers/Steam Tunnels
  - Marine mechanics

**FIGURE. Number and rate* of heat-related deaths among crop workers, by 5-year period — United States, 1992–2006**




* Per 100,000 workers. Rates calculated using annual national average estimates of employed civilians aged ≥15 years based on the Current Population Survey.

† 95% confidence interval for fatality rate.

U. S. Department of Health and Human Services
http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5724a1.htm

# Occupational Definition of Labor

- Marathon running: ~1000 kcal/hr
- Jogging 5 MPH: ~550 kcal/hr

- **Heavy Work Load: 350-500 kcal/hr**
  - Speed walking 4 MPH: ~350 kcal/hr
- **Moderate Work Load: 200-350 kcal/hr**
  - Walking 2.6 MPH: ~200 kcal/hr
- **Light Work Load: <200 kcal/hr**
  - Desk work: 140 kcal/hr
  - Resting: ~70kcal/hr

… assuming a 70 kg human

# Occupational Safety and Health Guidelines

**Table 6. WBGT Threshold limit values (°C)**

| Work-rest regimen | Work load | | |
|---|---|---|---|
| | Light | Moderate | Heavy |
| Continuous work | 30.0 | 26.7 | 25.0 |
| 75% work+25% rest; each hour | 30.6 | 28.0 | 25.9 |
| 50% work+50% rest; each hour | 31.4 | 29.4 | 27.9 |
| 25% work+75% rest; each hour | 32.2 | 31.1 | 30.0 |

From ACGIH (1996)

Parsons, K. Heat stress standard ISO 7243 and its global application. *Industrial Health*, **44**, 368-379 (2006).

American Conference of Governmental Industrial Hygienists (AGCIH) *Threshold Limit Values for chemical substances and physical agents. Biological Exposure Indices*. American Conference of Governmental Industrial Hygienists, Cincinnati, OH (1996).

# The U.S. Military has a lot of experience with this…

the Bahrain DESERT TIMES

Volume 8, Number 186 | Naval Support Activity Bahrain | June 29, 2011

# Heat stress

By HM1 Timeca Combs
*Naval Branch Health Clinic Bahrain*

**MANAMA, Bahrain —** Heat stress is something that can affect anyone. People suffer heat-related illnesses when their bodies are unable to compensate and properly cool themselves. The body normally cools itself by sweating, but under some conditions, sweating just isn't enough. In such cases, a person's body temperature rises rapidly. Very high body temperatures may damage the brain and other vital organs.

There are things that can increase your risk of heat injury: age, obesity, fever, dehydration, heart disease, mental illness, poor circulation, sunburn, prescription drug and alcohol use. To protect your health when temperatures are extremely high, remember to keep cool and use common sense.

*Drink plenty of water.* You will need to increase your fluid intake, regardless of your activity level.

*Don't wait until you're thirsty to drink.* During heavy exercise in a hot environment, drink two to four glasses (16-32 ounces) of cool fluids each hour. When you are sweating excessively, a sports beverage can replace the salt and minerals you lose in sweat. Do not take salt tablets unless under medical supervision. Doing too much on a hot day, spending too much time in the sun or staying too long in an overheated place can cause heat-related illnesses.

The 'Hot Season' has arrived in Bahrain. Persons exposed to hot environments risk heat related injuries if precautions are not taken. These injuries range from Heat Strain to Heat Stroke.

The Naval Branch Health Clinic maintains an Automated Heat Stress Monitoring System to measure the Wet Bulb Globe Temperature Index (WBGTI). The automated system updates every hour.

Flag conditions are displayed throughout the base as a means for command and individuals to adjust activities outdoors.

*White Flag:* is when the WBGTI is 80. During this condition extremely intense physical exertion may precipitate heat exhaustion or heat stroke caution must be taken.

*Green Flag:* is when the WBGTI is between 80 and 84.9. Discretion is required in planning heavy exercise for unacclimatized personnel. This is a marginal heat stress limit for all personnel.

*HEAT STRESS Page 4*

# Military Flag System For Heat Stress Advisory

32.2°C

**Black- Physical training and strenuous exercise must be suspended for all personnel. (excludes operational commitment not for training purposes).**

31.1-32.1°C

**Red- Strenuous exercise must be curtailed for all personnel with less than 12 weeks training in hot weather.**

29.4-31.0°C

**Yellow- Strenuous exercise and activity must be curtailed for new and unacclimatized personnel during first 3 weeks of heat exposure. Outdoor classes in sun must be avoided when WBGT exceeds 29.4°C.**

26.7-29.3°C

**Green- Discretion is required in planning heavy exercise for unacclimatized personnel. This is a marginal heat stress limit for all personnel.**

(numbers are Wet Bulb Globe Temperature Index- not temperature)

<26.7°C

**White - Extreme intense physical exertion may precipitate heat exhaustion or heat stroke, therefore, caution should be taken.**

Wearing body armor or NBC protective uniforms adds approximately 10 points to WBGT. Limits of exposure should be adjusted accordingly.

Ref: NAVMED P-5010/ NABLC INST 6110.3A

# Heat Stress in Endurance Athletics

- **National Athletic Trainers' Association 2002 Position Statement**
- **Applicable to endurance athletics (football, soccer, X-Country)**
- **Affirms American College of Sports Medicine 1996 Position Stand**
- **Note more conservative flag system than the military**

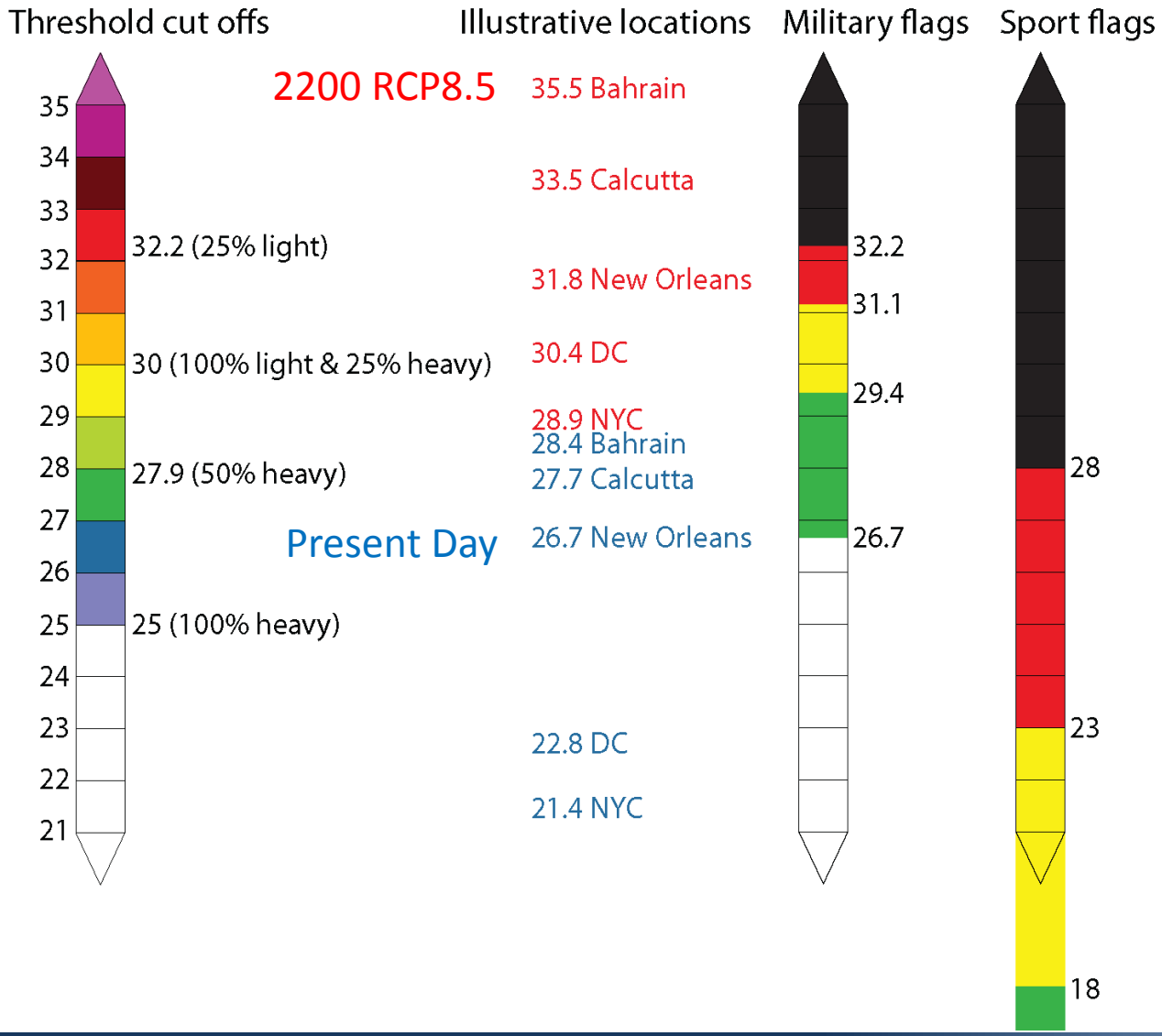
**Table 3. Wet-Bulb Globe Temperature Risk Chart[62–67]***

| WBGT | Flag Color | Level of Risk | Comments |
|---|---|---|---|
| <18°C (<65°F) | Green | Low | Risk low but still exists on the basis of risk factors |
| 18–23°C (65–73°F) | Yellow | Moderate | Risk level increases as event progresses through the day |
| 23–28°C (73–82°F) | Red | High | Everyone should be aware of injury potential; individuals at risk should not compete |
| >28°C (82°F) | Black | Extreme or hazardous | Consider rescheduling or delaying the event until safer conditions prevail; if the event must take place, be on high alert |

*Adapted with permission from Roberts.[67]

Binkley, H. M., Beckett, J., Casa, D. J., Kleiner, D. M., and Plummer, P. E. National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. *Journal of Athletic Training*, **37**, 329–343 (2002).
Armstrong, L. E., Epstein, Y., Greenleaf, J. E., et al. American College of Sports Medicine position stand: heat and cold illnesses during distance running. *Med. Sci. Sports Exerc.*, **28**, i–x (1996).

# WBGT Heat Stress Scales



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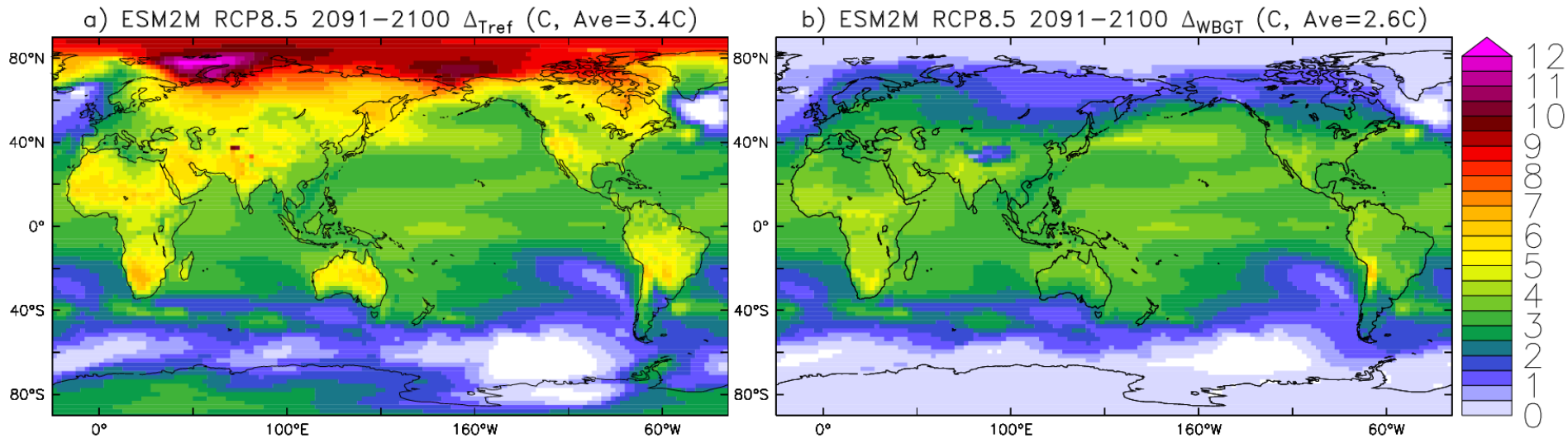
# $\Delta T_{Ref}$ vs. $\Delta$WBGT in ESM2M under RCP8.5

## $\Delta T_{Ref}$

## $\Delta$WBGT

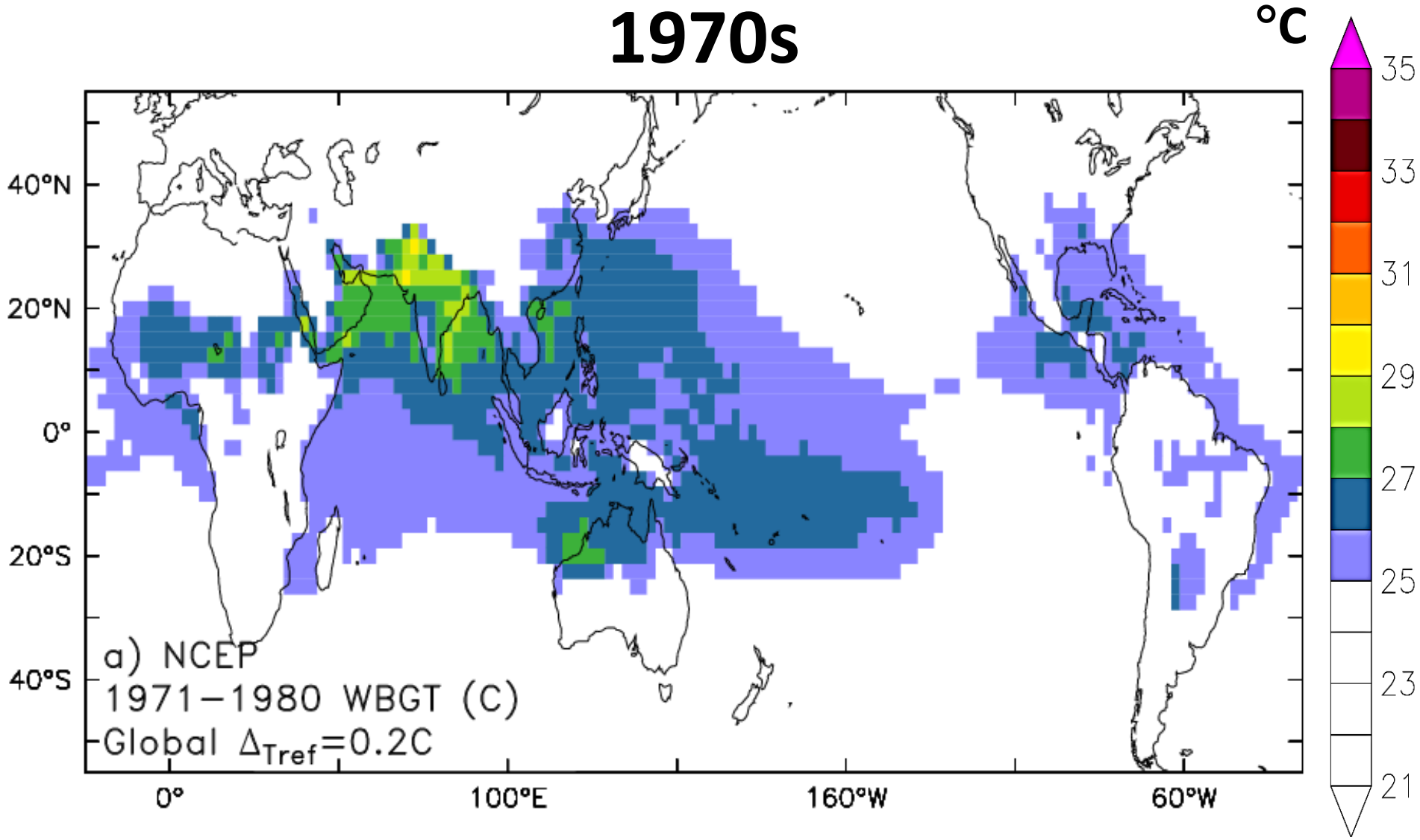



- $\Delta T_{Ref}$ has land and N polar amplification
- $\Delta$WBGT has smooth, tropical/mid-latitude amplification without strong land/sea contrast

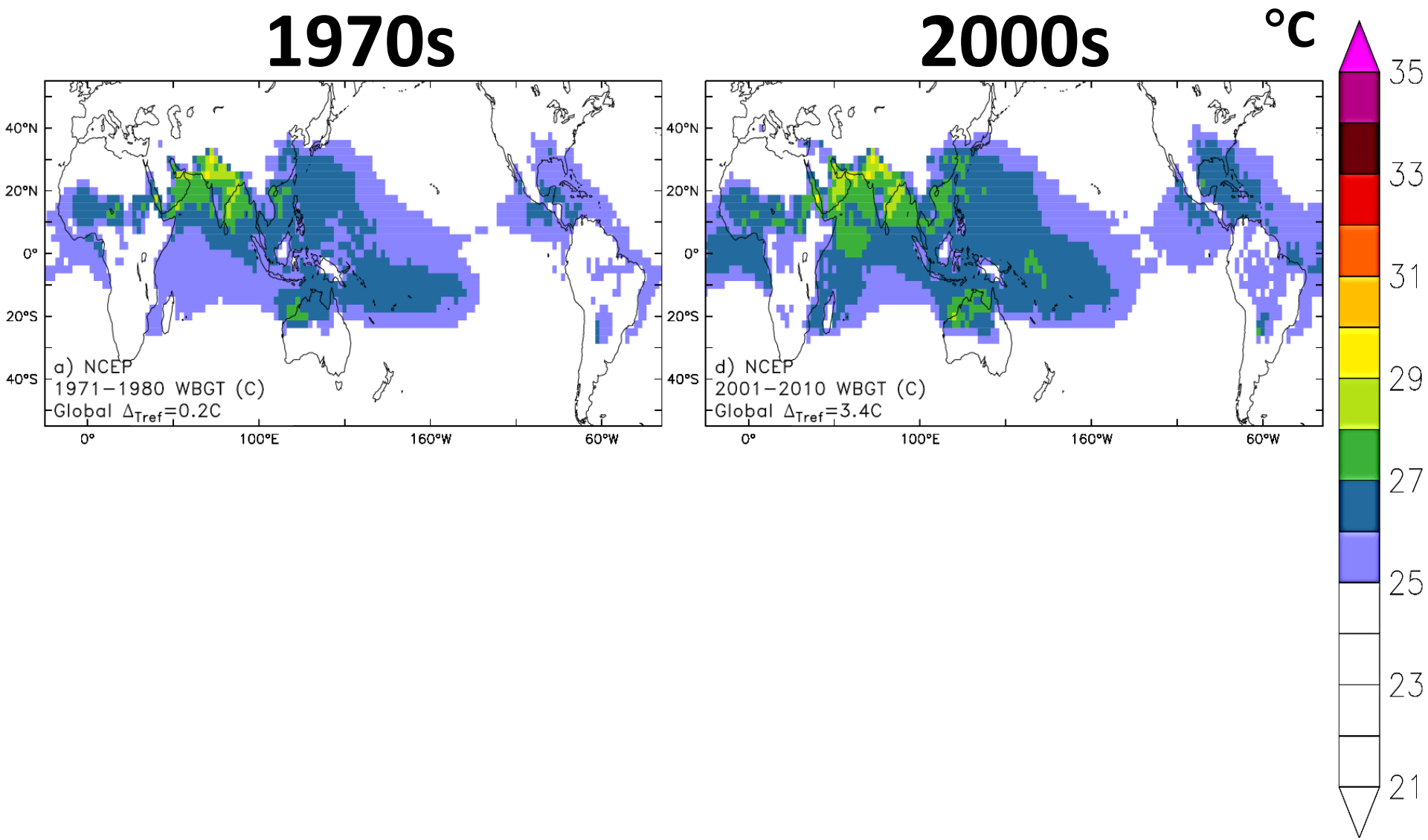
Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# Historical WBGT in NCEP Reanalysis

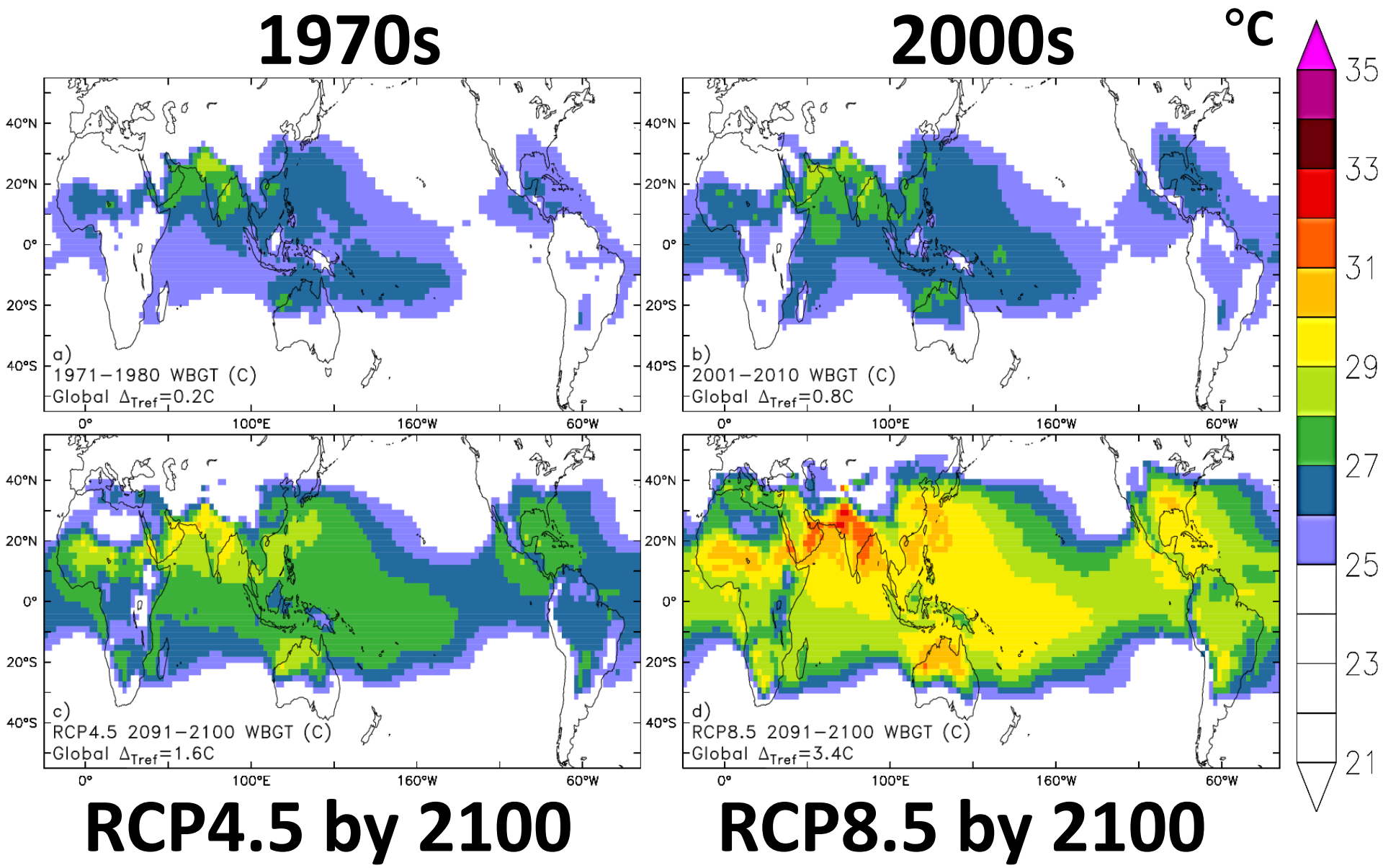
## 1970s



# NCEP Reanalysis Shows WBGT Increase

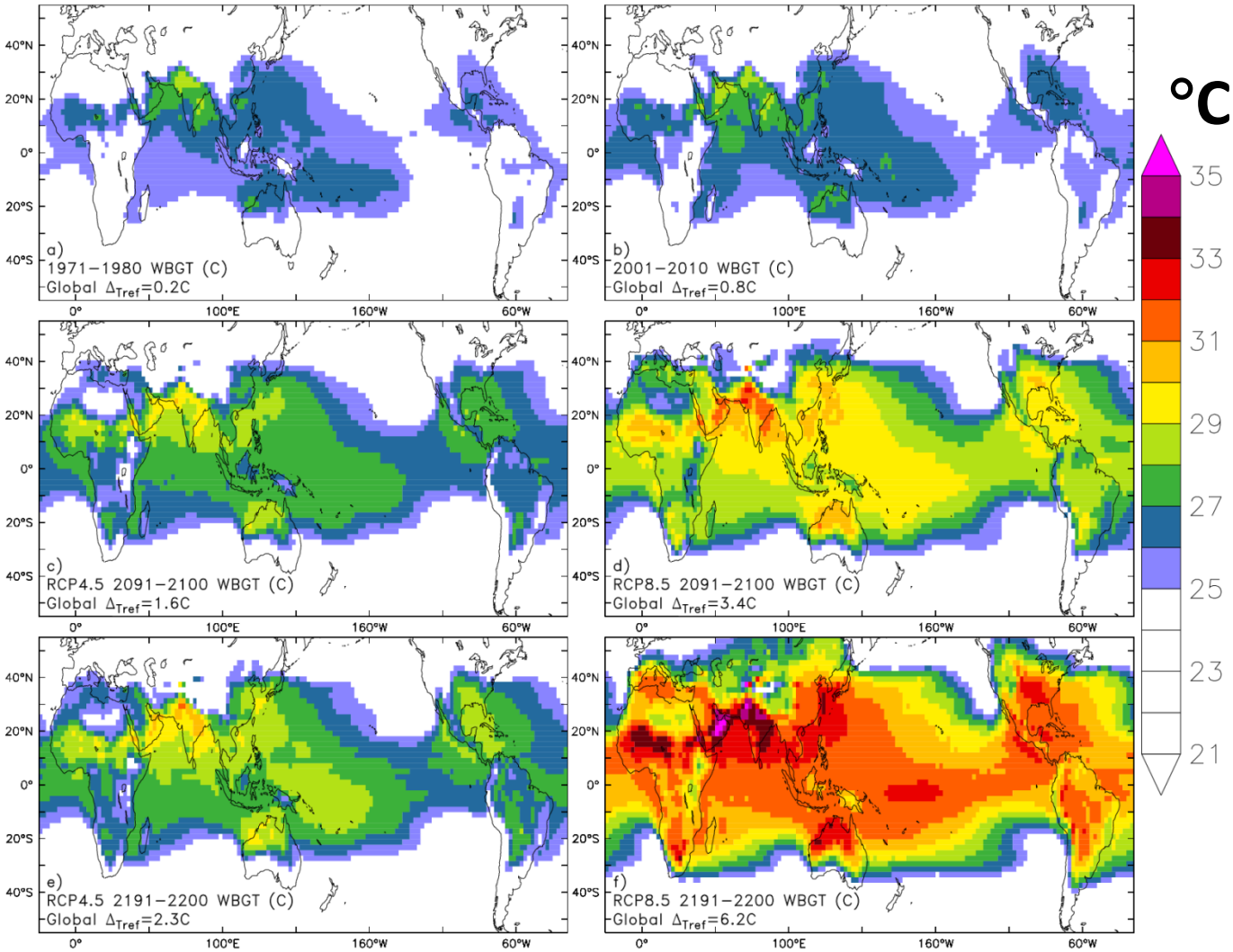


# Bias corr. ESM2M WBGT Hist/RCPs




**RCP4.5 by 2100** **RCP8.5 by 2100**

# Stark WBGT differences out to 2200



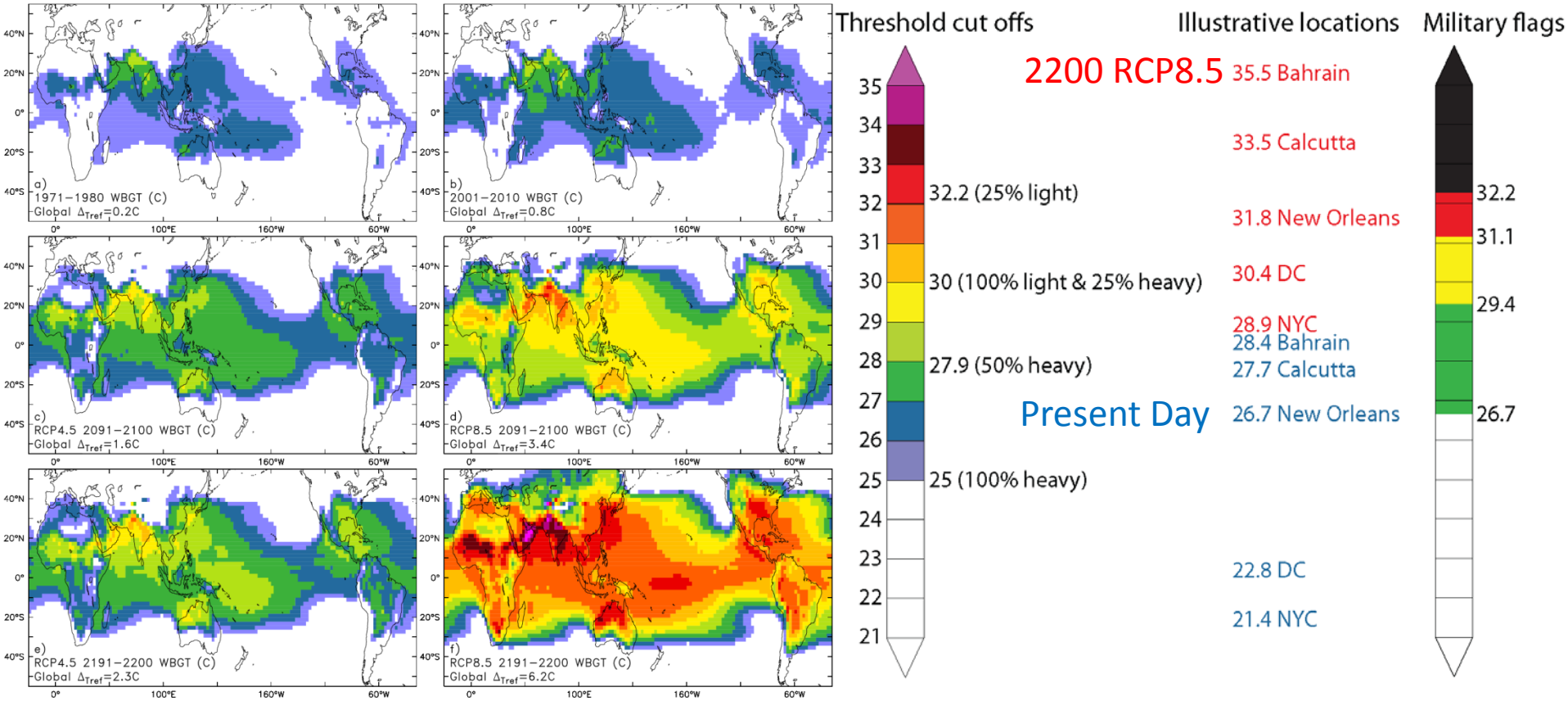

**Historical**

**2100**

**2200**

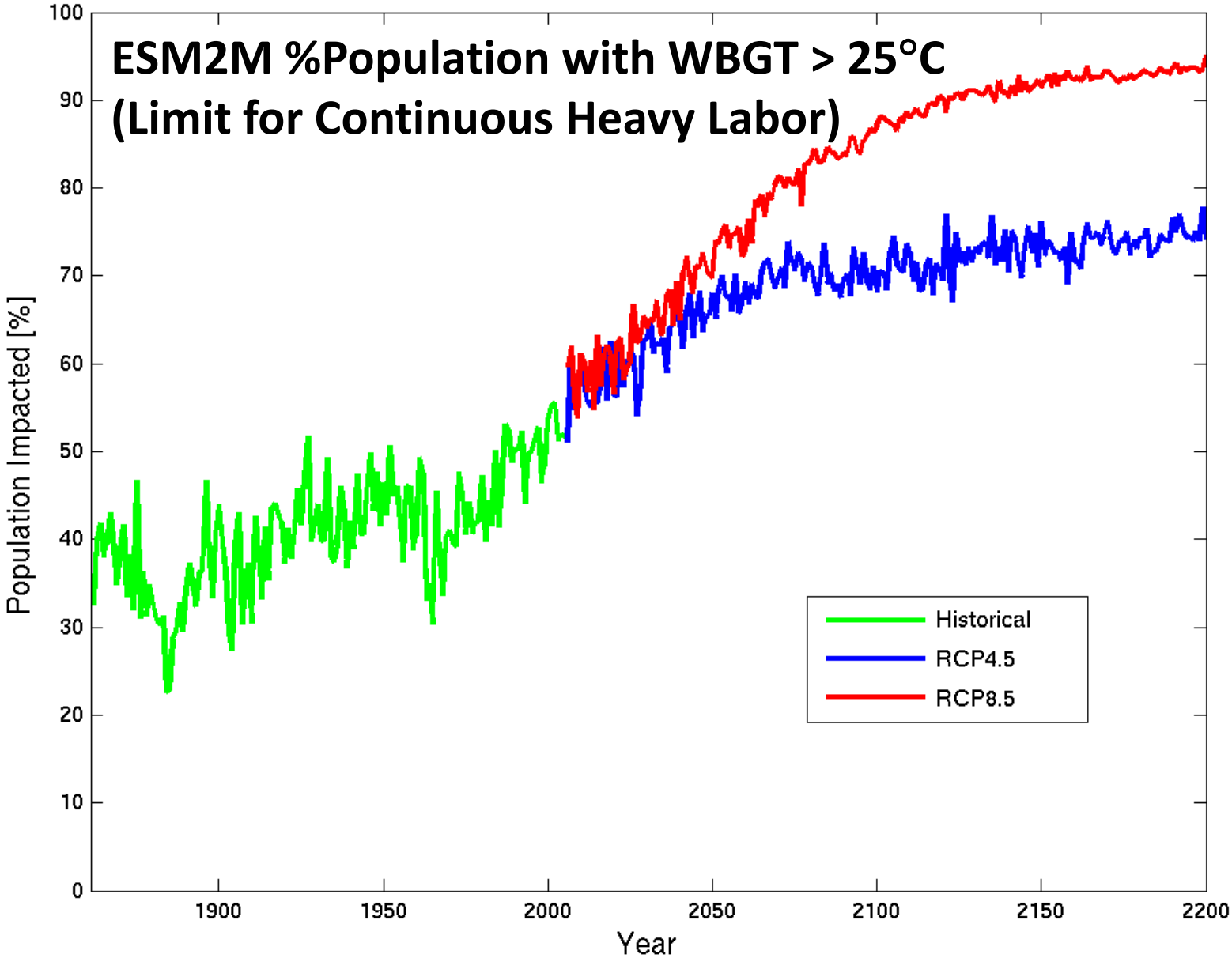
**RCP4.5** **RCP8.5**

# Severe Human Activity Restrictions

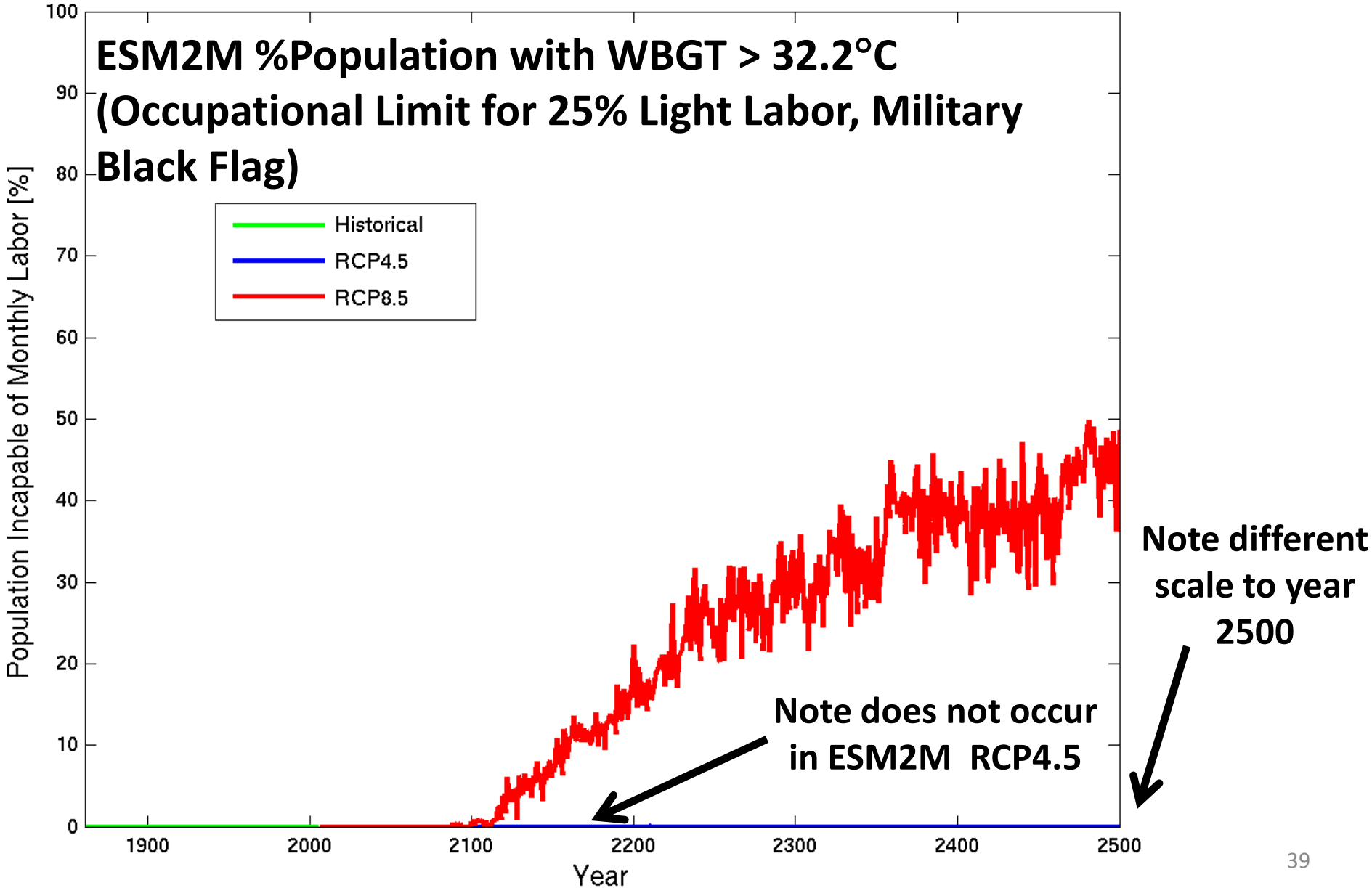



Dunne, J. P., Stouffer, R. J., and John, J. G. Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# Population with Labor Climatologically Limited Increases from 40-50% to 70-90% with Warming



# Strong warming (>3°C) Begins Widespread Climatological Incapacitation of Safe Labor



# Outline

- Background
  - Heat Stress Metrics
  - Heat Stress under Climate Change
  - Applicability of Heat Stress Metrics
- **ESM2M Response**
  - Wet Bulb Globe Temperature
  - **Labor Capacity**
- Exploration of Uncertainties
  - Model Biases
  - Population Change
  - Model Construction
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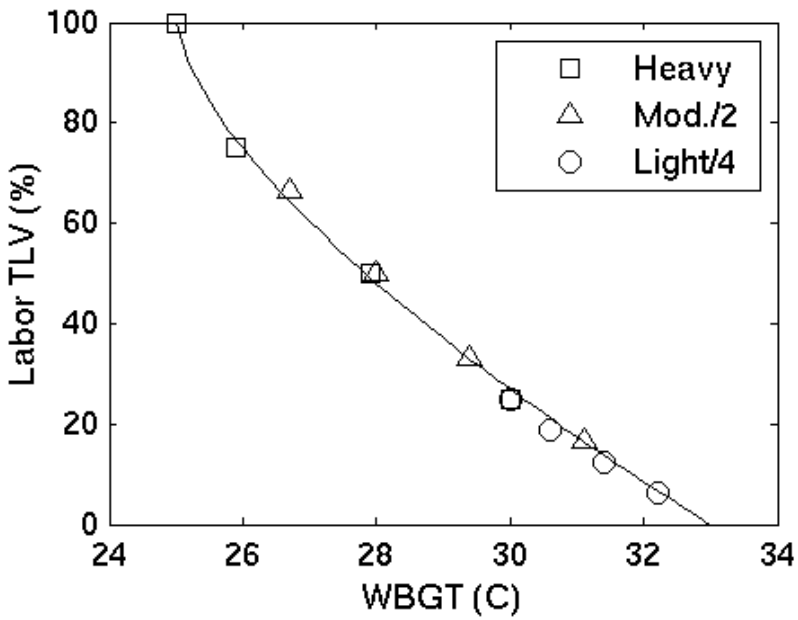
- Conclusions

# Heat Stress Reduction of Labor Capacity as a Continuum

We define *labor capacity* as a healthy, acclimated individual's occupational capacity to safely perform sustained labor under environmental heat stress.



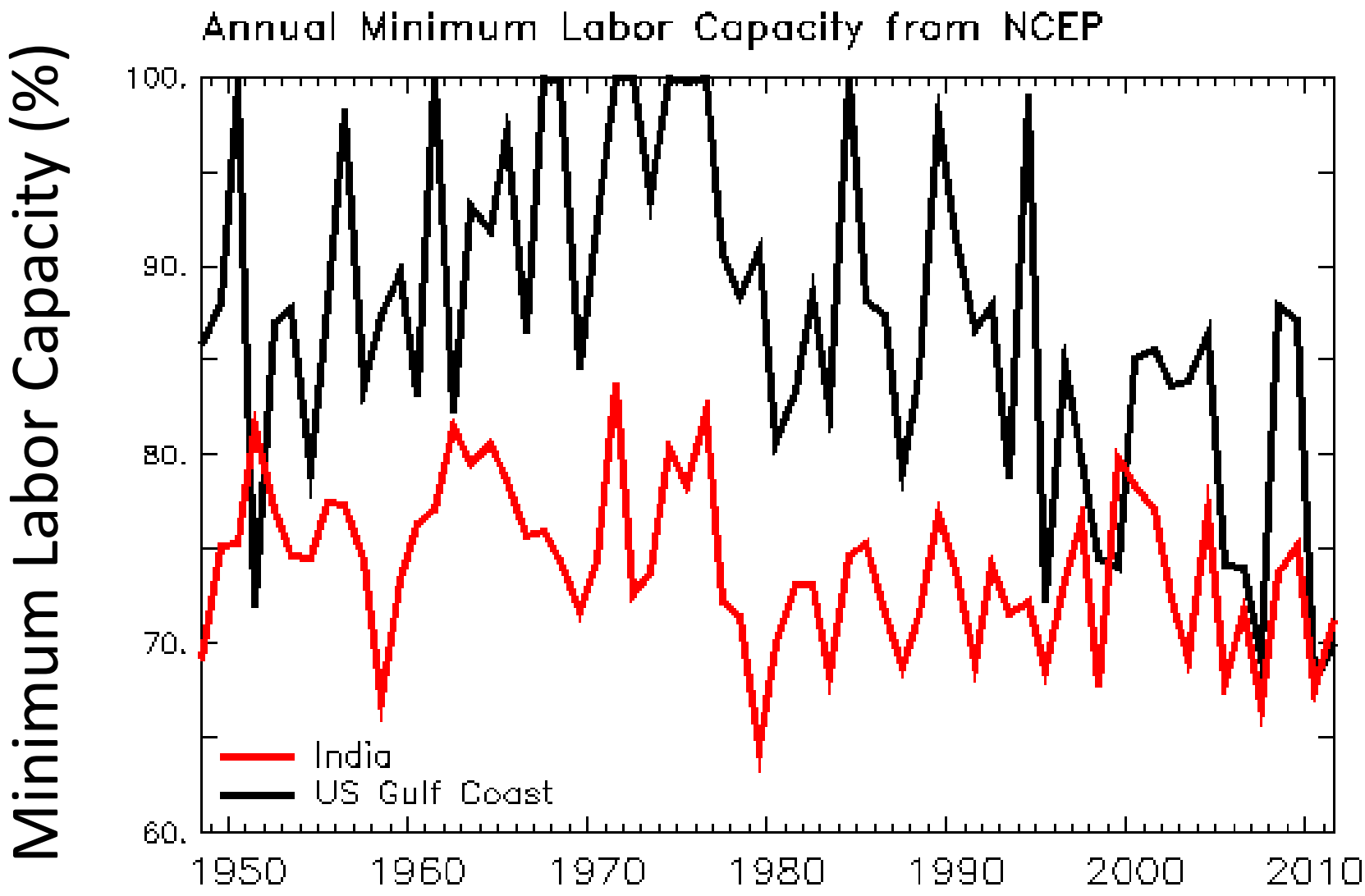

$$\textit{labor capacity} = 100 - 25 \cdot \max(0, \mathrm{WBGT} - 25)^{2/3}$$

Dunne, J. P., Stouffer, R. J., and John, J. G. Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

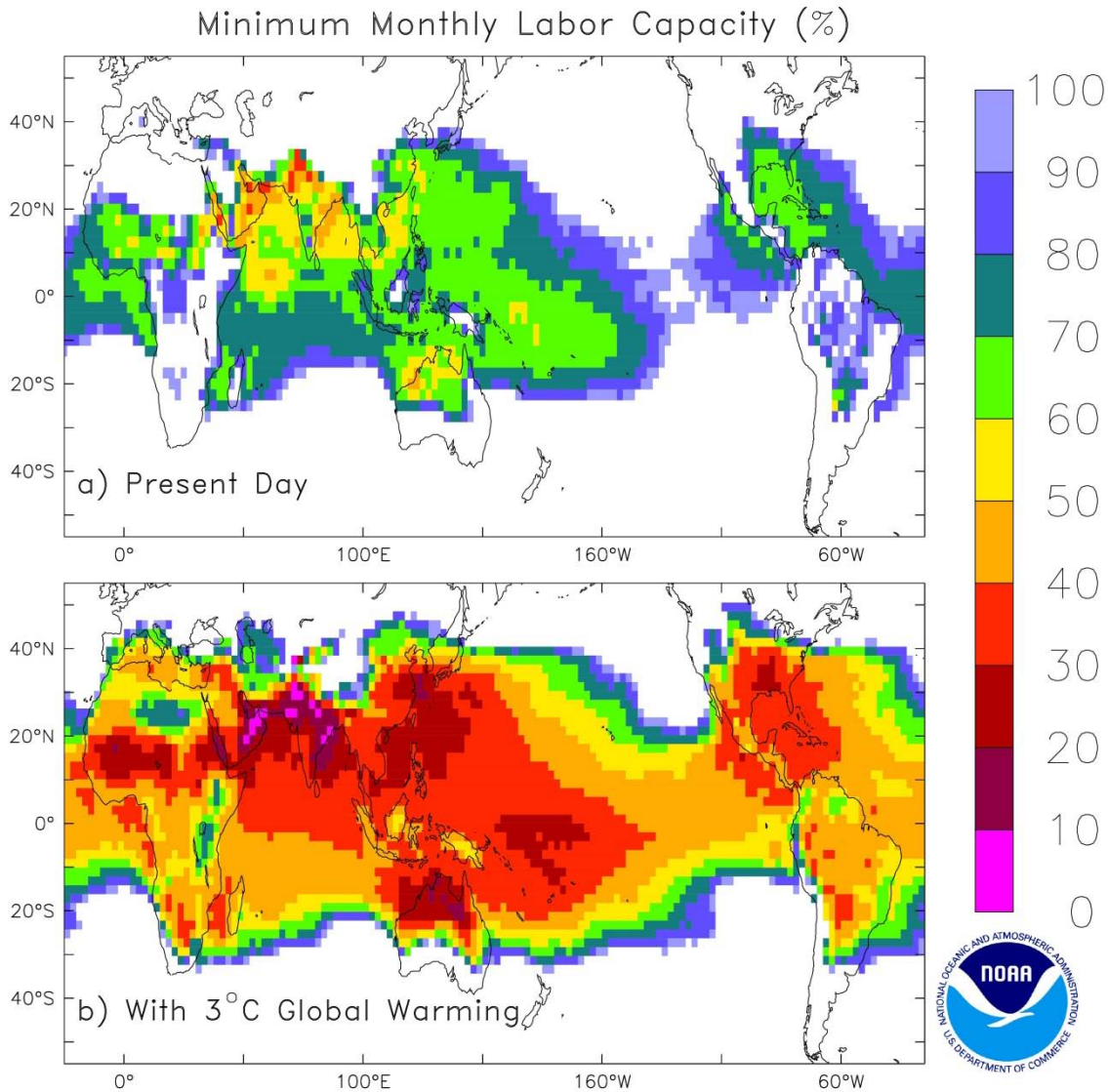
# Notes on Population-Normalized Labor Capacity

- 100% labor capacity signifies no heat stress limit to safe acclimated individual human labor.
- 0% labor capacity signifies a lack of safe ability for human labor.
- Assumes healthy, acclimated individuals with optimized clothing.
- Accounts for the heterogeneity of the population distribution
- Treats the Earth's population as a single human responding to heat stress.

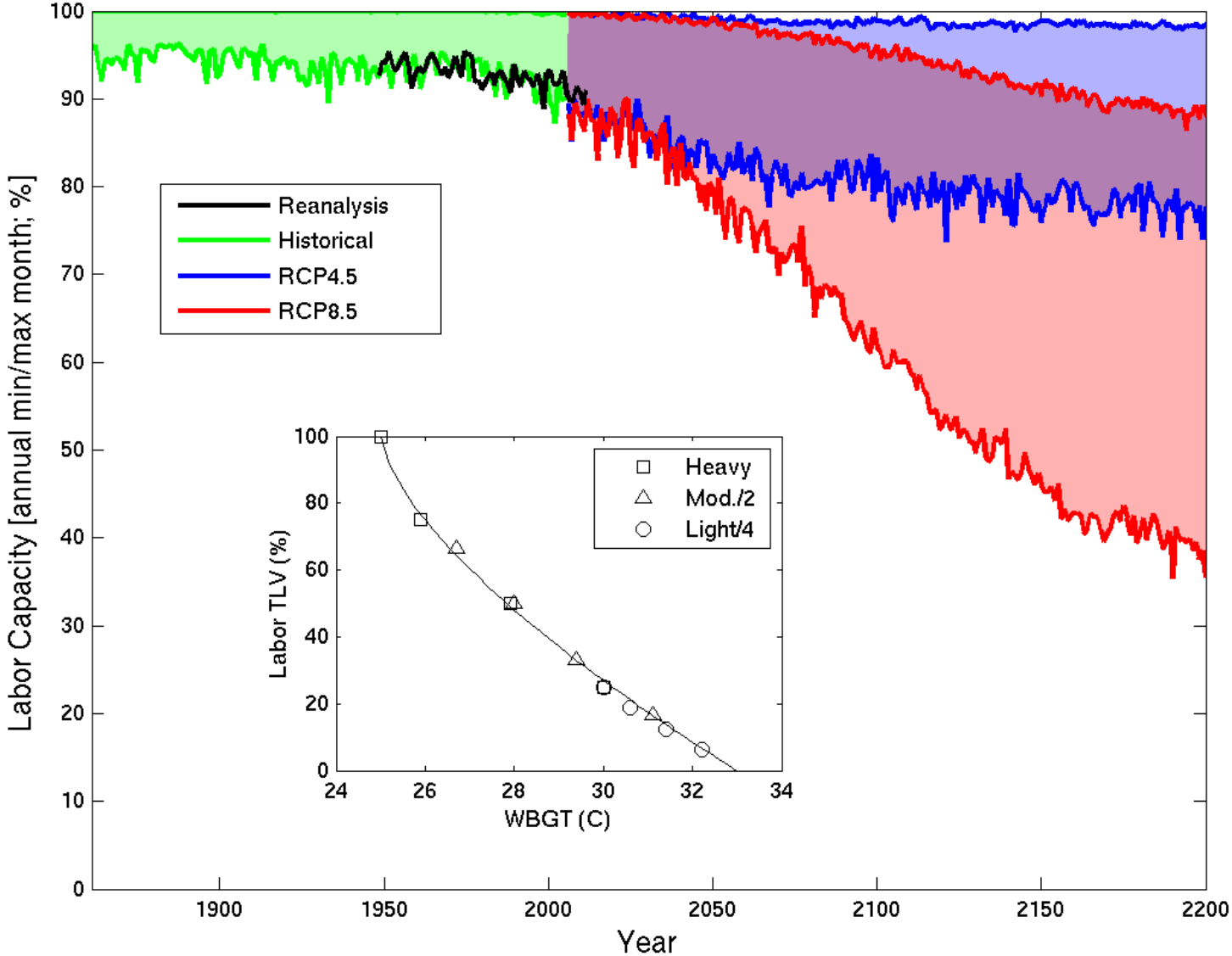
# Regional Examples of Historical Labor Capacity during Peak Heat-Stress Months



# Minimum Labor Capacity Reduction

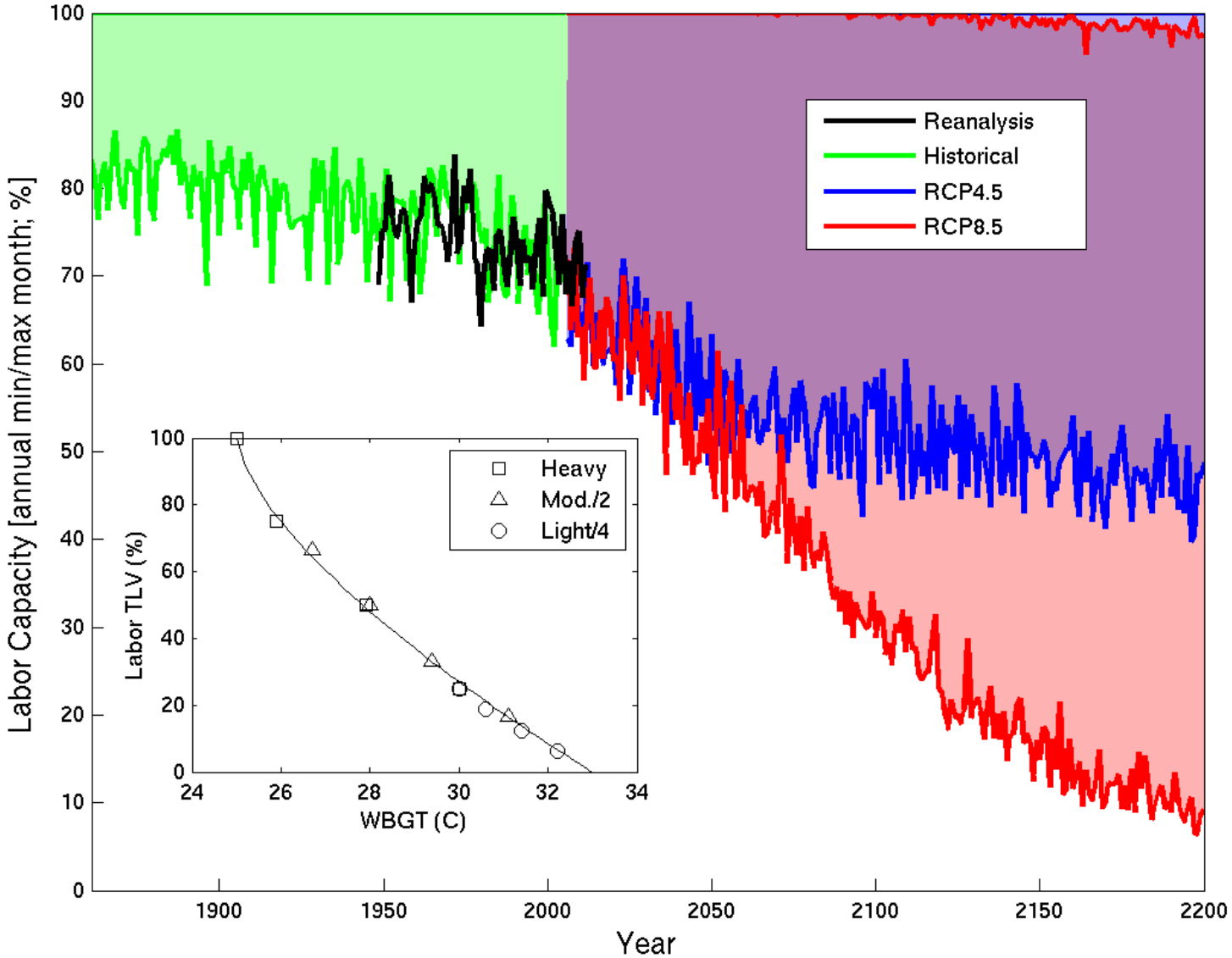


# Global Heat Stress Reduction of Labor Capacity
## (Annual minimum and maximum month)

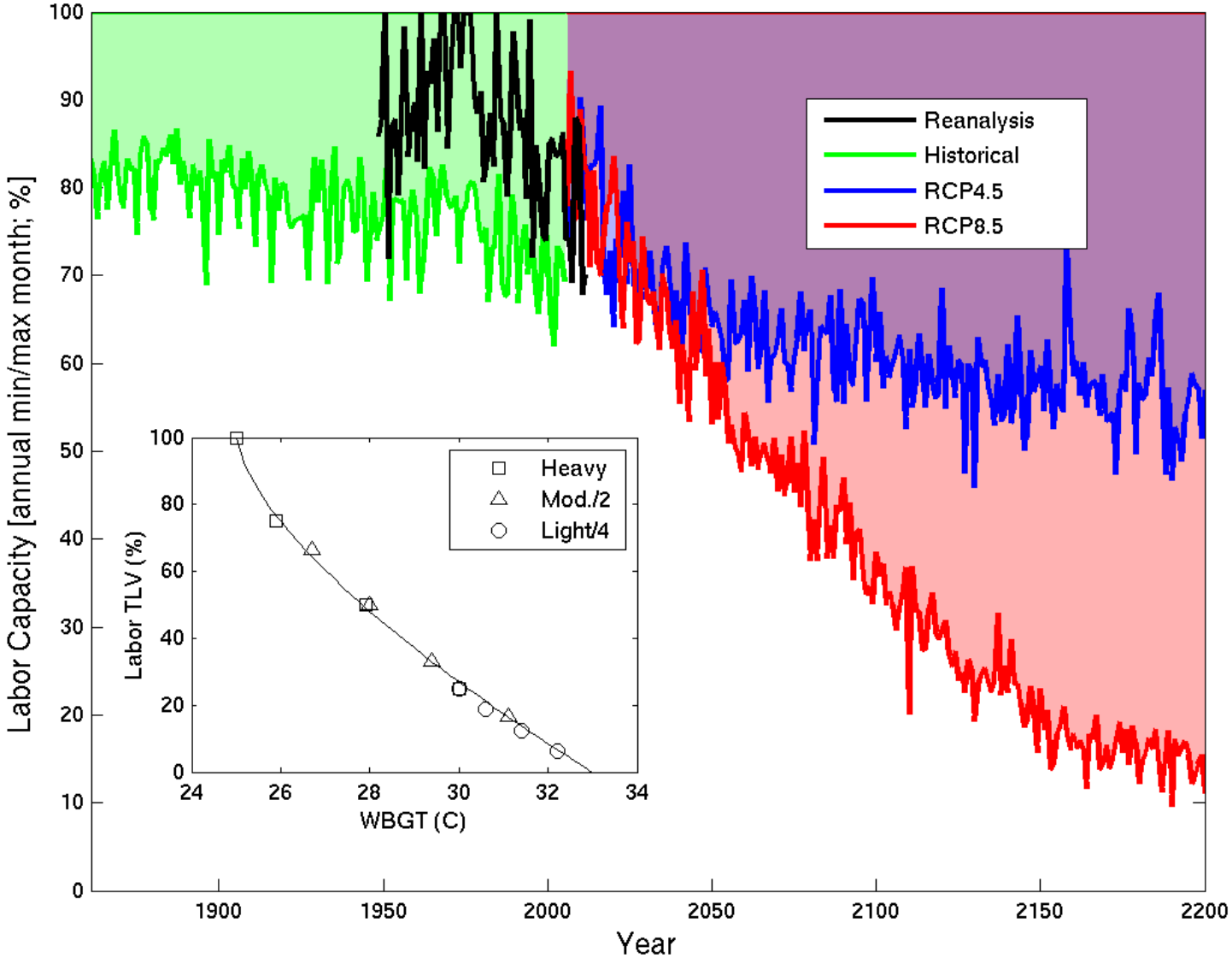



Dunne, J. P., Stouffer, R. J., and John, J. G. Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# Heat Stress Reduction of Labor Capacity: India only
## (Annual minimum and maximum month)



# Heat Stress Reduction of Labor Capacity: US Gulf Coast only
## (Annual minimum and maximum month)



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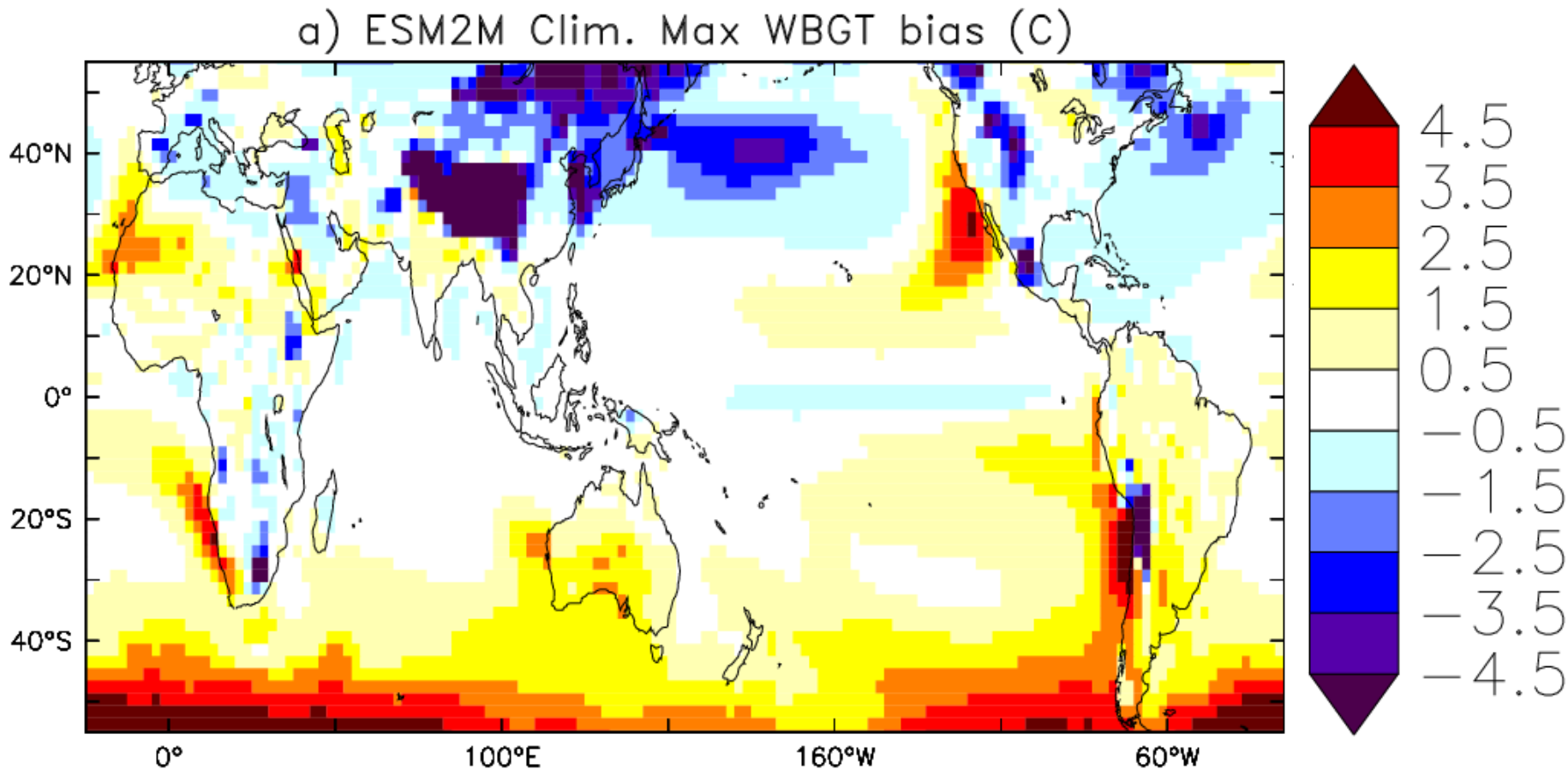
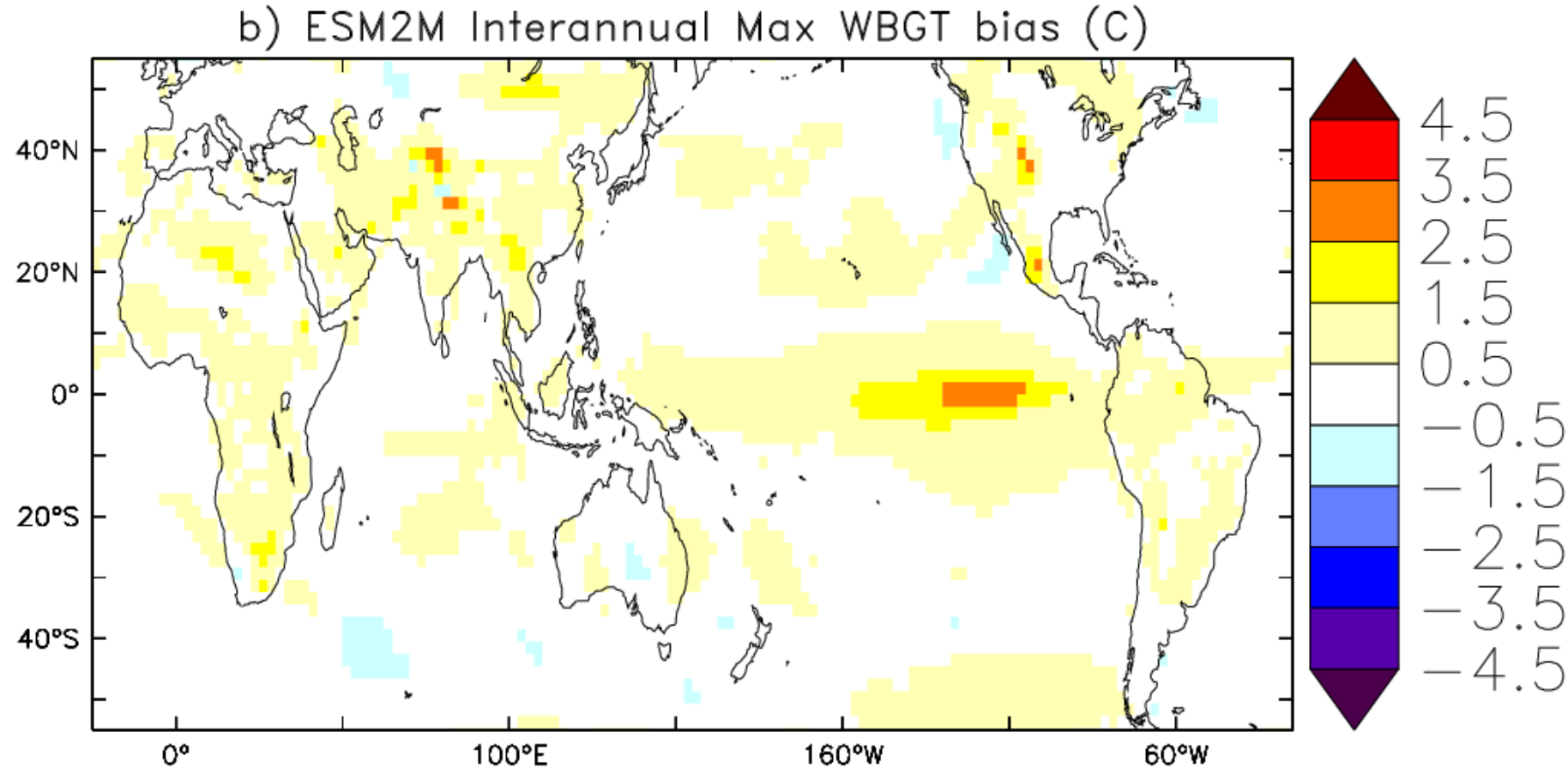
# ESM2M Climatological Maximum Biases




While considered among the best models in CMIP, gives warm Amazon, Australia, and Africa and cold Asia and America

Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# ESM2M Climatological Variability Biases




While considered among the best models in CMIP in terms of inter-annual variability, generally overestimates its strength

Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# ESM2M Clim. Max. and Var. correction

- First, we offset the model values to match the climatological monthly maximum from NCEP:

  Max_Mean_Corr = ESM2M + (NCEP_Clim_Max - ESM2M_Clim_Max)

- Then, we rescale the sub-decadal variability downward to agree with NCEP:

  Var_Corr = Max_Mean_Corr-(ESM2M_Ann_Max – ESM2M_Dec_Mean_Max) · (1 -NCEP_Dec_Max_Anom / ESM2M_Dec_Max_Anom)

- No variability correction if NCEP_Dec_Max_Anom > ESM2M_Dec_Max_Anom

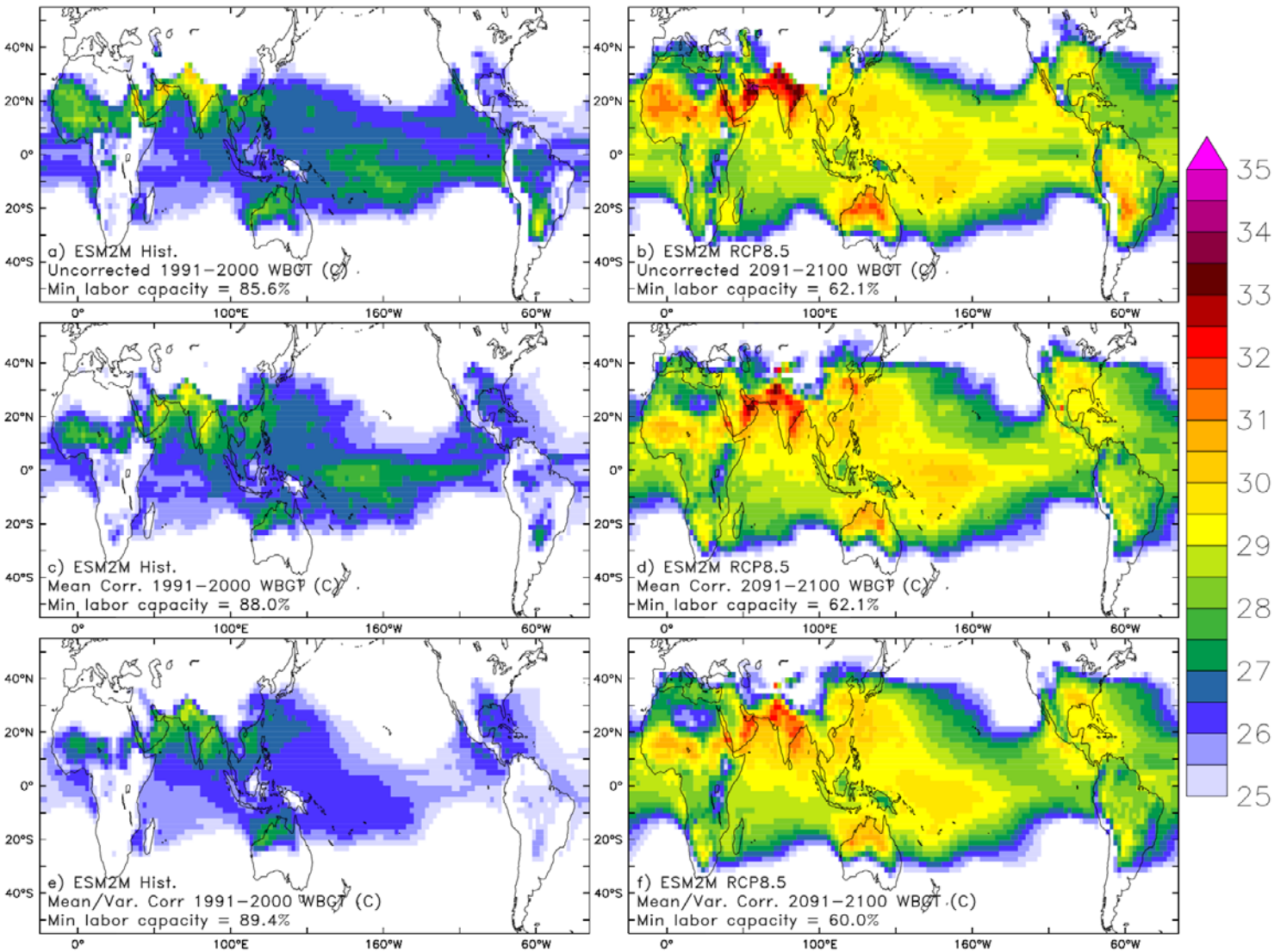
# ESM2M WBGT Clim. Max. and Var. correction

**Historical 1990s** | **RCP8.5 2090s**

**Uncorrected: Warm South /cold North**

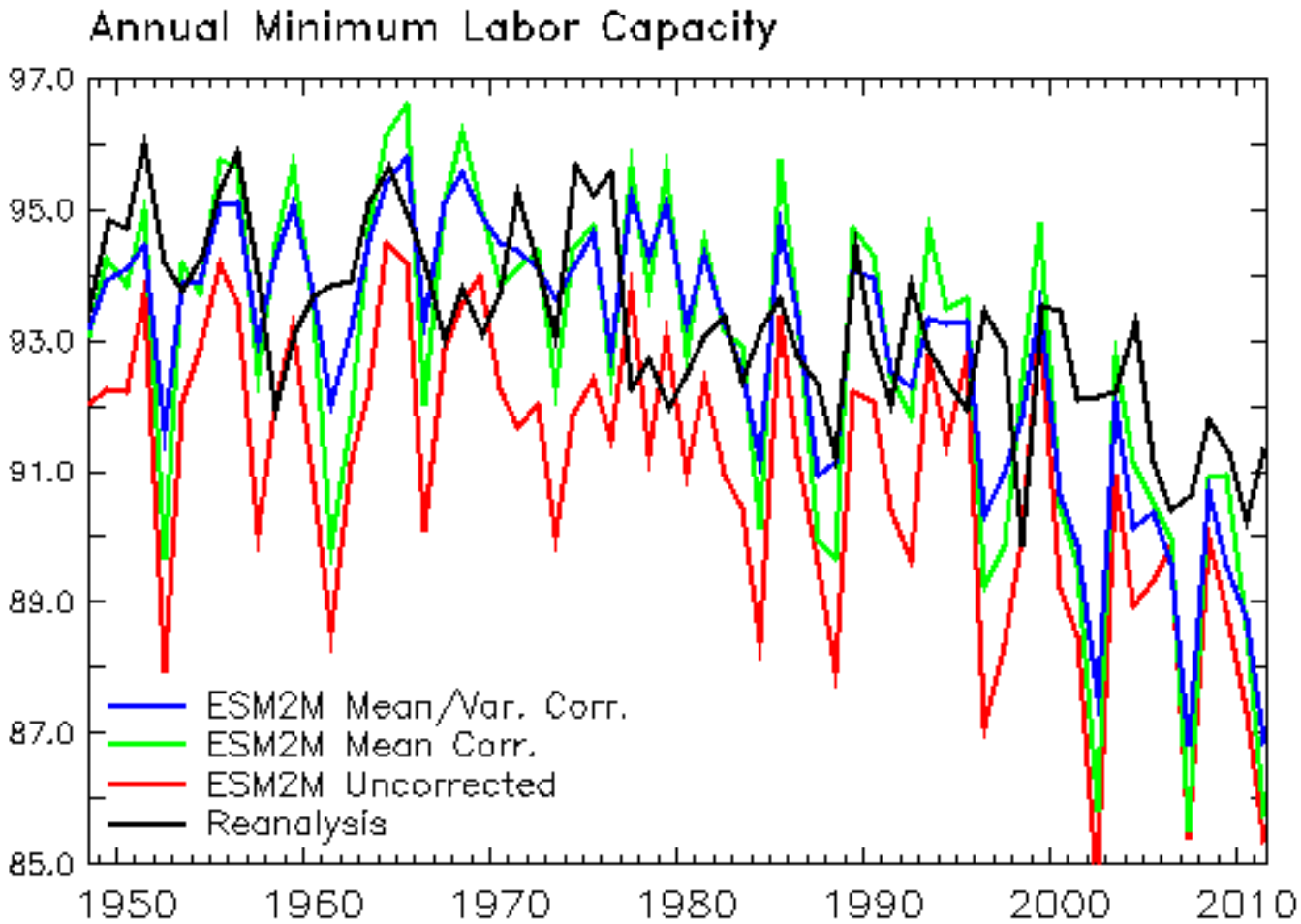
**Clim. Max. Corrected: Too much ENSO**

**Clim. Max. and Var. corrected**




Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# Small Global Labor Capacity Sensitivity

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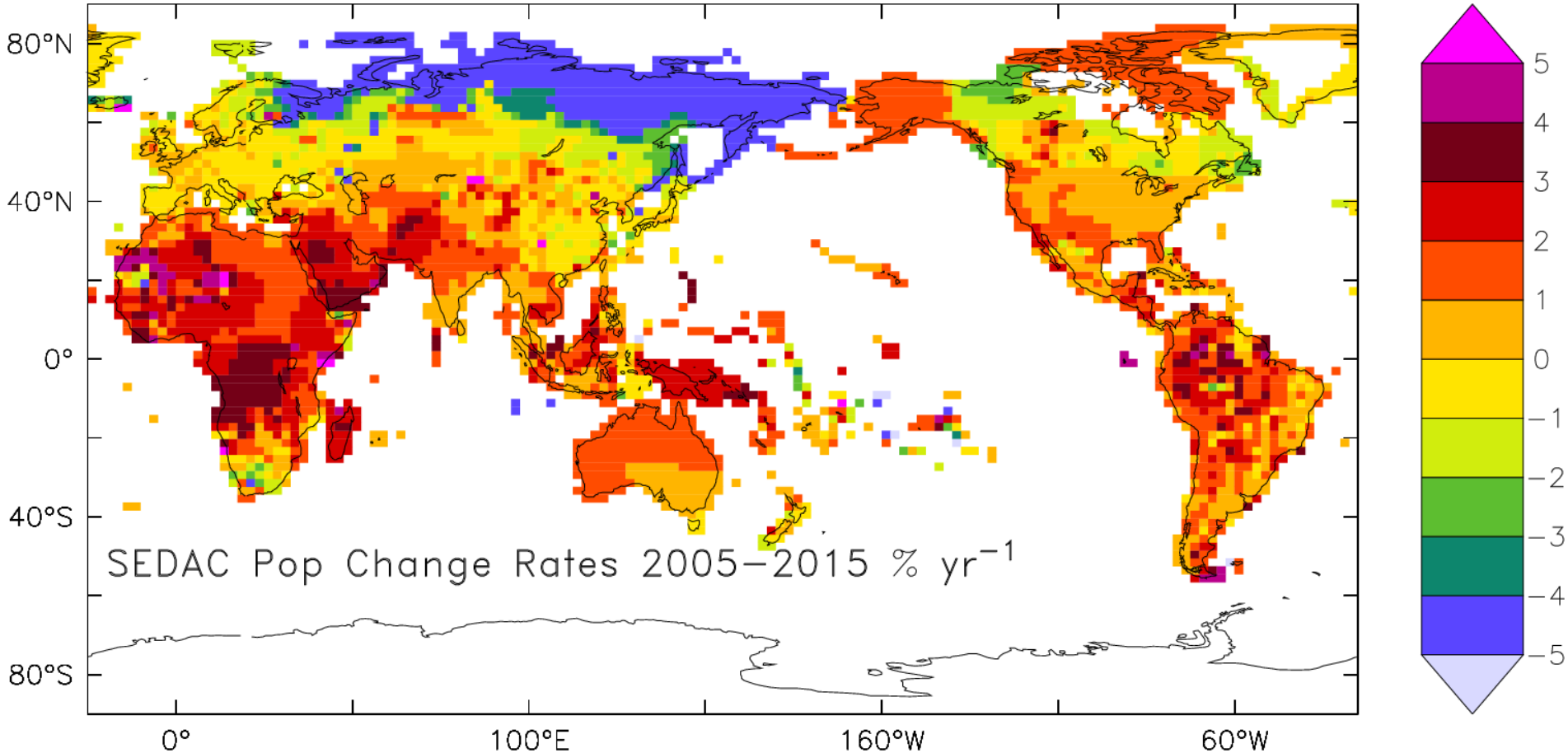
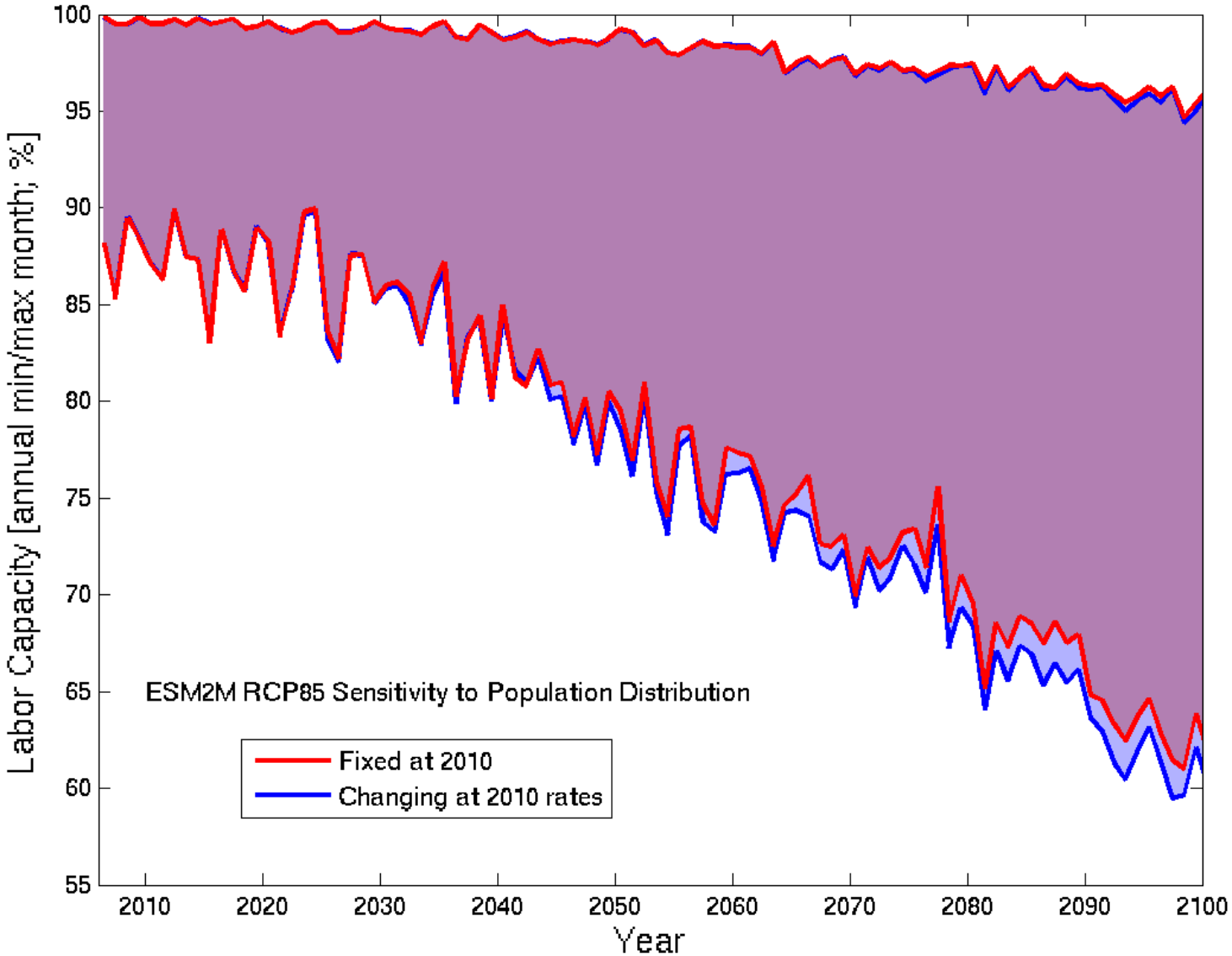
# Changing Population Distribution




Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

# Small Sensitivity to Changing Population Distribution

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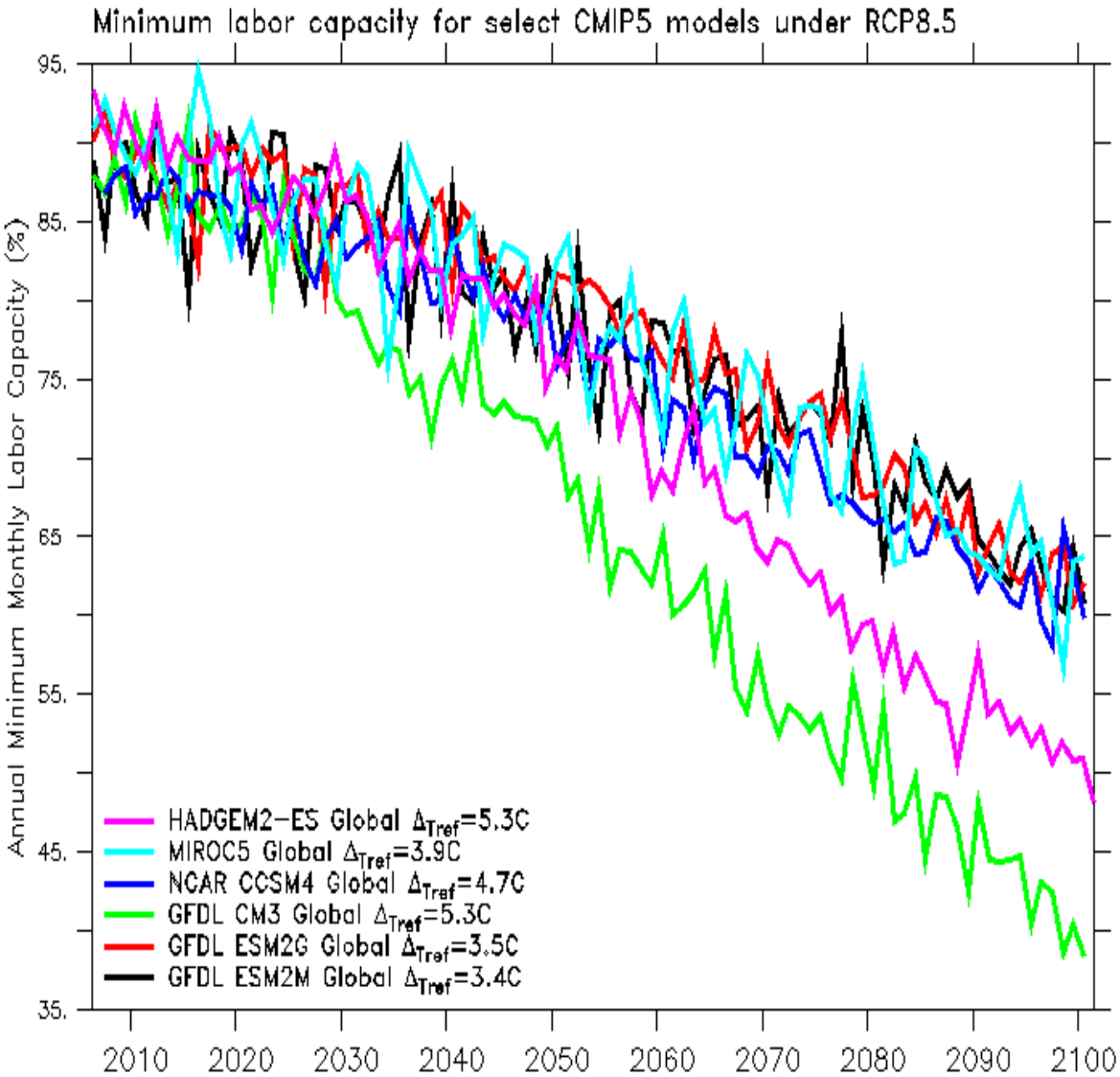
# Sensitivity to Model and Its Response




- With similar climate sensitivity, similar response in low res. (2°) ESM2M, ESM2G and high res. (1°) MIROC5
- High res (1°) CCSM4 larger $\Delta T_{Ref}$ change but focused in mountain regions
- Higher climate sensitivity models: CM3 distributes more warming over east Asia and North America than HADGEM-ES

Dunne, J. P., Stouffer, R. J., and John, J. G. Supplement to: Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

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# Emissions Projection Classifications

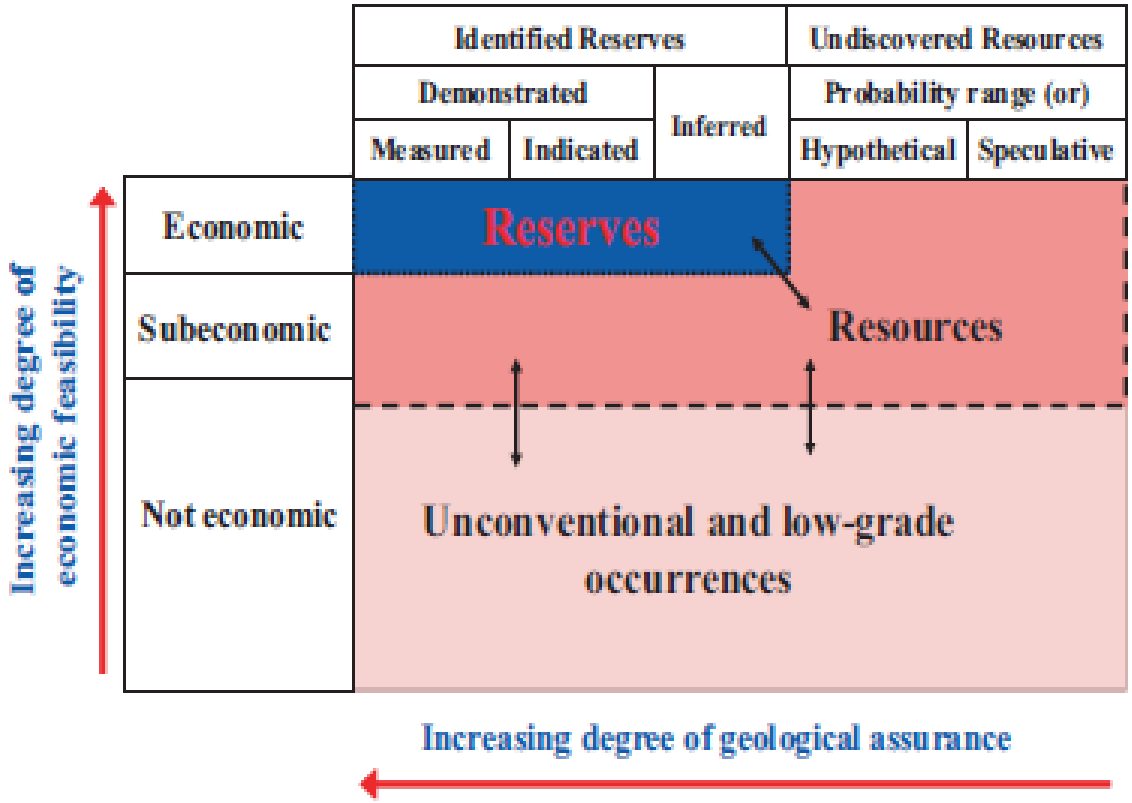


**Figure 7.1** | Principles of resource classification. Source: McKelvey, 1967.

Rogner et al, 2012: Chapter 7: Energy Resources and Potentials, IIASA

# IIASA Inventory Estimates

## Units are PgC

| | | Reserves | | Resources | | |
|---|---|---|---|---|---|---|
| Type | Through 2005 | Low | High | Low | High | Occurrence |
| conventional oil | 121 | 98 | 151 | 83 | 122 | 0 |
| unconventional oil | 10 | 75 | 111 | 224 | 295 | 796 |
| conventional gas | 44 | 72 | 102 | 104 | 128 | 0 |
| unconventional gas | 2 | 289 | 966 | 579 | 1755 | 14400 |
| coal | 170 | 439 | 533 | 7391 | 11049 | 0 |
| **sum oil, gas, coal** | **348** | **973** | **1865** | **8381** | **13349** | **15196** |

**At 1915 PgC by 2100, RCP8.5 exhausts high end of 'reserves'**

**At 4768 PgC by 2200, RCP8.5 exhausts much of 'resources'**

Adapted from Rogner et al, 2012: Chapter 7: Energy Resources and Potentials, International Institute for Applied Systems Analysis

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# Human Activity Implications

- On the global average, heat stress restricts safe human activity to 90% the unstressed value in peak months.
- This decreases to about 70% in the most prone regions.
- Practically, that means that summer daytime and weather-scale activity is commonly restricted.
- Under climate warming, these restrictions become increasingly severe and expand poleward.
- Air conditioning, structure optimization, automation of labor, migration, and other adaptations will become increasingly critical under climate warming.

# Limitations of Human Activity Implications

- **Focusing only on the climate scale, we underestimate diurnal- and weather- scale exacerbation of stress.**
- **We underestimate impacts on vulnerable individuals in focusing only on healthy, acclimated adults.**
- **We ignore ecological factors such as enhanced agricultural productivity under $CO_2$ fertilization and longer growing seasons.**
- **We ignore ameliorating direct factors such as labor productivity increases with reduced extreme cold, snow, and frozen soil.**
- **The utility of this metric to explain historical labor productivity variability is unclear.**

# Summary

- **WBGT and labor capacity combine to bring a new perspective on the direct human impacts of climate warming as:**
  - **Both the physical climate and direct human sensitivity to warming are fundamentally moist thermal responses**
  - **The vast attention paid to occupational heat stress provides a quantitative framework for impacts**
- **By 2100 in RCP8.5, heat stress in Wash. DC becomes higher than present New Orleans, and New Orleans exceeds present Bahrain.**
- **Heat stress reduces global labor capacity in peak months to 90% currently, 80% by 2050, 75% with 2.3°C warming and 39% with 6.2°C warming**
- **At this highest warming, >20% of the population is incapable of any safe labor during peak months.**
- **Economics, health, and mortality implications require further study**