The Problem of Translating Climate Change into Impacts

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Topics

- Climate models – some background
- Introducing economics into the picture
- Disaggregation and problems of scale
- Local extreme events
- Bringing risk into the picture

Climate models – some background

The starting point – A Global Circulation Model (GCM)

- A model that incorporates the principles of **physics**, **chemistry**, **biology** into a mathematical model of climate

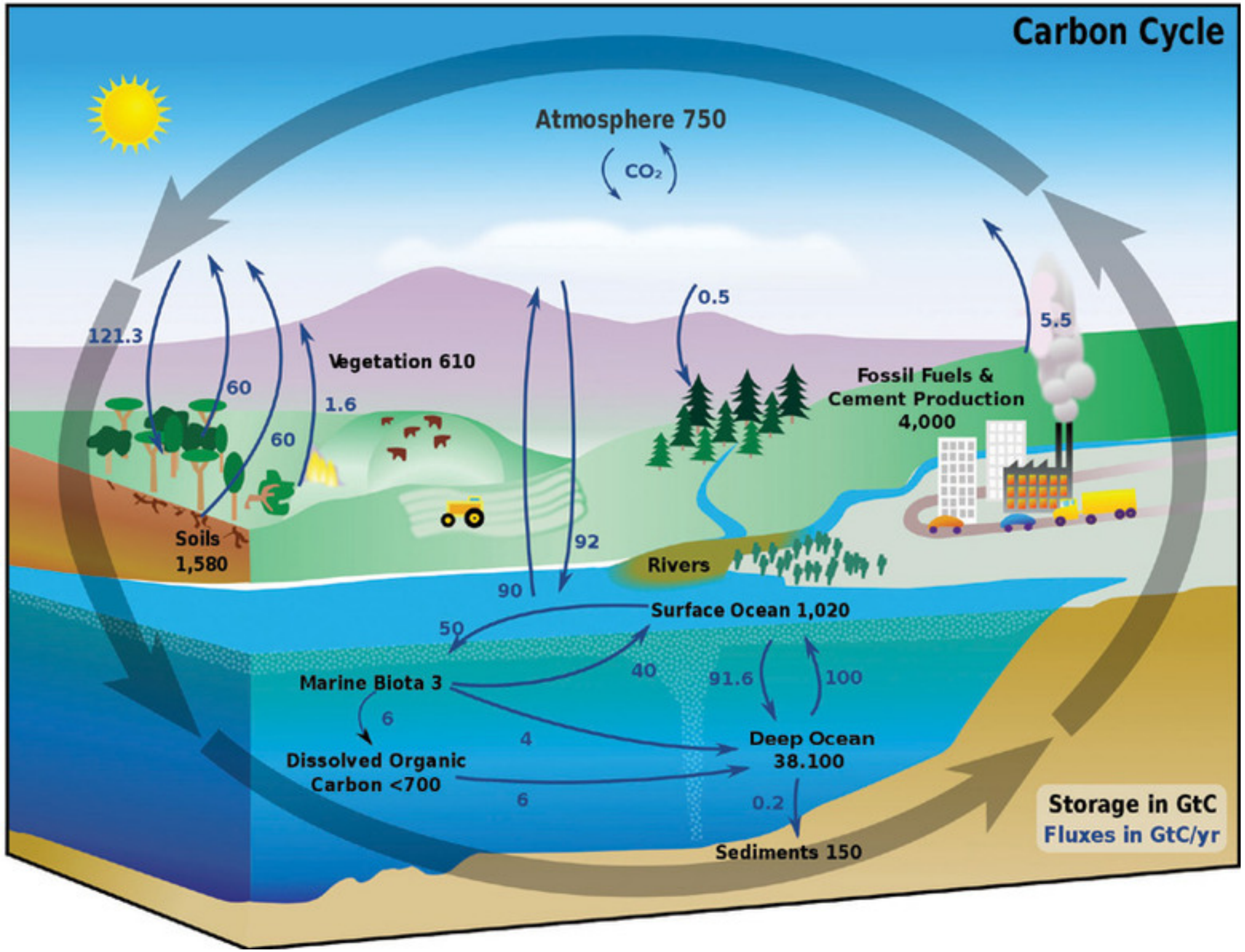
  e.g. GCM (Global Circulation Model)

- Such a model has to answer what happens to temperature, precipitation, humidity, wind speed and direction, clouds, ice and other variables all around the globe over time

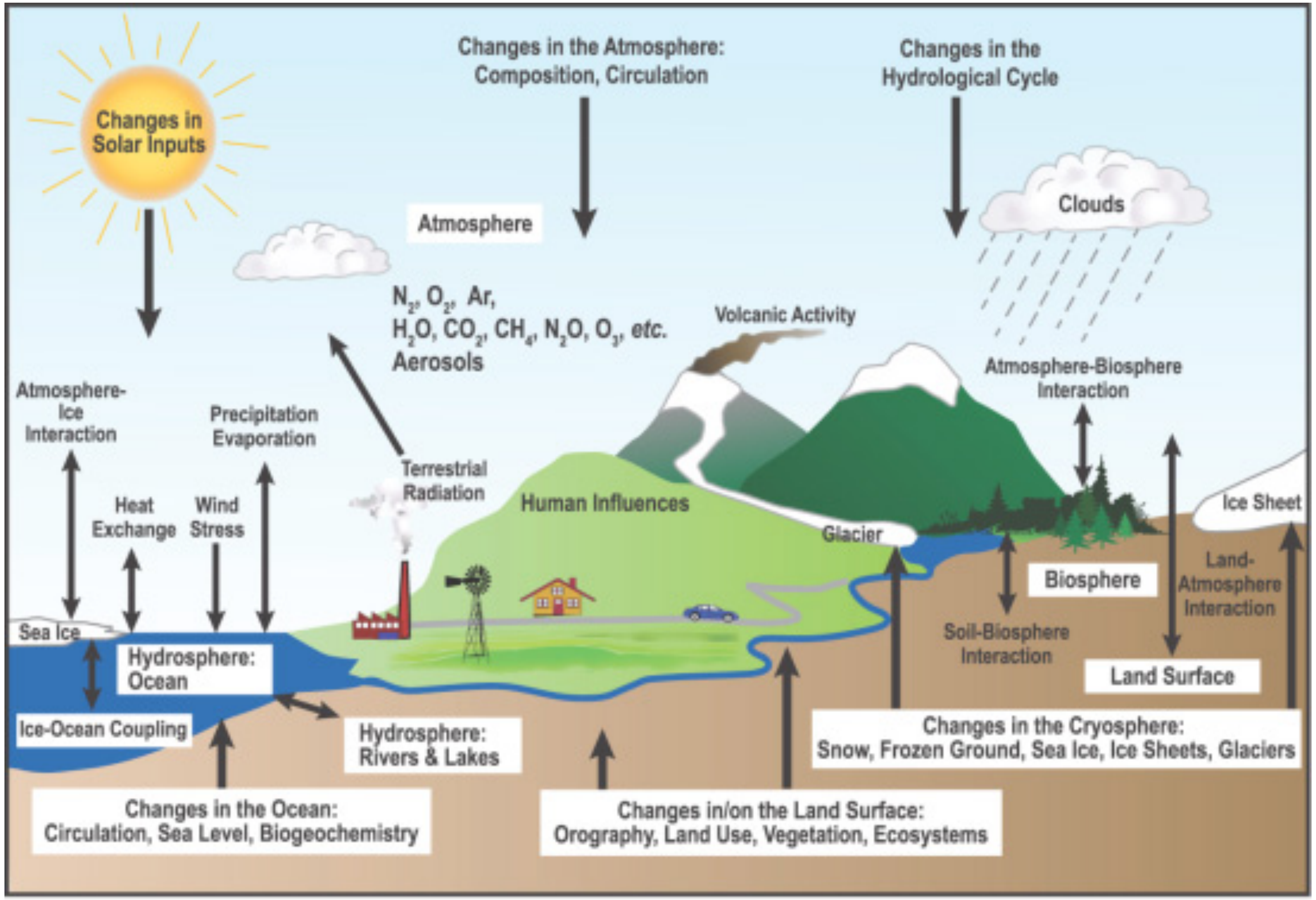
Climate models – key elements

- The Carbon Cycle
  - Where emissions go
  - The geographical complexity of the cycle
  - How fast emissions decay
- Feedbacks
  - The extent to which feedback are or are not included
  - If included, which ones and how?
- Non-linearities
- Emissions-Climate response
  - How sensitive the whole earth system is to emissions generally
  - How fast emissions cause temperature responses

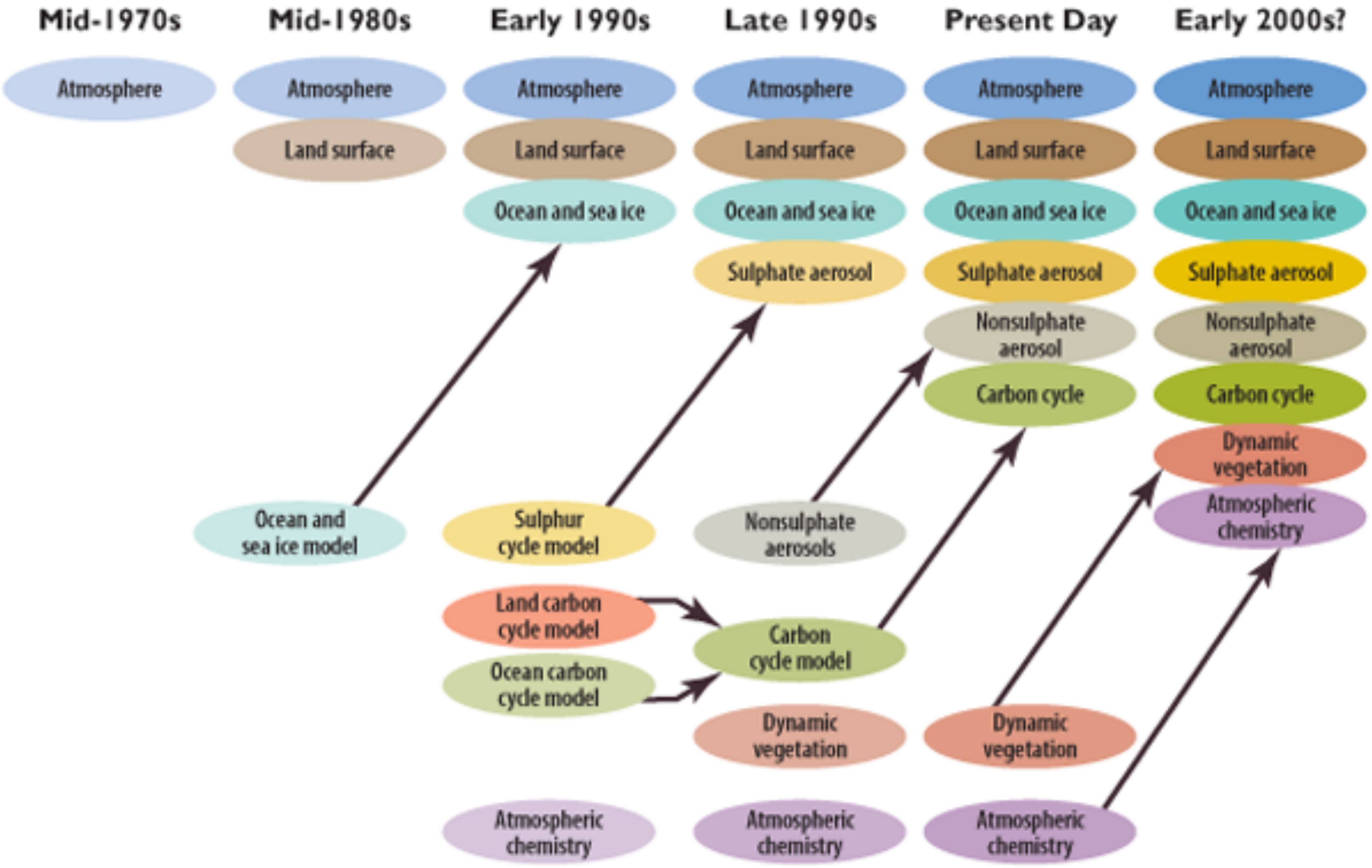
Carbon Cycle



A Simplified Climate Model



Development of Climate Models: Past, Present, and Future



Adapted from IPCC 2001

Discretization – in three-dimensional space

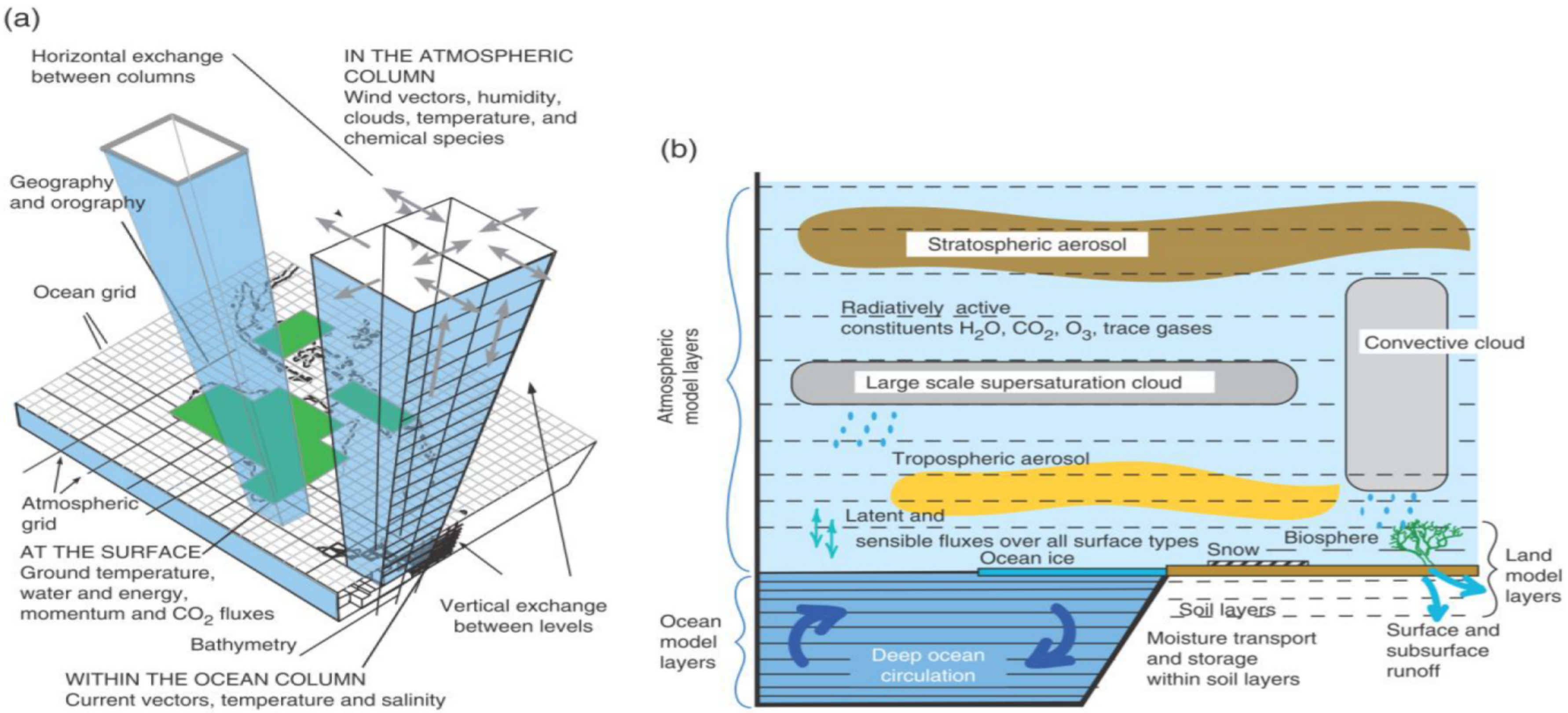


Figure 2.5 Discretisation (splitting into layers and boxes) is a basic characteristic of all three-dimensional climate models. The resolutions of the atmosphere, ocean and surface models frequently differ. (a) The atmosphere as a set of interacting columns of 'boxes' distributed around the Earth on a grid. (b) Processes in a single column of a 3D coupled climate model including various types of cloud, soil layers and tropospheric and stratospheric aerosols. Source: Hansen et al. (1983). Reproduced with permission of the American Meteorological Society.

The Climate Modelling Primer, Fourth Edition. Kendal McGuffie and Ann Henderson-Sellers.

Companion website: www.wiley.com/go/mcguffie/climatemodellingprimer

Multiple Processes

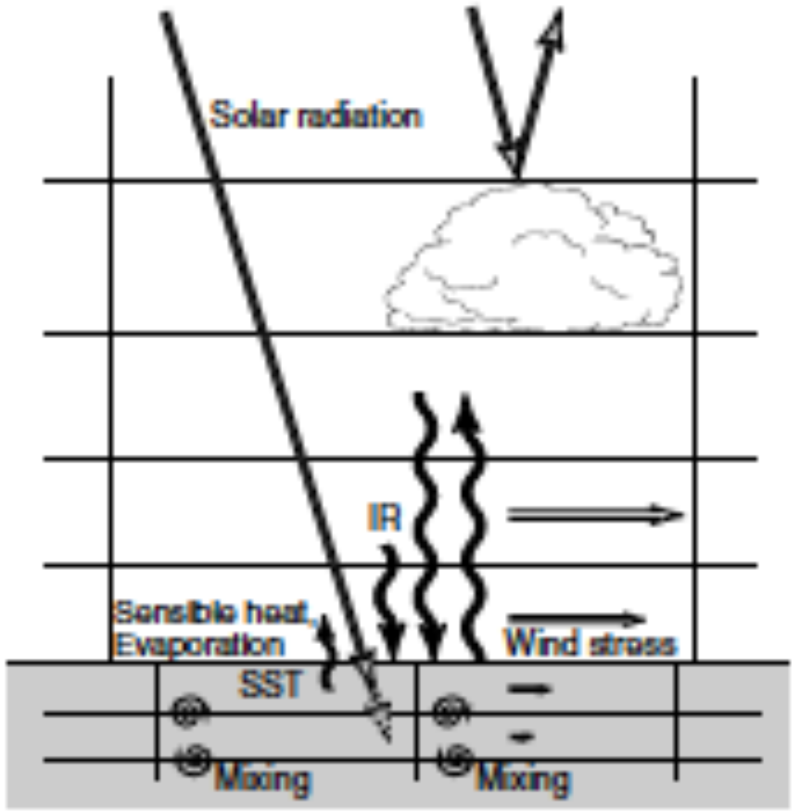
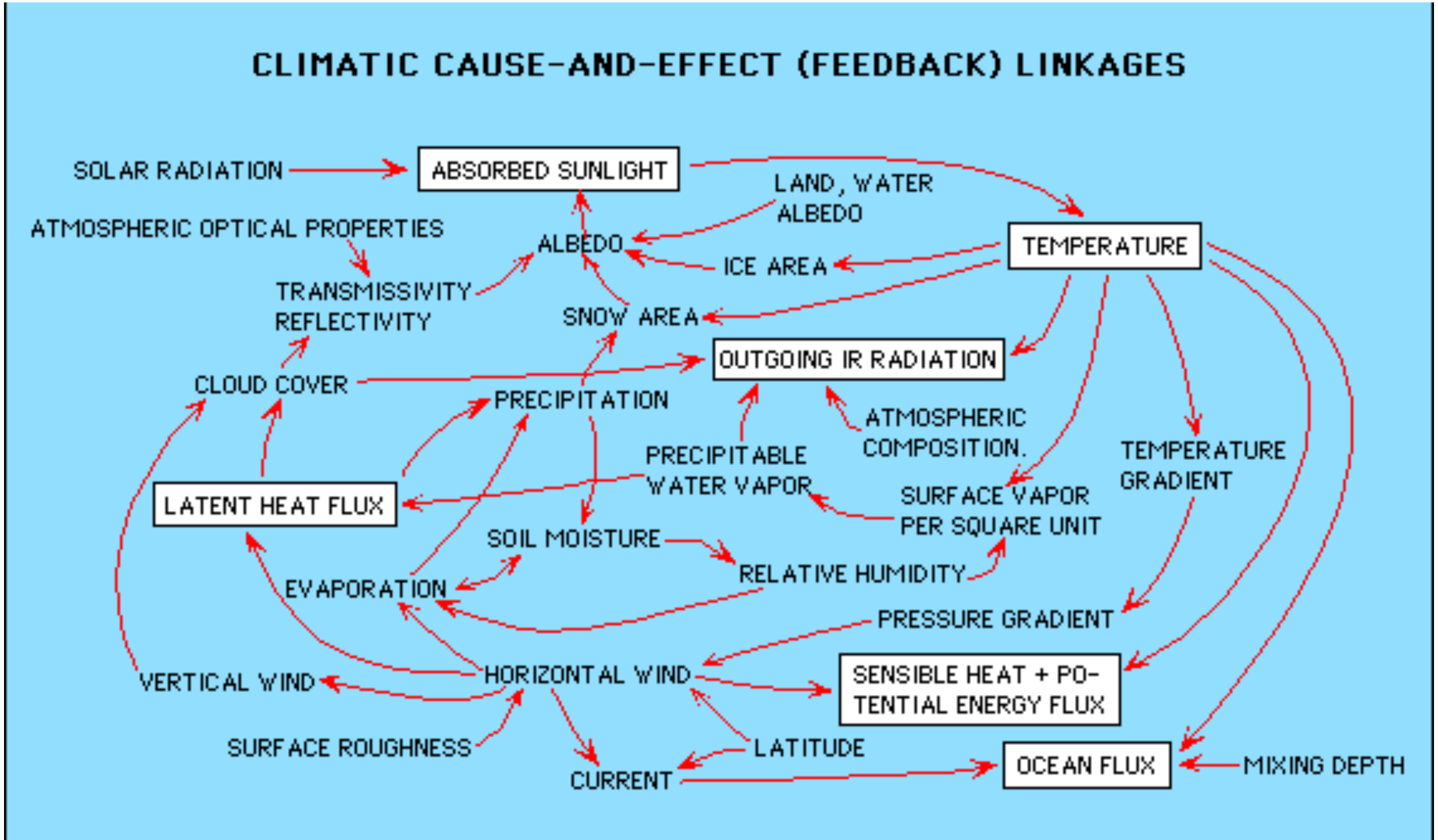


Fig. 5.5 Atmosphere–ocean coupling in a GCM via energy fluxes and wind stress.

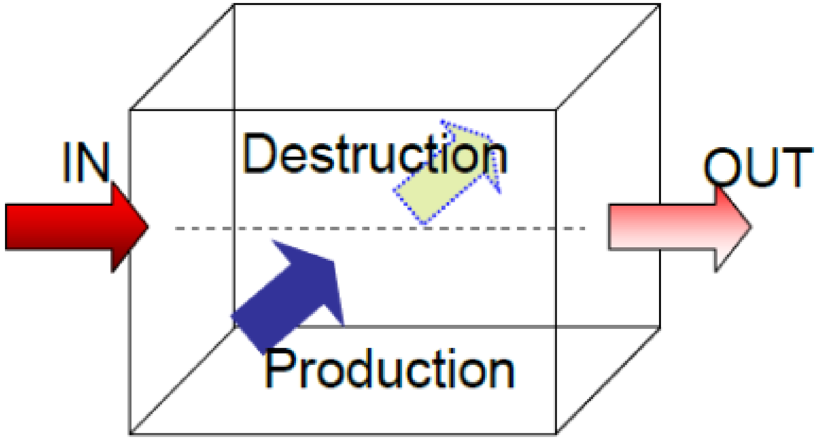
Climate Feedbacks



A diagram by Sellers shows the many cause-and-effect linkages that must be accounted for in a comprehensive climate model.

http://eesc.columbia.edu/courses/ees/slides/climate/feedback.gif

We can express changes in a grid cell at a given time step



CHANGE = (Production - Destruction) +/- (Gain or Loss by advection)

$$\left(\frac{\partial \Phi}{\partial t}\right) = \frac{d\Phi}{dt} - \frac{\partial}{\partial x}(u\Phi) - \frac{\partial}{\partial y}(v\Phi) - \frac{\partial}{\partial z}(w\Phi)$$

The total change (rate of accumulation) of Φ in the box

Actual production or destruction of Φ within the box

Change in Φ due to loss to downstream boxes or arrival of Φ from an upstream box (called advection or convection)

- We want to solve for the values of the variables described by these equations over time.

  i.e. to integrate the set of differential equations

- Essentially we have seven (or more) variables described by the same number of equations that describe change with respect to time. (T, p, ρ, u, v, w, water, etc.). So we should be able to solve for the values of the variables through time…

- BUT these equations **cannot be solved analytically**; there is no closed form solution

- So need to use numerics: discretize in time and space…

Choices in spatial discretization

The fluid equations for AGCMs are made discrete using either the finite difference method or the spectral method. For finite differences, a grid is imposed on the atmosphere. The simplest grid uses constant angular grid spacing (i.e., a latitude / longitude grid). However, non-rectangular grids (e.g., icosahedral) and grids of variable resolution[12] are more often used.[13] The LMDz model can be arranged to give high resolution over any given section of the planet. HadGEM1 (and other ocean models) use an ocean grid with higher resolution in the tropics to help resolve processes believed to be important for the El Niño Southern Oscillation (ENSO). Spectral models generally use a gaussian grid, because of the mathematics of transformation between spectral and grid-point space. Typical AGCM resolutions are between 1 and 5 degrees in latitude or longitude: HadCM3, for example, uses 3.75 in longitude and 2.5 degrees in latitude, giving a grid of 96 by 73 points (96 x 72 for some variables); and has 19 vertical levels. This results in approximately 500,000 "basic" variables, since each grid point has four variables (u,v, T, Q), though a full count would give more (clouds; soil levels). HadGEM1 uses a grid of 1.875 degrees in longitude and 1.25 in latitude in the atmosphere; HiGEM, a high-resolution variant, uses 1.25 x 0.83 degrees respectively.[14] These resolutions are lower than is typically used for weather forecasting.[15] Ocean resolutions tend to be higher, for example HadCM3 has 6 ocean grid points per atmospheric grid point in the horizontal.

Computation – a relatively simple model

Total Computation Time:

For example, for a 2.8° x 2.8 ° degree atmospheric model

How Many Grid Cells?

128	Longitudes
64	Latitudes
* 18	Vertical Levels

~ 150,000 Grid Cells

What Happens at each Grid Cell?

10	Variables
* 100	Computations Each

~ 1,000 Computations per Grid Cell per Time Step

How Many Time Steps Per Year?

24+	Time Steps per Day
365	Days per Year

~ 10,000 Time Steps per Year

$$150{,}000\ (\text{Grid Cells}) * 1{,}000\ \frac{\text{Computations}}{(\text{Grid Cell})\ (\text{Time Step})} * 10{,}000\ \frac{\text{Time Steps}}{\text{Year}} \approx 1.5\ \text{Trillion}\ \frac{\text{Calculations}}{\text{Year}}$$

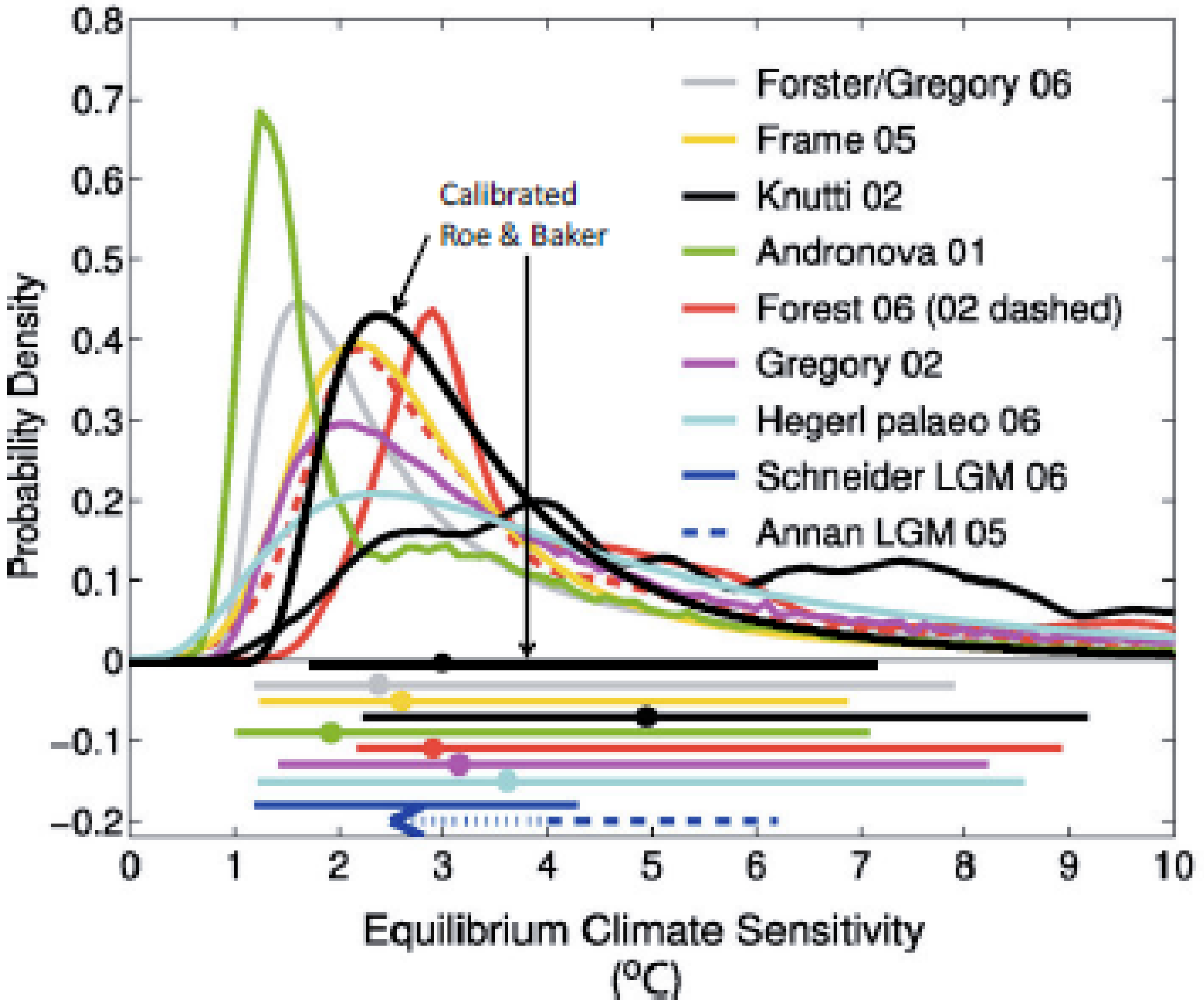
With a 1 GHz machine, a 1 year simulation takes about three hours

And, remember, this is just about the simplest possible model and we generally want to run the model for decades or centuries…

Overall Climate Response

- Climate Sensitivity is a key concept
  - Huge uncertainty about this – and has changed over time as science has developed
- Transient temperature response
  - Is a measure of how fast temperature changes
  - Models vary in their estimations how fast emissions will accumulate (decay functions) and how this will then translate into a rate of temperature change
- Equilibrium climate sensitivity
  - A parameter measuring how much the temperature will ultimately change given a doubling of atmospheric CO2 concentration.

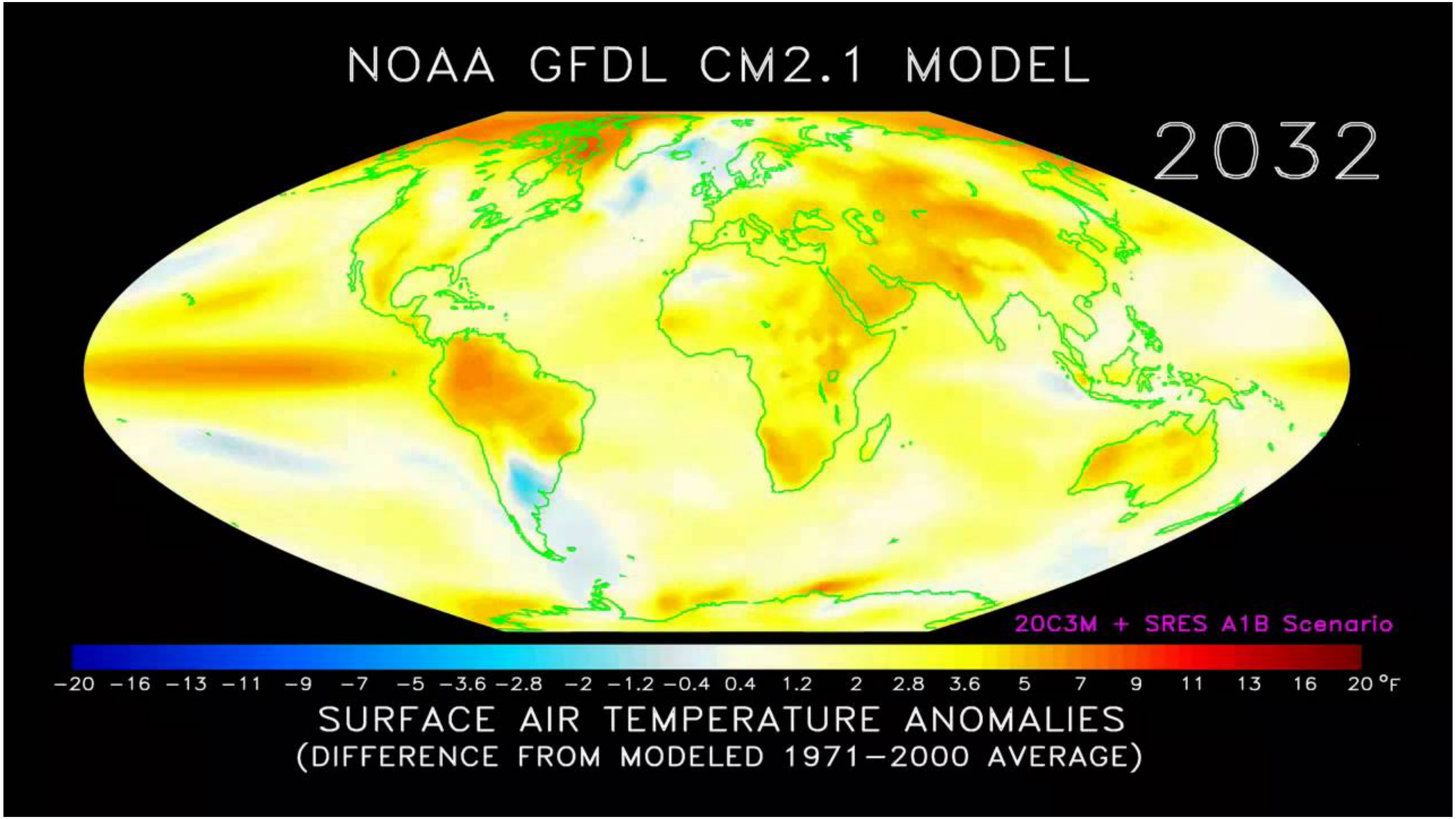
Figure 2: Estimates of the Probability Density Function for Equilibrium Climate Sensitivity (°C)



What GCMs do

- The GCMs typically start on January 1, 1900.
- They use the known/estimated annual emissions from then through the present.
- They employ scenarios to project annual emissions from now through the future (e.g., 2100).
- The output is a projection of monthly average temperate and precipitation in each 2-dimensional grid point on the earth's surface, under the given emission scenario.

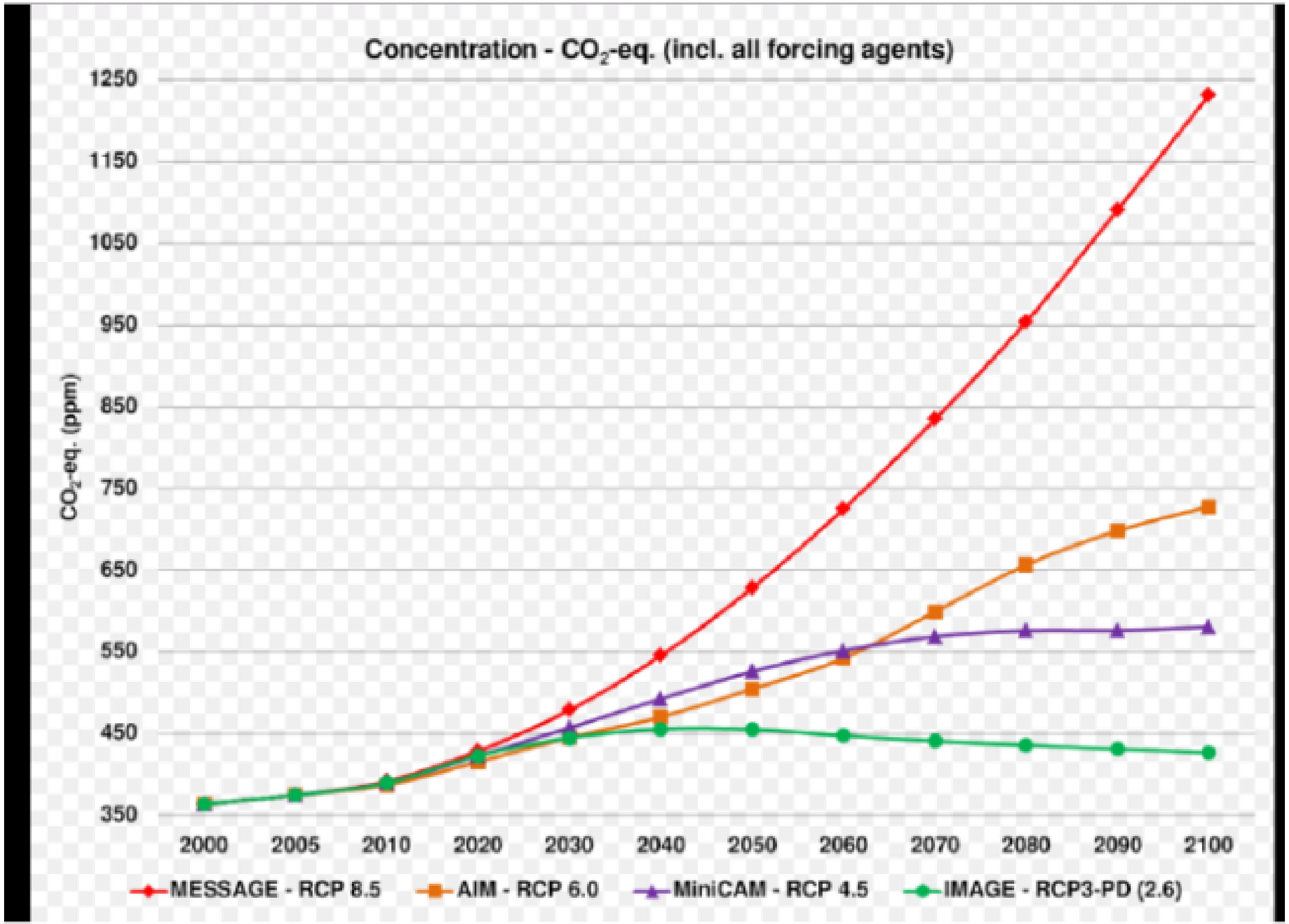
An example


NOAA GFDL CM2.1 MODEL
2032
20C3M + SRES A1B Scenario
−20 −16 −13 −11 −9 −7 −5 −3.6 −2.8 −2 −1.2 −0.4 0.4 1.2 2 2.8 3.6 5 7 9 11 13 16 20 °F
SURFACE AIR TEMPERATURE ANOMALIES
(DIFFERENCE FROM MODELED 1971−2000 AVERAGE)

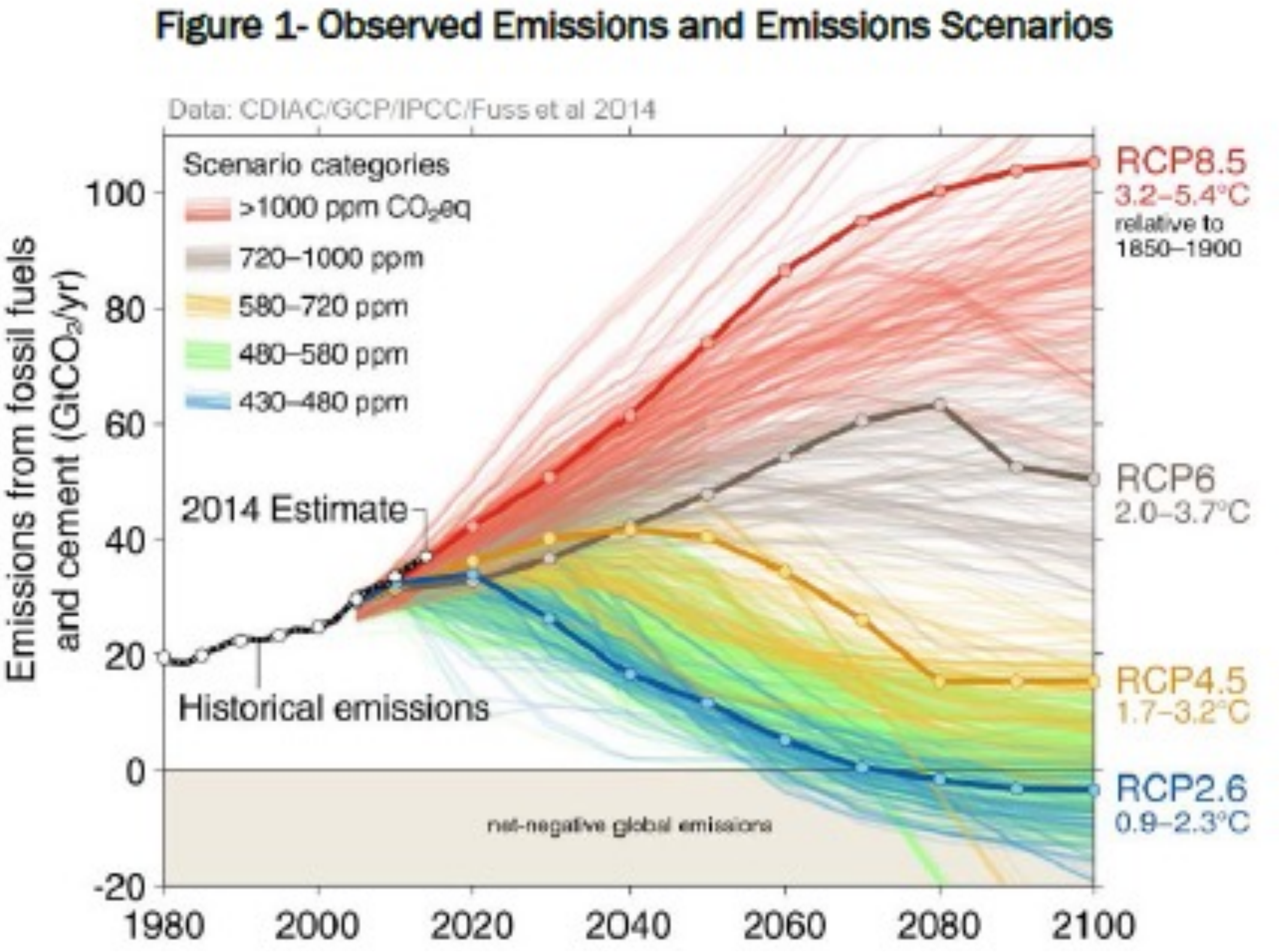
Emission scenarios

Representative Concentration Pathways (RCPs) are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014.[1] It supersedes Special Report on Emissions Scenarios (SRES) projections published in 2000.

The pathways are used for climate modeling and research. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively).[2]


Concentration - CO2-eq. (incl. all forcing agents)
CO2-eq. (ppm)
1250
1150
1050
950
850
750
650
550
450
350
2000
2005
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
MESSAGE - RCP 8.5
AIM - RCP 6.0
MiniCAM - RCP 4.5
IMAGE - RCP3-PD (2.6)

Actual emissions vs the RCPs and other projections



Introducing economics into the picture

Where do people come into the picture?

- They generate emissions
- They are affected – for the better or the worse – by the changes in climate.

- These linkages are represented in what are known as Integrated Assessment Models (IAMs).

Integrated Assessment Models

In principle, IAMs link:

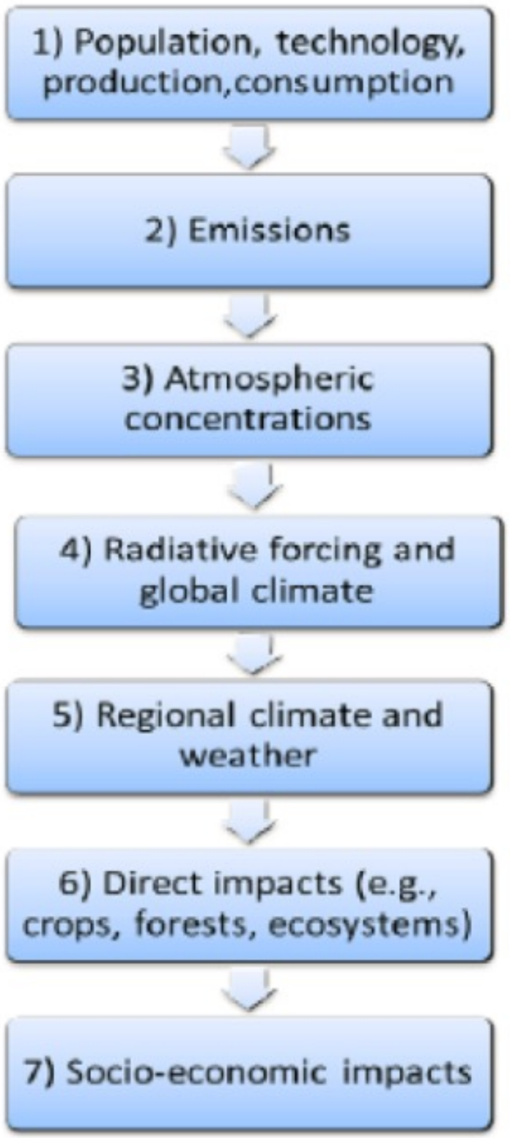
Economic activity.

The generation of GHG emissions.

The change in global average annual temperature, ΔT (via a **simplified** representation of the carbon cycle).

Impacts on human well being including changes in economic output.

Figure 1. Elements of an IAM

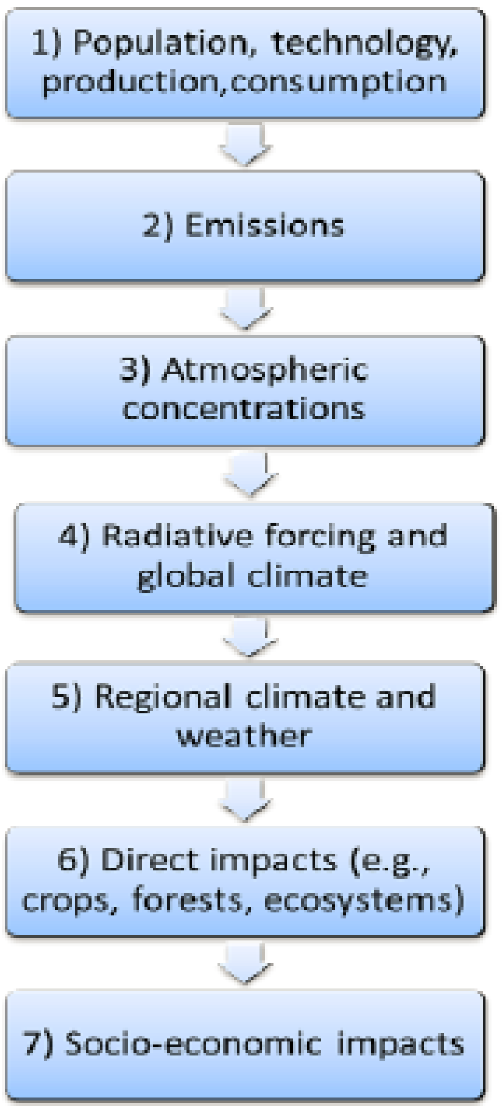


Need an IAM to measure these

- Boxes 3 - 5 are the are the carbon cycle

- Boxes 6 - 7 are the damage function.

Figure 1. Elements of an IAM



Two related ECONOMIC concepts

- The marginal damage from CO_2
  - The extra damage at some specified future time period from the emission of an additional ton of CO_2 now.
  - The damage avoided at some future time period by reducing emissions of CO_2 now by on ton.
- The Social Cost of Carbon
  - The discounted present value of additional future damages from the emission of an additional tone of CO_2 now.
  - The discounted present value of the future damages avoided by reducing emissions of CO_2 now by one ton.

Two types of IAM

I. Many economy-wide models do *not* represent the damages of climate change. They trace the link from economic activity to the emission of GHGs, to changes in global climate, but not the link from that to damages.
   - Typically with a detailed representation of the energy sector.
   - Used to measure the cost of meeting a target warming.

II. There is only a handful of IAMs that include a representation of the economic impacts ("damage") of climate change.
   - It is these models that have been used to calculate estimates of the Social Cost of Carbon.
   - These are the models on which I will focus

The main IAMs used to calculate the social cost of carbon

- Three IAMS have received most attention in this literature, all developed in the 1990s.
  - DICE, first version appears in 1991/1992.
    - Updates in 1999, 2007, 2010, 2013.
  - PAGE, first version appears 1991/1992.
    - Updates in 1995, 2002, 2009.
  - FUND, first version appears ~1994.
    - Multiple updates. Version 3.5 used in 2010; version 3.8 used in 2013.
  - The models have undergone various refinements and updates. While the details have changed, their general structure has stayed same.
    - Updating has focused more on the carbon cycle than on the damage function

Disaggregation and problems of scale

Aggregation – the fundamental tension

- From the point of view of mitigation (controlling emissions) what matters if aggregate emissions – it does not matter where on earth they arise.
  - Spatial aggregation is OK for projecting future changes in temperature.
  - For figuring how to reduce emissions, however, spatial detail matters.
- From the point of view of assessing impacts, and devising strategies to reduce those impacts (adaptation), spatial detail is essential.
  - Climate is spatially heterogeneous, and the changes from warming are spatially heterogeneous. Impacts depend partly on weather, which is temporally heterogeneous.
  - In order to account for impacts one needs a high degree of spatial resolution.

The constraints of economic data

- For many economic variables, data are often available only iun an aggregated form.
  - Annual or quarterly, or monthly, not weekly or daily.
  - National or regional, not at the county or city level.

- The IAMs, which run from now through 2300 – 2500, use multi-annual time steps, with the spatial scale being
  - The whole world (one unit)
  - Broad regions (world divided into 12-16 regions)
  - They cover only temperature, not precipitation or other variables.
    - The outcome variable is increase in average annual temperature either globally, or in a broad region of the globe.

The challenge of scale

- Climate, changes in climate, and impacts occur at a fine spatial scale (e.g., a watershed) and temporal scale (hours, days, weeks).
- GCM output is typically for regions about cells of about 200x200km and monthly average (daily data could be available, but over 100-200 years, this would generate a massive output file).
- The climate system component of the IAMs operates on a very aggregate spatial scale (broad regions, the world) and temporal scale (change in annual average daily temperature over a year or a decade).
- Impacts are felt on a finer spatial scale than GCM output – the GCM output needs to be *downscaled*.
    - Statistical downscaling
    - Dynamic (Regional Climate Models)
- If they could be measured accurately, the impacts would need to be need upscaled to become on the coarse scale of the IAMs.
- These translations of scale are a challenge – and a potential source of bias,

Table R. The regions in FUND.

Acronym	*Name*	*Countries*
USA	USA	United States of America
CAN	Canada	Canada
WEU	Western Europe	Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom
JPK	Japan and South Korea	Japan, South Korea
ANZ	Australia and New Zealand	Australia, New Zealand
CEE	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, FYR Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
MDE	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, West Bank and Gaza, Yemen
CAM	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
SAM	South America	Argentina, Bolivia, Brazil, Chile, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
SEA	Southeast Asia	Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam
CHI	China plus	China, Hong Kong, North Korea, Macau, Mongolia
NAF	North Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara
SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea- Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
SIS	Small Island States	Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Comoros, Cuba, Dominica, Dominican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Marshall Islands, Martinique, Mauritius, Micronesia, Nauru, Netherlands Antilles, New Caledonia, Palau, Puerto Rico, Reunion, Samoa, Sao Tome and Principe, Seychelles, Solomon Islands, St Kitts and Nevis, St Lucia, St Vincent and Grenadines, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu, Virgin Islands

Aggregation distorts conception of temperature change Hayhoe et al PNAS 2004

HOW TO CHARACTERIZE THE CHANGE IN TEMPERATURE, 2070-2099, USING HADCM3			
		EMISSION SCENARIO**	
		A1fi	B1
Change in global average annual temperature		4.1	2
Change in statewide average annual temperature in California*		5.8	3.3
Change in statewide average winter temperature in California*		4	2.3
Change in statewide average summer temperature in California*		8.3	4.6
Change in LA/Sacramento average summer temperature		~10	~5
*Change relative to 1990-1999. Units are ˚C			

Different Kinds of Downscaling

NCAR

- Simple (Giorgi and Mearns, 1991)
  - Adding coarse scale climate changes to higher resolution observations (the delta approach)
  - More sophisticated - interpolation of coarser resolution results (Maurer et al. 2002, 2007)
- Statistical
  - Statistically relating large scale climate features (e.g., 500 mb heights), predictors, to local climate (e.g, daily, monthly temperature at a point), predictands
- Dynamical
  - Application of regional climate model using global climate model boundary conditions

Statistical Downscaling

NCAR

- Various sub-methods
  - Weather classification schemes
  - Regression methods – multiple regression, artificial neural networks, canonical correlation
  - Weather generators

Weather Classification

NCAR

- Relate weather classes or categorizations to local climate variable
  - Discrete weather types are grouped according to cluster techniques
- Typical example is relating different pressure patterns to surface temperature
- Assumes same weather pattern in the future will be associated with the same local responses in the future
  - Changes in frequency of types

Dynamical Downscaling

Application of

Regional Climate Models

Atmospheric Time-slice Experiments

Stretched Grid Experiments

- Atmospheric Time-slice experiments – only the atmospheric (and land surface) models are used – lower boundary conditions are provided for sea surface temperatures and sea ice.
- Stretched Grid experiments - full atmosphere-ocean model is used but grid is made high resolution in only one part of the global domain

Downscaling – why bother

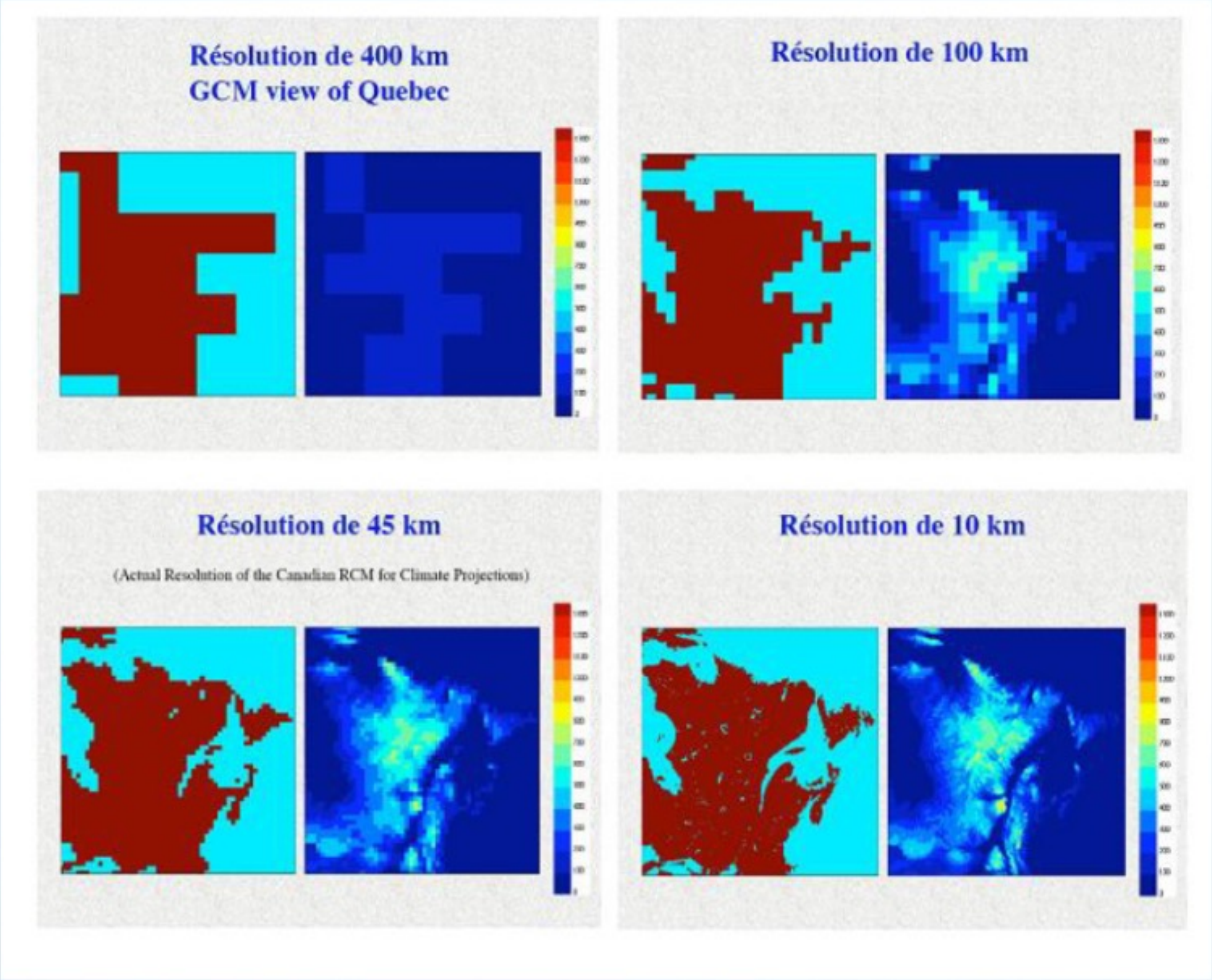
- However it is done, downscaling (spatial disaggregation) introduces an additional error and perhaps bias
- So, why bother to do it?
- Because not disaggregating introduces its own systematic bias.

Spatial Resolution of Quebec in GCMs and RCMs

NCAR

Land-sea Mask

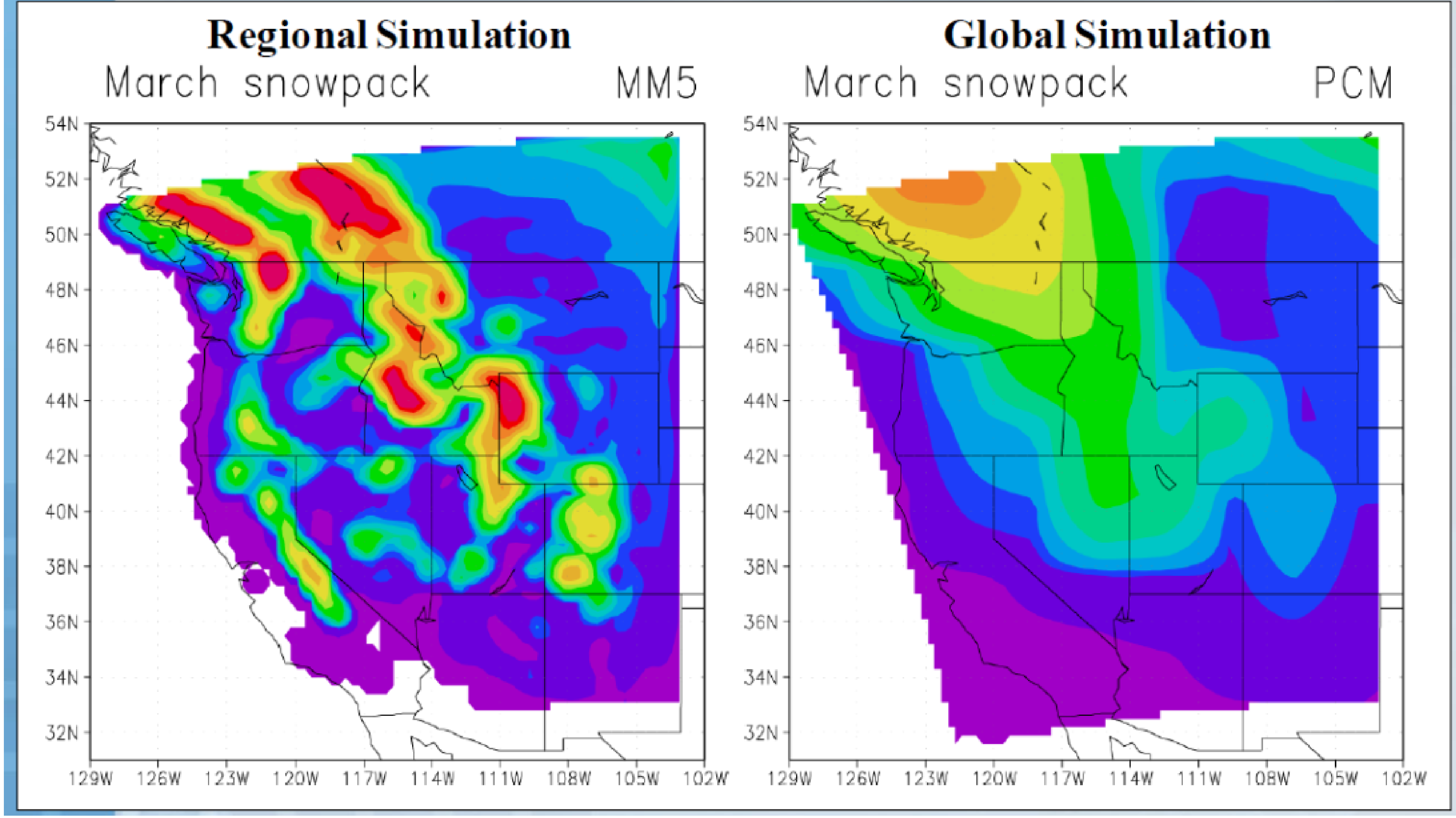
Annual Precip Totals

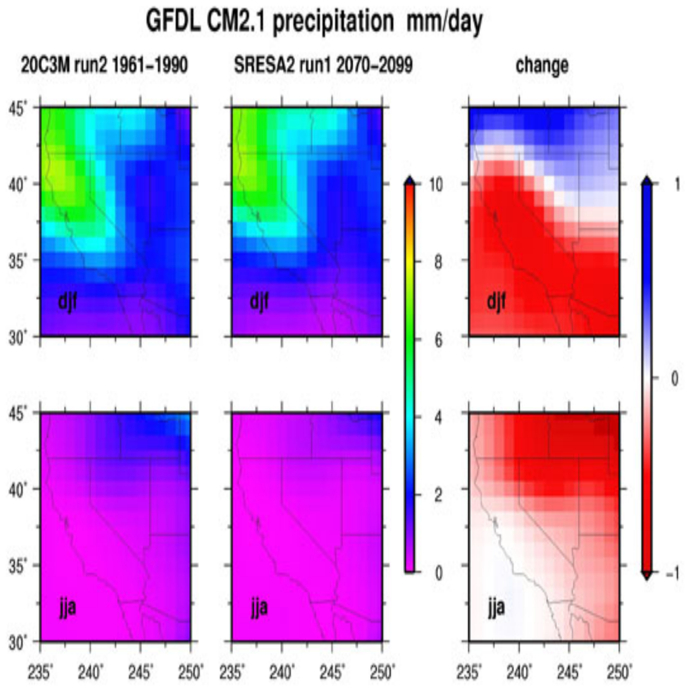


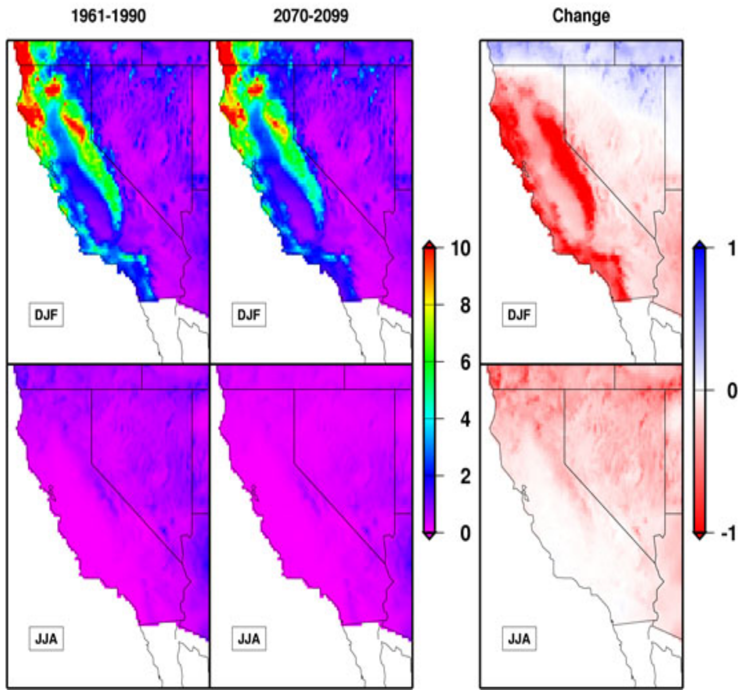
Global and Regional Simulations of Snowpack

NCAR

GCM under-predicted and misplaced snow







Global Climate Models compute Climate on a coarse grid

So, a "downscaling" procedure was used to provide temperature and precipitation over a finer mesh that is more commensurate with the California landscape

A hydrologic model is used to simulate stream flow, soil moisture and other hydrologic properties

Aggregation systematically biases down the damage estimate

- With convex damage function (increasing marginal damage), aggregation understates damages:

$$E\{D(\Delta T)\} > D(E\{\Delta T\}).$$

- A local approximation:

$$E\{D(\Delta T)\} = D(E\{\Delta T\}) + \sigma_\Delta^2 D''(E\{\Delta T\})$$

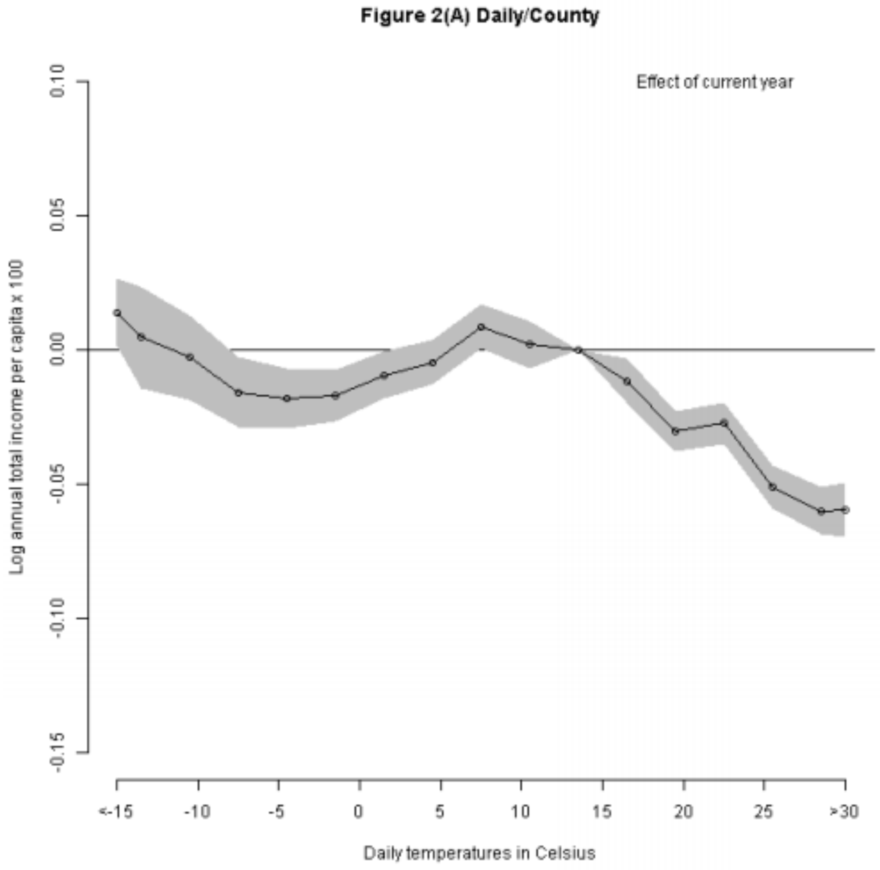
- The larger σ_Δ^2 and the larger $D''(.)$, the more $D(E\{\Delta T\})$ understates the aggregate damage $E\{D(\Delta T)\}$.
- In current research, I am measuring the degree of understatement for varying levels of spatial aggregation.
- What follows compares estimation of the impact on annual GDP of an extra day per year in various temperature bins, by US county versus US State.

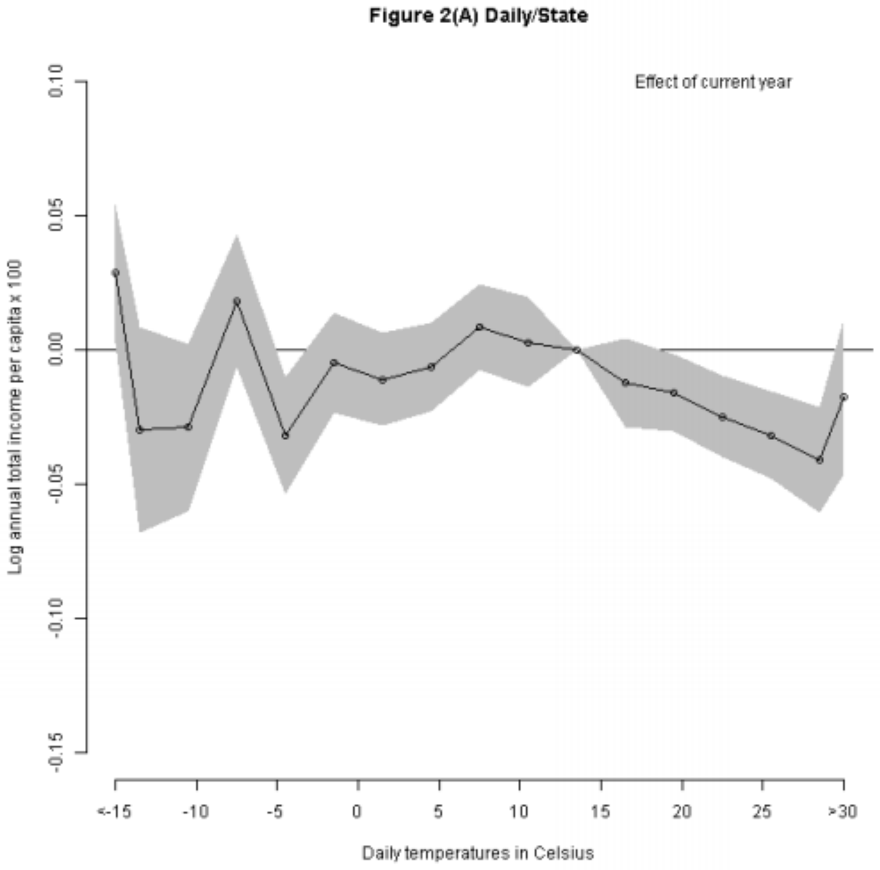
The data

- Weather data from the Global Historical Climatology Network (GHCN) in the National Ocean and Atmospheric Association (NOAA).
  - Daily historical observations from weather stations
  - TMAX, TMIN, PRCP
  - Values matched to counties using Latitude/Longitude coordinates and simple averaged within counties
  - TAVG = (TMAX + TMIN)/2
  - Daily values binned.
- Income data from the BEA
  - Specific measure: per capita personal income (CA4), measured at the county-year level.
  - Normalized to 2011 dollars

Temperature	Precipitation
$< -15°C$	$0\ mm$
$-15°C$ to $-12°C$	0 to 40 mm
$-12°C$ to $-9°C$	40 to 80 mm
$-9°C$ to $-6°C$	80 to 120 mm
$-6°C$ to $-3°C$	120 to 160 mm
$-3°C$ to $0°C$	160 to 200 mm
$0°C$ to $3°C$	200 to 240 mm
$3°C$ to $6°C$	240 to 280 mm
$6°C$ to $9°C$	280 to 320 mm
$9°C$ to $12°C$	320 to 360 mm
$12°C$ to $15°C$	360 to 400 mm
$15°C$ to $18°C$	$> 400\ mm$
$18°C$ to $21°C$	
$21°C$ to $24°C$	
$24°C$ to $27°C$	
$27°C$ to $30°C$	
$> 30°C$	

Spatial Aggregation Regression Results





What impacts are considered?

- Crop production, forestry, fisheries
- Human health morbidity and mortality
  - Increased disease
    - Due to
  - Direct exposure to extreme weather
- Water supply
- Flooding due to increased stream runoff
- Coastal flooding due to sea level rise
- Disruption of energy production
- Disruption of transportation systems
- Loss of productivity in manufacturing
- Impact on tourism
- Impact on GDP
- Loss of habitat and species

How are sectoral impacts assessed

- Process models (e.g., crop models, economic general equilibrium models)
  - Some of these function at fine spatial and temporal scale (crop models
  - Others function at a coarse scale (economic general equilibrium models function at annual and usually national scale)

- Statistical models (e.g., regressions on weather variables)
  - Temporal and spatial scale depend on the scale of the data used.

Some subtleties of time scale

- The effect of a variation in weather on, say, crop production, is not the same as the effect of a change in climate on production.
  - Weather is a short-run phenomenon, climate a long-run phenomenon. Climate is the long-run realization of weather.
  - The reaction -- adaptive opportunities – are different.
  - In some ways, can respond more readily (at less cost) to climate than to weather because there is more time to adapt.
  - In other ways, can respond less readily (at higher cost) to climate than to weather because some responses that are viable in the short run fail to be viable in the long run (e.g., temporarily over drafting groundwater).
  - Also damage may be a function of cumulative weather stresses – better captured by climate than by weather.
- In a statistical analysis, it is harder to capture the effects of climate than that of weather.
  - Would need much longer data series.
  - Assumption that other things remain constant besides climate unlikely to be true.

Need multiple time scales?

- Climate -- and climate change -- affects humans differently on different time scales.
- Need to distinguish chronic versus acute impacts from climate change. E.g., heat stress:
  - Chronic effect: reduced productivity of work in environment that deviates much from what is required to maintain body close to 98.6F.
  - Acute effect: die if exposed to extreme cold or extreme heat for period of several days.

Local extreme events

Local extreme events

- These are events that are local in space and time – unlike the catastrophic global tipping points discussed in the literature (Lenton et al., 2008) such as the ending of the thermohaline circulation in the Atlantic Ocean, the melting of the Antarctic & Greenland Ice Sheets, etc.
- Examples of local extreme events:
  - Drought in Colorado River Basin
  - Heat wave and deaths in Paris
  - Flooding of the Danube River
  - Wildfire in California and Arizona
  - The need for additional generating capacity depends on *hourly* peak power demand.
  - Crops die when temperatures exceed a certain threshold for several days in a row.
  - Coastal flooding occurs when a storm happens to coincide with a high tide.

Why focus on extreme events?

- Because this evidence suggests that most of the damages from climate change are associated with extreme climate events.
  - What percent, exactly?
    - This remains to be measured.
- My hunch: change in averages is essentially of minor importance, compared to change in extremes.
- But, most of existing damage literature (until last couple of years) has focused on changes in average conditions.

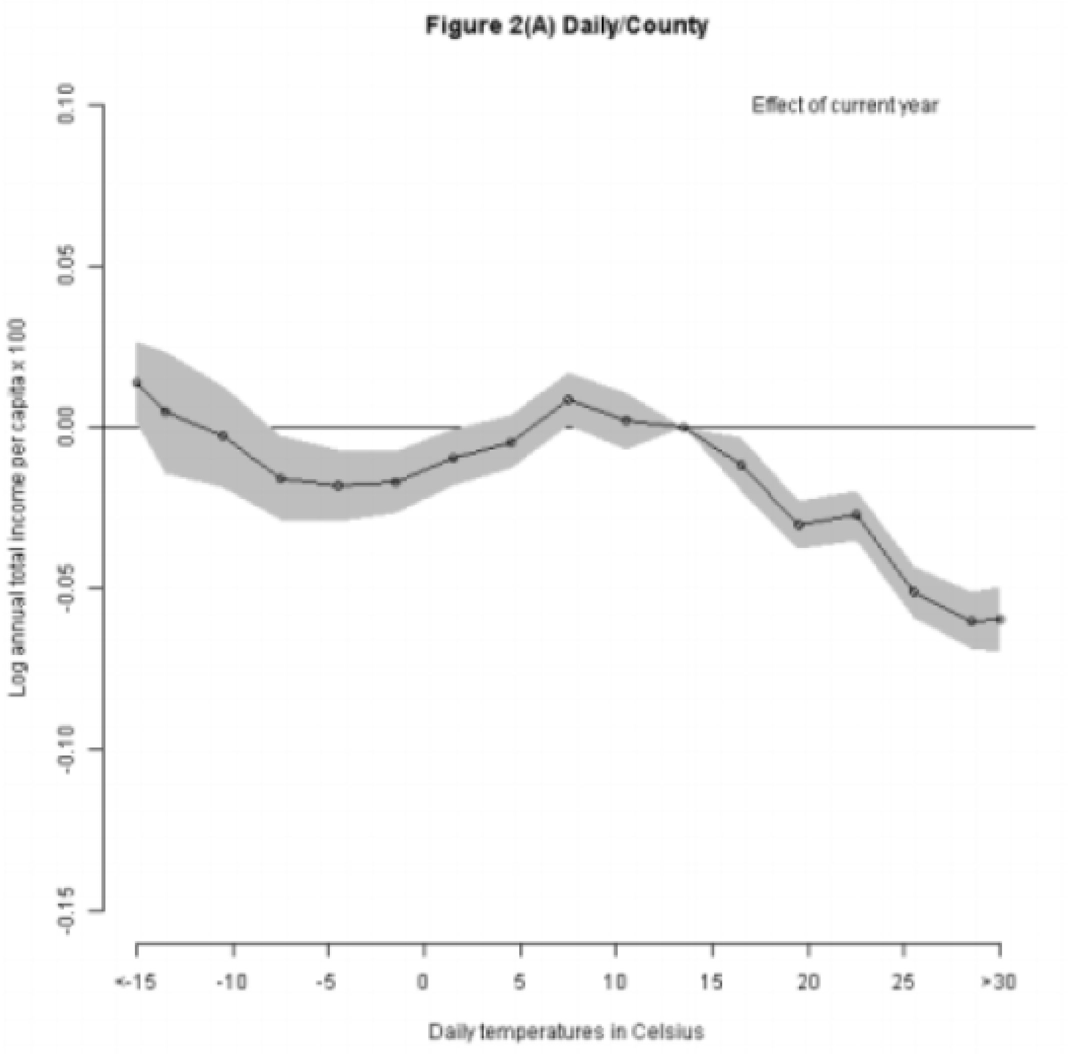
An example of the economic significance of local extreme events

- Illustrated by results in Schlenker, Fisher & Hanemann REStat 2006
- Distinguishes the effects of
  - Temperature within the regular range (8-32^{0}C)
  - Extreme temperature (above 34^{0}C)
  - Precipitation
- The overwhelming majority of the impact is associated with changes in the occurrence of extreme temperature.
- This has implications for what we should be measuring, and in which locations

Importance of extreme temperature, especially near-term (Schlenker et al., 2006)

	Proportion of net economic loss to US agriculture due to change in:	
	Precipitation & degree days 8-32C	Degree days over 34C
2020-2049 both emission scenarios 2070-2099 B1 scenario	10-20%	80-90%
2070-2099 A1Fi scenario	40%	60%

Another example (seen above): extra days with temperatures > 18C reduce GDP



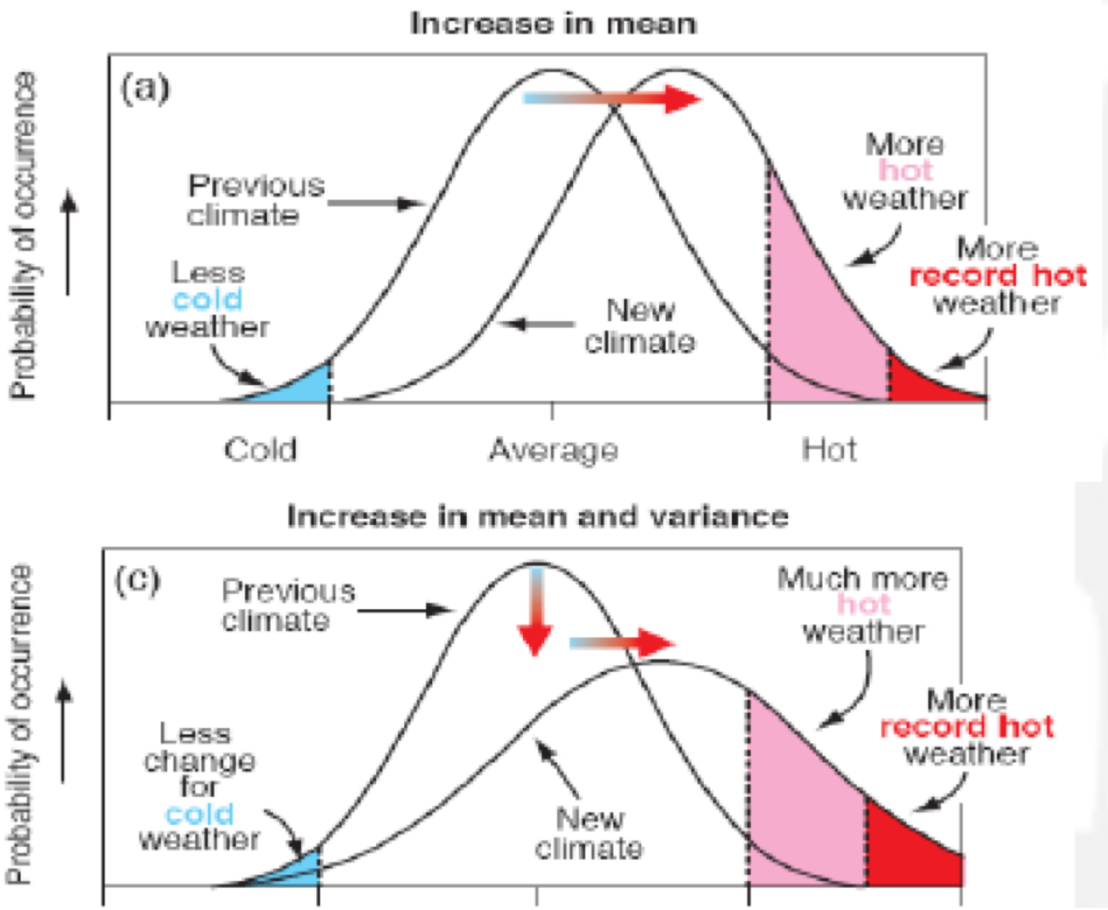
- It seems likely that, for the next three or four decades at least, most of the economic effects of climate change will be associated with such local extreme events.
  - If they occur infrequently, the economic effects will be small.
  - If they occur frequently, those effects will be larger.
- To model the incidence of local extreme events, one needs a fine spatial scale – with spatial downscaling – and one needs a finer temporal scale than the GCM outputs that have typically been used so far.
  - Daily rather than monthly.
  - In some cases (e.g., floods, energy demand and supply) hourly.
- Extreme events are not captured in existing damage functions used in the IAMs, which are framed around the change in *annual average* (*global*) temperature.

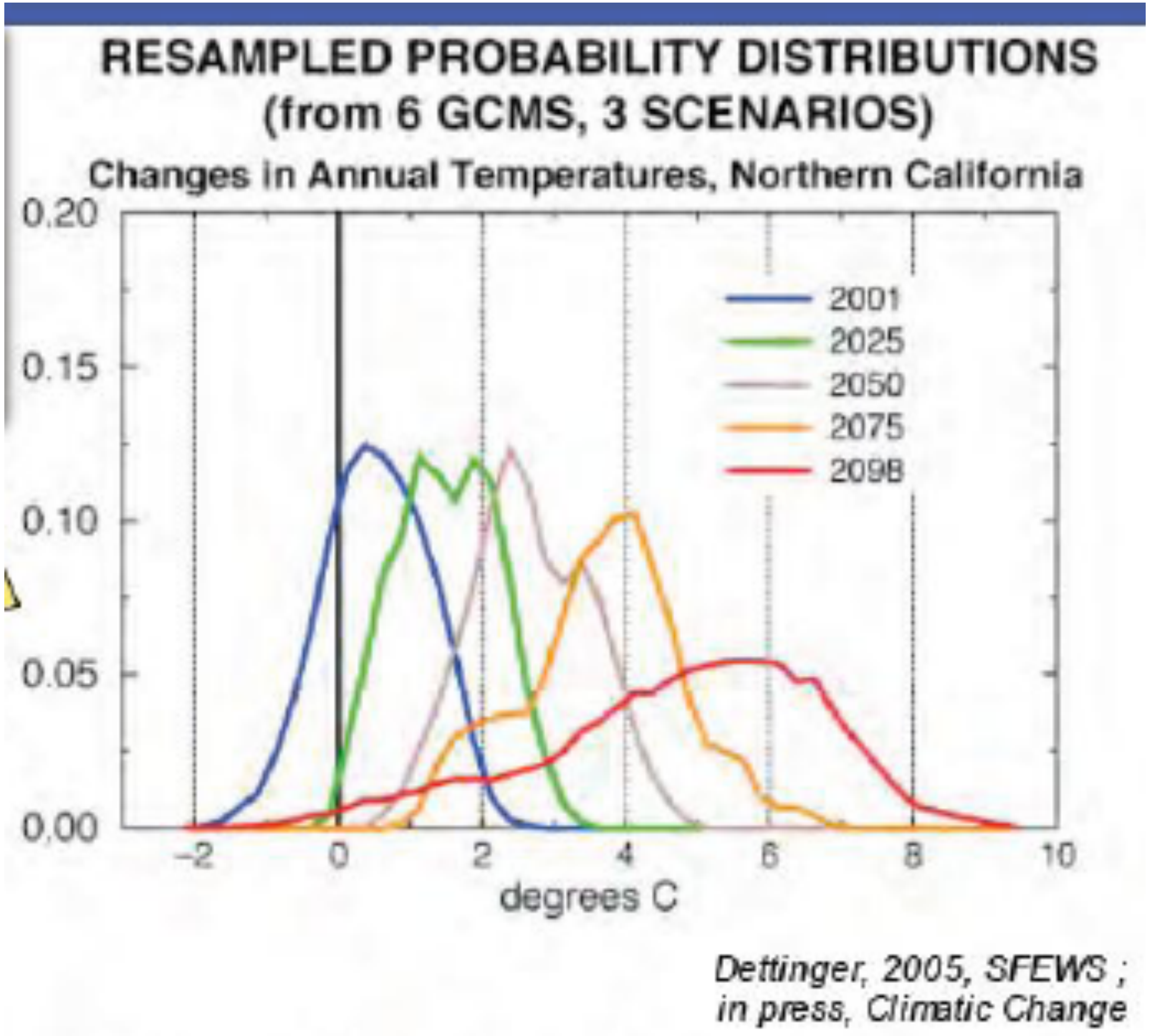
How are extreme events defined?

- Two perspectives:
- Climate perspective
  - An unusually high (or low) temperature or level of precipitation
    - Depends on the distribution temperatures/precip levels, extreme defined as higher than, say, the 90% quantile based on the past experience.
- Damage (impact) perspective
  - An unusually harmful consequence
    - Depends on the damage this causes – on the shape of the damage function. The outcome crosses a threshold.
  - Both become more likely as warming continues

Nonlinearities & extreme events

Exponential increase in probability of extreme event




RESAMPLED PROBABILITY DISTRIBUTIONS
(from 6 GCMS, 3 SCENARIOS)
Changes in Annual Temperatures, Northern California
0.20
0.15
0.10
0.05
0.00
-2
0
2
4
6
8
10
degrees C
2001
2025
2050
2075
2098
Dettinger, 2005, SFEWS ;
in press, Climatic Change

Nonlinear increase in flooding

- In winter storm, waves can be 5-6 ' higher than mean sea level. Therefore can have flood damage before sea reaches level of land.
- Scripps analysis based on an extreme wave: occurred 1 hour per year in San Francisco 1960-1980.
- By 2000, it was occurring 15-20 times per year.
- If the mean sea level at San Francisco rises by 20 cm between 2000 and 2100, expected to occur about 150-200 times per year.
- If it rises by 40 cm, an extreme hourly event would occur about 1,500 times per year.
- If it rises by 60 cm, an extreme hourly event would occur about 7,000 times per year.
- If it rises by 80 cm, an extreme hourly event would occur about 20,000 times per year.

Nonlinear increase in consequences

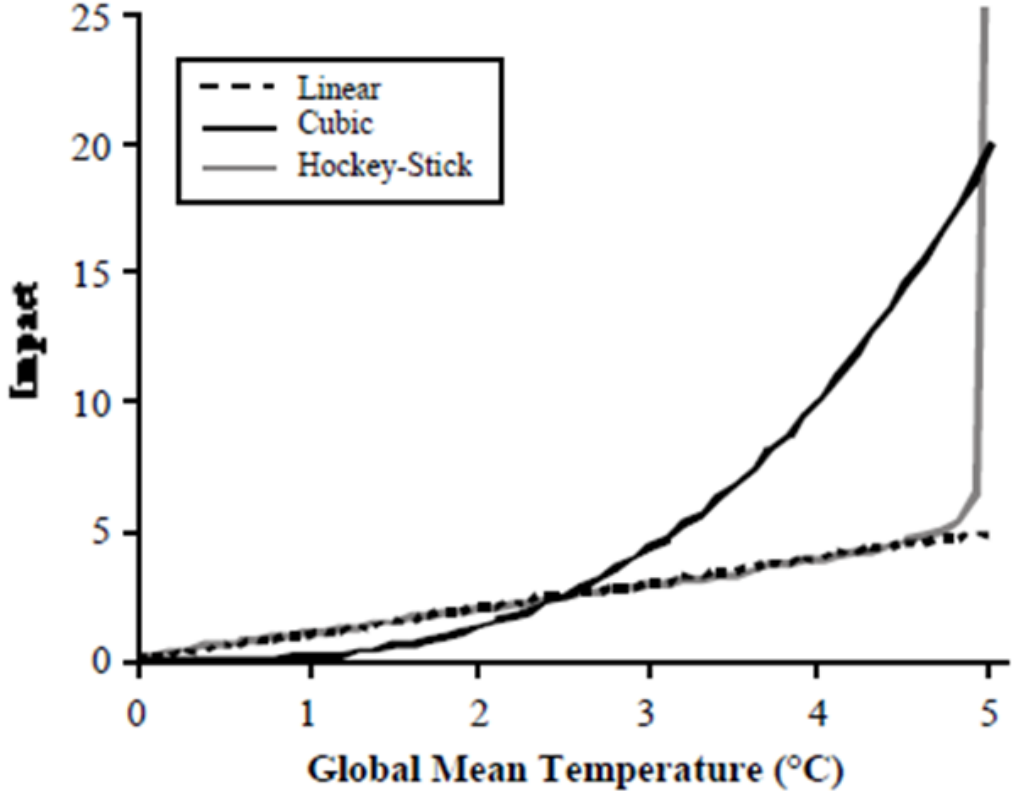


Figure 19-5: Aggregate impact of climate change as a function of global mean temperature. Displayed are hypothetical examples of a linear function, which assumes that impacts are proportional to temperature change since preindustrial times;

Risk

Bringing risk into the picture

- It has been argued – correctly in my view – that climate mitigation policy should be seen as an exercise in risk management. Reducing emissions today is a form of insurance against possible adverse future consequences.
- To make this approach meaningful, one needs to measure the risks.
- This is not done much in current assessments.
- Most of the economic analysis focus on the expected loss from climate change.
- In terms of economics, this is justified only if there is no risk aversion.
- That seems a very implausible assumption, given the types of outcomes that might occur with climate change.
- This creates twin imperatives of assessing risks more explicitly (i.e., more probabilistically) and also measuring risk aversion.

The challenge of risk measurement

- Uncertainty is an overwhelming feature of climate modeling. It enters every single step of the modeling exercise.
- Perhaps because it is so omnipresent, it has largely been swept under the rug – formally acknowledging and incorporating risk is an overwhelming task.
  - Model structure uncertainty; parameter estimation uncertainty; emission scenario uncertainty; uncertainty in climate model outputs; uncertainty of impacts.
  - Massive compounding and propagation of error.
- We will need to agree on what is a reasonable way of introducing risk – where to bring it in explicitly, and where to leave it out.

An example: the US government's estimate of estimation of the Social Cost of Carbon (2010, 2013, 2015)

- Used DICE, FUND, PAGE.
- Weighted results equally across IAMs.
- Standardized the emissions that drive the models.
    - Changed DICE from an optimization to a simulation mode.
    - Projected emissions through 2300
        - Used the best known four of the ten BAU emissions scenarios from the EMF-22 model inter-comparison in 2008.
        - Added a fifth emission scenario keyed to 550ppm in 2100.
        - Extended the five emissions projections from 2100 to 2300.
- Monte Carlo simulation of the value of the climate sensitivity; 10,000 draws from the Roe-Baker distribution.
- Three discount rates: 2.5%, 3% and 5%.
- 150,000 simulations for each of DICE, FUND, PAGE.
    - 5 emission scenarios; 3 discount rates; 10,000 draws.

How to generate the SCC value for 20xx

A. Run the model with the given emission trajectory and the given value of the climate sensitivity.

   a. The model starts in January 2010 and runs to December 2300.

B. For each time period, calculate the warming and the resultant damage in that period.

C. Introduce a one-time pulse of emissions in 20xx. In other periods, emissions are unchanged.

D. Re-run model.

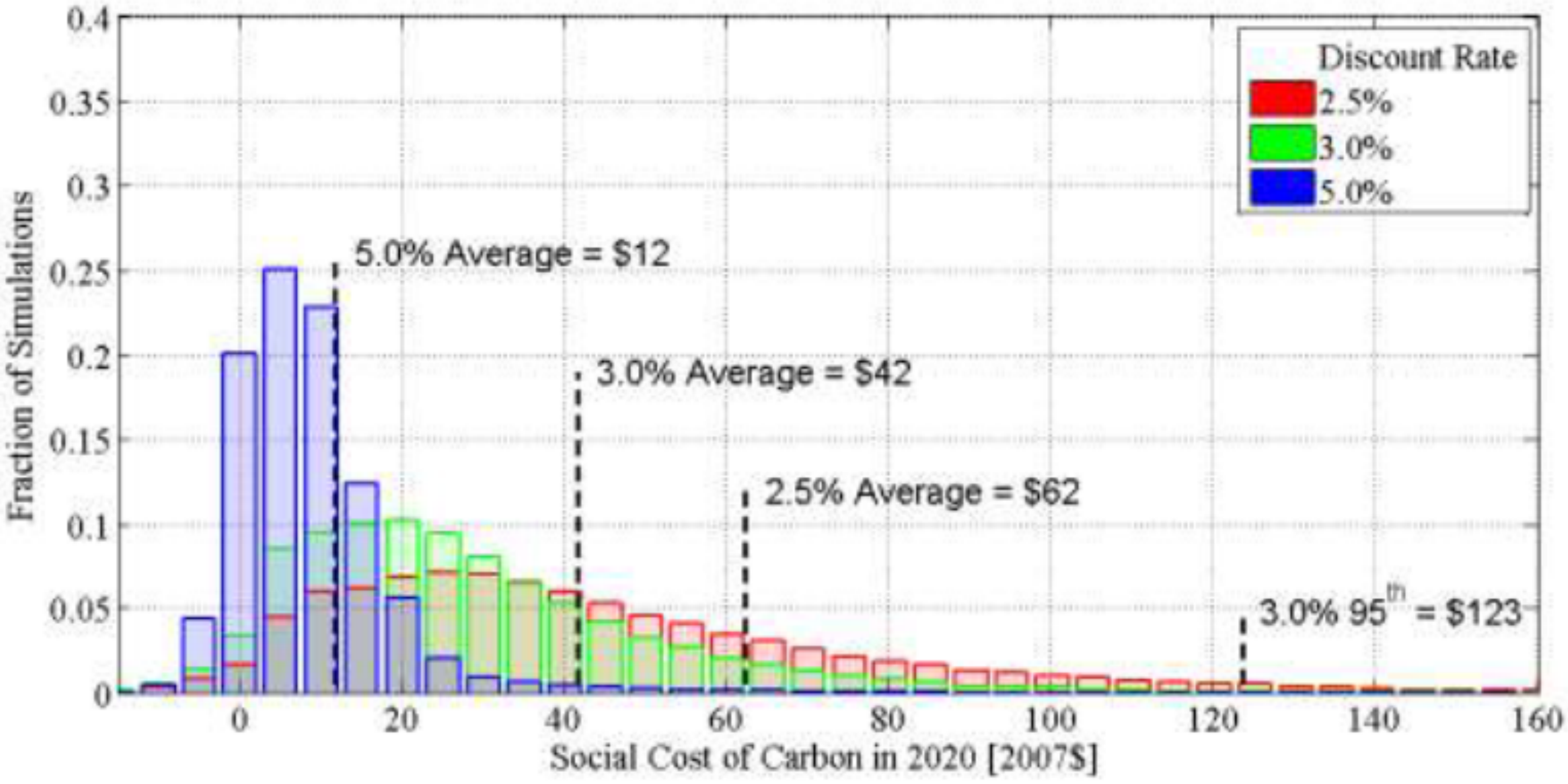
E. For each period, calculate the warming and the resultant damage in that period.

F. Calculate discounted present value of the differences in damages, (E) - (B), from 20xx through 2300.

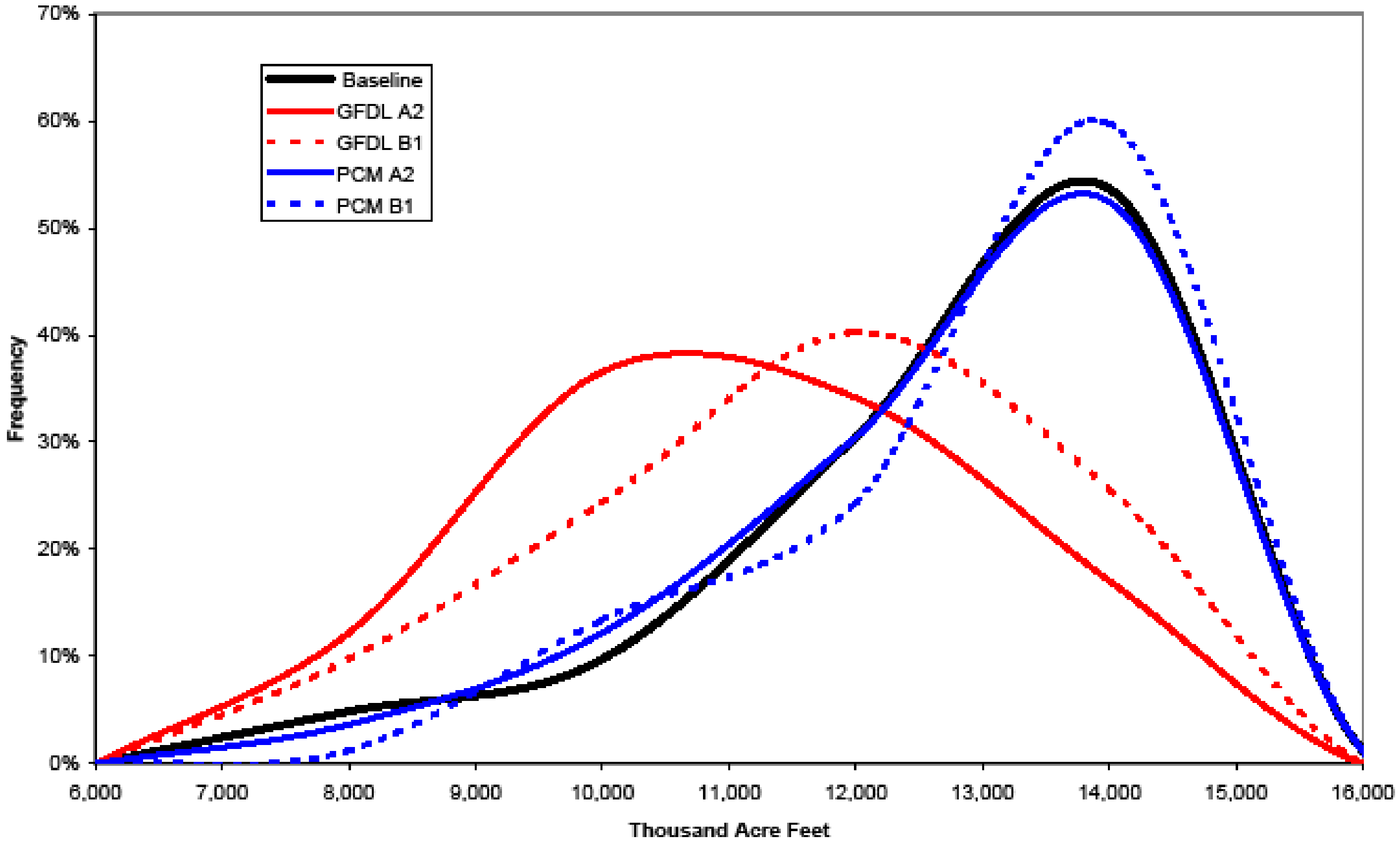
A distribution of SCC values

- For each of the three models, and each of the three discount rates, this generates an empirical pdf distribution of 50,000 values.
- The IWG presented the mean, and also the 95-percentile value, across the 150,000 values for each of the 3 models combined, using the given discount rate,

Distribution of SCC Estimates for 2020 (in 2007$ per metric ton CO_2)



Annual deliveries to Central Valley agriculture, 2085



Another example, some ways of bringing in risk measurement in the context of a statistical analysis

- Running conventional regression, but using assumed normality (?) of error distribution to generate an estimate of a tail probability.
- Using quantile regressing.
- Estimating order statistics (e.g., worst rainfall flooding)
- Combining alternative estimates found in the the literature via Bayesian Model Averaging

Accounting for risk aversion

- Once probability distribution of outcomes has been calculated, how can the risk be characterized?
  - Measure a tail probability – e.g., there is a 5% chance that GDP in 2050 will be reduced by x due to climate change; or a 10% chance that it will be reduced by y.
  - Calculate a risk premium and subtract it from the expected value to obtain a certainty equivalent – e.g., given a risk aversion coefficient value of 2.5, the reduction in GDP is equivalent to a reduction of x.
    - Conventional risk aversion
    - Downside risk aversion
    - Ambiguity aversion

In summary

- Accounting for the possible consequences of climate change in a thoughtful and meaningful manner presents many challenges for (applied) mathematicians.
- Please become involved!