# Climate Change and Water

**MWD Board Session**
**Los Angeles, CA**
**July 28, 2015**

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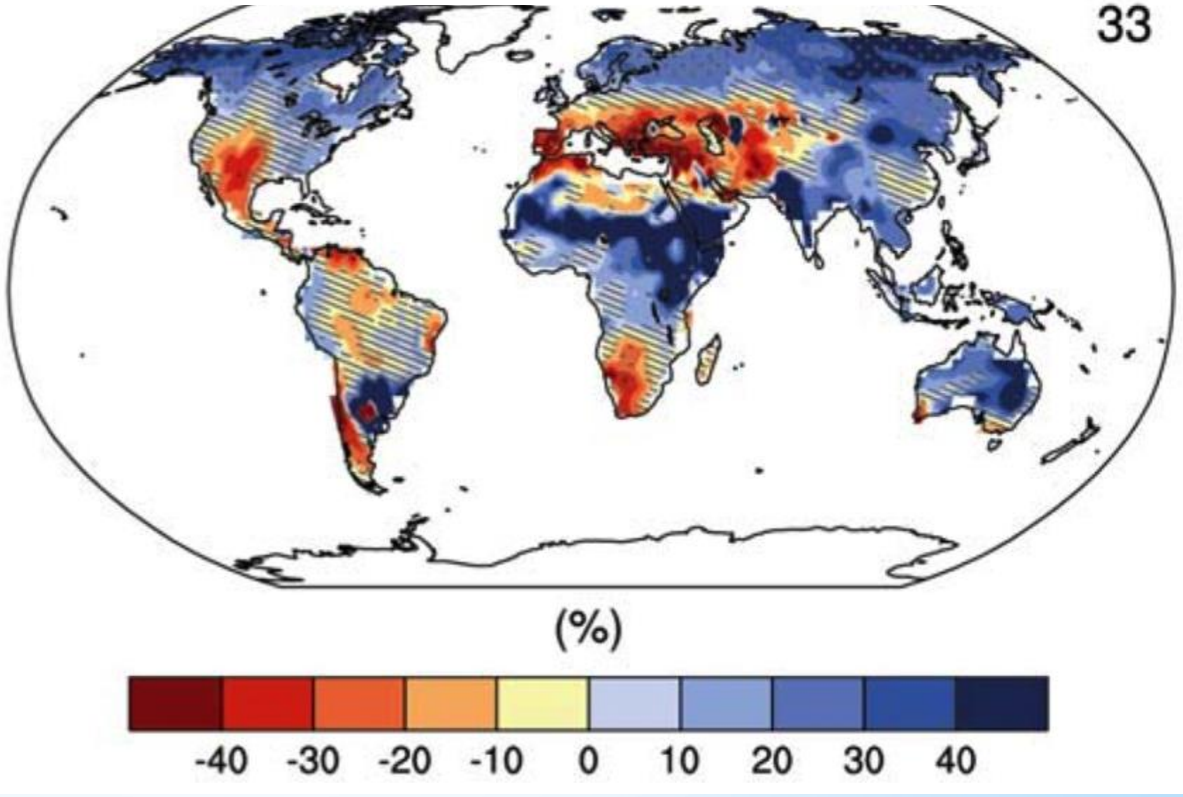
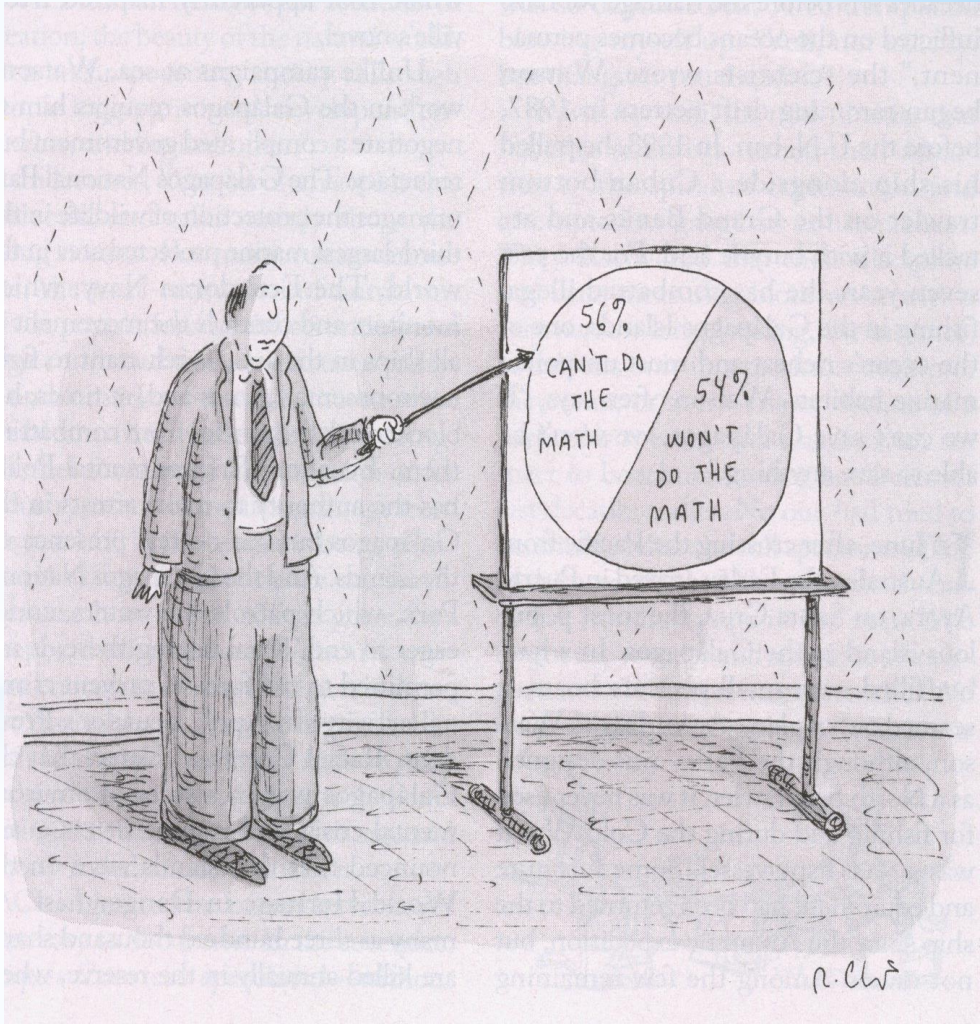
**Bradley.Udall@colostate.edu**

Projected Runoff at 2100

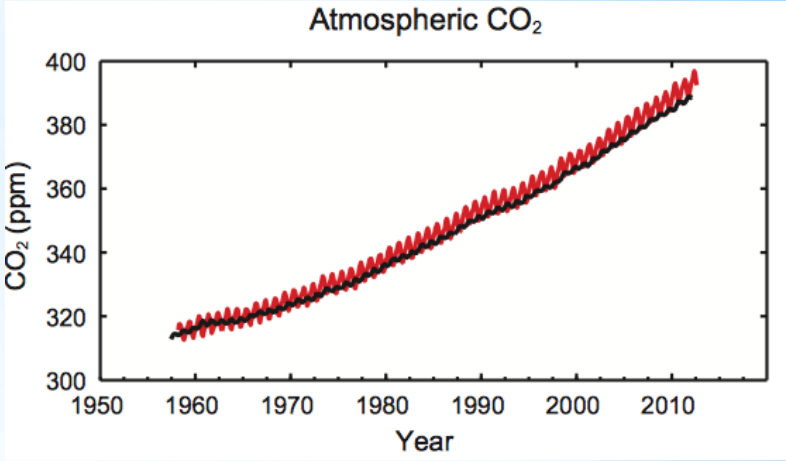


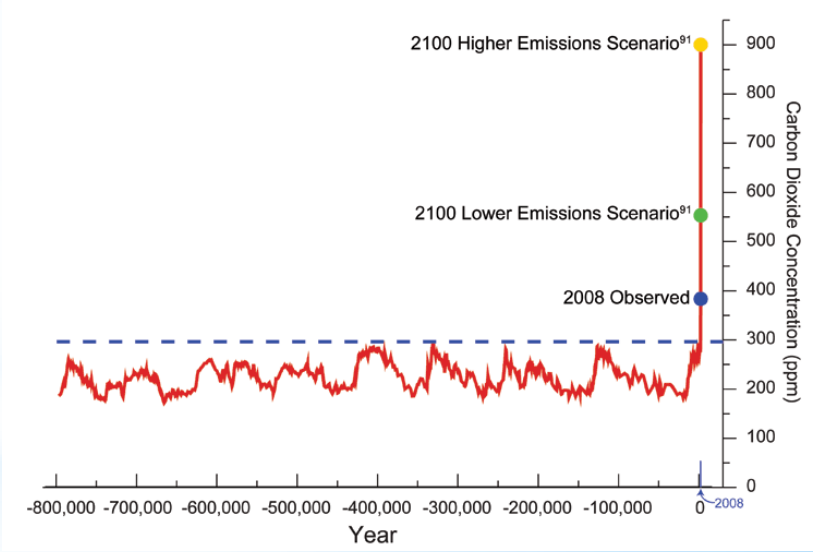
# *Outline

* Climate Change Basics
* Evolution of Findings
* Regional Downscaling
* Climate Change Science Weaknesses, Improvements
* Water Agency Key Points



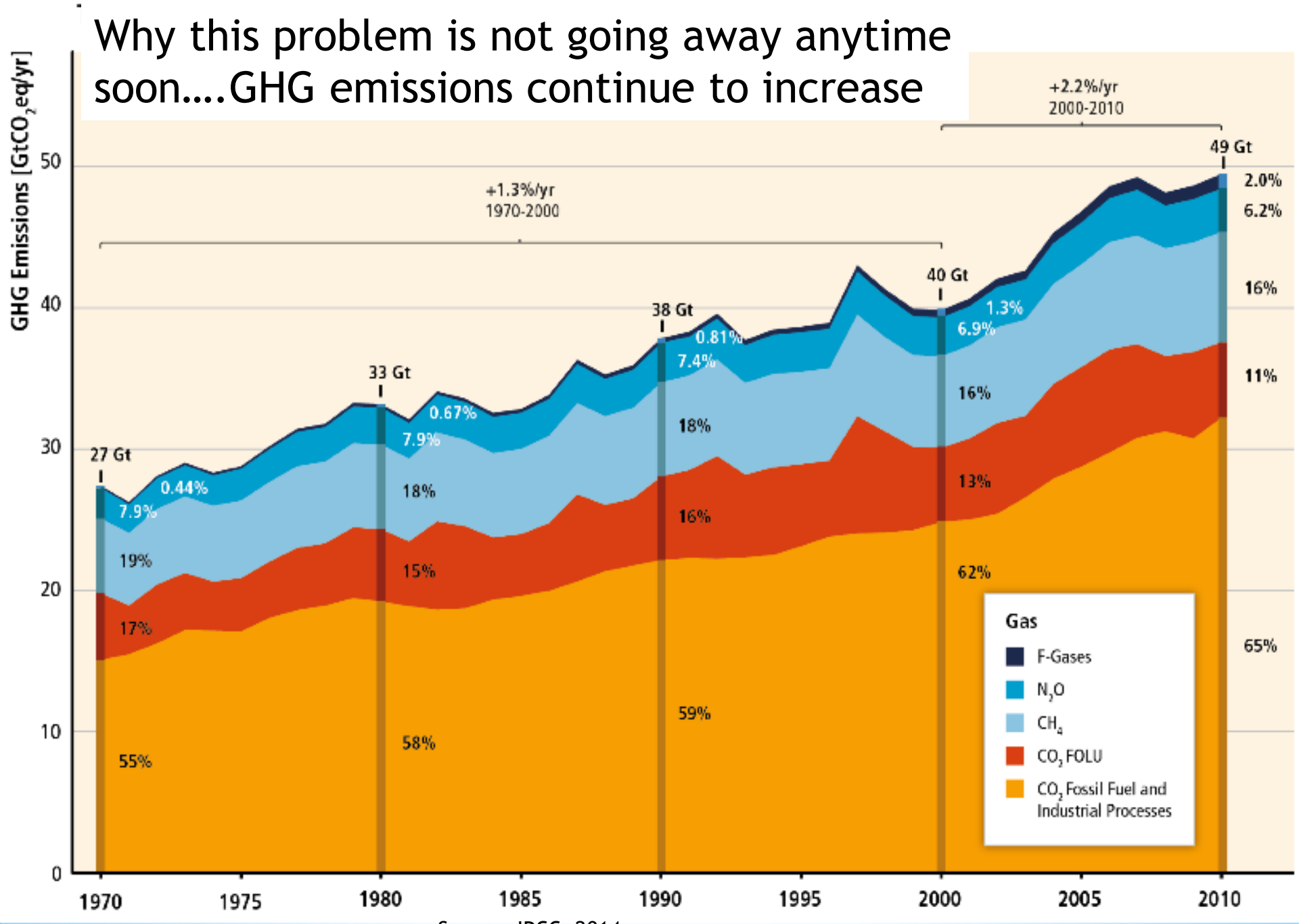
- Earth is about 60F warmer than it should be
- Very Small Concentrations of Greenhouse Gasses (GHGs) are the cause
  - Almost every gas other than Oxygen ($0_2$) and Nitrogen ($N_2$) are GHGs. $CO_2$ is most important one.
- Earth's Temperatures have fluctuated widely over its 4.5B year history
  - But NOT during human ascendency of last 2k years
- Humans are adding enormous amounts of GHGs to the atmosphere every day and it is increasing over time
  - About half of emitted CO2 remains in the atmosphere
  - On a path to double CO2 by 2050
- Planet is now 1.4F warmer due to GHG emissions
  - No other plausible explanation for the warming
- Total Warming will be related to GHG concentrations, not emissions
  - If you stop tomorrow, you still have a 1000-year problem
- Humans are also modifying the planet in many other ways
  - 'The Anthropocene'



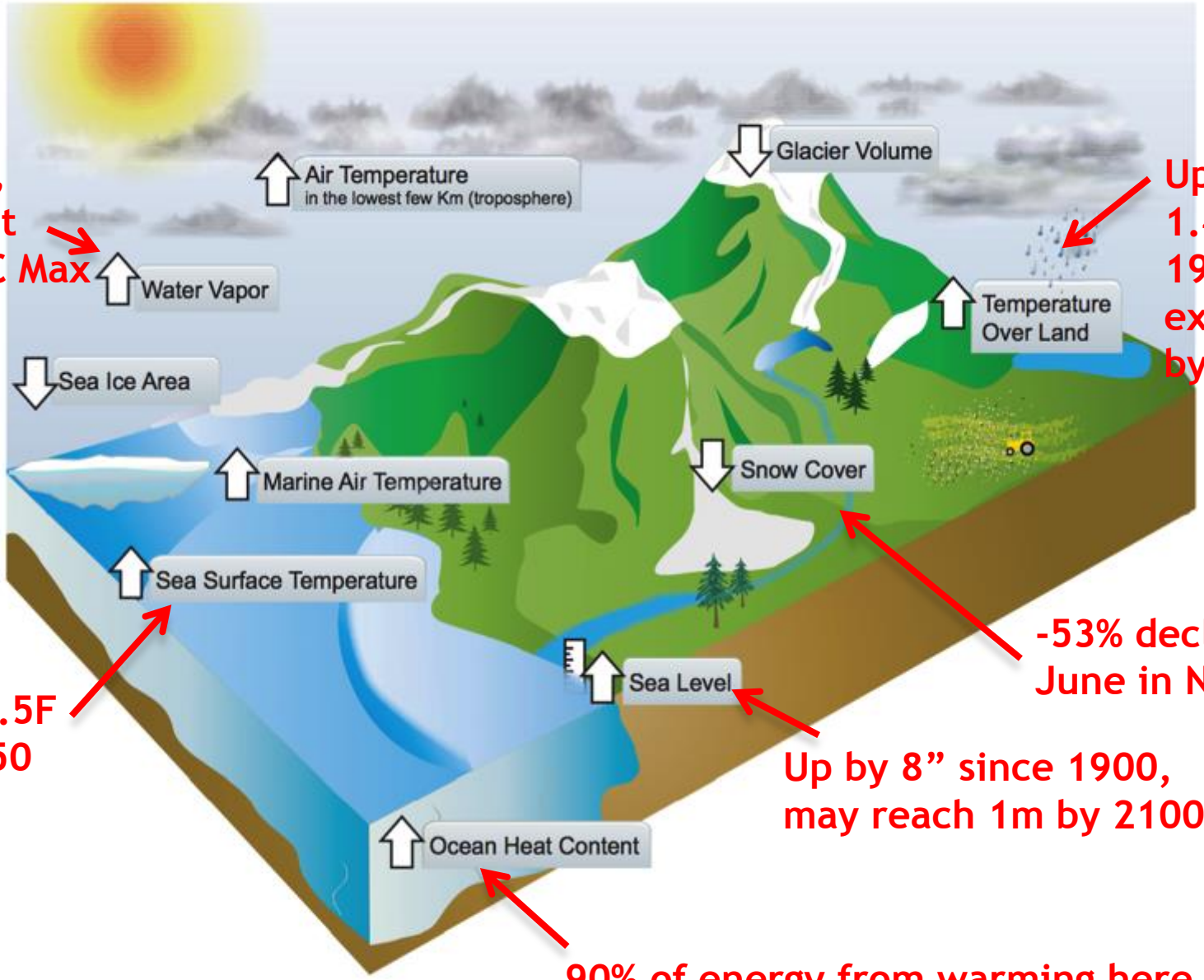

# *Climate Change Basics

# Why this problem is not going away anytime soon….GHG emissions continue to increase




Source: IPCC, 2014

# IPCC: All Kinds of Observations are Consistent with Climate Change Expectations. Many are water cycle related.




Up by 5%, Consistent with 7%/C Max Rate

Up by 1.4F Since 1950, May exceed 7F by 2100

-53% decline in June in NH

Up by ~0.5F since 1950

Up by 8" since 1900, may reach 1m by 2100

90% of energy from warming here

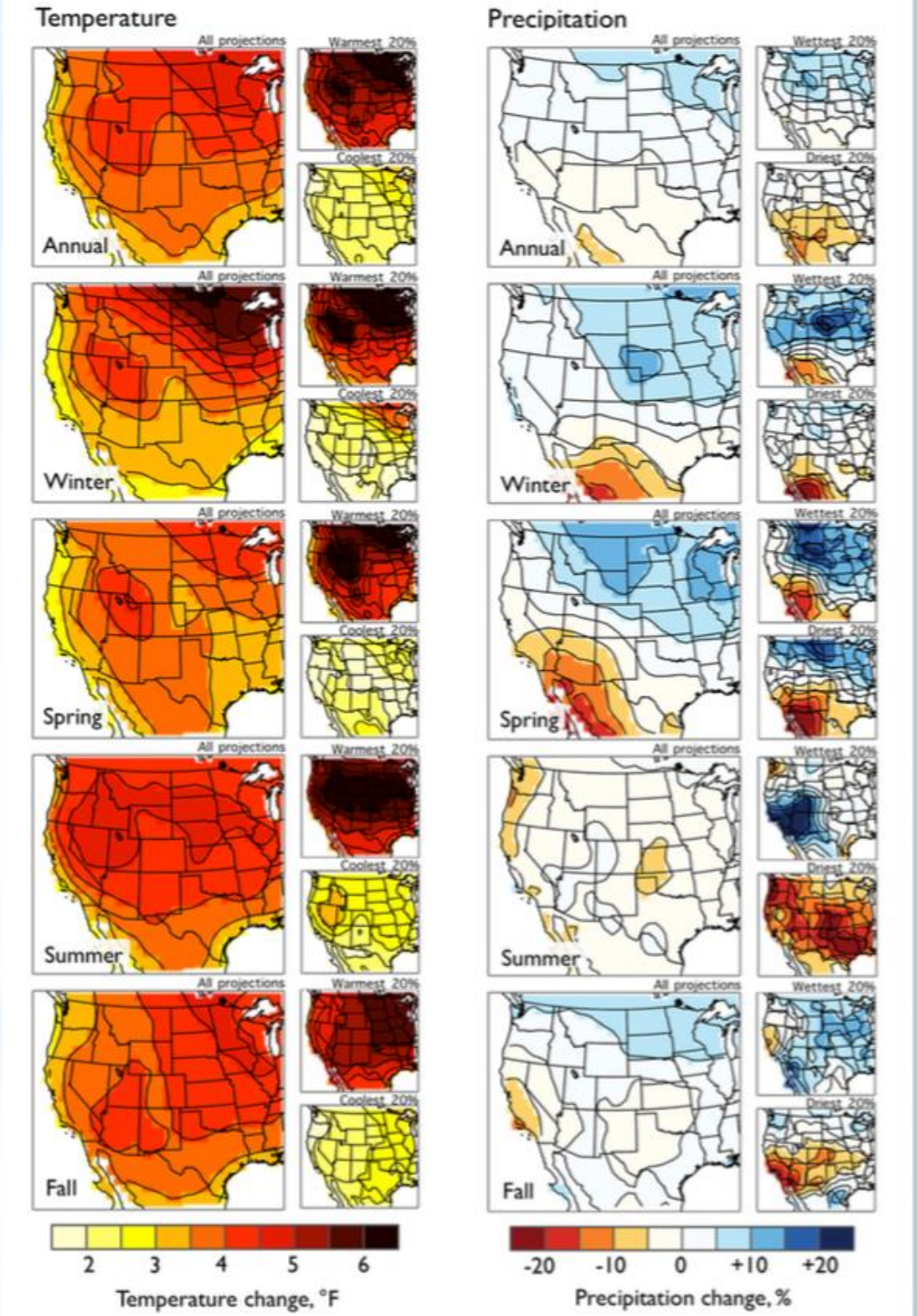
# Climate Change is Water Change

- Heat Drives the Water Cycle –
  1000 km3 evaporates daily from the oceans

- The Water Cycle mixes heat from areas of too much to too little
- As the Atmosphere Warms it Holds More Moisture:
  ~5F warming is 20% increase
- Heating Up the Earth (and uneven heating) results in Water Cycle changes
  - More Evaporation, More Precipitation, More Moisture
  - Changes in weather patterns
  - Wet Wetter, Dry Drier Standard Rule
  - More Intense Floods and Droughts
- All Kinds of Water Changes Already Noted
  - More rain/less snow, Earlier Runoff, Higher Water Temps, More Intense Rain
- Many of the most critical impacts of climate change will arise through water cycle changes driven by higher temps, not just higher temps rising temperatures

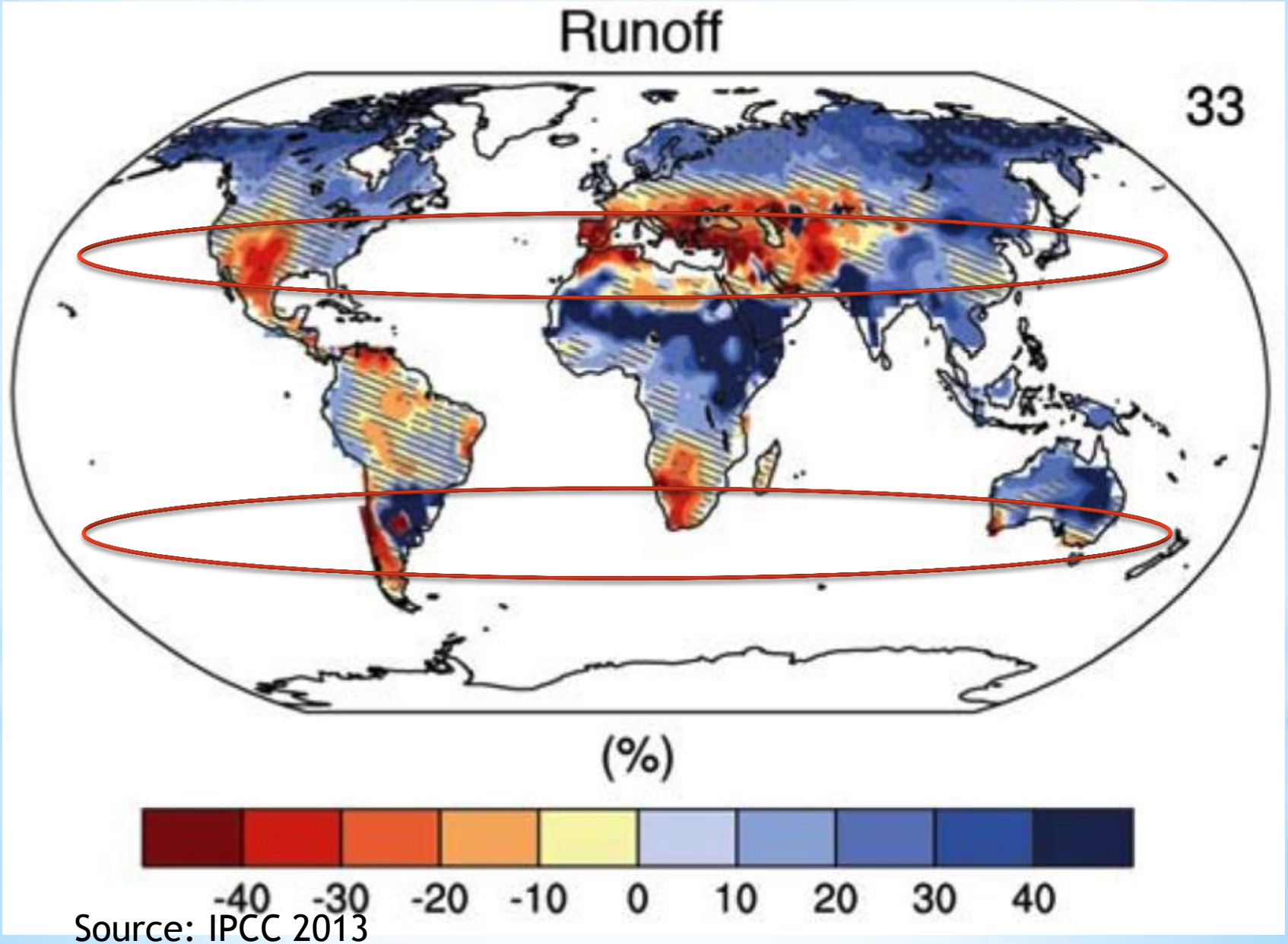
# Climate Projections Mid-Century, Moderate Emissions

- Warming
  - All Seasons Warm
  - Less Warming on the Coast
  - Average Warming is 4-5F
  - 2 to 3X current warming of ~1.5F
- Precipitation
  - Little Annual Precipitation Change
  - South Dries, North Wets
- Not Shown
  - Much warming ‘baked in’
  - Runoff is not Precipitation
    - 3% decline / 1 °F Warming
    - 2:1 Leverage on P Changes



# IPCC 5th Results RCP 8.5 at 2081 to 2100

Repeat after me: Precipitation is not runoff!



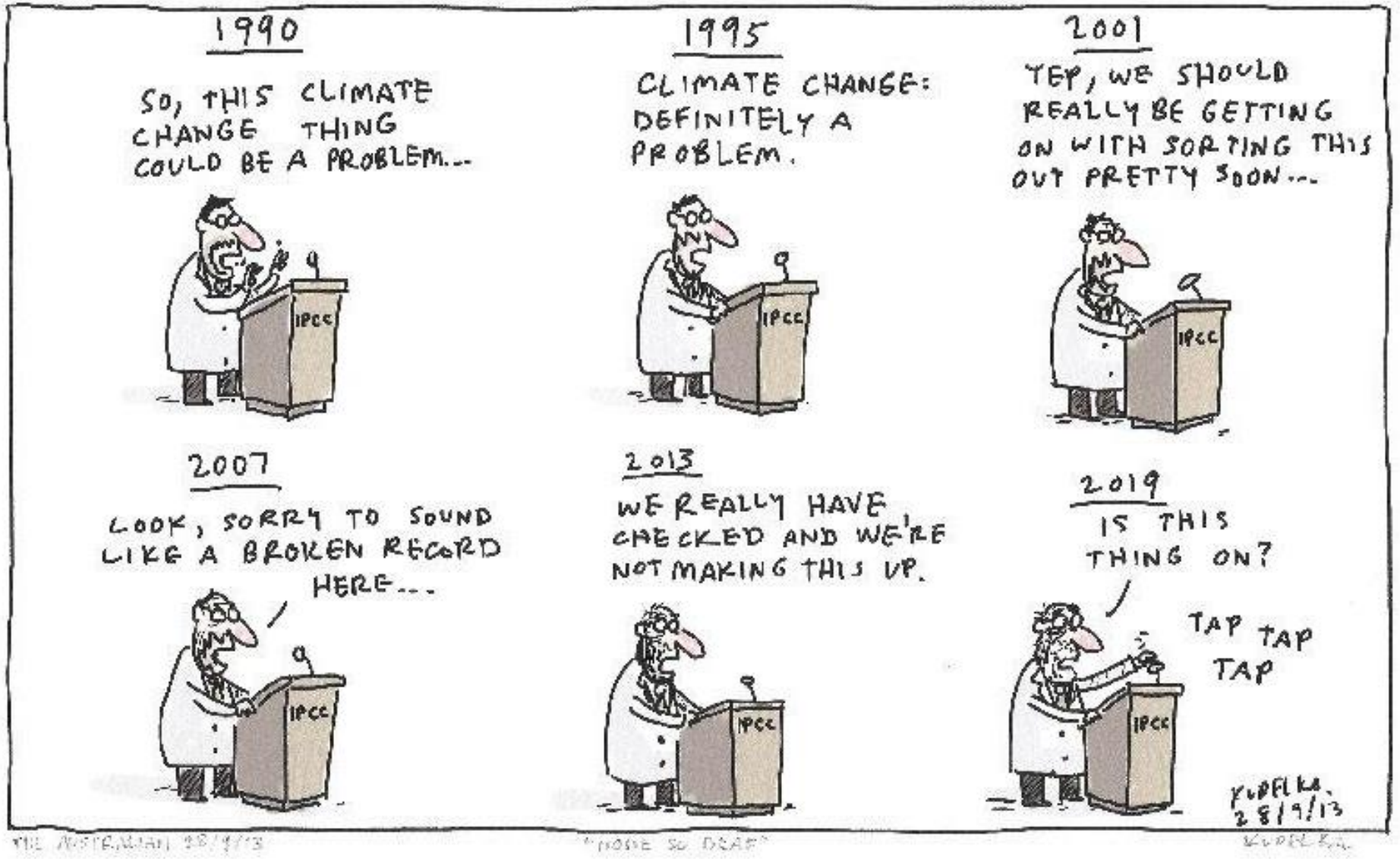

Source: IPCC 2013

# Outline

* Climate Change Basics
* Evolution of Findings
* Regional Downscaling
* Climate Change Science Weaknesses, Improvements
* Water Agency Key Points

*"Those who ignore history are entitled to repeat it."*

# IPCC Statements Over the Years
# (And How I feel Today)



* Long History of Climate Change Science
* Water Cycle Key Driver and Key Impact
* Amazingly Broad Support from Science Community
* Recent Evolution with IPCC FAR
  * More Certainty as to Human Contribution
  * More Sea Level Rise
  * On the big scale, mostly continuity of findings

## The Effects of Doubling the $CO_2$ Concentration on the Climate of a General Circulation Model[1]

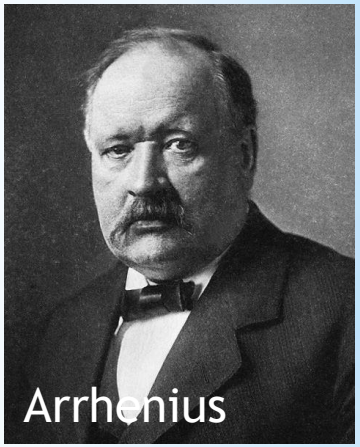
SYUKURO MANABE AND RICHARD T. WETHERALD

*Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, N.J. 08540*

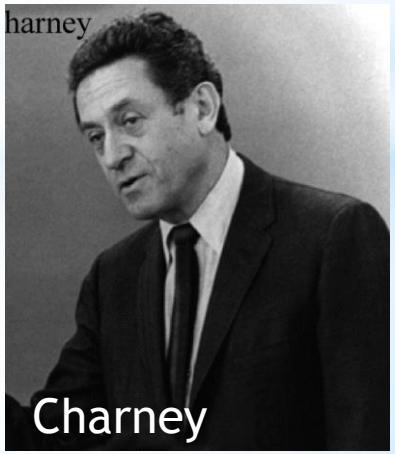
(Manuscript received 6 June 1974, in revised form 8 August 1974)

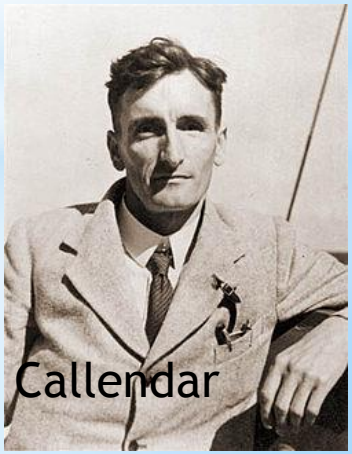
ABSTRACT

An attempt is made to estimate the temperature changes resulting from doubling the present $CO_2$ concentration by the use of a simplified three-dimensional general circulation model. This model contains the following simplifications: a limited computational domain, an idealized topography, no heat transport by ocean currents, and fixed cloudiness. Despite these limitations, the results from this computation yield some indication of how the increase of $CO_2$ concentration may affect the distribution of temperature in the atmosphere. It is shown that the $CO_2$ increase raises the temperature of the model troposphere, whereas it lowers that of the model stratosphere. The tropospheric warming is somewhat larger than that expected from a radiative-convective equilibrium model. In particular, the increase of surface temperature in higher latitudes is magnified due to the recession of the snow boundary and the thermal stability of the lower troposphere which limits convective heating to the lowest layer. It is also shown that the doubling of carbon dioxide significantly increases the intensity of the hydrologic cycle of the model.



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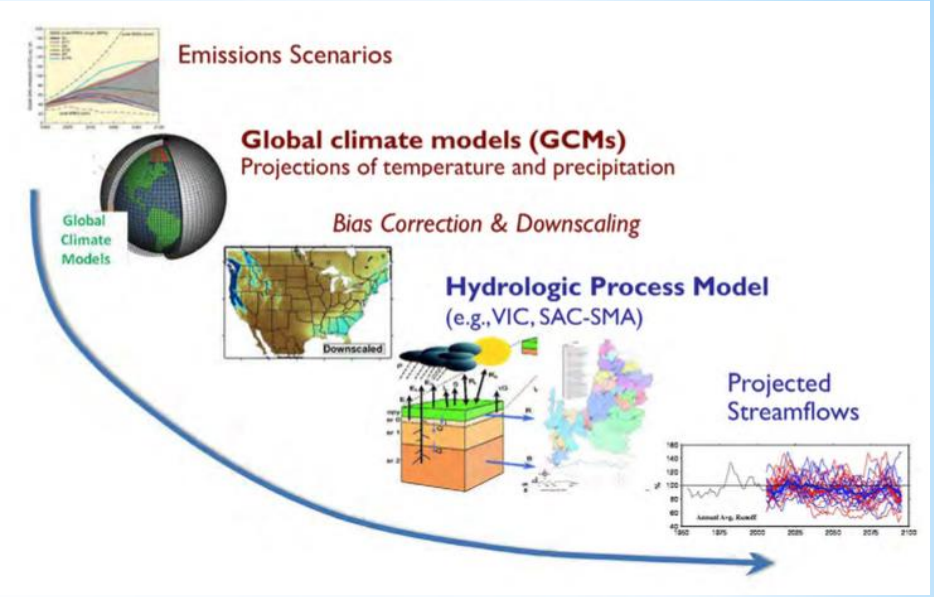
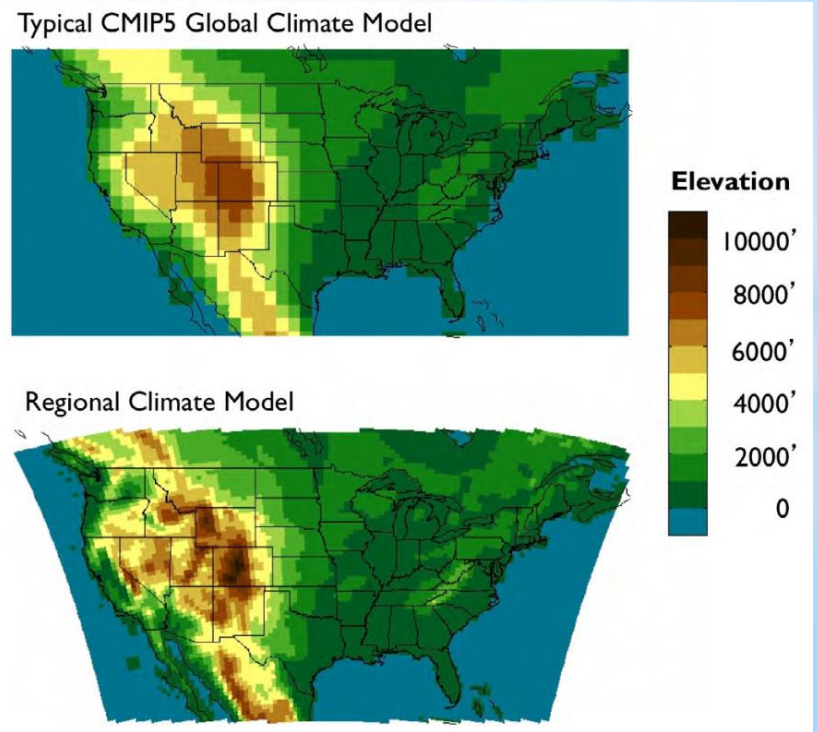
* Climate Change
* Evolution of Findings
* Regional Downscaling
* Weaknesses, Improvements
  * Are we playing dumb?
* Water Agency Keys
* Closing Thoughts

Downscaling Metaphor?

# * Downscaling

- Provide More Realistic Future Simulations by adding details to GCMs
- Necessary Evil for Some Purposes
  - e.g., Hydrology/Operations Model in 2050
- What you can add/fix
  - Topography
  - Model "Biases"
- What you can not add/fix
  - ENSO Changes
  - Monsoons
  - Model Precipitation Uncertainty
  - Atmospheric Rivers
- Future of Downscaling
  - Climate Models halve grids every 5 years
  - 10-20 Years will reduce need
- Still helpful, so long as we don't fool ourselves
- Use to help think
- "Envisioning the Future"
- Do not confuse accuracy with precision



# * Regional Climate Change Assessments

nature
Vol 463 | Issue no. 7283 | 18 February 2010

## Validation required

Transparency and quality control are essential in the highly uncertain business of assessing the impact of climate change on a regional scale.

Climate scientists are engaged in a lively debate about how — or whether — the Intergovernmental Panel on Climate Change (IPCC) should reform itself (see *Nature* **463**, 730–732; 2010). At a minimum, the panel needs to hold itself to the highest possible standards of quality control in future assessments.

But so do climate scientists themselves — especially those who study the links between global climate change and its potential regional effects on factors such as weather patterns, ecosystems and agriculture. Governments faced with the need to make difficult, disruptive and politically fraught decisions about when and how to respond to climate change are understandably eager for certainty. But certainty is what current-generation regional studies cannot yet provide. Researchers need to resist the pressures to overstate the robustness of their conclusions, and to be as open as possible about where the uncertainties lie.

As an example of the scientific challenges involved, imagine a regional authority wanting to plan for water resources in a river basin over the next four decades. An applicable study might be probabilistic in approach. It could take into account a range of global greenhouse-gas-emission trajectories, and involve multiple runs of global climate models using different values for a number of parameters. However, such models cannot reproduce some important atmospheric phenomena such as circulation trapping, and cannot be validated against real climate behaviour over decadal timescales. The multiple runs will produce a probability distribution of precipitation which itself will contain intrinsic uncertainties. These outcomes then need to be fed into a catchment model with its own range of parameters and limitations of knowledge, and which in turn needs to be coupled to models of water demand as local housing and populations change over the period (M. New *et al. Phil. Trans. R. Soc. A* **365**, 2117–2131; 2007, and other papers in that issue).

Climate projections at the national level are crucial for such efforts. One such study was published last year, when the UK Met Office produced its climate projections of the next eight decades, including analysis down to a resolution of 25-kilometre squares (http://ukclimateprojections.defra.gov.uk). The British government is now conducting a national climate-change risk assessment, due for completion in early 2012, that uses the projections. But such an application could well be problematic: it is likely that the projections reflect the limitations of the models and analyses as much as probabilities intrinsic to the real world. Yet regional planners and others might easily miss the detailed discussions of uncertainties, and misguidedly seize on these projections as a solid basis for investment decisions. And depressingly for decision-makers, the more the uncertainties are explored, the greater the ranges in the projected possible outcomes are likely to become.

This combination of projections and risk analysis is one way in which an over-reliance by decision-makers on modelling may be setting up the scientific community for a loss of trust. What is more, like regional-impact studies, such analyses often appear not in peer-reviewed journals but in 'the grey literature' — in reports, or on websites. Yet they are no less important in representing the outputs of climate science, and need to be included in the IPCC assessment. For these reasons, such grey studies should be transparently peer reviewed as a part of their commission.

**"Grey-literature studies should be transparently peer reviewed as a part of their commission."**

Uncertainties about future climate effects do not undermine the case for action to reduce greenhouse-gas emissions. But there is a long way to go in the science before regional-impact studies provide a suitable basis for detailed planning. Whatever the pressures, statements by scientists and government agencies about such studies need to be well qualified, and policies based on them need to be kept as flexible as possible. It is intrinsic to this research, after all, that scientists' best judgements will be subject to change. ■

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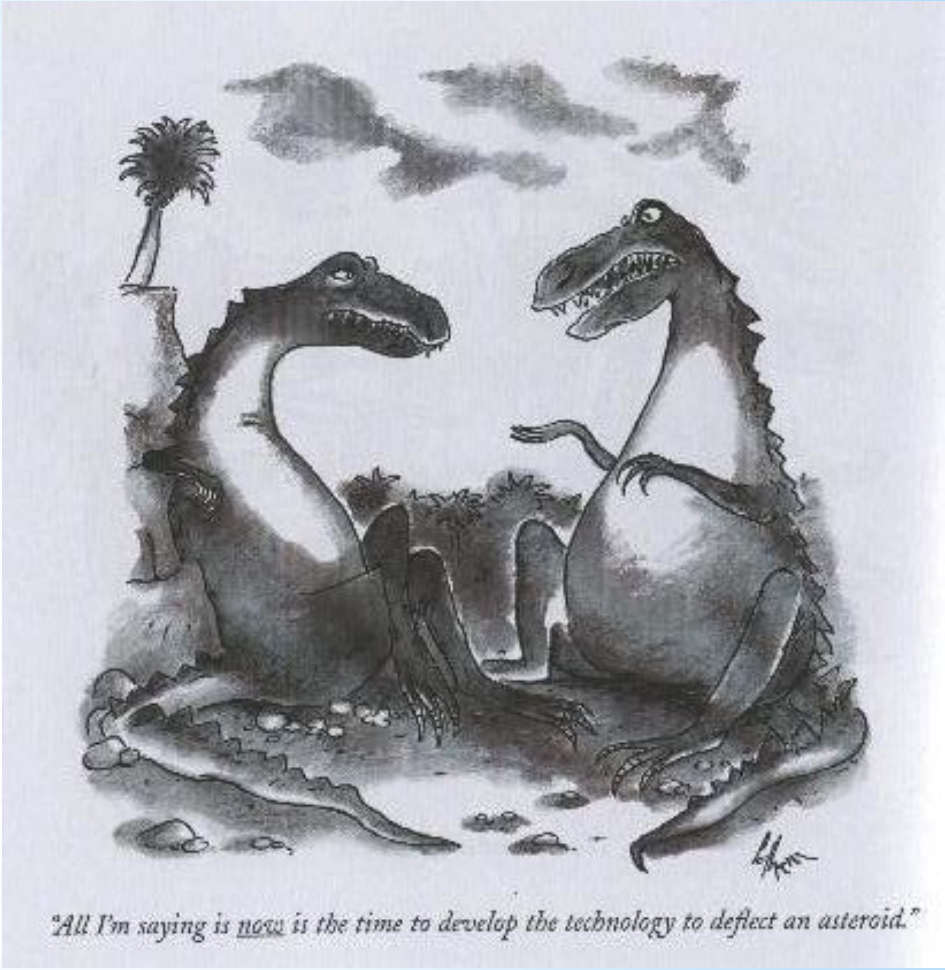


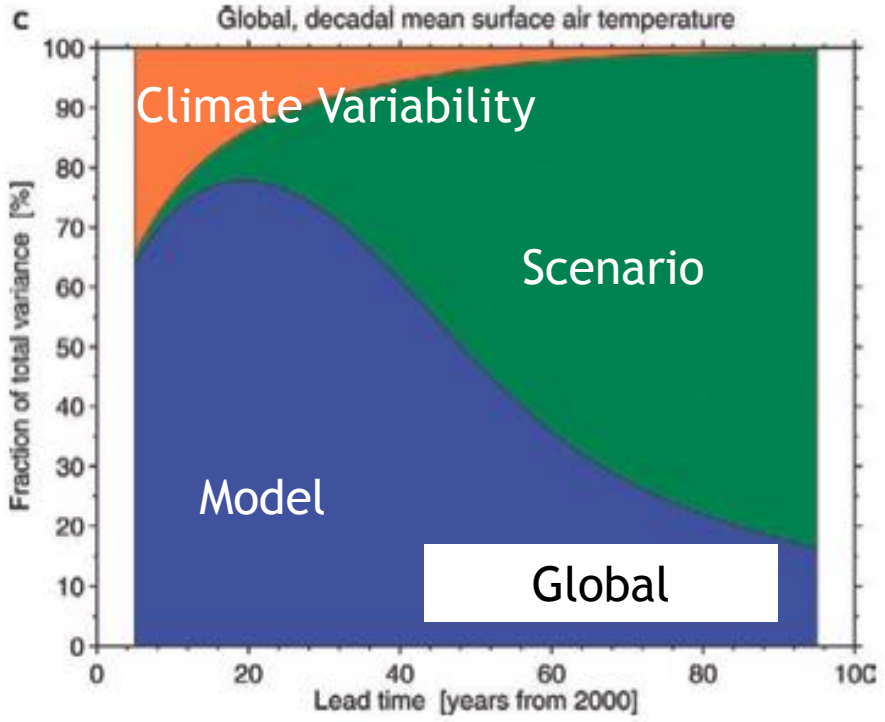
# Uncertainty in Science and its role in Climate Policy

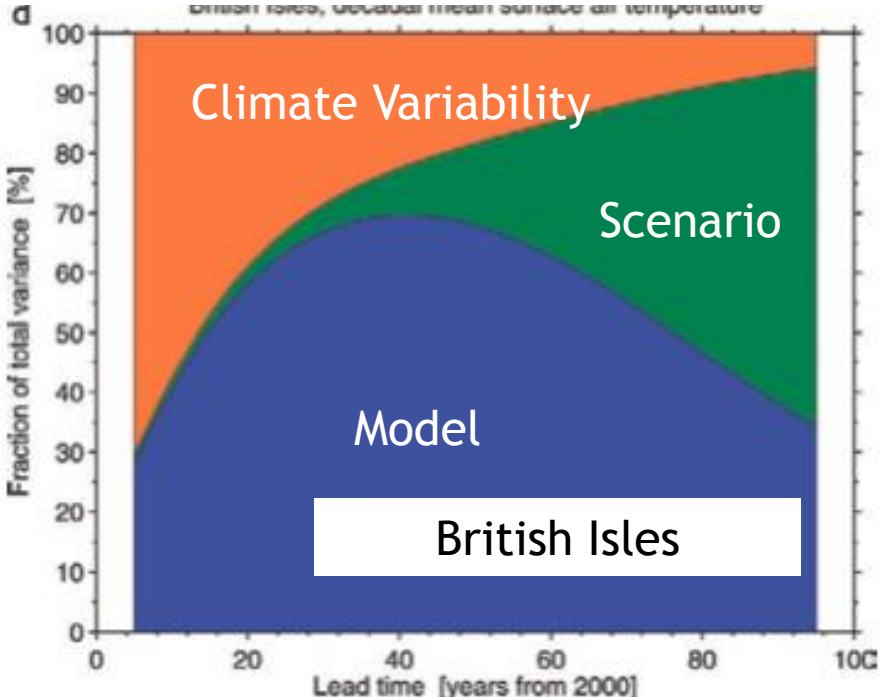
- Terrific, Thought-Provoking Article Worth a Read
- Key Points
  - Large Uncertainties do not mean small risks
    - Uncertainty can support immediate action in some cases
  - A lack of certainty provides no rational argument against action
  - Varieties of uncertainty:
    - Imprecision – can be quantified by PDF
    - Ambiguity – impacts known but can't be quantified via PDF, e.g. 100 yr impacts
    - Intractability – not solvable, e.g. no equations or lack computers
    - Indeterminacy – also not solvable, e.g., a societal value or non-physical parm.
  - "Models can increase our understanding long before they start providing realistic numbers."
  - These concepts not appreciated by both modeling community and user community
  - Key Point: we need to move away from scientific uncertainty to managing risk

**Uncertainty in science and its role in climate policy**
Leonard Smith and Nicholas Stern
*Phil. Trans. R. Soc. A* (2011) **369**, 1–24 doi:10.1098/rsta.2011.0149

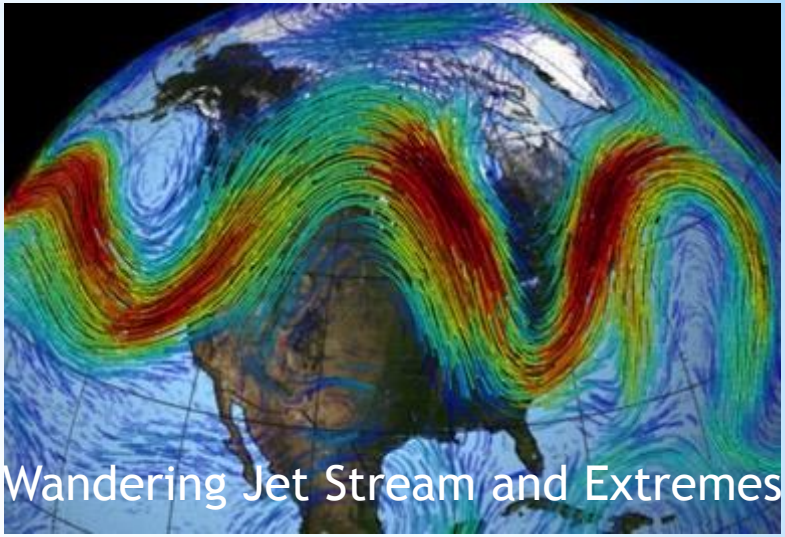
# * Major Uncertainties

* Emissions Uncertainties
  * When do we stop emitting GHGs?
* Climate Response Uncertainties
  * Feedbacks Critical: clouds, water vapor
  * El Nino Southern Oscillation
  * Natural Variability
  * Amount of Warming – but not if it will warm
* Sea Level Rise
  * Big Ice Sheet Dynamics not understood
* Regional Impacts
  * Precipitation



# *Is it or Isn't it Climate Change?




* This is a 'poorly formed' question. Really 3 Questions Need to be Asked
* 1. Is this (drought/flood/etc) caused by climate change?
  * Natural Variability makes it hard to discern climate change 'signal' from natural variability 'noise'
  * Usually the answer will be 'No' due to statistical hurdles. Gives mistaken impression that climate change is not happening or is not affecting events
  * Scientists prefer to err on side of 'Trojan Horse' than 'Cry Wolf'
* 2. Is climate change affecting this event?
  * Generally, Yes.
  * More atmospheric moisture for sure
  * Higher temps and more drying
  * Other factors may be at work, too
  * Lots of possible climate change effects: intensity, duration, frequency
* 3. How will climate change affect future droughts/floods/etc ?
  * All the usual answers apply
  * More extremes: bigger droughts and bigger floods

**The 2 Kinds of Errors we make with Predictions**

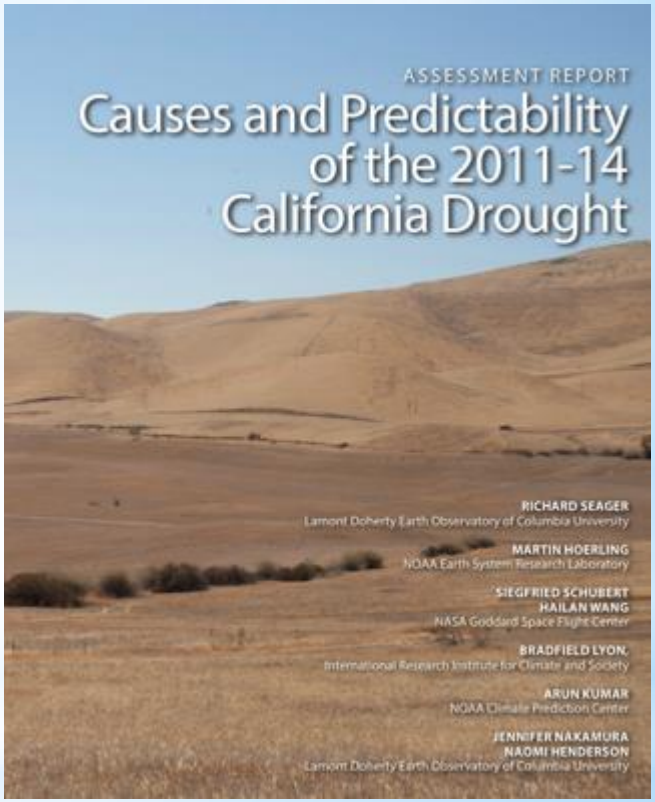
| | | **Truth** | |
|---|---|---|---|
| | | *No Climate Change* | *Yes Climate Change* |
| **Scientific Prediction** | *No Climate Change* | Good Prediction | Trojan Horse Error |
| | *Yes Climate Change* | Cry Wolf Error | Good Prediction |

Credits to: Trenberth, Gleick

# NOAA report says California drought mostly due to natural causes, not global warming

The Washington Post

* NOAA says the drought is just ‘natural variability’
  * I think they are confused and this is the wrong message
* Lots of Push Back from Other Scientists
  * Not Peer Reviewed
  * Misses many things
* Holdren Testimony 2014:
  * Ongoing debate over CA circulation patterns – variability vs. change
  * Climate change has 4 drought causing mechanisms all at work here: (1) more downpours and less absorption, (2) more rain and less snow (3) earlier snow melts, (4) higher evaporation
* My take
  * Intensity: Future droughts will be as intense or more intense as this drought
  * Duration: Hard to say
  * Frequency: Hard to say but ….
* State will get slammed by floods, too, at some point
* And don’t forget about sea level rise
* Sources: Dan Swain Blog, Cliff Mass Blog, Revkin Blog, Peter Gleick, Holdren, Michael Mann




* California Drought Attribution Battles How Dumb are we?

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*"You will make the same foolish mistakes you have made before, not only once but many, many times again."*

SundayReview | OPINION

# Playing Dumb on Climate Change

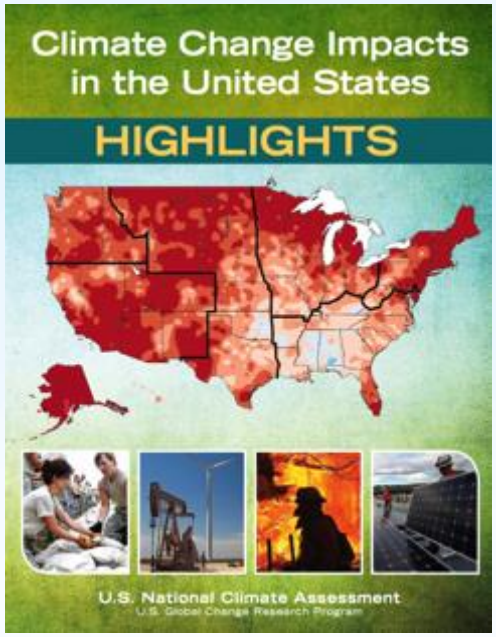
By NAOMI ORESKES JAN. 3, 2015

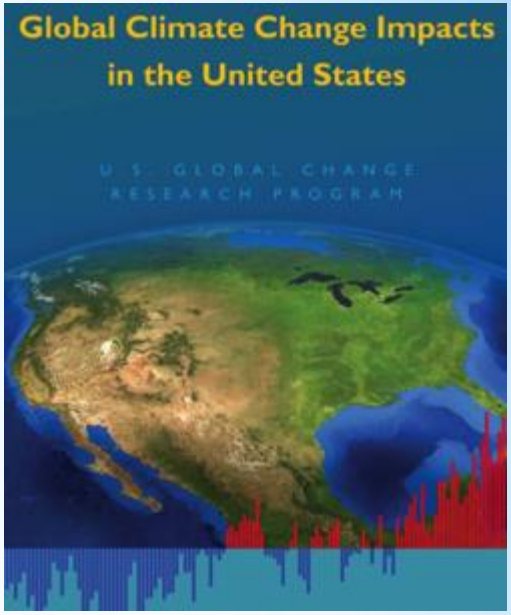
* Scientists often accused of exaggerating the risk of climate change but ought to be more emphatic about the risk
* Science is actually quite conservative and new knowledge met with skepticism
  * Copernicus on Sun, Wegner on Continental Drift, Alvarez's on Dinosaur Extinction Event
* 95% Confidence Limit Often used
  * Avoids a 5% chance that the finding Is by chance
  * A convention from early statistician, RA Fisher
  * Has no basis in nature, a value judgment
  * Avoids Type 1 Errors: Cry Wolf Error which scientists hate
  * But automatically increases Type 2 Errors: Trojan Horse Error
  * Leads us to understate the risk and play dumb
* But we are not dumb at all; we know climate change a big threat

# * Water Manager Key Points

* Climate Change is Real, Here, Important
  * There is NO uncertainty about this
* Climate Change is Water Change
  * Precipitation is not runoff
  * Annual Runoff Does Not Tell the Whole Story
  * A Shifting Hydrograph is a problem
* California will have all kinds of problems…
  * Mediterranean Climate – Drying
  * High Temperatures
  * Sea Level Rise in the Delta
  * Flooding via Atmospheric Rivers
  * Loss of Snowpack – More rain, less snow
  * Fires
* Is/Is Not Attribution Studies not helpful
  * Some Scientists are Playing Dumb
  * Climate Change affecting lots of things already
* Science very steady but also large range of futures
  * Do not expect much more from science in at least next 10 years
  * Uncertainty should not prevent action; We know enough to act
* Act to Manage Risks
  * Risk: probability * consequence
  * Especially Consider Low Probability High Consequence Events
* Climate Change makes _____ Worse
  * ____ = CA Delta, Drought, Floods, CWA, ESA, And just about anything else in the Southwest
* “Americans always do the Right Thing” ~ Churchill


ipcc
INTERGOVERNMENTAL PANEL ON climate change
CLIMATE CHANGE 2013
The Physical Science Basis
WORKING GROUP I CONTRIBUTION TO THE
FIFTH ASSESSMENT REPORT OF THE
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE


Climate Change Impacts
in the United States
HIGHLIGHTS
U.S. National Climate Assessment
U.S. Global Change Research Program


Global Climate Change Impacts
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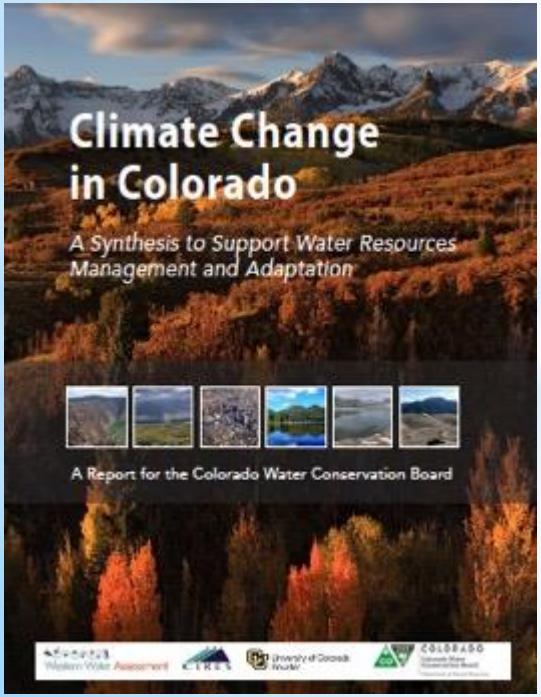
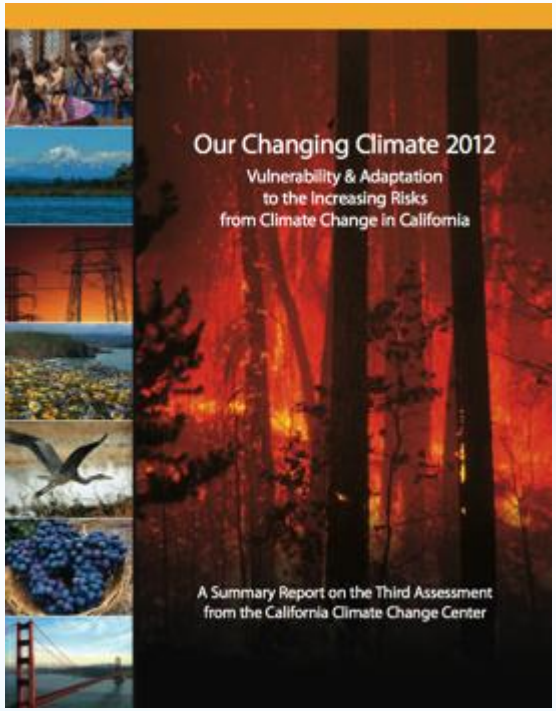
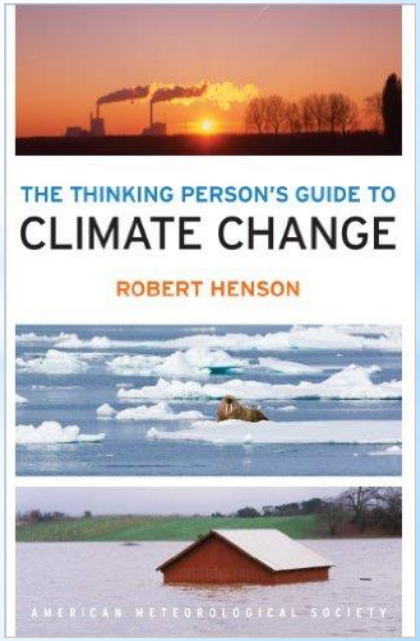
U.S. GLOBAL CHANGE
RESEARCH PROGRAM


Climate Change
in Colorado
A Synthesis to Support Water Resources
Management and Adaptation
A Report for the Colorado Water Conservation Board


Our Changing Climate 2012
Vulnerability & Adaptation
to the Increasing Risks
from Climate Change in California
A Summary Report on the Third Assessment
from the California Climate Change Center

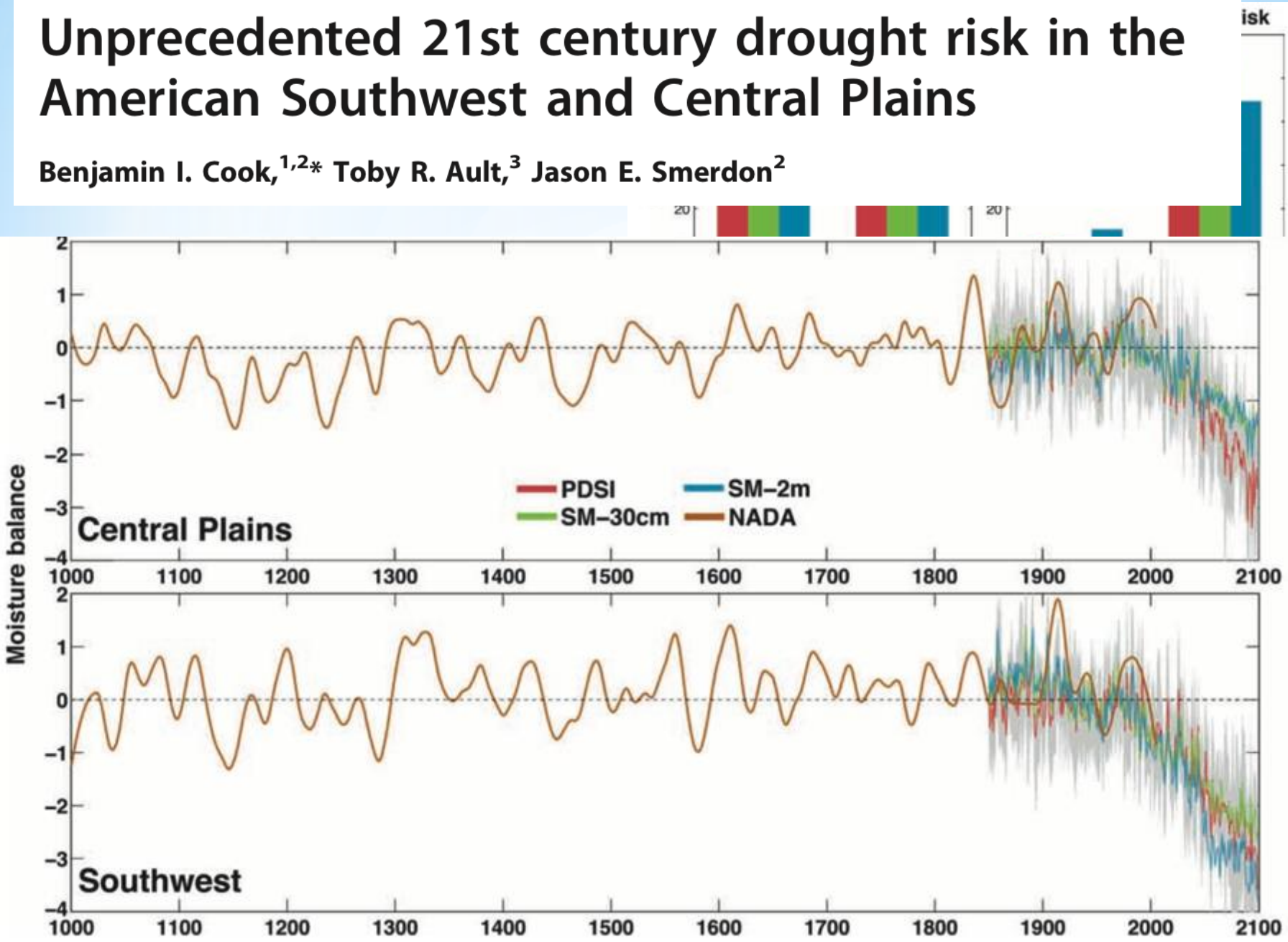

THE THINKING PERSON'S GUIDE TO
CLIMATE CHANGE
ROBERT HENSON
AMERICAN METEOROLOGICAL SOCIETY

*"Perhaps you'd like a second opinion?"*

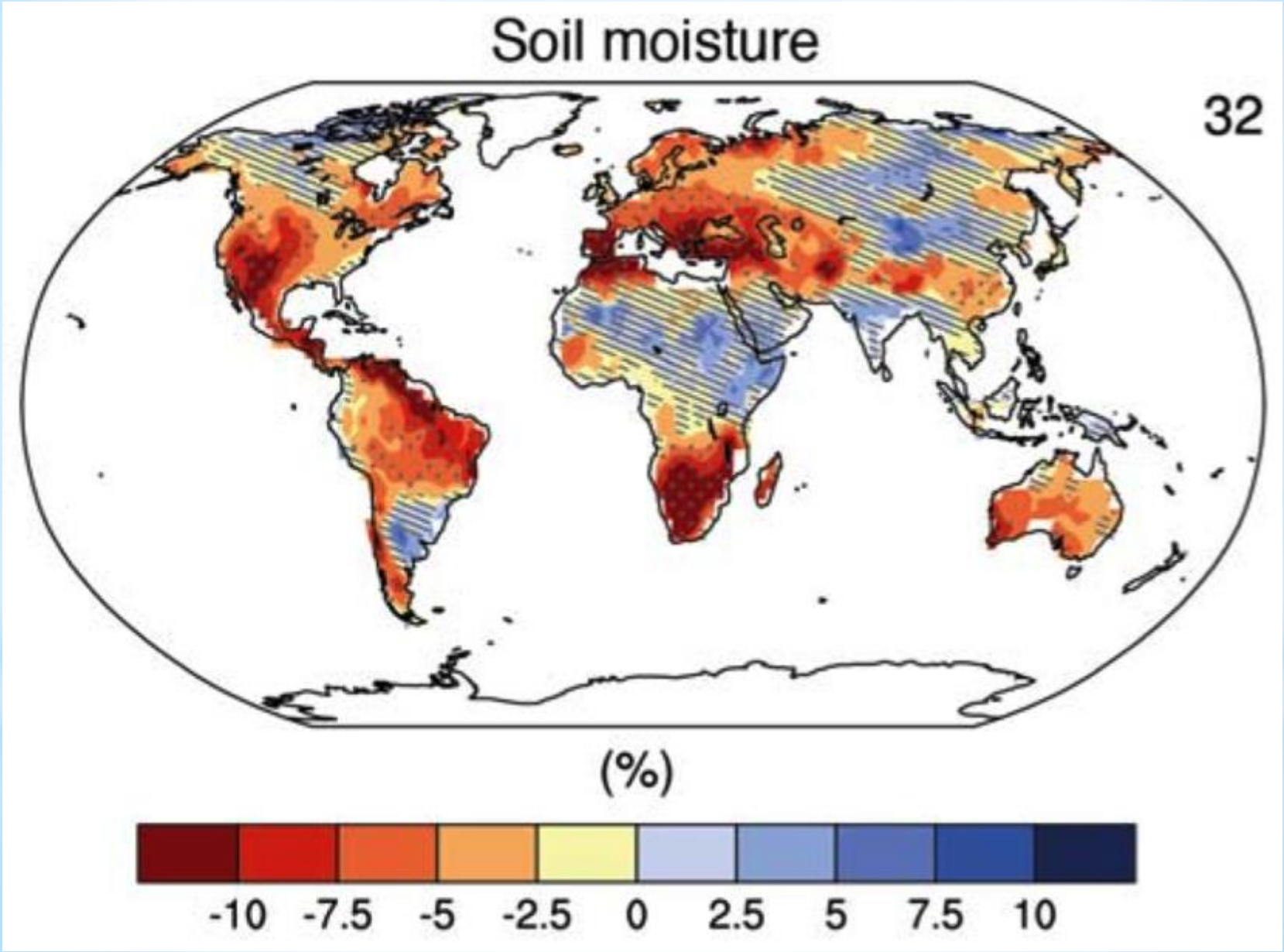
CLIMATOLOGY

# Unprecedented 21st century drought risk in the American Southwest and Central Plains

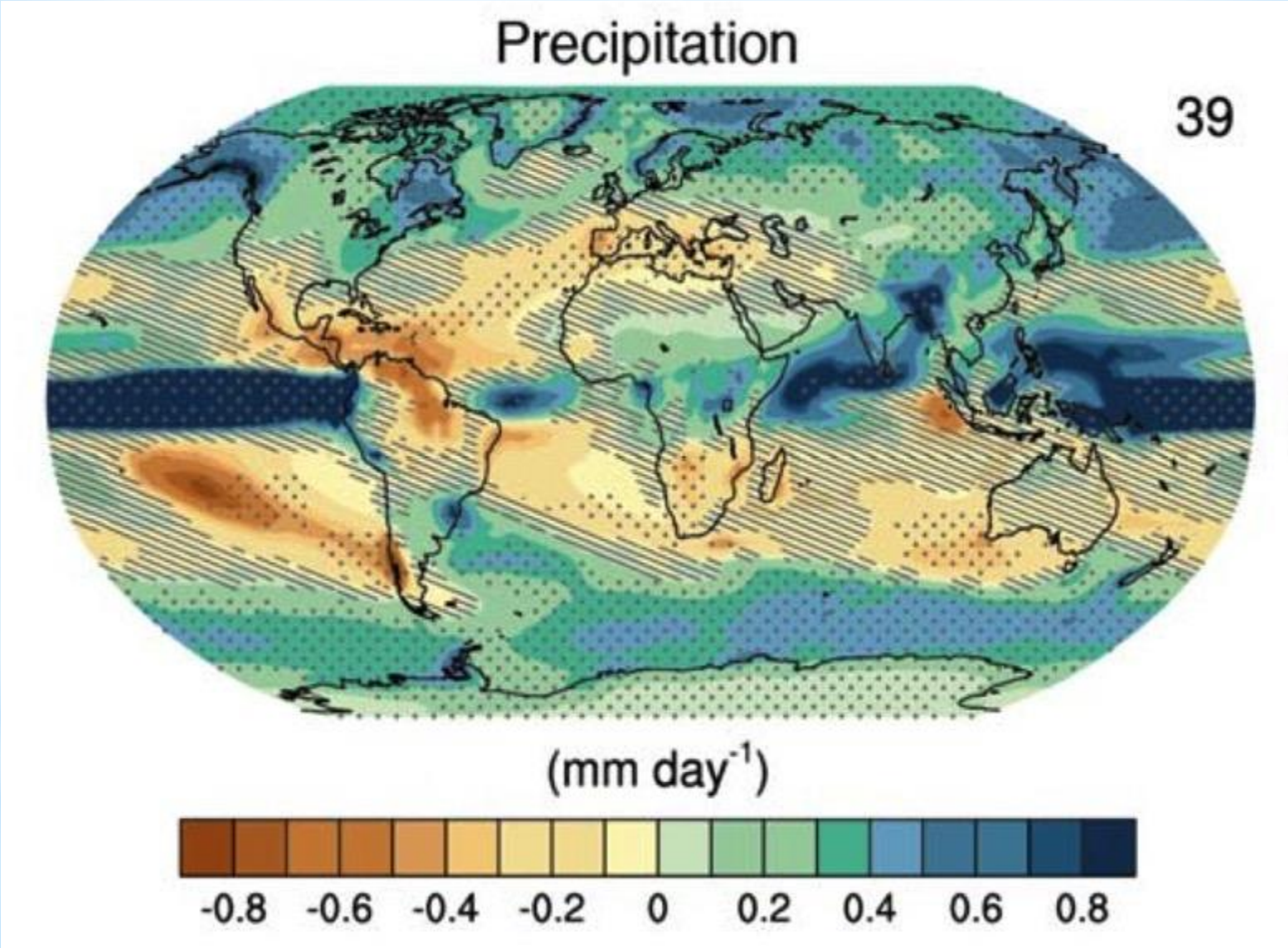
Benjamin I. Cook,[1,2]* Toby R. Ault,[3] Jason E. Smerdon[2]



# IPCC FAR Results RCP 8.5 at 2081 to 2100

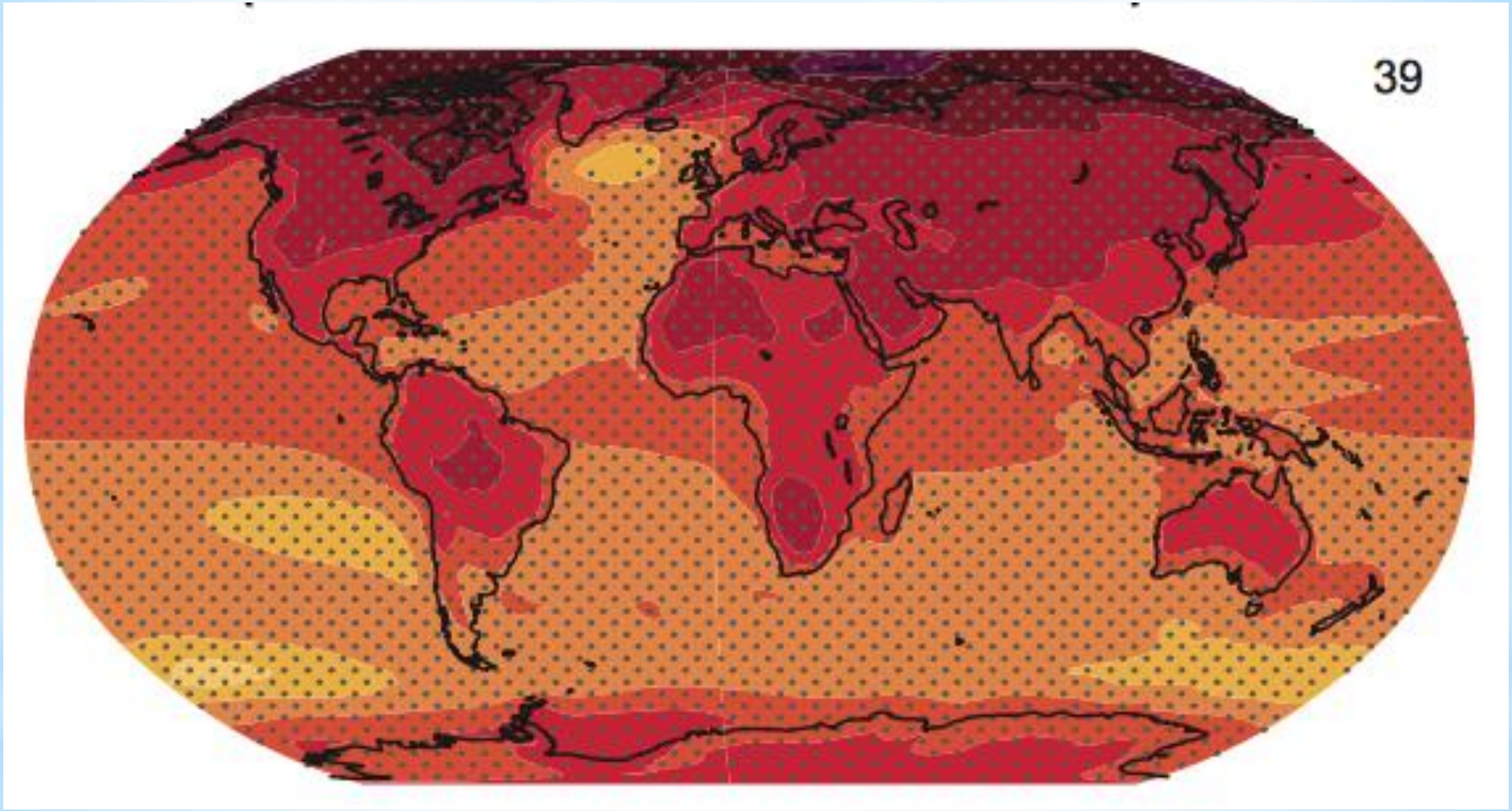


# IPCC FAR Results: RCP 8.5 Precipitation at 2081-2100




Source: IPCC 2013

# IPCC FAR Results: RCP 8.5 Temps at 2081-2100



CLIMATE CHANGE

# Dry Times Ahead

Jonathan Overpeck[1] and Bradley Udall[2]

Science, June 25, 2010

The climate of the western United States could become much drier over the course of this century.

* 2F Warming since 1900
* Snowpack Reductions and Changes in Runoff Timing Already Present
* Most Severe Drought since records kept
* Powell and Mead at 50% of capacity now, full 2000
* Tree Mortality Rates High
* Increase in Wildfire Frequency
* Drought may be natural, but exacerbated by higher temperatures
* Snowpack Reductions and Runoff Timing attributed to climate change
* Continued drying likely as temperatures increase and storm tracks shift
* Megadroughts independent of climate change a possibility with severe consequences if combined with warming

# *Recent Science Articles on Similar Themes*

PREDICTING CLIMATE CHANGE

## Vital Details of Global Warming Are Eluding Forecasters

Decision-makers need to know how to prepare for inevitable climate change, but climate researchers are still struggling to sharpen their fuzzy picture of what the future holds

SCIENCE VOL 334 14 OCTOBER 2011

ADAPTATION TO CLIMATE CHANGE

## Time to Adapt to a Warming World, But Where's the Science?

With dangerous global warming seemingly inevitable, users of climate information—from water utilities to international aid workers—are turning to climate scientists for guidance. But usable knowledge is in short supply

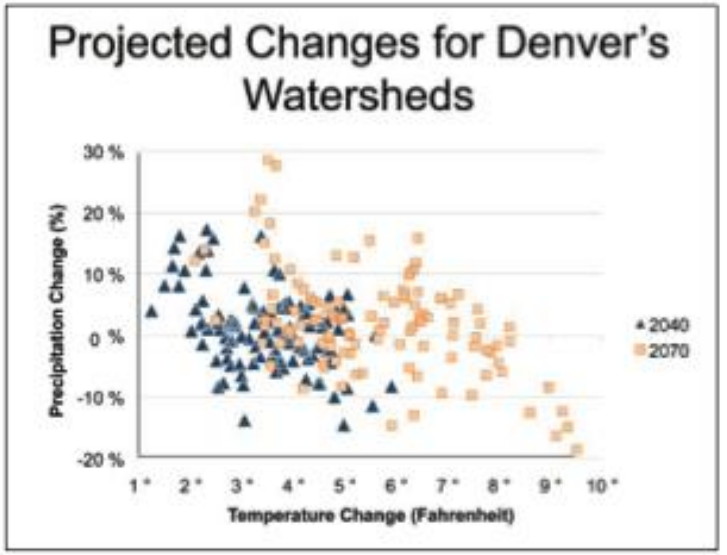
25 NOVEMBER 2011 VOL 334 SCIENCE

"Many regional modelers don't do an adequate job of quantifying issues of uncertainty."

"We are not confident predicting the things people are most interested in being predicted."

"The problem is that precision is often mistaken for accuracy."

~ Christopher Bretherton
University of Washington




**A fuzzy future.** Sixteen climate models run under three greenhouse gas emission scenarios consistently showed warmings (horizontal spread), but some projected more precipitation and others less (vertical spread).

# Confidence, Uncertainty and Decision-Support Relevance in Climate Predictions

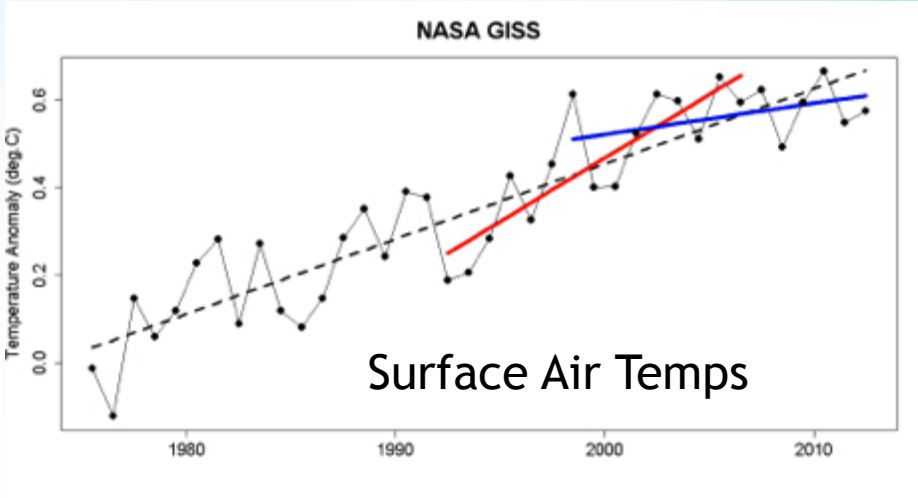
- Models can't be calibrated – simulating never before seen state
  - Contrast with Weather where models interpolate
  - Climate models: no archive over time, run once, projection times >> model life
- PDFs can be made but what they represent is not what we thought
  - We thought a 'PDF of the Future' initially
  - But models are only a Lower Bound on Range of Uncertainty
  - True Future PDF is wider
- At least 3 Sources of Uncertainty
  - Forcing
    - Emissions Scenario
  - Initial Conditions
    - Makes a Difference to End Results
    - Does Not Make a Difference to End Results
  - Model Imperfection
    - Model Uncertainty – e.g. parameters for physical processes
    - Model Inadequacy – incorrect formulation
- No rational way to weight models now

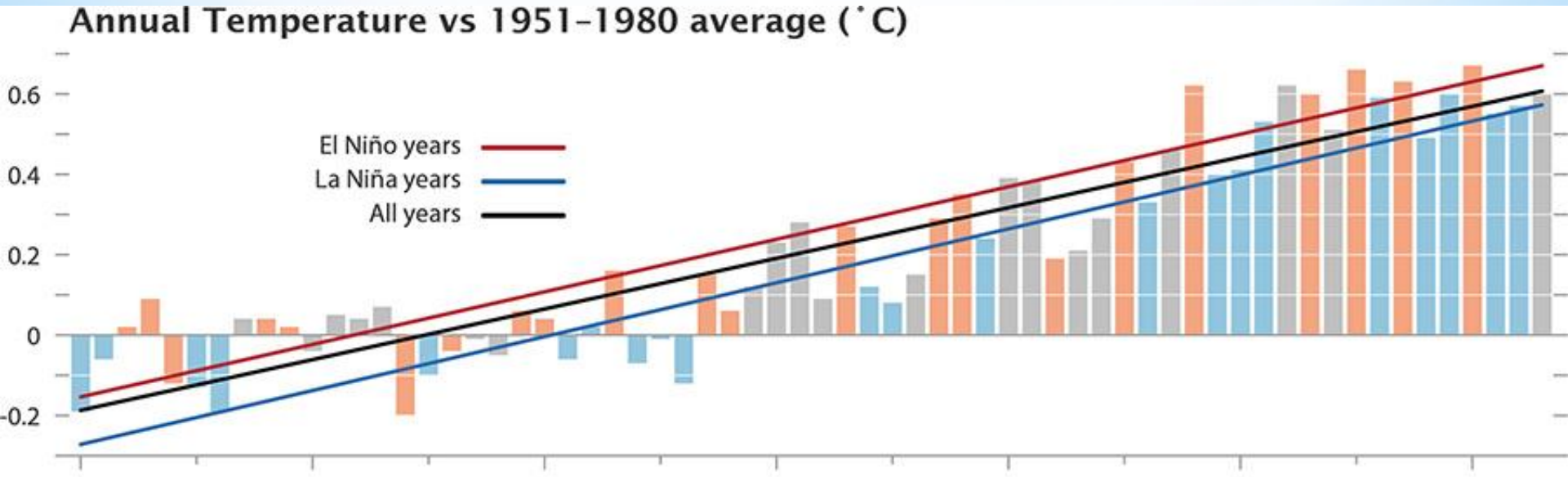
**Confidence, uncertainty and decision-support relevance in climate predictions**
D.A Stainforth, M.R Allen, E.R Tredger and L.A Smith
*Phil. Trans. R. Soc. A* 2007 **365**, 2145-2161 doi: 10.1098/rsta.2007.2074

# * the "Faux Pause"

## Where Did the Heat go?
## 1998 - 2014

- Multiple Theories about the fate of the 'missing' extra heat
- El Nino works both ways –
  - 1998 Released Heat
  - La Nina can store heat deep in the ocean via winds
- Other Contributors
  - We may not be measuring polar temperatures correctly
  - Slightly less solar output (but not much!)
  - Volcanic Cooling?



# An Australian Example - Kiem and Verdon-Kidd

## Steps toward "useful" hydroclimatic scenarios for water resource management in the Murray-Darling Basin

Anthony S. Kiem[1] and Danielle C. Verdon-Kidd[1]

Received 29 July 2010; revised 8 February 2011; accepted 21 March 2011; published 16 June 2011.

[1] There is currently a distinct gap between what climate science can provide and information that is practically useful for (and needed by) natural resource managers. Improved understanding, and model representations, of interactions between the various climate drivers (both regional and global scale), combined with increased knowledge about the interactions between climate processes and hydrological processes at the regional scale, is necessary for improved attribution of climate change impacts, forecasting at a range of temporal scales and extreme event risk profiling (e.g., flood, drought, and bushfire). It is clear that the science has a long way to go in closing these research gaps; however, in the meantime water resource managers in the Murray-Darling Basin, and elsewhere, require hydroclimatic projections (i.e., seasonal to multidecadal future scenarios) that are regionally specific and, importantly, take into account the impacts, and associated uncertainties, of both natural climate variability and anthropogenic change. The strengths and weaknesses of various approaches for supplying this information are discussed in this paper.

**Citation:** Kiem, A. S., and D. C. Verdon-Kidd (2011), Steps toward "useful" hydroclimatic scenarios for water resource management in the Murray-Darling Basin, *Water Resour. Res.*, *47*, W00G06, doi:10.1029/2010WR009803.

# KVK - Identified Shortcomings with Current Approach

- Failure to simulate synoptic patterns that drive rainfall, especially extremes
- Large Scale Processes not well simulated: ENSO, IOD, Others
  - Not understood, either
- Of 39 GCM runs, 22 show increases, 17 show decreases in precipitation
- None of the models could reproduce the drying trend since mid 1990s
- GCMs couldn't distinguish between wet coastal strip and dry interior 300 km away
- Climate model outputs at monthly and submonthly scale do not reproduce historical climate and show significant biases
  - Downscaling (Bias Correction and Change Factor) introduce 'false precision' and introduce an additional layer of uncertainty
  - Bias Corrections assumed to be stationary over time
- Climate to Hydrology Connection is Poorly Understood

# KVK - "A 5-Step Way Forward"

- Step 1: Communication Between Climate Scientists, Hydrologists, and Water Resource Managers
  - Define what is 'practically useful'
  - Disconnects about what can be expected and How to act in face of uncertainty
- Step 2: Quantify Baseline Risk Associated with Natural Climate Variability
  - Need to understand paleoclimate better
    - How dry can it get and for how long?
  - Need to understand drivers of variability
  - Stochastic Framework needed to integrate both
- Step 3: Incorporate the Projected Impacts of Anthropogenic Change
  - Identify physical processes driving hydroclimate
  - Identify or Develop models that simulate these processes
  - Determine how processes will change in the future and apply changes in stochastic framework
- Step 4: Develop Appropriate Adaptation Strategies
  - Need Reliable Probabilities of Uncertainties
  - Robust Quantification of Uncertainties Needed
  - Identify Win-win Adaptation Strategies
- Step 5: Ongoing Communication