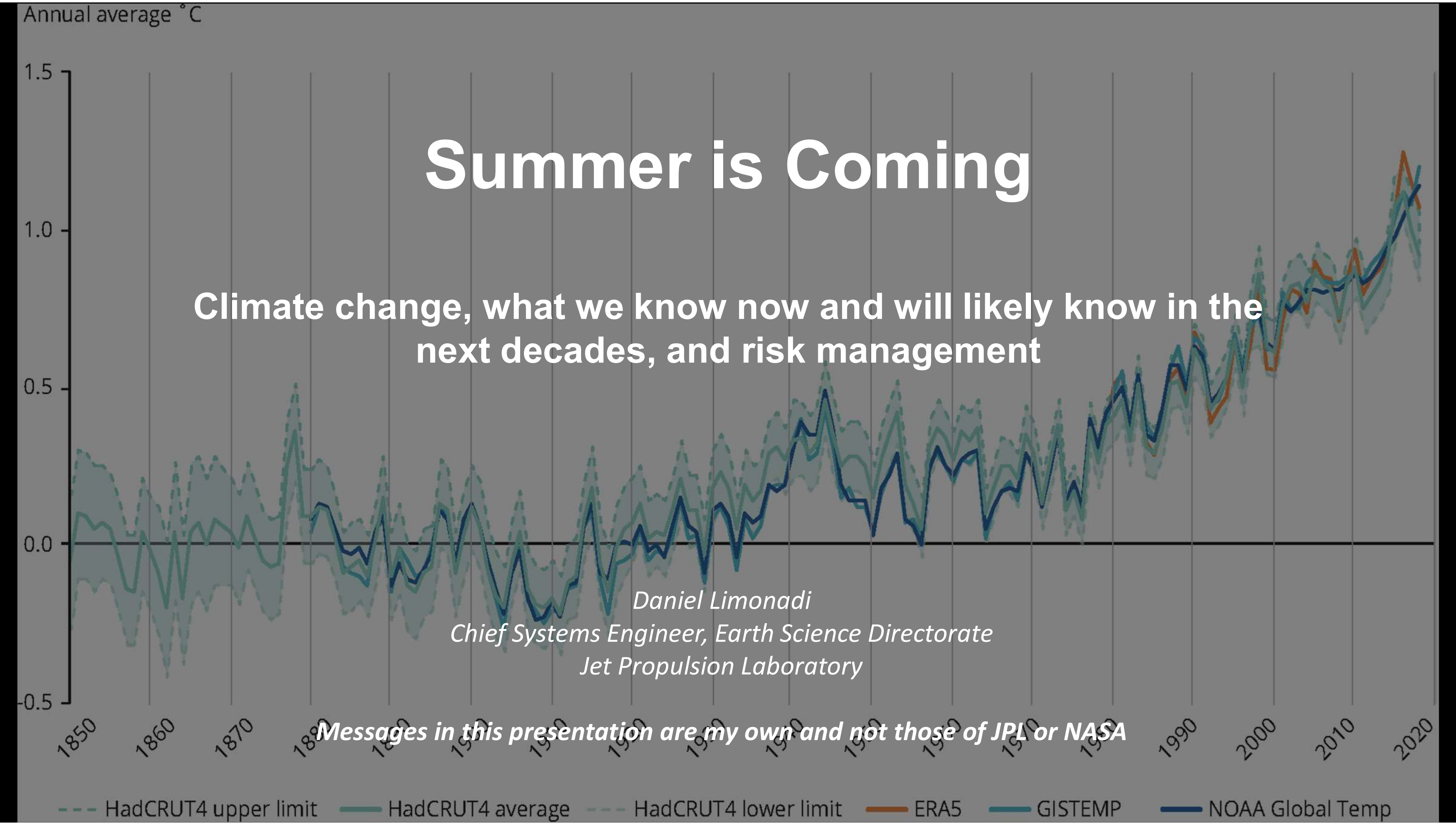


Summer is Coming

Climate change, what we know now and will likely know in the next decades, and risk management

Daniel Limonadi
Chief Systems Engineer, Earth Science Directorate
Jet Propulsion Laboratory

Messages in this presentation are my own and not those of JPL or NASA

Contents

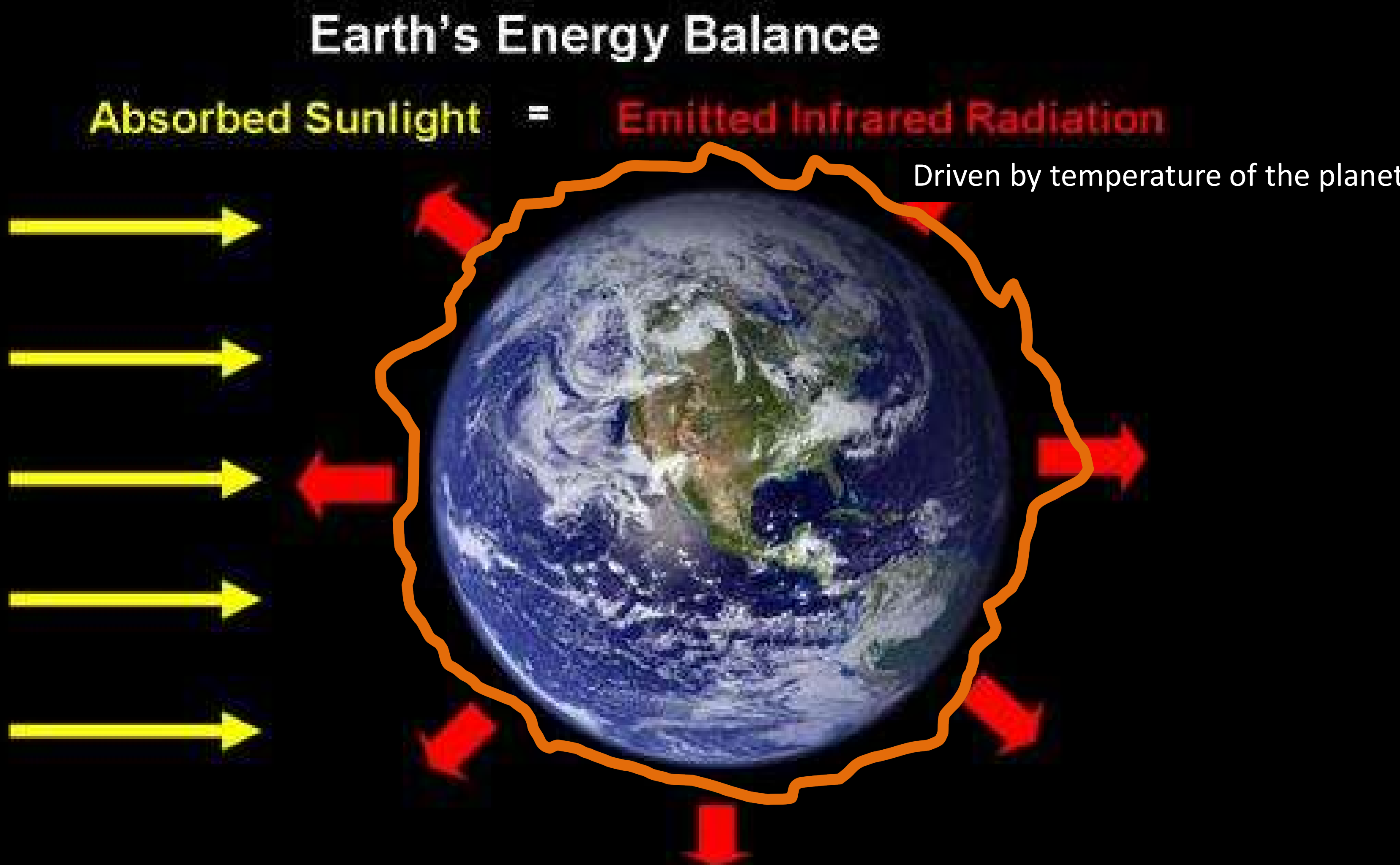
- What is going on?
- How we know what we know
  - – Physics, observations, models
- What we know – summary of key observed changes and predictions
- Some key residual uncertainties (aka what we know we don't know)
- Risk Implications

Weather vs Climate

- **Weather** – happens hour to hour, day to day at a given location
  - E.g. Today it is sunny, yesterday it snowed
- **Climate** – the long term average weather for a given location
  - E.g. June is usually mild in Southern California
  - Decade scale average conditions

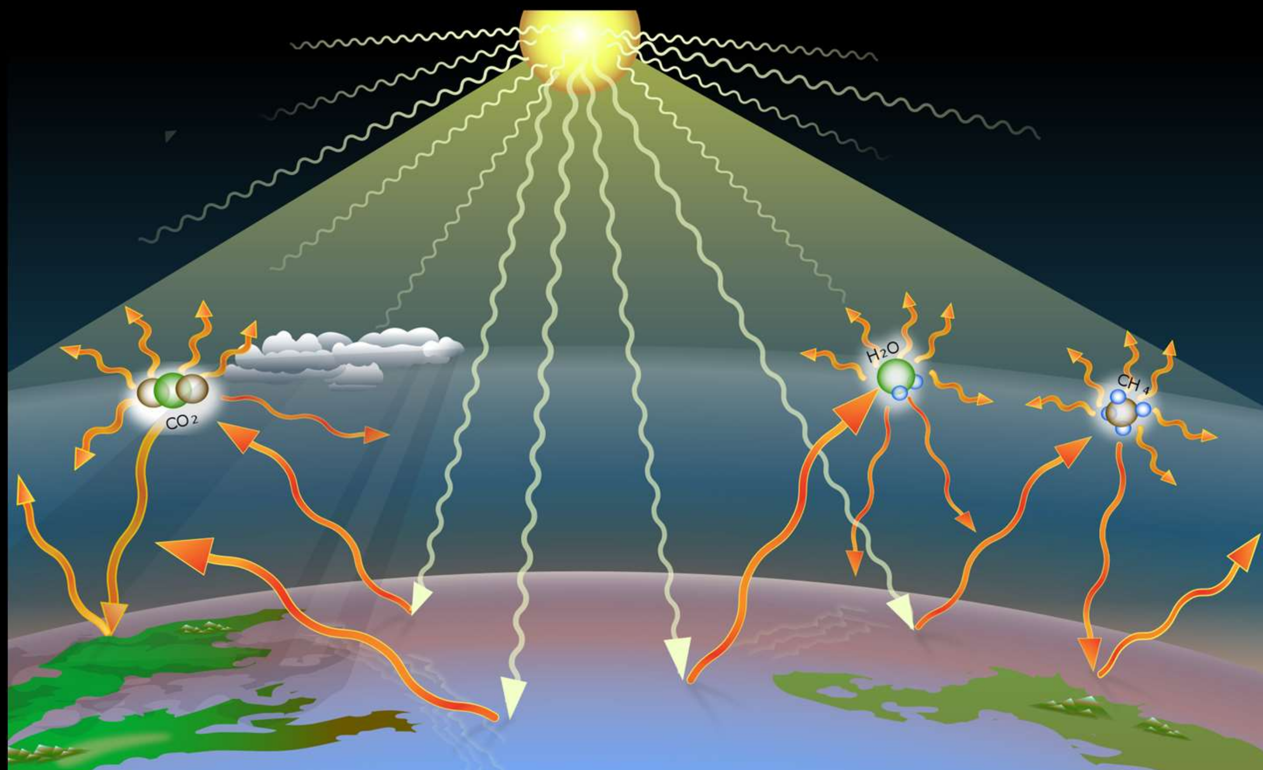
- Climate can have a background trend of warming, while weather can still have a lot of day to day variability

WHAT IS GOING ON AND WHY?



Green house – like being in your car on a sunny day with the windows closed

What is a “Greenhouse Gas”?



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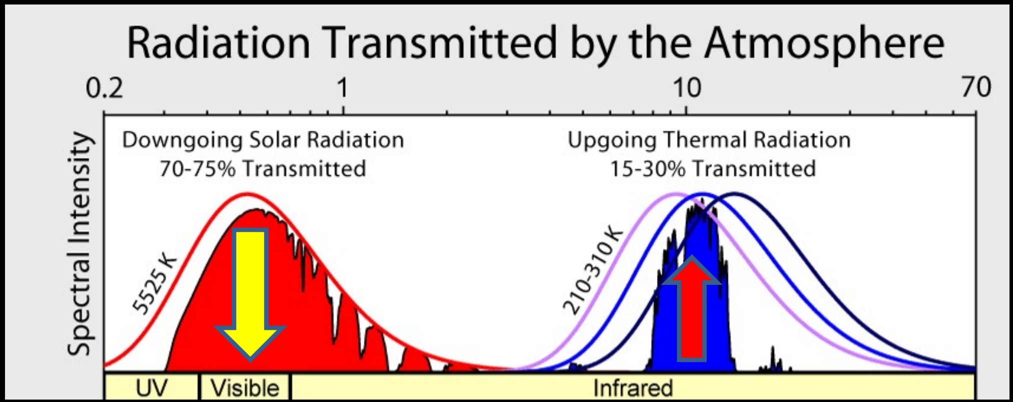

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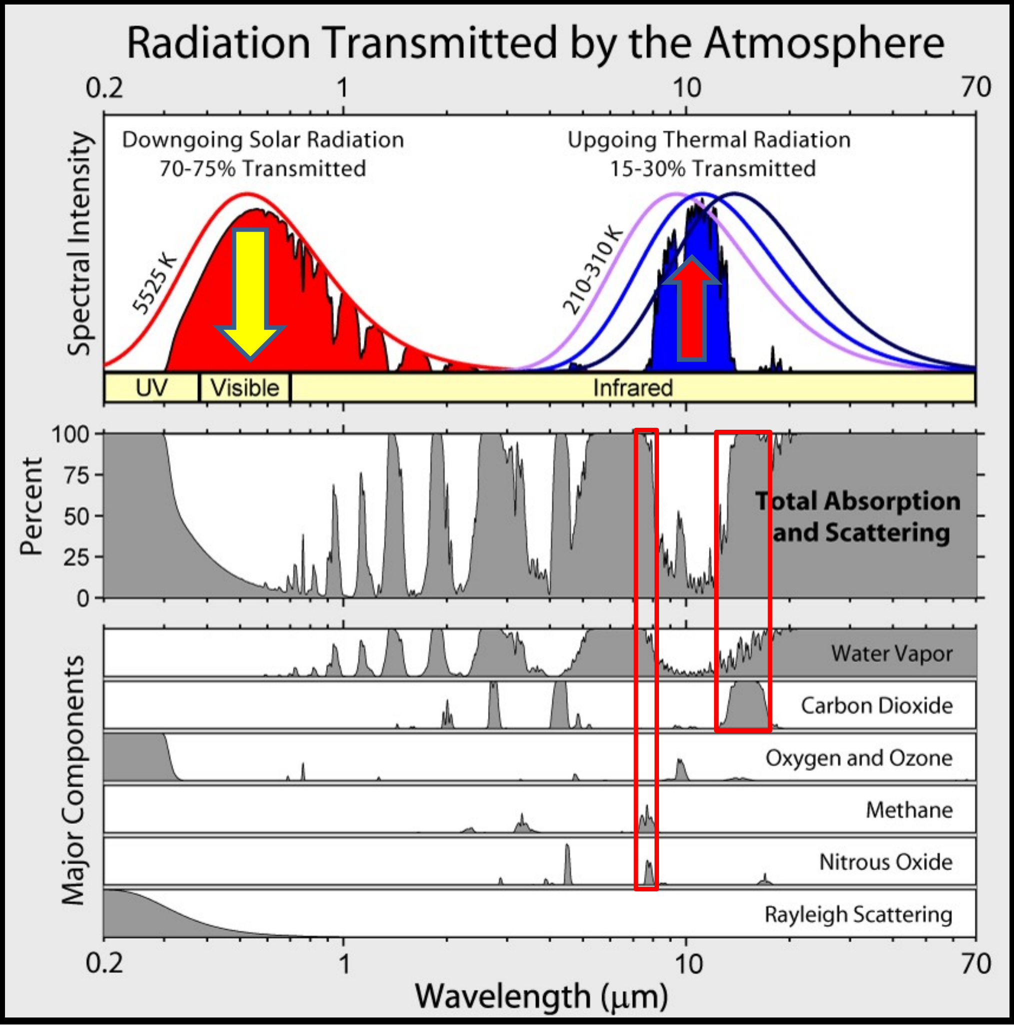
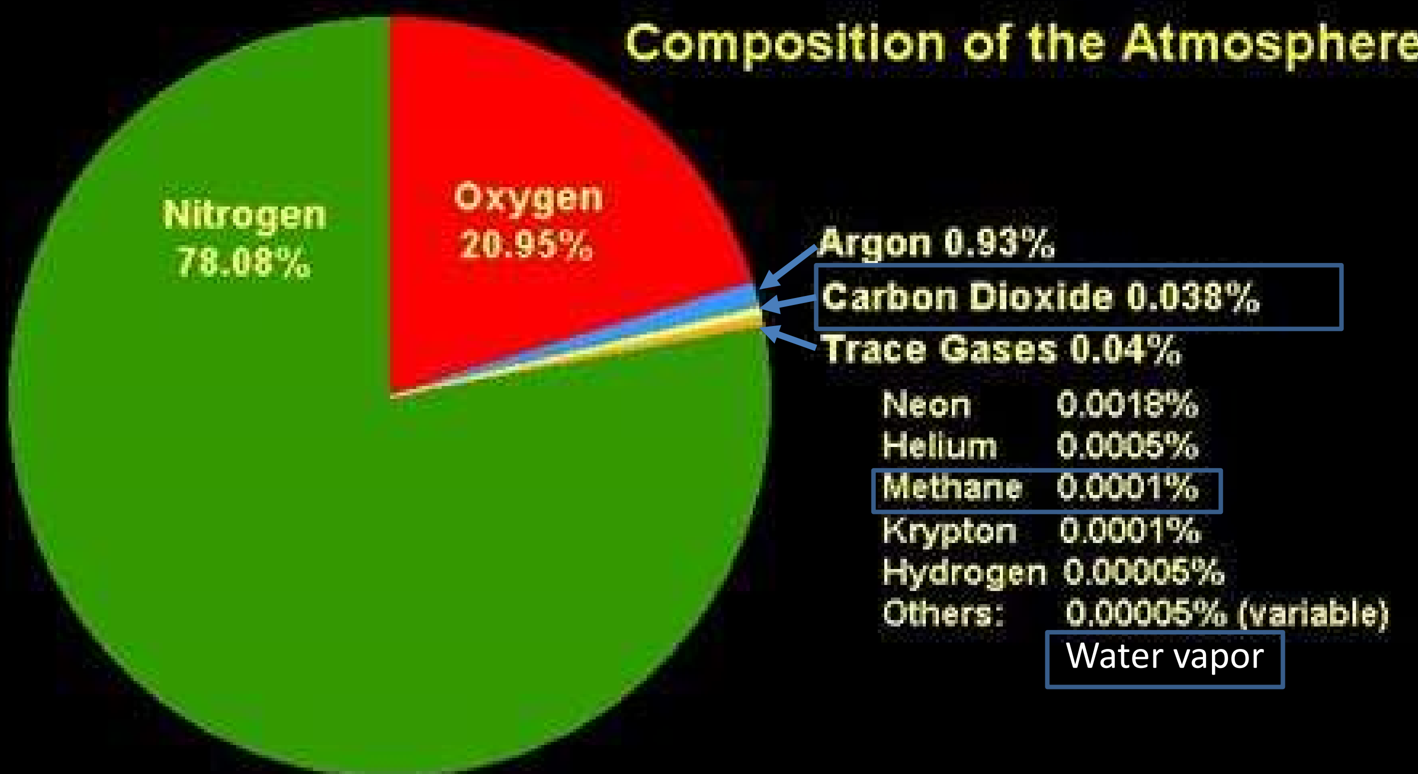
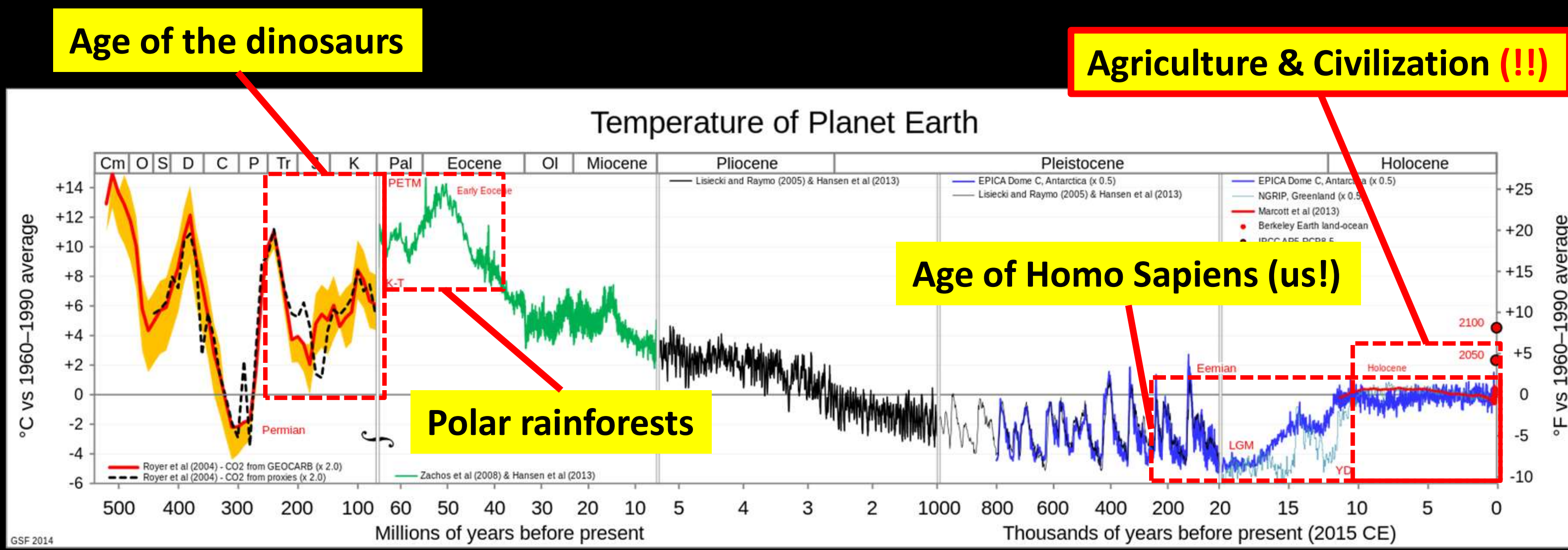


Earth's Atmosphere




ANY QUESTIONS?

Climate Has Varied A LOT in Earth's History



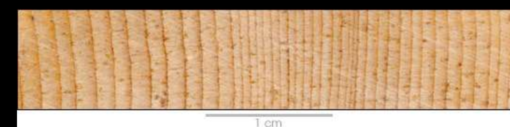
Climate is driven by many things – green house gas concentrations, solar output, orbital dynamics, atmospheric aerosols, makeup and position of the land, etc.

Planet Earth doesn't care about climate change – *currently existing life* does -> life will go on, but will humans and the things we are used to, go on?

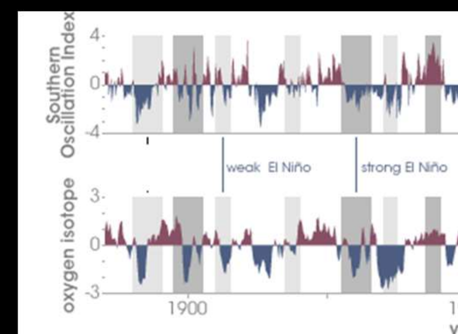
How Do We Know About Past Climate?

"Climate Proxies" - Multiple "noisy sources" that are combined to form a pretty consistent picture of the past

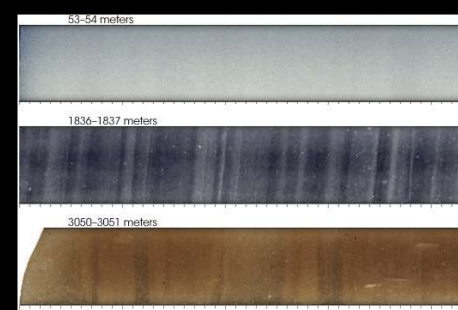
- **Tree Rings** – Good for about 10,000 yrs of precipitation, sunlight, temperature information… depending on location



- **Coral Reefs and other fossil shells** – global temperature and water balance. Absorb oxygen in their structure, and we know the ratio of oxygen isotopes available in ocean water is a function of global temperature (how much water is in ice and on land vs ocean) – can go back thousands to millions of years



- **Ice Cores** – air mixture, global temperature, global dust/volcanic loading – good for up to nearly 1 million years in the deepest locations of Antarctica

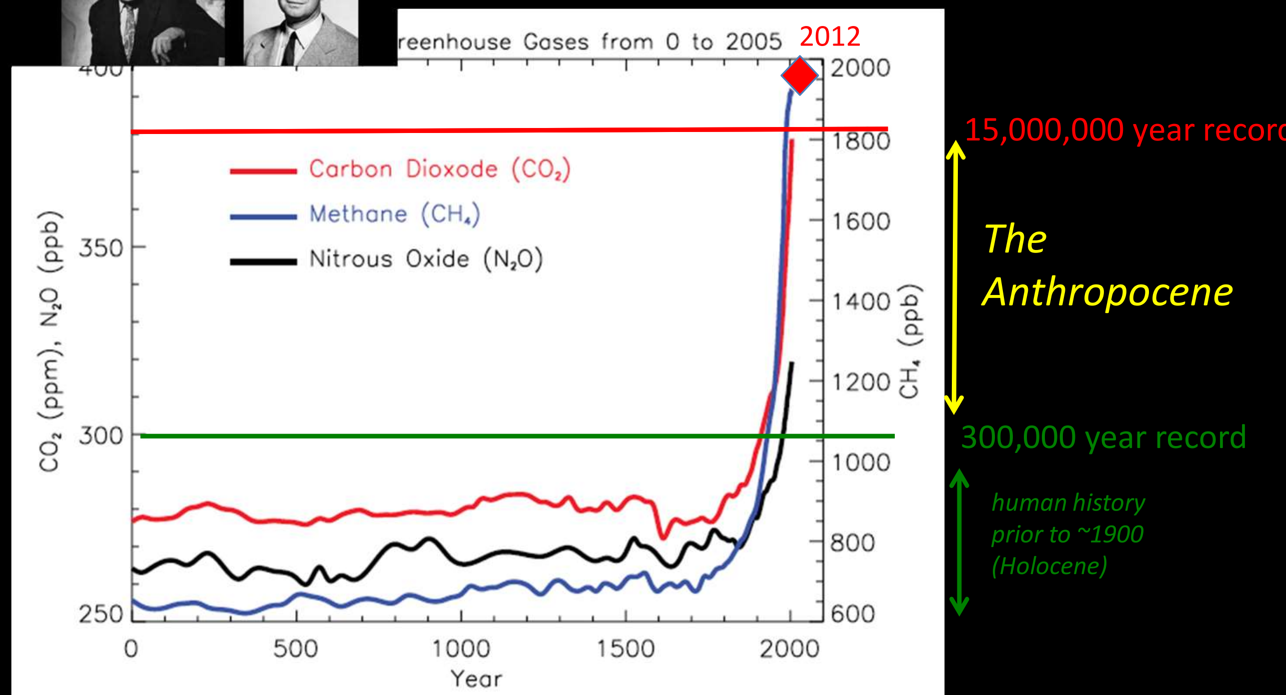


- **Others** – rock & sediment records (e.g. Grand Canyon), Earth's orbit over time, star brightness trends, climate models, etc – hundreds of millions of years and more, thermometer and tide gauge records for the last 200 years

Modern Observed CO2 Concentrations

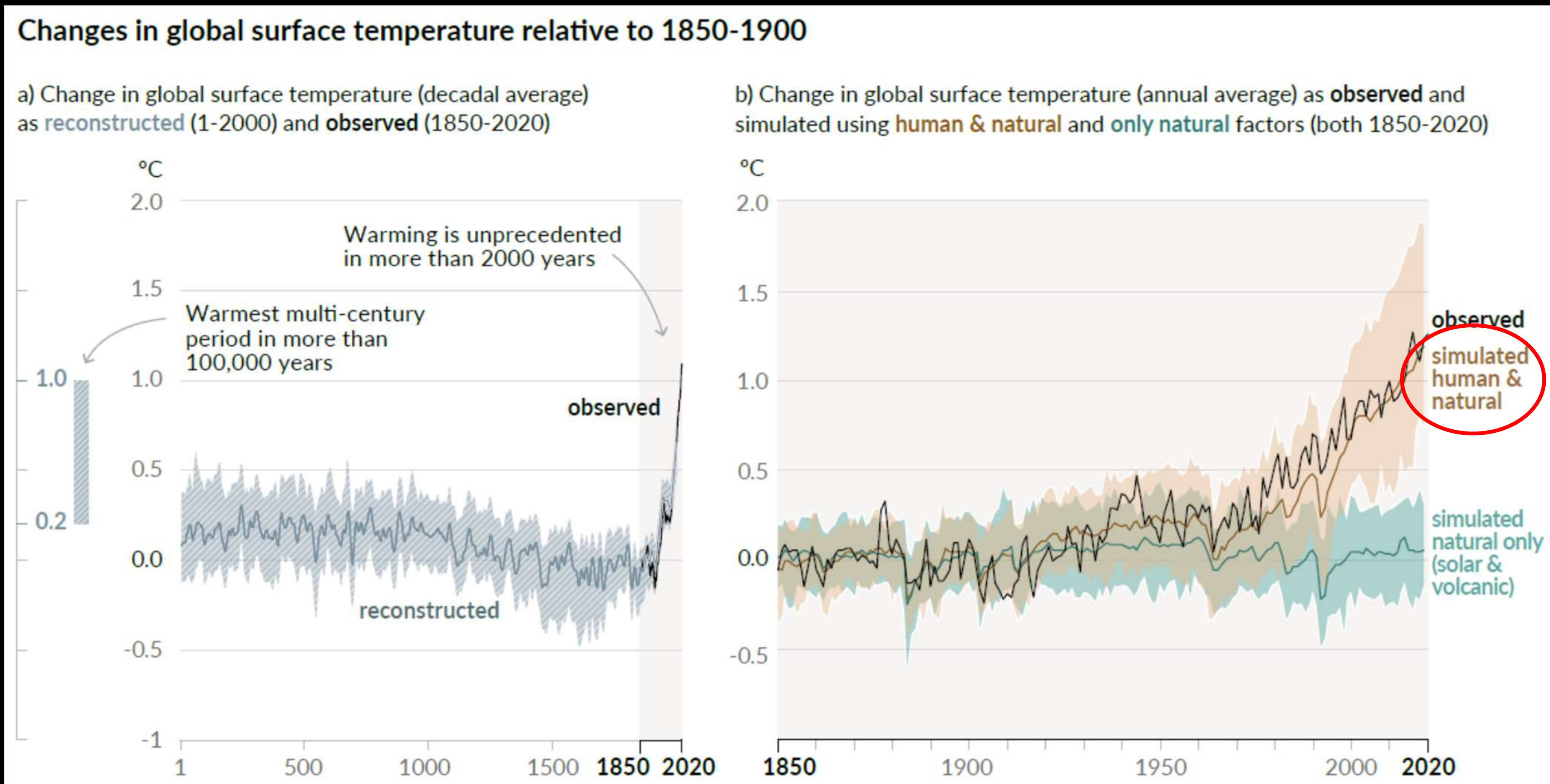
"Human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."

-Roger Revelle and Hans Suess, 1957



CO_2 growth in the atmosphere is **unprecedented**

Modern Observed Warming



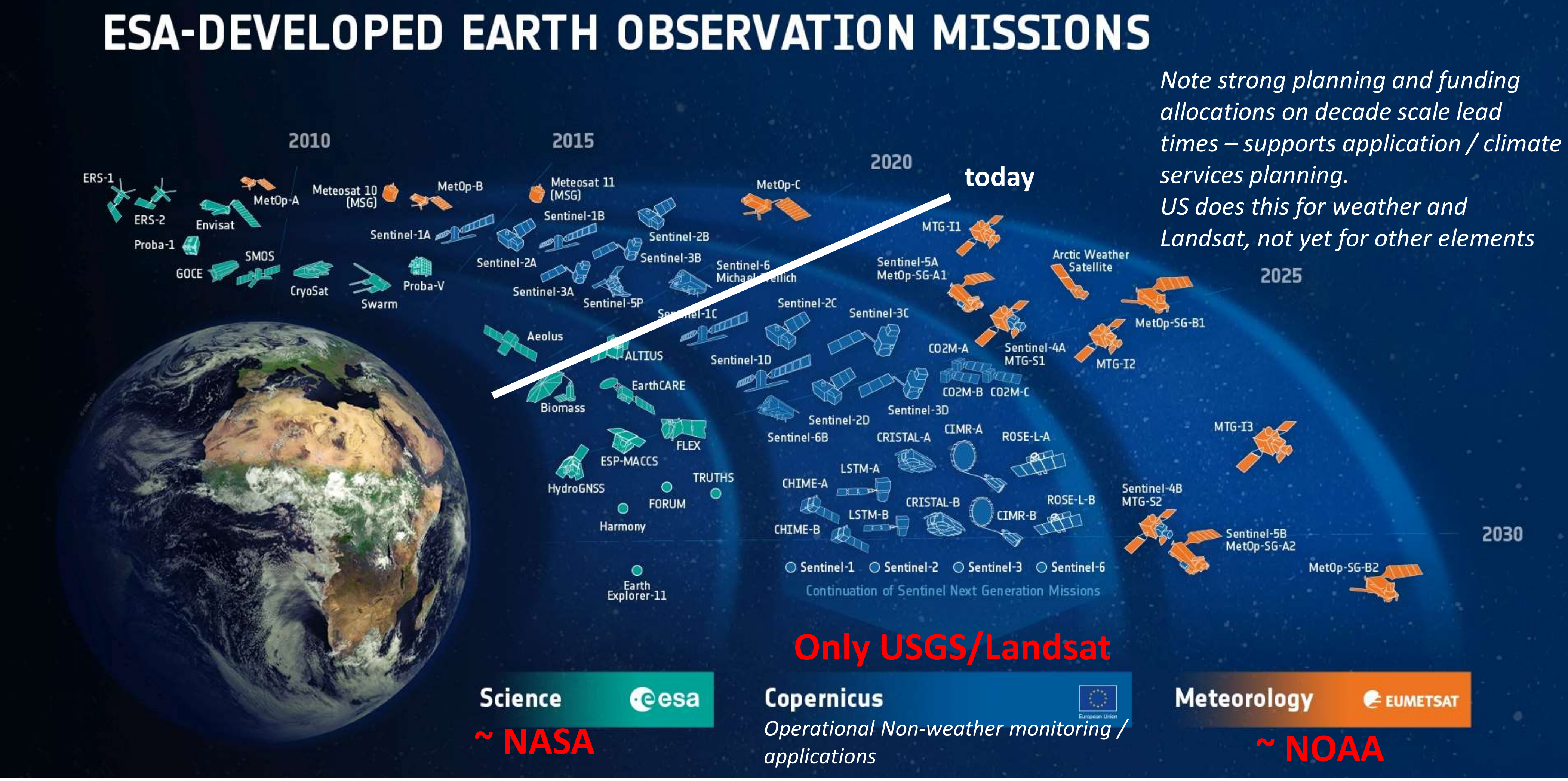
IPCC AR 6 WG1 summary for policy makers

Gives confidence in the models, gives insight into uncertainty

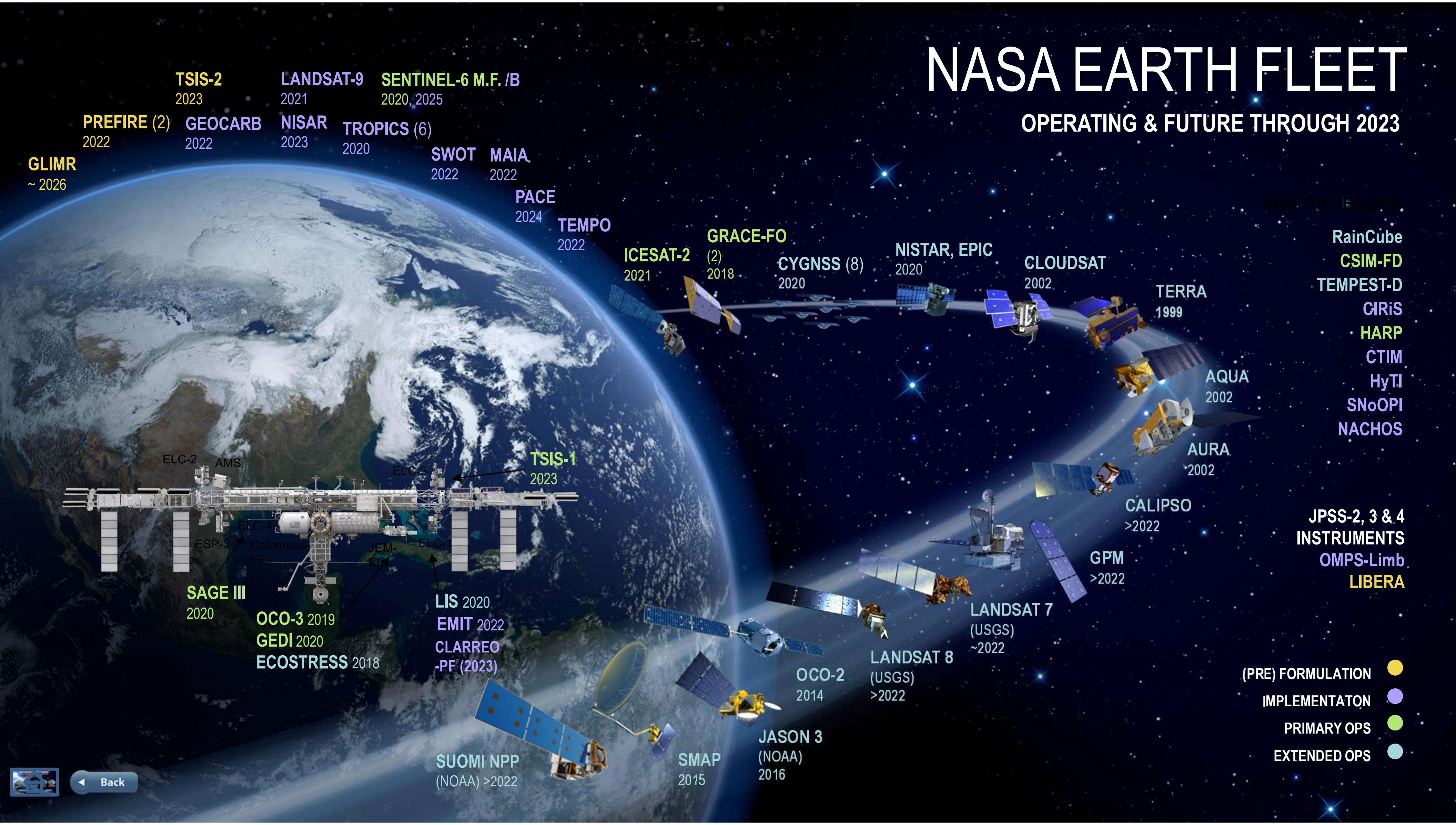
HOW WE KNOW WHAT WE KNOW:

EARTH OBSERVING FLEET

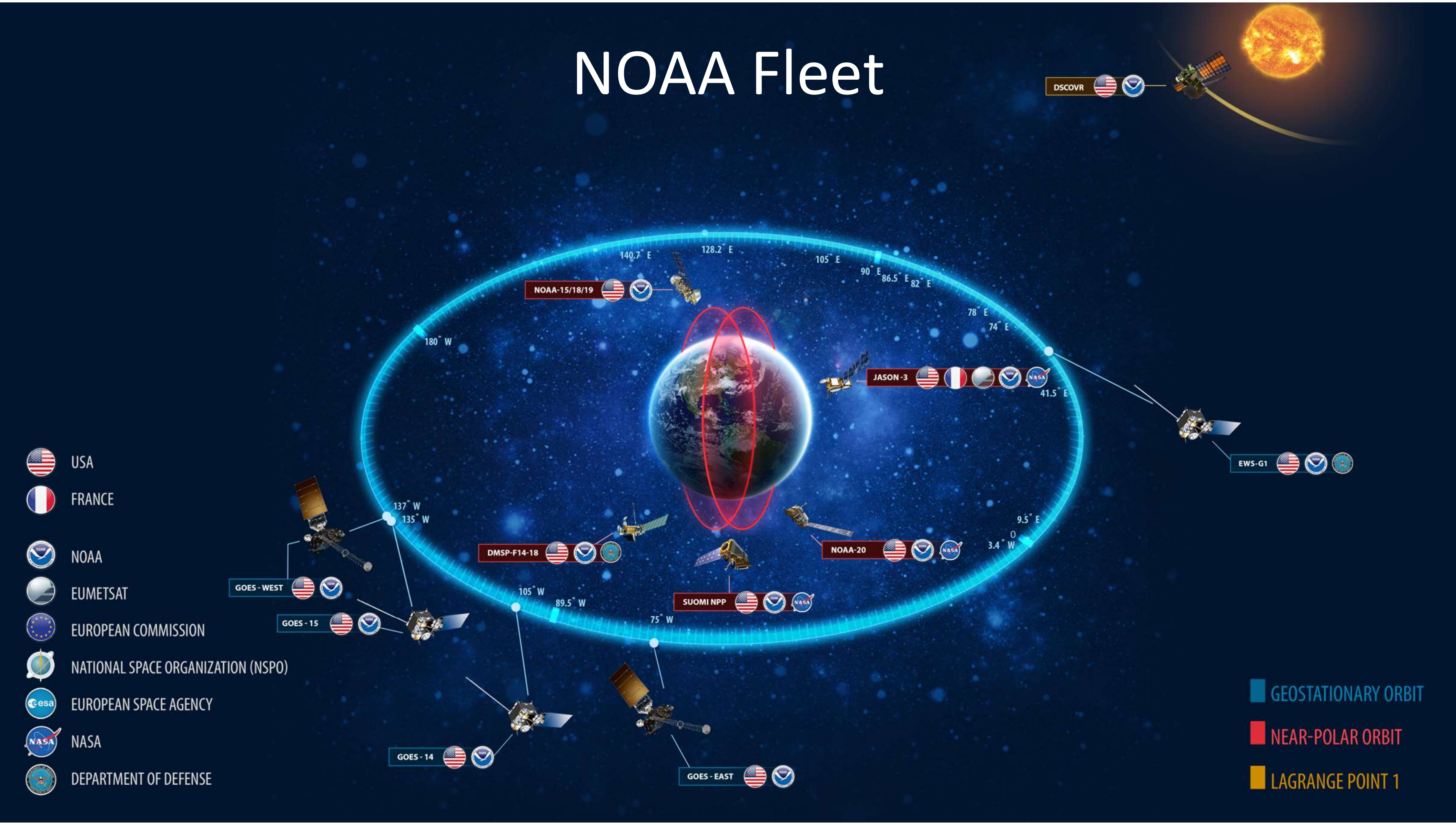
ESA / EU Fleet



ESA-DEVELOPED EARTH OBSERVATION MISSIONS
Note strong planning and funding allocations on decade scale lead times – supports application / climate services planning.
US does this for weather and Landsat, not yet for other elements
2010
2015
2020
2025
2030
today
ERS-1
ERS-2
Proba-1
Envisat
MetOp-A
GOCE
SMOS
CryoSat
Swarm
Proba-V
Meteosat 10 (MSG)
MetOp-B
Sentinel-1A
Meteosat 11 (MSG)
Sentinel-1B
Sentinel-2A
Sentinel-3A
Sentinel-2B
Sentinel-3B
Sentinel-5P
Sentinel-6
MetOp-C
Aeolus
ALTIUS
EarthCARE
Biomass
FLEX
ESP-MACCS
HydroGNSS
TRUTHS
FORUM
Harmony
Earth Explorer-11
Sentinel-1D
Sentinel-2C
Sentinel-3C
Sentinel-2D
Sentinel-3D
Sentinel-6B
CRISTAL-A
CIMR-A
ROSE-L-A
LSTM-A
CHIME-A
CRISTAL-B
CIMR-B
ROSE-L-B
LSTM-B
CHIME-B
CO2M-A
CO2M-B
CO2M-C
MTG-I1
Sentinel-5A MetOp-SG-A1
Sentinel-4A MTG-S1
Arctic Weather Satellite
MetOp-SG-B1
MTG-I2
MTG-I3
Sentinel-4B MTG-S2
Sentinel-5B MetOp-SG-A2
MetOp-SG-B2
Sentinel-1
Sentinel-2
Sentinel-3
Sentinel-6
Continuation of Sentinel Next Generation Missions
Only USGS/Landsat
Science
esa
~ NASA
Copernicus
Operational Non-weather monitoring / applications
Meteorology
EUMETSAT
~ NOAA


NASA EARTH FLEET
OPERATING & FUTURE THROUGH 2023
TSIS-2 2023
LANDSAT-9 2021
SENTINEL-6 M.F. /B 2020, 2025
PREFIRE (2) 2022
GEOCARB 2022
NISAR 2023
TROPICS (6) 2020
GLIMR ~ 2026
SWOT 2022
MAIA 2022
PACE 2024
TEMPO 2022
ICESAT-2 2021
GRACE-FO (2) 2018
CYGNSS (8) 2020
NISTAR, EPIC 2020
CLOUDSAT 2002
TERRA 1999
AQUA 2002
AURA 2002
CALIPSO >2022
GPM >2022
LANDSAT 7 (USGS) ~2022
LANDSAT 8 (USGS) >2022
OCO-2 2014
JASON 3 (NOAA) 2016
SMAP 2015
SUOMI NPP (NOAA) >2022
ELC-2
AMS
ELC-3
ELC-4
ESP-3
Columbus EF
JEM-EF
ELC-1
TSIS-1 2023
SAGE III 2020
OCO-3 2019
GEDI 2020
ECOSTRESS 2018
LIS 2020
EMIT 2022
CLARREO -PF (2023)
RainCube
CSIM-FD
TEMPEST-D
CIRiS
HARP
CTIM
HyTI
SNoOPI
NACHOS
JPSS-2, 3 & 4 INSTRUMENTS
OMPS-Limb
LIBERA
(PRE) FORMULATION
IMPLEMENTATON
PRIMARY OPS
EXTENDED OPS
Back

NOAA Fleet

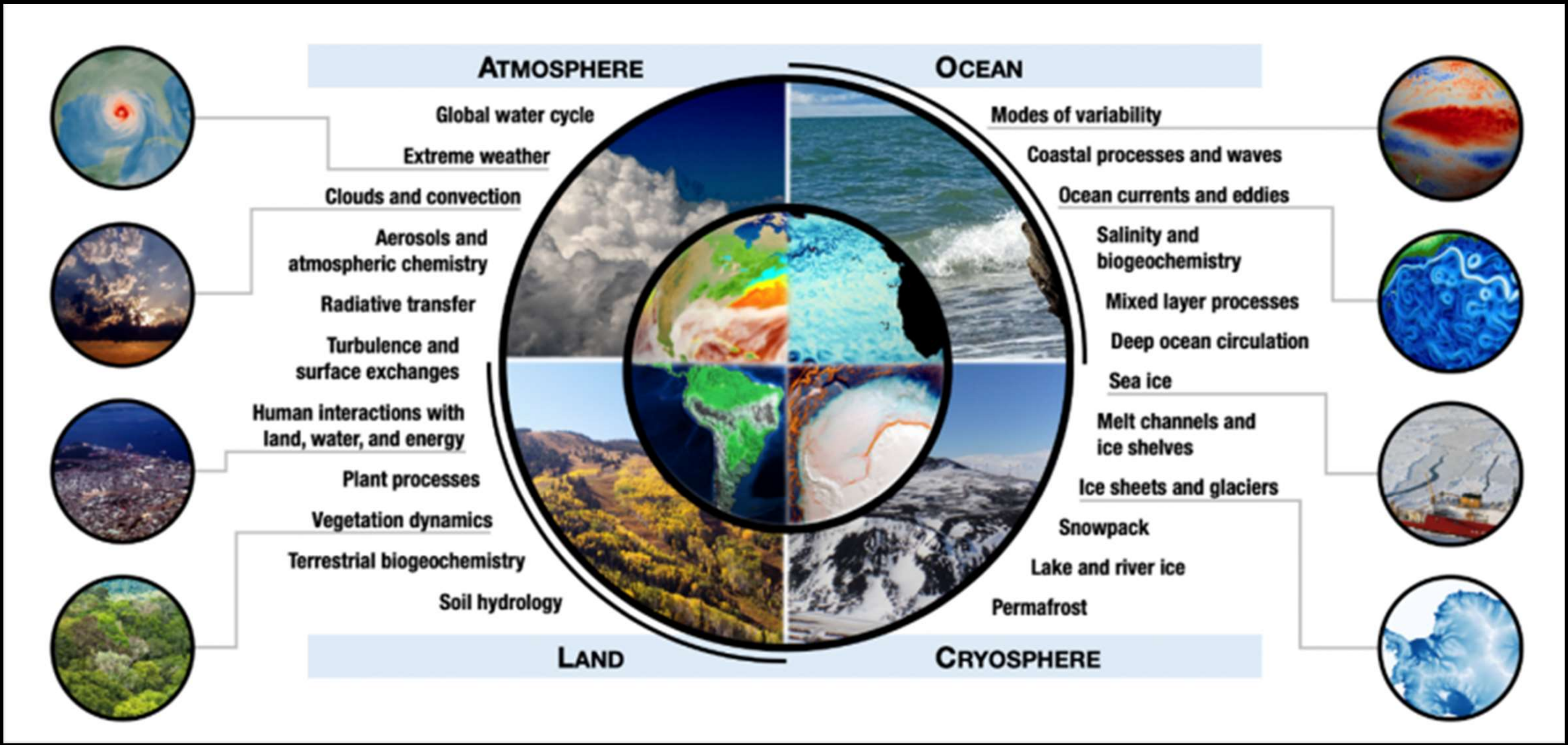

DSCOVR
NOAA-15/18/19
JASON-3
EWS-G1
DMSP-F14-18
NOAA-20
SUOMI NPP
GOES - WEST
GOES - 15
GOES - 14
GOES - EAST
140.7° E
128.2° E
105° E
90° E
86.5° E
82° E
78° E
74° E
41.5° E
9.5° E
0
3.4° W
180° W
137° W
135° W
105° W
89.5° W
75° W
USA
FRANCE
NOAA
EUMETSAT
EUROPEAN COMMISSION
NATIONAL SPACE ORGANIZATION (NSPO)
EUROPEAN SPACE AGENCY
NASA
DEPARTMENT OF DEFENSE
GEOSTATIONARY ORBIT
NEAR-POLAR ORBIT
LAGRANGE POINT 1

HOW WE KNOW WHAT WE KNOW:

MODELS

mage credit: NASA's Scientific Visualization Studio – visualization of global CO2 concentrations, with concentration difference exaggerated

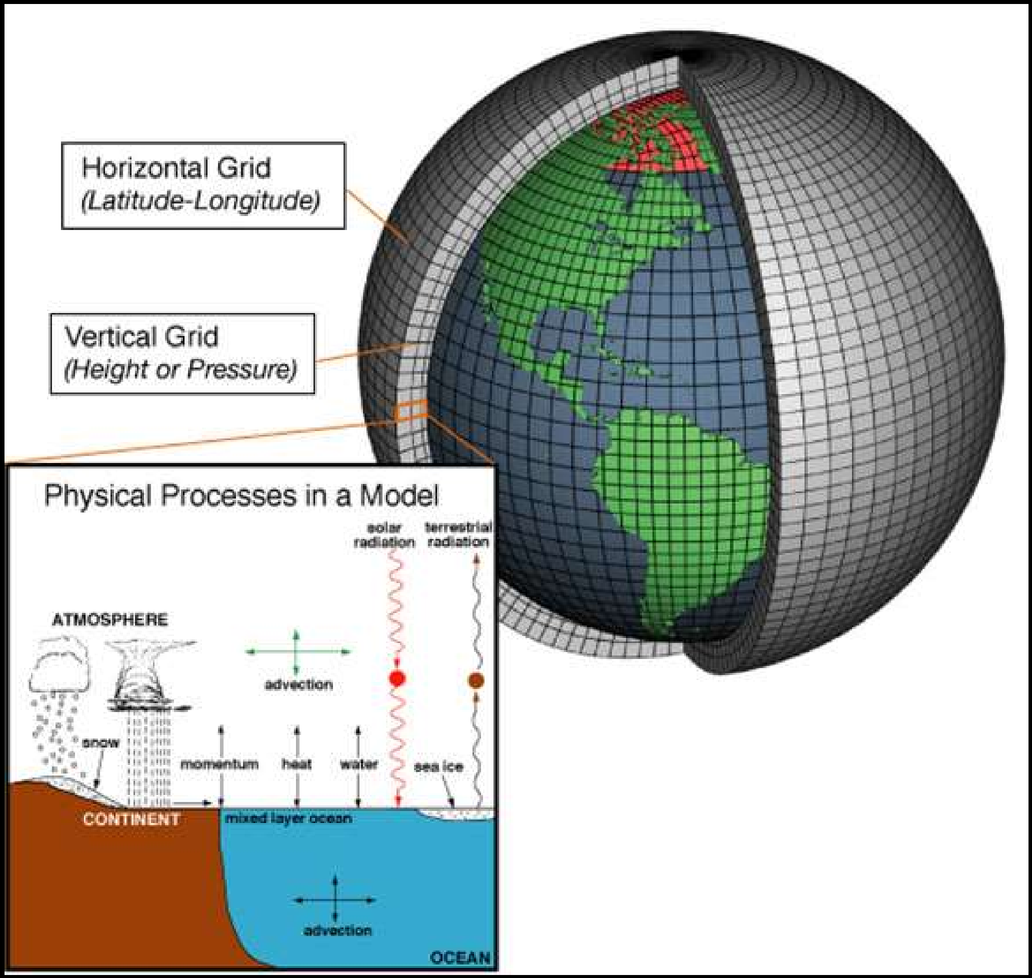
Models



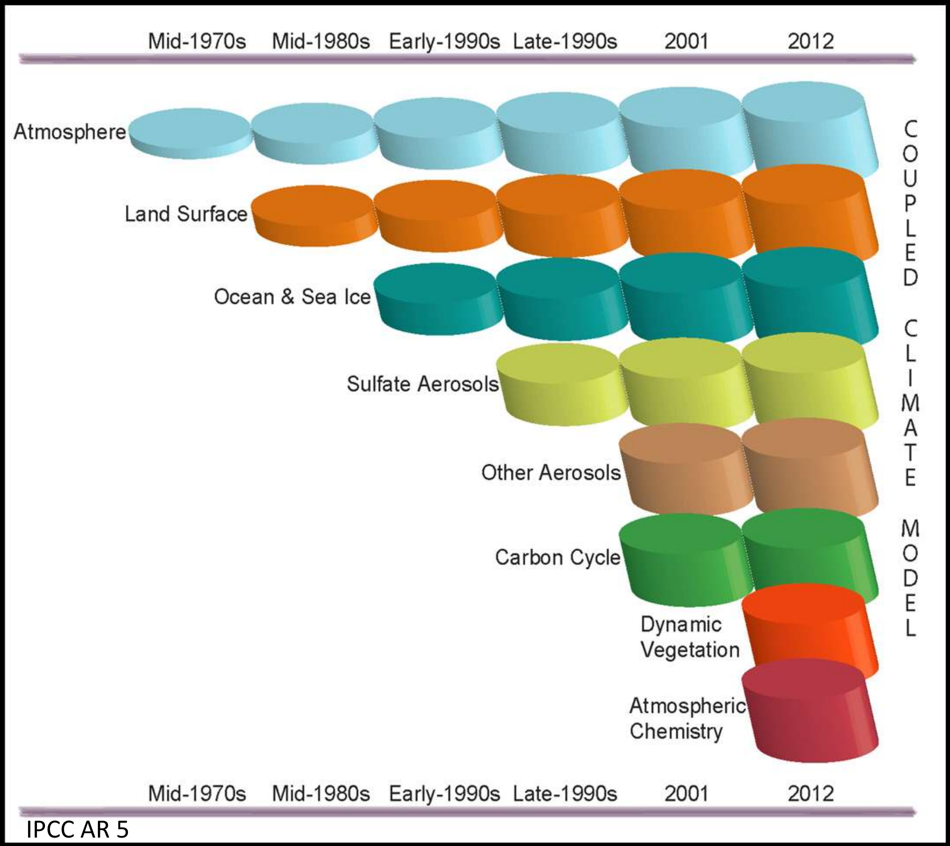
ATMOSPHERE
OCEAN
Global water cycle
Extreme weather
Clouds and convection
Aerosols and atmospheric chemistry
Radiative transfer
Turbulence and surface exchanges
Human interactions with land, water, and energy
Plant processes
Vegetation dynamics
Terrestrial biogeochemistry
Soil hydrology
Modes of variability
Coastal processes and waves
Ocean currents and eddies
Salinity and biogeochemistry
Mixed layer processes
Deep ocean circulation
Sea ice
Melt channels and ice shelves
Ice sheets and glaciers
Snowpack
Lake and river ice
Permafrost
LAND
CRYOSPHERE

Gridded Climate Model – Atmosphere Example

- “All models are wrong, some of them are useful”
- You have to design the model to answer your question, test it, and understand its strengths and weaknesses
- Remember – climate models are aimed at looking at how average conditions will change over time, NOT make predictions for what the weather this Wednesday at 2pm will be.



Climate Model Content vs Time



Still missing (only in stand alone models with any significant physics):

- Dynamic Surface and subsurface hydrology
- Dynamic Cryosphere - Ice sheets & Mountain Glaciers

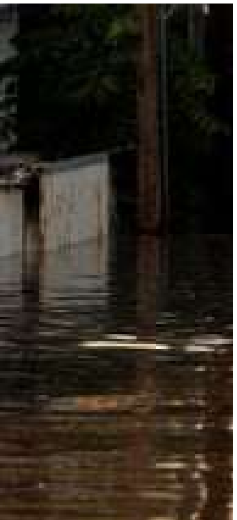
Spatial and temporal resolution has increased several orders of magnitude in the same period (yay for Moore's law!)

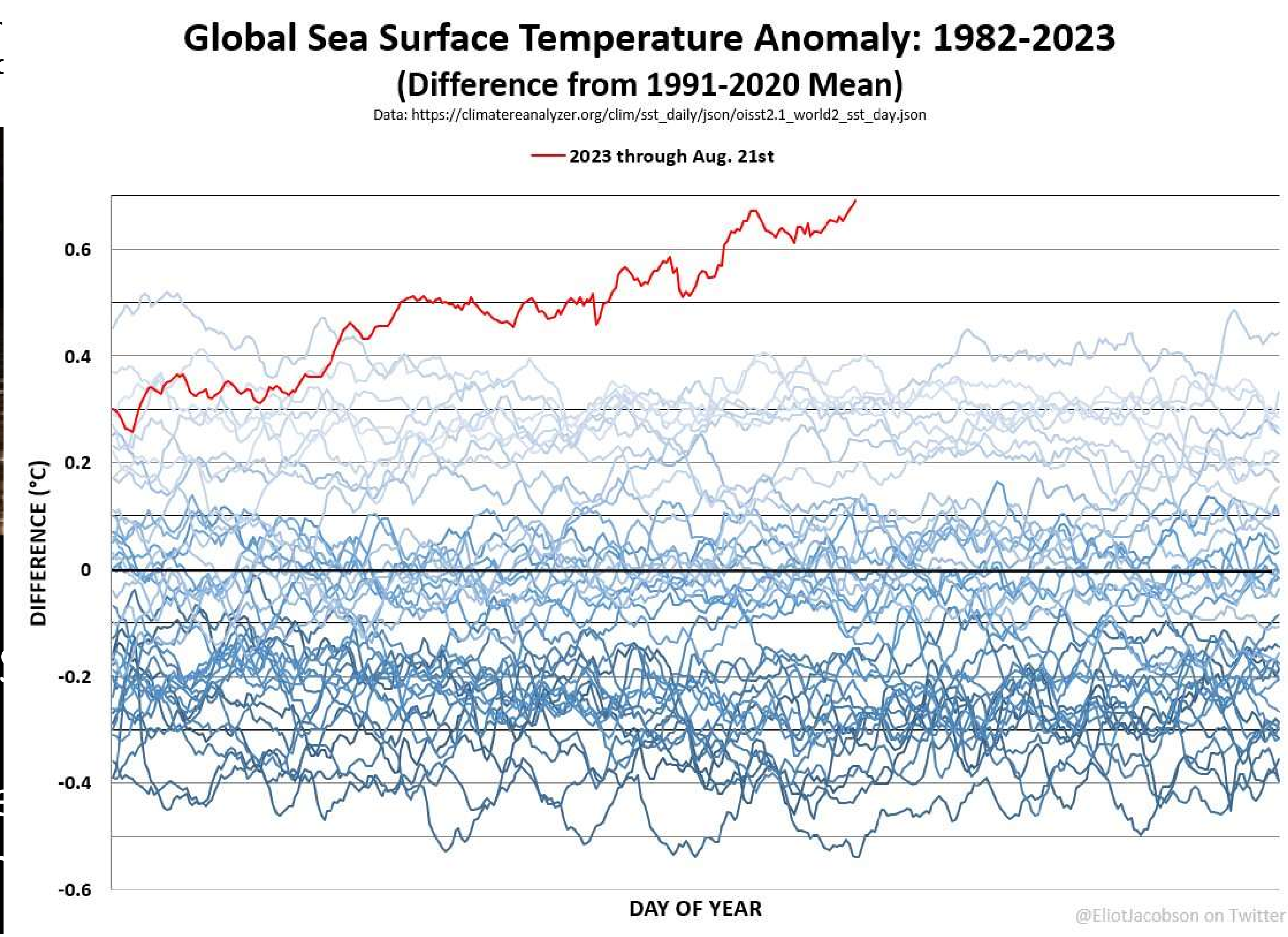
IMPACTS:

EXISTING TRENDS
NEW EXPECTATIONS

Image Residents drive through a flooded road after the passing of Hurricane Maria, in Toa Baja, Puerto Rico, in September 2017. | Carlos Giusti/AP Photo

Greece – near
devastating flo
Ionian Sea on





at least
known

2023: S

Climate
break r

What Environmental Hazard Causes the Most Deaths Each Year? (global)

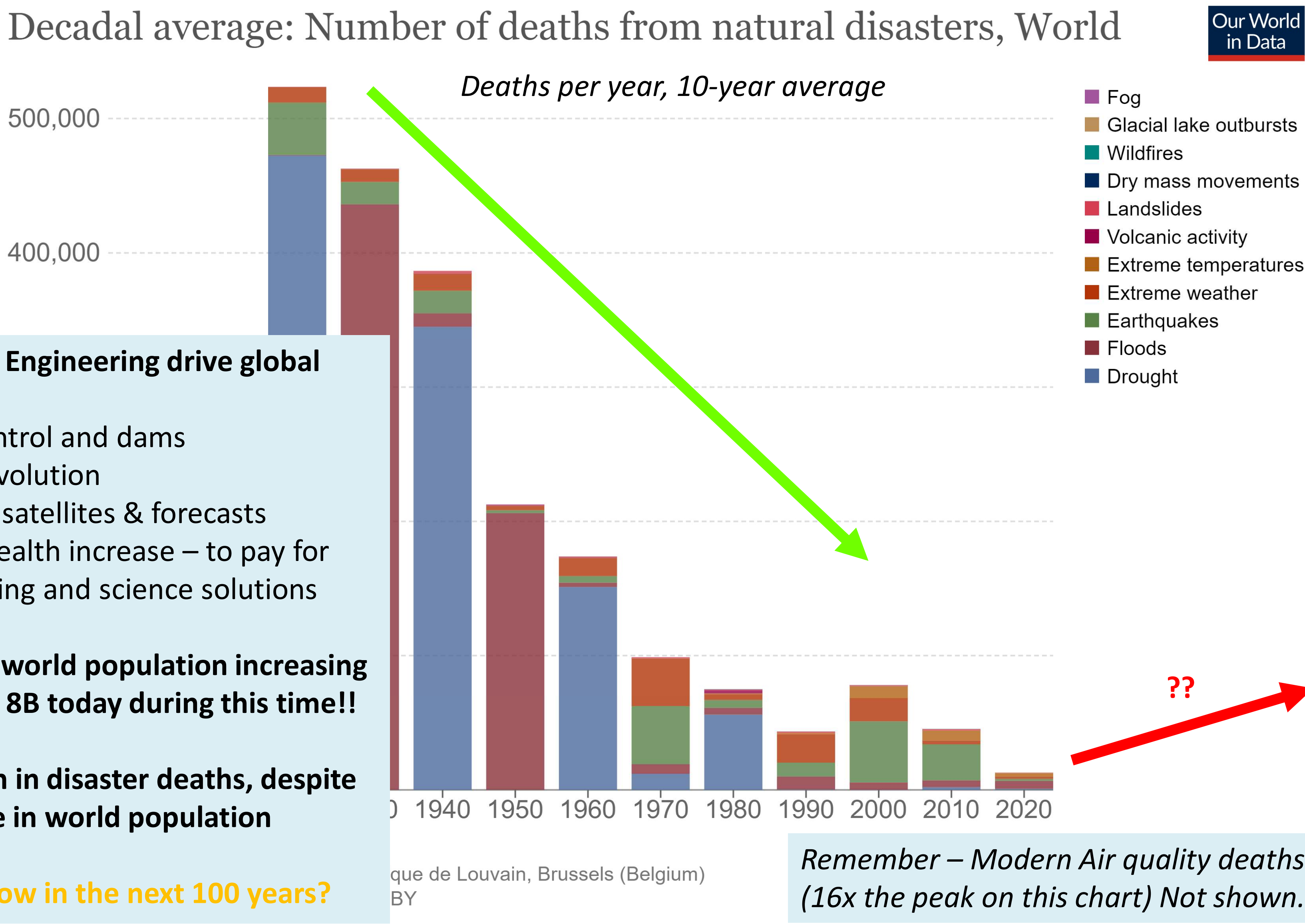
1. Heat
2. Floods (and famine)
3. Drought (and famine)
4. Hurricanes / Typhoons
5. Earthquakes
6. Thunderstorms / Tornados
7. Bad Air Quality

Impact is steadily increasing – likely to overtake earthquakes in the next few decades

Historically the biggest killer, but greatly reduced over the last 100 yrs

#2 Modern day. Largest "disaster" killer

#1 -> 8Million people / yr on average (almost exclusively fossil-fuel pollution)



Science and Engineering drive global trend down

- Flood control and dams
- Green revolution
- Weather satellites & forecasts
- Global wealth increase – to pay for engineering and science solutions

Despite the world population increasing from <2B to 8B today during this time!!

5x reduction in disaster deaths, despite >5x increase in world population

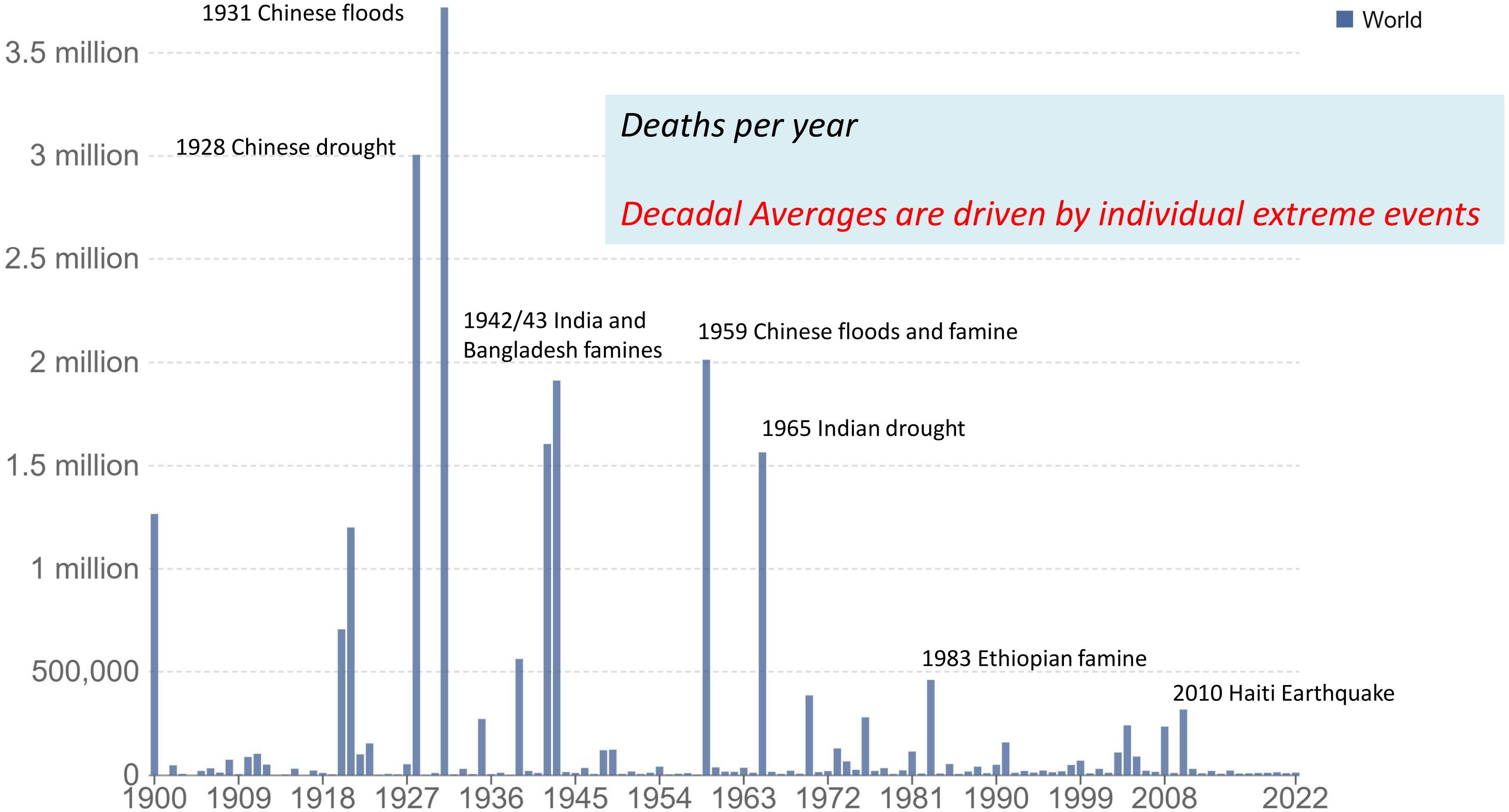
Will it stay low in the next 100 years?

Remember – Modern Air quality deaths 8+M/yr, (16x the peak on this chart) Not shown.

EXISTING TRENDS

Number of deaths from disasters

Disasters include all geophysical, meteorological and climate events including earthquakes, volcanic activity, landslides, drought, wildfires, storms, and flooding.



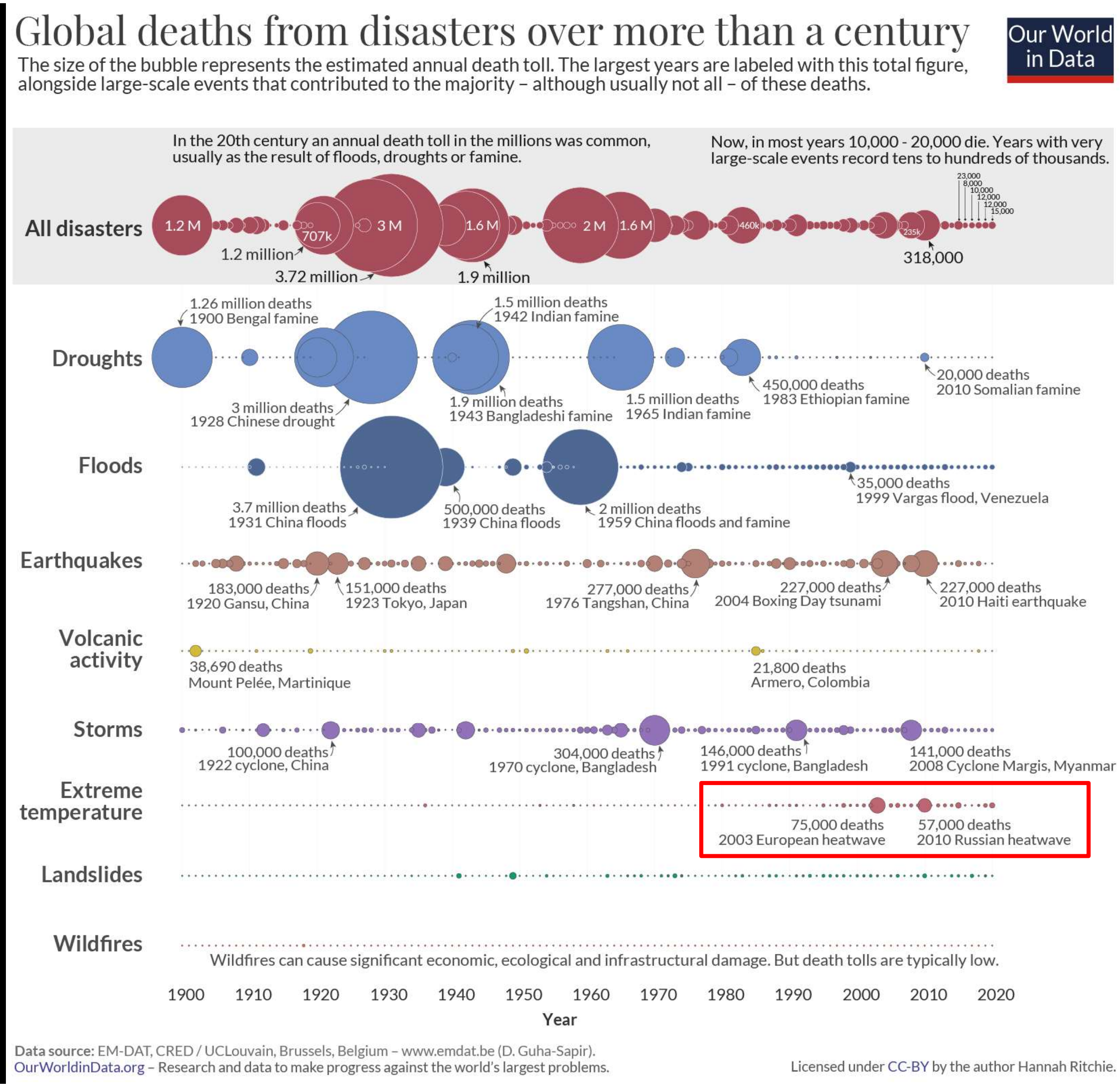
Deaths per year

Decadal Averages are driven by individual extreme events

Source: Our World in Data based on EM-DAT, CRED / UCLouvain, Brussels, Belgium – www.emdat.be (D. Guha-Sapir)

CC BY

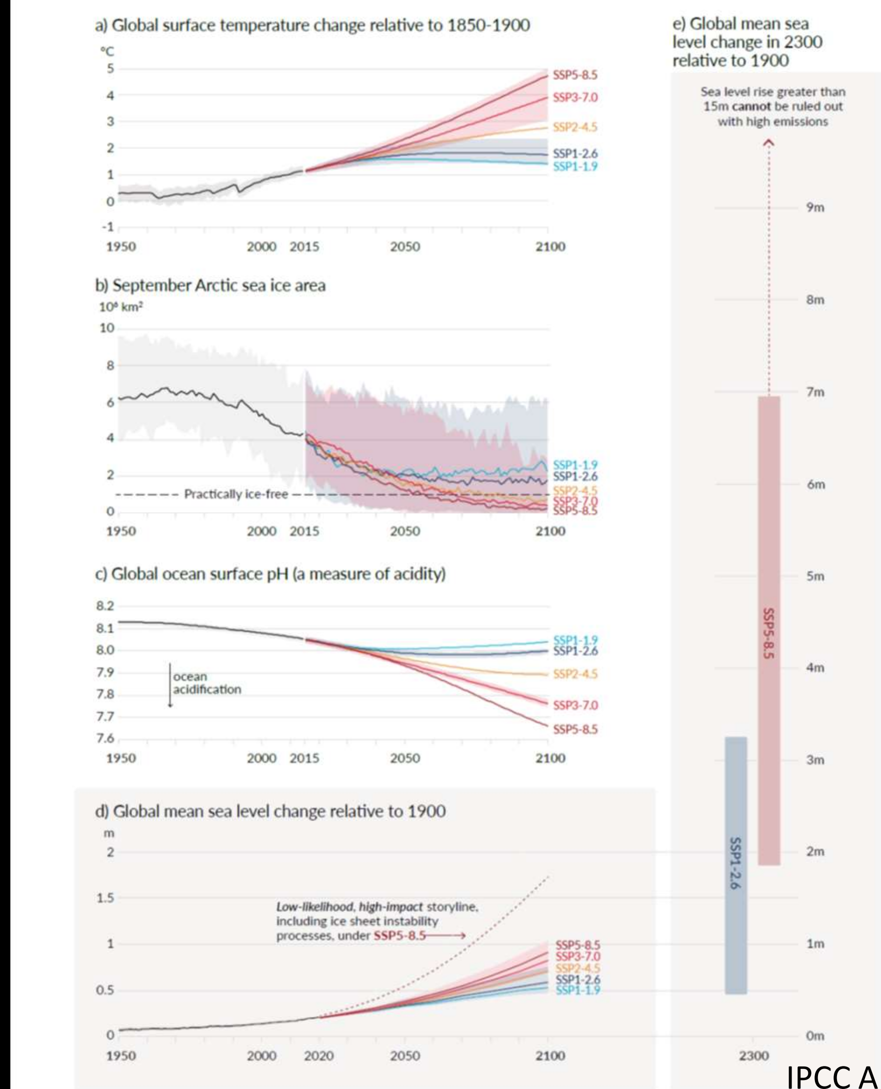
EXISTING TRENDS



Beginning of things to come

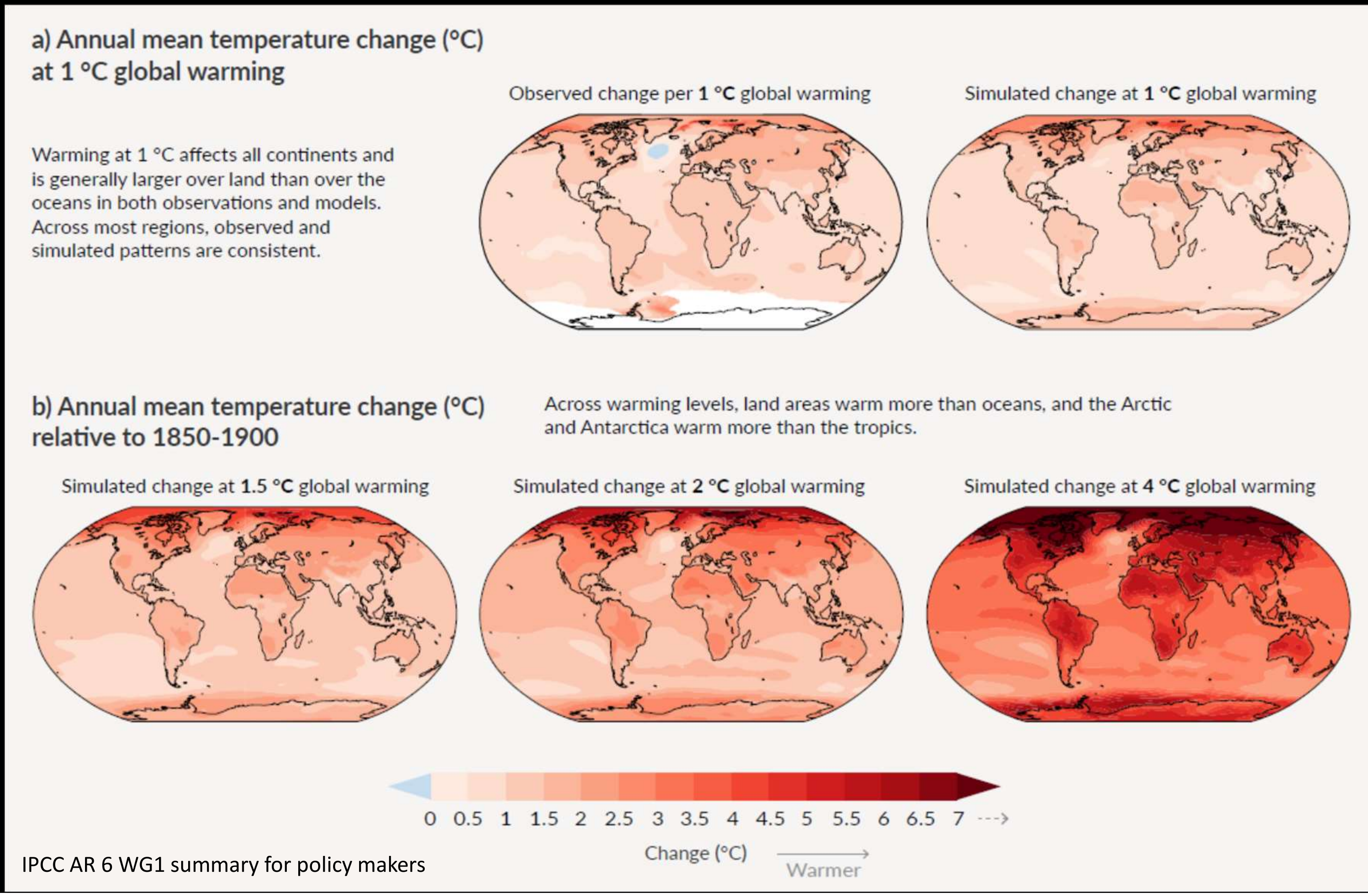
Future Climate Impacts

Human activities affect all the major climate system components, with some responding over decades and others over centuries



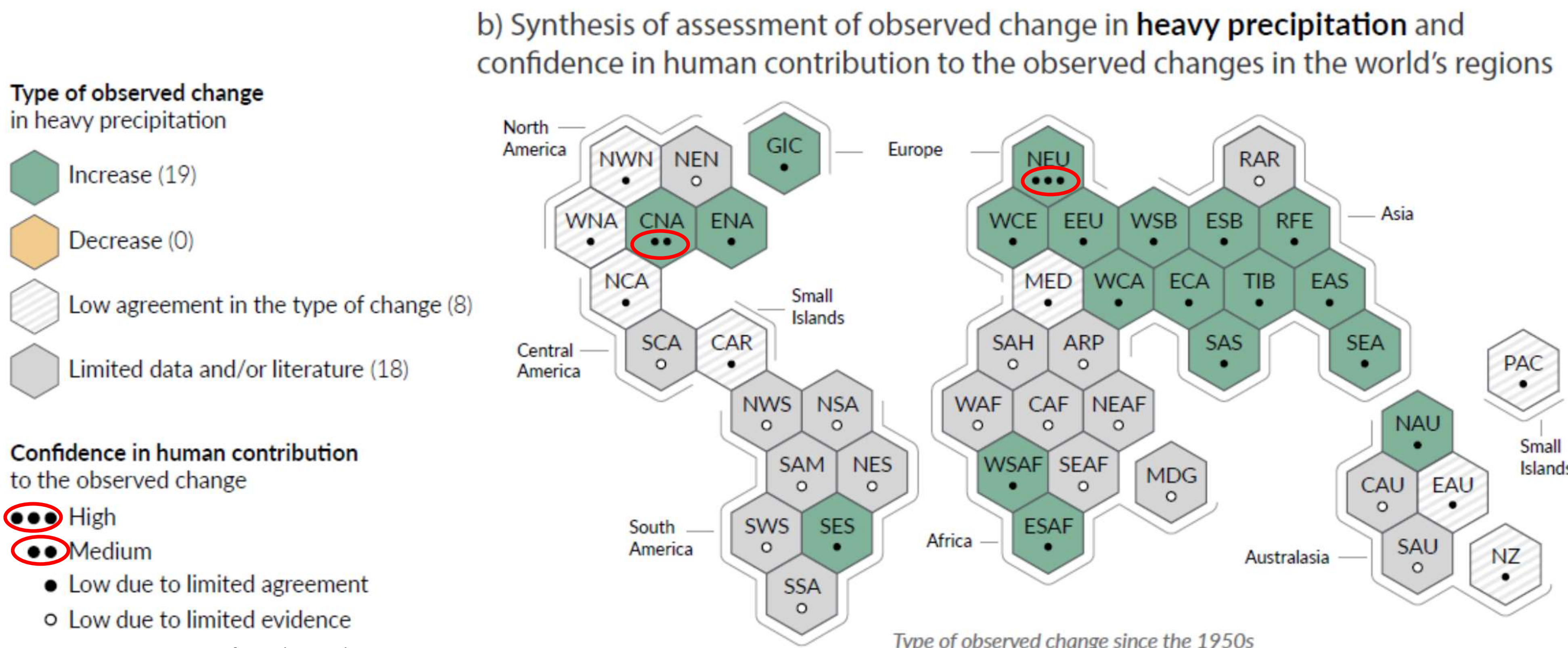
IPCC AR6

Projected Future Warming



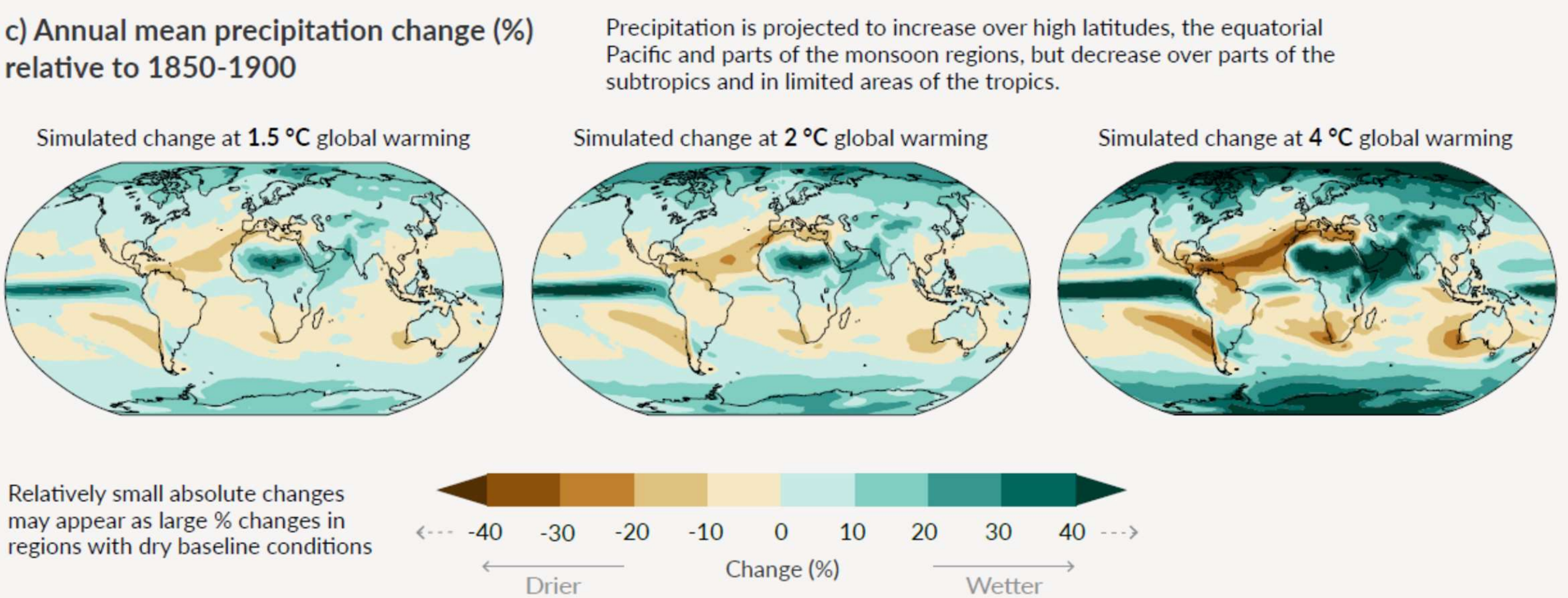
IPCC AR 6 WG1 summary for policy makers

Observed Heavy Precipitation Changes



IPCC AR 6 WG1 summary for policy makers

Projected Mean Precipitation Changes

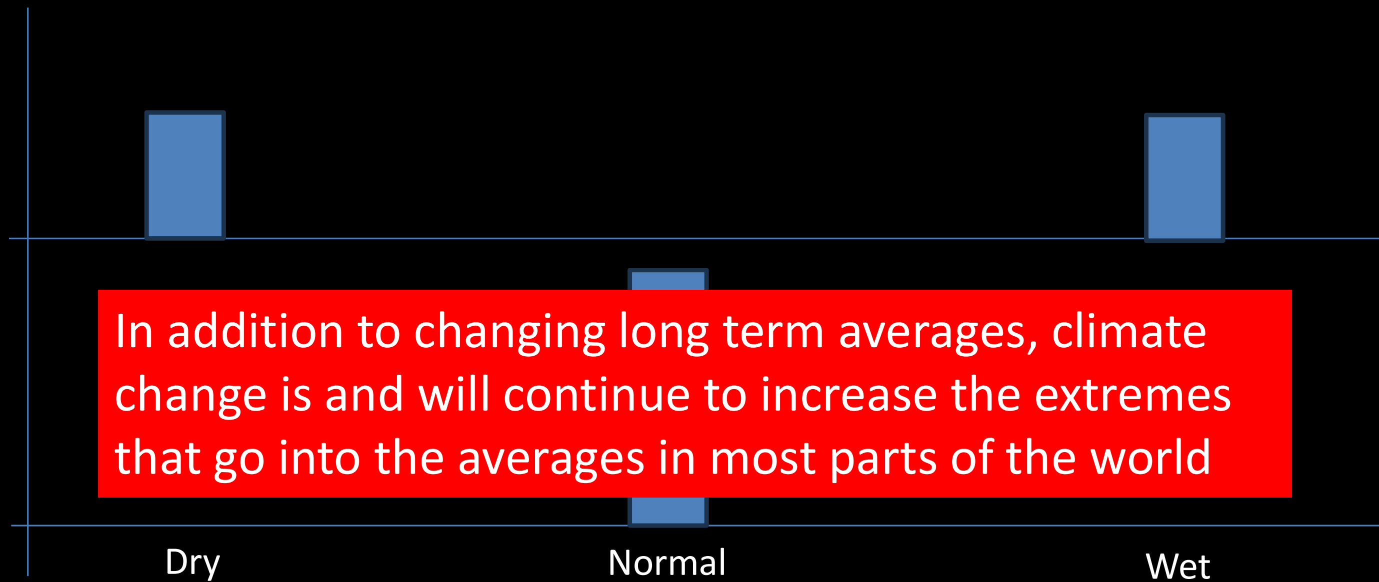


IPCC AR 6 WG1 summary for policy makers

We know that for every degree C of warming, the atmosphere holds 7–10% more water.

Important Reminder on Averages (Mean)

This is California



In addition to changing long term averages, climate change is and will continue to increase the extremes that go into the averages in most parts of the world

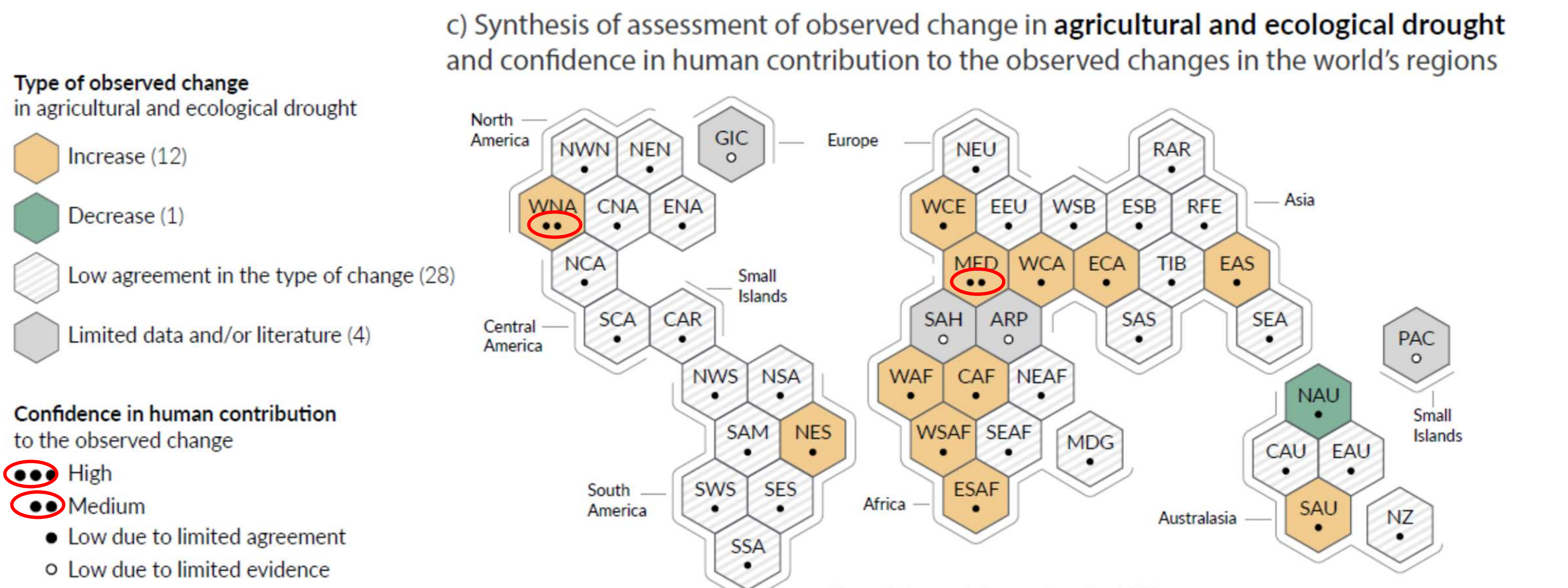
Both have the same average value!

"You could have your head in the refrigerator and your feet in the oven and have a perfectly nice average temperature."

Large Alluvial Fans – Markers of Past Extreme Flash Flood Events

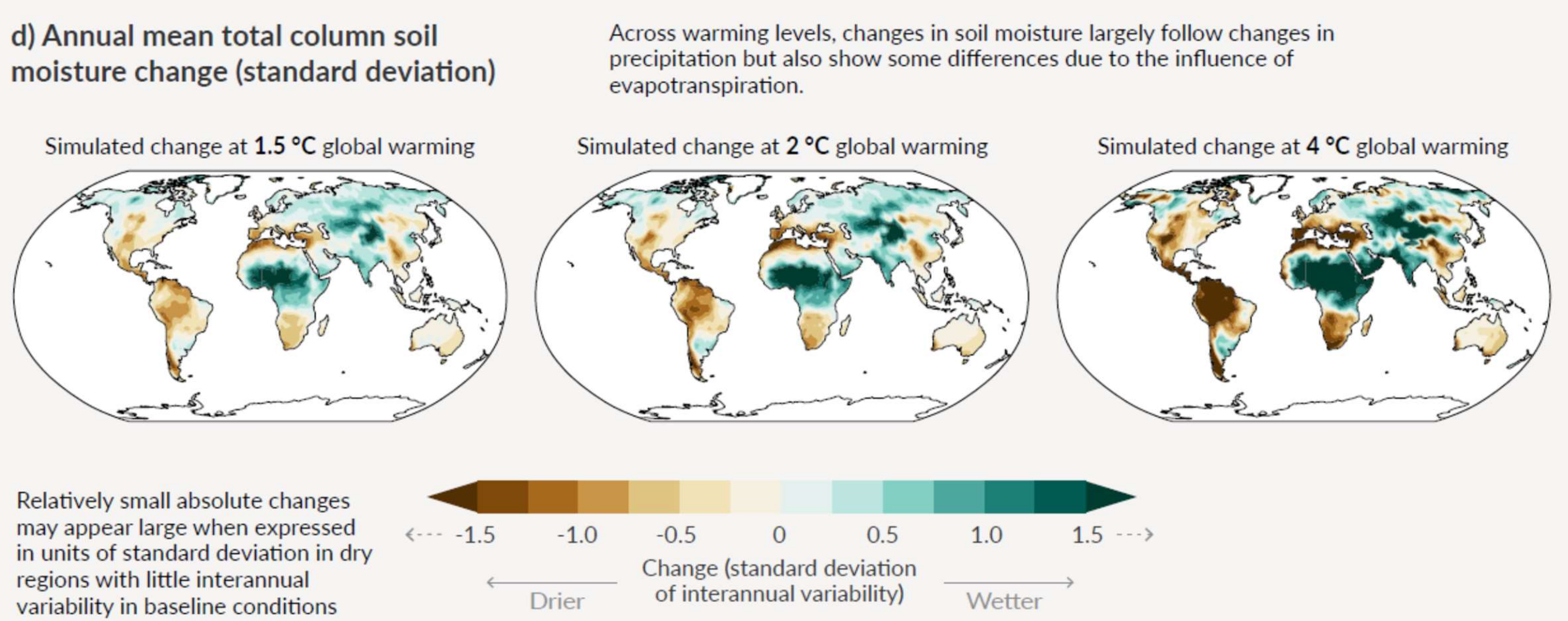
Erosion is reaaaallllly slow, until it isn’t

Observed Drought Condition Changes



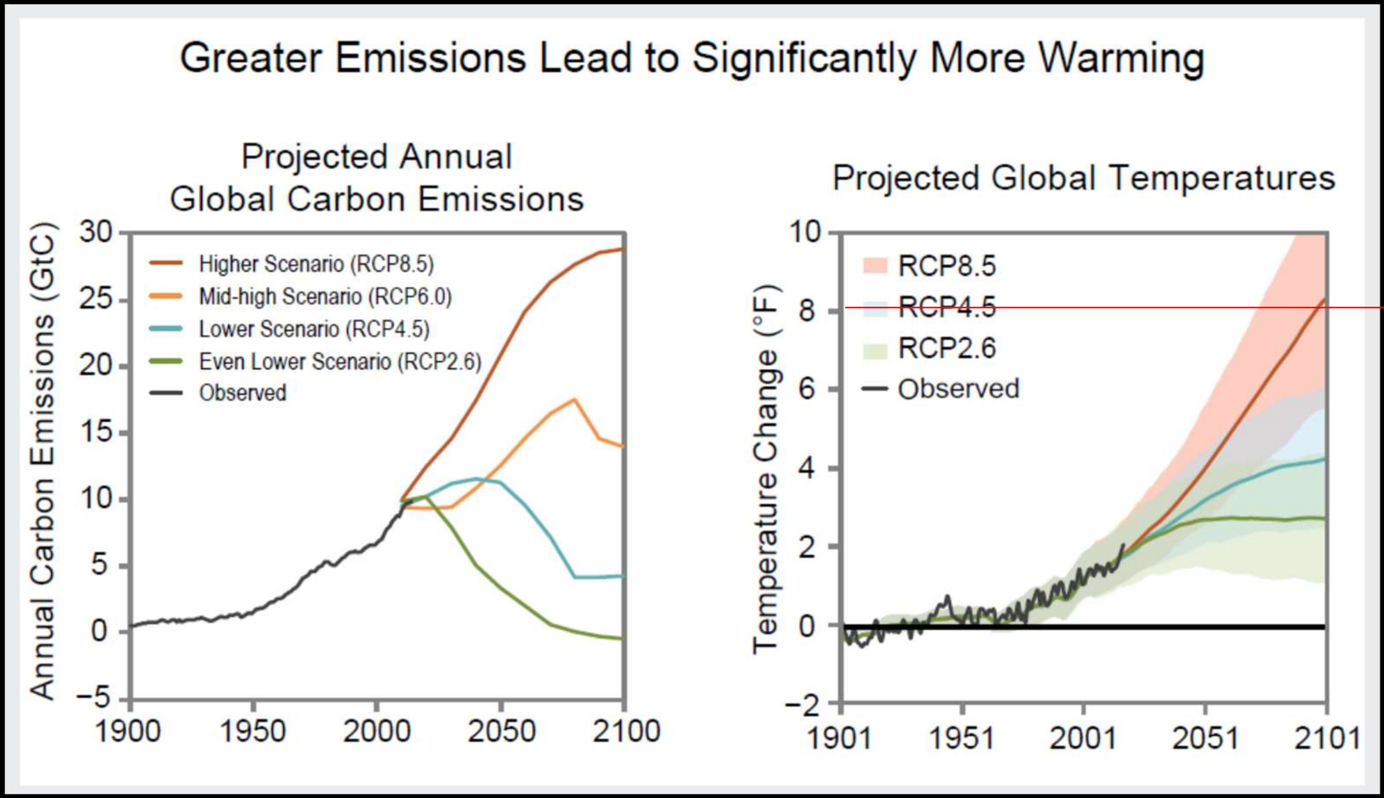
IPCC AR 6 WG1 summary for policy makers

Projected Mean Soil Moisture Changes



IPCC AR 6 WG1 summary for policy makers

Why Emissions Need To Be Lowered



The last time the Earth was this hot was ~4 Million years ago

USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

(SOME) HIGH LEVEL RESIDUAL UNCERTAINTIES

AKA what we know we don’t know (or the “known unknowns”)

The Obvious

- Future human behavior is the largest driver of uncertainty in our ability to predict future climate states
  - Hence climate scenario “projections” and not “predictions”
- Having said that, there are still important things to work on to best guide planning and decision making

Big Picture - 1

- **Climate science (observations, models, analysis) HAS SETTLED the broad outlines of the problem**
  - Complex models continue to confirm what simple models predicted decades ago
  - Causes of warming, trends, global scale distribution of impacts (e.g. arctic will heat more), approximate pace of expected changes under different scenarios
  - **Enough information to inform broad policy** – e.g. mitigate emissions ASAP

See for example – "The scientific challenge of understanding and estimating climate change", Palmer & Stevens, PNAS December 3, 2019 116 (49) 24390-24395; first published December 2, 2019; https://doi.org/10.1073/pnas.1906691116

Big Picture - 2

- **Not settled – but improving every year**
  - In physics based models:
    - **NOT Enough** resolution and confidence in MOST regio… jection to allow reasonably efficient management since s… for resources
      - E.g. How soon to put adaptation …
    - Magnitude and likelihoo… erent scenarios
      - Import… etc), **in general they are likely u… ith models**
  - In Integ… e + economics):
    - Typica… esentations of climate elements, lack complex feedbac… most human social / economic elements
      - **Likely … nder-estimate total human / earth system coupling and potential extreme outco…**

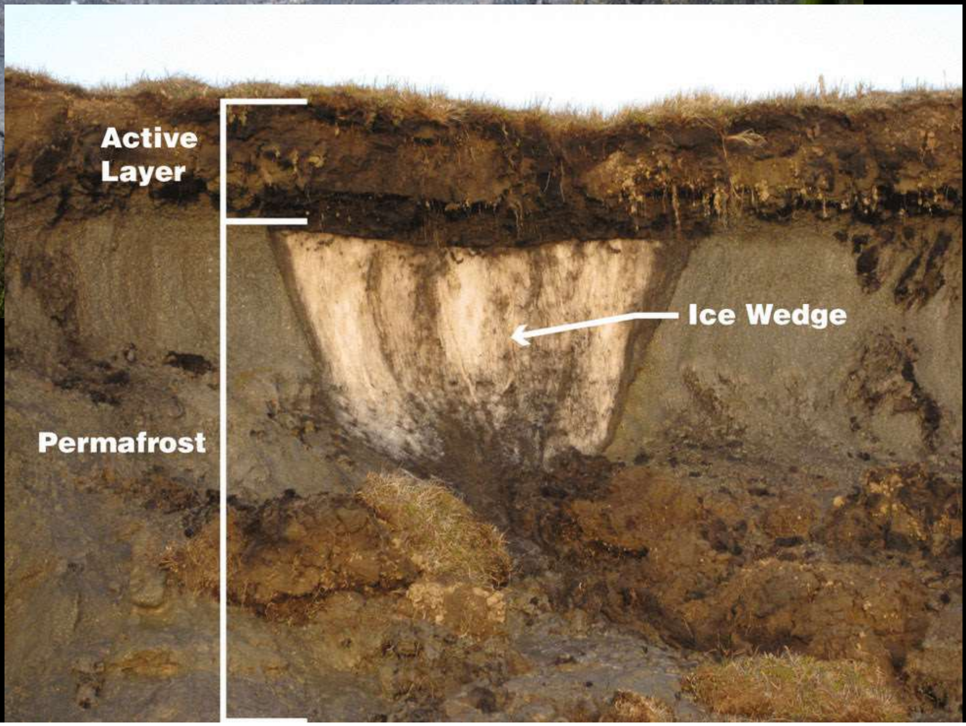
This is a nuanced story, and can/is misused by bad actors, and not easily understood by non-technical people. Current under-estimation of future impacts is likely LARGE

See for example – "The scientific challenge of understanding and estimating climate change", Palmer & Stevens, PNAS December 3, 2019 116 (49) 24390-24395; first published December 2, 2019; https://doi.org/10.1073/pnas.1906691116

KEY RISKS NOT FACTORED INTO CURRENT CLIMATE COST MODELS

Extreme events poorly resolved / modeled ->

very likely under-represented



Some key climate feedbacks not well modelled

- Fires, and associated CO_2 emissions
- CO_2 and Methane release from thawing permafrost not well understood or modelled
- …

UN: In 2018 alone, 17.2 million new displacements associated with disasters in 148 countries and territories were recorded (IDMC) and drought displaced 764,000 people in Somalia, Afghanistan and several other countries. - https://www.un.org/sustainabledevelopment/blog/2019/06/lets-talk-about-climate-migrants-not-climate-refugees/

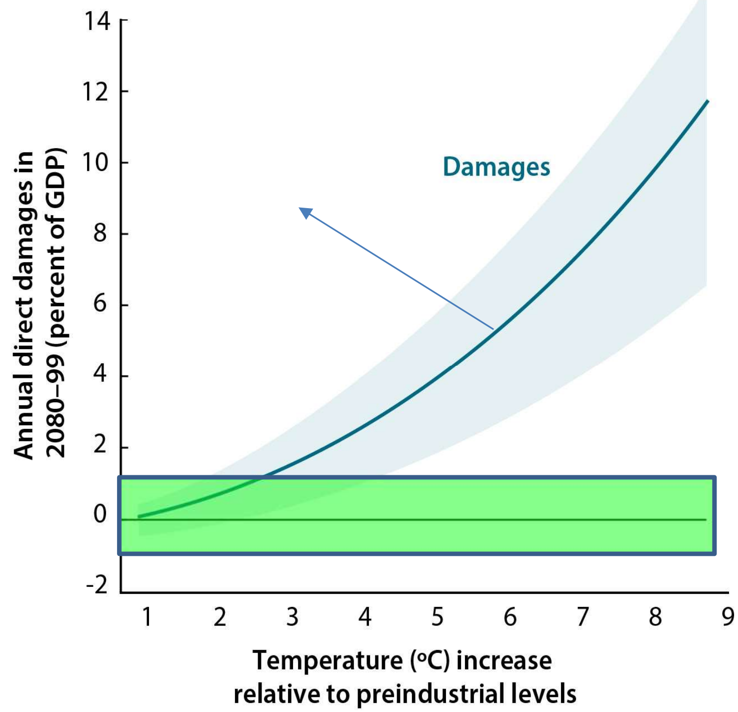
Earth / Human system interactions are not factored in cost models

- migration waves due to temperature, drought / famine, sea level
- Political instability associated with lack of food, migrant absorption, etc.
- Associated impacts on investment stability, etc

Example Estimates of Costs

FIGURE 1.

U.S. Economic Damages from Climate Change in 2080–99 by Temperature Increa



Source: Hsiang et al. 2017.

Note: The shaded area represents a 90 percent confidence interval around the central estimate for a given temperature increase. Costs associated with mitigation are excluded.

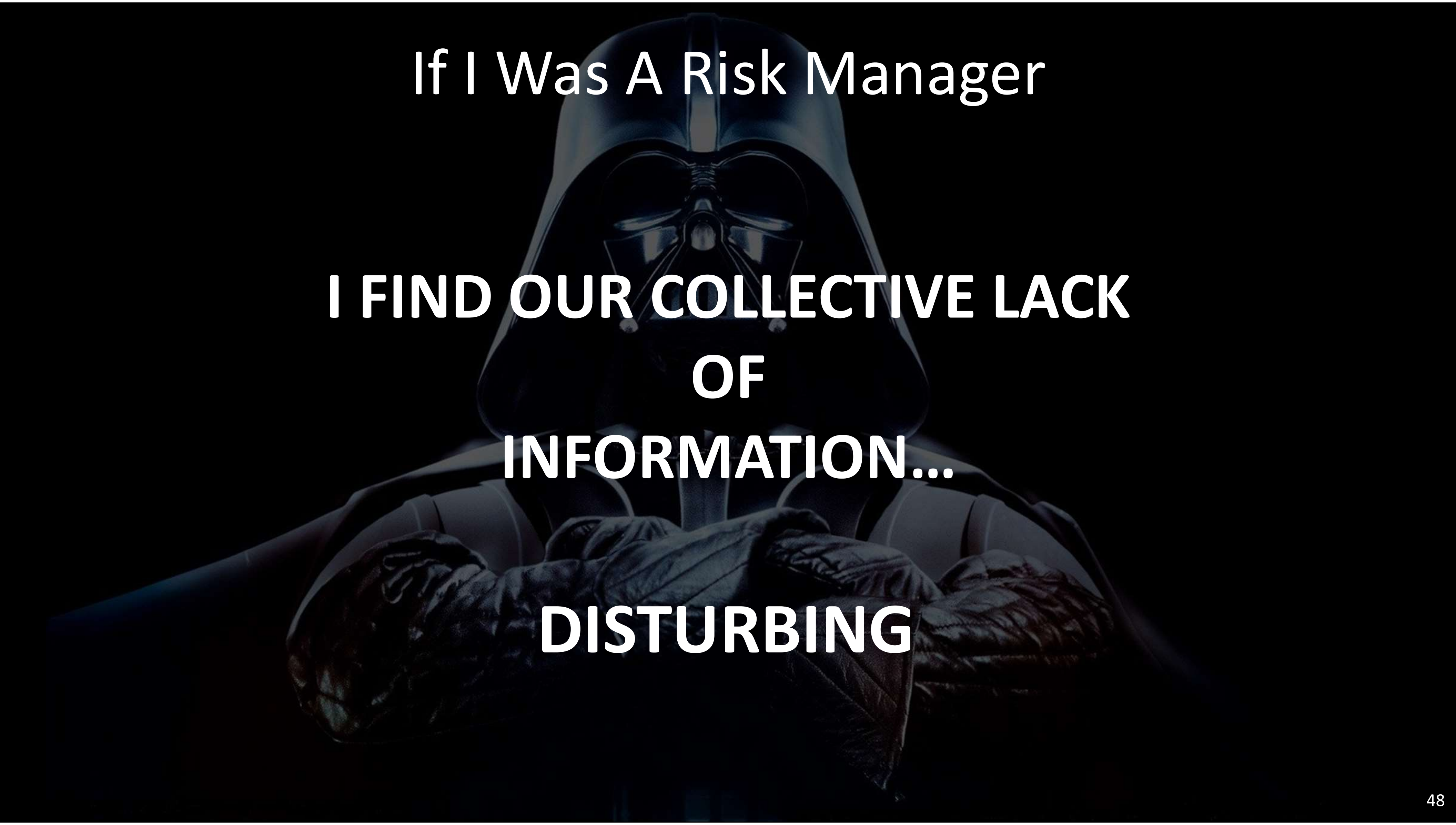
THE HAMILT PROJ BROOKINGS

No action - "predictable" costs – like storms, fires, sea level rise, and heat waves. These costs ***do not*** take into account potential social/political instability costs like mass migration and war

Mitigation costs estimates – typically 1-2% GDP, though some economist argue a green-economy transition might be net positive for GDP growth

If I Was A Risk Manager

- **Knowledge:**
  - Look for more ways to get companies and consumers to factor risks and impacts into decisions
    - requires risk transparency and findability
  - Continue to demand corporate and government insight and transparency on climate change risk exposure
  - Ask for better investment in climate change knowledge and prediction capability, actionable information distribution (under-funded) -> models/computing, sensors
    - Private sector players are planning on filling SOME gaps
- **Control: Use market incentives to change behavior**
  - Higher premiums in high-risk areas
    - US Government needs to stop subsidizing under-costed insurance in high-risk areas.
  - Positive incentives for resiliency improvements to housing and infrastructure, corporate capital investments
    - Some of this is already happening
    - Is there room for (more) private / public partnership here?
  - Mitigation is much cheaper than just taking the hits, but often politically painful



If I Was A Risk Manager

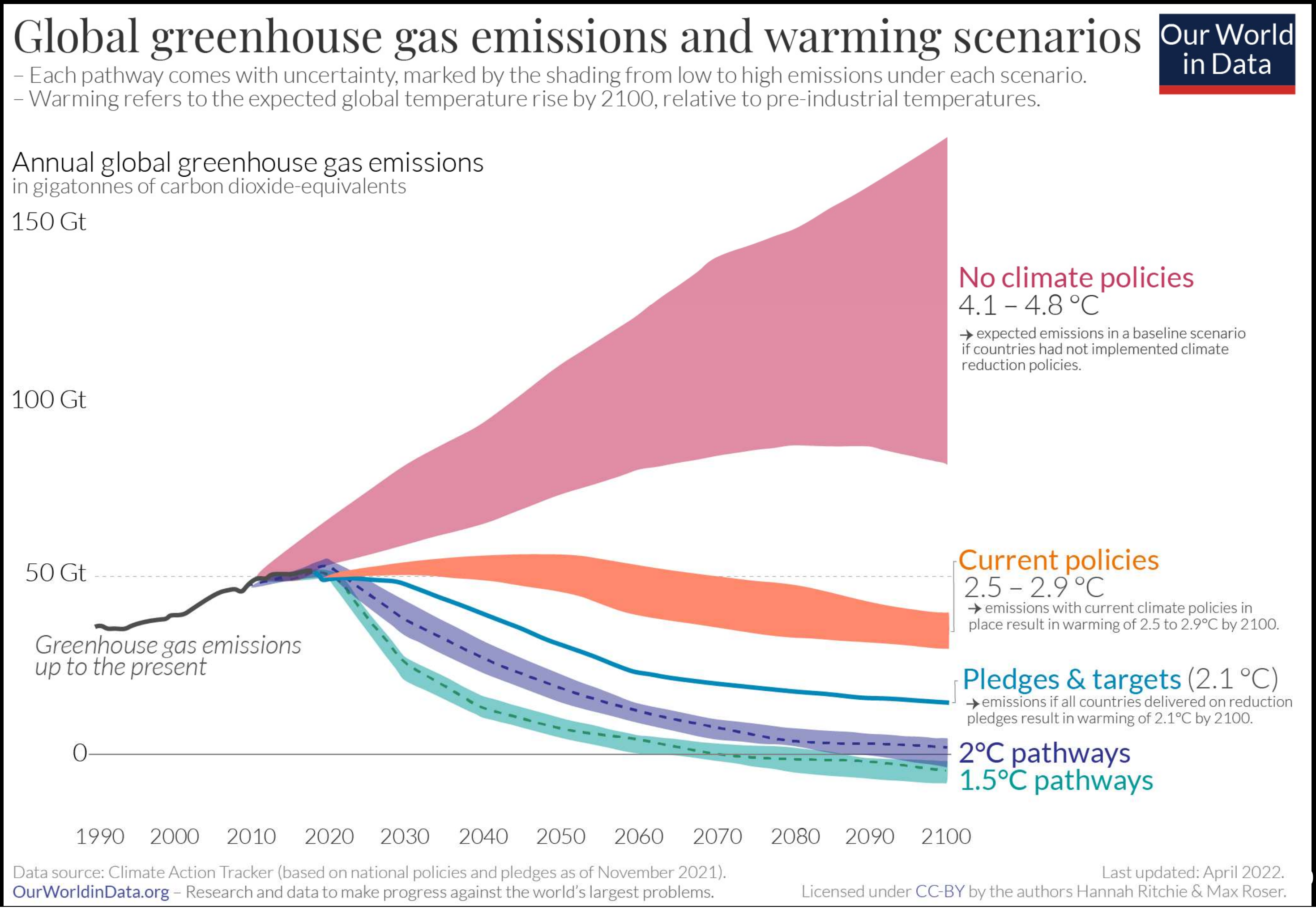
I FIND OUR COLLECTIVE LACK
OF
INFORMATION…

DISTURBING

CONCLUDING REMARKS

Keep it up!

We Need More Action, But Are Having A positive Impact Already



There is a lot that can be done to keep reducing the worst case consequences, and starting late is better than never.

The Bottom Line

- The climate is warming, humans are causing it
- Climate change presents a risk to human society because our civilization has grown and been optimized around a relatively narrow and stable climate range
- Fossil fuel emissions and land use change has caused about +1.1 deg C (+1.8F) of warming so far
- Human choices drive the largest uncertainty in how warm things might get – ***It is NEVER too late to act to reduce future damage. We are making progress but need much more.***
- **Uncertainties in our knowledge warrant playing things CONSERVATIVELY to avoid unexpected / worst case consequences**
- Mitigation actions have positive economic impacts, maintain our quality of life, and have many positive health impacts, and are **MUCH** cheaper than dealing with "business as usual" climate change
  - *E.g. green energy will massively reduce air pollution and save millions of lives per year from that factor alone*


ANY QUESTIONS?

Thank you

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BACKUP

Modern Earth System Science - Framing Motivations:

Unprecedented Challenges Require Unprecedented Foresight

What is going on?

How and Why is it happening?

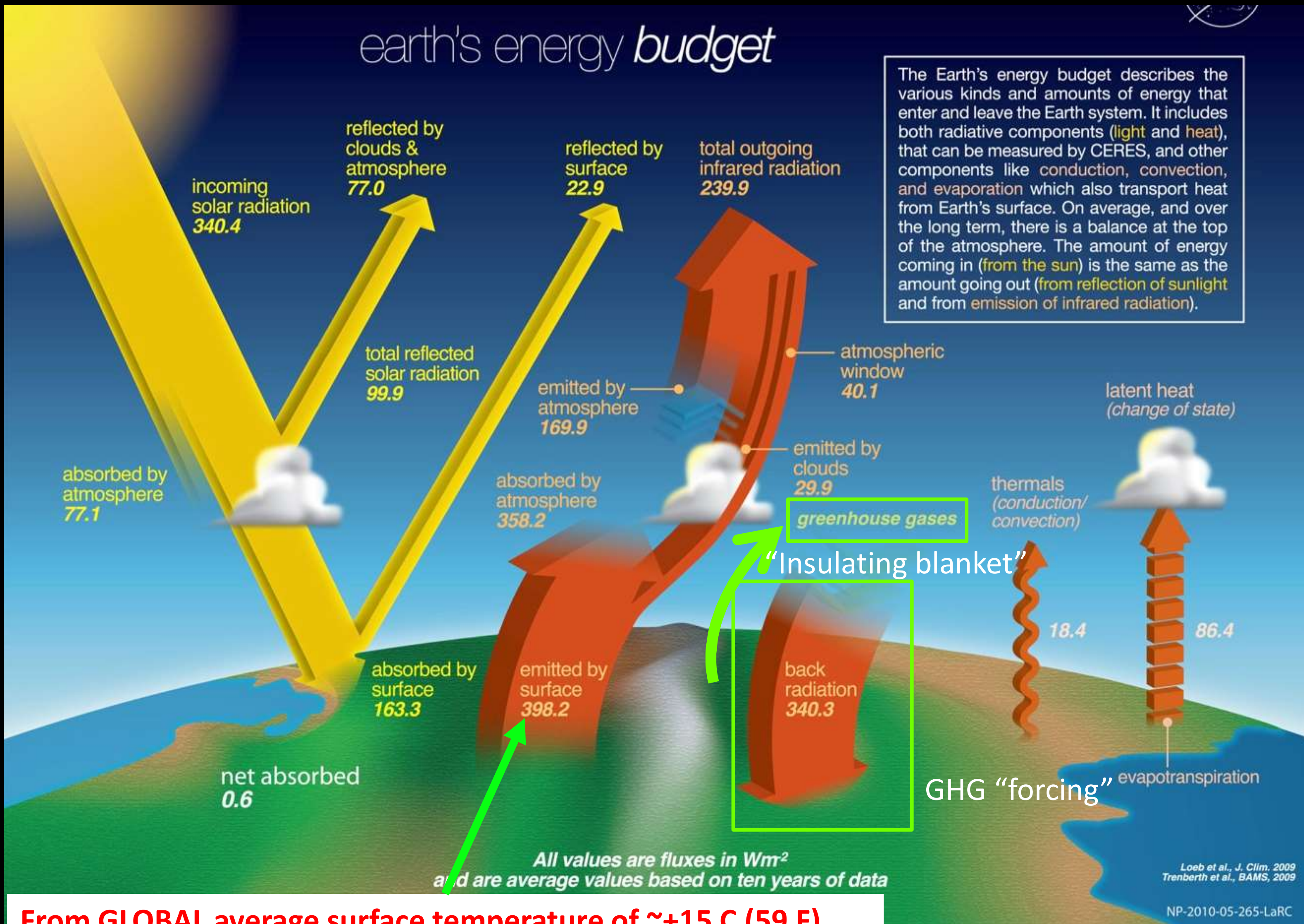
What could/will happen in the future?

How might our actions impact the future?

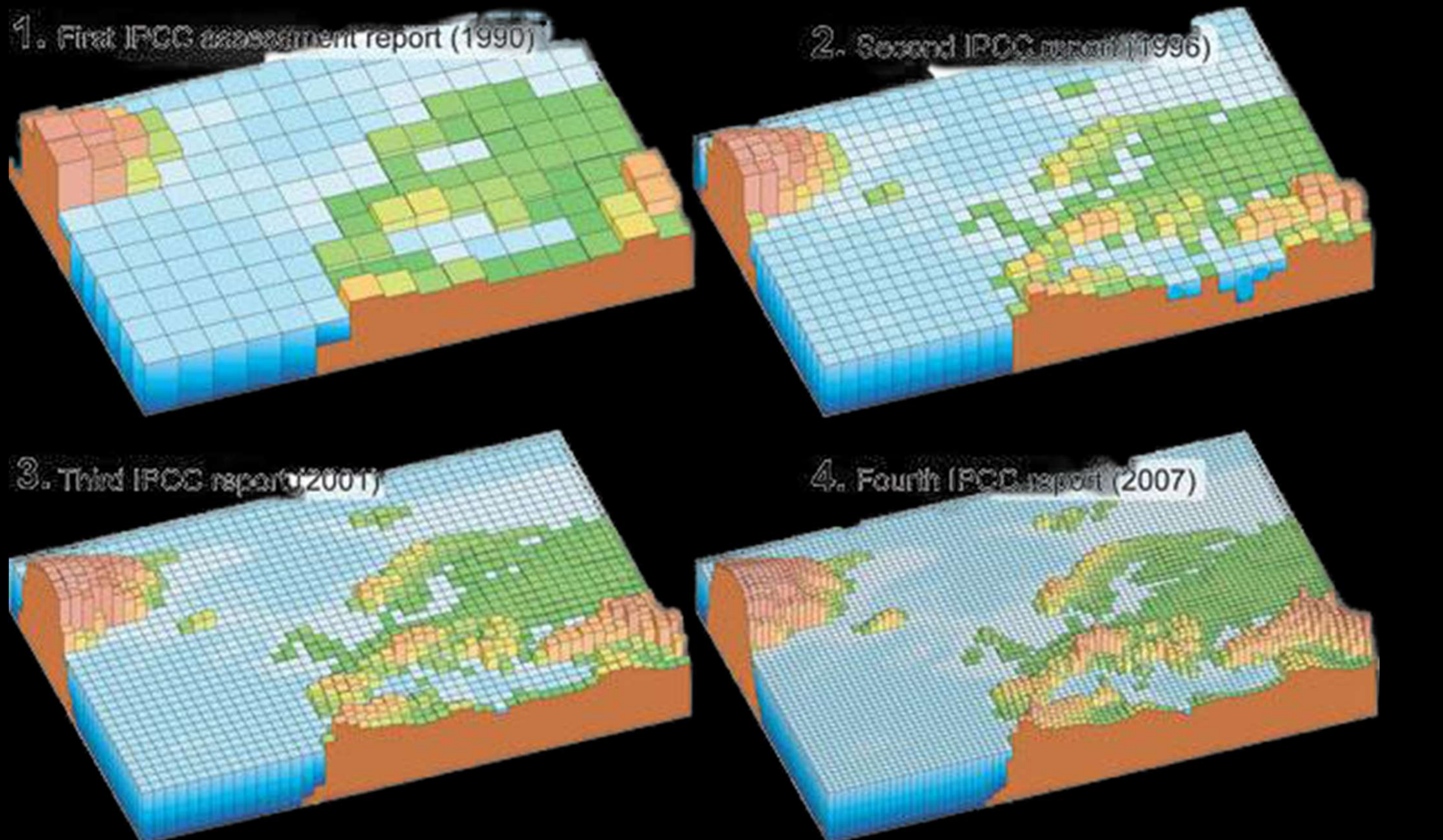
What are the most effective actions to achieve the future we want?

=> What information do decision makers need to build societal resilience?

– On time scales from days to decades, and spatial scales of meters to globe spanning



From GLOBAL average surface temperature of ~+15 C (59 F)


1. First IPCC assessment report (1990)
2. Second IPCC report (1996)
3. Third IPCC report (2001)
4. Fourth IPCC report (2007)

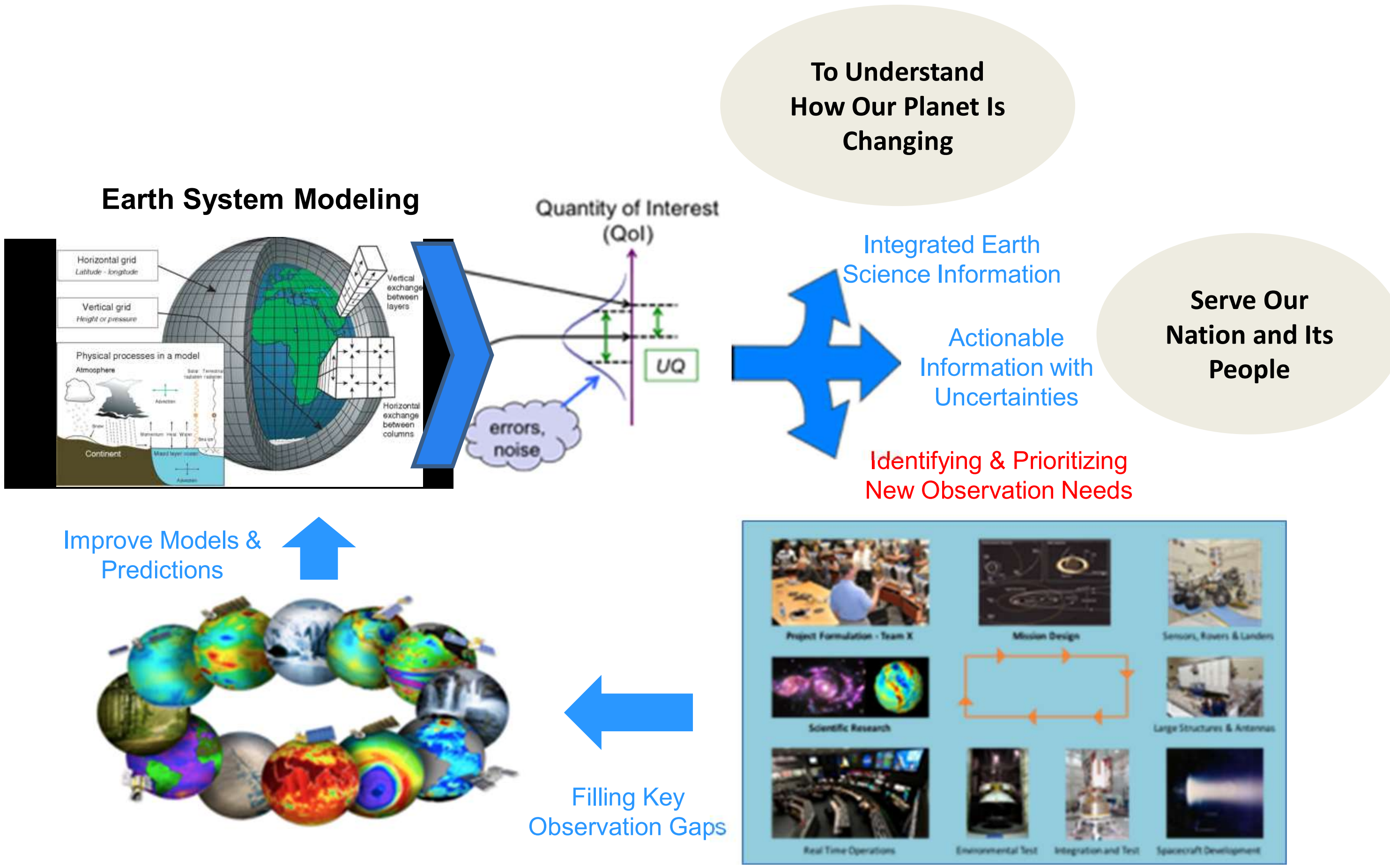
Specific Gaps - 1

- **Spatial and Temporal Resolution, Computing Power**
  - Many key aspects of physical processes are ~perfectly understood (e.g. ocean and atmosphere circulation governing equations) but lack of available computing power sometimes results in “missed behavior”
    - E.g. small eddy circulation in ocean models
    - Downscaling / regional model runs can alleviate this, but don’t feed back well into global scale runs used for climate prediction
- **Process understanding –**
  - key aspects of fine scale physical processes are often parameterized (e.g. convection, cloud physics…)
  - Need observations aimed at gaining process understanding, together with model development funding to incorporate the missing physics into the models

Specific Gaps - 2

- **Natural variability vs new trend**
  - Many Earth system state variables do not have a sufficiently high accuracy and/or resolution observation record to truly distinguish between variability and new trend
    - Not true for global mean temperature, mixed GHG concentrations, sea level, etc (extensive paleo records)
    - But – Antarctic ice shelve circulation + temperature + salinity, fine scale global plant species distribution, deep ocean circulation, others are under-observed
- **-> need to observe more of the natural & human world at appropriate resolution and duration**

HOW: End to End System Development Process



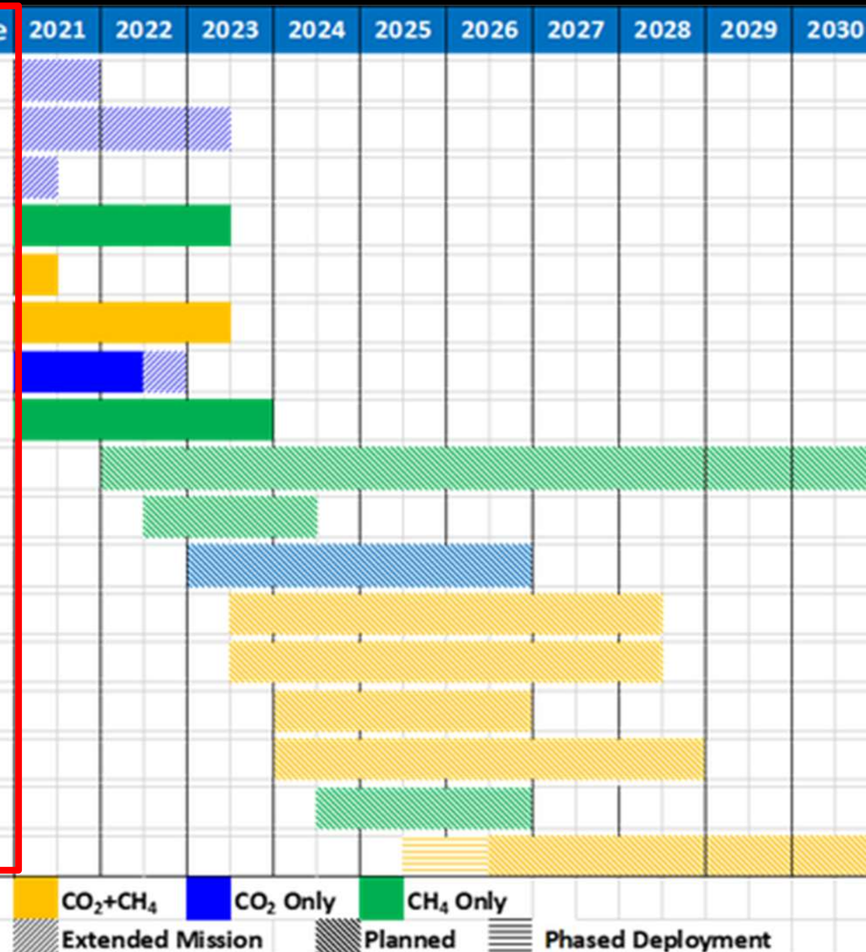
WHAT: (sample) New Observing System Plans

- **Global Hyperspectral Imaging & Monitoring**
  - Initial hyperspectral imaging systems coming on line – DLR DESIS (ISS), NASA EMIT ('22)…
  - NASA SBG-VSWIR, ESA CHIME -> 30m resolution, ~380-2500nm coverage in 10nm channels, 16 day revisit (each single mission, ~185 km swaths)
    - launches starting late 2020s
- **Global Multi-Spectral Thermal Infrared Monitoring**
  - Landsat 8/9 – 2 channels, 100m+ resolution, 16 day revisit each
  - CNES/ISRO TRISHNA, NASA SBG-TIR, ESA LSTM -> 60-100m resolution, 5-8 spectral channels, 3 day revisit (each single mission -> ~900 km swaths)
    - Launching mid to late 2020s
- **Global Interferometric SAR Monitoring** -> land elevation changes, biomass, etc
  - Sentinel-1, Radarsat, Cosmo-sky med,… – X band SARs
  - NASA/ISRO NISAR (L and S band combined), ESA ROSES L
    - Launching 2023 and late 2020s

Great resource - http://database.eohandbook.com/timeline/timeline.aspx

WHAT: The coming GHG Observation Armada

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●	
OCO-2	NASA/USA	●		●	
GHGSat-D - Claire	GHGSat/Canada		●		●
Sentinel 5P TROPOMI	ESA/Europe		●	●	
GaoFen-5 GMI	CHEOS/China	●	●	●	
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●	
OCO-3	NASA/USA	●			
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada		●		●
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
MethaneSAT	EDF/USA		●		●
MicroCarb	CNES/France	●		●	
Feng Yun 3G (CMA)	CMA-NMSC/China	●	●	●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	● (grey)	●	● (grey)	● (grey)
GeoCarb	NASA/USA	●	●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
MERLIN	DLR/Germany-CNES/France		●	●	
CO2M	EC Copernicus/Europe	●	●	●	



Source: CEOS (https://ceos.org/), Spacenews - https://spacenews.com/u-s-role-in-global-greenhouse-gas-constellation-still-up-in-the-air/

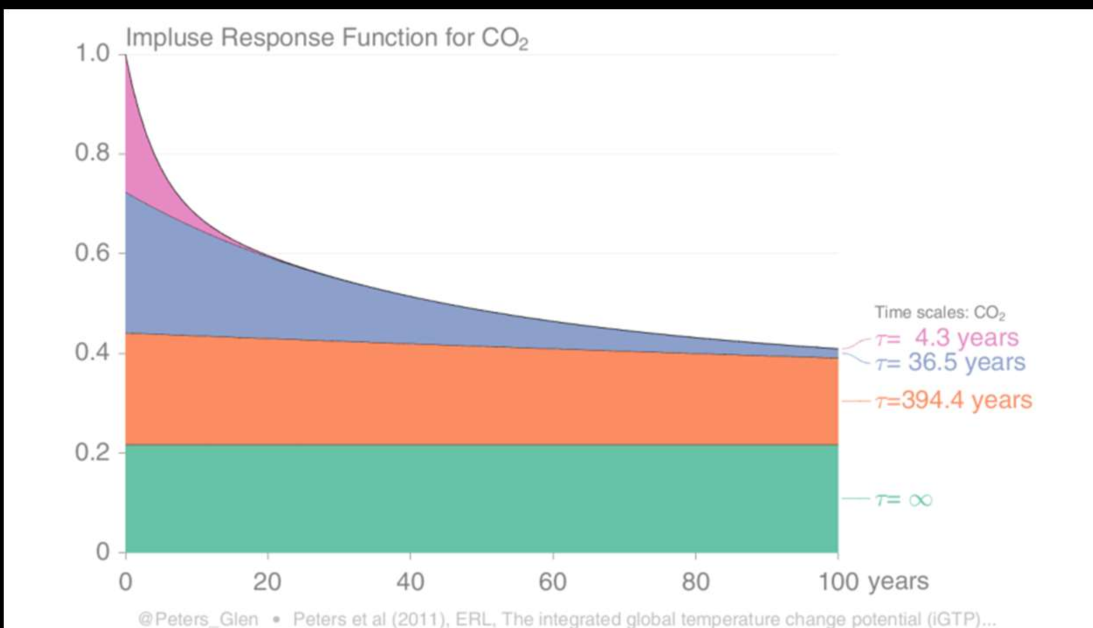
WHAT: Improved Climate Modelling

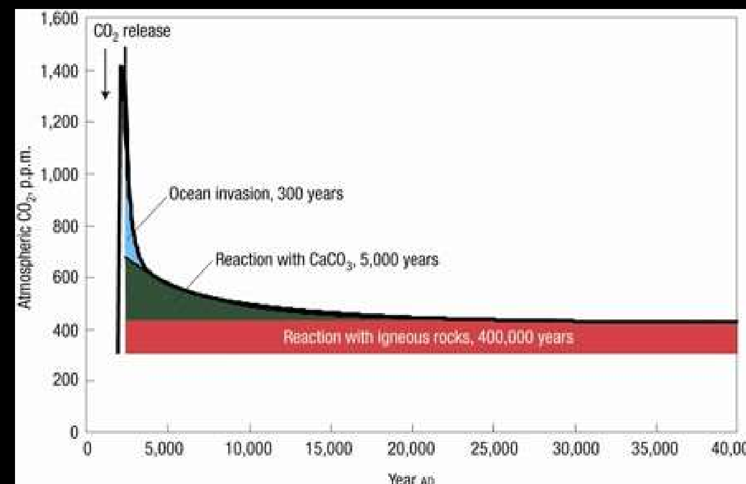
- The US has 6 federal lab supported climate modelling centers, plus more at the university level
- Difficult to find well documented and planned large scale investment in better climate models (likely mostly reflects my lack of insight)
  - Funding levels generally much lower than, and development is sometimes less formal than, space based observing systems
  - Areas needing improvement not well advertised by climate community (see “nuanced story” note earlier)
  - “value of information” is not well understood by policy makers or climate community
  - -> slow but steady incremental improvement continues?
  - Exceptions
    - DOE Exascale computing, NOAA is also starting to invest more heavily
    - Climate modeling summits have recently started among key US modelling entities to help remedy the above

- Integrated Assessment Models (IAMs)
  - Multi-layered network models hold promise of more sophisticated dynamic system representation, perhaps also better coupling mechanisms between physical and social systems

See for example, National Research Council 2012. *A National Strategy for Advancing Climate Modeling*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13430

CO_2 residence time





Archer, D. *The Long Thaw: How Humans Are Changing the Next 100,000 Years of Earth's Climate* (Princeton Univ. Press, 2008).

Common Climate Change Denial Points

- **"Climate's changed before"** -> Yes it has, a lot… but not with human civilization around, and usually much more slowly
- **"There is no consensus"** -> 97% of climate experts agree that a preponderance of evidence from multiple sources shows humans are driving climate change
- **"Animals and plants can adapt"** -> eventually, yes… but not without the mass extinction of species which can not adapt quickly
- **"It's the sun"** -> the sun can and has effected climate. But, in the last 35 years, the sun has been very slightly less bright (couple Watts/m^2 out of ~1350 W/m^2 at the top of the atmosphere)
- **"It's not going to be bad"** -> climate change will potentially force ***hundreds of millions*** of people to leave coastal areas and parts of the world that will not have enough water, food, be too hot, etc. How well has the world adapted to trying to handle a few million refugees from Syria?
- **"Responding to climate change forces collective action at the national and international level, this will lead to a global communist system with the UN taking over"** -> What?!? Agreeing on mitigation targets will require coordination, and yes there will be some new rules, but many of the technological solutions are DISTRIBUTED not CENTRALIZED and increase local community robustness and independence (e.g. solar power and storage), and result in net creation of jobs
  - *There are many ways to solve this problem while maintaining a free and open society, and the independence of each citizen of the planet. You can even keep being greedy, just not with zero regard to your children's children and to the health of your fellow humans*