CLIMATE CHANGE:
SCIENCE, ECONOMICS and POLICY

Ronald G. Prinn

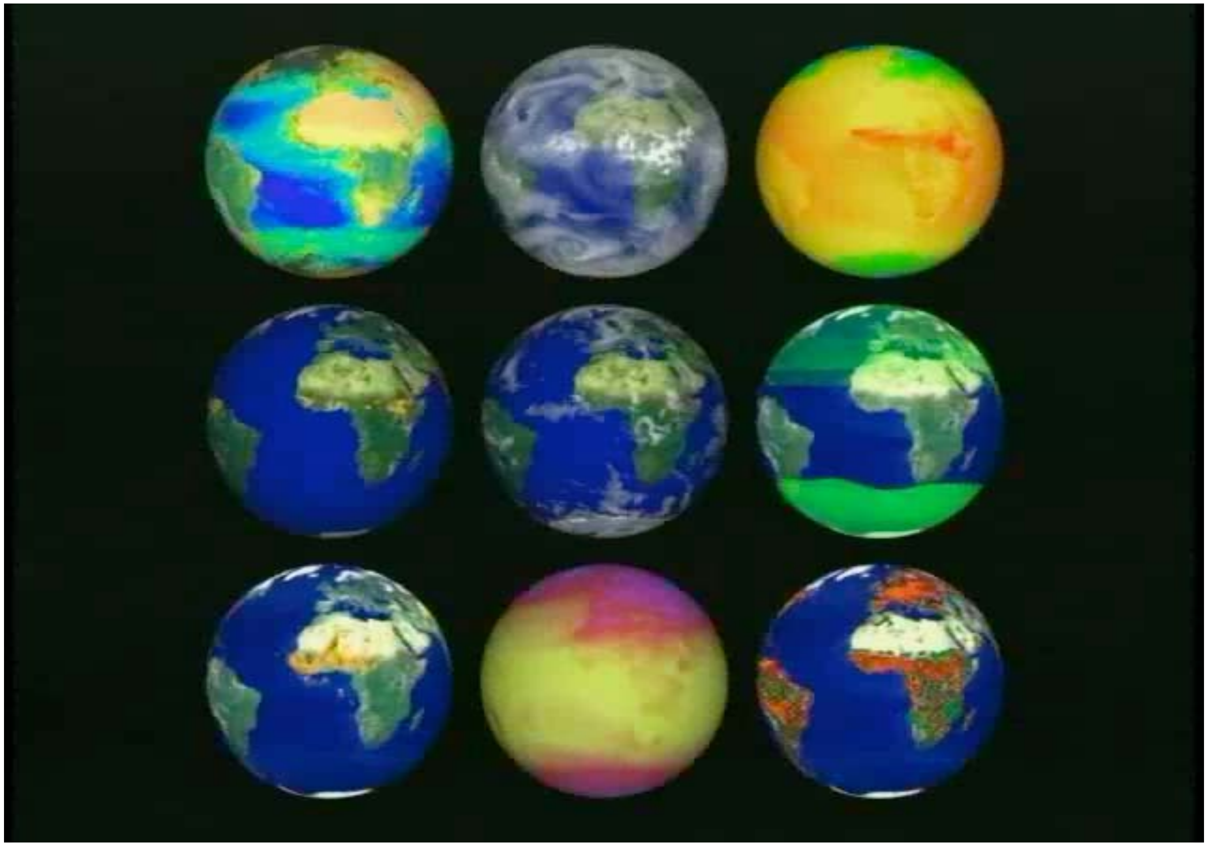


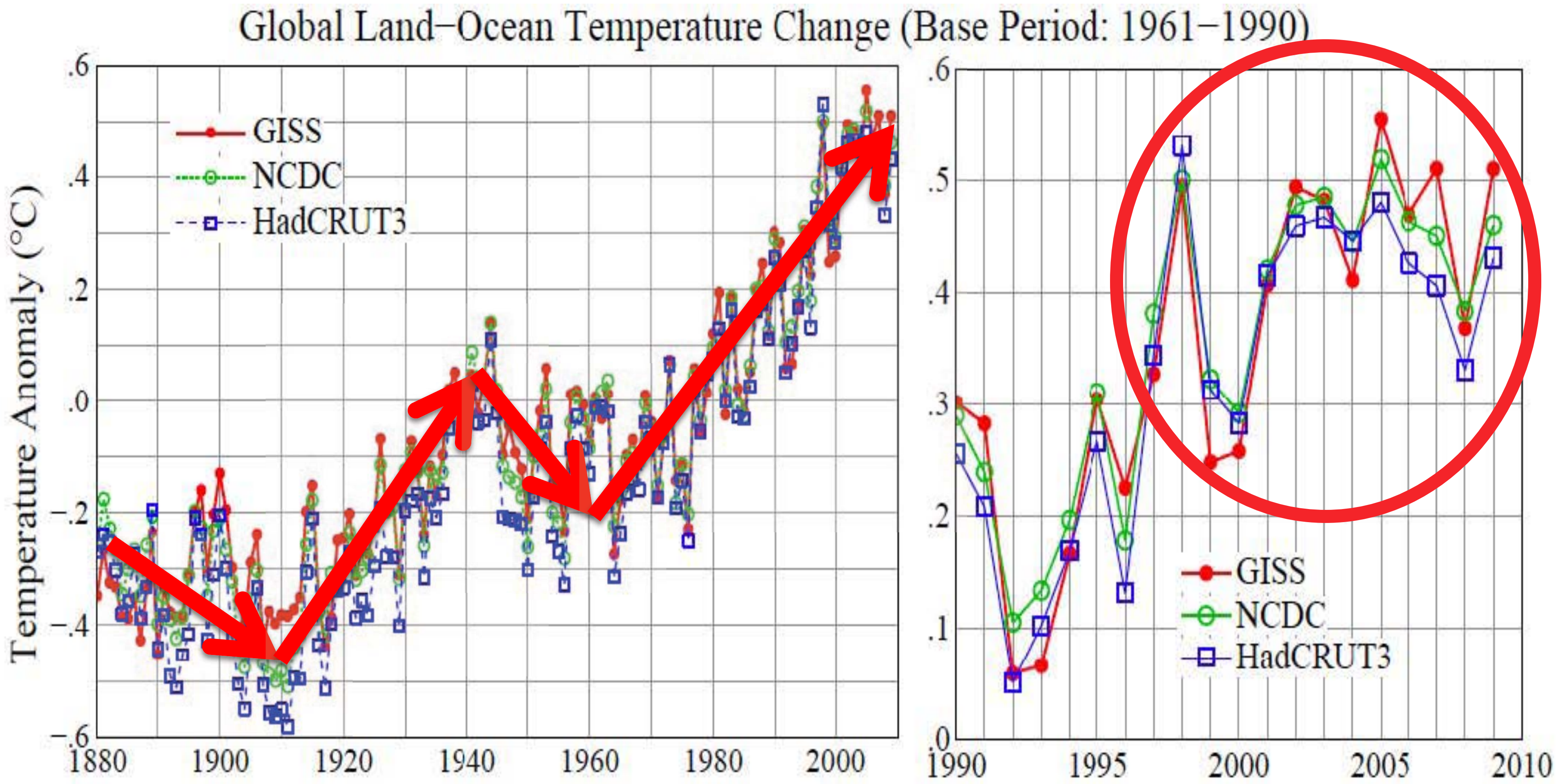
Image by NASA. From Visible Earth.

IMAGES From NASA's TERRA satellite

PRESENTATION TO
22.811J: SUSTAINABLE ENERGY
MIT, CAMBRIDGE MA
SEPTEMBER 14, 2010

HOW HAS TEMPERATURE EVOLVED OVER THE PAST 130 YEARS?

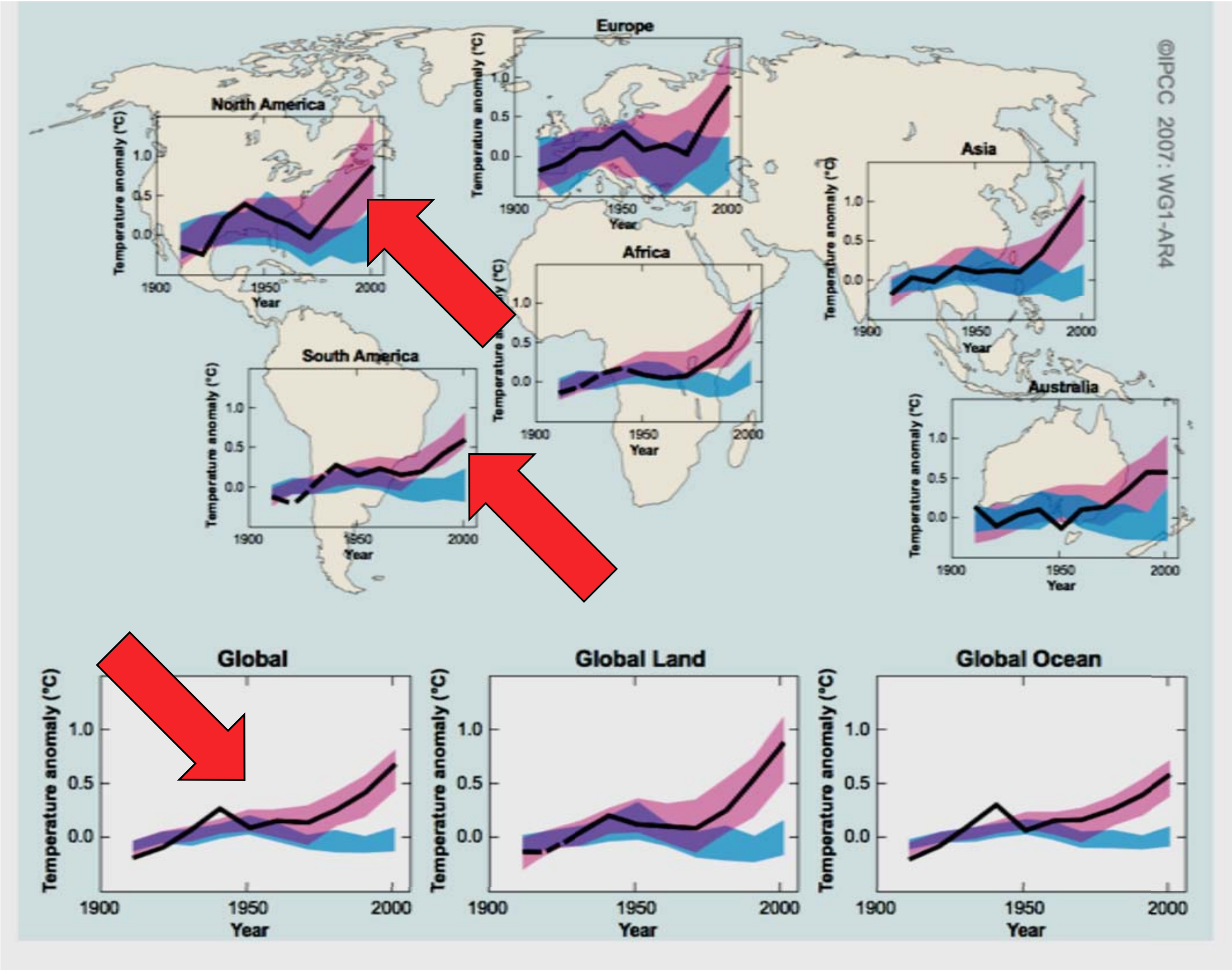
Global annual surface air temperature anomaly as estimated from observations by NASA-GISS, NOAA-NCDC, & UKMO-Hadley Center Climatic Research Unit (Hansen et al, 2010).



Source: Hansen, J., et al. "Global Surface Temperature Change." *Review of Geophysics* 48 (2010): RG4004. http://dx.doi.org/10.1029/2010RG000345.

CLIMATE FORCING DUE TO INCREASES IN GREENHOUSE GASES AND AEROSOLS FROM 1850-2005 WAS:
1.6 W m^{-2} x 5.1 x 10^{14} m^2 = 8.16 x 10^{14} W = 816 TW (about 52 times current global energy consumption)

HOW HAVE GLOBAL & CONTINENTAL TEMPERATURES CHANGED OVER THE PAST CENTURY (1906-2005), AND WHY?



Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.4. IPCC, Geneva, Switzerland.

Black lines:observed changes. Blue bands: range for 19 model simulations using natural forcings. Red bands: range for 51 model simulations using natural and human forcings.

Ref: IPCC 4th Assessment, Summary for Policymakers, 2007

TWO COMMON WAYS TO EXPRESS POLICY GOALS FOR CLIMATE MITIGATION

(1) AIM TO KEEP GLOBAL GREENHOUSE GASES BELOW SPECIFIED LEVELS

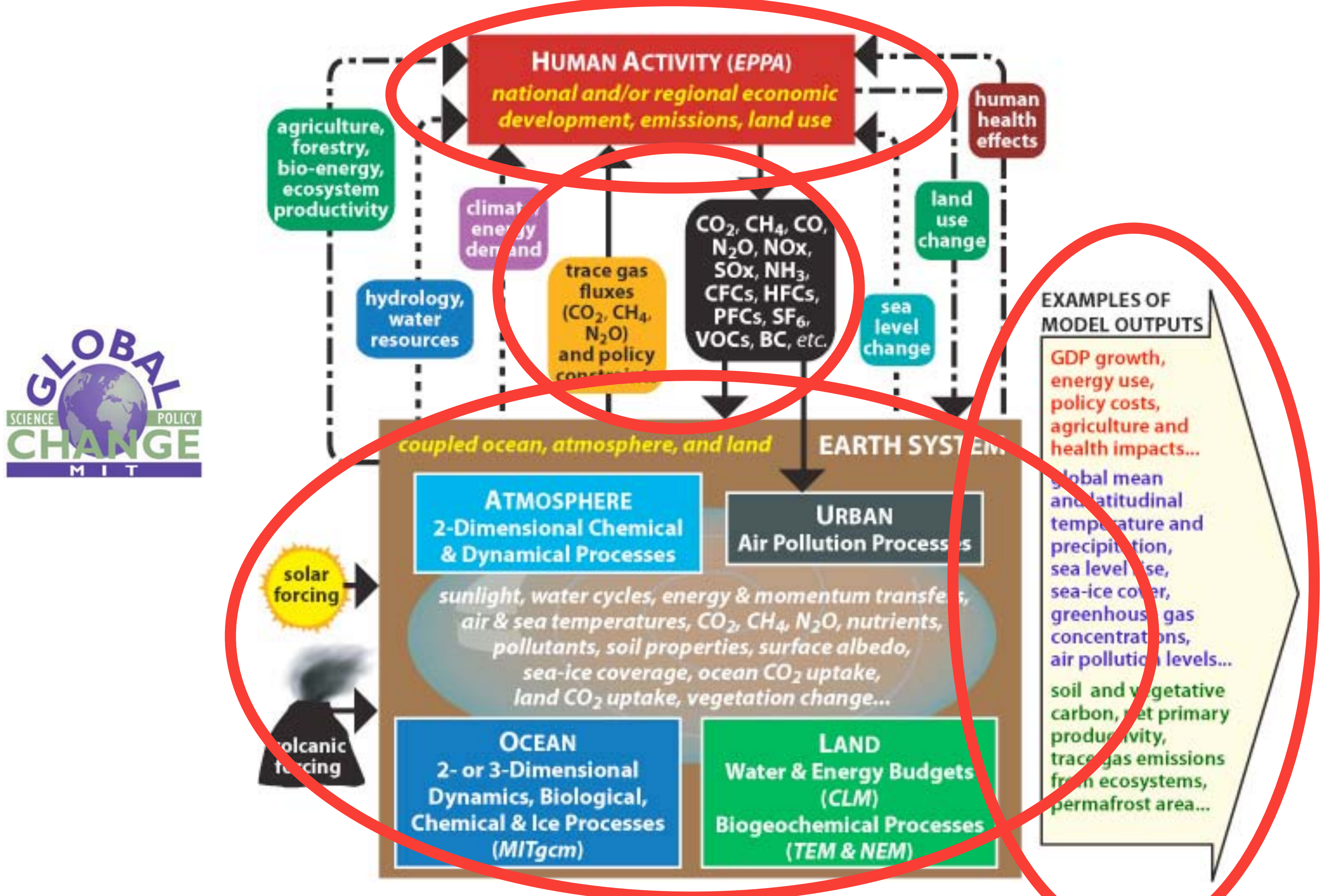
(for this purpose levels of non-CO_2 gases are typically converted to their equivalent levels of CO_2 that would have the same effect on climate; we are currently at about 470 ppm CO_2 equivalents)

(2) AIM TO KEEP GLOBAL TEMPERATURE INCREASES BELOW SPECIFIED AMOUNTS

(relative to say pre-industrial or 1990; we are currently about 0.8°C above pre-industrial)

BUT THESE SIMPLE CONCEPTS ARE AFFECTED BY THE SIGNIFICANT UNCERTAINTIES IN PROJECTIONS OF ECONOMIES AND CLIMATE:
NEED TO EVALUATE POLICIES BASED ON THEIR ABILITY TO LOWER RISK, AND RE-EVALUATE DECISIONS OVER TIME

WHAT IS THE RELATIONSHIP BETWEEN GREENHOUSE GAS STABILISATION TARGETS AND TEMPERATURE CHANGE TARGETS UNDER UNCERTAINTY?



WE USE THE MIT INTEGRATED GLOBAL SYSTEM MODEL

Cumulative PROBABILITY OF GLOBAL AVERAGE SURFACE AIR WARMING from 1981-2000 to 2091-2100, WITHOUT (1400 ppm-eq CO_2) & WITH A 550, 660, 790 or 900 ppm-equivalent CO_2 GHG STABILIZATION POLICY

(400 forecasts per case. Ref: Sokolov et al, Journal of Climate, 2009)

	ΔT > 2°C (values in red relative to 1860 or pre-industrial)	ΔT > 4°C	ΔT > 6°C
No Policy at 1400	100% (100%)	85%	25%
Stabilize at 900 (L4)	100% (100%)	25%	0.25%
Stabilize at 790 (L3)	97% (100%)	7%	< 0.25%
Stabilize at 660 (L2)	80% (97%)	0.25%	< 0.25%
Stabilize at 550 (L1)	25% (80%)	< 0.25%	< 0.25%

WITH THESE PROBABILITIES FOR WARMING EXCEEDING 2°C ABOVE PRE-INDUSTRIAL, HOW FEASIBLE IS A POLICY TARGET TO LIMIT WARMING TO LESS THAN 2°C?

POLES WARM MUCH FASTER THAN TROPICS; IF ICE SHEETS MELT, HOW MUCH SEA LEVEL RISE COULD OCCUR?

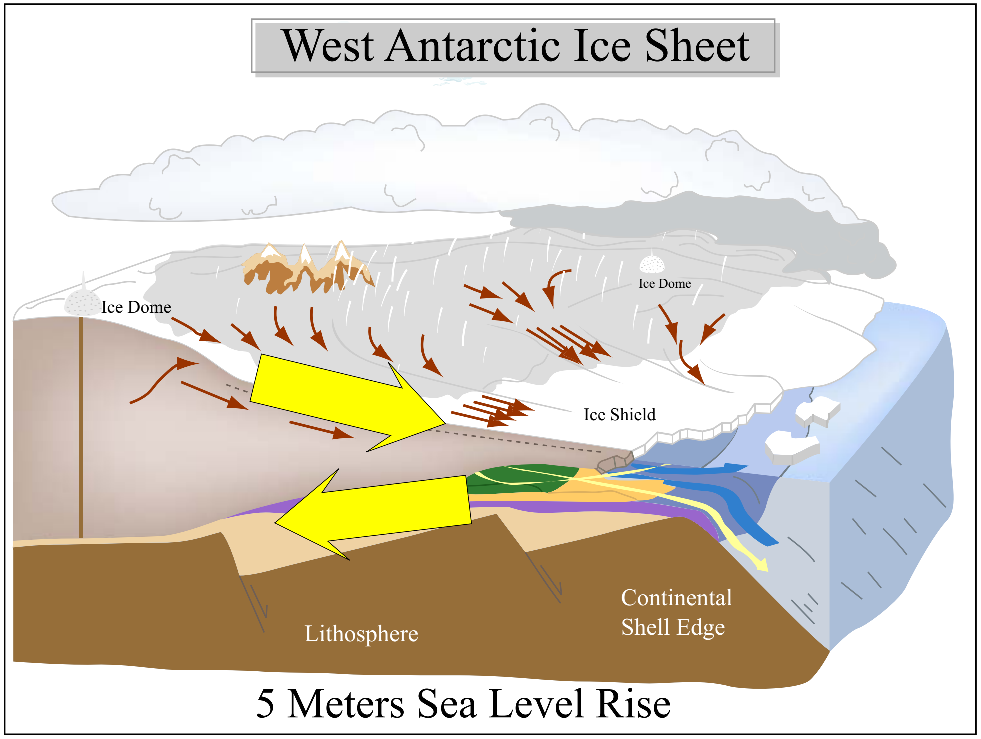


Image by MIT OpenCourseWare.

STABILITY OF WEST ANTARCTIC ICE SHEET

REFs: Bindschadler et al; ACIA, Impacts of a Warming Arctic, Climate Impact Assessment Report, 2004

Map showing retreat of Greenland coastline due to 7 meters sea level rise has been removed due to copyright restrictions. See page 21 in Arctic Climate Impact Assessment (ACIA). "Impacts of a Warming Arctic Climate Impact Assessment." Cambridge University Press, 2004.

STABILITY OF GREENLAND ICE SHEET

The last time the polar regions were significantly warmer (~4 ºC) than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 meters of sea level rise.

Map showing retreat of Greenland coastline due to 7 meters sea level rise has been removed due to copyright restrictions. See page 21 in Arctic Climate Impact Assessment (ACIA). "Impacts of a Warming Arctic Climate Impact Assessment." Cambridge University Press, 2004.

THIS WOULD INDUCE EMISSION OVER TIME OF THE 1670 BILLION TONS OF CARBON STORED IN ARCTIC TUNDRA & FROZEN SOILS (TARNOCAI ET AL, GBC, 2009). THIS IS ABOUT 200 TIMES CURRENT ANNUAL ANTHROPOGENIC CARBON EMISSIONS. THESE EMISSIONS WOULD INCLUDE METHANE FROM NEW & WARMER WETLANDS.

WHAT WOULD HAPPEN IF ARCTIC TUNDRA & PERMAFROST THAWS?

REF: ACIA, Impacts of a Warming Arctic, Climate Impact Assessment Report, 2004

IS ARCTIC SEA ICE AT THE END OF WINTER & SUMMER DECREASING?

Time series of the percent difference in ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979–2000.

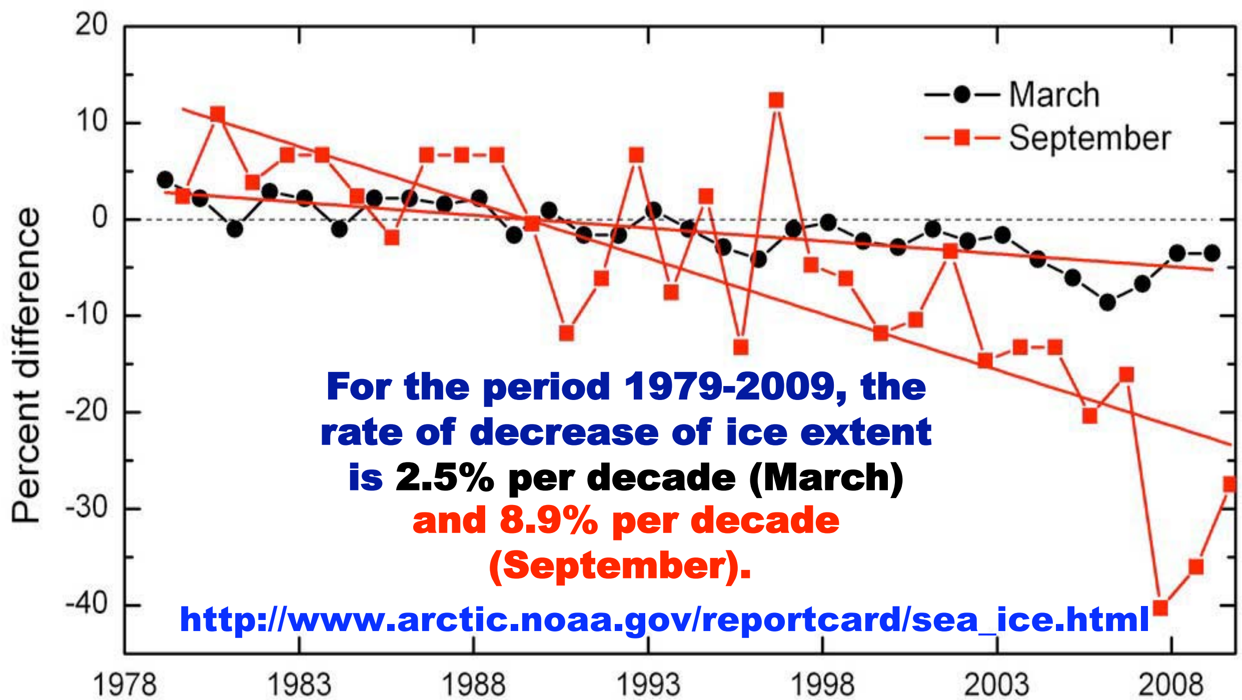
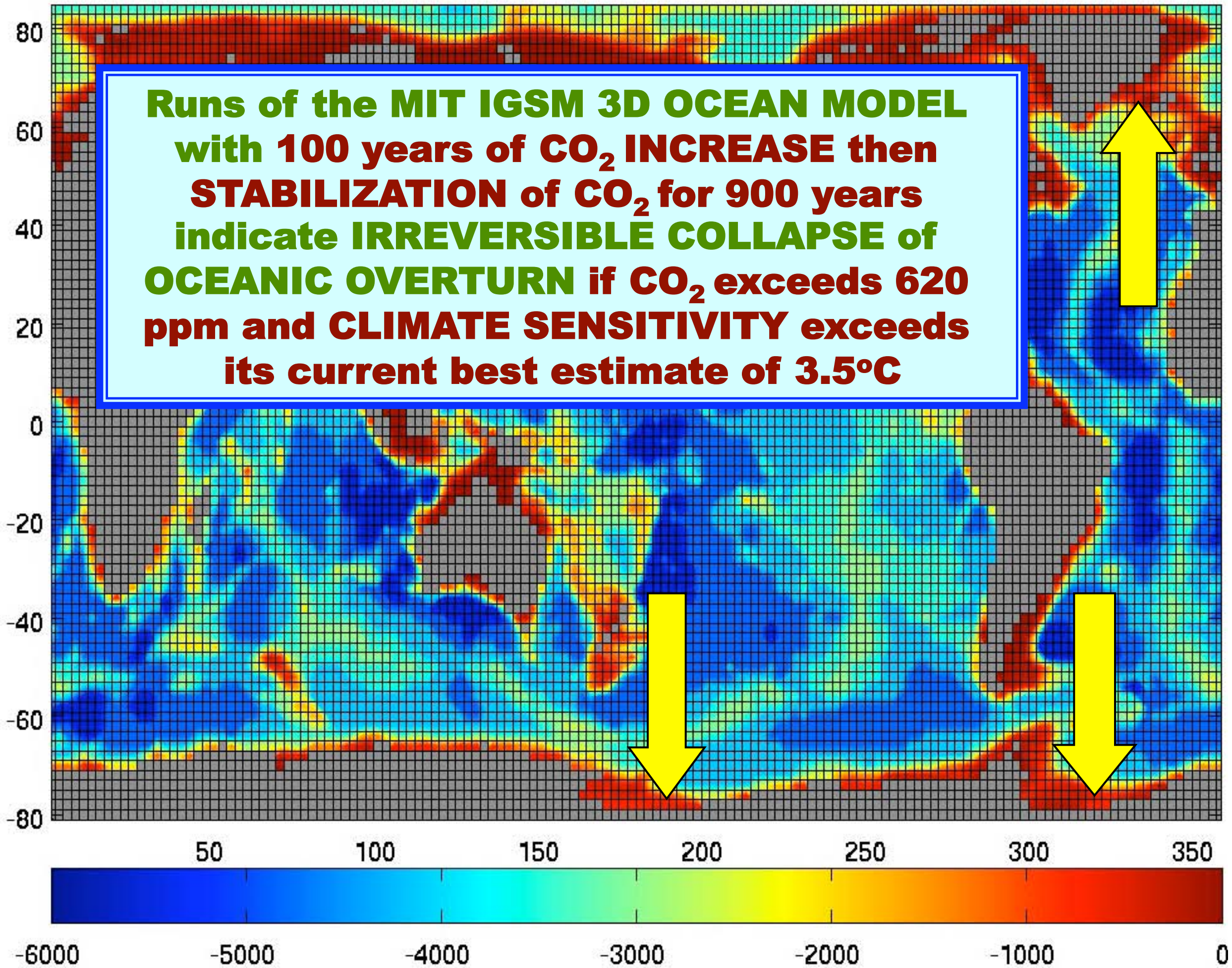


Image from Perovich, D., et al. "Sea Ice Cover." *Arctic Report Card 2010*, NOAA.

IF THE POLAR LATITUDES WARM TOO MUCH, COULD THE DEEP OCEAN CARBON & HEAT SINK COLLAPSE?



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

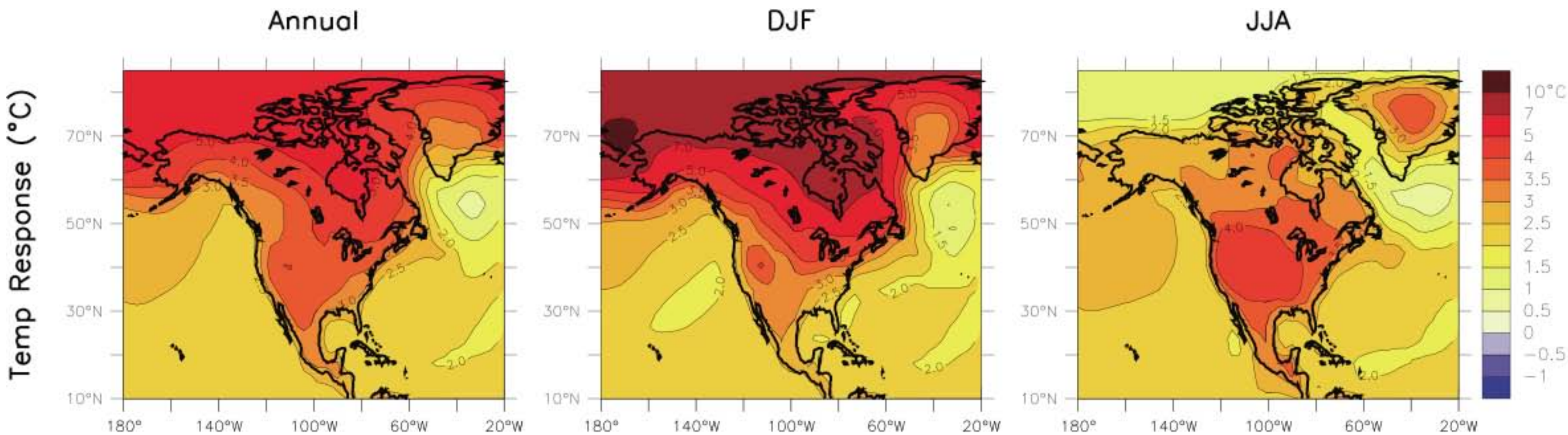
OVERTURN DRIVEN BY SINKING WATER IN THE POLAR SEAS (Norwegian, Greenland, Labrador,Weddell, Ross)

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

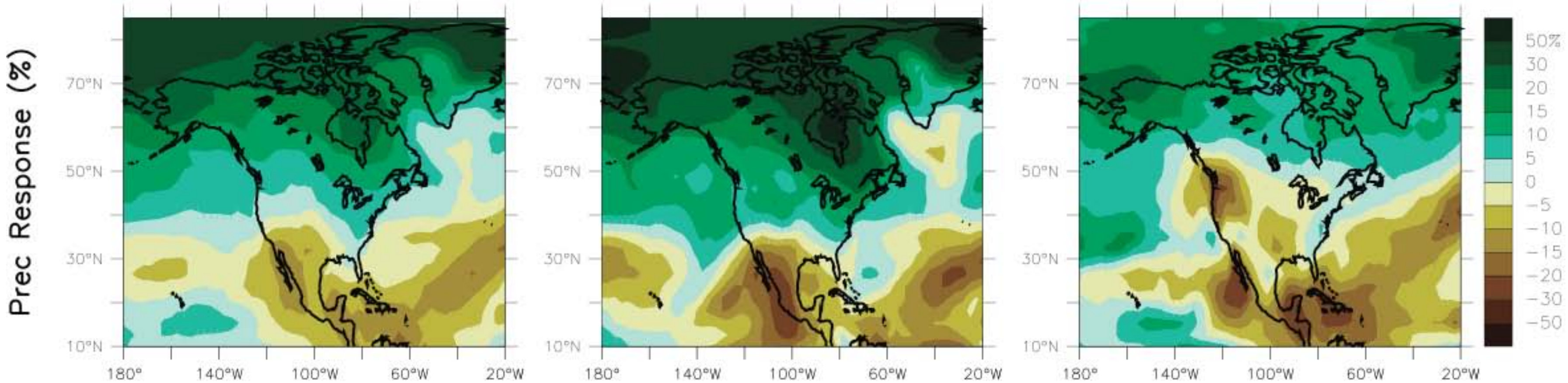
INCREASED RAINFALL, SNOWFALL & RIVER FLOWS, & DECREASED SEA ICE, EXPECTED WITH GLOBAL WARMING

Ref: Scott et al, MIT Joint Program Report 148, Climate Dynamics, v30, p441-454, 2008

WHAT ARE THE PROJECTED PATTERNS OF CHANGES IN TEMPERATURE (°C) AND RAINFALL (%) (e.g. FOR NORTH AMERICA)?



MAXIMUM WARMING IN HIGH LATITUDE REGIONS



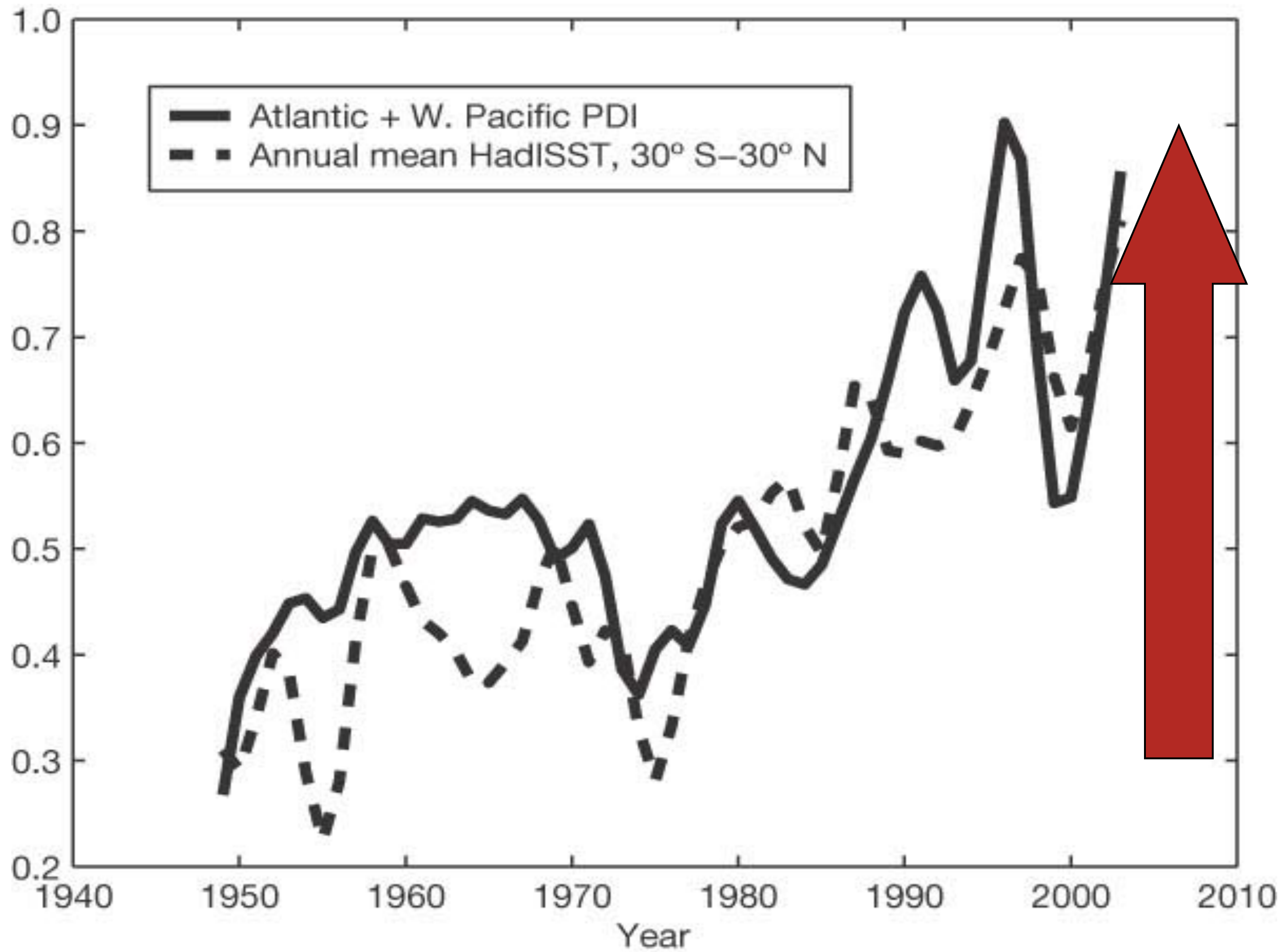
MAXIMUM % PRECIPITATION INCREASE IN POLAR REGIONS

Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 11.15. Cambridge University Press.

Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models with A1B emissions scenario (-1 to +10°C).
Bottom row: same as top, but for fractional change in precipitation (+/-50%).
Ref: IPCC 4th Assessment, Working Group 1, Chapter 11, 2007

TYPHOONS/CYCLONES/HURRICANES & OCEANIC WARMING: INCREASING DESTRUCTIVENESS OVER THE PAST 30 YEARS?

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



HOW MUCH WILL IT COST?
EPPA MODEL Sectors and Technologies

Sectors

Non-Energy

- Agriculture
- Energy Intensive
- Other Industry
- Services
- Industrial Transport
- Household Transport
- Other Household Cons.

Energy

- Crude & Refined oil,
- Biofuel
- Shale oil
- Coal
- Natural gas
- Synthetic gas (from coal)
- Electricity

Agriculture →

Crops
Livestock
Forestry
Food processing
Biofuel crops
Biomass Elec.

Crude & Refined oil →

Crude slate & gasoline, diesel, petcoke heavy oil, biodiesel, ethanol, NGLs & explicit upgrading

Electricity →

Technologies Included

Fossil (oil, gas & coal)
IGCC with capture
NGCC with capture
NGCC without capture
Nuclear
Hydro
Wind and solar
Biomass

HOW MUCH WILL IT COST?
EPPA MODEL Sectors and Technologies

Sectors

Non-Energy

- Agriculture
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- Other Industry
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- Industrial Transport
- Household Transport
- Other Household Cons.

Energy

- Crude & Refined oil,
- Biofuel
- Shale oil
- Coal
- Natural gas
- Synthetic gas (from coal)
- Electricity

Transport Alternatives

Conventional Gasoline/Diesel (continue to improve)
Hybrid Electric Vehicle
Plug-in Hybrid Electric Vehicle
Pure Electric Vehicle
Bio-fueled Vehicle
Compressed Natural Gas Vehicle

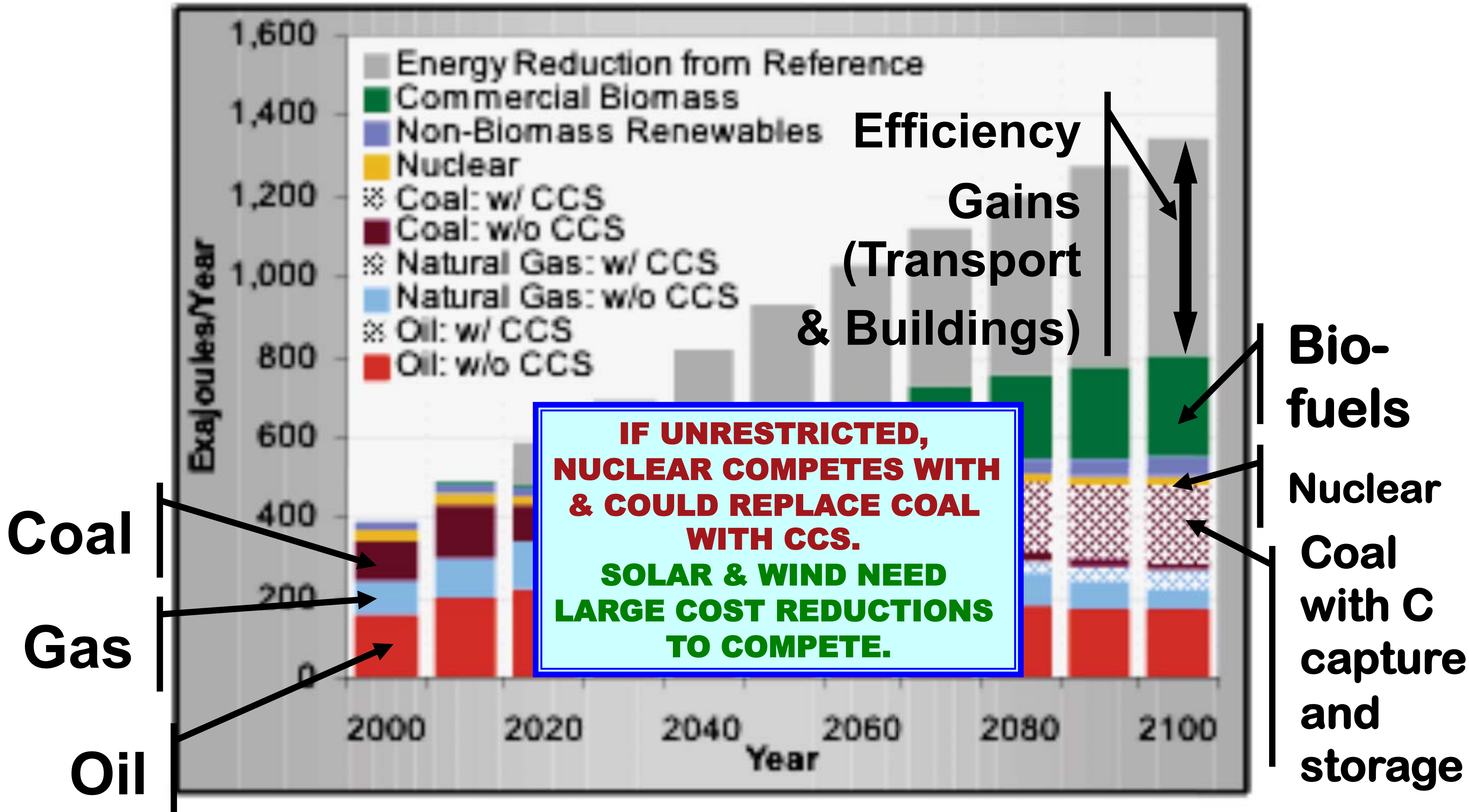
USING EPPA MODEL, WHAT IS THE PROBABILITY FOR GLOBAL MITIGATION COSTS (expressed as % WELFARE* LOSSES in 2050), WITH A 550, 660, 790 or 900 ppm-eq CO_2 STABILIZATION POLICY?

	ΔWL>1%	ΔWL>2%	ΔWL>3%
No Policy	-	-	-
Stabilize at 900	1%	0.25%	<0.25%
Stabilize at 790	3%	0.5%	<0.25%
Stabilize at 660	25%	2%	0.5%
Stabilize at 550	70%	30%	10%

*Approximately the total consumption of goods & services

WHAT IS THE SCALE OF THE CHALLENGE TO TRANSFORM THE GLOBAL ENERGY SYSTEM?

e.g. Using EPPA Model, Global Primary Energy for a ~660 ppm CO_2-equivalent stabilization scenario with nuclear restricted.

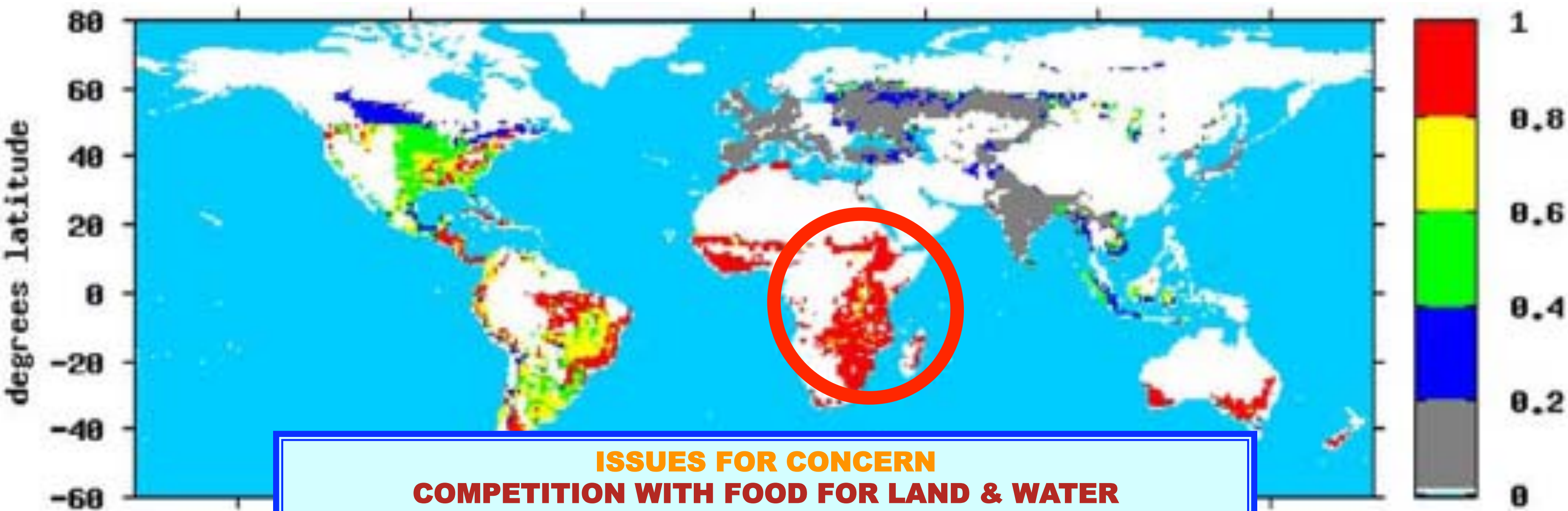


*Carbon price ~$1750/tonC in 2100

ARE THERE ISSUES REGARDING THE CONVERSION OF LAND FOR RENEWABLE ENERGY AT LARGE SCALES?

For bio-fuels to provide 240 EJ/year (7.5 TW or 60% of current demand or 18% of 2100 demand) requires more than 3.4 billion acres of land dedicated to crops producing ethanol, which is 8.5 times the total US cropland, assuming 40% efficiency in the conversion of the biomass (cellulose).

FRACTION OF LAND IN 2100 DEVOTED TO BIO-FUELS PRODUCTION for TRANSPORTATION, etc. WITH A 660 ppm CO_2-equivalent STABILIZATION POLICY & DEFORESTATION



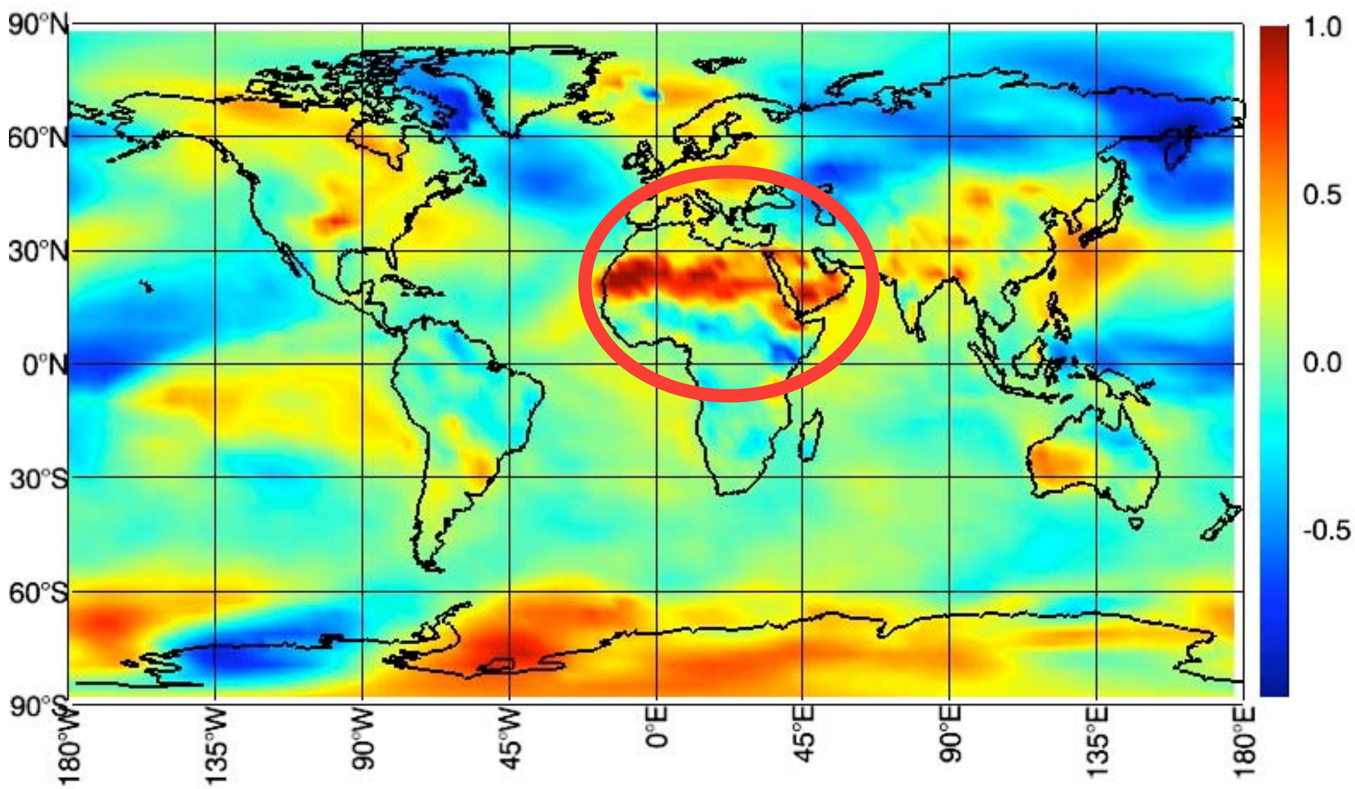
ISSUES FOR CONCERN
COMPETITION WITH FOOD FOR LAND & WATER
GREENHOUSE GAS RELEASE DURING LAND CONVERSION
LOSS OF NATURAL ECOSYSTEMS (TROPICAL FORESTS)
CLIMATE EFFECTS OF LAND CONVERSION

Ref: Melillo, et al, 2009

SOLAR PANELS WARM INSTALLED DESERT REGIONS & WARM/COOL ELSEWHERE

WHAT ARE EFFECTS OF SOLAR ARRAYS AT LARGE SCALES (5.3 TW OVER SAHARAN & ARABIAN DESERTS) ON SUNLIGHT ABSORPTION (W/m²) AND SURFACE TEMPERATURE (°C)? (Ref: Wang & Prinn, 2009)

Surface Air Temperature Change (K): Last 20 Year Mean



NEED BACKUP GENERATION CAPACITY, POSSIBLY INCLUDING ON-SITE ENERGY STORAGE

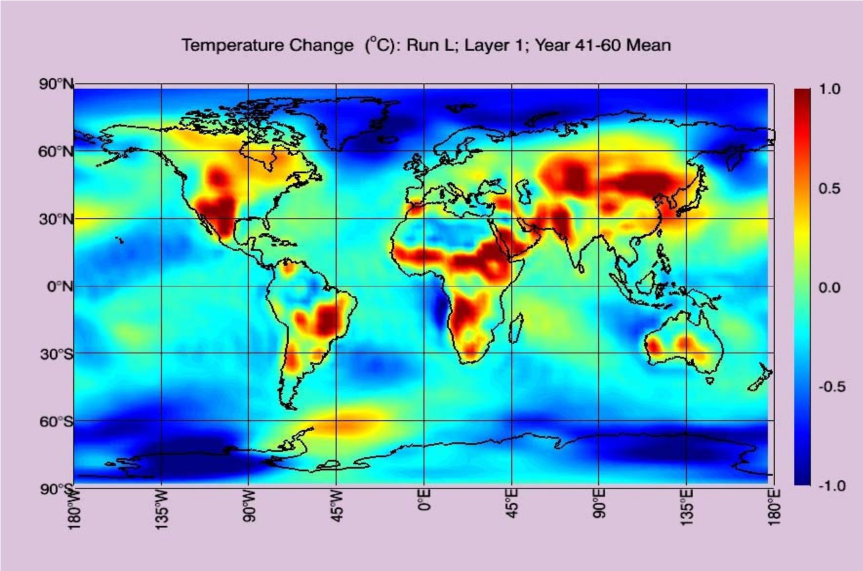
CAN AVOID THESE EFFECTS BY ADDING REFLECTORS TO THE ARRAY TO YIELD ORIGINAL REFLECTIVITY

Photo by Sint Smeding on Flickr.

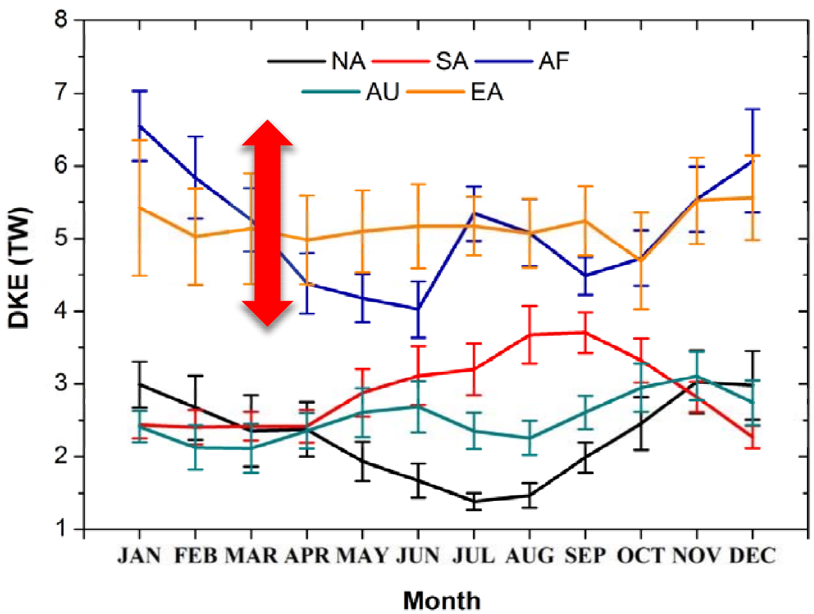
WHAT ARE EFFECTS OF WINDMILL ARRAYS AT LARGE SCALES ON SURFACE TEMPERATURE OVER SEMI-ARID LAND (L, 5TW, 58 million km^2) (Ref: Wang & Prinn, *Atmos. Chem. Phys.*, 2010)

LINEAR ARRAYS PERPENDICULAR TO WINDS FAVORED

WINDMILLS WARM INSTALLED LAND REGIONS & WARM/COOL ELSEWHERE



INTERMITTENCY CHALLENGE: Twenty-year averages and standard deviations of the monthly mean wind power consumption (dKE/dt) by simulated windmills installed in: North America (NA), South America (SA), Africa and Middle East (AF), Australia (AU), and Eurasia (EA).



NEED BACKUP GENERATION CAPACITY, POSSIBLY INCLUDING ON-SITE ENERGY STORAGE

Source: Wang, C., and R. G. Prinn. "Potential Climatic Impacts and Reliability of Very Large-Scale Wind Farms." *Atmospheric Chemistry and Physics* 10 (2010): 2053-2061. http://dx.doi.org/10.5194/acp-10-2053-2010.

CLIMATE MITIGATION and/or ENERGY SECURITY?

Security Concerns	Harmonies	Conflicts
• **Oil** Foreign balance Political dependence	Policy reduces demand and enhances biomass fuels	***BUT MOST CONFLICTS ALLEVIATED WITH CARBON CAPTURE AND STORAGE***
• **Natural gas** Political dependence	Policy reduces demand and enhances supply diversity	
• **Nuclear** Proliferation Safety & Waste	Policy encourages needed regulatory reform	

CLIMATE ADAPTATION in addition to CLIMATE MITIGATION?

WE ARE ALREADY COMMITTED TO SOME UNAVOIDABLE WARMING EVEN AT CURRENT GREENHOUSE GAS LEVELS (ABOUT 0.6°C; IPCC, 2007)

ADAPTATION CAN HELP IN THE SHORT TERM WHILE MITIGATION HELPS IN THE LONG TERM

ADAPTATION MEASURES SHOULD INCLUDE:

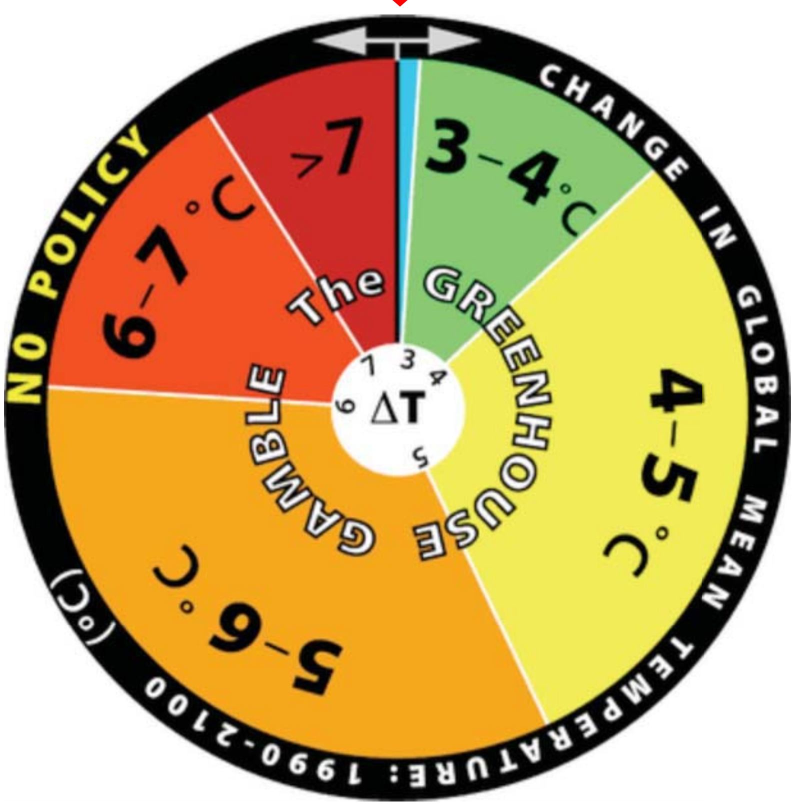
WATER MANAGEMENT (QUALITY, QUANTITY)
FOOD PRODUCTION (FLEXIBILITY, GENETICS)
DEFENDING OR RETREATING FROM COASTAL REGIONS
HUMAN HEALTH INFRASTRUCTURE (HEAT, DISEASE)
DEFENSE AGAINST SEVERE STORMS
REBUILDING PERMAFROST INFRASTRUCTURE

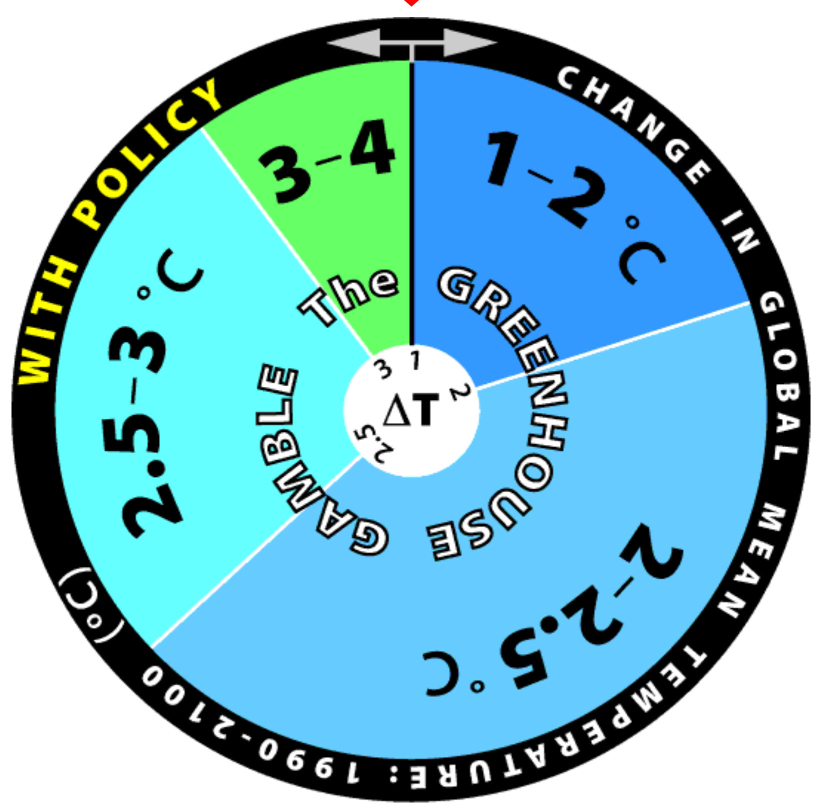
HOW CAN WE EXPRESS THE VALUE OF A CLIMATE POLICY UNDER UNCERTAINTY?

Compared with NO POLICY

What would we buy with STABILIZATION at 660 ppm-equivalent of CO_2?

A NEW WHEEL with lower odds of EXTREMES





http://web.mit.edu/global change