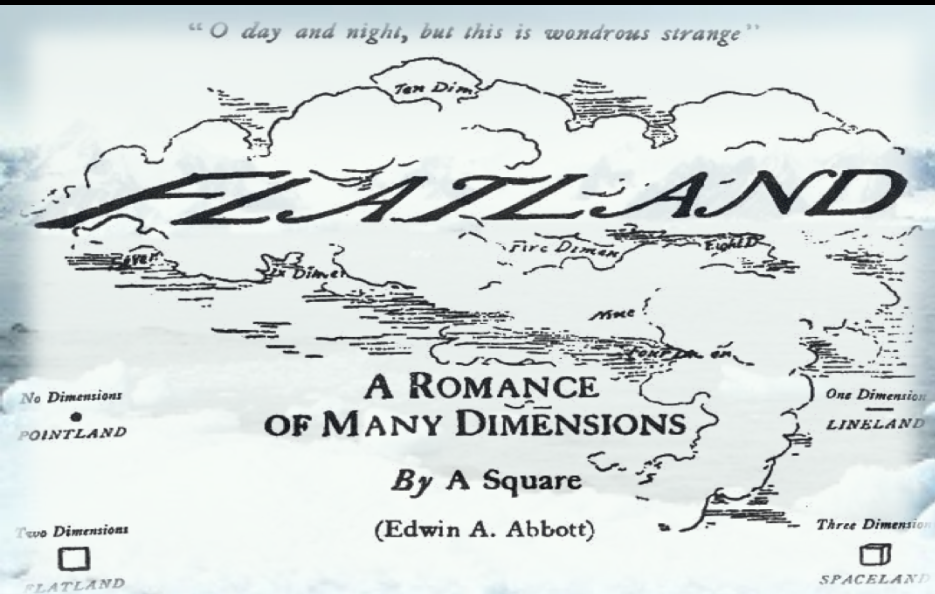
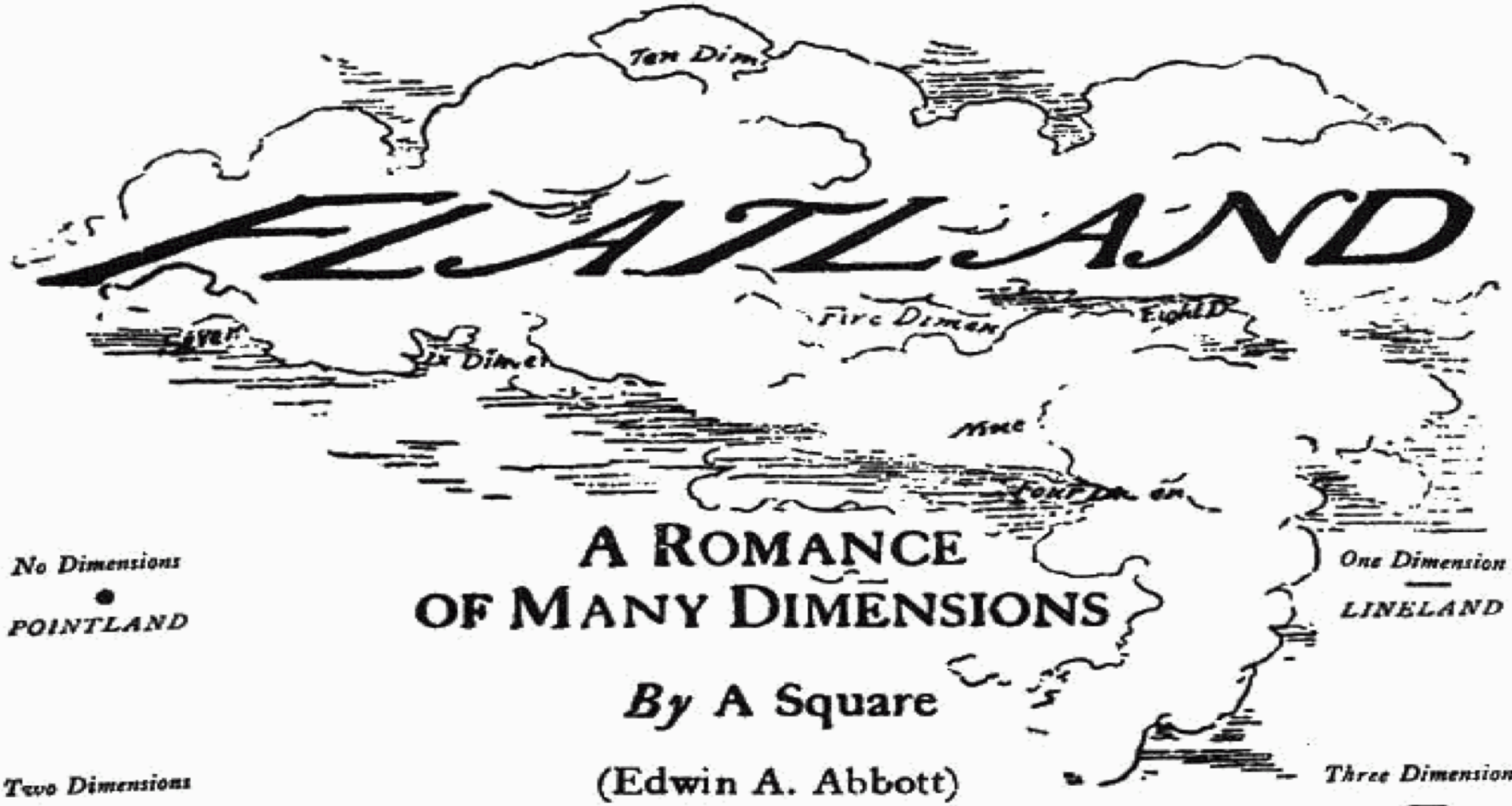


From Flatland to Our Land

A mathematician's journey through our changing planet

Emily Shuckburgh @emilyshuckburgh
British Antarctic Survey

"O day and night, but this is wondrous strange"



A ROMANCE OF MANY DIMENSIONS

By A Square

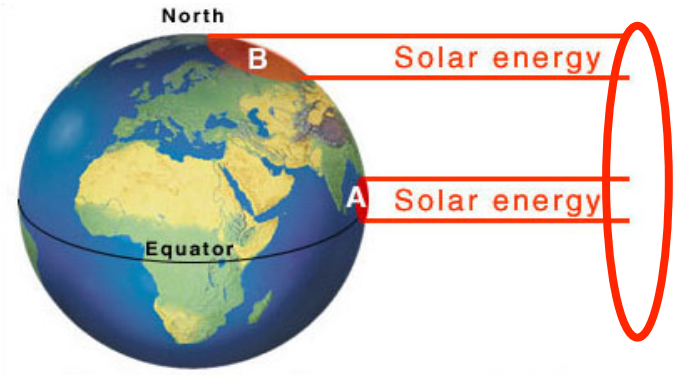
(Edwin A. Abbott)

Joseph Fourier, 1827: Mémoire sur les témperatures du globe terreste et des espaces planétaires

He said he hoped:

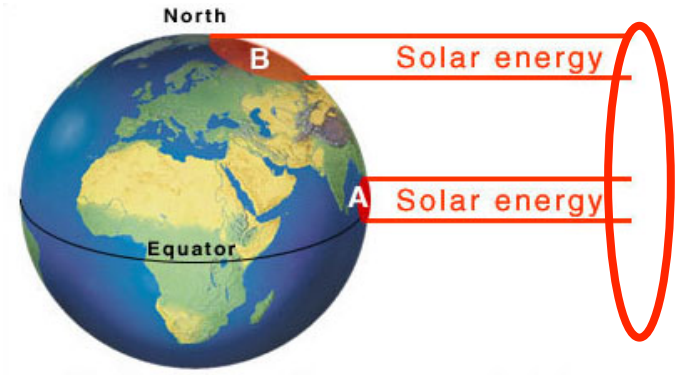
"geometers would not only go on in their researches into questions of calculus, but they would consider… the question of terrestrial temperature, one of the most important and most difficult of all of natural philosophy".

What determines the Earth's temperature?



- Incident solar flux $F = 1370\ \mathrm{W/m^2}$
- Cross-sectional area πa^2
- 30% reflected (albedo $\alpha = 0.3$)
- incoming power $= (1-\alpha)F\pi a^2$

What determines the Earth's temperature?



- Incident solar flux $F = 1370\ \mathrm{W/m^2}$
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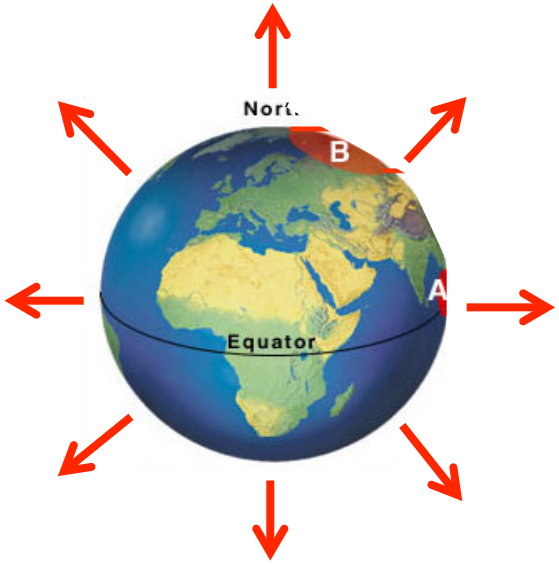
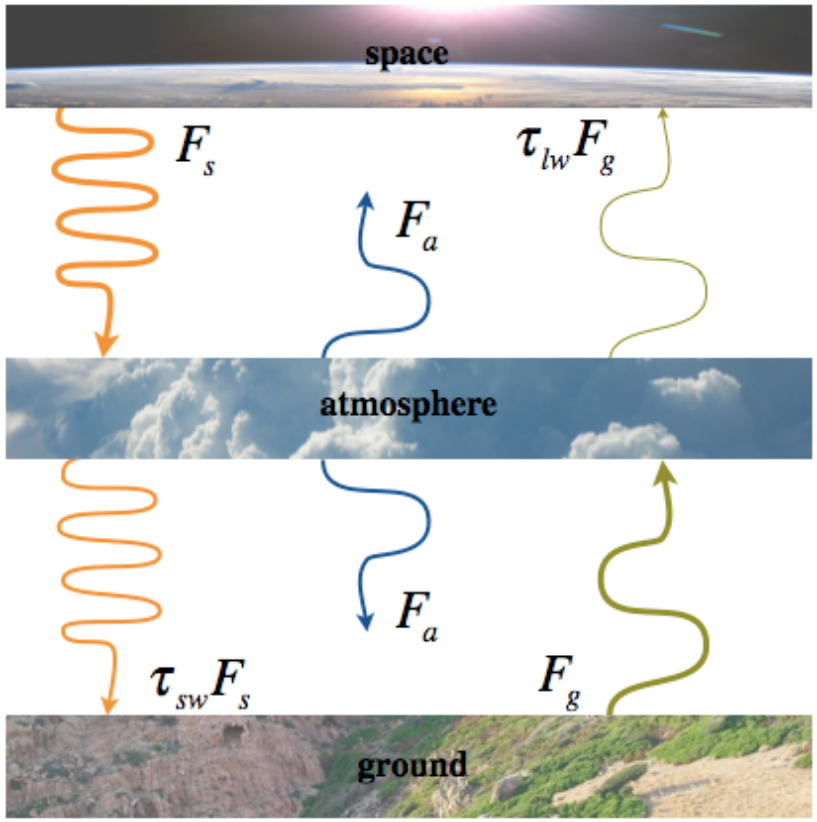


- Assume Earth is black body at T_{bb}
- Emits from surface following Stefan-Boltzmann law: outgoing power $= 4\pi a^2 \sigma T_{bb}^4$

incoming = outgoing

$$T_{bb} = 255\mathrm{K}$$

observed surface temperature ~288K

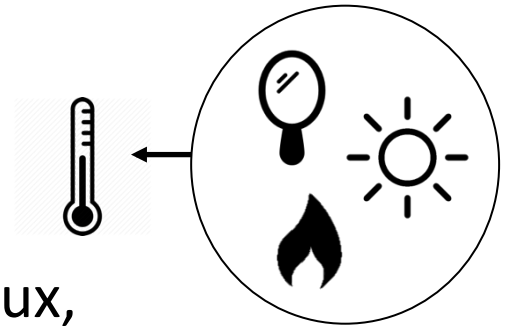


Atmosphere transmits larger fraction of shortwave ($\tau_{sw} = 0.9$) than longwave ($\tau_{lw} = 0.2$) radiation

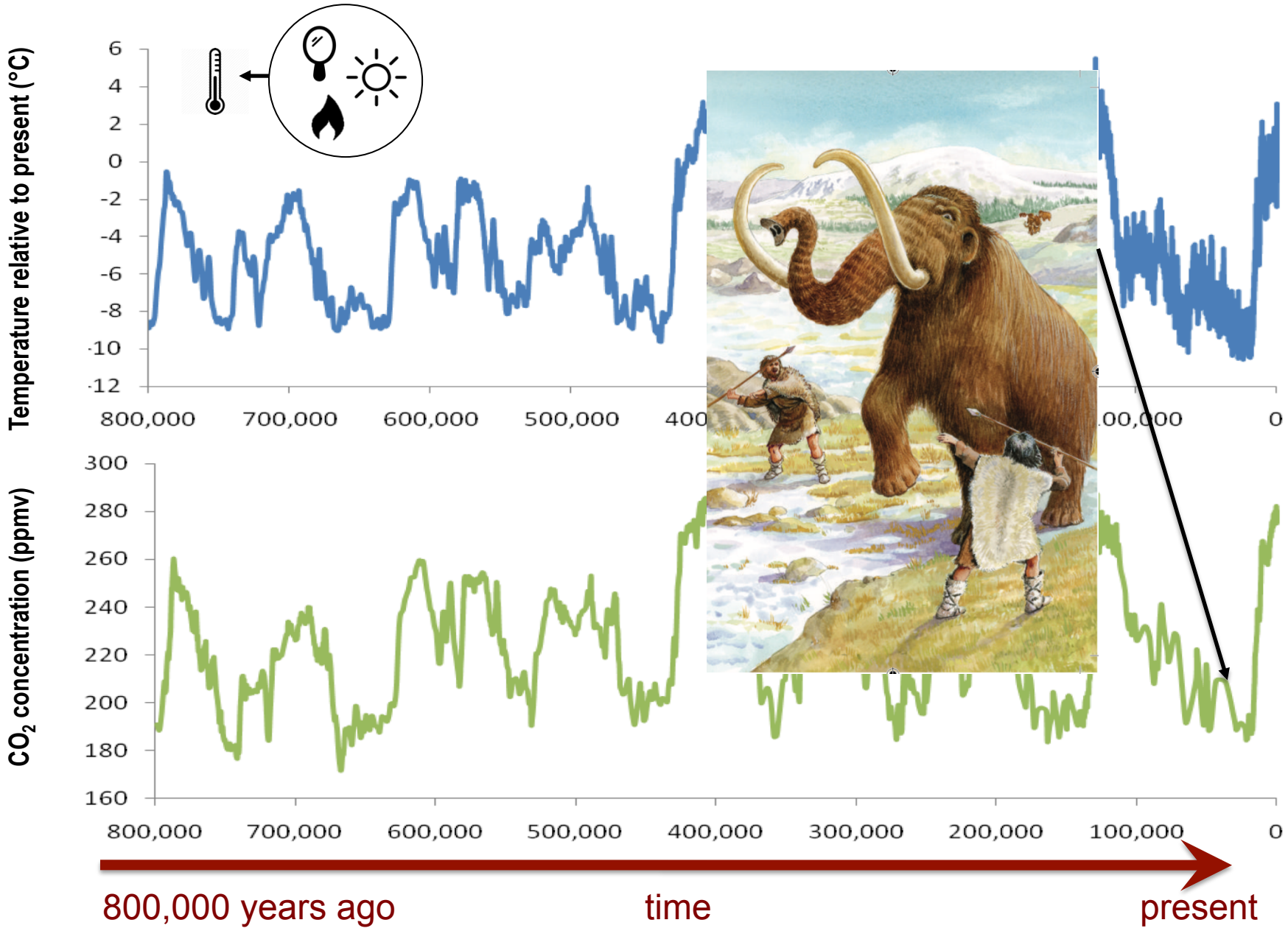
$$T_g = \left(\frac{(1-\alpha)(1+\tau_{sw})}{4\sigma(1+\tau_{lw})} F \right)^{1/4}$$

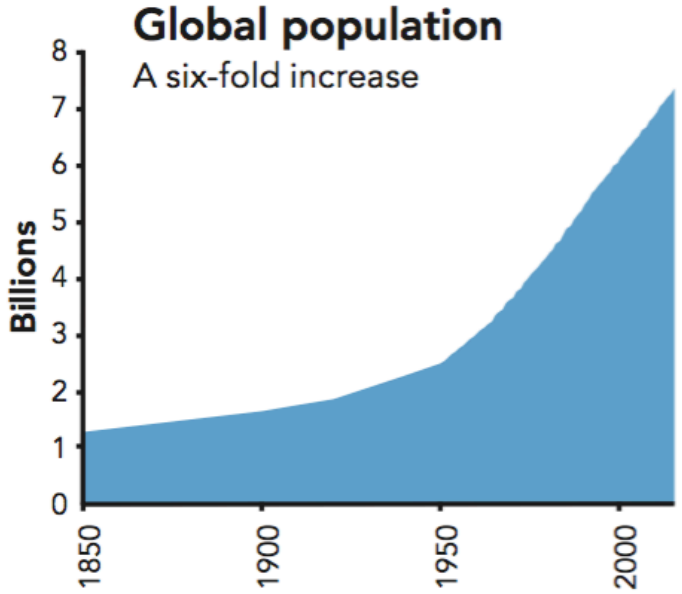
$$T_g = 286K$$

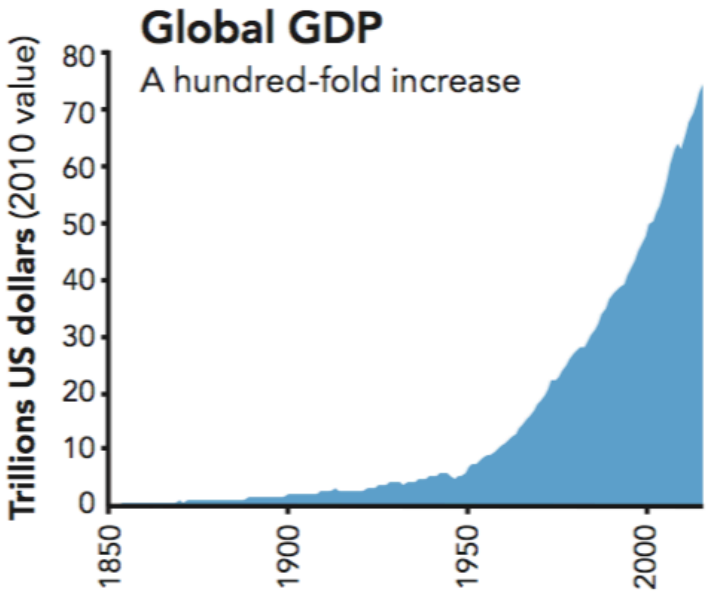
observed surface temperature ~288K

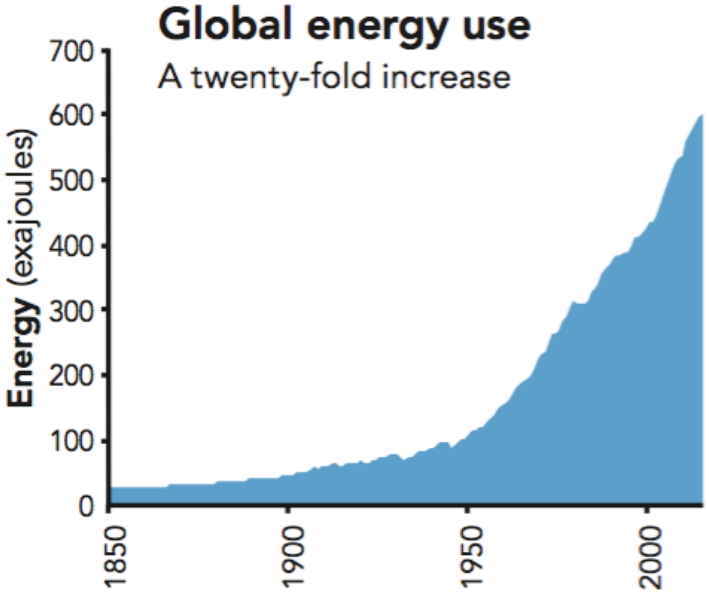


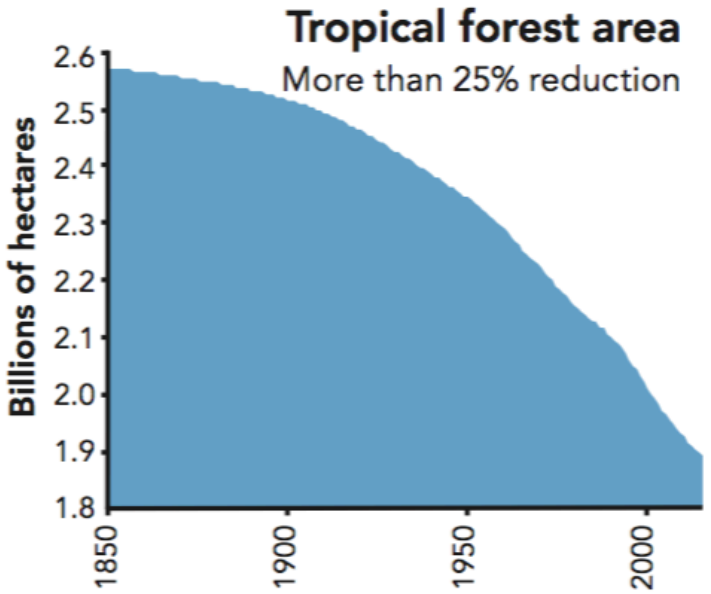
Temperature can change by changing solar flux, fraction of radiation transmitted or reflectivity.

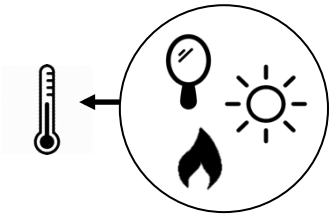

Temperature relative to present (°C)
6
4
2
0
-2
-4
-6
-8
-10
-12
800,000
700,000
600,000
500,000
400
00,000
0
CO_2 concentration (ppmv)
300
280
260
240
220
200
180
160
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
800,000 years ago
time
present


Global population
A six-fold increase
Billions
0
1
2
3
4
5
6
7
8
1850
1900
1950
2000

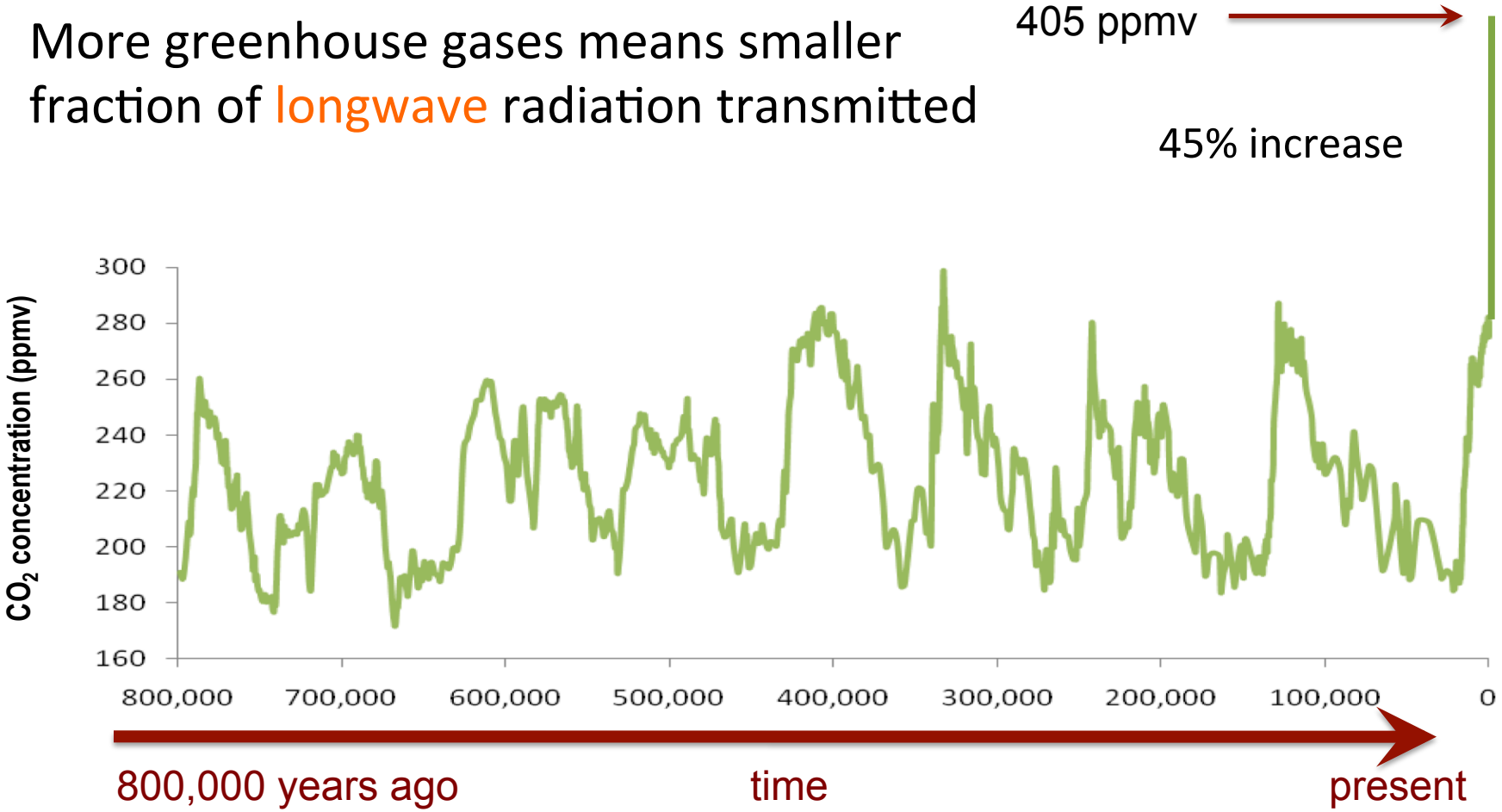

Global GDP
A hundred-fold increase
Trillions US dollars (2010 value)
0
10
20
30
40
50
60
70
80
1850
1900
1950
2000


Global energy use
A twenty-fold increase
Energy (exajoules)
0
100
200
300
400
500
600
700
1850
1900
1950
2000


Tropical forest area
More than 25% reduction
Billions of hectares
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
1850
1900
1950
2000



More greenhouse gases means smaller fraction of longwave radiation transmitted

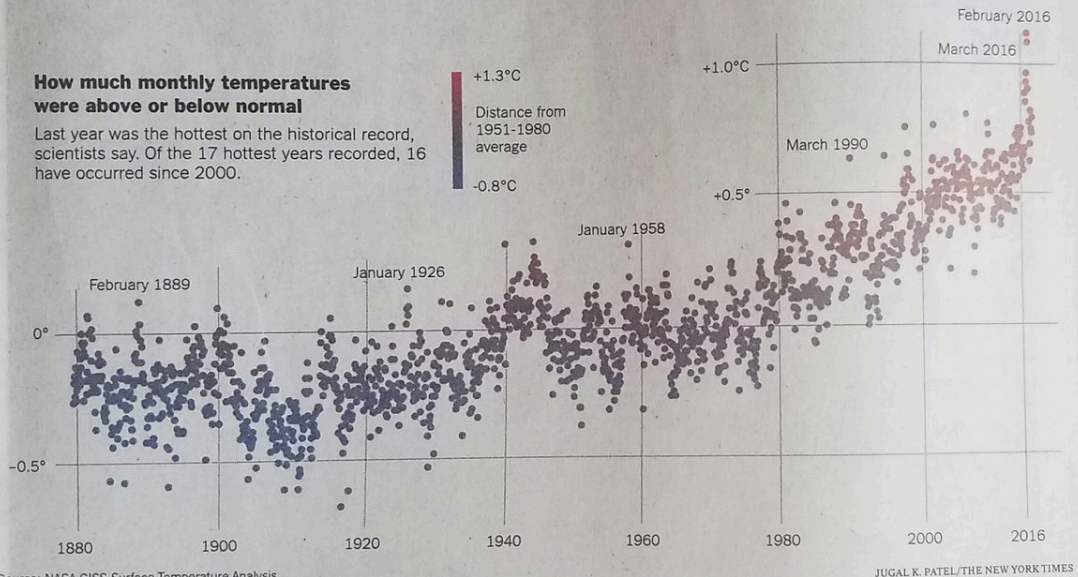


"All the News That's Fit to Print"

The New York Times

National Edition
Northern California: Cloudy. Rain. Mountain snow showers. Highs in 30s to 50s. Heavy rain and mountain snow tonight. Lows in teens to 40s. Weather map appears on Page A28.

VOL. CLXVI .... No. 57,482 THURSDAY, JANUARY 19, 2017 Printed in California $2.50



FOR THIRD YEAR, THE EARTH IN 2016 HIT RECORD HEAT

Threat to Society and Nature Is Rising — Scale of Shift Startles Scientists

By JUSTIN GILLIS

Marking another milestone for a changing planet, scientists reported on Wednesday that the Earth reached its highest temperature on record in 2016, trouncing a record set only a year earlier, which beat one set in 2014. It is the first time in the modern era of global warming data that temperatures have blown past the previous record three years in a row.

The findings come two days before the inauguration of an American president who has called global warming a Chinese plot and vowed to roll back his predecessor's efforts to cut emissions of heat-trapping gases.

In reality, the Earth is heating up, a point long beyond serious scientific dispute, but one becoming more evident as the records keep falling. Temperatures are heading toward levels that many experts believe will pose a profound threat to both the natural world and to human civilization.

In 2015 and 2016, the planetary warming was intensified by the weather pattern known as El Niño, in which the Pacific Ocean released a huge burst of energy and water vapor into the atmos-

gases.

"A single warm year is something of a curiosity," said Deke Arndt, chief of global climate monitoring for the National Oceanic and Atmospheric Administration. "It's really the trend, and the fact that we're punching at the ceiling every year now, that is the real indicator that we're undergoing big changes."

The heat extremes were especially pervasive in the Arctic, with temperatures in the fall running 20 to 30 degrees Fahrenheit above normal across large stretches of the Arctic Ocean. Sea ice in that region has been in precipitous decline for years, and Arctic communities are already wrestling with enormous problems, such as rapid coastal erosion, caused by the changing climate.

"What's going on in the Arctic is really very impressive; this year was ridiculously off the chart," said Gavin A. Schmidt, head of the Goddard Institute for Space Studies in Manhattan, a unit of the National Aeronautics and Space Administration that tracks global temperatures.

But Arctic people were hardly alone in feeling the heat. Drought

In Farewell, Obama Sets Red Lines That Would Pull Him Back

By MICHAEL D. SHEAR and PETER BAKER

WASHINGTON — When President Obama arrived in office eight years ago, the departing President George W. Bush essentially withdrew from public life, declaring that his successor "deserves my silence." It was an approach that Mr. Obama greatly appreciated but does not intend to follow.

At the final news conference of his presidency, Mr. Obama made clear on Wednesday that he finds

that normal functioning of politics and certain issues or certain moments where I think our core values may be at stake," Mr. Obama told reporters in the White House briefing room.

Mr. Obama continued: "I put in that category if I saw systematic discrimination being ratified in some fashion. I put in that category explicit or functional obstacles to people being able to vote, to exercise their franchise. I'd put in that category institutional efforts

Pledge to Re-enter Fray When 'Core Values May Be at Stake'

country."

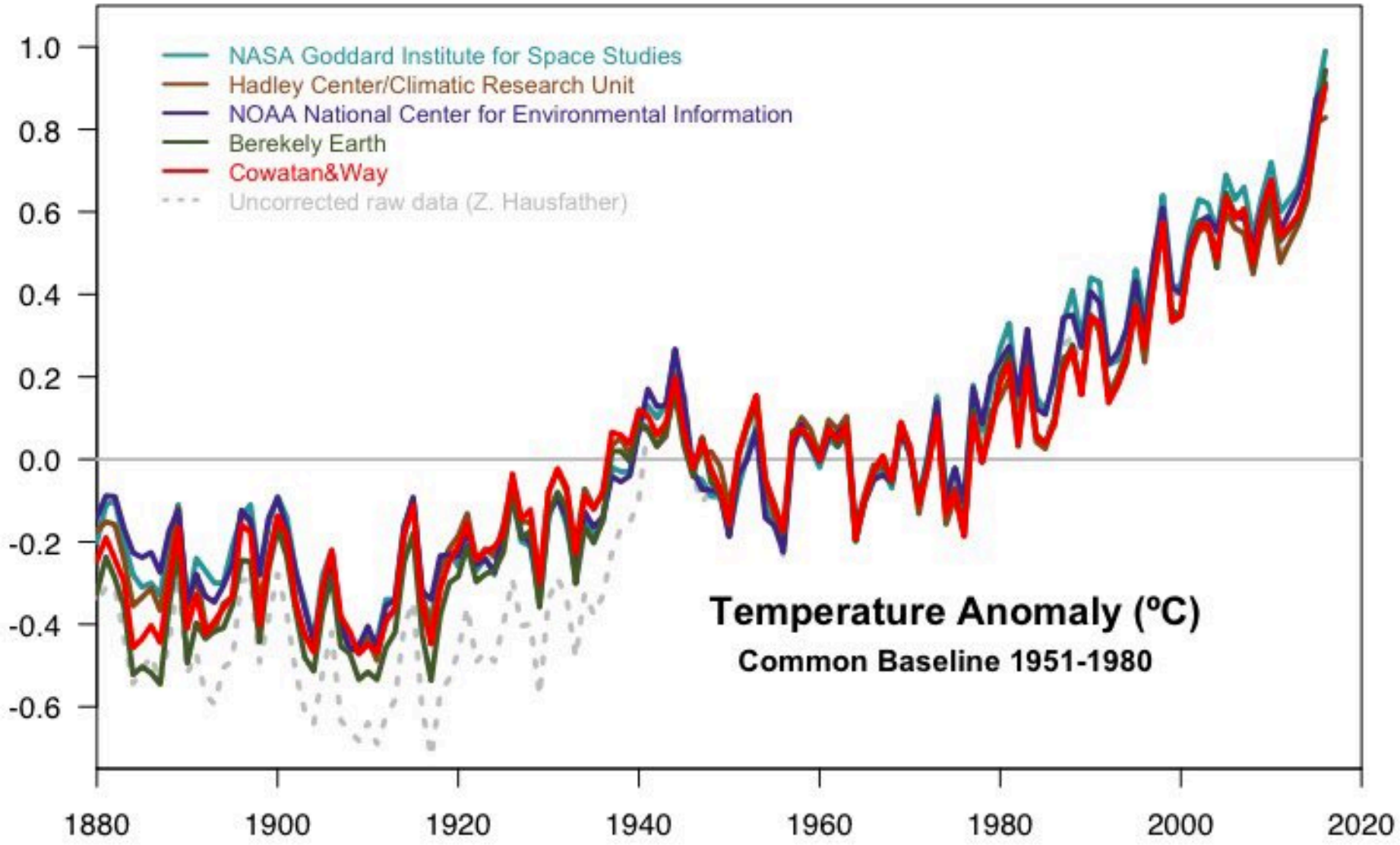
All of his red lines seemed to refer to positions taken in the past by Mr. Trump, foreshadowing the possibility of a periodic clash of ideas over the next four years be-

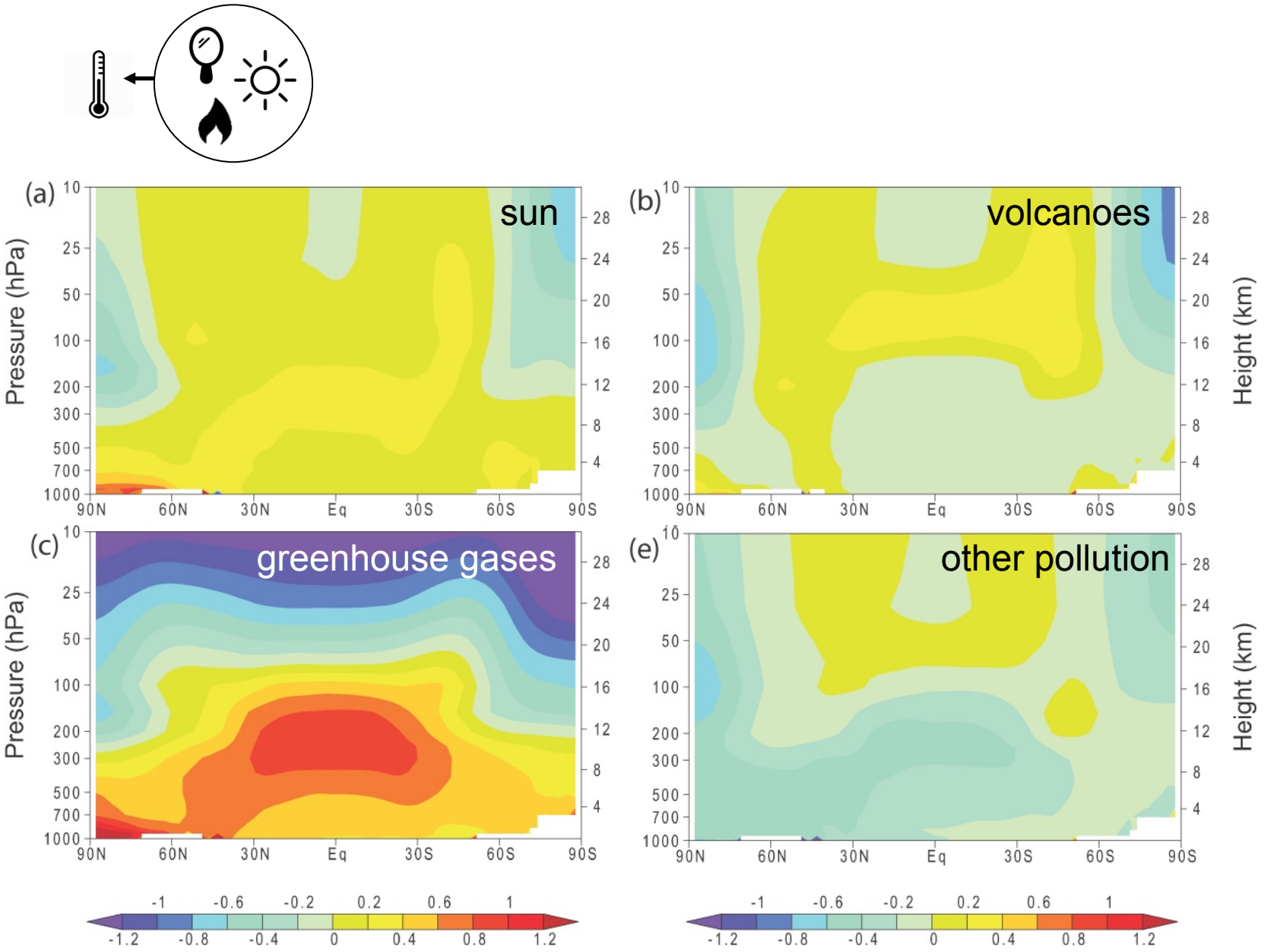
office since Woodrow Wilson.

Mr. Obama did say he was looking forward to some quiet time and does not plan to stay involved in the hurly-burly of politics. He has told advisers and friends that he wants to be careful not to become such a regular public critic of Mr. Trump that he alienates the mercurial new president.

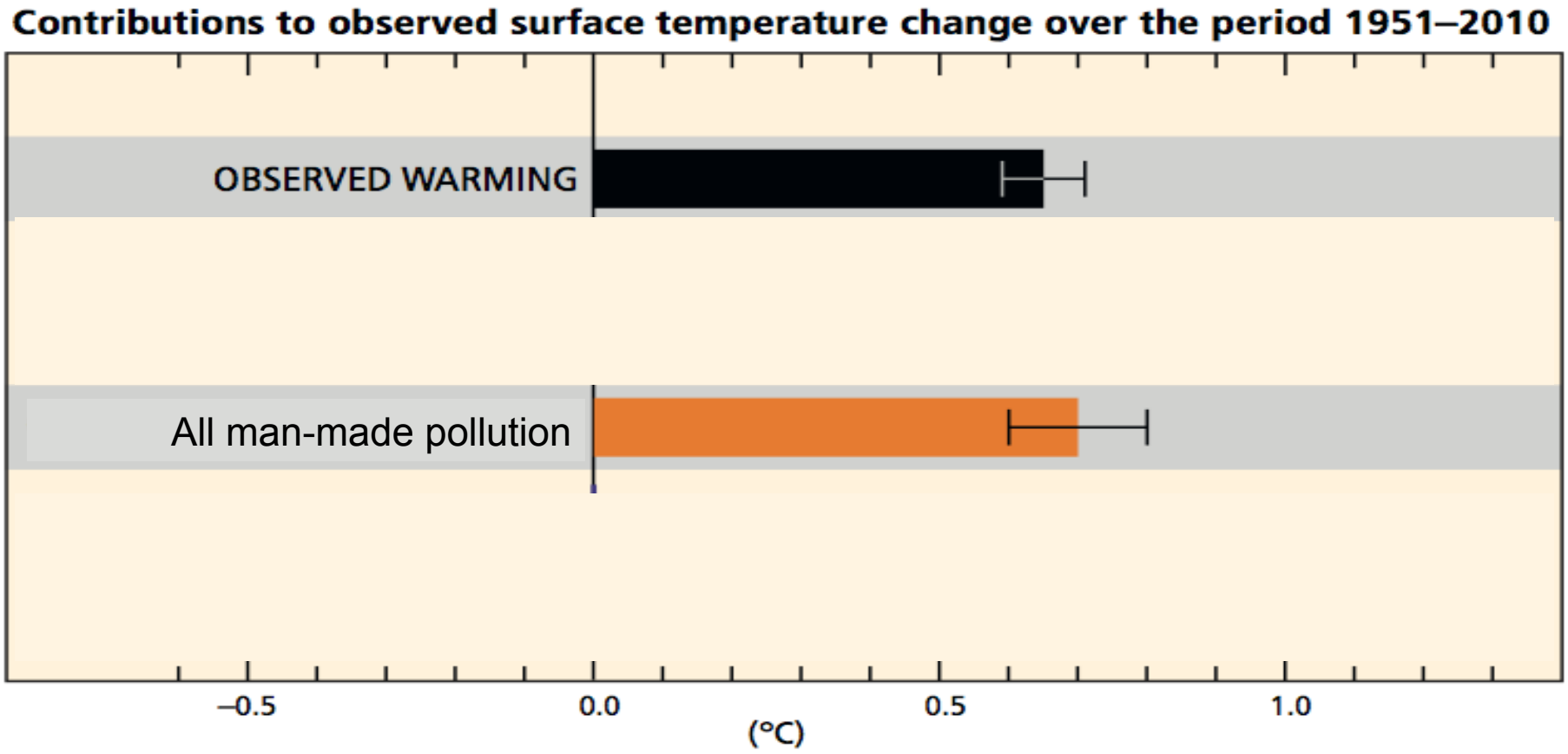
Since the election, the departing president has tried to forge a relationship of sorts with his successor and hopes to keep lines of

Mary Ellen Thomas, Nunavut Research Institute: *“It is as if a friend that we could trust is suddenly acting strangely”*


NASA Goddard Institute for Space Studies
Hadley Center/Climatic Research Unit
NOAA National Center for Environmental Information
Berekely Earth
Cowatan&Way
Uncorrected raw data (Z. Hausfather)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1880
1900
1920
1940
1960
1980
2000
2020
Temperature Anomaly (ºC)
Common Baseline 1951-1980

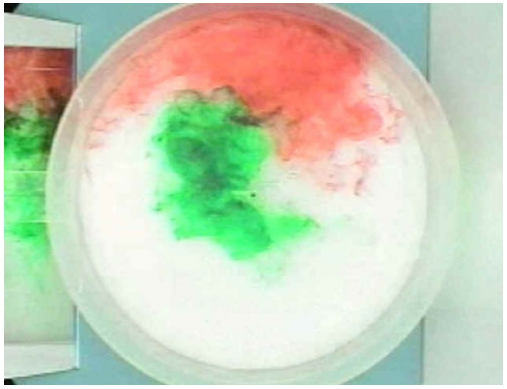


IPCC AR4 WG1 9.1



IPCC AR5 SYR SPM.3

Fluid on a rotating sphere



non-rotating

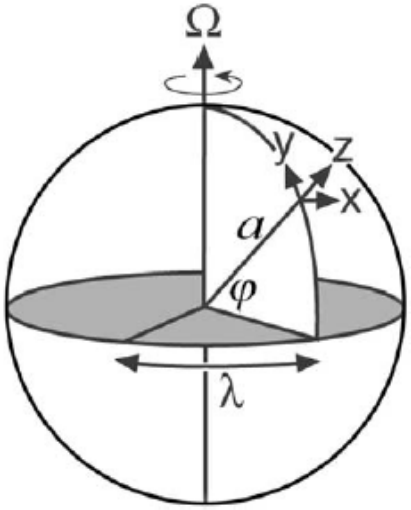
rotating

Equations of motion

Newton's 2nd law: $$\frac{D\mathbf{u}}{Dt} + \frac{1}{\rho}\nabla p + g\hat{\mathbf{z}} = \mathcal{F}$$

Rotating frame: $$\mathbf{u}_{inertial} = \mathbf{u}_{rotating} + \boldsymbol{\Omega} \times \mathbf{r}$$

Sphere: $$\boldsymbol{\Omega} = (0, \Omega\cos\varphi, \Omega\sin\varphi) \quad f = 2\Omega\sin\varphi$$



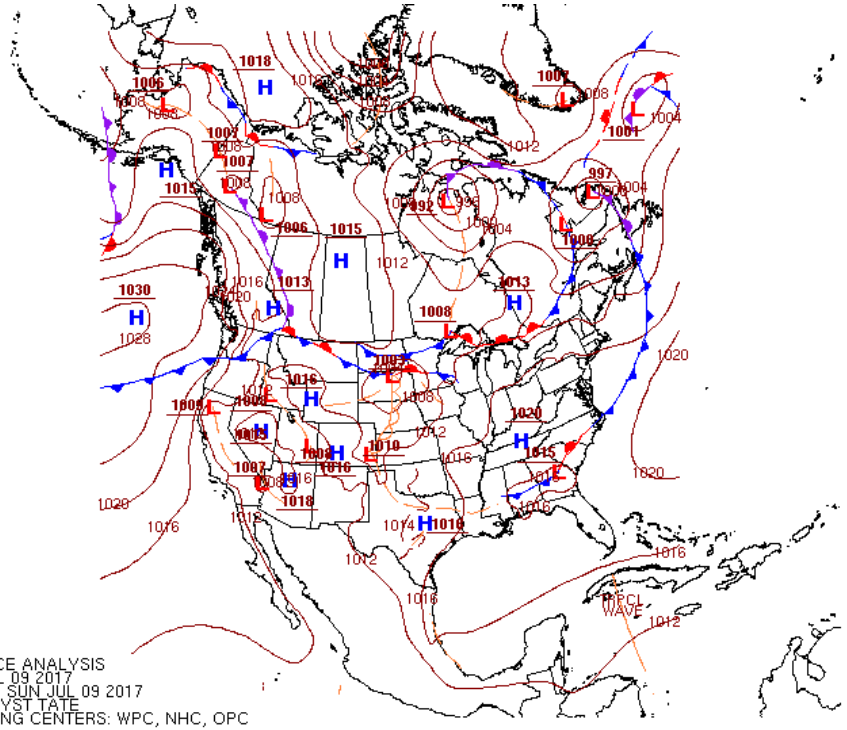
Equations in weather and climate models

$$\frac{Du}{Dt} + \frac{1}{\rho}\frac{\partial p}{\partial x} - fv = \mathcal{F}_x$$

$$\frac{Dv}{Dt} + \frac{1}{\rho}\frac{\partial p}{\partial y} + fu = \mathcal{F}_y$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z} + g = 0$$

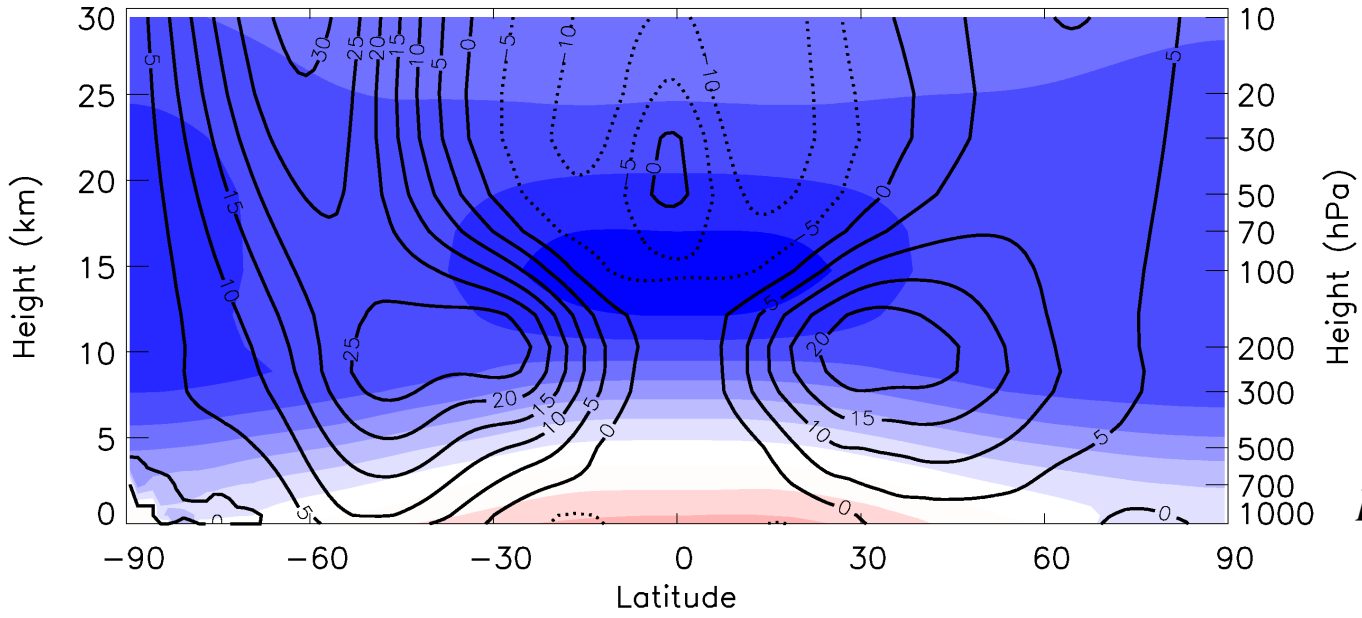
"Geostrophic balance"



Atmosphere is an ideal gas: $\frac{p}{\rho} = RT$

$$\frac{\partial u}{\partial p} = \frac{R}{fp}\frac{\partial T}{\partial y}$$

"Thermal wind"



$p = p_0 e^{-gz/RT}$

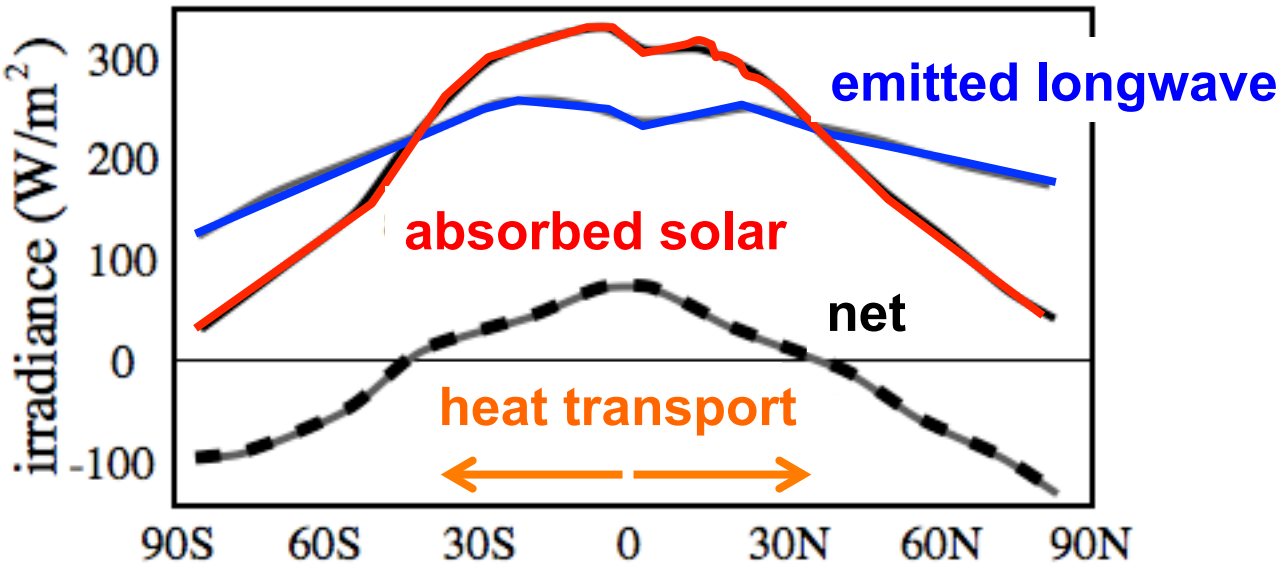
$$u = \bar{u} + u'$$
$$v = \bar{v} + v'$$

mean flow + “eddies”

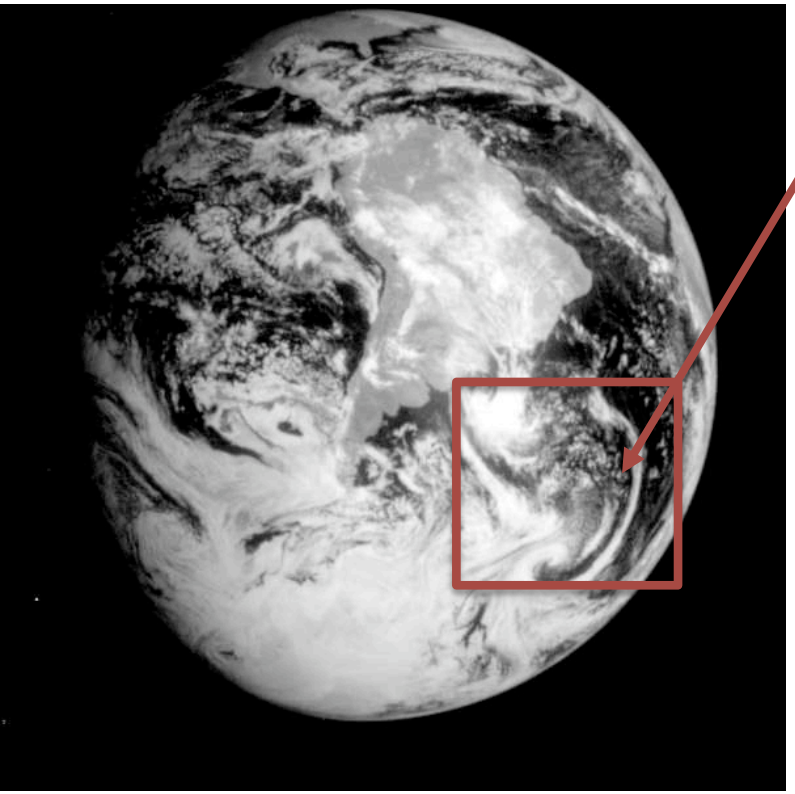
$$\frac{\partial \bar{u}}{\partial t} - f\bar{v} = -\frac{\partial}{\partial y}\overline{u'v'} + \overline{\mathcal{F}_x}$$

eddy fluxes can drive mean flows

observed annual mean radiation



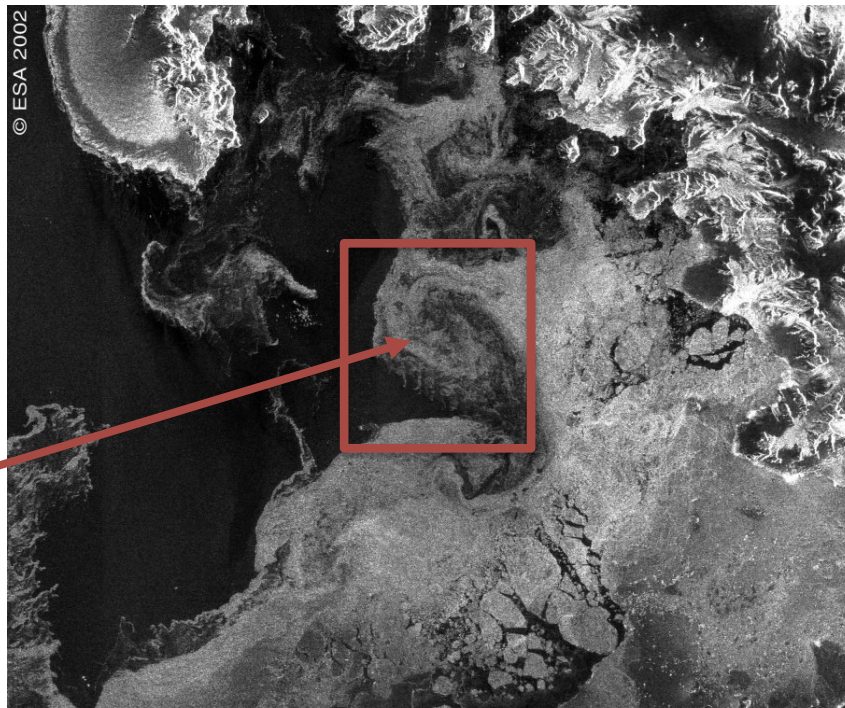
Eddies in the atmosphere and ocean



Eddies in atmosphere of size ~1000 km

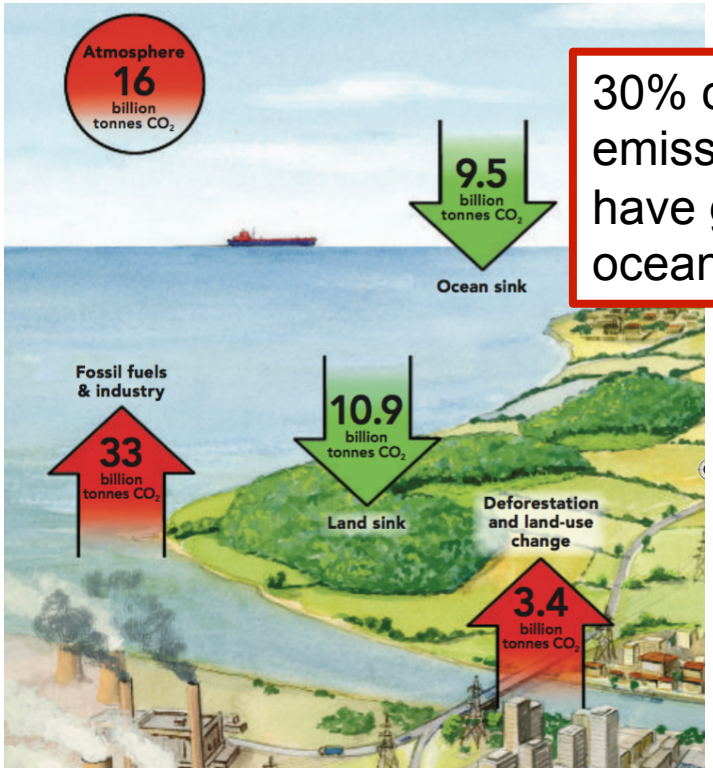
This near-infrared photograph of the Earth was taken by the Galileo spacecraft

ENVISAT/ASAR image shows the marginal ice zone outside the ice shelf at Marguerite Bay on the west side of the Antarctic Peninsula.

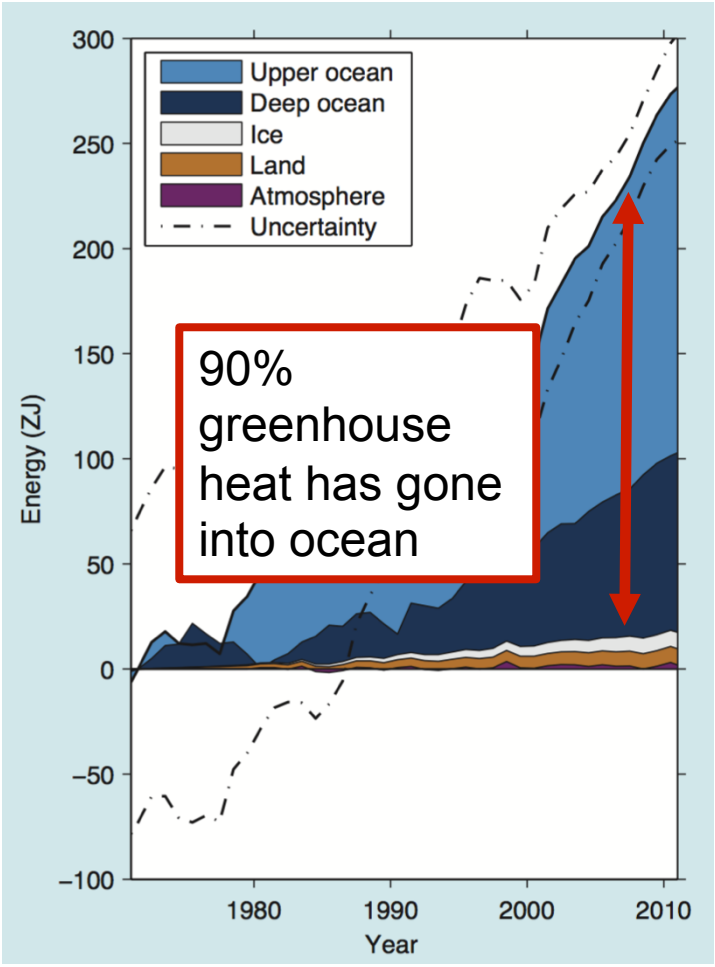


Eddies in ocean size ~25 km

(40 times smaller than atmosphere & usually parameterized in climate models)

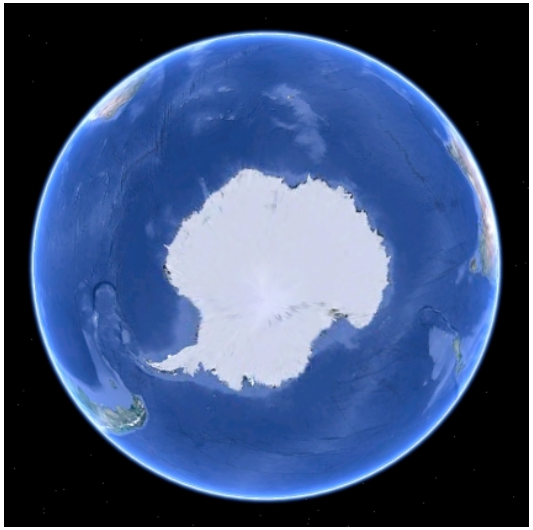


30% carbon emissions have gone into ocean

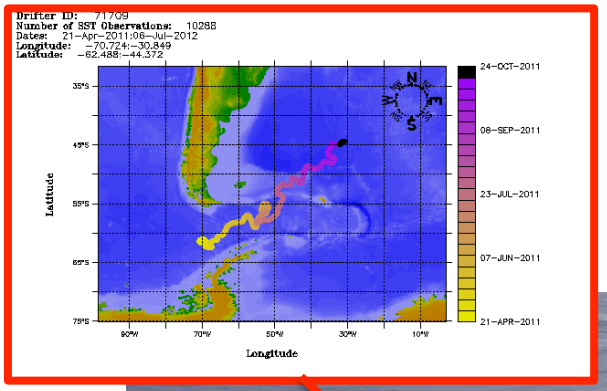


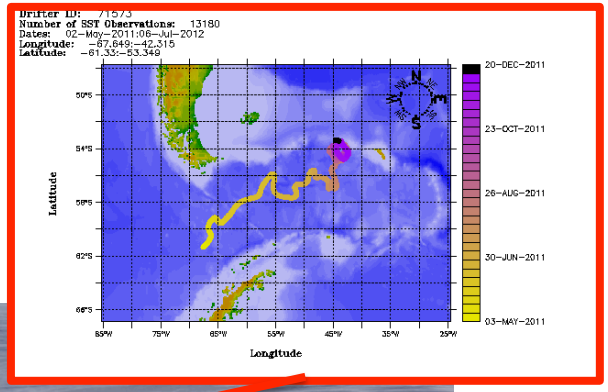
90% greenhouse heat has gone into ocean

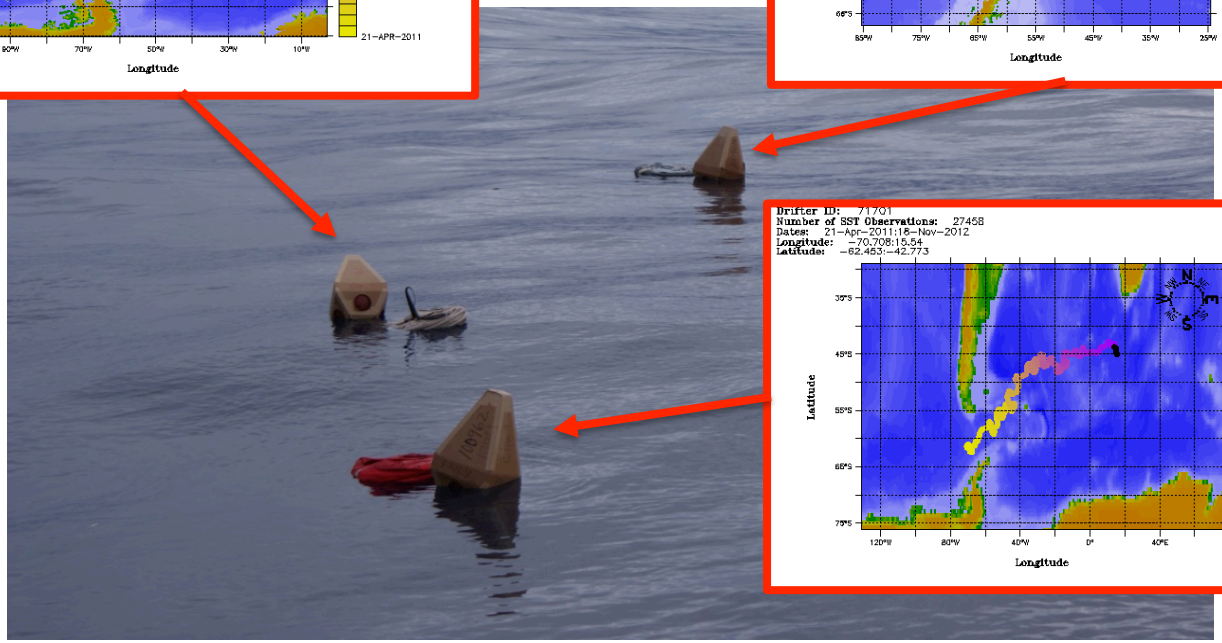
WG1 Box 3.1

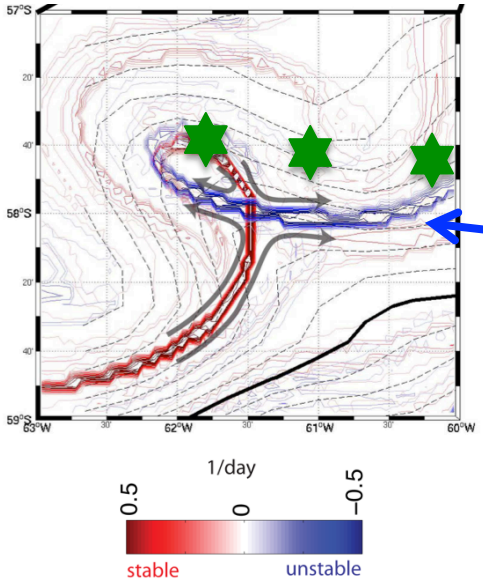


Southern Ocean estimated to be responsible for about 40% of ocean carbon uptake and 75% of ocean heat uptake. Why? Eddies.



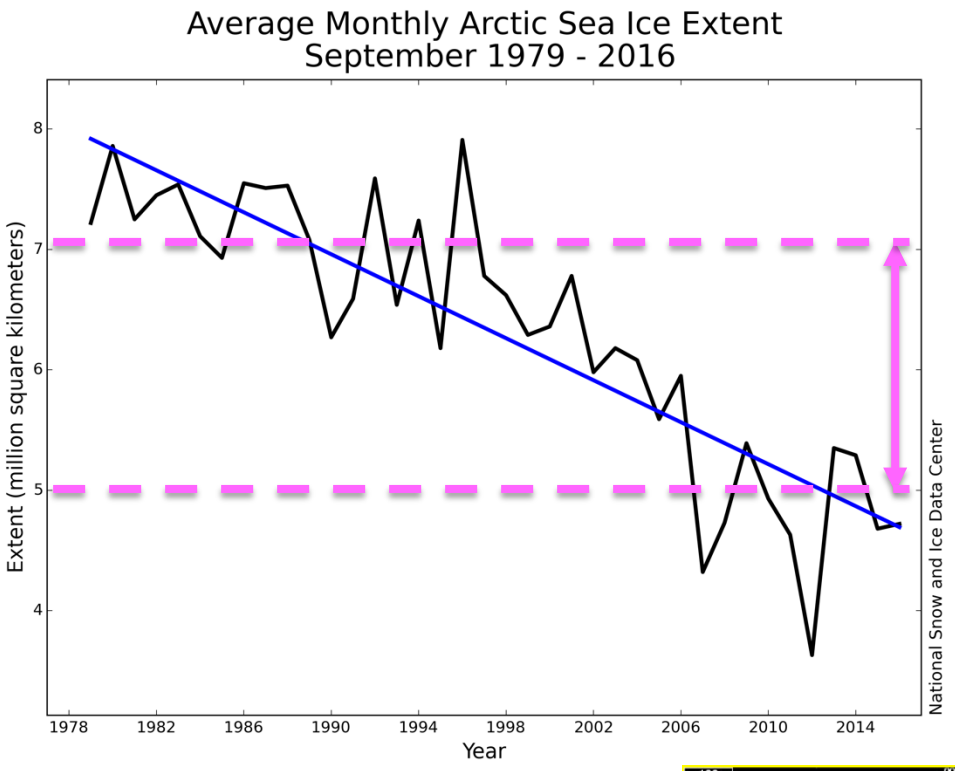




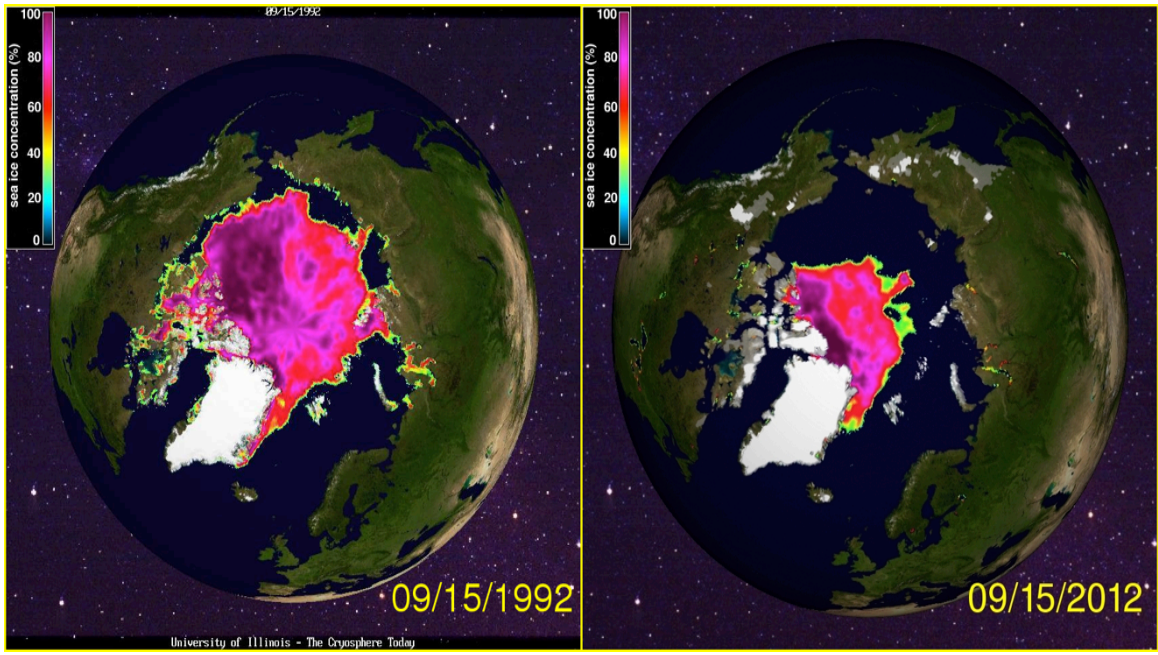


Ridges in backward-time finite-size Lyapunov exponents

Release floats ≤10 km apart along altimetry-estimated unstable manifold, **close to hyperbolic point**



2m km^2 = California, New Mexico, Arizona, Nevada & Texas



Climate Change

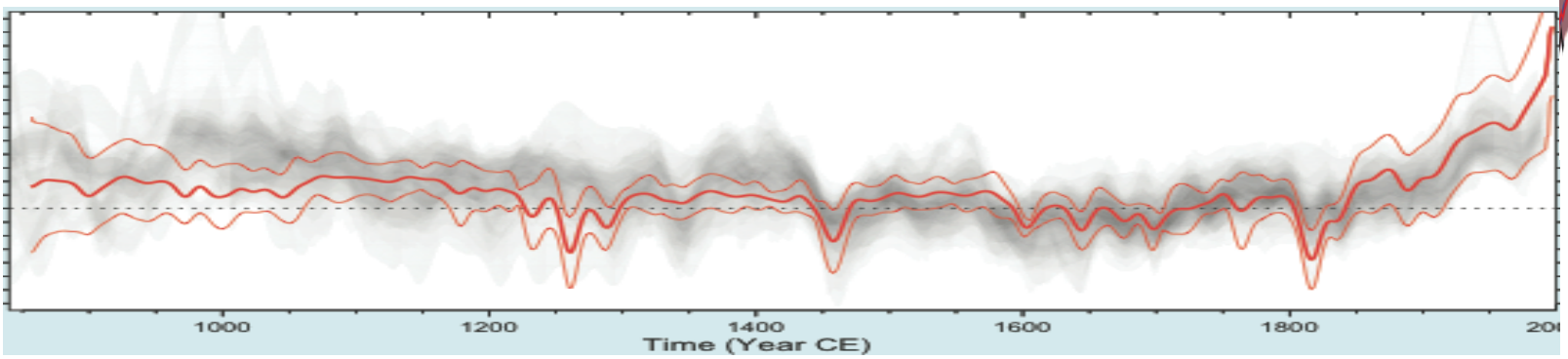
HRH The Prince of Wales
Tony Juniper
Emily Shuckburgh

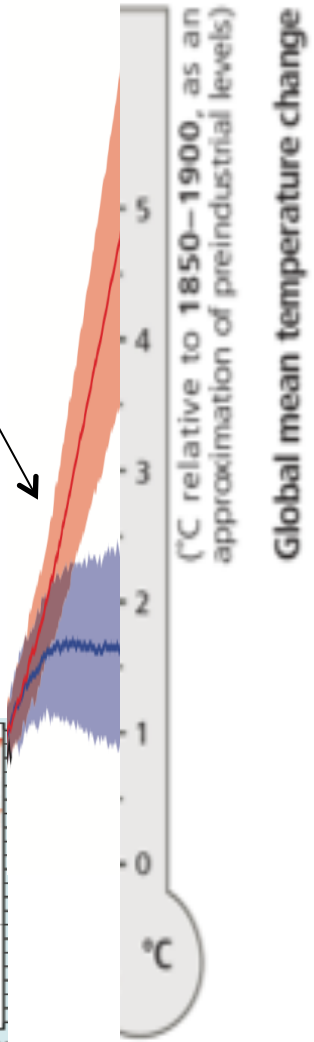
A Ladybird Expert Book

Projected temperature change to 2100 under two possible futures:

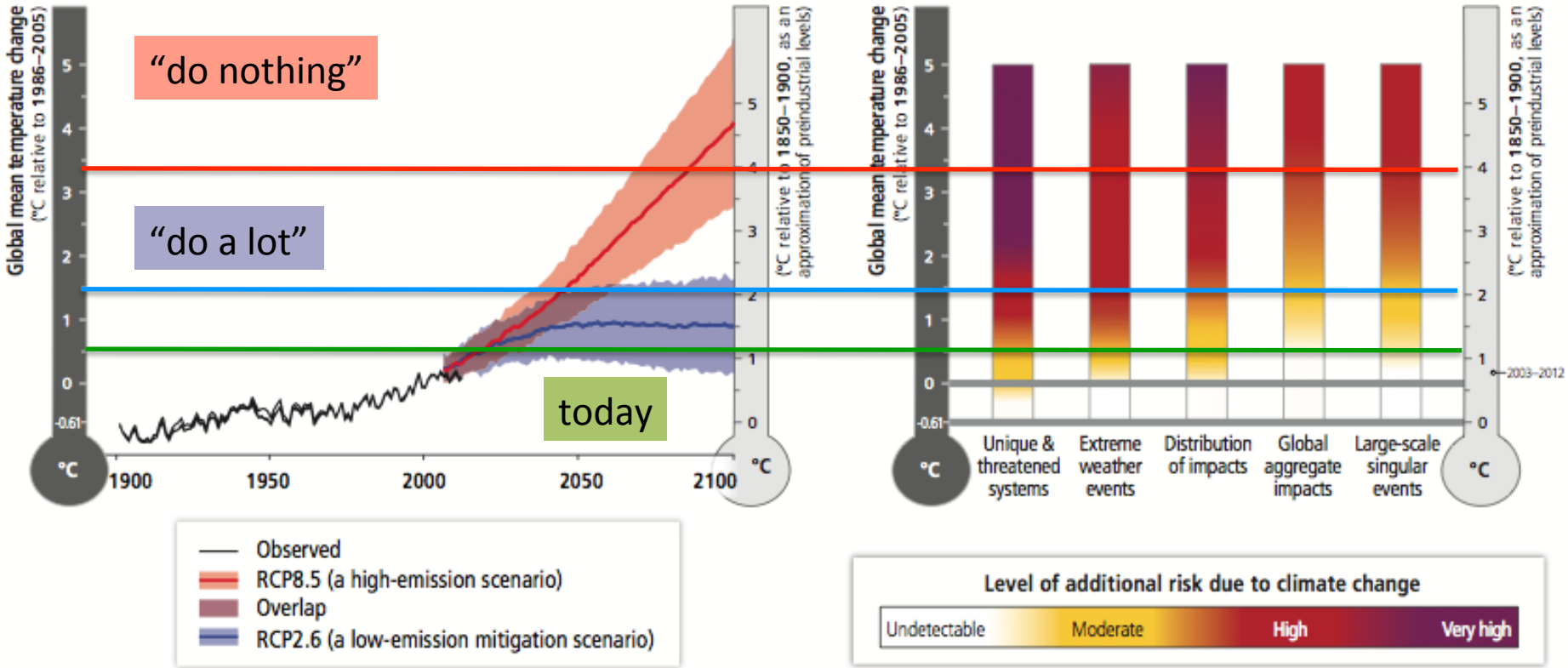
"do nothing"

"do a lot"

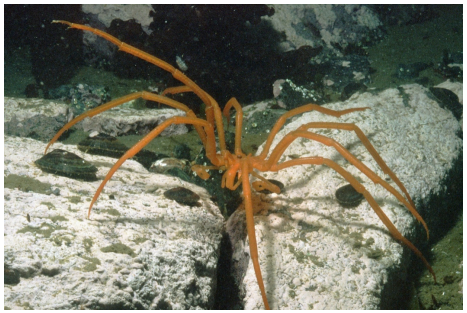




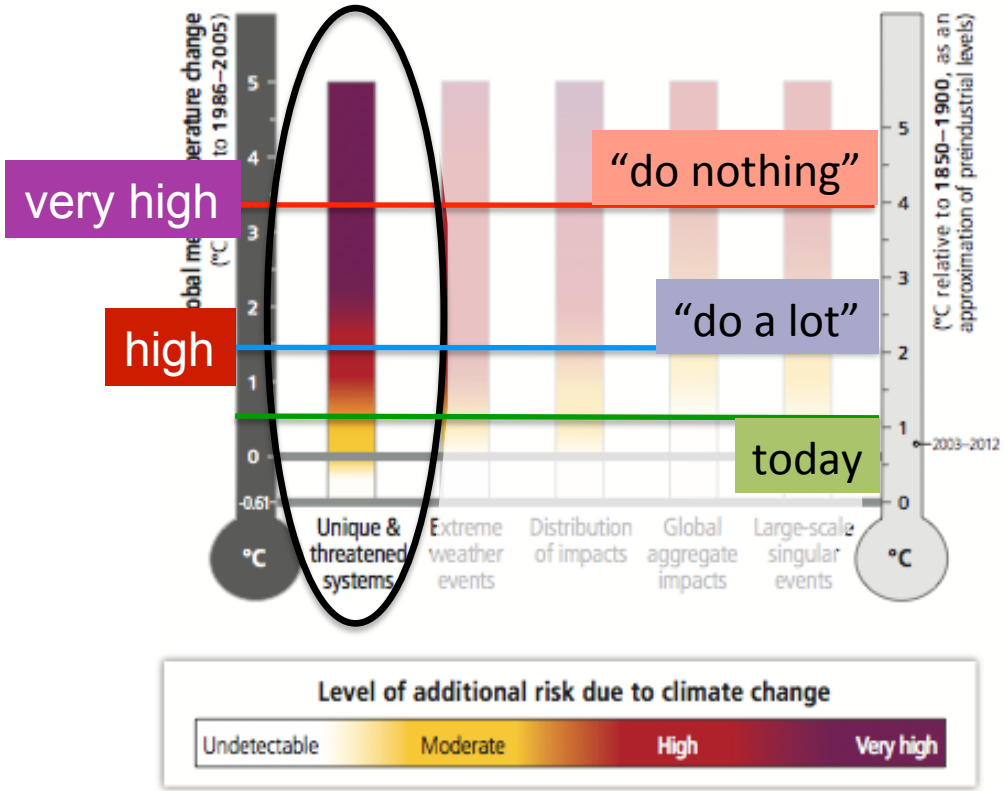
Risks of future climate change



WG2 Box SPM.1

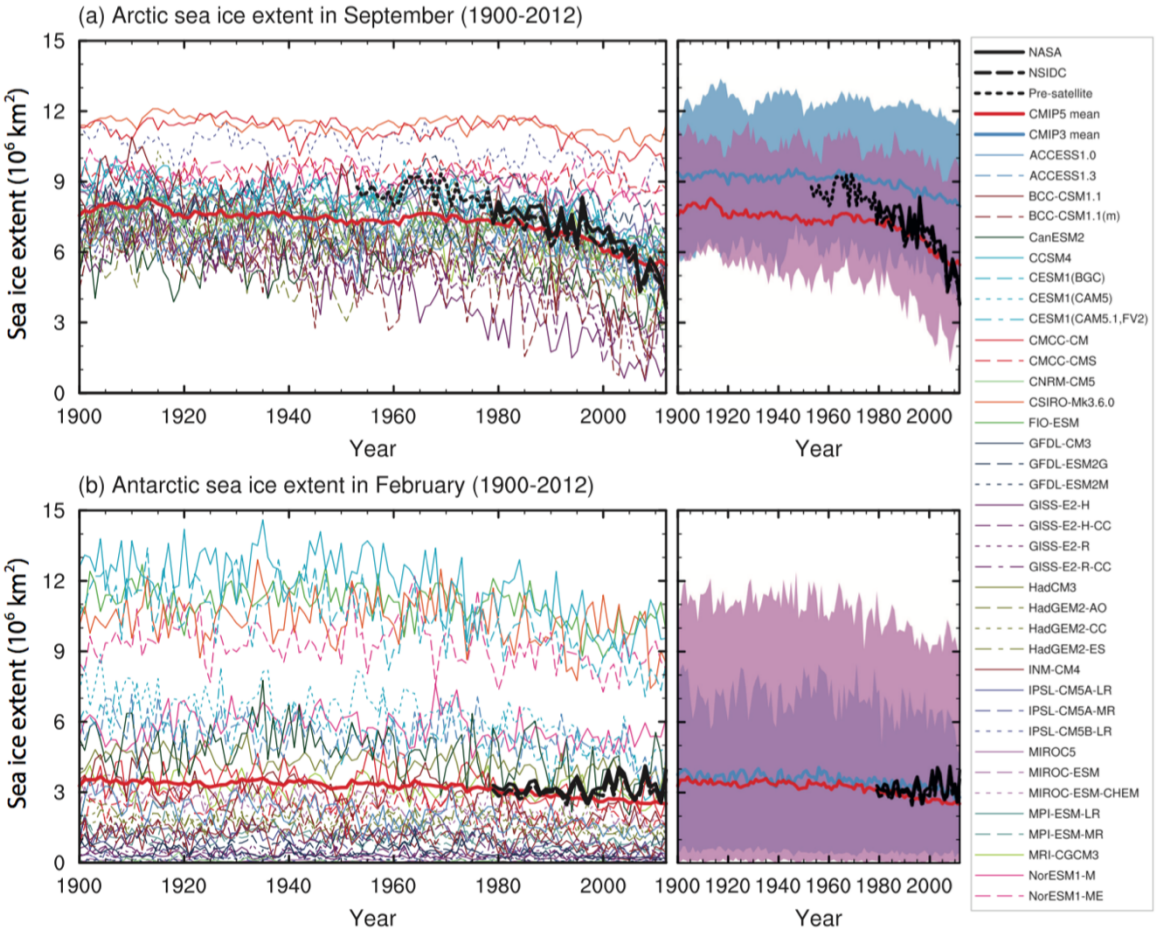


Unique & threatened systems



WG2 Box SPM.1

Predicting future sea ice



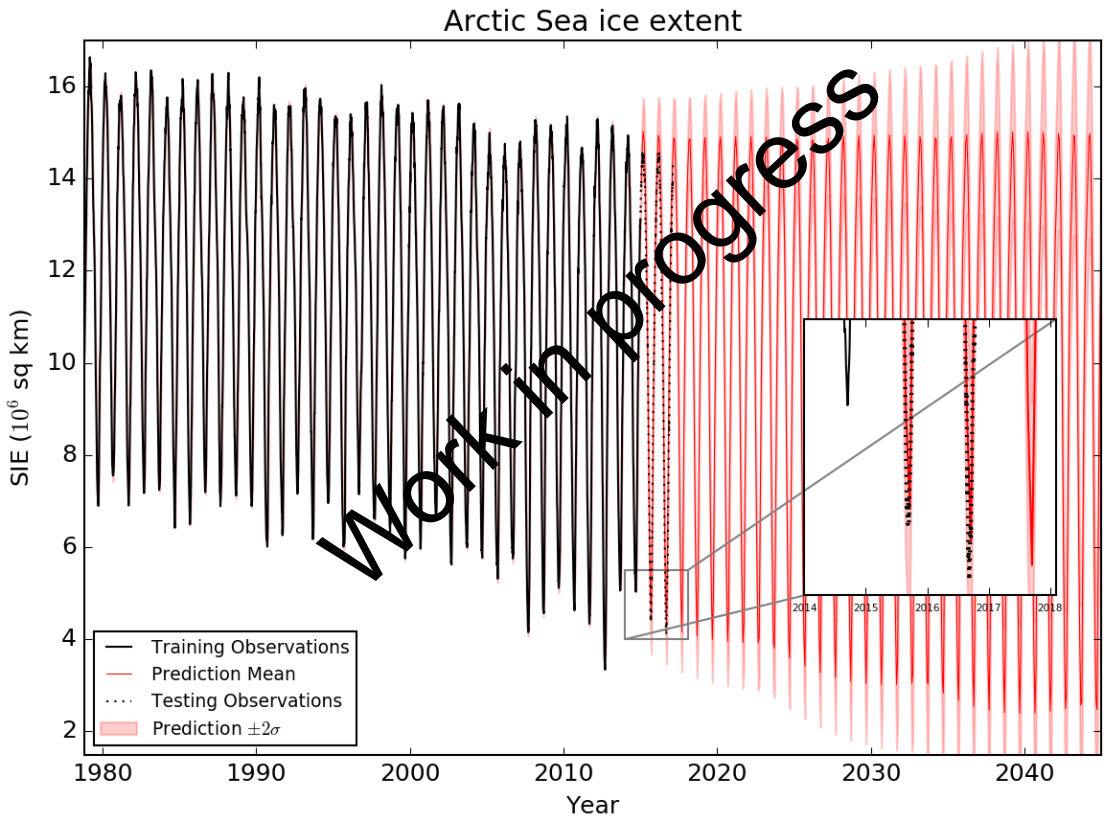
Depending on its morphology & microstructure, ice may behave as an elastic, brittle, viscoelastic or quasi-liquid material.

Sea-ice consists of solid fresh-water ice, liquid salty brine, gas inclusion & possibly some other components, which makes it difficult to describe.

Isaac Newton Institute for Mathematical Sciences

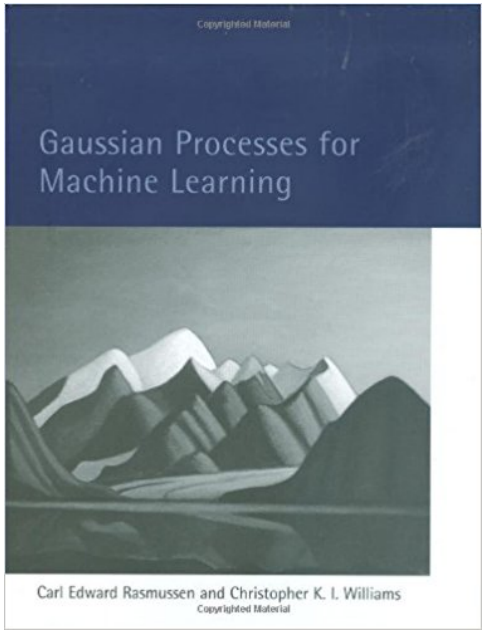
Mathematics of sea ice phenomena

Machine Learning tools (Gaussian Processes) using observational data



with Scott Hosking

Include: robust information from climate models for future (e.g. global average temperature), information on long-term variability from other datasets (e.g. North Atlantic)



C. E. Rasmussen & C. K. I. Williams, Gaussian Processes for Machine Learning, the MIT Press, 2006, ISBN 026218253X. www.GaussianProcess.org/gpml

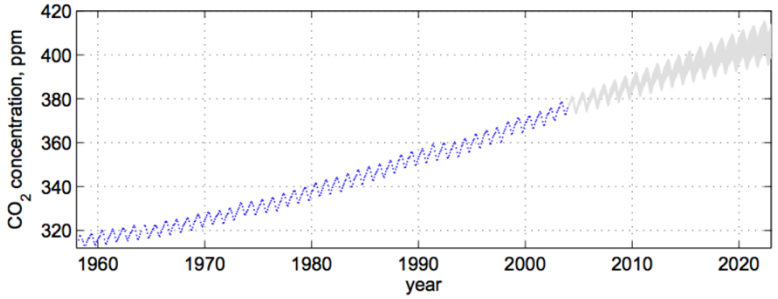
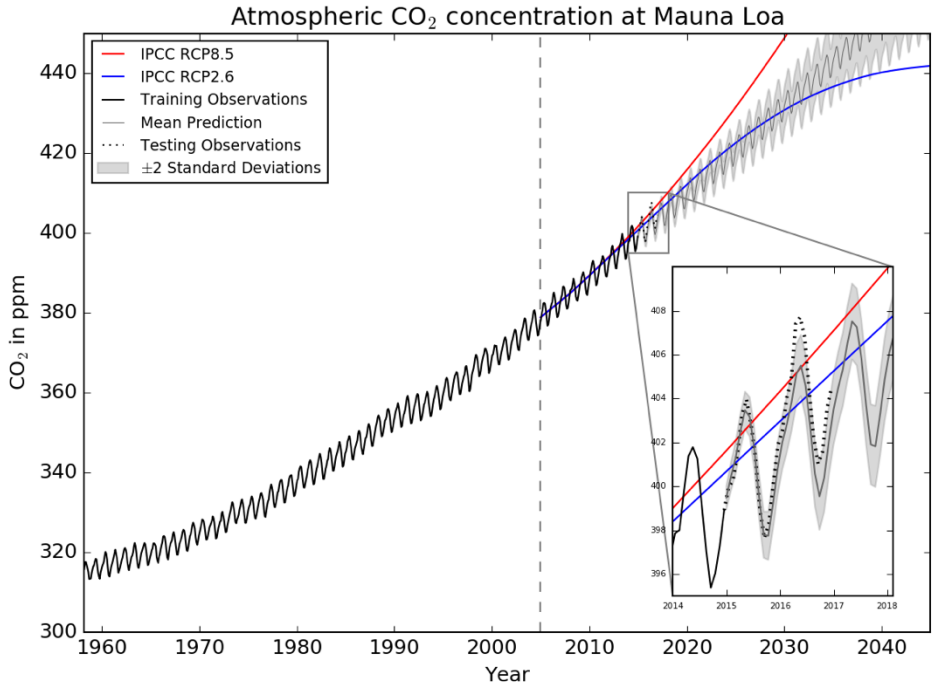
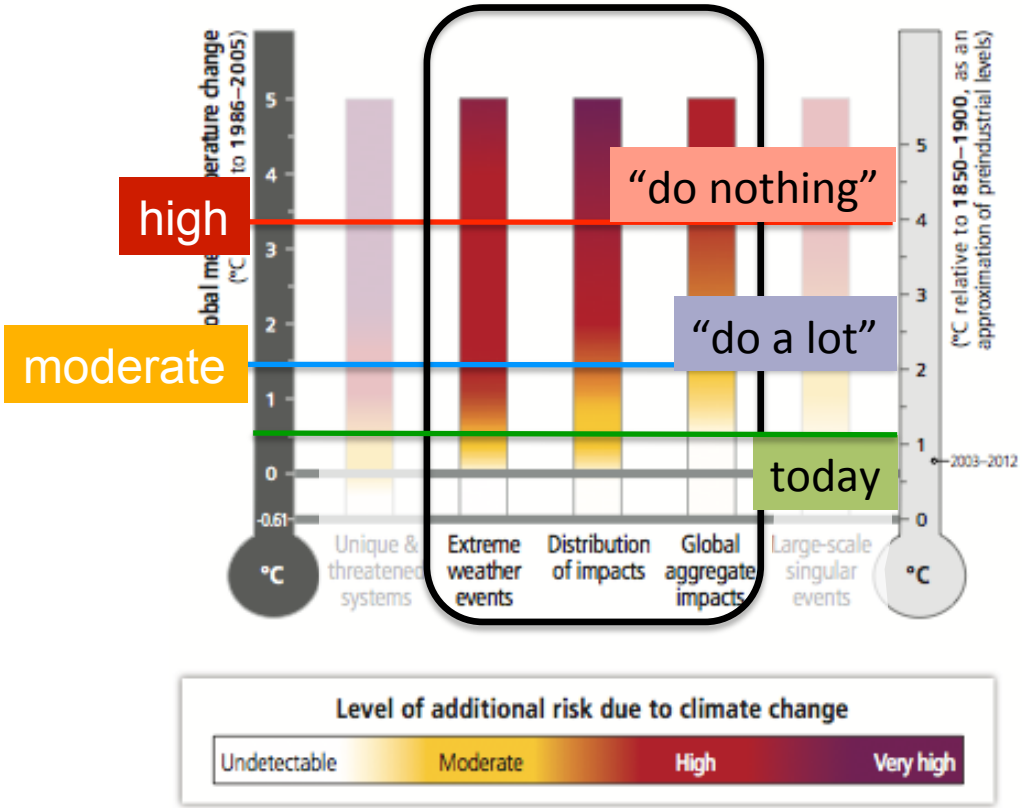


Figure 5.6: The 545 observations of monthly averages of the atmospheric concentration of CO_2 made between 1958 and the end of 2003, together with 95% predictive confidence region for a Gaussian process regression model, 20 years into the future. Rising trend and seasonal variations are clearly visible. Note also that the confidence interval gets wider the further the predictions are extrapolated.



Include information about the future

Extreme weather, distribution & global aggregate of impacts



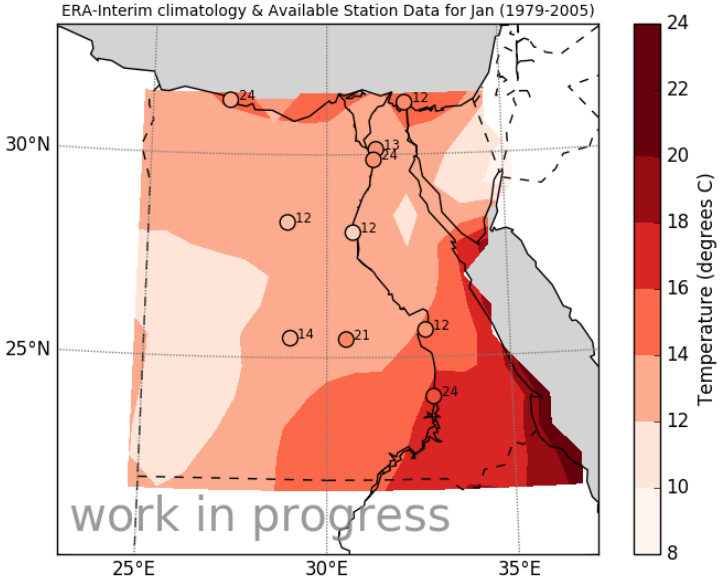
WG2 Box SPM.1

Egyptian heatwave, Aug 2015: more than 90 deaths

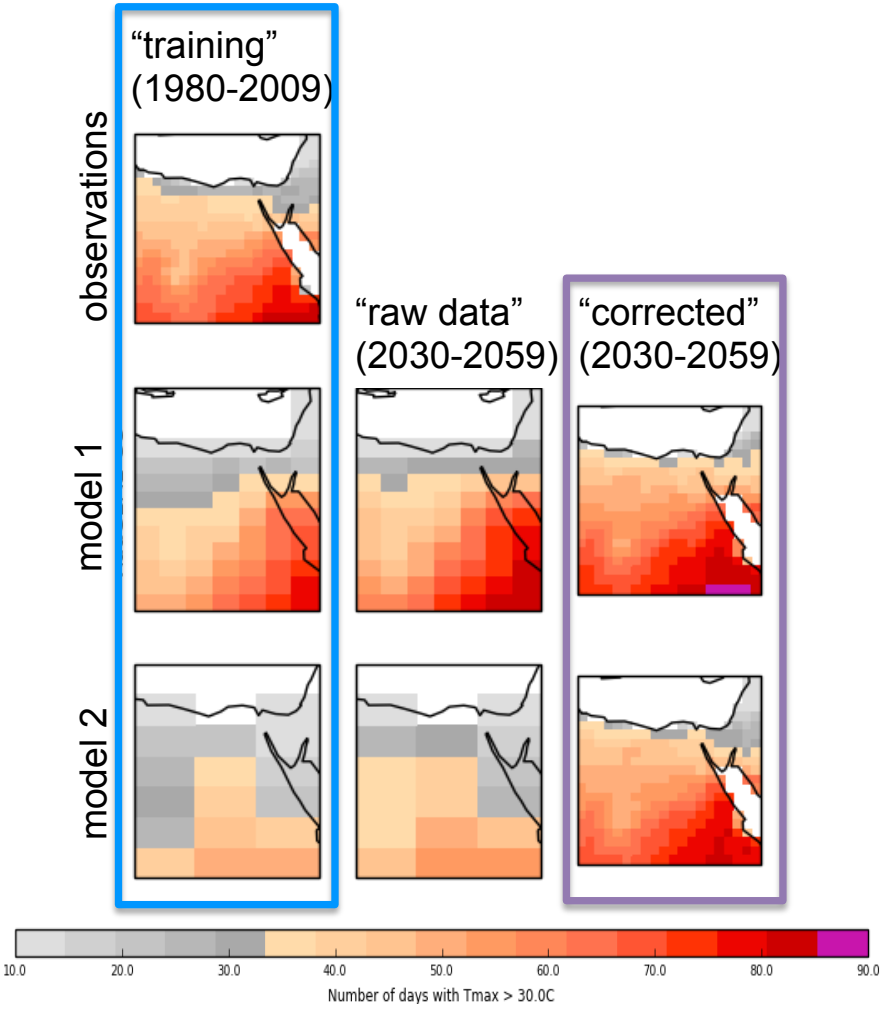
70% more likely due to climate change

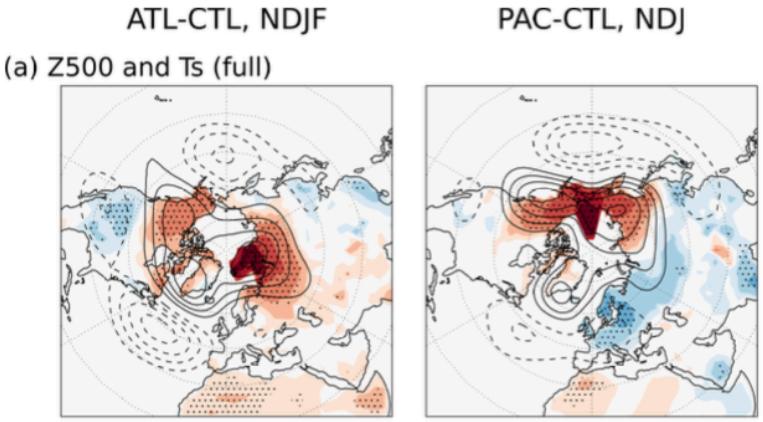
Mitchell, 2016

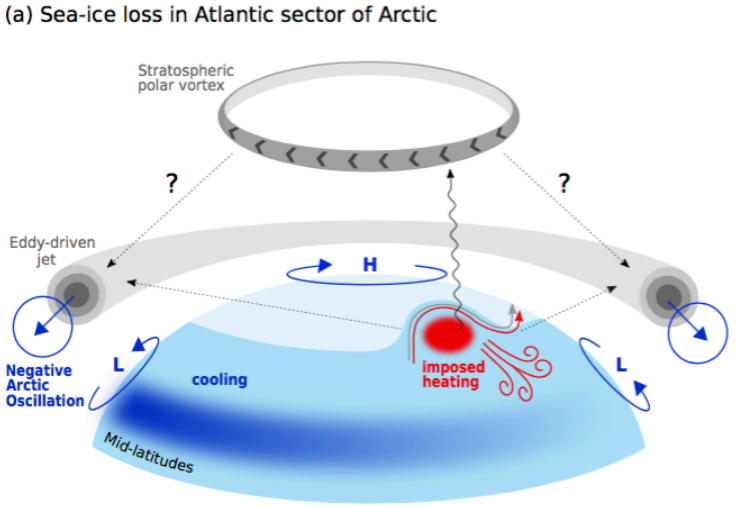
DEVELOPMENT FINANCE: future need for air conditioning in Cairo & impact on power network?

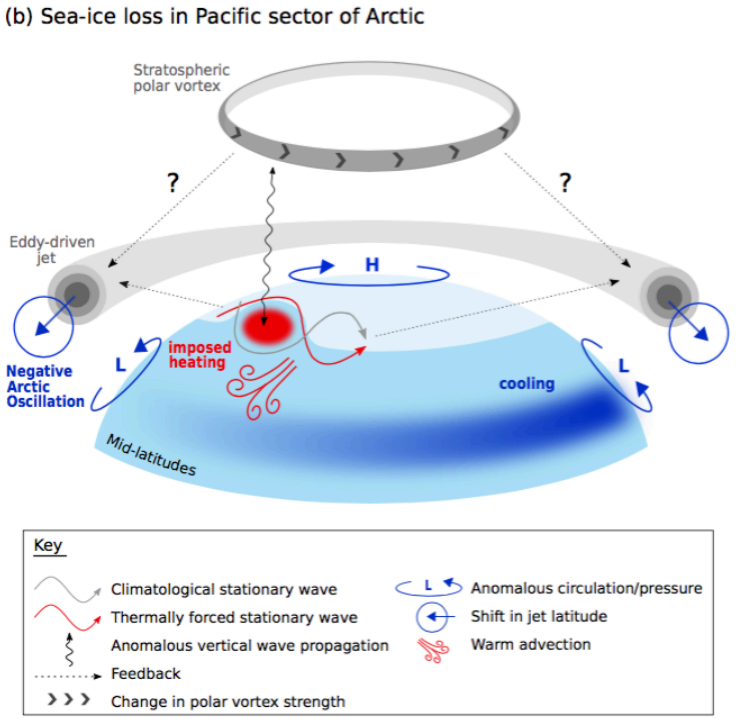


with Scott Hosking







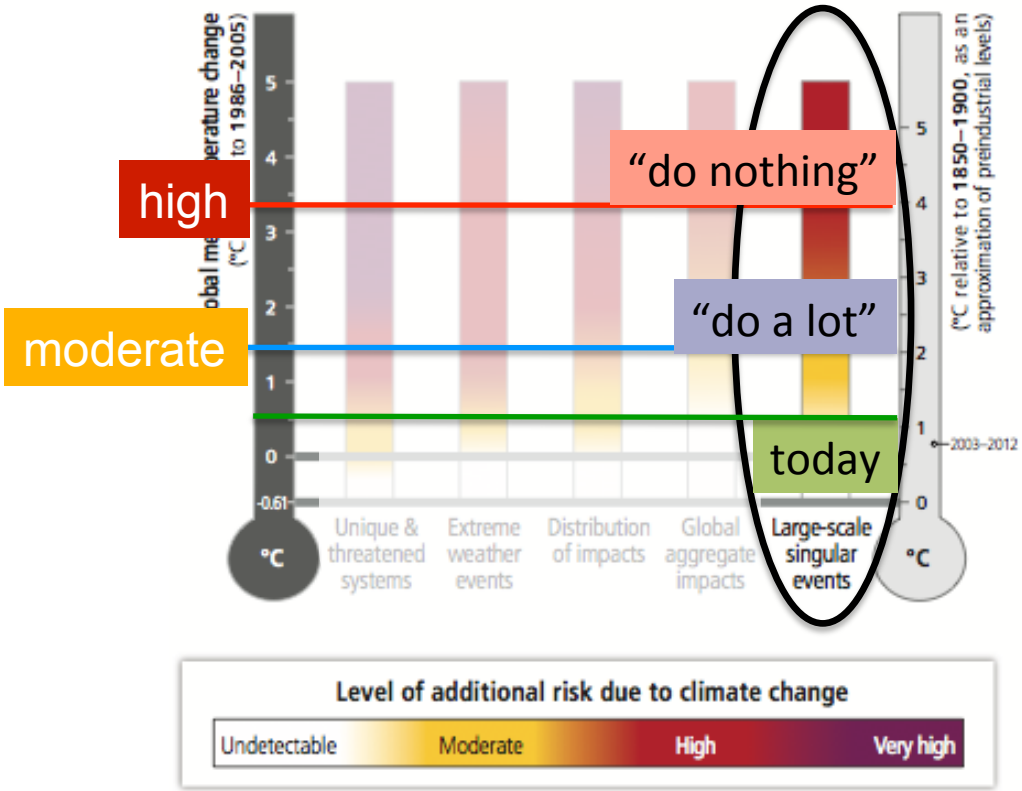


Modelling studies used to identify dynamical pathways of response to Arctic sea ice loss

Indicates that it can impact weather patterns across Europe, Asia and North America

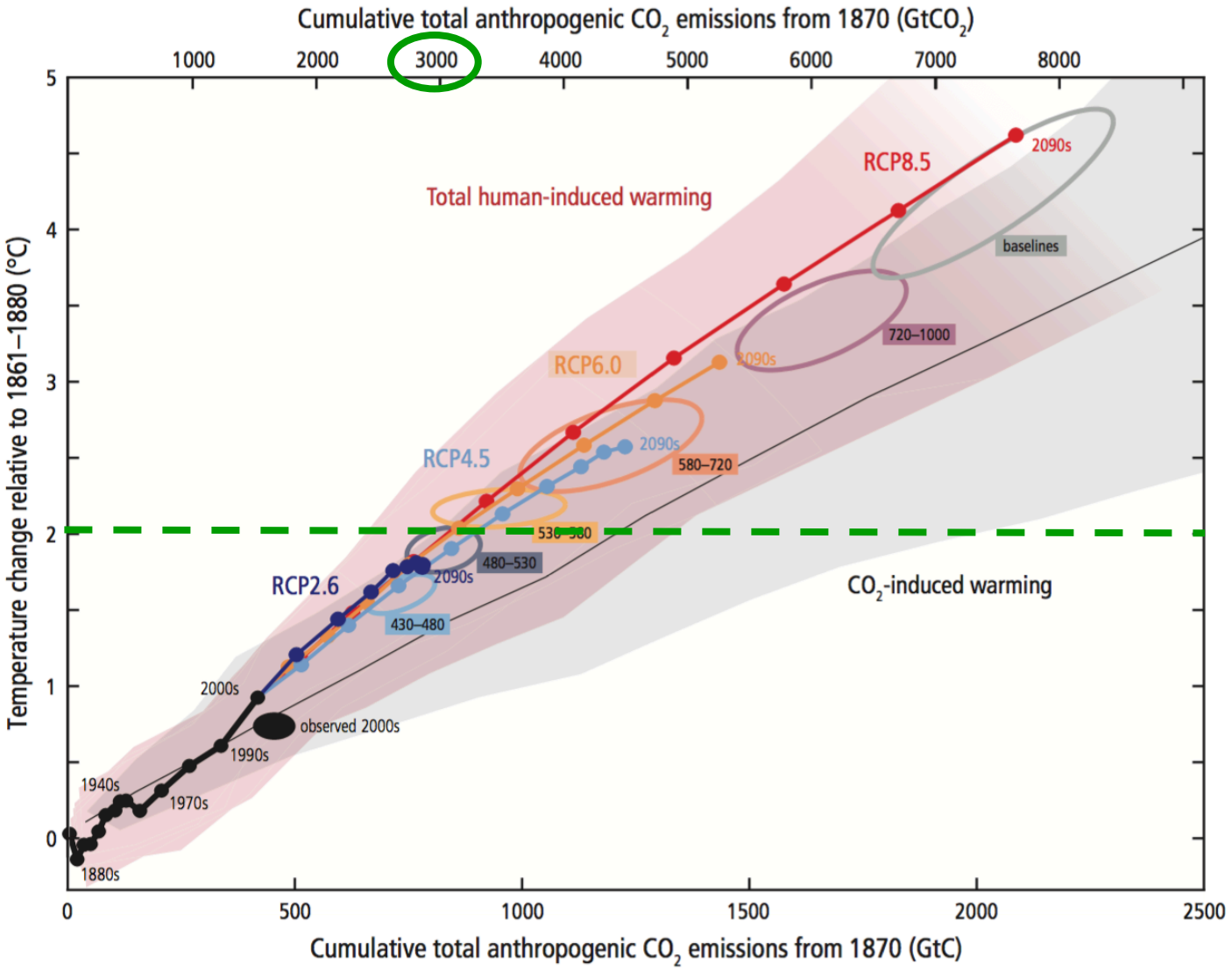
with Christine McKenna, Tom Bracegirdle

Large-scale singular events

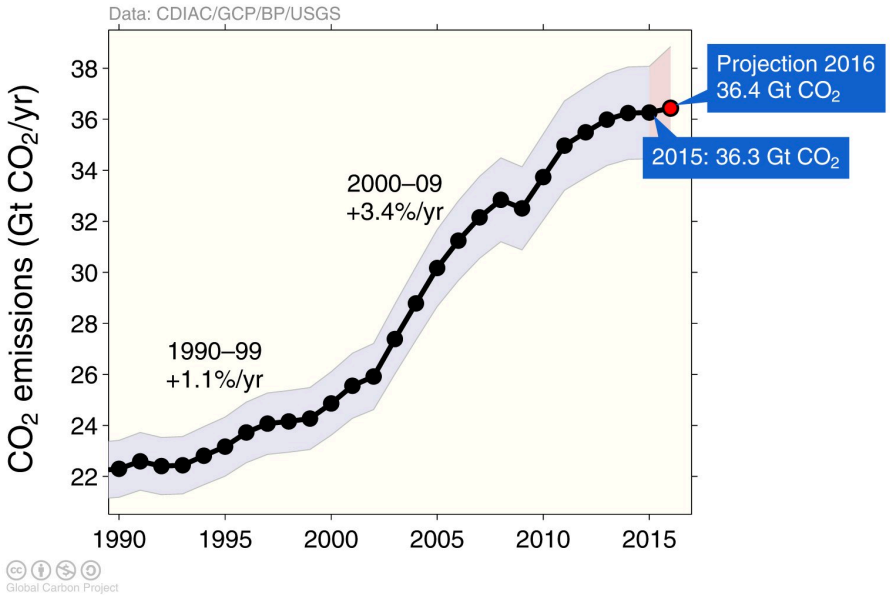


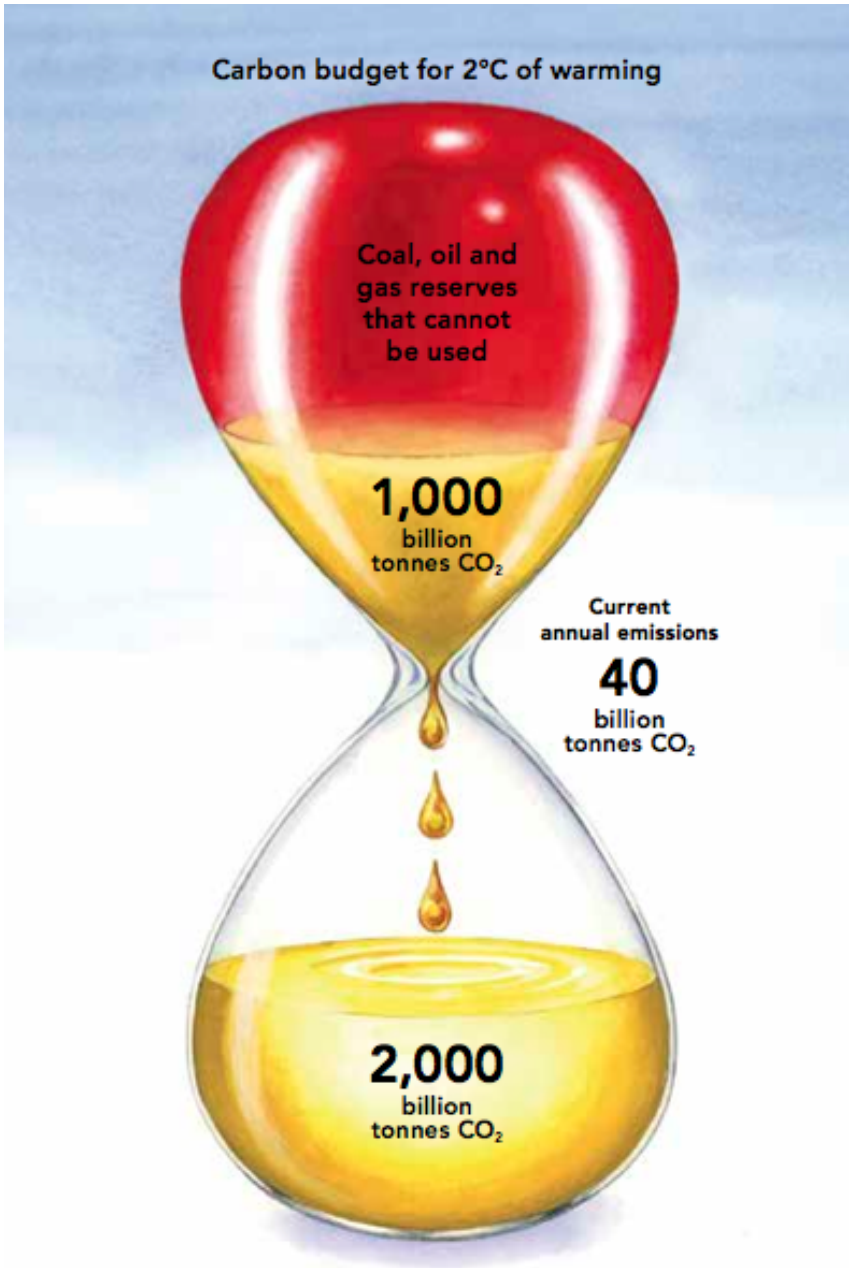
WG2 Box SPM.1

e.g. Feldmann & Levermann, 2015


Cumulative total anthropogenic CO_2 emissions from 1870 ($GtCO_2$)
1000
2000
3000
4000
5000
6000
7000
8000
Temperature change relative to 1861–1880 (°C)
0
1
2
3
4
5
Total human-induced warming
RCP8.5
2090s
baselines
720–1000
RCP6.0
2090s
RCP4.5
2090s
580–720
530–580
480–530
RCP2.6
2090s
430–480
CO_2-induced warming
2000s
observed 2000s
1990s
1970s
1940s
1880s
0
500
1000
1500
2000
2500
Cumulative total anthropogenic CO_2 emissions from 1870 (GtC)

SYR Fig 2.3





For likely chance of staying below 2°C have about 30 years emissions left at current level

[Estimates of $20 trillion put on “unburnable” carbon]

Our understanding of our climate is rooted in mathematics

Climate change is one of the greatest challenges of our time

The application of mathematical ideas & tools is driving forward our knowledge of our changing climate and the risks posed to society and the natural world, and is guiding our response to this global threat

It is a clear demonstration of the power of mathematics to address the world's most pressing issues

Credit: NASA