Impacts of agriculture on regional climate: 
Looking at climate change from the ground up

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Outline

• Observed climate change
• Potential forcings
• Agricultural effects on regional climate
  • Irrigation
    • Background
    • Potential mechanisms
    • Methodology of study
    • Results
    • Conclusions and implications
  • Agricultural intensification
• Take-home messages
Observed climate change
Observed change in surface temperature 1901–2012

IPCC, 2013
Observed change in annual precipitation over land

1901–2010

1951–2010

(mm yr⁻¹ per decade)
Warm days (Tmax > 90th percentile)
Very wet days (%/decade)

Alexander, 2016
Potential forcings
Global anthropogenic CO₂ emissions

Quantitative information of CH₄ and N₂O emission time series from 1850 to 1970 is limited

- Fossil fuels, cement and flaring
- Forestry and other land use

IPCC, 2013
Atmospheric CO$_2$ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

May 4
Global Mean Estimates based on Land and Ocean Data

Temperature Anomaly (°C)

- Annual Mean
- Lowess Smoothing

Atmospheric CO₂ at Mauna Loa Observatory

NASA GISS, 2017
Pielke et al, 2011 (adapted)

Cropland + Pastureland

0.05 0.1 0.2 0.4 0.6 0.8 0.9
Crop Yield

Ray et al., 2012
Irrigation

• Global area equipped for irrigation (Siebert et al., 2015)
  • 1900 = 63 million ha
  • 1950 = 111 million ha
  • 2005 = 306 million ha

• Irrig water withdrawal
  • 2217-3185 km$^3$ yr$^{-1}$
    (Siebert et al., 2015)

Source: Atlas of the Biosphere, University of Wisconsin
Connection to the atmosphere

• Established links between:
  • Vegetation,
  • Soil moisture,
  • Evapotranspiration (ET),
  • Temperature, and
  • Precipitation

• Especially during summer
  • e.g., Koster et al. 2004, Betts 2004, Findell and Eltahir 2003 a,b

Koster et al., 2004
Mueller et al., 2015

**Cropland area**

![Map of Cropland Area Trend (% grid cell decade⁻¹)](image)

**Irrigated area**

![Map of Irrigated Area Trend (% county area decade⁻¹)](image)

![Box plots for Crop area trend (% grid cell decade⁻¹)](image)
Research questions

- **What are the impacts of irrigation development on regional climate?**
  - How does the *temporal aspect* of irrigation compare to the historical rainfall and temperature records?
  - Are there *regional differences* in the climatic response to irrigation?
  - What are the *potential mechanisms* that lead from irrigation to rainfall and temperature change?
Background
Important Irrigation Studies

• Barnston and Schickedanz (1984)
  • First comprehensive paper about “irrigation effect” on precipitation in West Texas

• DeAngelis et al. (2010)
  • July precipitation increases 15-30% several hundred km downwind of irrigated areas
DeAngelis et al., 2010

Harding and Snyder, 2012b

U.S. Midwest July precip anomalies (%)

May-Sept mean irrigation-induced precip (mm)
Other irrigation studies

- Irrigation may affect:
  - Soil moisture
  - Surface energy budget
  - Air temperature
  - Atmospheric moisture
  - Wind patterns
  - Rainfall

- The effects of irrigation on rainfall are most difficult to determine

Source: Boucher et al., 2004 (adapted)
Potential mechanisms
Irrigation application increases soil moisture—more energy goes toward evaporating surface moisture, so \(\text{SH}\) decreases and \(\text{LH}\) increases.

**Key shift:**

- More evapotranspiration (ET) and more water vapor

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**Schematic of the atmospheric properties and processes potentially induced by irrigation (Boucher et al. 2004).**

Difference in ET between irrigated and crop simulations for August 2003 (Ozdogan et al. 2010).

Greater LH + smaller SH =
Latent Heat Flux

Sensible Heat Flux

Harding and Snyder, 2012a
Irrigation application increases soil moisture—more energy goes toward evaporating surface moisture, so SH decreases and LH increases.

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Local effects:
Over irrigated area

Greater soil moisture

Non-local effects:
Downwind of irrigated area

\[ \text{Difference} = \text{greater moisture} + \text{higher temperature} \]
Irrigation application increases soil moisture – More energy goes toward evaporating surface moisture, so SH decreases and LH increases.

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Lower cloud base (LCL) and lower PBL height.
LCL (Lifted Condensation Level)

Qian et al., 2013

PBL (Planetary Boundary Layer) Height

Harding and Snyder, 2012a
Irrigation application increases soil moisture – more energy goes toward evaporating surface moisture, so $SH$ decreases and $LH$ increases.

Key shift:

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- Greater soil moisture
- Local effects: Over irrigated area
- Non-local effects: Downwind of irrigated area

More energy available for convection...
CAPE (Convective Available Potential Energy)

Im et al., 2014

Harding and Snyder, 2012a
Irrigation application increases soil moisture—more energy goes toward evaporating surface moisture, so SH decreases and LH increases.

Key shift:

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Schematic of the atmospheric properties and processes potentially induced by irrigation (Boucher et al. 2004).

Difference in ET between irrigated and crop simulations for August 2003 (Ozdogan et al. 2010).

...but more energy needed to achieve convection.

...Greater soil moisture.

Local effects: Over irrigated area.

Non-local effects: Downwind of irrigated area.
CIN (Convective Inhibition)

Im et al., 2014

Harding and Snyder, 2012a
Irrigation application increases soil moisture – More energy goes toward evaporating surface moisture, so SH decreases and LH increases.

Key shift:

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Convection hindered

Greater soil moisture

Local effects:
Over irrigated area

Non-local effects:
Downwind of irrigated area
Less frequent convection (days)

Im et al., 2014 (adapted)
Irrigation application increases soil moisture – more energy goes toward evaporating surface moisture, so SH decreases and LH increases.

Key shift:

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Schematic of the atmospheric properties and processes potentially induced by irrigation (Boucher et al. 2004).

Difference in ET between irrigated and crop simulations for August 2003 (Ozdogan et al. 2010).

Greater moisture gradient and moisture transport.
Moisture advection

Huber et al., 2014
Irrigation application increases soil moisture—more energy goes toward evaporating surface moisture, so SH decreases and LH increases.

Key shift:

More evapotranspiration (ET) and more water vapor.

Schematic of the atmospheric properties and processes potentially induced by irrigation (Boucher et al. 2004).

Difference in ET between irrigated and crop simulations for August 2003 (Ozdogan et al. 2010).

Non-classical mesoscale circulation.
Non-classical mesoscale circulation

Qian et al, 2013
Irrigation application increases soil moisture—More energy goes toward evaporating surface moisture, so SH decreases and LH increases.

Key shift

More evapotranspiration (ET) and more water vapor

Schematic of the atmospheric properties and processes potentially induced by irrigation (Boucher et al. 2004).

Difference in ET between irrigated and crop simulations for August 2003 (Ozdogan et al. 2010).

Wind convergence

CAPE utilized

Additional source of lift

Greater soil moisture

Local effects:
Over irrigated area

Non-local effects:
Downwind of irrigated area
Wind convergence (m/s)

Im et al., 2014 (adapted)
Irrigation application increases soil moisture – More energy goes toward evaporating surface moisture, so SH decreases and LH increases.

Key shift:

More evapotranspiration (ET) and more water vapor

Schematic of the atmospheric properties and processes potentially induced by irrigation (Boucher et al. 2004).

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Enhanced rainfall

Alter et al., 2015b (adapted)
West Africa

• “Hot spot” for soil moisture-rainfall coupling (Koster et al. 2004)

• Simulations with hypothetical irrigated areas

• Opposing effects on rainfall

Im et al., 2014 (adapted)

Im and Eltahir, 2014 (adapted)
Motivation for work in East Africa

- West Africa studies are only hypothetical

- No large-scale irrigation schemes in West Africa for validation

- We need observations to substantiate theoretical results

Adapted from FAO, 2013
Methodology

• Simulations using the MIT regional climate model – MRCM

• Three 30-year simulations from 1979 to 2008 (90 total years)
  • 20-km horizontal grid increments

• Irrigated grid cells are wetted to relative field capacity from July to September

Alter et al., 2015
Observational Analysis

• **Manaqil Extension (MEX)**
  - Rapid expansion from 1958-1962 (blue vertical bar)

• **Obs time periods used**
  - Pre-MEX – 1930-59
  - Post-MEX – 1970-99

• **Data sources**
  - Gridded data (University of Delaware - UDel)
  - Station data (GHCN)

Alter et al., 2015 (data from Ministry of Water Resources and Electricity in Sudan)
Results
Mean MODIS Land Surface Temperature (K) - JAS

Alter et al., 2015
(Control run) minus (observations)

Control - Observed

Mean Rainfall

Alter et al., 2015
Observed (UDel)

Simulated

July

August

(a)

(b)

Dots
Where irrig rainfall > control rainfall in at least 70% of model years

(c)

(d)

Dots
≥80th percentile of Consistency of Relative Change Index (CRCI)

Alter et al., 2015
Variability in irrigation-induced rainfall changes

Mask applied where control rainfall <1.5 mm/day to avoid inflation effect.
Gedaref

Wad Medani

GHCN

Alter et al., 2015
**Proposed Mechanism**

- **Wind @ 925 hPa (m s\(^{-1}\))**
- **Surface air temperature (K)**
- **Rainfall**
- **Omega @ 700 hPa (Pa s\(^{-1}\))**
- **Rainfall**

**Source:** Im et al. 2014

**Alter et al., 2015**
Conclusions and Implications

• **Simulations and observations point to:**
  • Consistent enhancement of rainfall around irrigated areas
  • Reduction of rainfall over irrigated areas

• Negative effects over irrigated area
  • Possible feedback loop that challenges hydrological sustainability

• Positive effects in surrounding areas
  • Can improve productivity of existing crops (e.g., Gedaref) or create new areas of cropland

• **Strategic placement of irrigated cropland can be beneficial for economies in Africa and the rest of the world**
Agricultural intensification
Temperature [°C]


Alter et al., submitted
Mueller et al., 2015

peak monthly chlorophyll fluorescence (mW/m²/sr/nm)
B

Area harvested [$10^3$ hectares]; production [10^9 bushels]

- production
- area
- yield

Year

Yield [bushels hectare$^{-1}$]

Alter et al., submitted
Take-home messages

• **Cropland irrigation** (and potentially, agricultural intensification)...

  • *...is a major forcing of regional climate change*
    • Reduces air temperature
    • Can have both local and remote effects on rainfall patterns

  • *...may influence regional crop productivity, harvest risk, and water resources*

  • *...warrants future consideration in plans to adapt to and mitigate climate change around the world*
Thank you!

Gezira Irrigation Scheme, Sudan

Source: Visible Earth, NASA