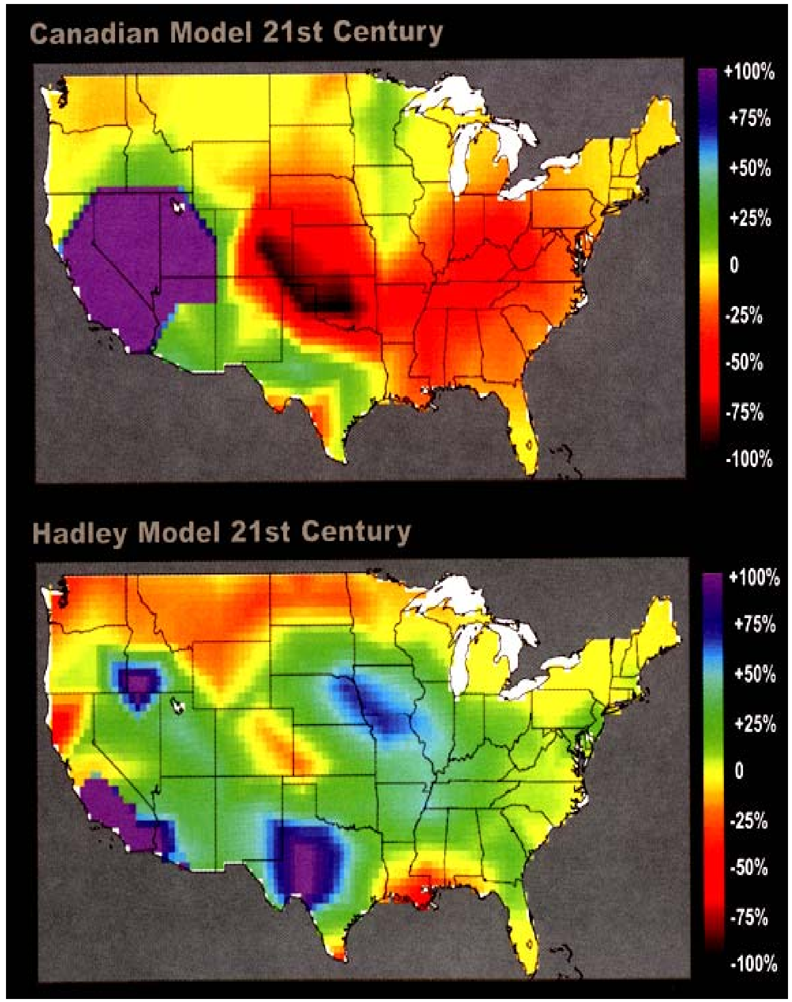
15.023J / 12.848J / ESD.128J Global Climate Change: Economics, Science, and Policy
Spring 2008

THE CLIMATE MACHINE V: Unresolved Problems in Climate Analysis

R. PRINN, May 5, 2008

1. Predicting Regional Climate: Local Effects?
2. Impacts of Climate Change: Biosphere?
3. Severe Storms: Damages Increase with Warming?
4. Cooling Effects of Aerosols: Unveiling of True Warming?
5. Critical Thresholds: Stability of Ice Sheets, Tundra, Carbon Sinks and Oceanic Overturn?
6. Stabilization of GHGs: What Levels Will Avoid Danger?
7. Energy Solutions: Effects at Large Scale?
8. Geo-engineering: Viable option or dangerous diversion?
9. Possible Defining Climate Events: The next 20 years?

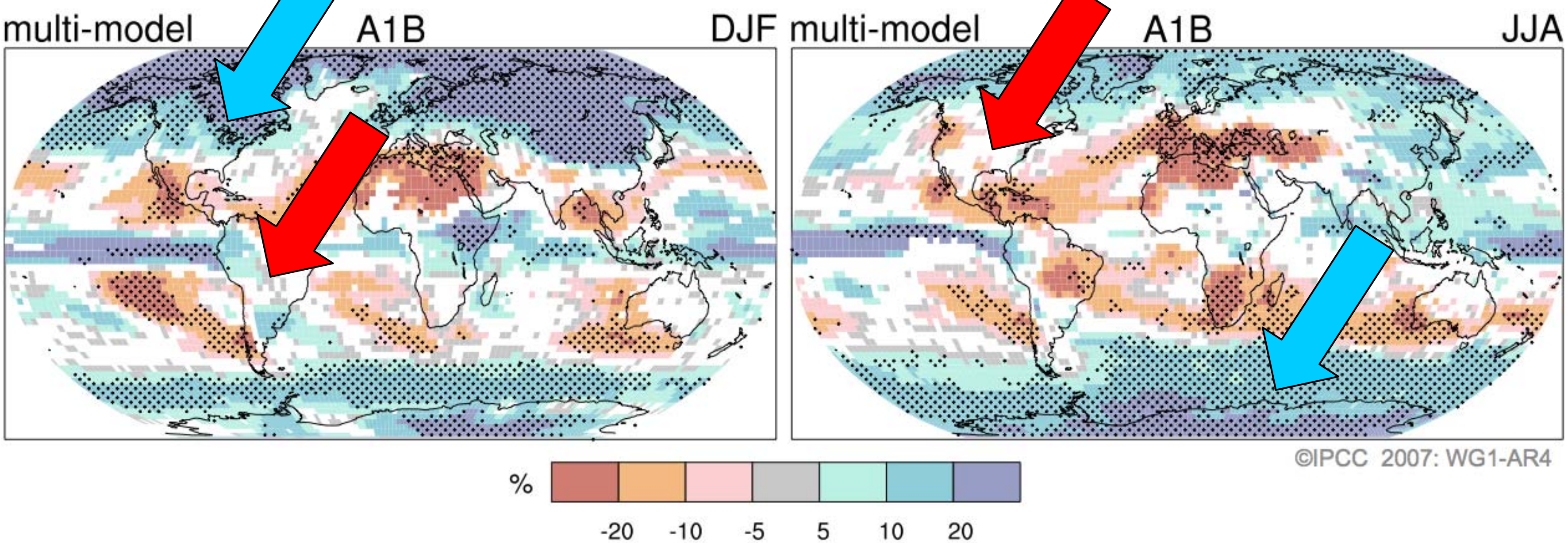
1. PREDICTING REGIONAL CLIMATE
Some Results for soil moisture-very important for agriculture



MESSAGE:
CURRENT REGIONAL FORECASTS ARE VERY UNCERTAIN!

REF: US GCRP: CLIMATE CHANGE IMPACTS ON THE UNITED STATES

Projected Patterns of Precipitation Changes



Multimodal average percentage changes in precipitation for 2090-2099 relative to 1980-1999 (A1B SRES emission scenario).

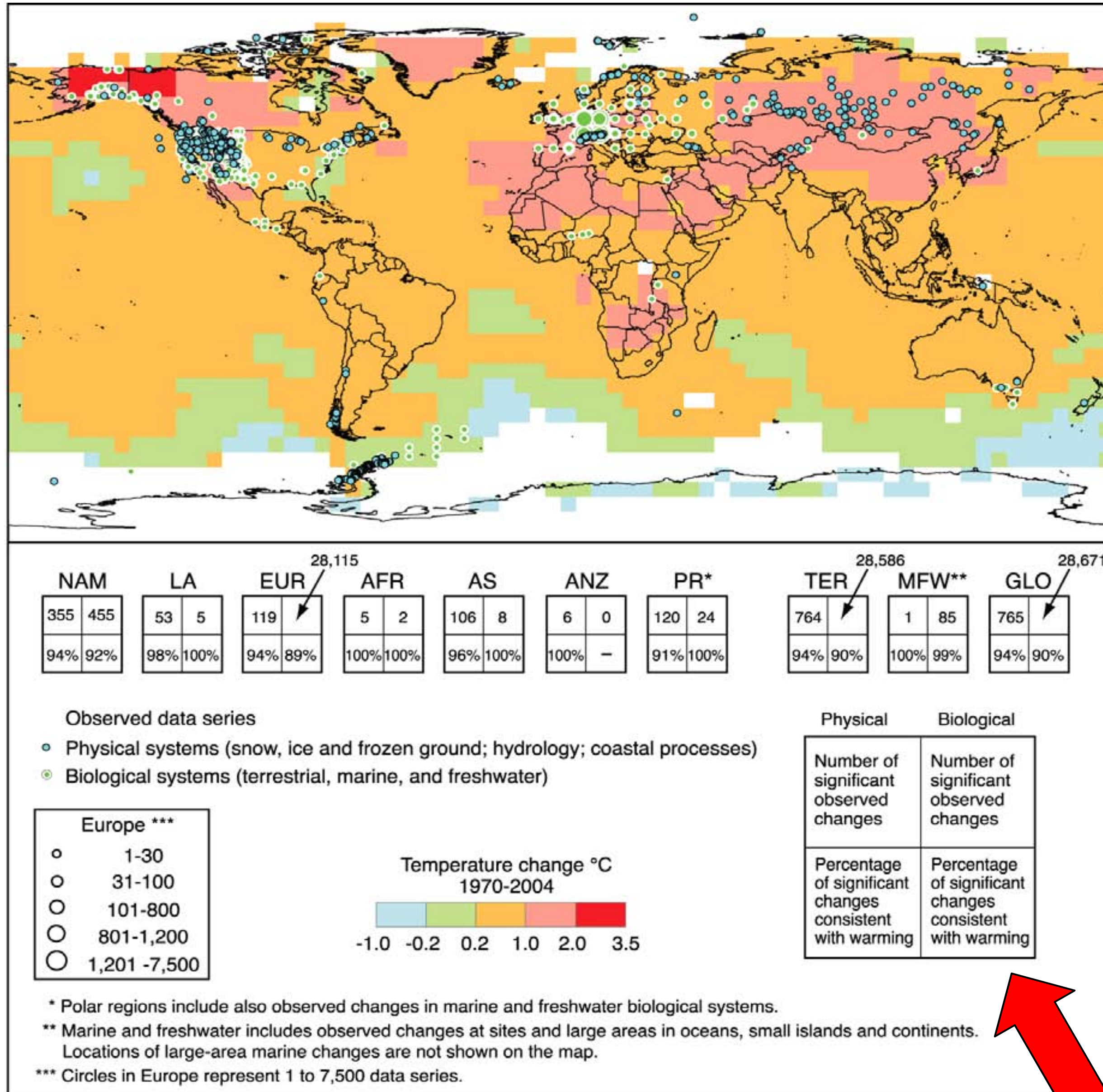
White areas: <66% of models agree in sign of change.

Stippled Areas: >90% of models agree in sign of change.

Ref: IPCC 4th Assessment, Summary for Policymakers, Feb. 2, 2007

2. IMPACTS OF CLIMATE CHANGE
Physical and Biological Systems

Figure SPM-1. Locations of significant changes in observations of physical systems (snow, ice and frozen ground; hydrology; and coastal processes) and biological systems (terrestrial, marine, and freshwater biological systems), are shown together with surface air temperature changes over the period 1970-2004.

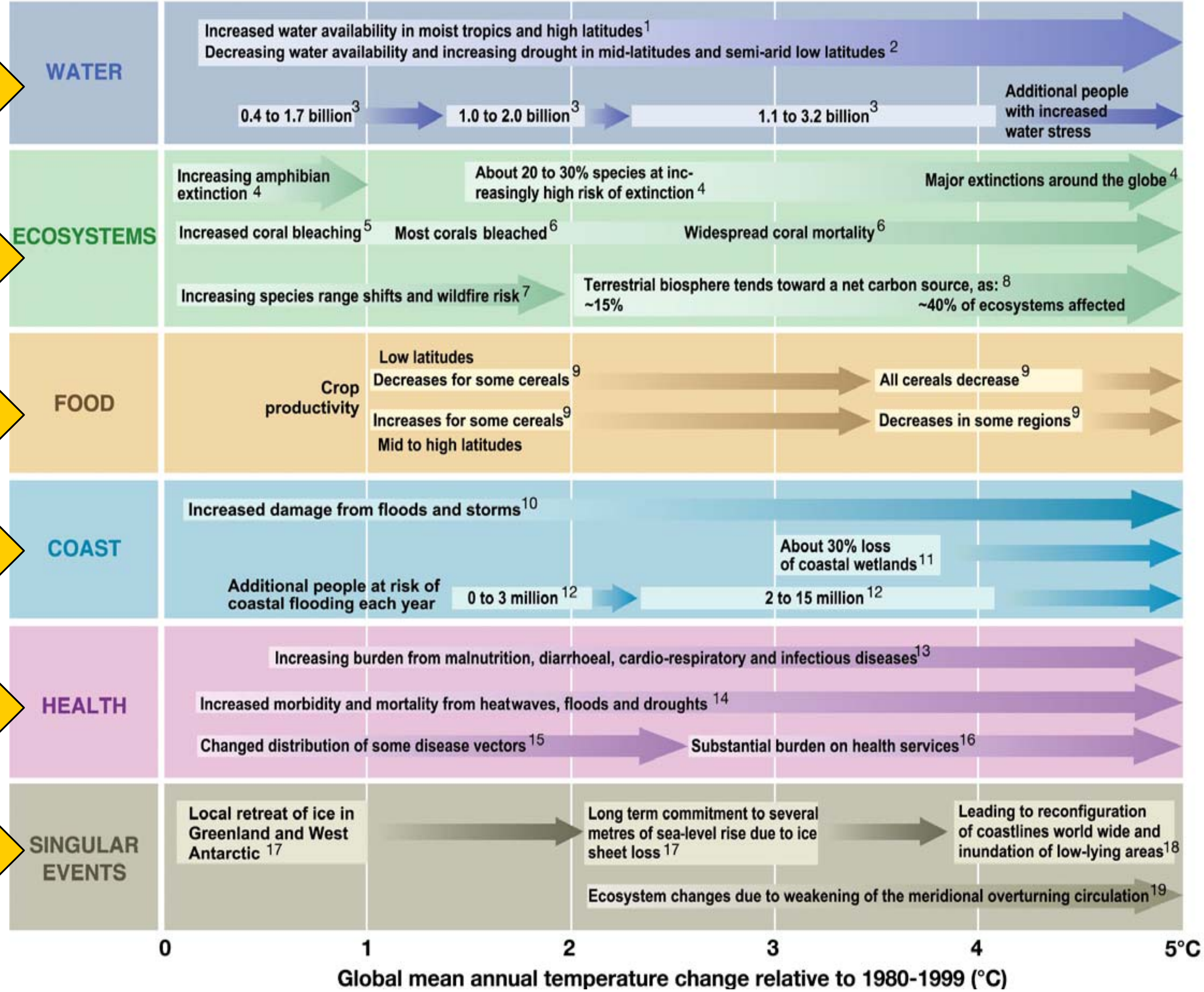


From: Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Figure SPM.1, Cambridge University Press.

Summary for Policymakers IPCC WGII Fourth Assessment Report, April 2007

Key impacts as a function of increasing global average temperature change

(Impacts will vary by extent of adaptation, rate of temperature change, and socio-economic pathway)



BUT, HOW RELIABLE ARE THESE PROJECTIONS?

Table SPM-1. Illustrative examples of global impacts projected for climate changes (and sea-level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century [T20.7]. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left hand side of text indicates approximate onset of a given impact. Confidence levels for all statements are high.

Summary for Policymakers IPCC WGII Fourth Assessment Report, April 2007

3. SEVERE STORMS
Damages Increase with Warming?

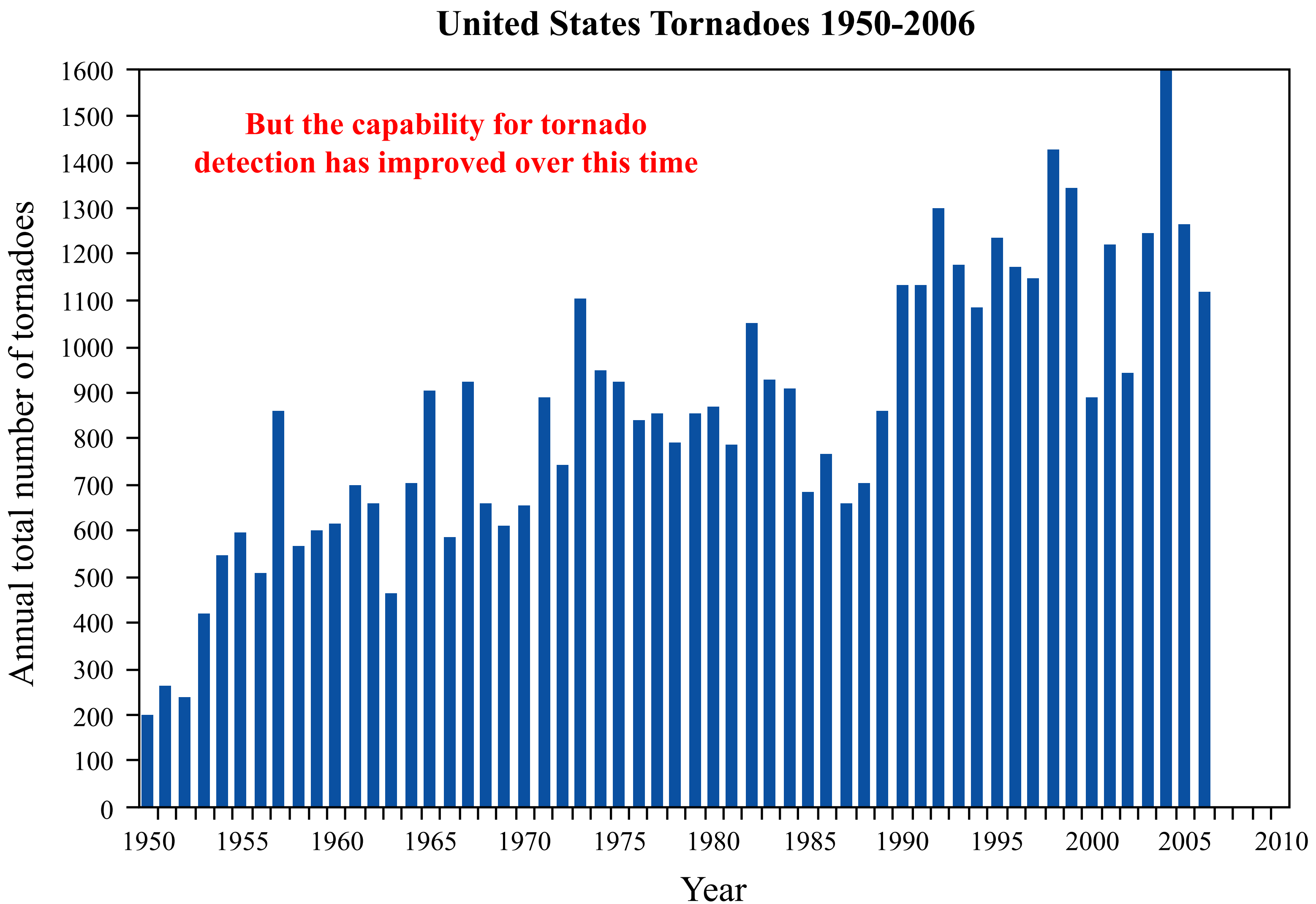
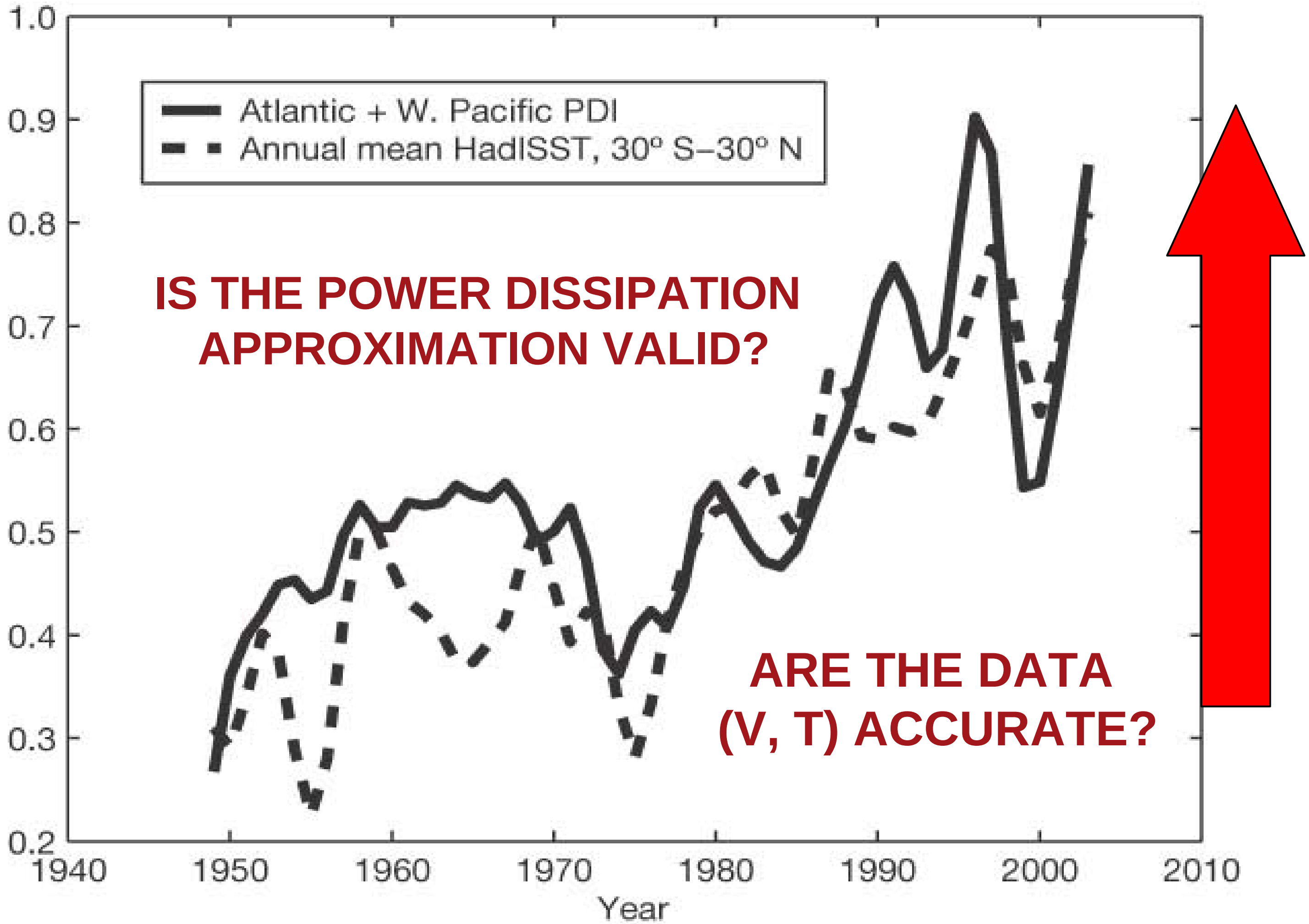


Figure by MIT OpenCourseWare.

HURRICANES:
INCREASING DESTRUCTIVENESS OVER THE PAST 30 YEARS?

Power Dissipation Index (PDI) $= \int_0^T V_{max}^3 \, dt$ (a measure of storm destruction)



Courtesy of Kerry Emanuel. Used with permission.

SOURCE: Emanuel, K., *Nature*, vol. 436, 4 August 2005

4. COOLING EFFECTS OF AEROSOLS
Unveiling of true warming?

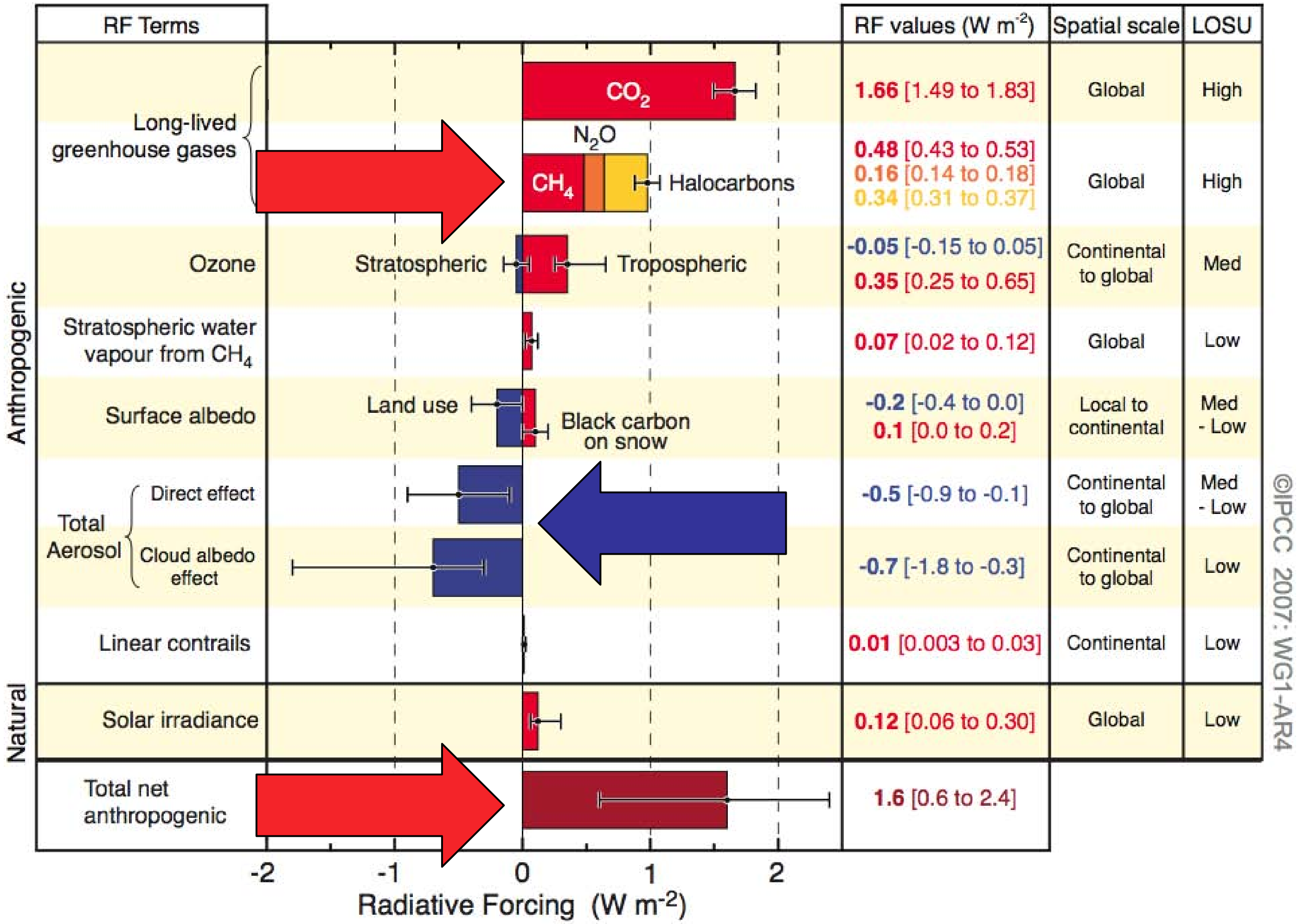
WHAT ARE THE EFFECTS OF AEROSOLS ON CLIMATE?

(A) Direct Effect: Aerosols reflect (sulfates) or absorb (black carbon) sunlight

(B) Indirect Effects: activated aerosols create more and smaller cloud droplets which: (1) increases reflection, and (2) suppresses rainfall

(C) Semi-direct effect: absorbing aerosols heat air and cool surface suppressing convection and condensation

Radiative Forcing Components



Ref: IPCC 4th Assessment, Summary for Policymakers, Feb. 2, 2007

5. CRITICAL THRESHOLDS
Stability of ice sheets, tundra, carbon sinks and oceanic overturn

STABILITY OF WEST ANTARCTIC ICE SHEET

Are "moulins" lubricating ice streams and is warm water undermining ice shelves?

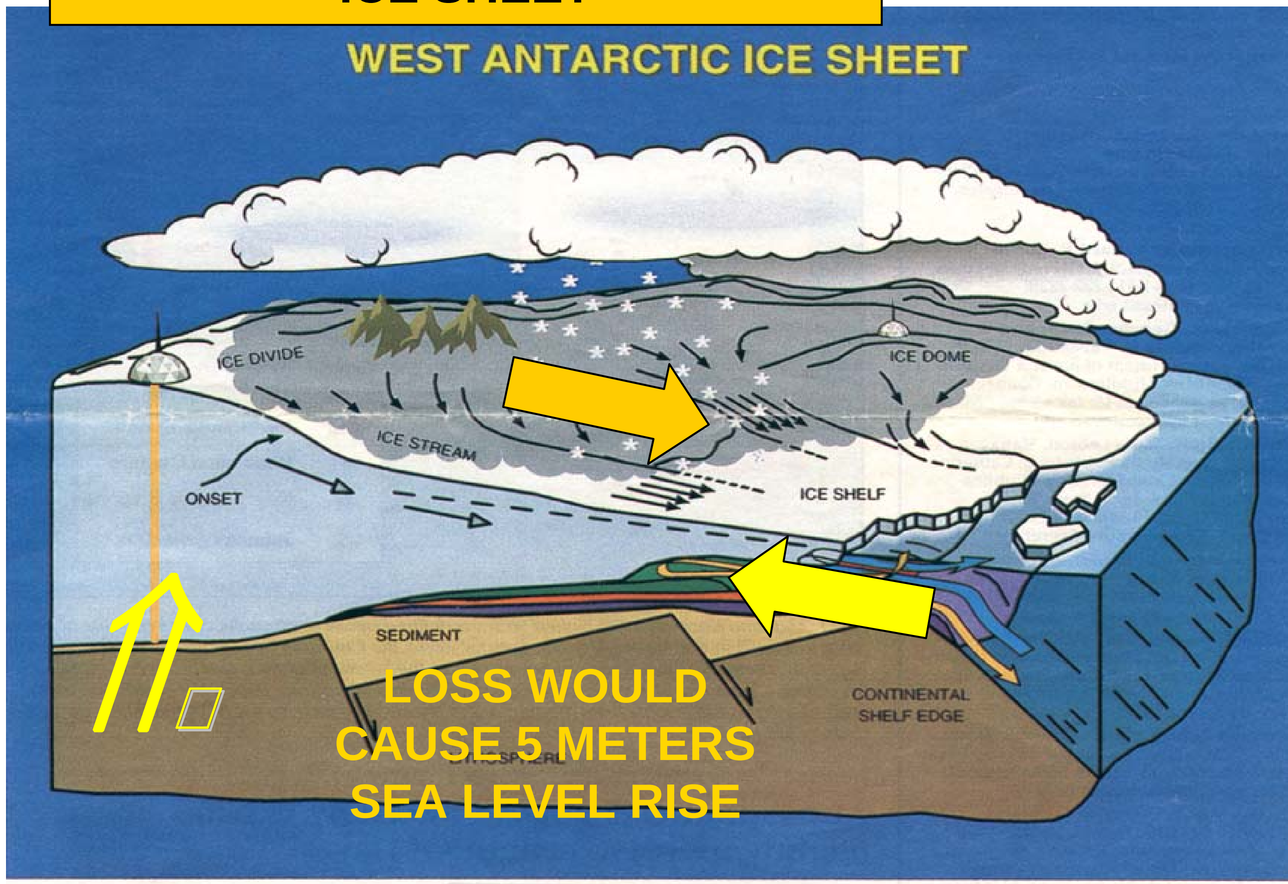
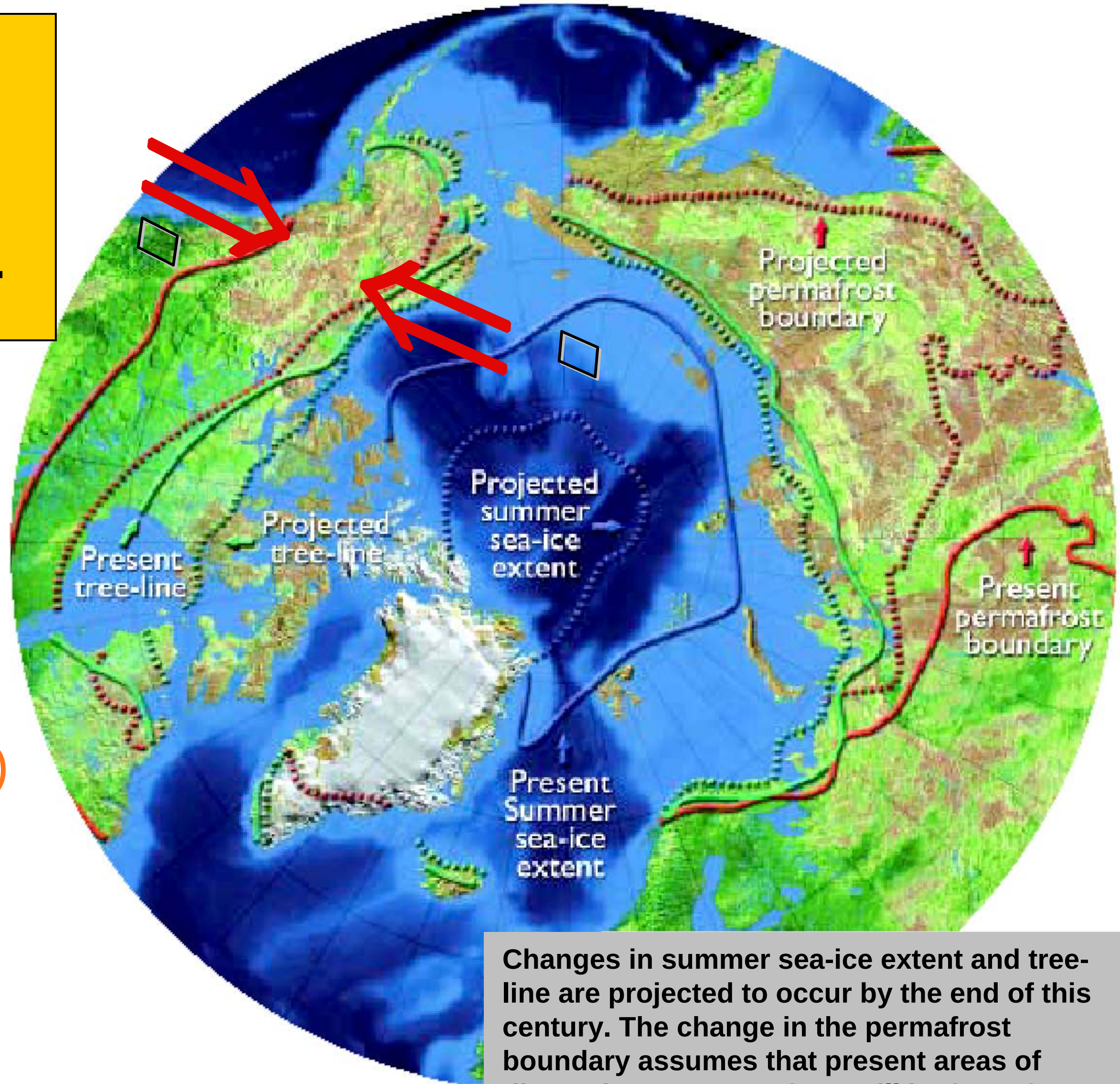


Fig. 1. West Antarctica is a tightly coupled, dynamic environment. The size of the ice sheet depends on snow accumulation, wind-driven ablation, iceberg calving, and subglacial melting and freezing. Under the floating ice shelves, circulating waters can drive melt rates in excess of 10 m per year and freeze on large volumes of marine ice. The shape of the ice sheet depends on ice-flow, which varies more than two orders of magnitude from the slow interior to the rapidly sliding ice streams. Subglacial water and till properties strongly influence where faster motion occurs. Ice domes and divides are the most stable locations for deposition and englacial archiving of past atmospheric samples. Records of past ice-sheet extents are found in isolated mountains that are high enough to emerge from the ice-sheet surface and on the floor of the seas surrounding the ice sheet.

Reference: Bindschadler et al.

Bindschadler, R. A., R. B. Alley, J. Anderson, S. Shipp, H. Borns, J. Fastook, S. Jacobs, C. F. Raymond, What is happening to the west antarctic ice sheet?, Eos Trans. AGU, 79(22), 257-257, 1998.

STABILITY OF ARCTIC TUNDRA & PERMAFROST



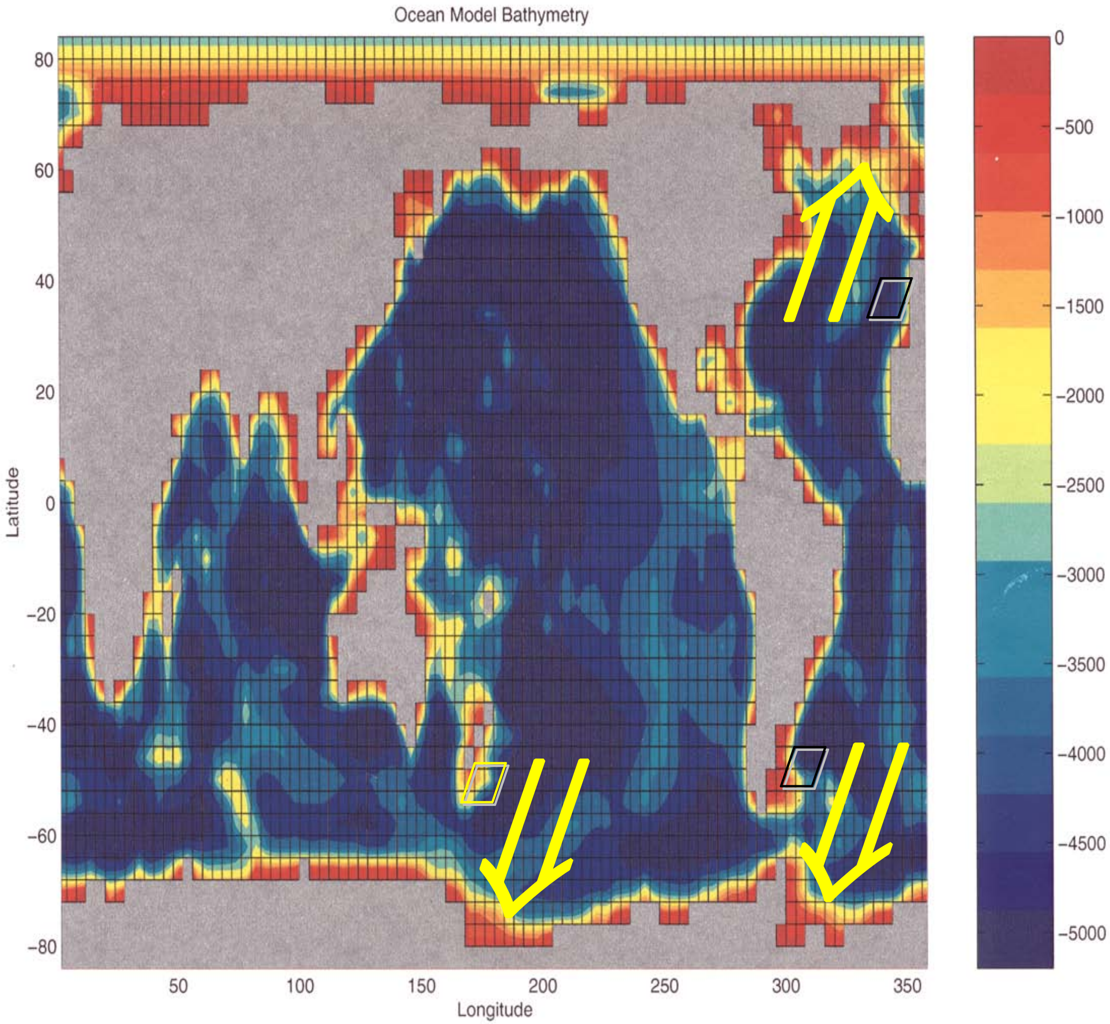
About 546 Pg (Gt) carbon stored in Arctic tundra and frozen soils ! (SCOPE 2004)

Changes in summer sea-ice extent and tree-line are projected to occur by the end of this century. The change in the permafrost boundary assumes that present areas of discontinuous permafrost will be free of any permafrost in the future and this is likely to occur beyond the 21st century.

Courtesy of the Arctic Climate Impact Assessment, 2004. Used with permission.

Source: ACIA, Impacts of a Warming Arctic, *Climate Impact Assessment Report*, Cambridge University Press, 2004

HOW STABLE IS THE OCEANIC CARBON AND HEAT SINK?



OCEAN BOTTOM DEPTHS (meters)
(MIT 3D OCEAN MODEL)

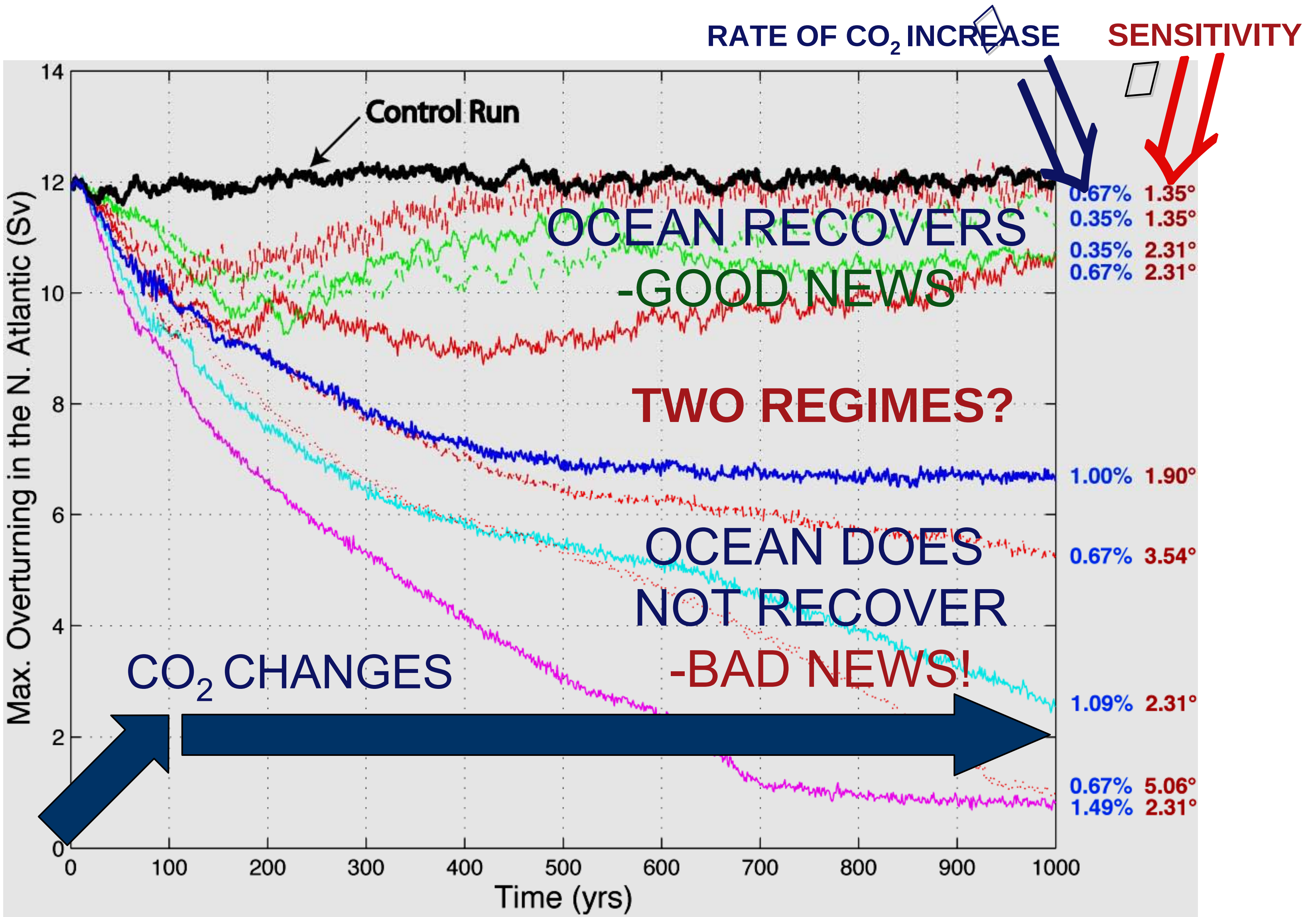
DRIVEN BY SINKING WATER IN THE POLAR SEAS (Norwegian, Greenland, Labrador, Weddell, Ross)

SLOWED BY DECREASED SEA ICE & INCREASED FRESH WATER INPUTS INTO THESE SEAS

INCREASED RAINFALL, SNOWFALL & RIVER FLOWS, & DECREASED SEA ICE, EXPECTED WITH GLOBAL WARMING

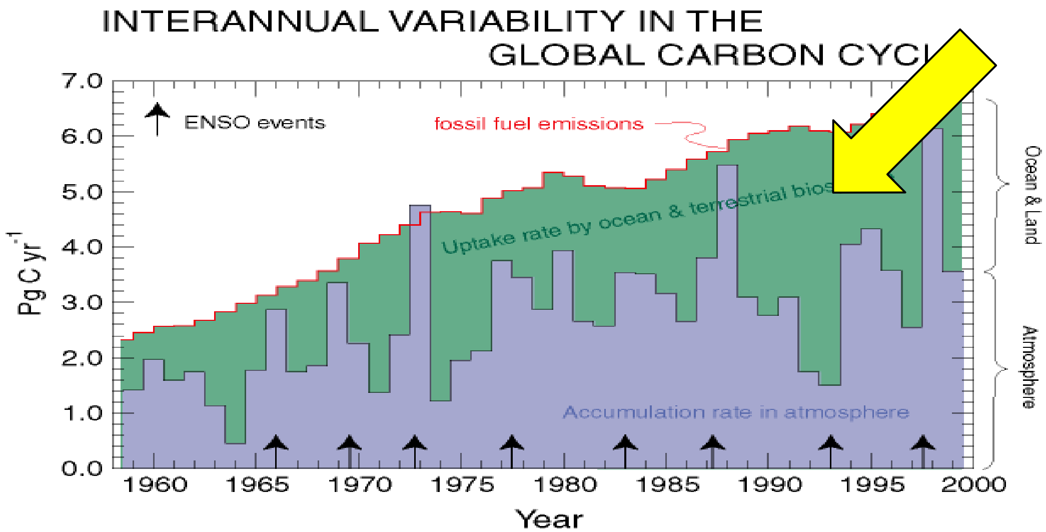
WILL THERE BE A DANGEROUS SLOWDOWN OF OCEANIC OVERTURN?

MIT IGSM 3D OCEAN MODEL (100 years of CO_2 increase then stabilization)

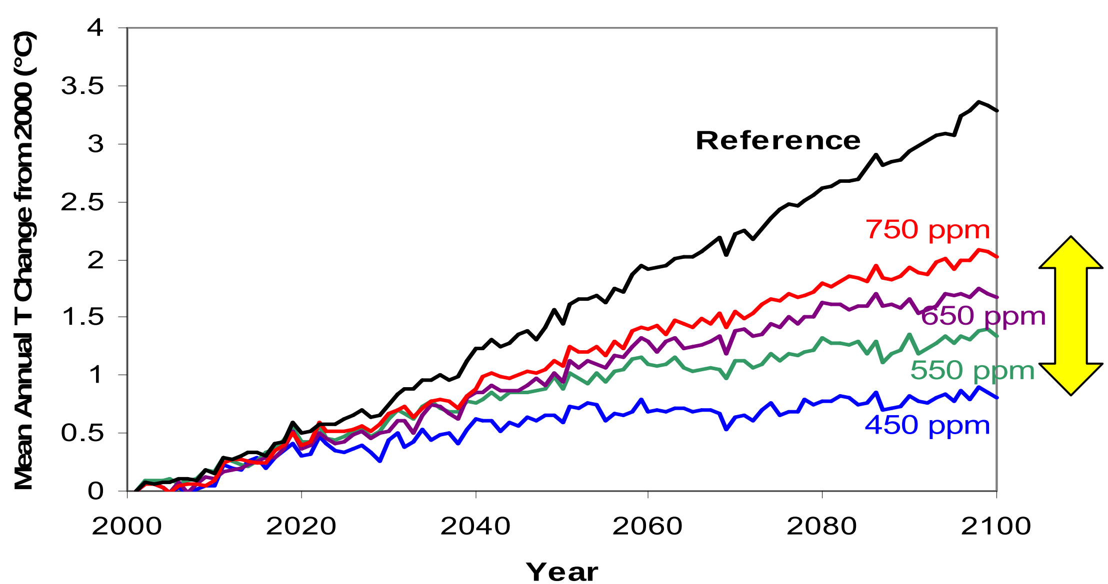


Ref: Scott et al, MIT Joint Program Report 148,Climate Dynamics, in press,2007

6. WHAT ARE THE GREENHOUSE GAS EMISSIONS & STABILIZATION LEVELS NEEDED TO AVOID DANGEROUS INTERFERENCE IN THE CLIMATE SYSTEM?



Courtesy of the American Institute of Physics. Used with permission.



THE VIEW FROM THE STERN REPORT: "THE ECONOMICS OF CLIMATE CHANGE"

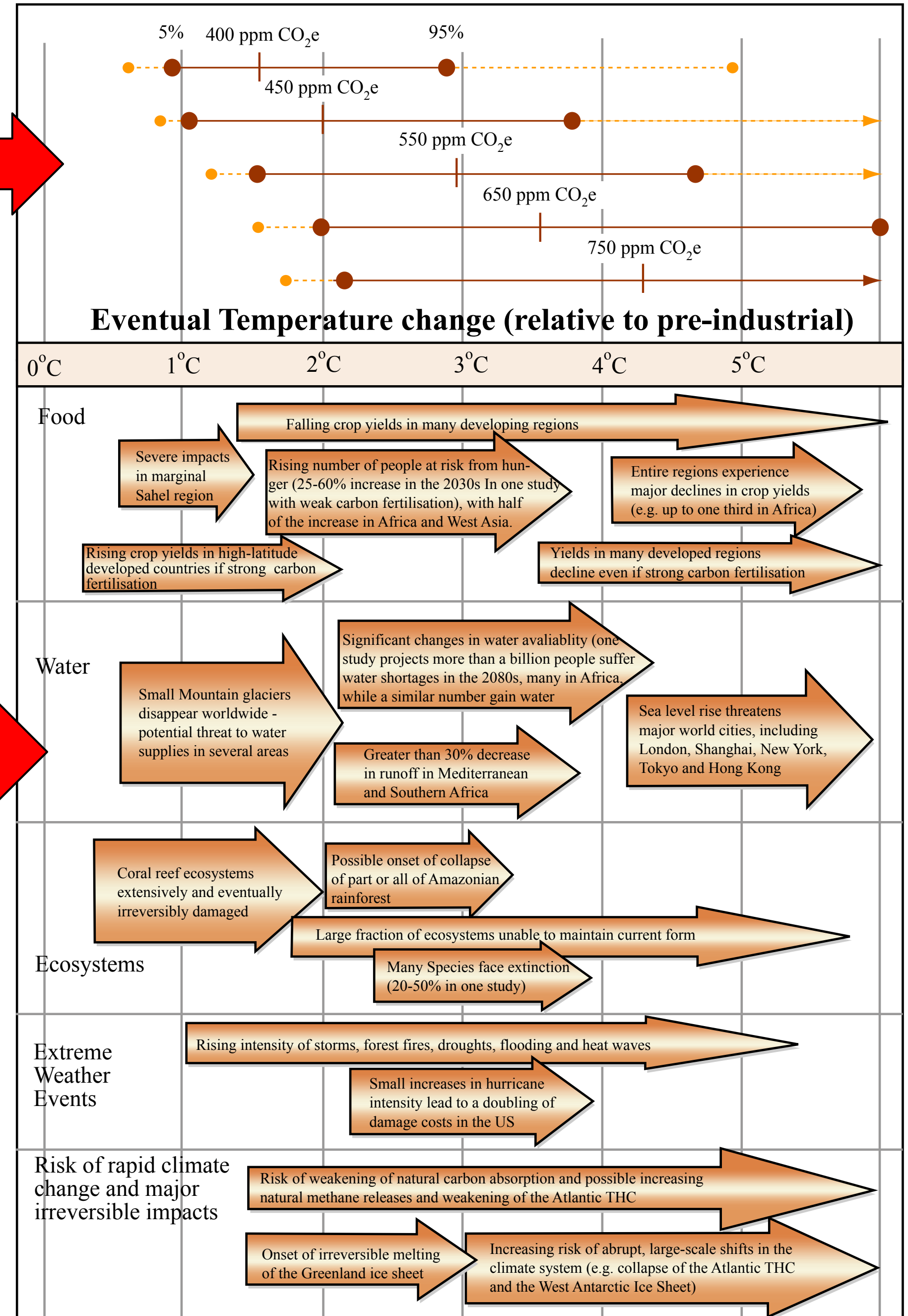
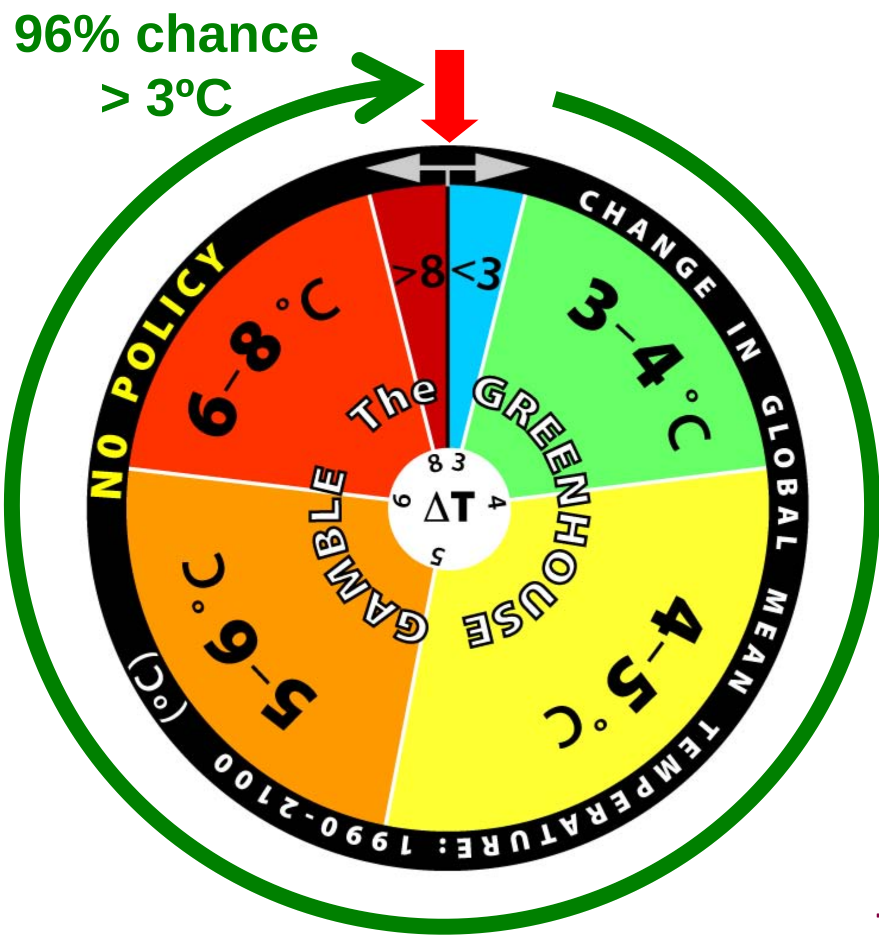
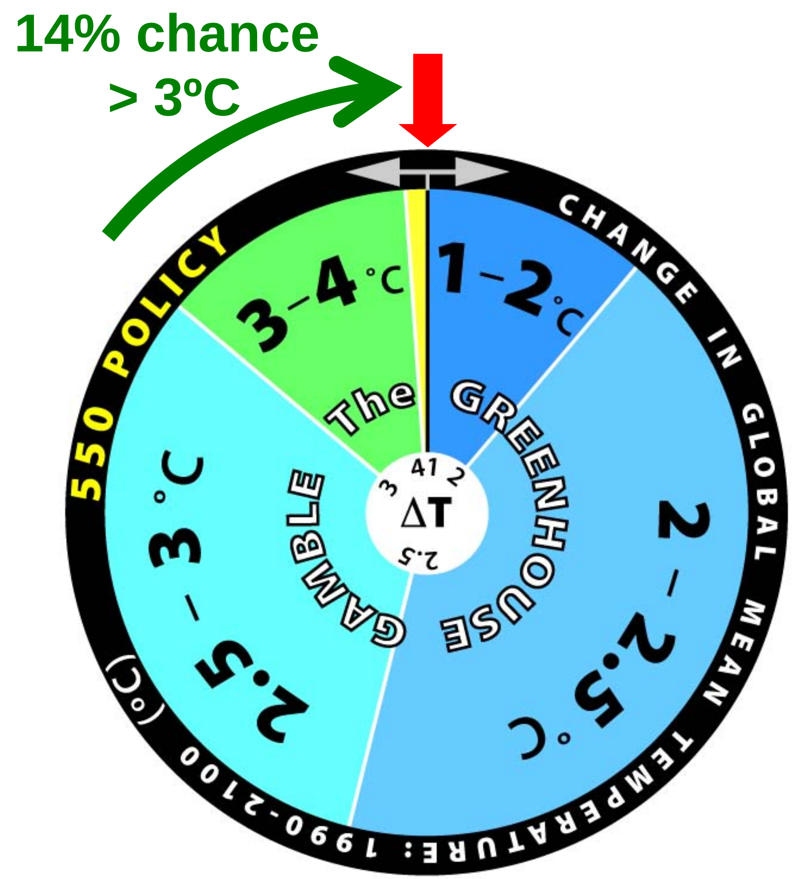


Figure by MIT OpenCourseWare, adapted from Stern Review.

NEW CALIBRATION OF IGSM: ODDS OF DANGEROUS WARMING MUCH GREATER!





Temperature increase 1990-2100 with no new greenhouse gas policy

Temperature increase 1990-2100 with stabilization of greenhouse gases at 550 ppm CO_2 equivalents

Reference: MIT Joint Program on the Science and Policy of Global Change, 2008 (http://web.mit.edu/globalchange/)

7. WHAT ARE THE ENVIRONMENTAL & ECONOMIC EFFECTS OF NEW ENERGY SOURCES AT LARGE SCALE?

World Energy Consumption: 400 exaJoules (EJ) in 2002 (87% fossil) rising to as much as 1400 EJ in 2100

Serious contenders to meet future needs must operate at large scales (e.g. 140 EJ/year or 4.4 terawatts [TW])

Environmental (climate) & Health Effects, & Economic & Technical barriers for contenders operating at these scales may be substantial

This requires in depth studies of their ENVIRONMENTAL IMPACTS and ECONOMIC VIABILITY through INTEGRATED ASSESSMENT

CHALLENGES REGARDING THE CONVERSION OF LAND FOR RENEWABLE ENERGY AT LARGE SCALES

For bio-fuels to provide 140 EJ/year (4.4 TW or 35% of current demand or 10% of 2100 demand) requires more than 2 billion acres of land dedicated to crops producing ethanol, which is 5 times the total US cropland, assuming 40% efficiency in the conversion of the biomass (cellulose).

For wind turbines to provide 4.4 TW, we need for example 4.4 million 1 MW wind turbines operating continuously, "occupying" tens of millions of km^2 for reasonable spacing, and removing 17.6 TW of atmospheric kinetic energy assuming 25% efficiency.

For solar panels (10% efficiency) to supply 4.4 TW we need to completely cover many hundred thousand km^2 with panels for typical average surface sunlight levels.

CLIMATIC EFFECTS OF RENEWABLES AT LARGE SCALES

The conversion of billions of acres of sunlight-reflecting marginal land to relatively absorbing grasslands for bio-fuels has the potential to cause significant alteration of the heat and water cycles and thus significant changes in continental climates.

Similarly, a very large scale deployment of solar panels which replace a highly reflective desert surface with highly absorbing solar panels will lead to surface warming.

Also, the massive expansion of continental wind power generators could change surface friction enough to alter atmospheric circulation and boundary layer mixing and hence regional climates.

FRACTION OF LAND DEVOTED TO BIO-FUELS PRODUCTION WITH A 550 ppm CO_2-equivalent STABILIZATION POLICY

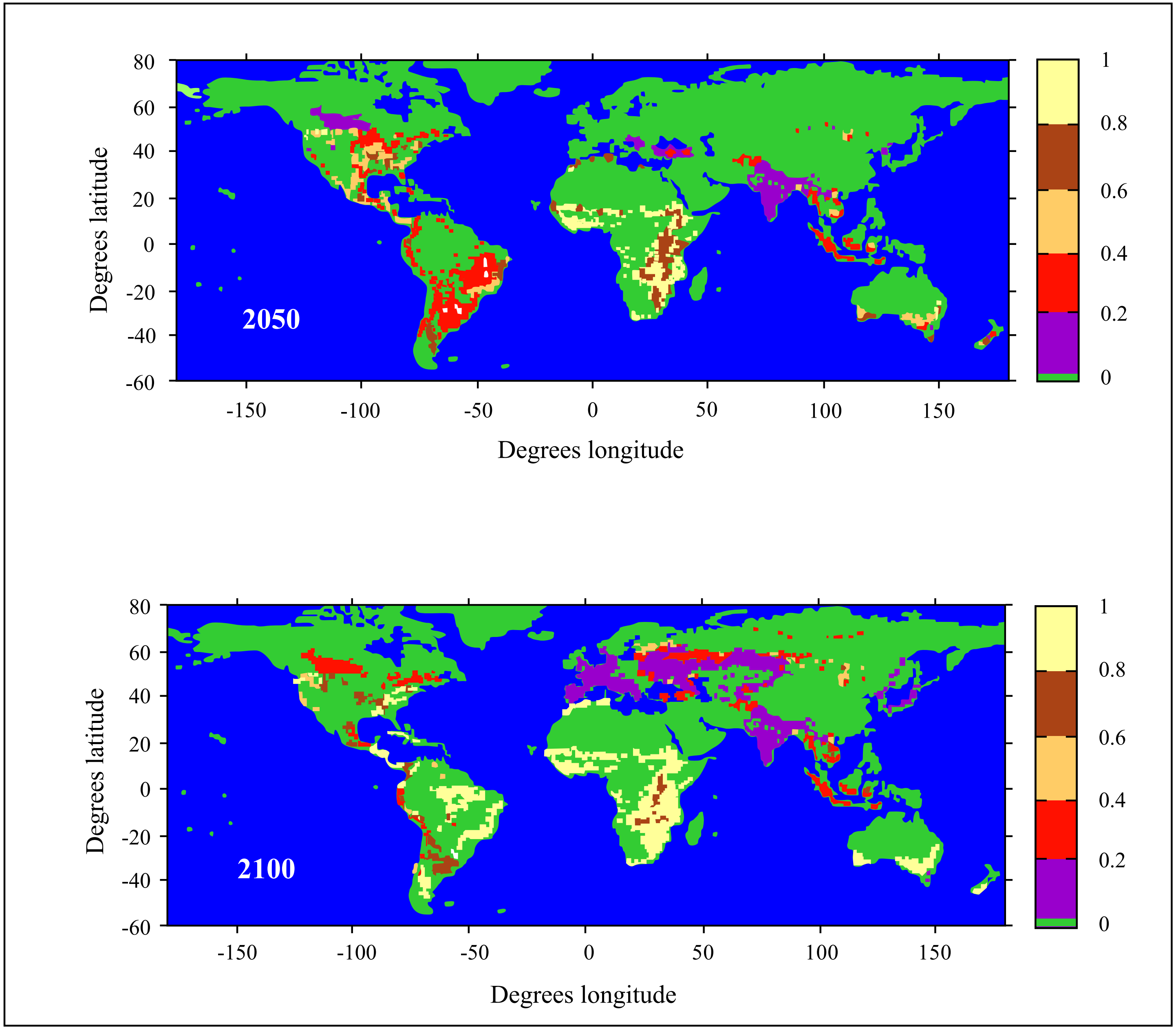


Figure by MIT OpenCourseWare.

KEY QUESTIONS REGARDING BIOFUELS AT LARGE SCALES

- Effects on food prices detrimental to large scale biofuels? Second generation bio-fuels at scale of current global oil production may have modest impacts (5-10% for crops and livestock, 20-30% for forest products).
- Transportation creates inevitable demand for bio-fuels? If other technologies successful (Plug-in Electric Hybrid Vehicles), market for biofuels may be limited.
- What carbon/fuel price is needed to drive switch to bio-fuels? Second-generation biofuels probably competitive at gasoline prices of $4-5/gallon.
- Are bio-fuels really carbon friendly? Existing technologies (e.g. corn-based ethanol) not very carbon friendly. Cellulose-based fuels could be more carbon friendly if bio-fuels used for process energy. To minimize deforestation need to price greenhouse gas emissions from land use change.
- Can bio-fuels become an abundant U.S. domestic resource? Comparative advantage for bio-fuels in the tropics and food/fiber crops in temperate regions. Domestic bio-fuel production requires importing food and fiber products?
- Will other land-use resources limit biofuels? Water implications and long-term soil management issues. Climate change feedbacks potentially undermining existing productivity.

ENVIRONMENTAL EFFECTS OF SOLAR & WIND ENERGY AT LARGE SCALES

(e.g. 10% of 2100 energy demand or about 4.4 TW)

NUMERICAL EXPERIMENTS USING A CLIMATE MODEL

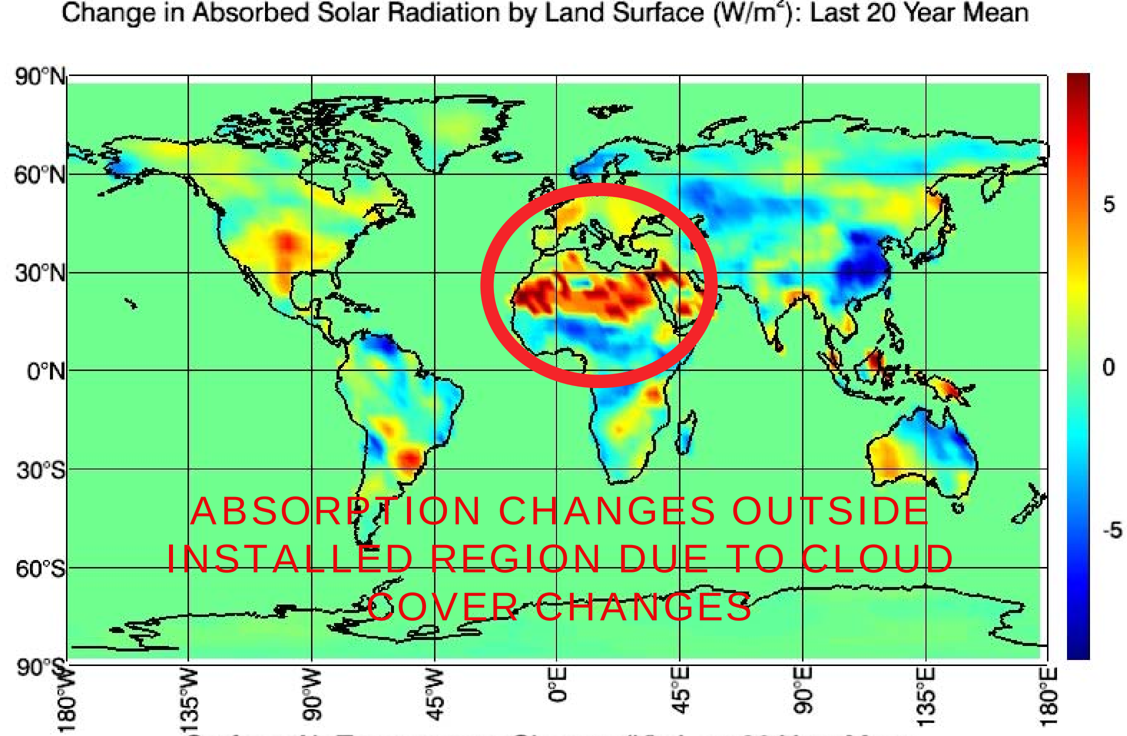
MIT/NCAR CCM3 (slab ocean, T42 (2.8 degree) resolution)

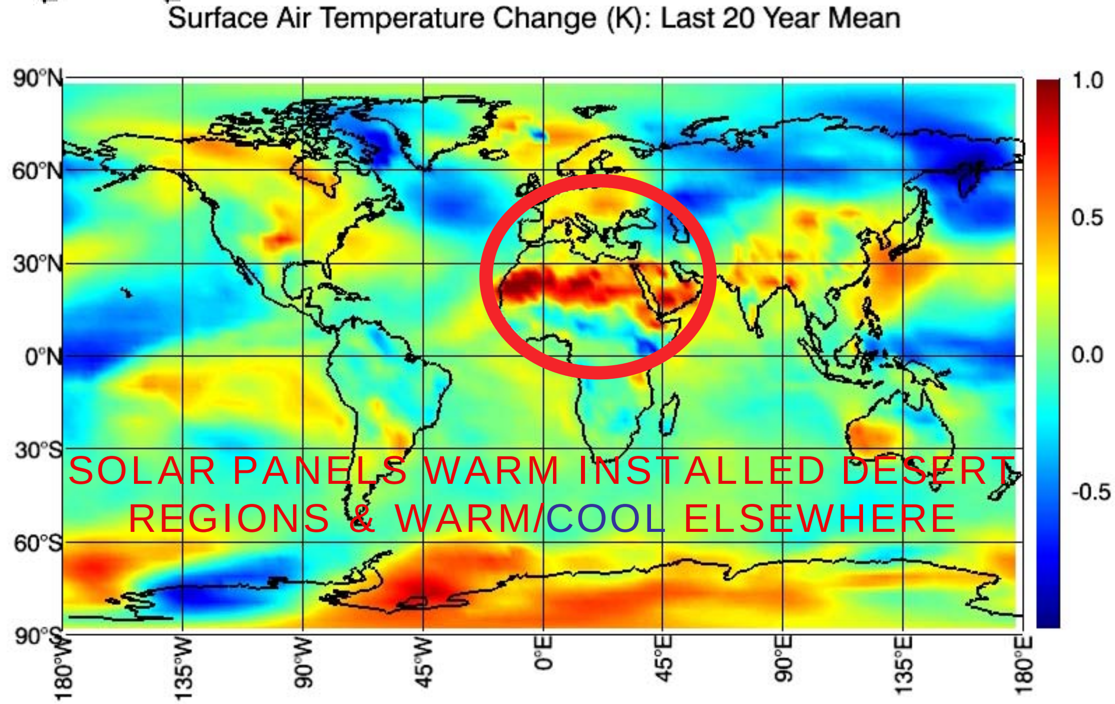
Solar Panels sparsely installed over 10 million km^2 of the *Saharan and Arabian Deserts*
Use settings in the model for surface sunlight absorption to simulate the needed solar energy extraction by solar panels with *10% conversion to electrical power (5.3TW) and 90% conversion to surface heating*

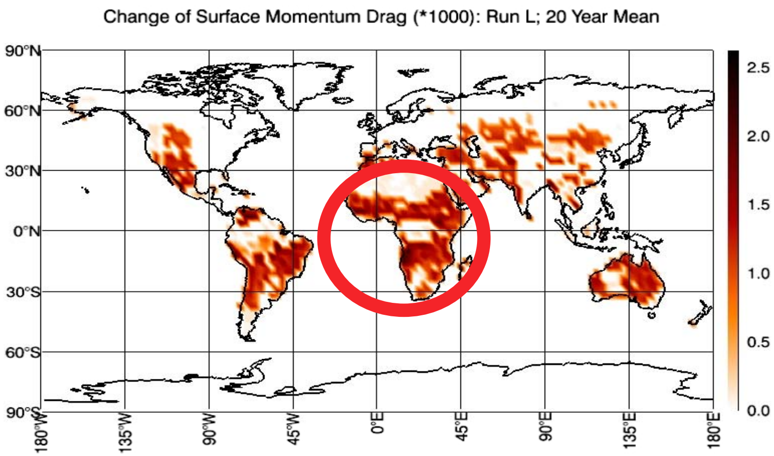
Windmills sparsely installed in all *grass land and shrub regions (58 million km^2)* or all *coastal ocean regions where ocean depth less than 200m (10 million km^2).*
Use settings in the model for the *displacement level* and *roughness (land) or surface drag* (ocean) to simulate the needed kinetic energy extraction by windmills (operating at *25% conversion efficiency giving 5TW (land) & 3TW (ocean))*

- Two *60-year* runs *with* and *without* solar panels or windmills
- Use the *average of the differences between the 2 runs* over the *last 20-years* to isolate the effects of solar panels or windmills

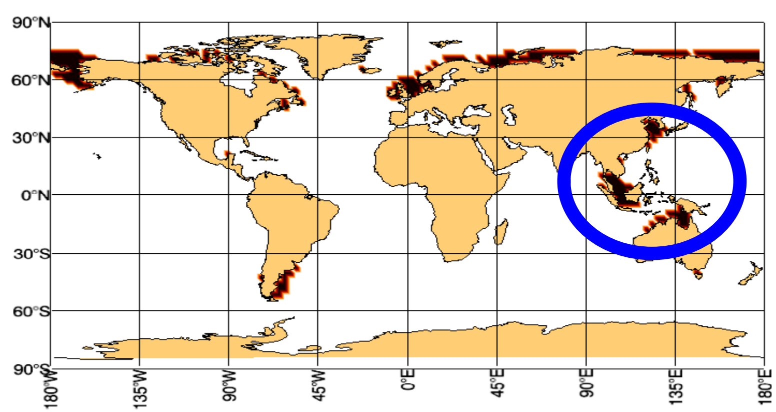
WHAT ARE EFFECTS OF SOLAR ARRAYS AT LARGE SCALES ON SUNLIGHT ABSORPTION (W/m^2) AND SURFACE TEMPERATURE (^oC)?

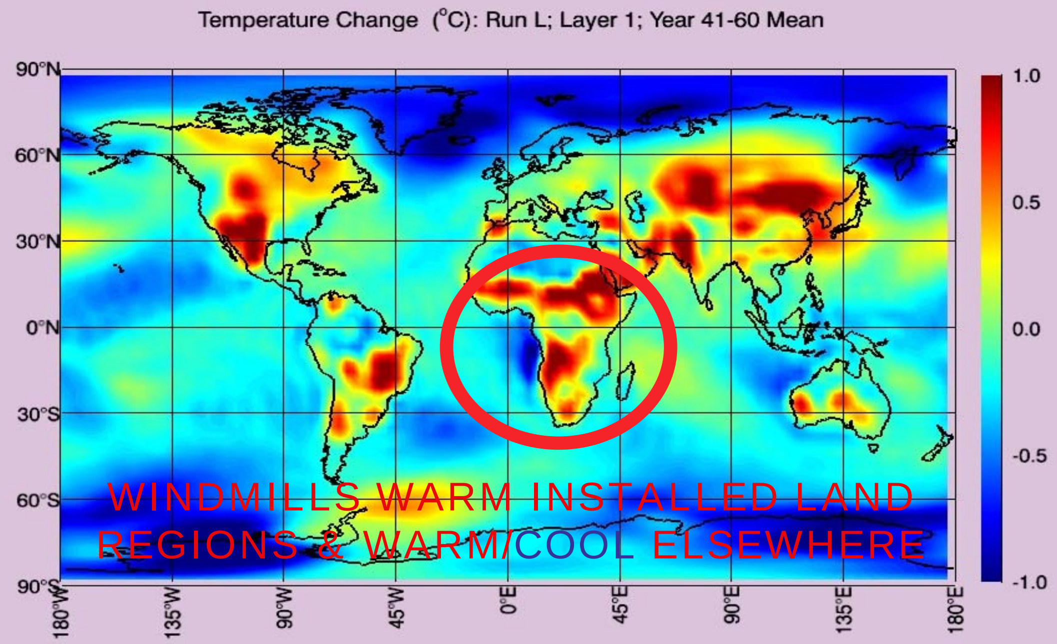


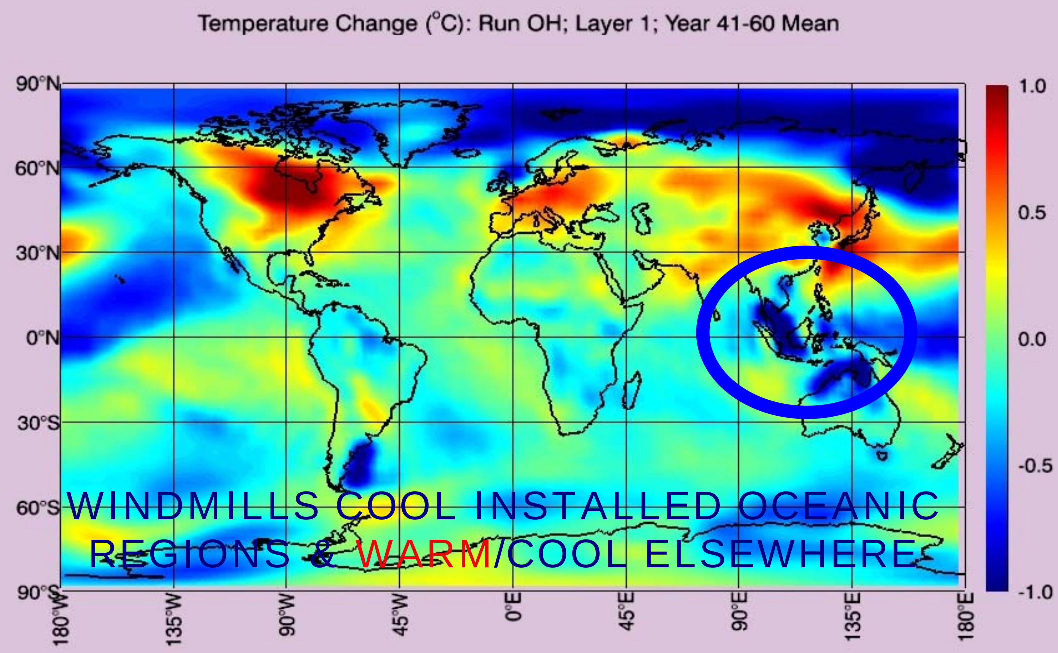




WHAT ARE EFFECTS OF WINDMILL ARRAYS AT LARGE SCALES ON SURFACE TEMPERATURE OVER LAND AND OCEAN?







IMPLICATIONS FOR FUTURE SOLAR PHOTOVOLTAIC & WIND ENERGY AT LARGE SCALE:

ENVIRONMENTAL EFFECTS INCREASE WITH POWER GENERATED AND DECREASE WITH CONVERSION EFFICIENCY. EFFECTS MINIMAL FOR LESS THAN 1 TW GENERATION EVEN WITH CURRENT TECHNOLOGIES.

LARGEST EFFECTS IN INSTALLATION REGIONS, BUT WITH SOME SIGNIFICANT GLOBAL EFFECTS. ANY POLICY RESPONSE WOULD HAVE MORE ANALOGIES WITH AIR POLLUTION THAN WITH GLOBAL WARMING.

FOR WINDMILLS, LEAST EFFECTS FOR INSTALLATION IN COASTAL OCEANS IN ARRAYS NARROW ALONG PREVAILING WIND DIRECTION AND WIDE PERPENDICULAR TO THAT DIRECTION (SAME TRUE FOR LAND?).

FOR SOLAR PANELS, LEAST EFFECTS FOR INSTALLATION OVER LOW ALBEDO REGIONS (INCLUDING COASTAL OCEAN?) AND/OR CO-INSTALL REFLECTING WHITE PANELS TO OFFSET ABSORBING SOLAR PANELS.

CONCLUSIONS DEPENDENT UPON:

ACCURACY OF CLIMATE MODEL SURFACE AND BOUNDARY LAYER PROCESSES.

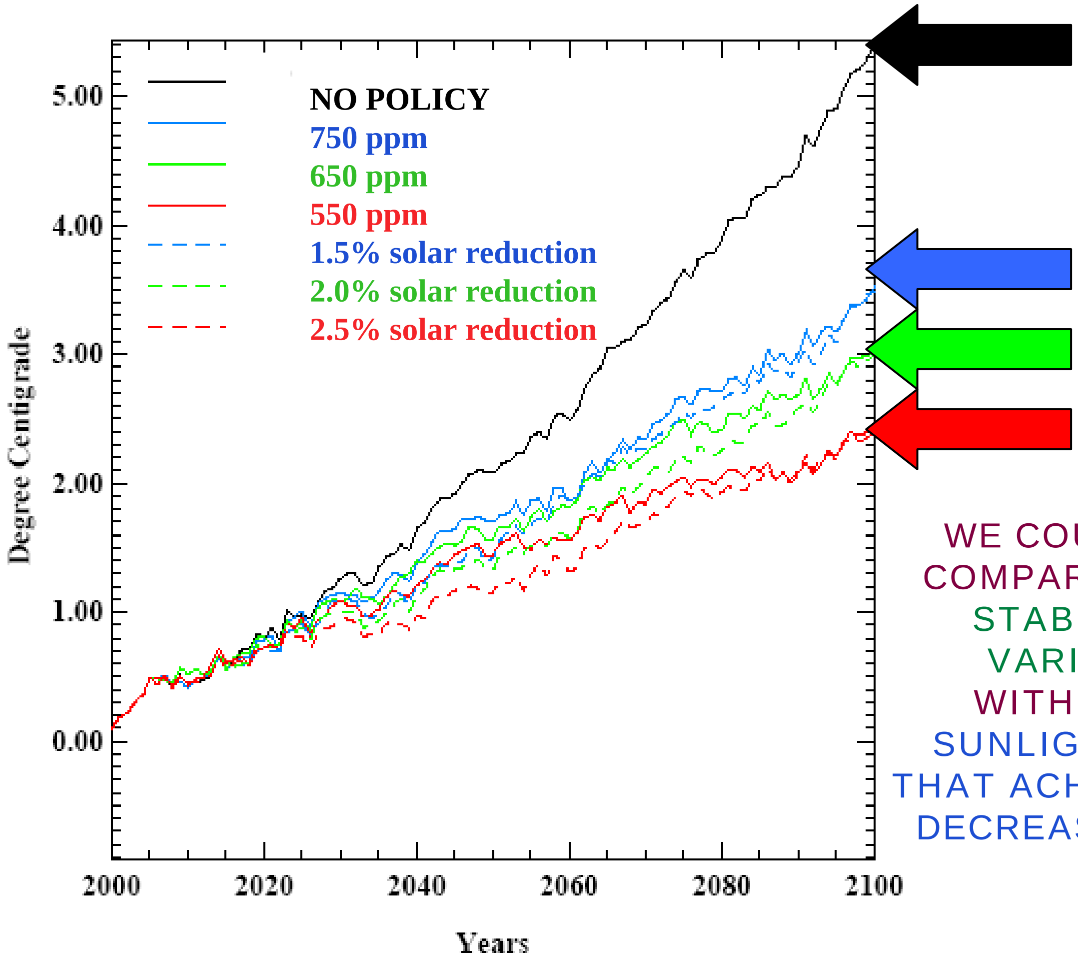
ACCURACY OF SIMULATING WINDMILLS WITH DISPLACEMENT LEVEL, ROUGHNESS & DRAG ADJUSTMENTS, & SOLAR PANELS WITH SURFACE SUNLIGHT ABSORPTION ADJUSTMENTS (USE HIGHER RESOLUTION?, NEED NEW FIELD MEASUREMENTS?).

SLAB OCEAN APPROXIMATION BEING ADEQUATE (USE FULLY COUPLED 3D OCEAN?).

8. GEO-ENGINEERING: Viable Option or Dangerous Diversion?

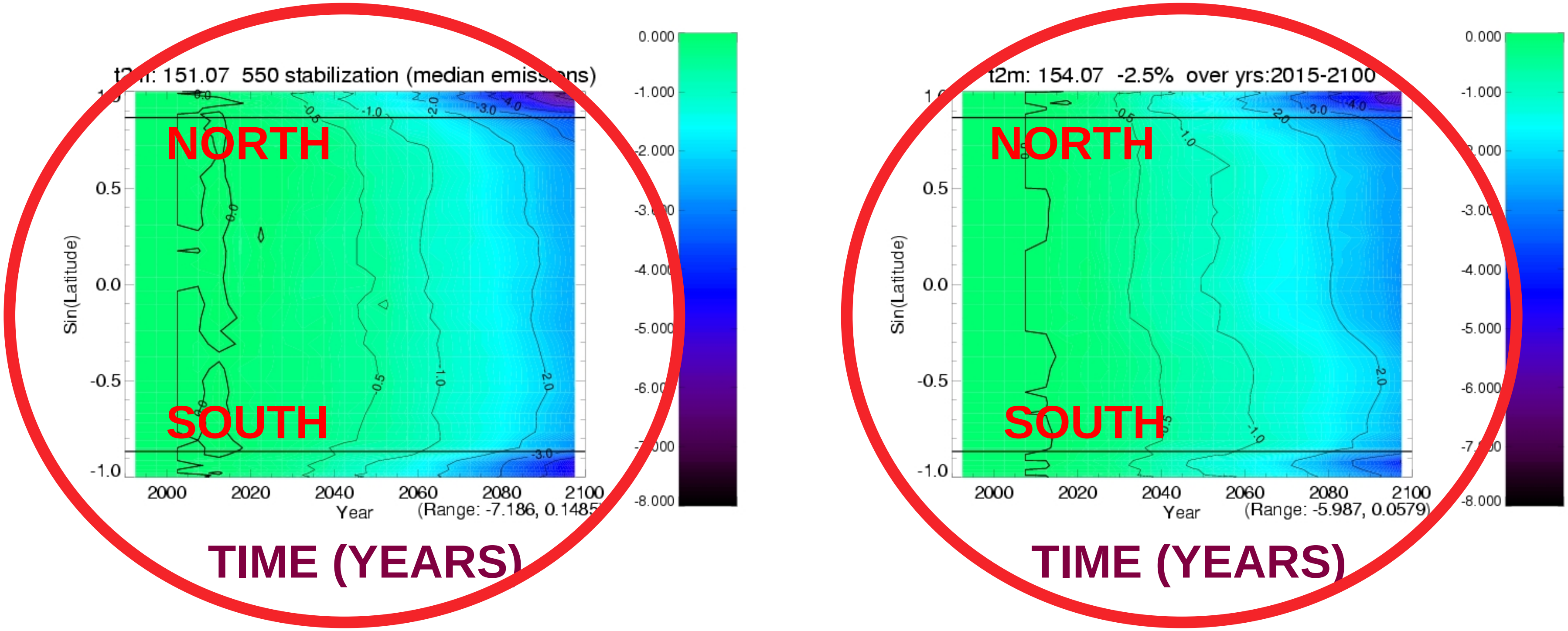
e. g. EFFECTS ON TEMPERATURE (°C) OF REDUCING SOLAR INPUT (by X% between 2015 and 2100) WITH NO POLICY COMPARED TO GREENHOUSE GAS STABILIZATION POLICIES (at Y ppm CO_2-eq). (MIT IGSM results)

"NO-POLICY" EMISSIONS CASE LEADS TO ABOUT 900 ppm CO_2 in 2100



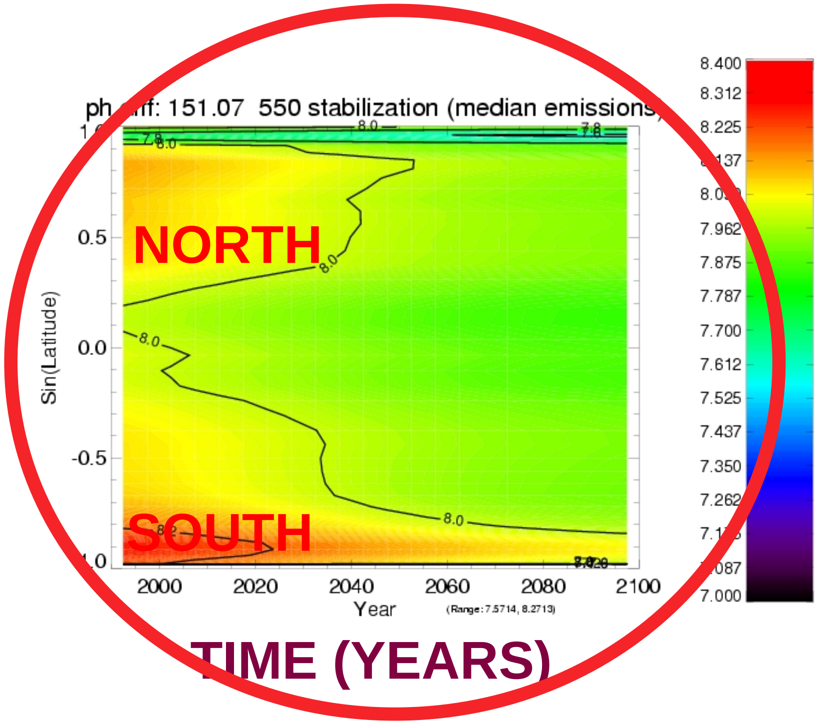
WE COULD USEFULLY COMPARE THE COST OF STABILIZATION AT VARIOUS LEVELS WITH THE COST OF SUNLIGHT REDUCTION THAT ACHIEVES THE SAME DECREASE IN WARMING

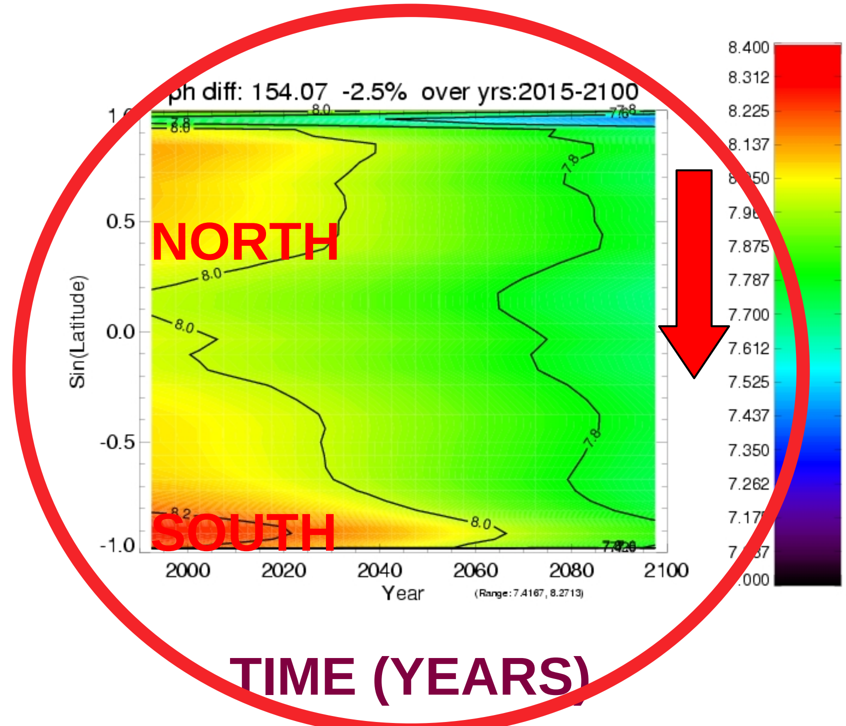
TEMPERATURE CHANGE (^{o}C):
STABILIZATION versus GEO-ENGINEERING



SPACE-TIME REDUCTIONS IN WARMING VERY SIMILAR

OCEANIC ACIDITY (pH) (MIT IGSM results):
550 ppm STABILIZATION versus GEO-ENGINEERING





pH REDUCTIONS (ACIDITY INCREASES) MUCH GREATER FOR SUNLIGHT SHADING!

A DROP IN pH OF 0.5 or GREATER COULD LEAD TO DECIMATION OF CALCAREOUS PHYTOPLANKTON

OF COURSE TO SOLVE THIS PROBLEM, WE COULD ADD SODIUM HYDROXIDE TO THE GLOBAL OCEANS AND/OR GENETICALLY ENGINEER NEW PHYTOPLANKTON !

FINAL CAUTIONARY COMMENT:
WE ARE ARGUABLY NO BETTER AT PREDICTING THE EFFECTS OF GEO-ENGINEERING THAN PREDICTING THE EFFECTS OF ALLOWING GREEN HOUSE GASES TO RISE

THERE ARE SURE TO BE UNINTENDED CONSEQUENCES LEADING TO INTERNATIONAL CONFLICT

SHOULD THE "LITTLE OLD LADY WHO SWALLOWED THE FLY" THEN SWALLOW THE SPIDER OR REGURGITATE THE FLY?

9. POSSIBLE DEFINING CLIMATE EVENTS

The Next Twenty Years?

1. **Ominous Trends:** **Rapidly Accelerated Warming**
2. **Dangerous Events:** **More Super-Hurricanes, Mega-Heat Waves?**
3. **Thresholds Reached:** **Disappearing Arctic Summer Sea Ice or Mountain Glaciers, Sudden Rapid Ice Sheet Flows?**
4. **OR, temporary cooling?**