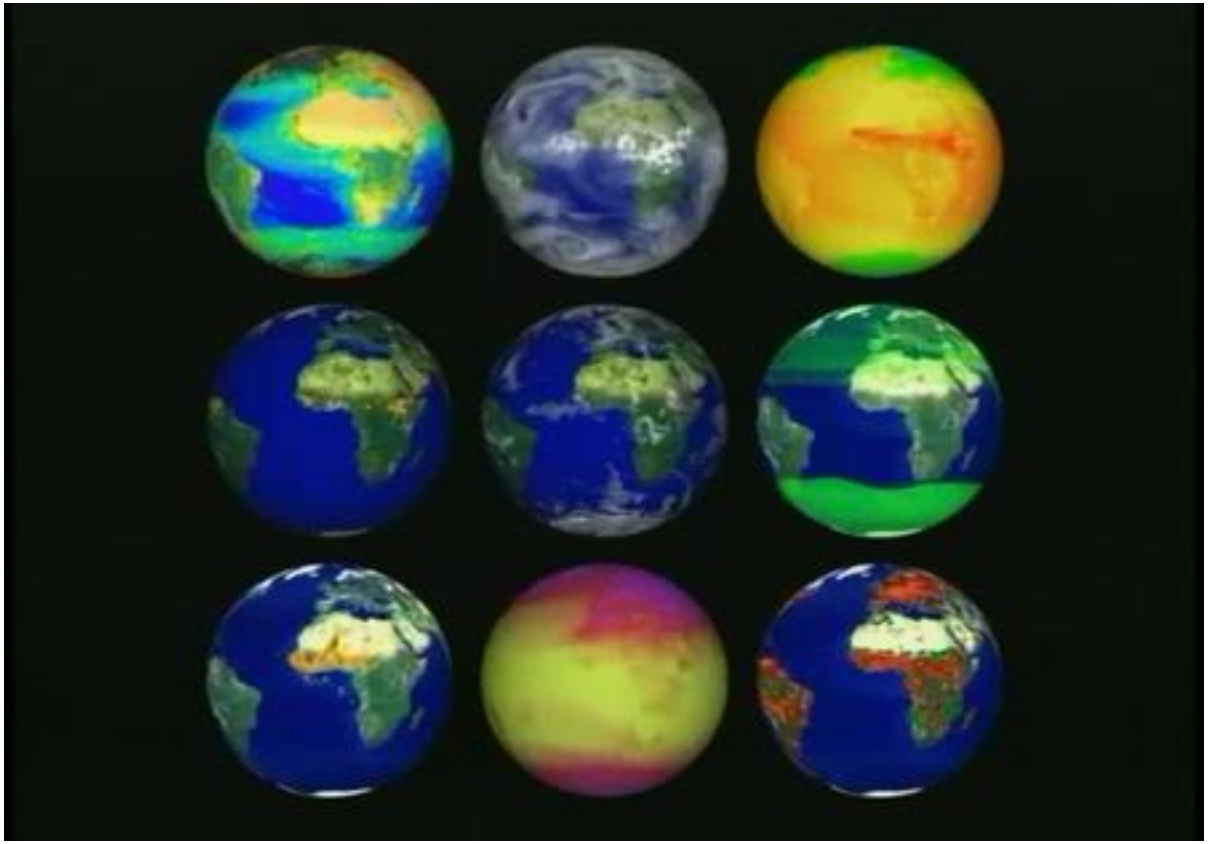
AIR POLLUTION & CLIMATE CHANGE: TRENDS, CAUSES, & FUTURE IMPACTS

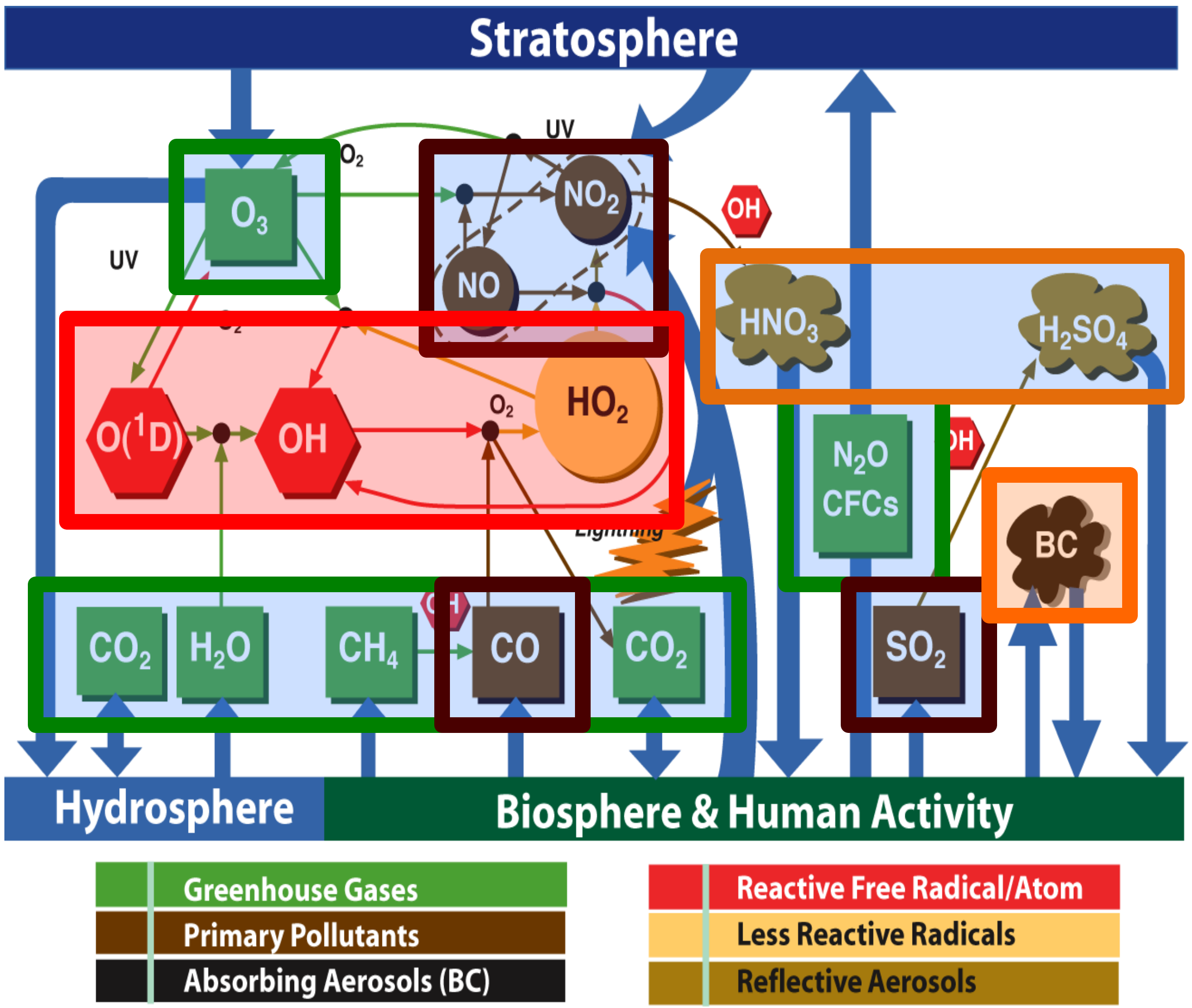
Ronald G. Prinn, MIT



IMAGES From NASA's TERRA satellite

Presentation to **LAB4ENERGY**

February 14, 2014



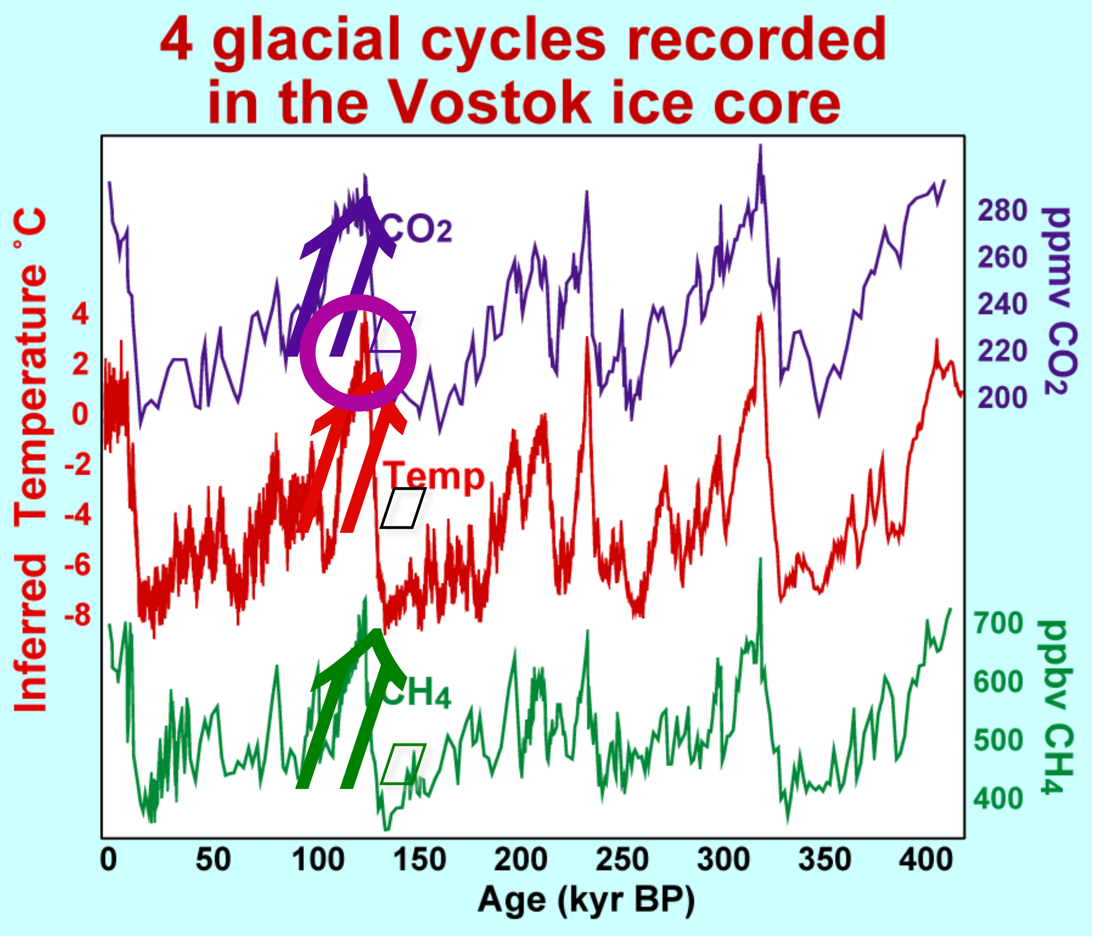
AIR POLLUTION & CLIMATE ARE CLOSELY LINKED: SHARED CHEMISTRY, PHYSICS & SOURCES

Summary of the photochemistry in the atmosphere important in air pollution and climate. Organic compounds (not shown) are similar to CH_4 in their reactions with OH, but they form acids, aldehydes and ketones in addition to CO.

HOW HAVE TEMPERATURE & GREENHOUSE GASES CHANGED OVER THE PAST 400,000 YEARS AND WHY?

Reference: Petit *et al.*, *NATURE*, 399: 429-436 (1999)

IN THE EEMIAN, SEA LEVEL WAS 4 TO 8 METERS HIGHER & POLAR TEMPERATURES 3 TO 4 °C WARMER THAN TODAY



BUT TO EXPLAIN THE LARGE TEMPERATURE CHANGES, WE REQUIRE LARGE POSITIVE FEEDBACKS TO AMPLIFY THE MILANKOVICH CYCLE CHANGES IN SOLAR INPUT : H_2O, CO_2, CH_4, N_2O, ICE/SNOW, etc.

CAUSES FOR TIMING: MILANKOVICH CYCLES YIELD VERY SMALL CHANGES IN NH & SH SOLAR INPUTS

-tilt (or obliquity) of the Earth's axis (22-25°, 41Kyr)

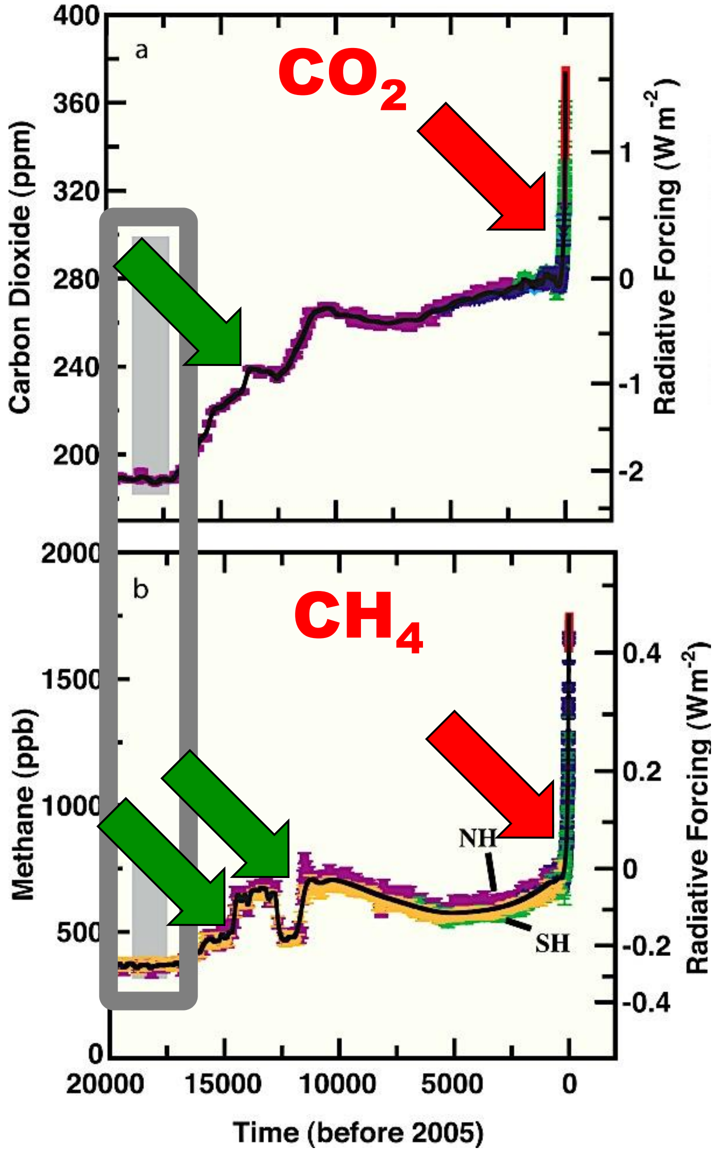
-eccentricity of the orbit (100Kyr, 400Kyr)

-direction of the axis tilt at a given point of the orbit (precession, 22Kyr)

- NH/SH land/ocean differences

ATMOSPHERIC GREENHOUSE GAS LEVELS OVER THE LAST 20,000 YEARS SHOW STRONG HUMAN INFLUENCE & POSITIVE CLIMATE-GHG FEEDBACK

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



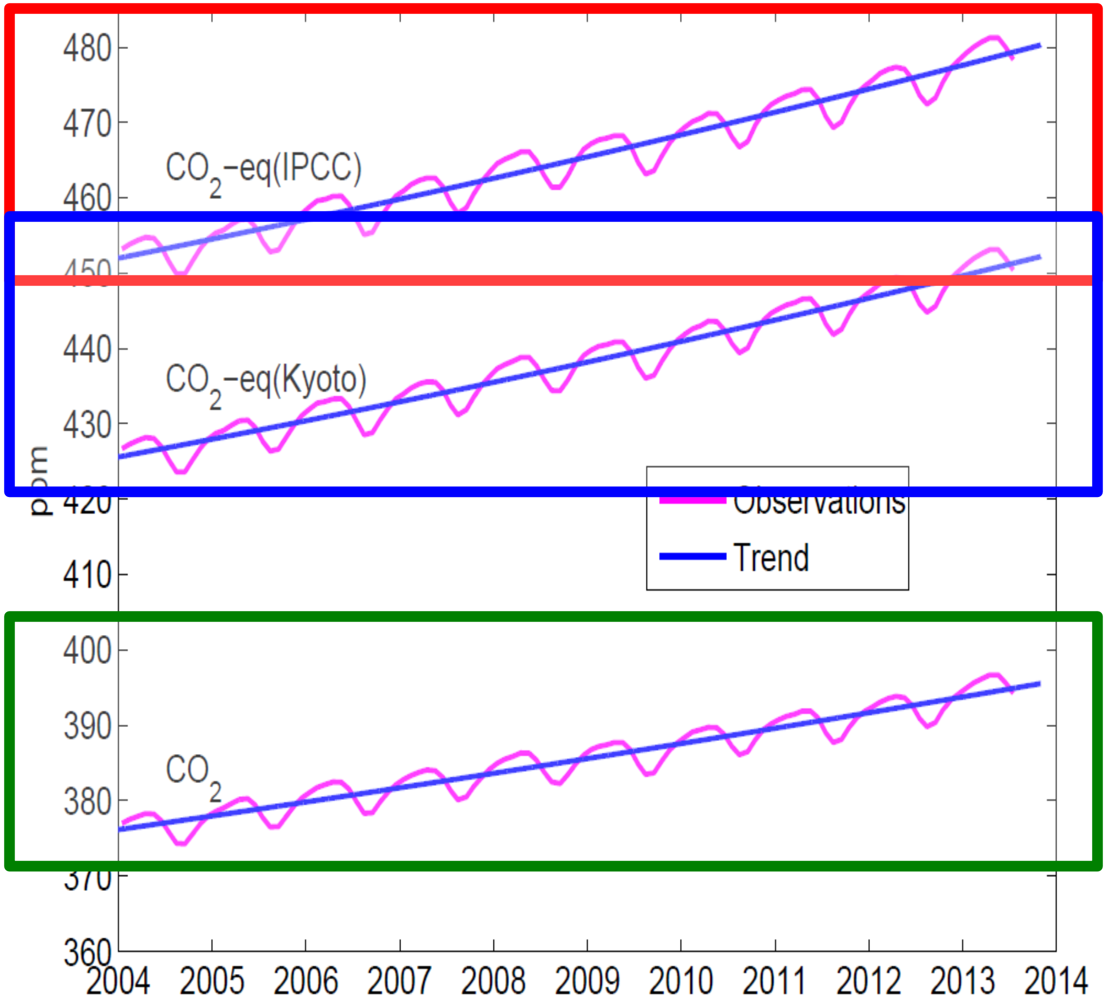
Concentrations and radiative forcing by carbon dioxide (CO_2) & methane (CH_4) over the last 20,000 years reconstructed from Antarctic and Greenland ice and firn data and direct atmospheric measurements.

The grey bars shows the reconstructed range of natural variability for the past 650,000 years.

IT WAS BIG NEWS THAT WE EXCEEDED 400 PPM OF CO_2 IN 2013, BUT WE ACTUALLY EXCEEDED 400 PPM IN CO_2 EQUIVALENTS (CO_2 plus non-CO_2 greenhouse gases) IN THE MID-1980s

GLOBAL TRENDS IN MOLE FRACTIONS (ppm CO_2 equivalents) OF TOTAL LONG-LIVED GREENHOUSE GASES (GHGs)

(CO_2 from NOAA and non-CO_2 from AGAGE; Huang et al, MIT Joint Program Report #174, 2009)

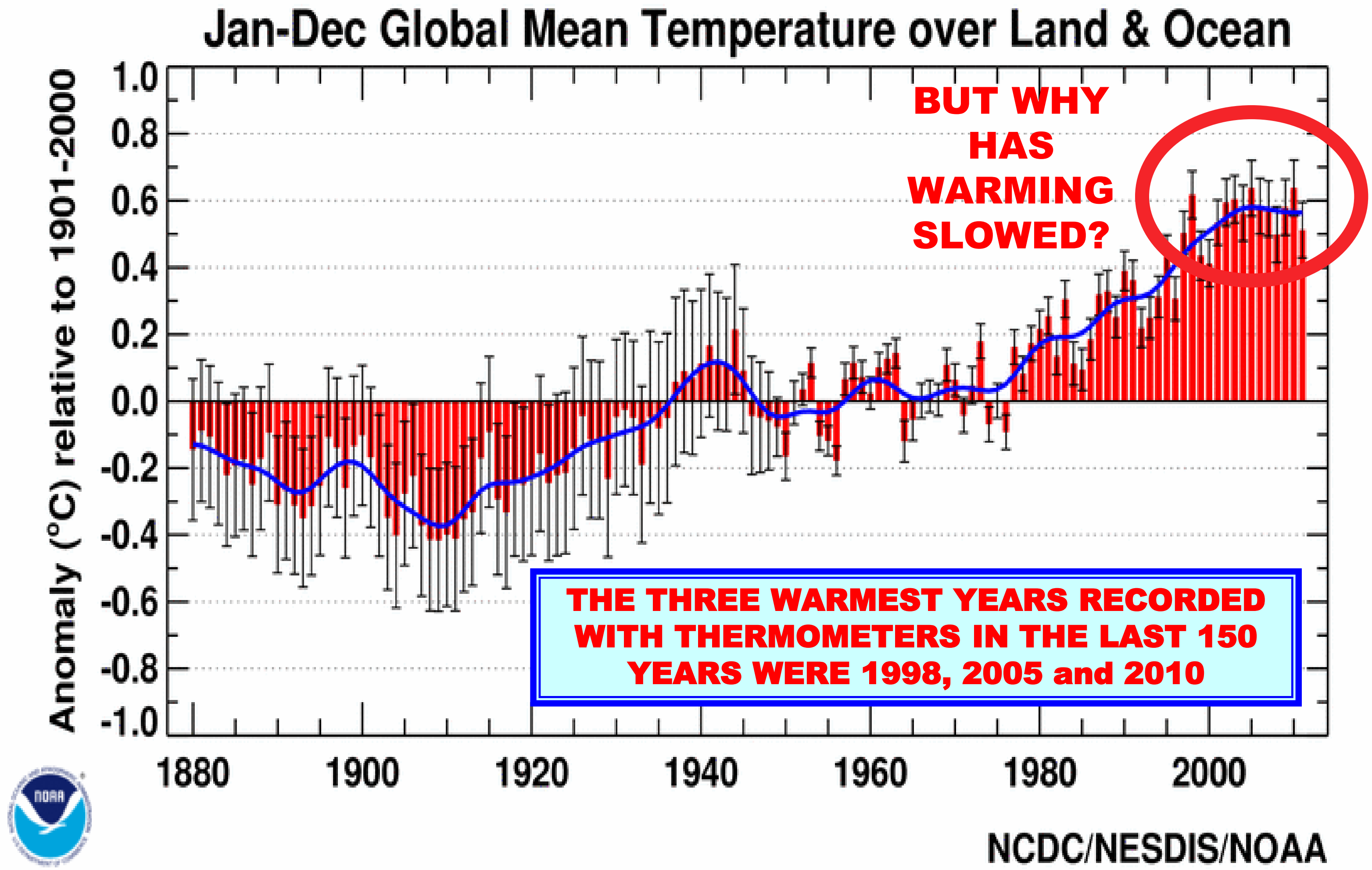


IPCC refers to Kyoto Protocol + Montreal Protocol greenhouse gases.

FOR A "NO POLICY" CASE, THE MEDIAN GHG LEVELS IN 2091-2100 are projected to be 870 ppm for CO_2 PLUS 460 ppm CO_2 equivalents for the non-CO_2 GHGs ***Ref: Sokolov et al, Journal of Climate, 2009; Webster et al, Climatic Change, 2011***

HOW HAVE TEMPERATURES EVOLVED OVER 1880-2012?

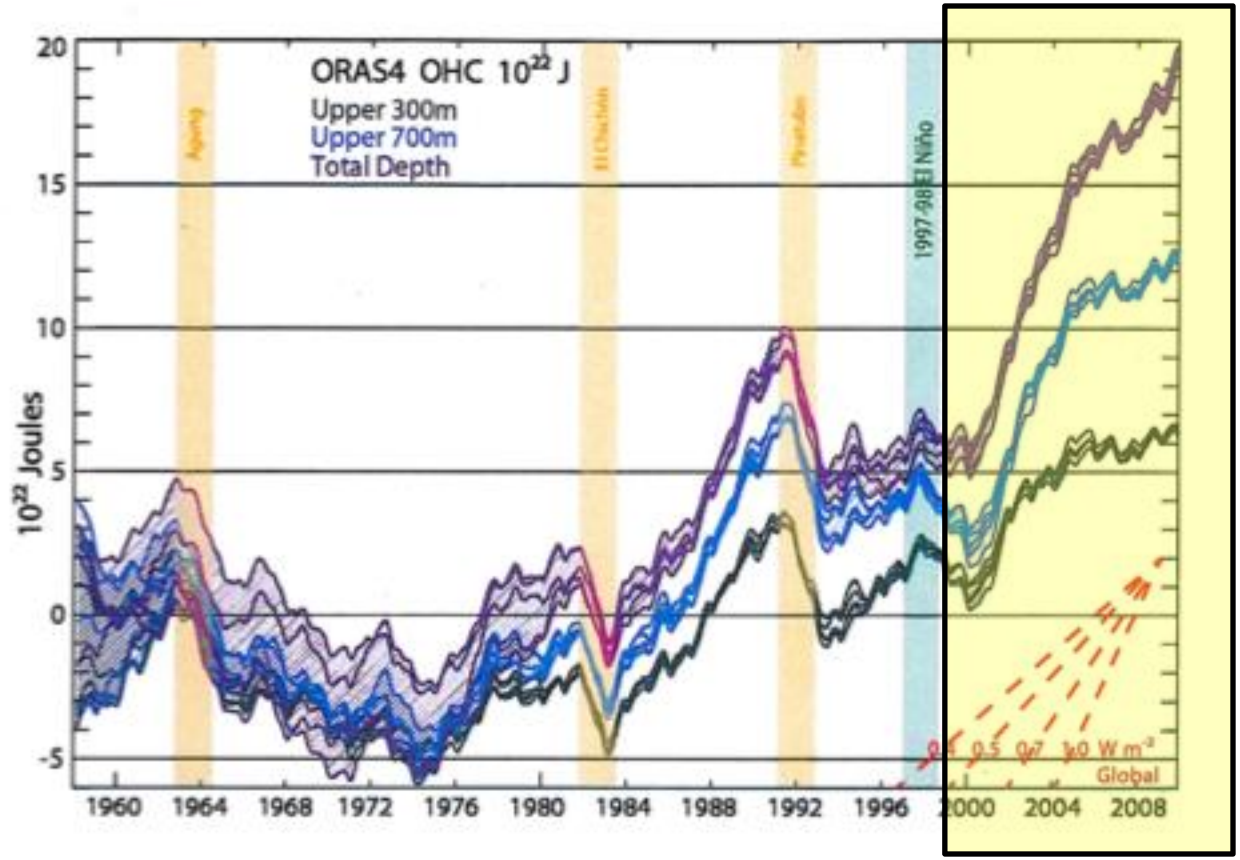
Global annual surface air temperature anomaly (relative to 1901-2000 average) as estimated from observations by NOAA-NCDC (www.ncdc.noaa.gov)



WHY HAS THE SURFACE WARMING APPEARED TO HAVE SLOWED POST-1998 WHEN THE GREENHOUSE EFFECT SHOULD BE CONTINUOUSLY ADDING MORE HEAT TO THE EARTH?

THERE ARE NO 1998-LEVEL EL NINO'S AFTER 1998. HENCE THE VERTICAL MIXING OF WATER IN THE TROPICS SHOULD BE ENHANCED.

BUT IF THIS IS THE EXPLANATION, THEN THE OCEAN MUST BE WARMING STRONGLY POST-1998.

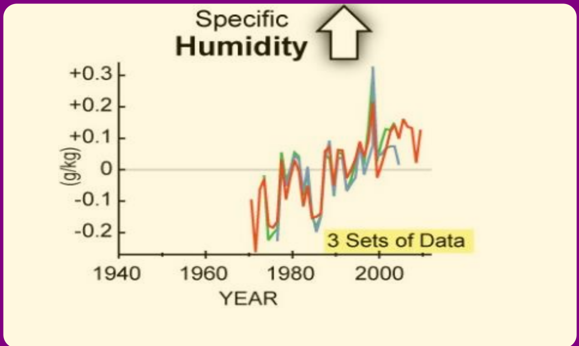


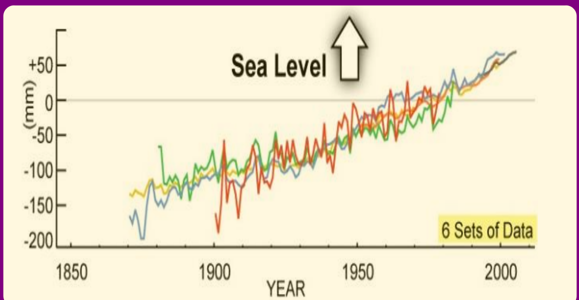
OCEAN HEAT CONTENT TRENDS IN 3 OCEAN LAYERS (10^{22} JOULES,12-MONTH RUNNING MEANS RELATIVE TO 1958-1965 AVERAGE)

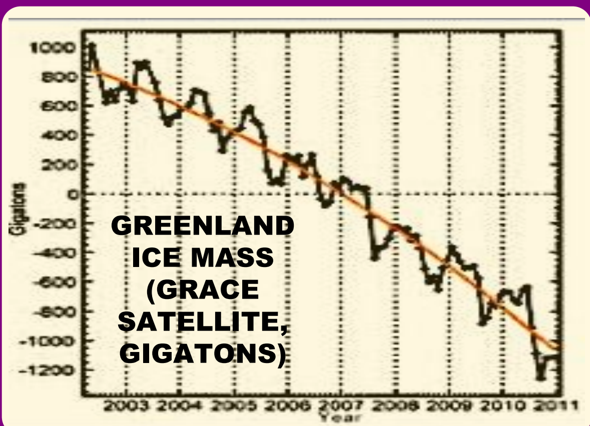
from ECMWF-ORAS4 5-member re-analyses with ship & Argo (began 2000-2004) temperatures. Large pre-1980 uncertainty range due to sparse data. Vertical bars show times of influence of large volcanic eruptions (orange) and large El Ninos (blue). Linear slopes for various global heating rates (Wm^{-2}) also shown. Ref: Balmaseda, Trenberth & Kallen, Geophys. Res. Lett., 2013

BEYOND RISING TEMPERATURES, THERE ARE NOW MULTIPLE INDICATORS OF GLOBAL CLIMATE CHANGE

Ref: Arndt, D. S., M. O. Baringer, and M. R. Johnson, Eds., 2010: State of the Climate in 2009. Bull. Amer. Meteor. Soc., 91 (7), S1-S224. **Ref: Rodell et al, Bulletin AMS, 92, S50-S51, 2011.**

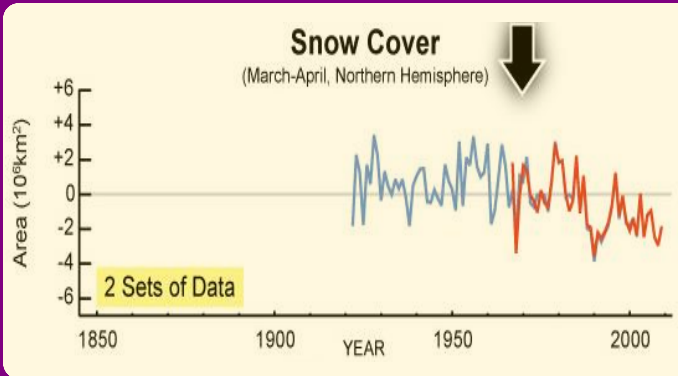


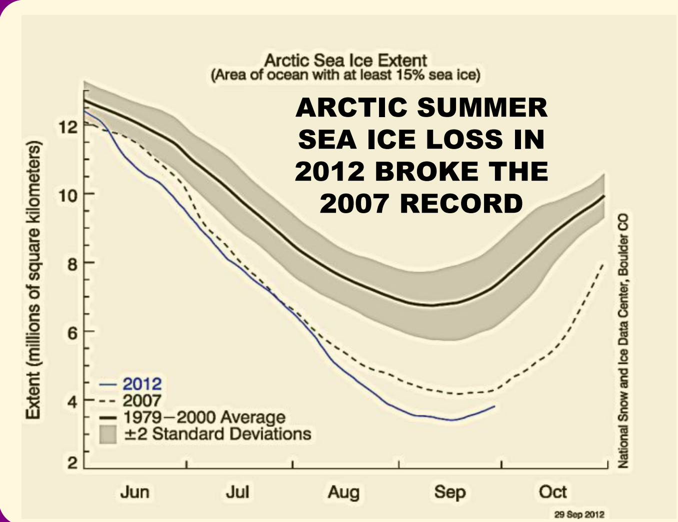




Shown are changes from the time averages except for Arctic sea ice extant

RISING HUMIDITY & DECREASING SEA ICE, LAND ICE, & SNOW COVER, ARE ALL "POSITIVE FEEDBACKS" THAT ACCELERATE THE WARMING.





Is Typhoon/Cyclone/Hurricane Destructive Power Increasing?

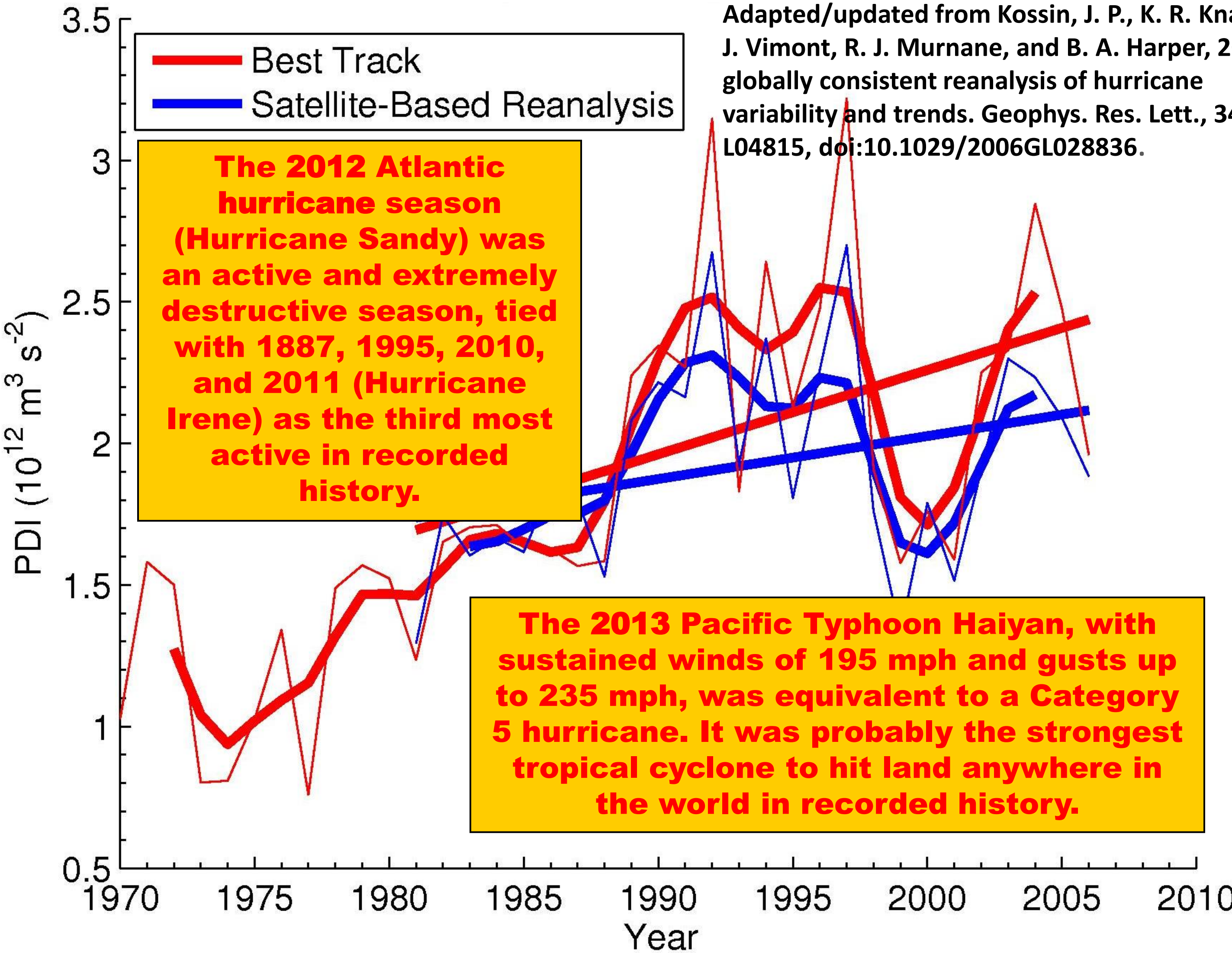
Power Dissipation Index (PDI) = $\int_0^T V_{max}^3\, dt$ is globally aggregated to provide a measure of total storm destruction.

[Courtesy of Tom Karl, Director, National Climate Data Center, NOAA]

Thick wavy lines are smoothed versions of thin annual lines using a binomial filter.

Thick straight lines are linear trends.

Adapted/updated from Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper, 2007: A globally consistent reanalysis of hurricane variability and trends. Geophys. Res. Lett., 34, L04815, doi:10.1029/2006GL028836.



The 2012 Atlantic hurricane season (Hurricane Sandy) was an active and extremely destructive season, tied with 1887, 1995, 2010, and 2011 (Hurricane Irene) as the third most active in recorded history.

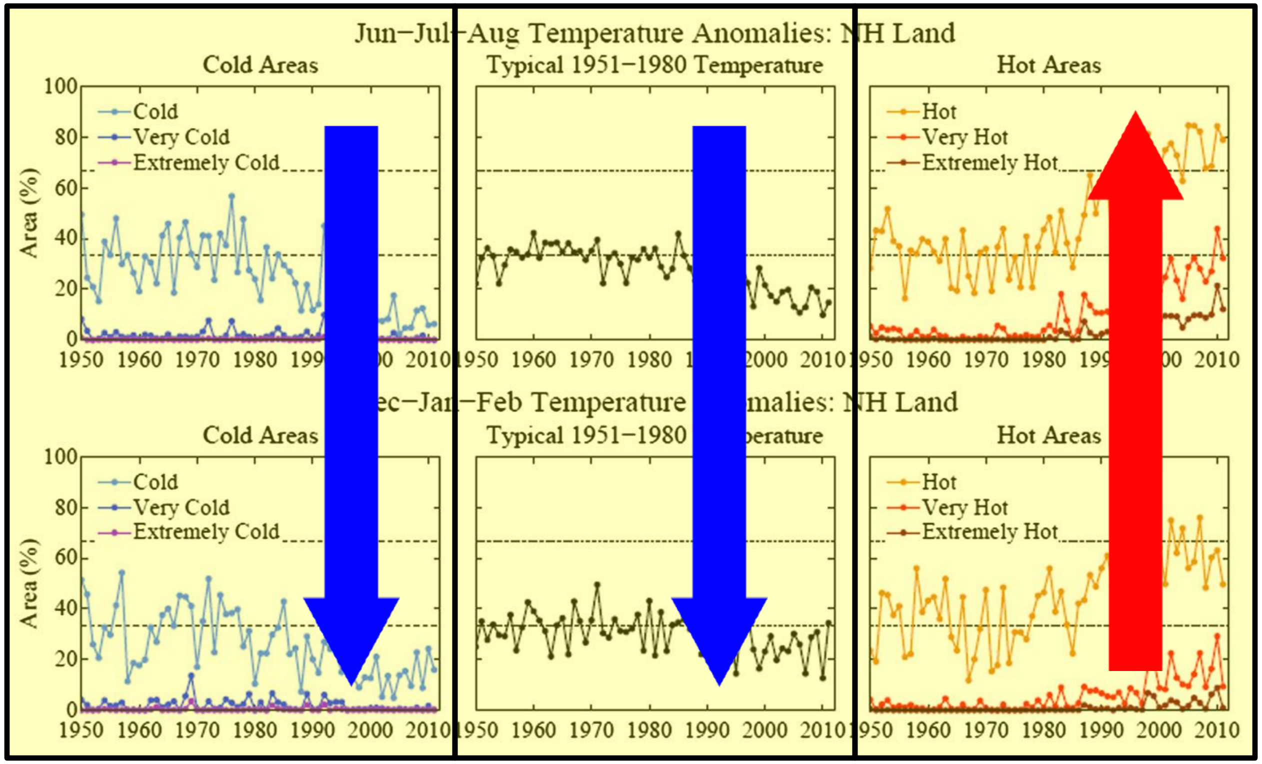
The 2013 Pacific Typhoon Haiyan, with sustained winds of 195 mph and gusts up to 235 mph, was equivalent to a Category 5 hurricane. It was probably the strongest tropical cyclone to hit land anywhere in the world in recorded history.

CHANGING AREAS OF HOT & COLD CLIMATE EXTREMES (define cold/hot, very cold/hot, and extremely cold/hot areas that contain 50%, 5% and 1% of extremes)

PERCENT OF LAND AREA COVERED BY TEMPERATURE EXTREMES (RELATIVE TO 1951-1980 PERIOD) FOR NORTHERN HEMISPHERE SUMMER AND WINTER.

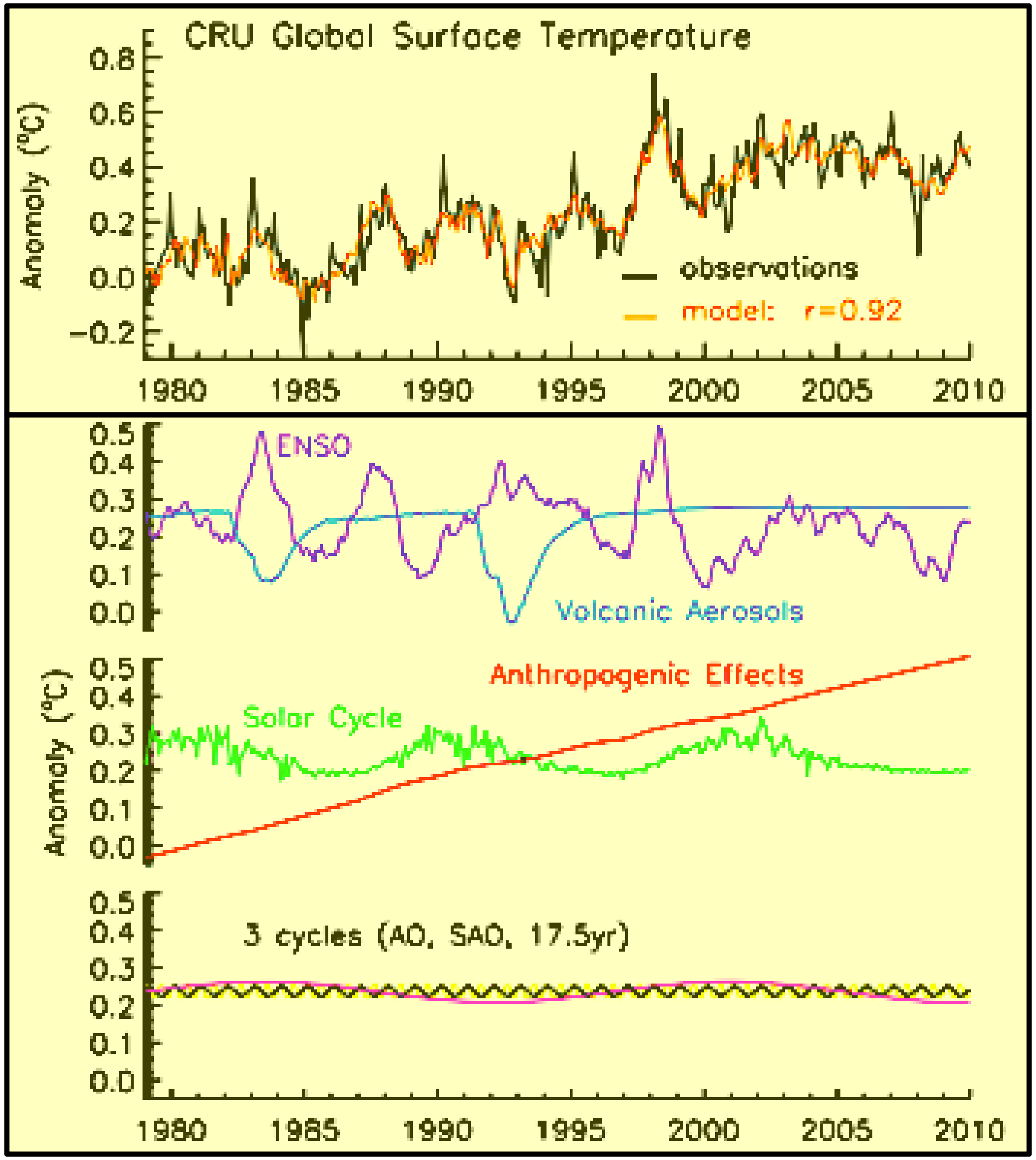
IN ALL CASES, THE AREA OF COLD EXTREMES IS SHRINKING, THE AREA OF TYPICAL 1951-1980 TEMPERATURES IS ALSO SHRINKING, AND THE AREA OF HOT EXTREMES IS EXPANDING.

Ref: HANSEN et al, Proc. National Academy of Science, 2012.



WHAT ARE THE RELATIVE CONTRIBUTIONS TO CLIMATE CHANGES OF VARIABILITY IN SPECIFIC NATURAL PROCESSES (El Nino, La Nina, Volcanoes, Solar Cycle) & ANTHROPOGENIC EFFECTS?

From theory, we expect warming during El Nino (suppressed tropical oceanic heat uptake), cooling during La Nina (enhanced tropical oceanic heat uptake), and cooling by sulfur-rich volcanic eruptions (reflecting aerosols)

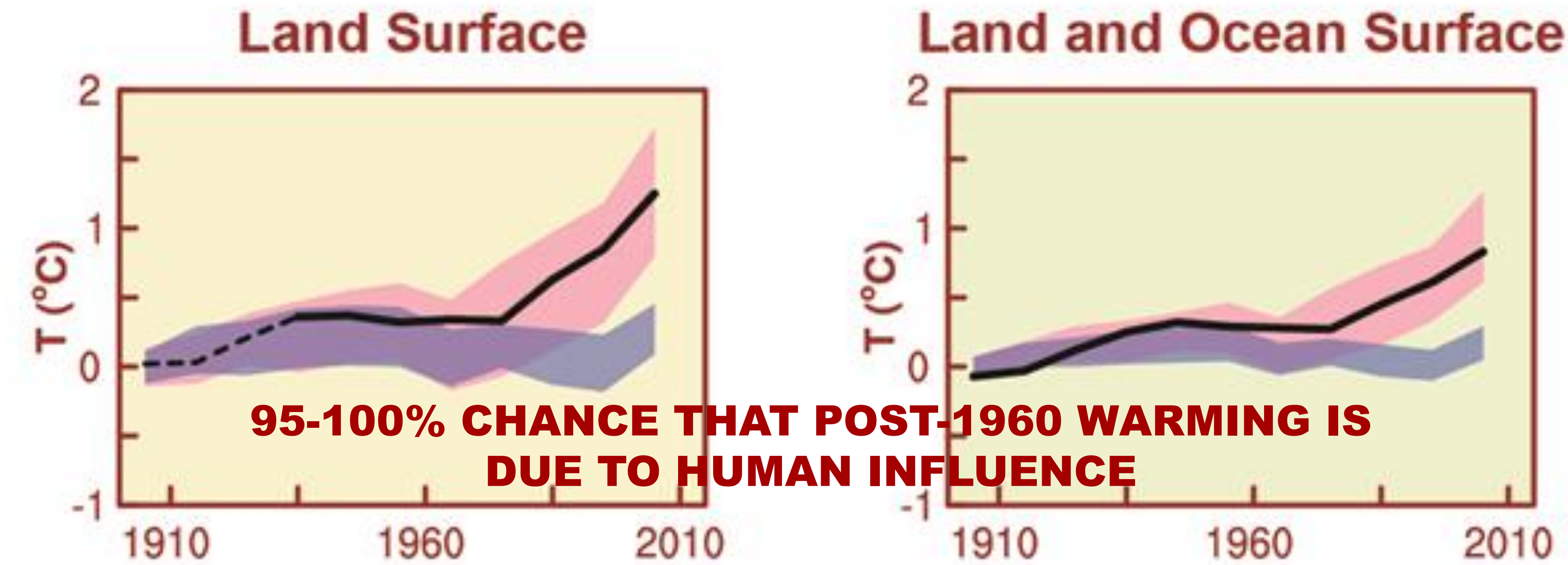


Top panel shows monthly mean variations in the global temperature anomalies (relative to 1951-1980 avgs.) of the Earth's surface, from the Climatic Research Unit (CRU, black) and an empirical model (orange, following Lean and Rind [2009]) that combines four primary influences and three minor cycles shown in the 3 lower panels. After removing the four primary effects, namely ENSO (purple) at three different lags, volcanic aerosols (blue) at two different lags, solar irradiance (green), and anthropogenic effects (red), minor cycles identifiable as annual (AO, black), semi-annual (SAO, yellow), and 17.5 year oscillations (pink) are evident in the residuals

Ref: Kopp & Lean, GRL, 2011.

WHAT ARE THE RELATIVE ROLES OF HUMAN & NATURAL PROCESSES IN DRIVING THE OBSERVED GLOBAL & CONTINENTAL TEMPERATURE CHANGES FROM 1906 to 2010?

Ref: IPCC 5th Assessment, Summary for Policymakers, 2013



95-100% CHANCE THAT POST-1960 WARMING IS DUE TO HUMAN INFLUENCE

Red band: full range for multiple independent model simulations using natural and human forcing.

Blue band: full range for multiple independent model simulations using natural forcing only.

Black line: observed changes.

HUMAN-DRIVEN GLOBAL CLIMATE FORCING by greenhouse gases and aerosols (1750-2011) is about 2.3 W m^{-2} x 5.1 x 10^{14} m^2 = 11.7 x 10^{14} W = 1170 TW (about 74 times current global energy consumption)

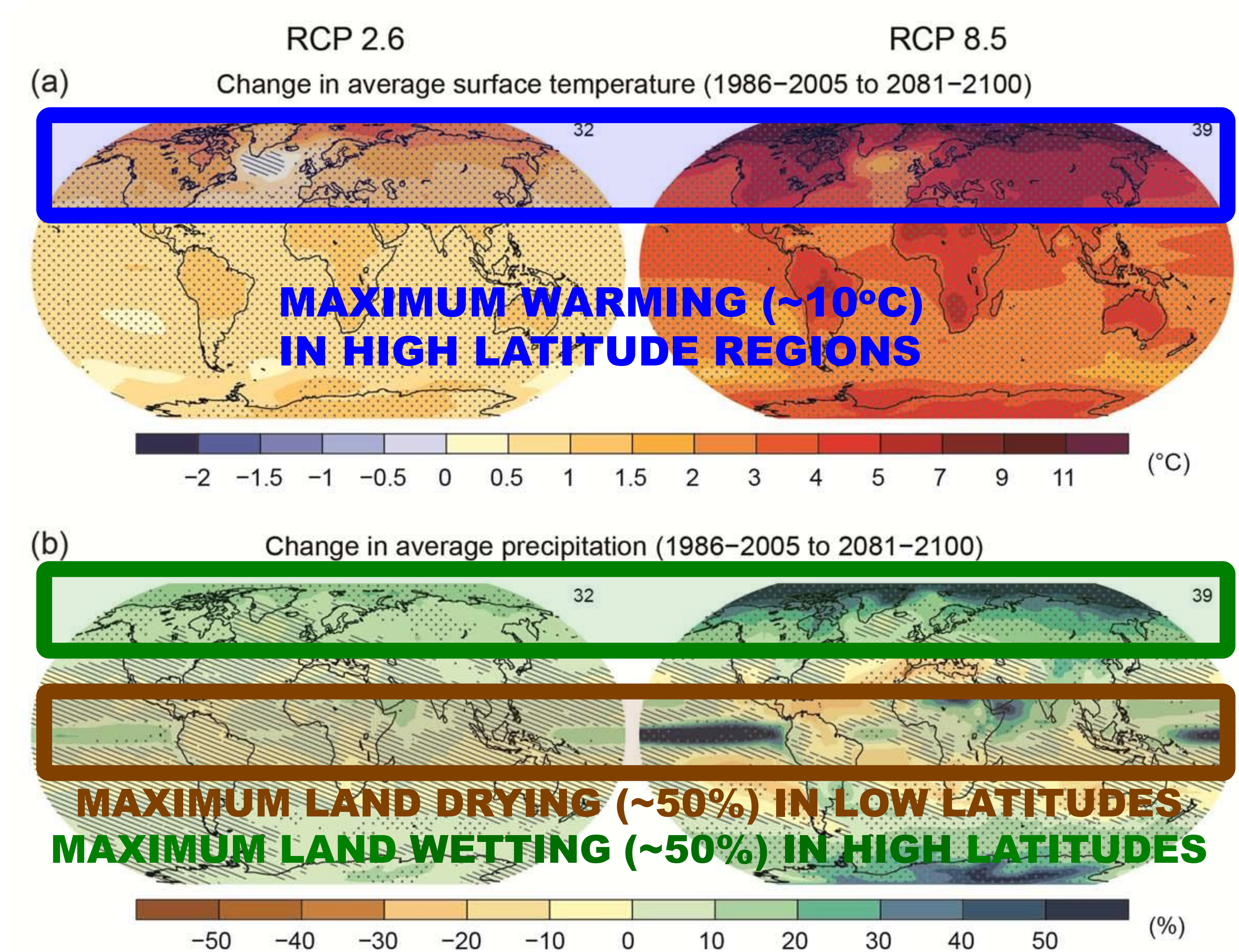
WHAT ARE NATIONAL & FOOD SECURITY IMPLICATIONS OF THE PROJECTED PATTERNS OF CHANGES IN TEMPERATURE (°C) AND RAINFALL (%)?

CAN AGRICULTURE ADAPT TO CLIMATE CHANGE?

(a) Top row: Annual mean temperature change between 1986 to 2005 and 2081 to 2100, averaged over multiple models with low & high emissions scenarios (-2 to +11°C).

(b) Bottom row: same as top, but for fractional change in precipitation (+/-50%).

Ref: IPCC 5th Assessment, Summary for Policymakers, 2013

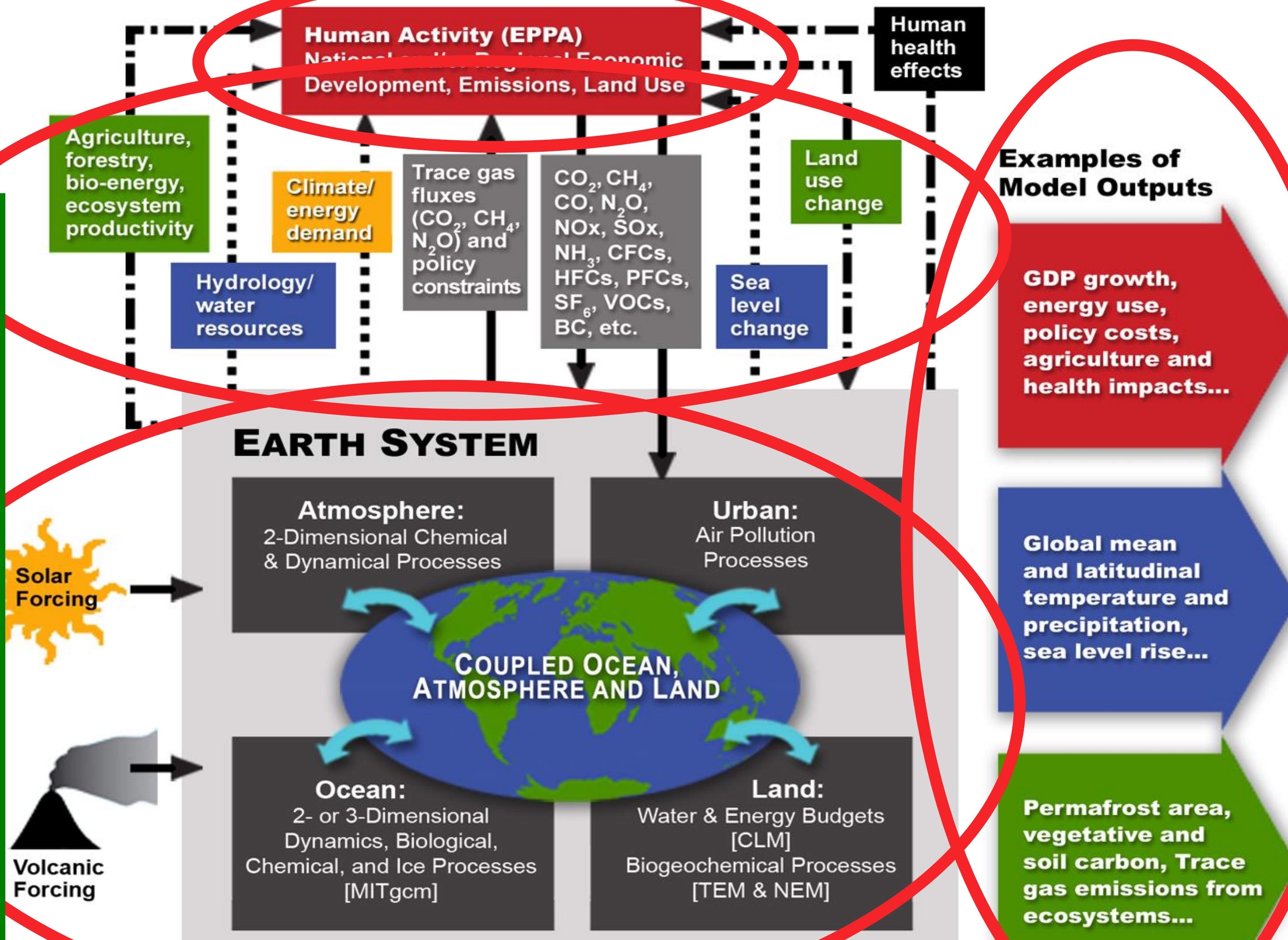


USING A PROBABILISTIC APPROACH, WHAT IS THE RELATIONSHIP BETWEEN GREENHOUSE GAS & AIR POLLUTANT LEVELS AND FUTURE CLIMATE?

(non-CO_2 gases converted to their equivalent levels of CO_2 that would have the same effect on climate; currently at about 480 ppm CO_2 equivalents)

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

TO FORECAST PROBABILITY, we do 400 IGSM runs (1750-2100) with different but equally probable assumptions about uncertain parameters and structures in the economics and climate sub-models



THE MIT INTEGRATED GLOBAL SYSTEM MODEL
http://web.mit.edu/global change

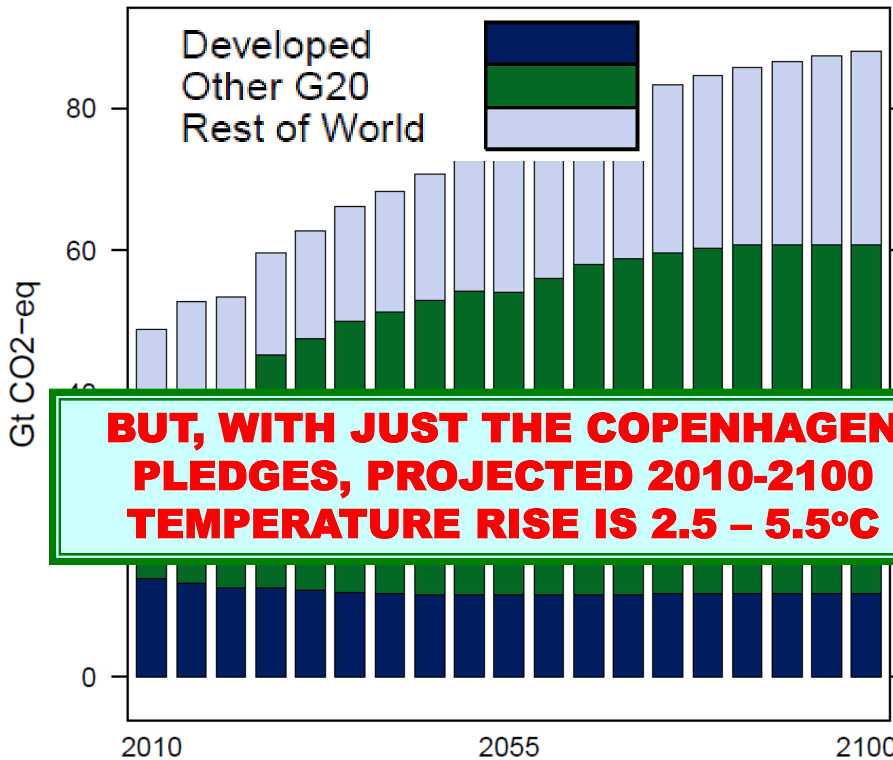
ASSUMING 2009 UN COPENHAGEN PLEDGES ARE HONORED, WHAT ARE FUTURE EMISSIONS BY COUNTRY GROUP & WILL THEY SOLVE THE CLIMATE PROBLEM?

[MIT ENERGY & CLIMATE OUTLOOK, 2013: http://globalchange.mit.edu/]

INCORPORATES 2020 EMISSIONS REDUCTION TARGETS G20 NATIONS MADE AT THE 2009 UN FRAMEWORK CONVENTION ON CLIMATE CHANGE (I.E. COPENHAGEN PLEDGES), SHOWING HOW FAR THESE PLEDGES TAKE US, AND WHAT IS AT RISK IF WE FAIL TO PUSH BEYOND THESE GOALS.

Reports results for 3 broad groups: Developed G20 countries (USA, Canada, Europe, Japan, Australia and New Zealand); Other G20 nations (China, India, Russia, Brazil, Mexico, and several fast-growing Asian economies); and the Rest of the world.

FROM IGSM RUNS, WHAT NATIONS BY GROUP WILL THE EMISSIONS (Gton CO_2-eq/year) COME FROM?



BUT, WITH JUST THE COPENHAGEN PLEDGES, PROJECTED 2010-2100 TEMPERATURE RISE IS 2.5 – 5.5°C

Emissions in developed countries decrease ≈10% in the near term (due to pledges), then remain constant after 2020.

Slow growth in emissions in other G20 nations, but unless targets are extended, emissions increase 130% contributing ≈55% of global emissions by 2100.

Due to population growth and the absence of climate policy, the rest of the world's emissions will nearly triple by 2100.

HOW EFFECTIVE IS A GLOBAL COAL to SHALE GAS TRANSITION FOR SLOWING WARMING?

(IGSM RESULTS, Prinn, Sokolov & Paltsev, 2013)

MIT JOINT PROGRAM SCIENCE POLICY GLOBAL CHANGE

(1) Reference-No Policy (REF)

(2) Force Gas to replace Coal in Electricity linearly from 2015 to 2050 (GAS ELEC)

(3) In addition to (2), starting from 2030, force Gas to replace Coal and Oil everywhere (GAS ALL)

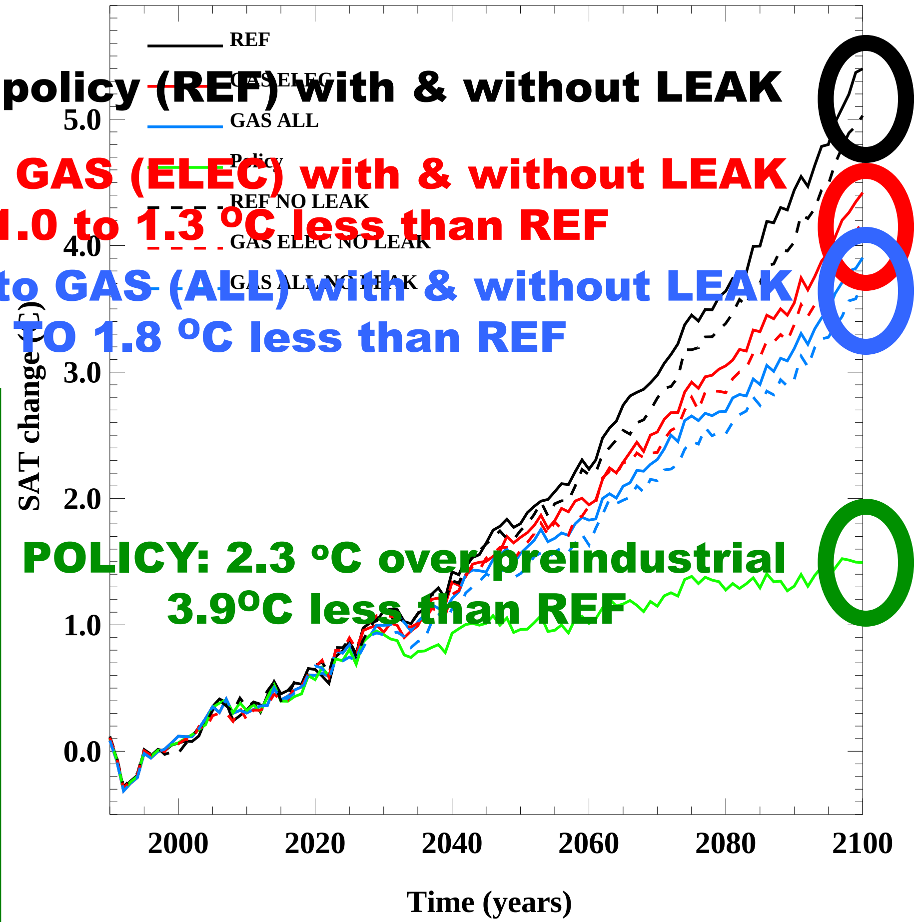
(4) In (1), fix gas-related methane leakage (REF NO LEAK)

(5) In (2), fix gas-related methane leakage (GAS ELEC NO LEAK)

(6) In (3), fix gas-related methane leakage (GAS ALL NO LEAK)

(7) Cap & Trade Policy to obtain ~2.3 °C increase above pre-industrial by 2100 (POLICY)

INCREASES IN SURFACE AIR TEMPERATURE ABOVE 1981-2000 AVERAGES (using climate sensitivity = 2.9°C)



BUT NEED TO SOLVE REGURGITATED POLLUTED FRACTURING WATER (typically 1/3 to 3 times injected volume), AND LOCAL GAS LEAKAGE PROBLEMS.

WHAT ARE THE ODDS OF GLOBAL AVERAGE SURFACE AIR WARMING from 1981-2000 to 2091-2100 EXCEEDING VARIOUS LEVELS, WITHOUT (median 1330 ppm-equiv. CO_2) & WITH A 560, 660, 780 or 890 median ppm-equiv. CO_2 GHG STABILIZATION POLICY ***(400 IGSM forecasts per case)***

Ref: Sokolov et al, Journal of Climate, 2009; Webster et al, Climatic Change, 2012

MIT JOINT PROGRAM SCIENCE POLICY GLOBAL CHANGE	ΔT > 2°C (values in red relative to 1860 or pre-industrial)	ΔT > 4°C	ΔT > 6°C
No Policy at 1330	100% (100%)	85%	25%
Stabilize at 890 (L4)	100% (100%)	25%	0.25%
Stabilize at 780 (L3)	97% (100%)	7%	< 0.25%
Stabilize at 660 (L2)	80% (97%)	0.25%	< 0.25%
Stabilize at 560 (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?

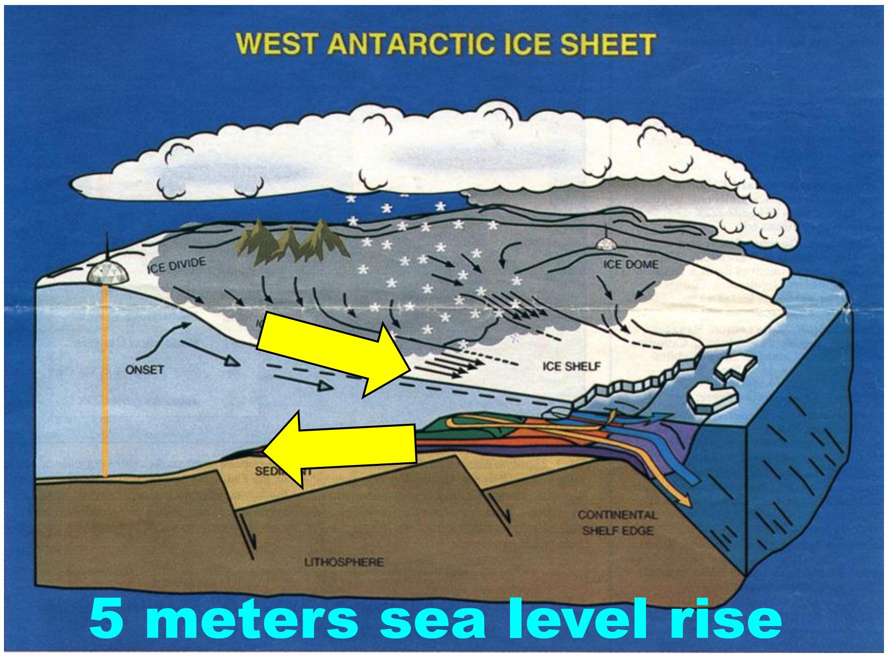
WHAT ARE THE ODDS OF ARCTIC (60°N to 90°N) SURFACE AIR WARMING from 1981-2000 to 2091-2100 EXCEEDING VARIOUS LEVELS, WITHOUT (median 1330 ppm-equiv. CO_2) & WITH A 560, 660, 780 or 890 median ppm-equiv. CO_2 GHG STABILIZATION POLICY ***(400 IGSM forecasts per case)***

Ref: Sokolov et al, Journal of Climate, 2009; Webster et al, Climatic Change, 2012

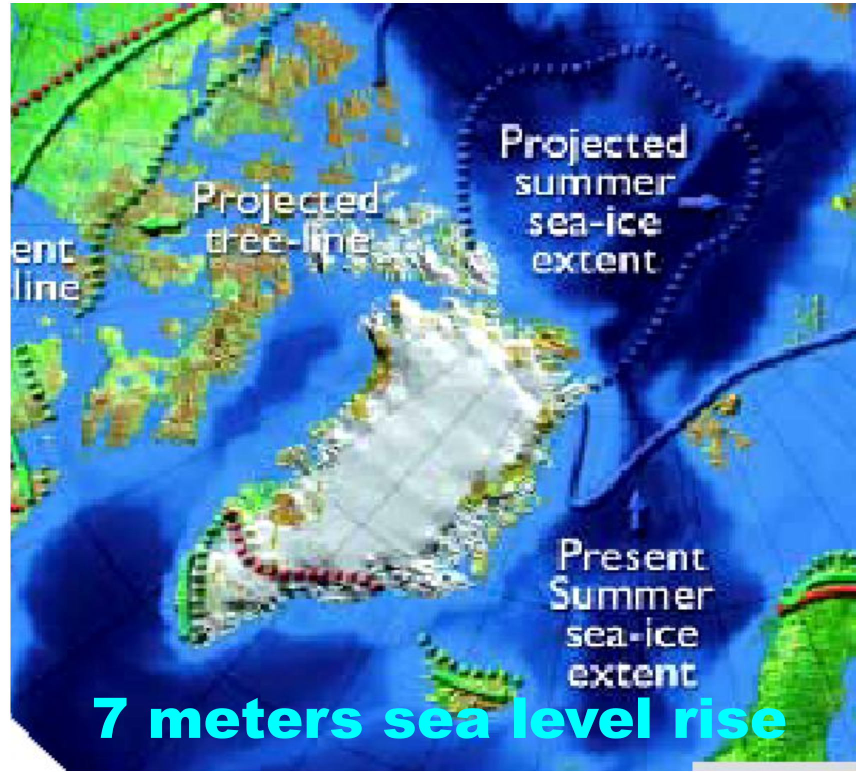
MIT JOINT PROGRAM GLOBAL CHANGE	ΔT > 4°C	ΔT > 6°C	ΔT > 8°C
No Policy at 1330	100%	95%	70%
Stabilize at 890 (L4)	95%	30%	3%
Stabilize at 780 (L3)	80%	9%	0.25%
Stabilize at 660 (L2)	25%	0.25%	< 0.25%
Stabilize at 560 (L1)	0.5%	< 0.25%	< 0.25%

Last time polar regions were about 4°C warmer than present (Eemian: 125,000 years ago), reductions in polar ice volume led to 4 to 8 meters of sea level rise.

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



STABILITY OF WEST ANTARCTIC ICE SHEET



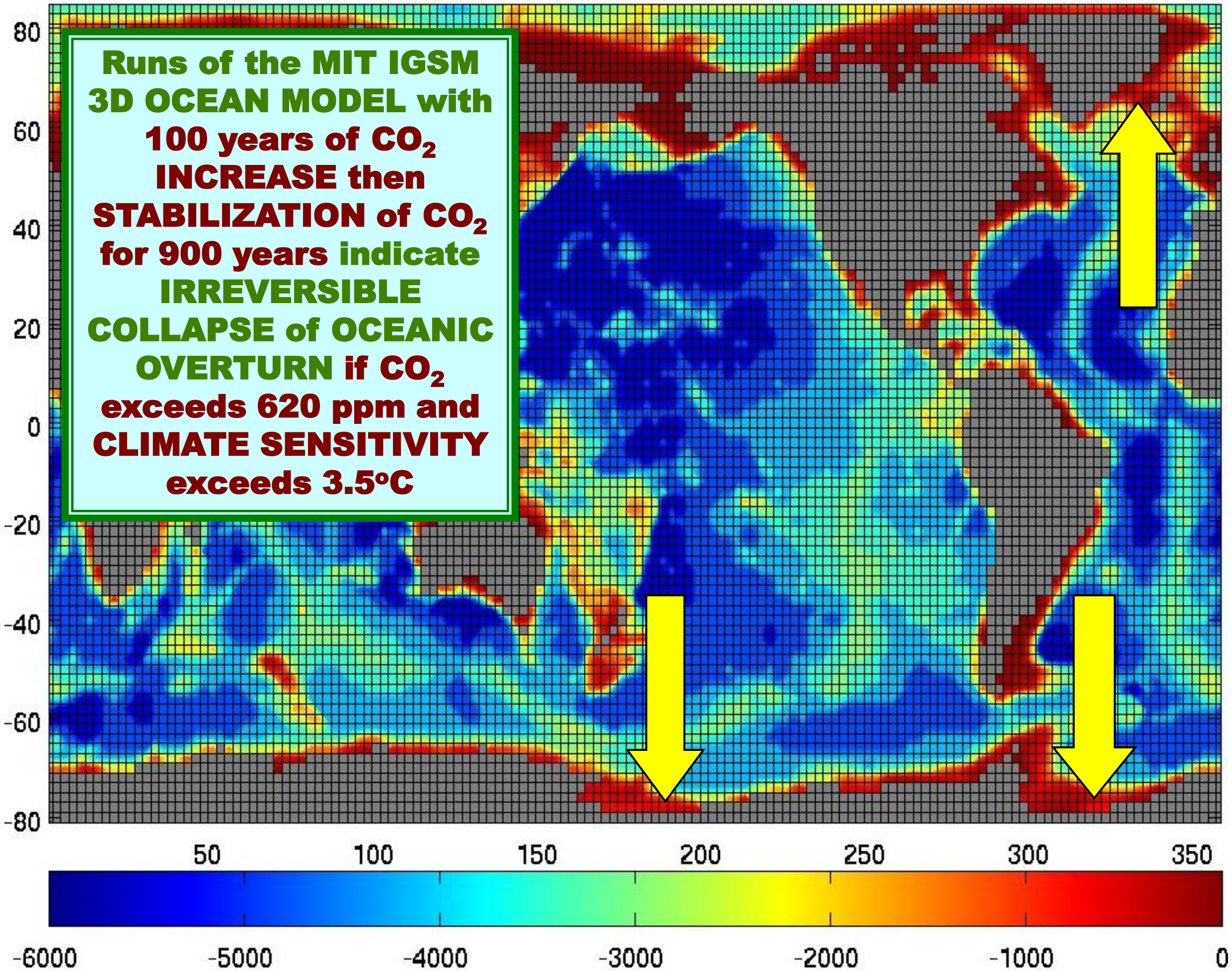
STABILITY OF GREENLAND ICE SHEET

The last time the polar regions were significantly warmer (~4 °C) than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 8 meters of sea level rise.

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

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

Runs of the MIT IGSM 3D OCEAN MODEL with 100 years of CO_2 INCREASE then STABILIZATION of CO_2 for 900 years indicate IRREVERSIBLE COLLAPSE of OCEANIC OVERTURN if CO_2 exceeds 620 ppm and CLIMATE SENSITIVITY exceeds 3.5°C



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 SOME LEADING ENVIRONMENTAL RISKS WHOSE ODDS OR AMPLITUDES COULD BE LOWERED BY STABILIZATION AT SAY 560 ppm CO_2-equivalents?

DEPLETION OF ARCTIC SUMMER SEA ICE

Replacing reflecting with absorbing surface. New RECORD LOW in Sept 2012

INSTABILITY OF GREENLAND & WEST ANTARCTIC ICE SHEETS

7+5=12 meters of potential sea-level rise (Eemian sea level rise = 4-8 meters)

DEEP OCEAN CARBON & HEAT SINK SLOWED BY DECREASED SEA ICE & INCREASED FRESH WATER INPUTS INTO POLAR SEAS

e.g. collapse if CO_2 >620 ppm & CLIMATE SENSITIVITY >3.5ºC (Scott et al, 2008)

INSTABILITY OF ARCTIC TUNDRA & PERMAFROST

About 1670 billion tons of carbon stored in Arctic tundra & frozen soils; equivalent to >200 times current anthropogenic emissions (Tarnocai, GBC, 2009)

DELETERIOUS INCREASES OF OCEANIC ACIDITY

pH drop exceeding 0.5 (>875 ppm CO_2) could decimate calcareous phytoplankton

SHIFTING CLIMATE ZONES

Maximum warming & % precipitation increase in polar regions
More arid sub-tropics & lower mid-latitudes (IPCC, 2013)

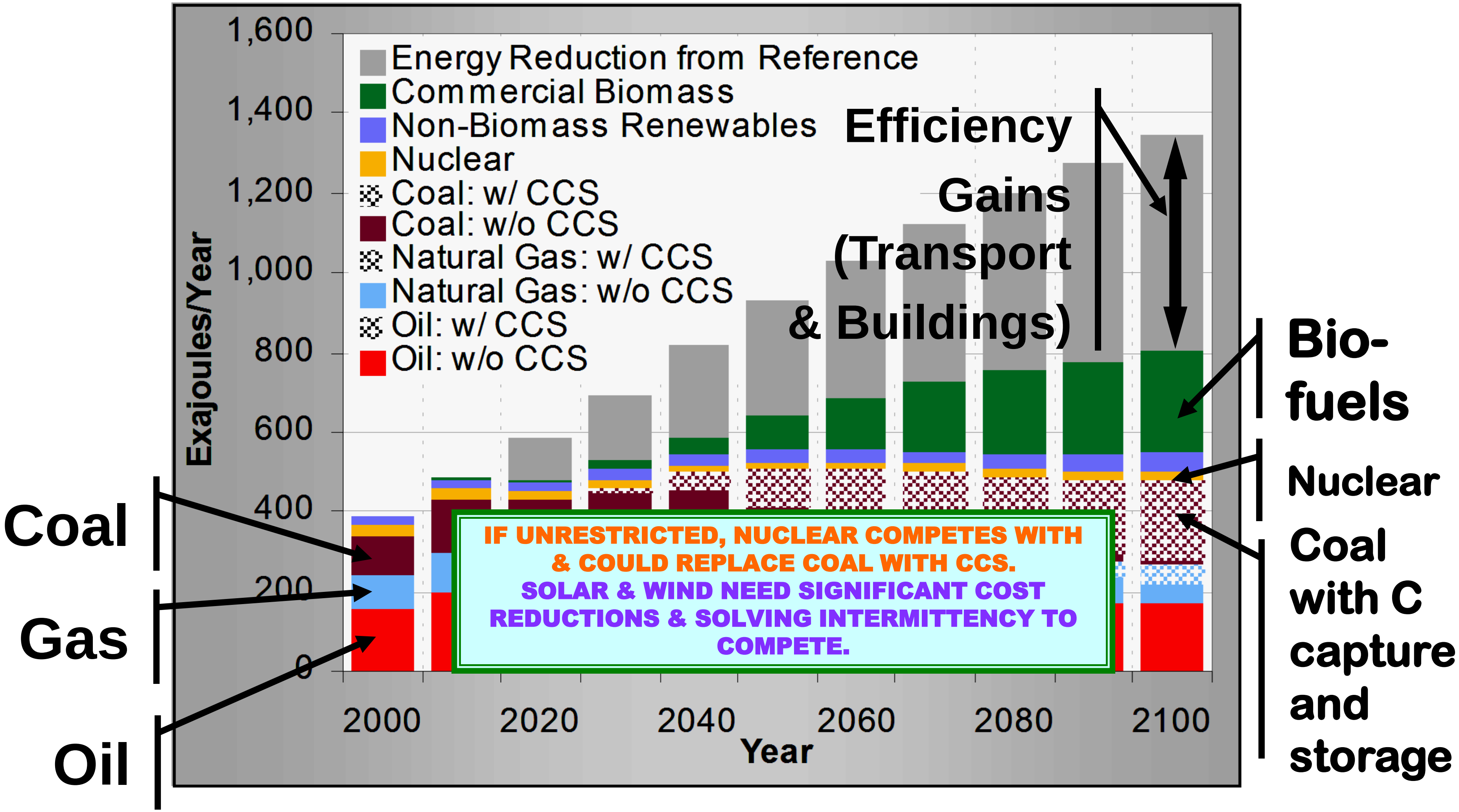
INCREASING DESTRUCTIVENESS OF TYPHOONS/HURRICANES

Increased 2-3 times post-1960 and correlated with sea-surface warming (Emanuel, Sci., 2005; Kossin et al, GRL, 2007)

TO MITIGATE CLIMATE CHANGE, 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.

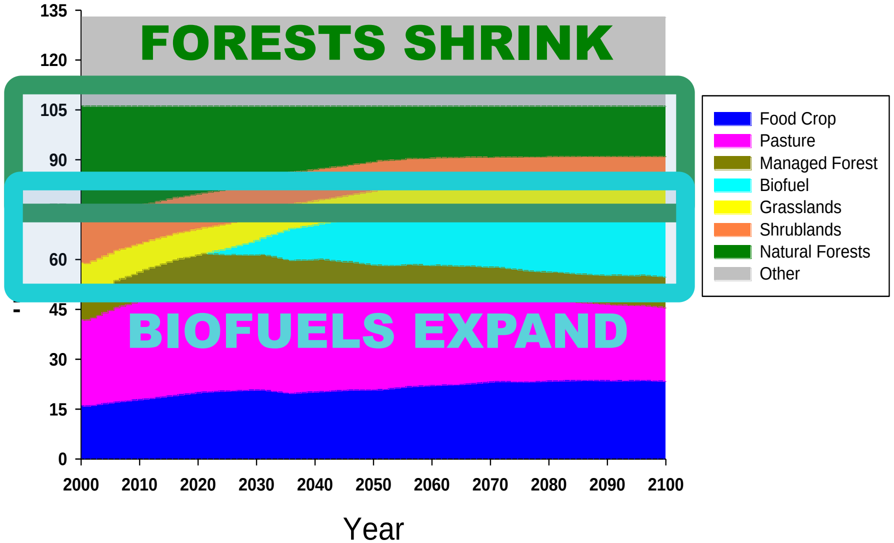
(Carbon price ~$1750/tonC in 2100)



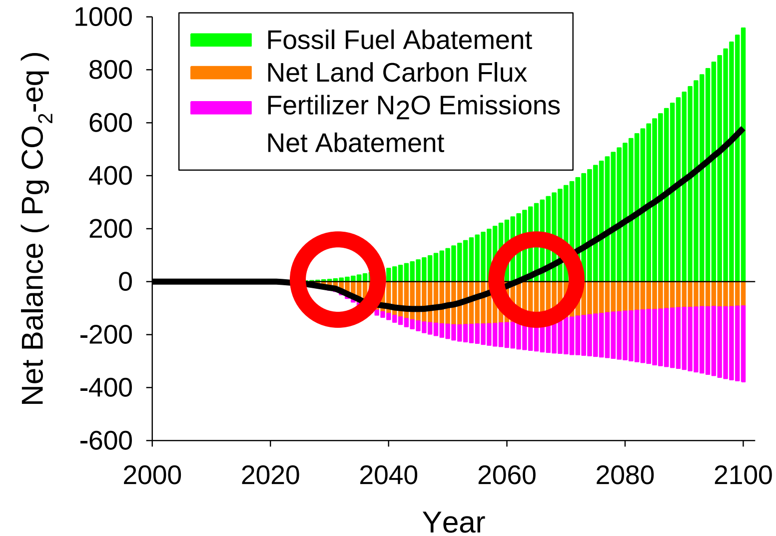
One way to help achieve stabilization is to develop BIOFUELS at large scale. Using IGSM to show Land and Climate Effects

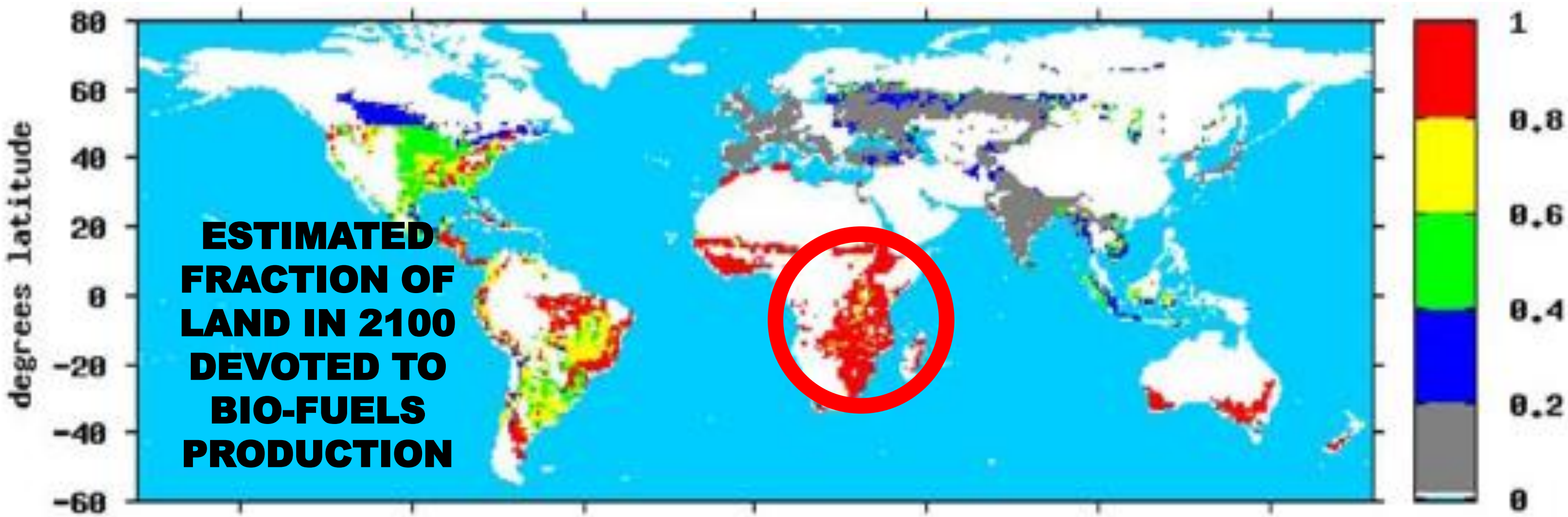
Melillo, et al., 2009, Science, 326:1397-99 (partial deforestation scenario)

Areas (Mkm^2) of Different Land Uses



Net GHG Balance

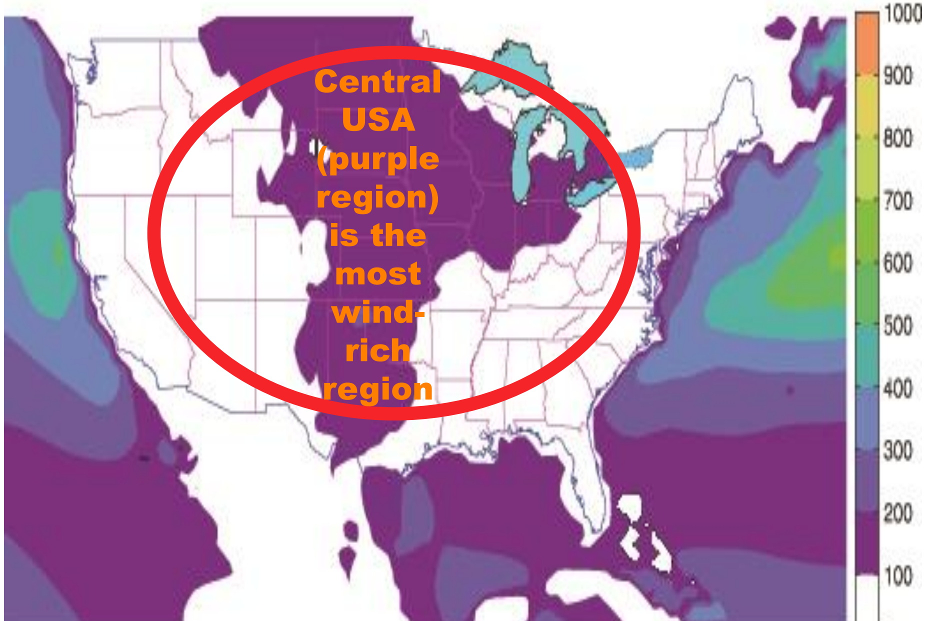




Another way toward stabilization is to develop **Wind Energy at Large Scale** (e.g. USA): But is there a problem regarding Intermittency?

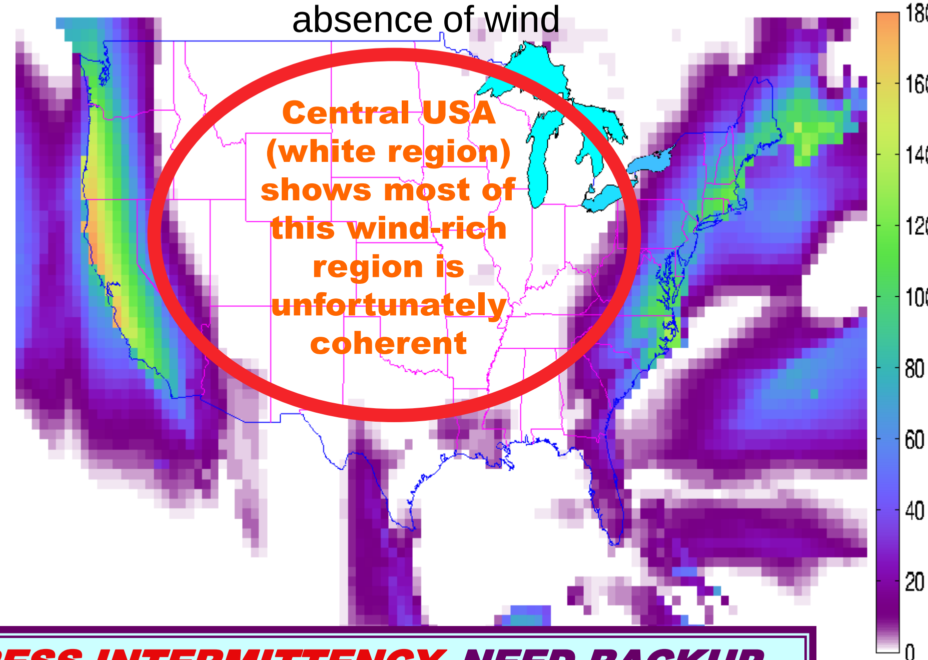
MIT JOINT PROGRAM SCIENCE POLICY GLOBAL CHANGE

Median Wind Power Density W/m^2



DEGREE OF ANTI-COINCIDENCE

number of grid points in surrounding (1000 km x 1000 km) region having at least 50% power to compensate absence of wind



CANNOT RELY ON THE GRID TO ADDRESS INTERMITTENCY. NEED BACKUP GENERATION CAPACITY, POSSIBLY INCLUDING ON-SITE ENERGY STORAGE

AREA OF LARGEST CENTRAL TENDENCY OF WIND POWER RESOURCE IS ALSO THE REGION THAT EXPERIENCES THE STRONGEST AND MOST EXPANSIVE COINCIDENT INTERMITTENCY.

(Bhaskar & Schlosser, 2012)

DO WE NEED CLIMATE ADAPTATION in addition to CLIMATE MITIGATION?

WE ARE ALREADY COMMITTED TO SOME UNAVOIDABLE WARMING EVEN AT CURRENT GREENHOUSE GAS LEVELS (ABOUT 0.6^{o}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

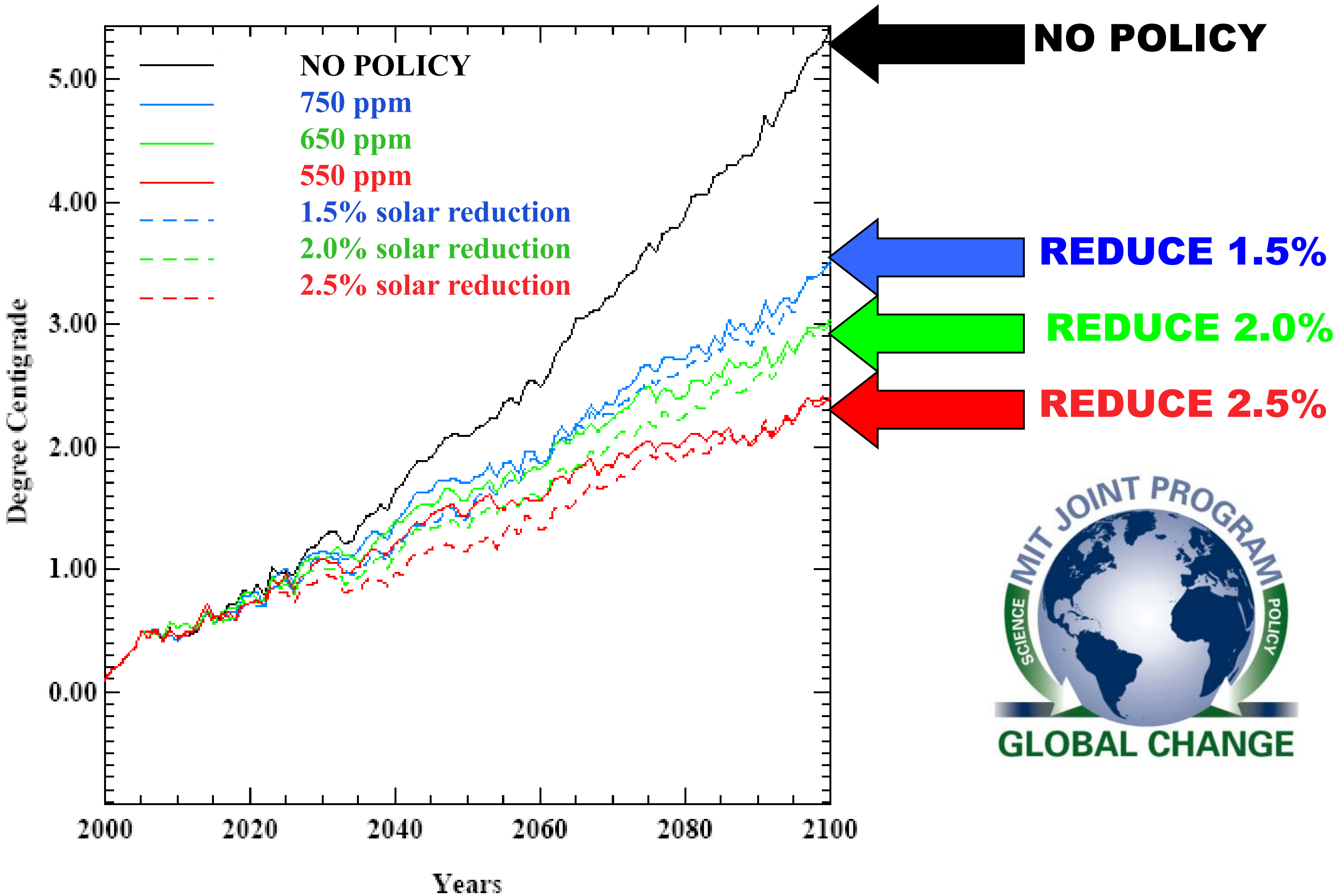
GEO-ENGINEERING: VIABLE OPTION OR DANGEROUS DIVERSION?

e.g. EFFECTS ON TEMPERATURE (°C) OF REDUCING SOLAR INPUT linearly between 2015 and 2100) WITH NO POLICY COMPARED TO FOUR GREENHOUSE GAS STABILIZATION POLICIES (MIT IGSM results)

BUT "SHADING" THE EARTH DOES NOT PREVENT THE DECIMATION OF CARBONATE SHELLED PHYTOPLANKTON

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

AND,THERE ARE SURE TO BE UNINTENDED CONSEQUENCES LEADING TO INTERNATIONAL CONFLICT



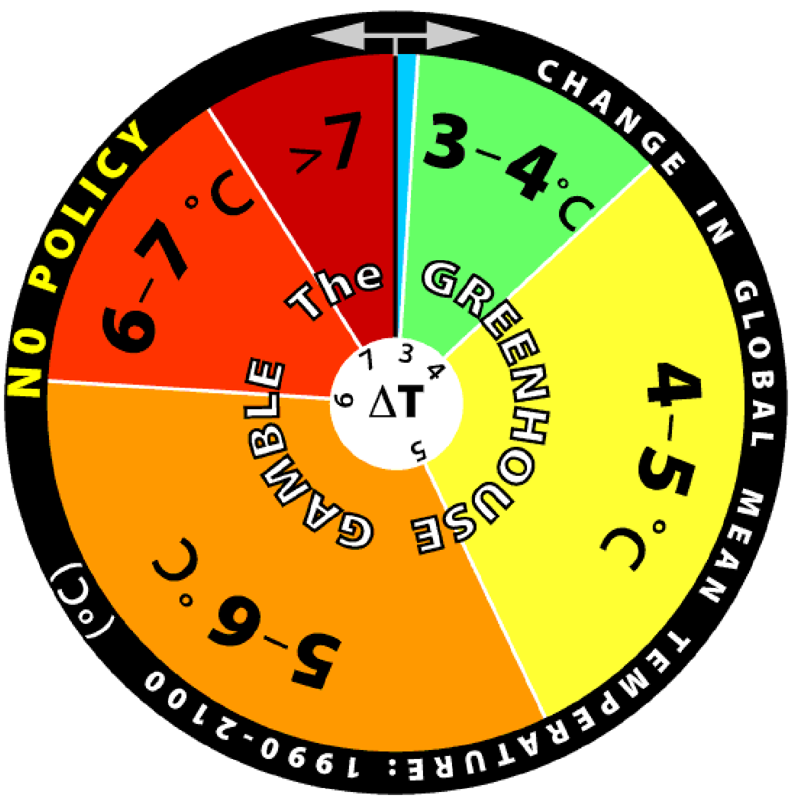
MIT JOINT PROGRAM SCIENCE POLICY GLOBAL CHANGE

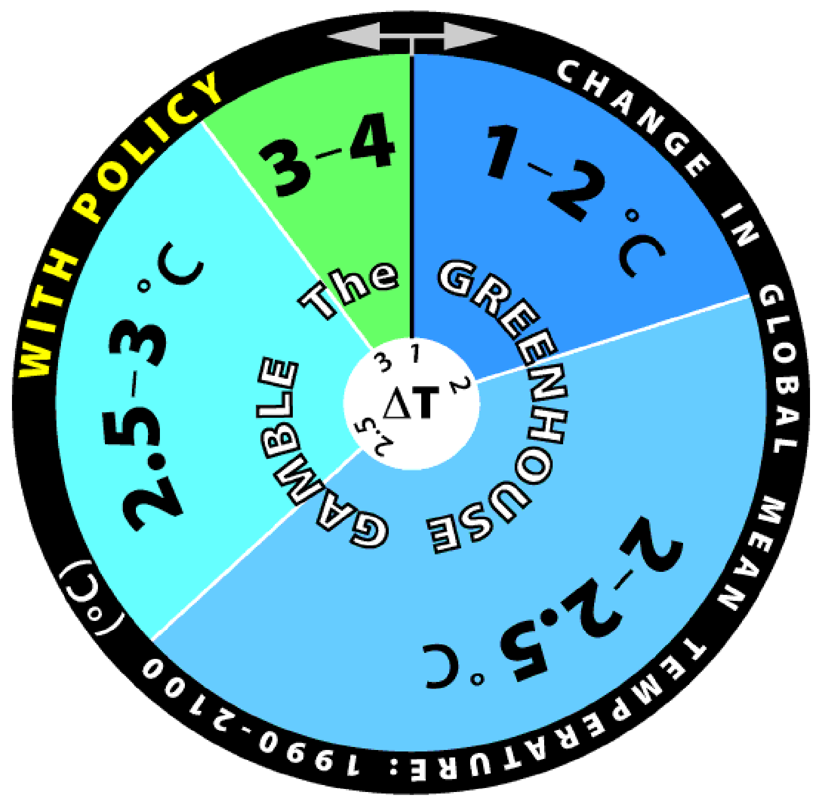
COMMUNICATING THE VALUE OF CLIMATE POLICY UNDER UNCERTAINTY: IGSM RESULTS

Compared with NO POLICY

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

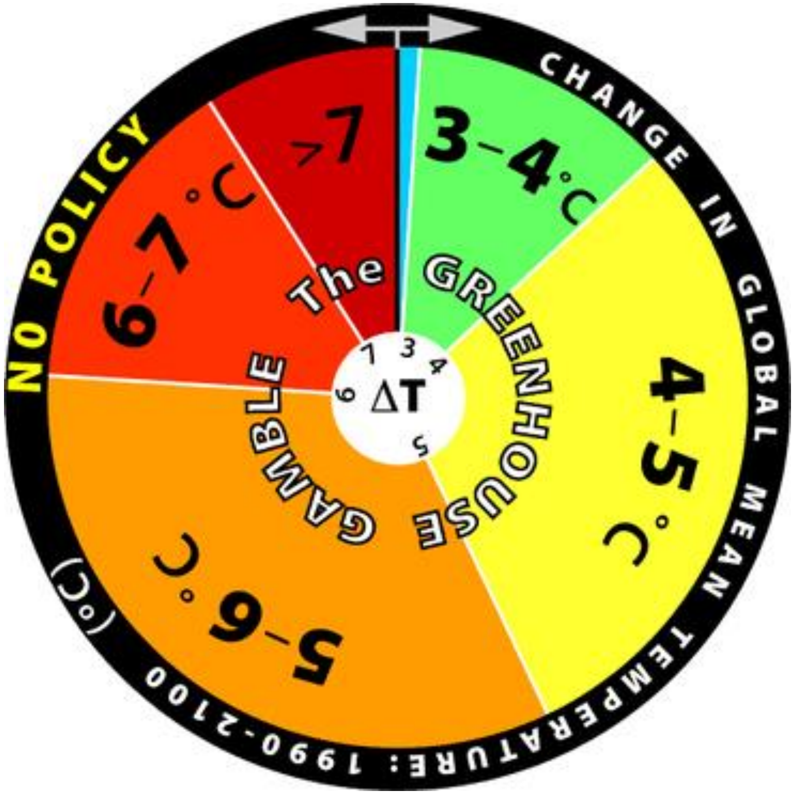
A NEW WHEEL with lower odds of EXTREMES

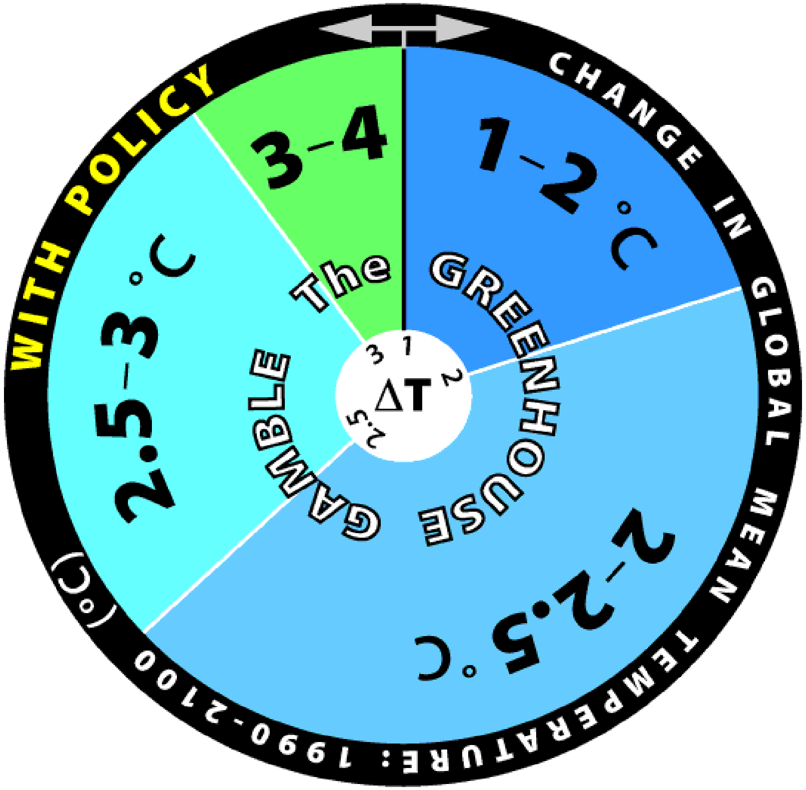




WE ARE CURRENTLY GAMBLING OUR PLANET'S FUTURE ON THE LEFT HAND WHEEL.

THE CHALLENGE IS TO MOVE TO A MUCH LESS RISKY WHEEL LIKE THE RIGHT HAND ONE.





FOR MORE INFORMATION ON THE GLOBAL CHANGE JOINT PROGRAM SEE:
http://globalchange.mit.edu/