Lecture 2

Climate Modelling and Uncertainty about Future Climate Change

Roman Frigg, LSE

Finally, the total energy emitted per second and per square meter by an object at temperature T is:

$$P = \sigma T^4$$

"Stefan-Boltzmann Law", where σ is the Stefan-Boltzmann constant.

($\sigma = 5.67*10^{-8}\,Wm^2/K^4$)

Main Aim of this Lecture

Understand what kind of thing a global climate model is, how it is constructed, and what uncertainties attach to it.

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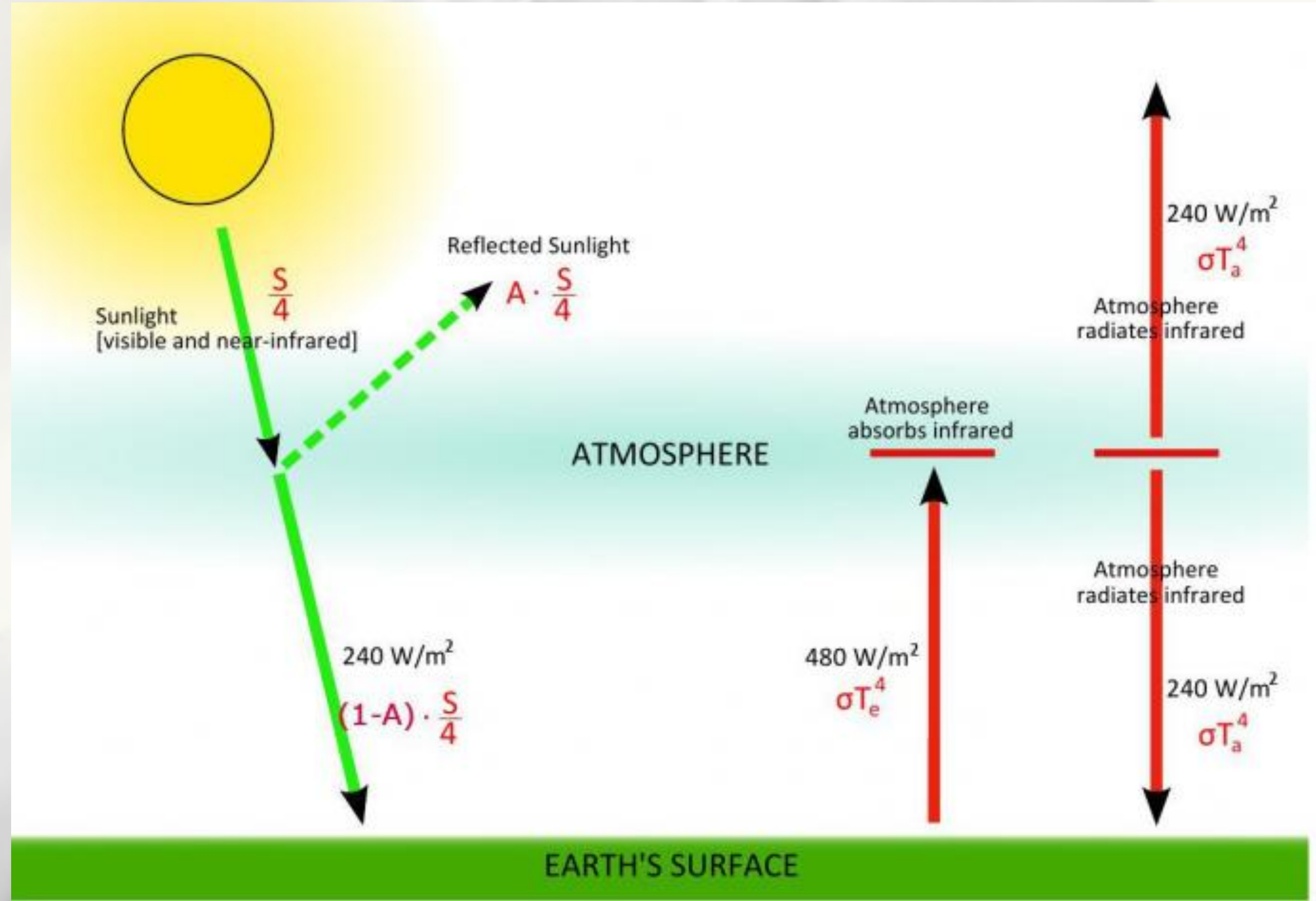
Uncertainty:

Plan

1. Recapitulation: EBMs in Lecture 1
2. Extending Simple EBMs
3. The Architectonic of a GCM
4. Uncertainty
5. Manifestations of Uncertainty
6. Multi Model Ensembles
7. Living with Uncertainty

1. Recapitulation: EBMs in Lecture 1



Modelling assumptions:

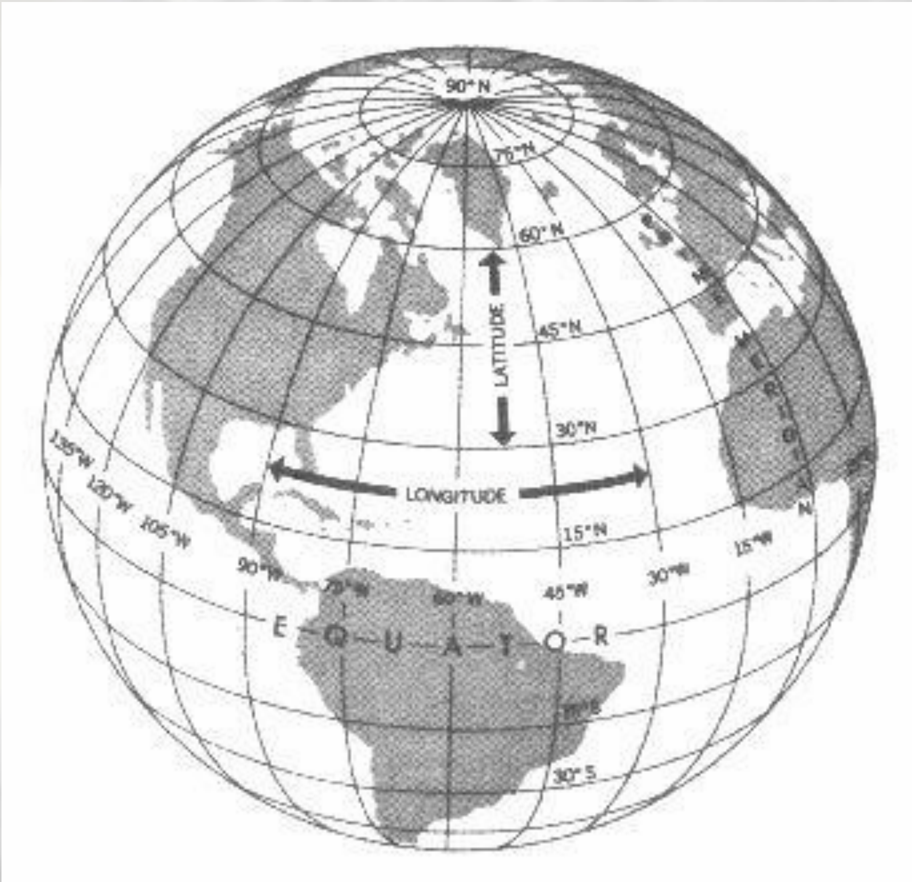
- The earth is a homogeneous sphere radiating equally in all directions.
- Albedo is the same everywhere
- The earth receives the same amount of solar energy everywhere.
- The surface of the earth is static (no flow of matter on the earth).
- The atmosphere is static (no flow of matter in the atmosphere).
- No rotation
- ….

These assumptions are unrealistic!

Possible extensions and factors to account for:

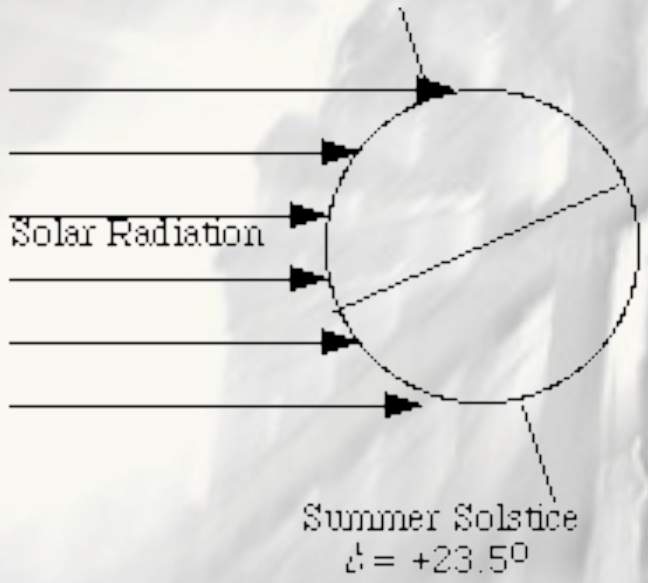
- Land and water
- Different albedo for land and water
- Ocean currents
- Atmospheric currents
- Topography (below and above water)
- Solar variability
- Vertical height in the atmosphere
- Vegetation
- …

Terminology:



2. Extending Simple EBMs

(a) Introduce a Latitudinal Dimension



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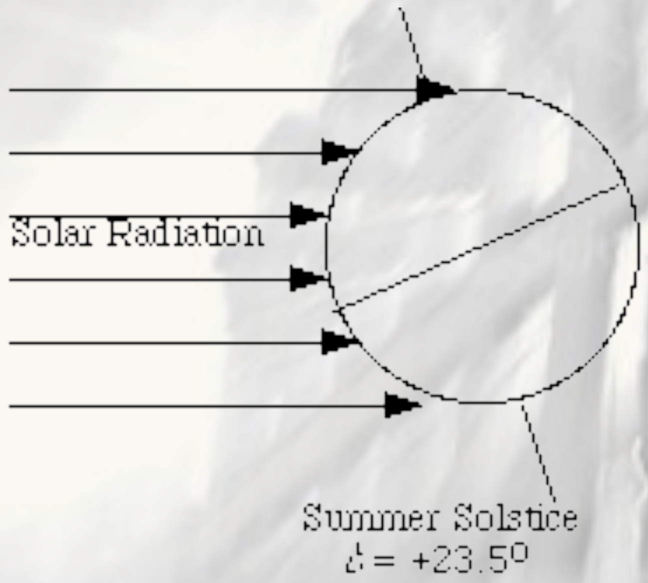
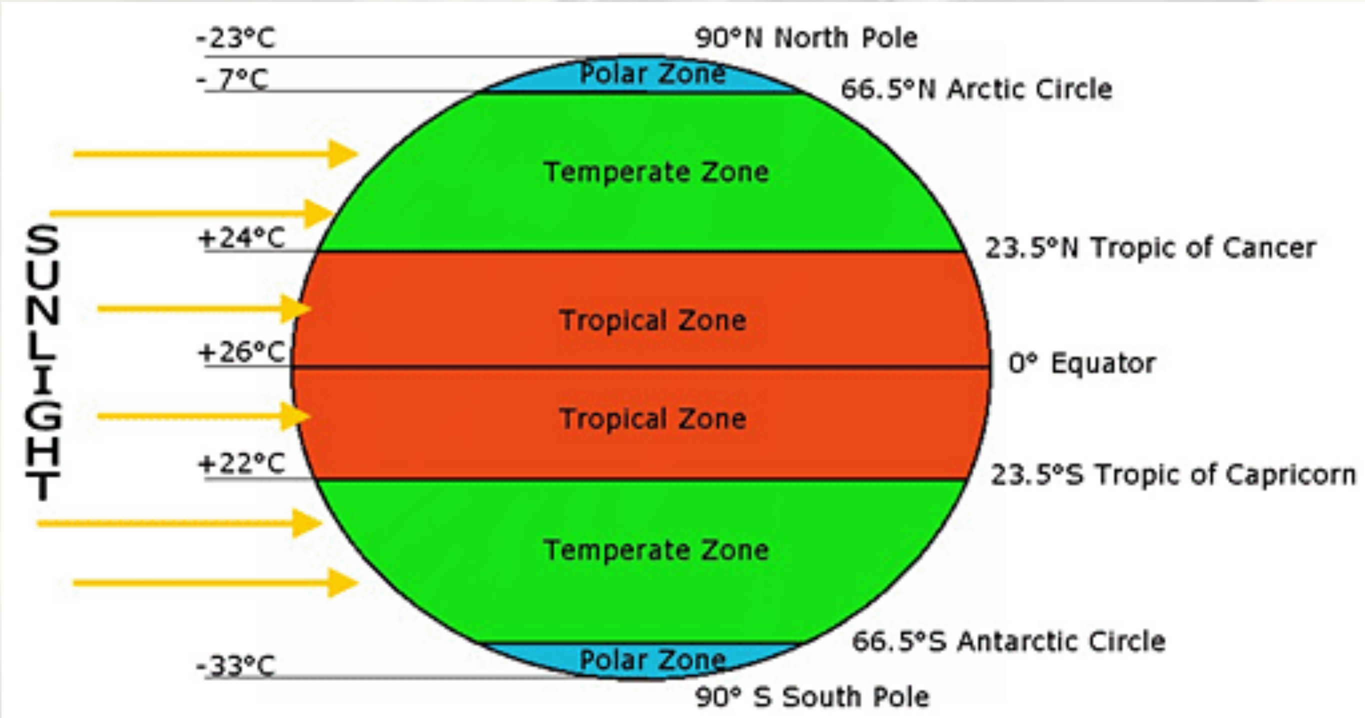


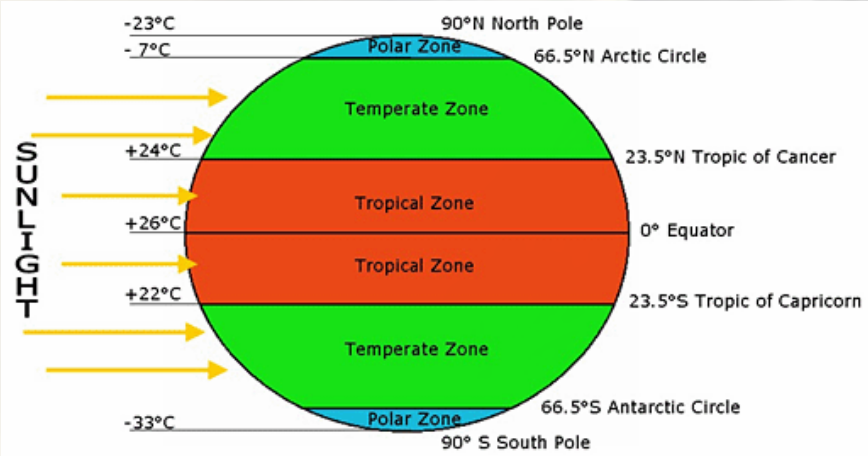
The equator receives more energy than the poles!

→ It's warmer at the equator than at the poles!

→ Latitude zones:



For simplicity, take the temperate and polar zones on each hemisphere together and call them SH-extra-tropics and NH-extra-tropics.



} one zone

Question: again using energy balance considerations, what is the equilibrium temperature, what is the equilibrium temperature on the three parts of the globe?

Calculations show:

Tropics: 59°C

SH and NH -extra-tropics: -73°C

(calculations assume earth is perpendicular)

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Tropics: 59°C

SH and NH -extra-tropics: -73°C

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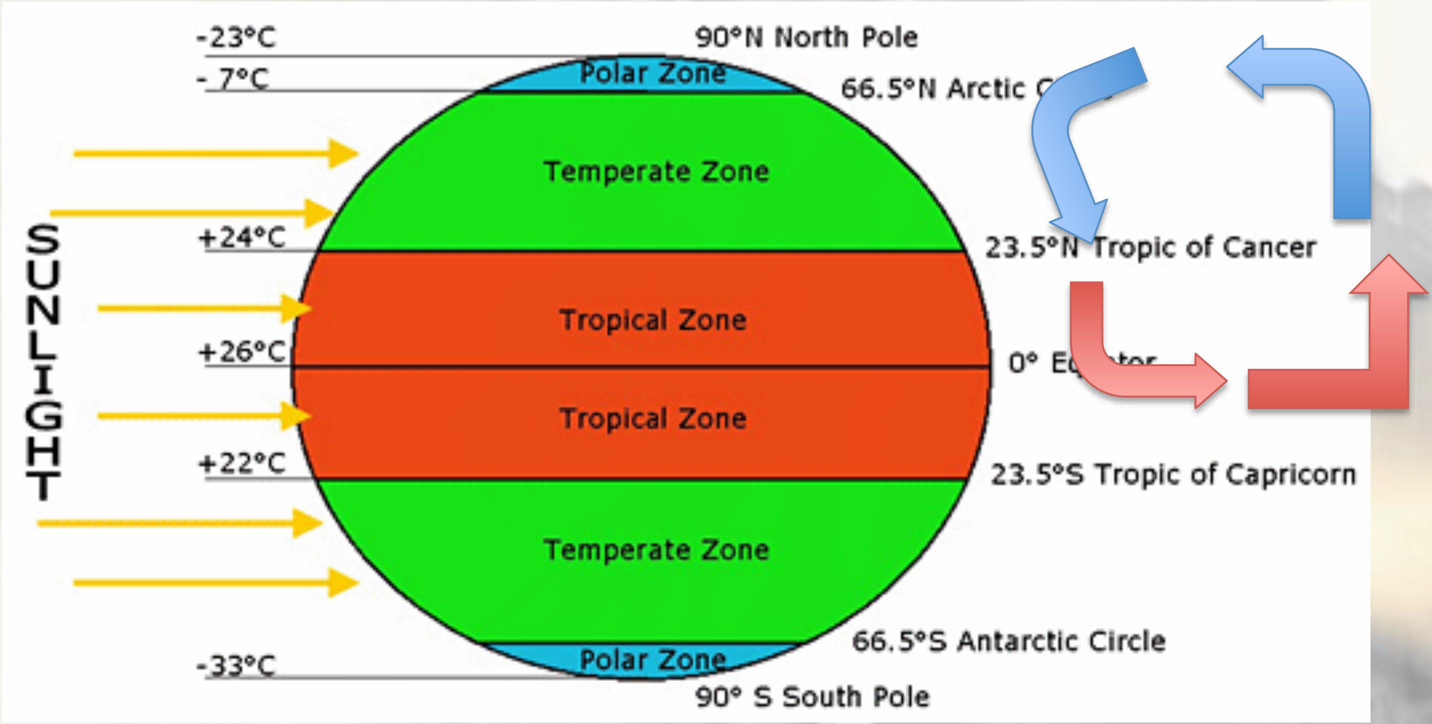
This is too extreme!

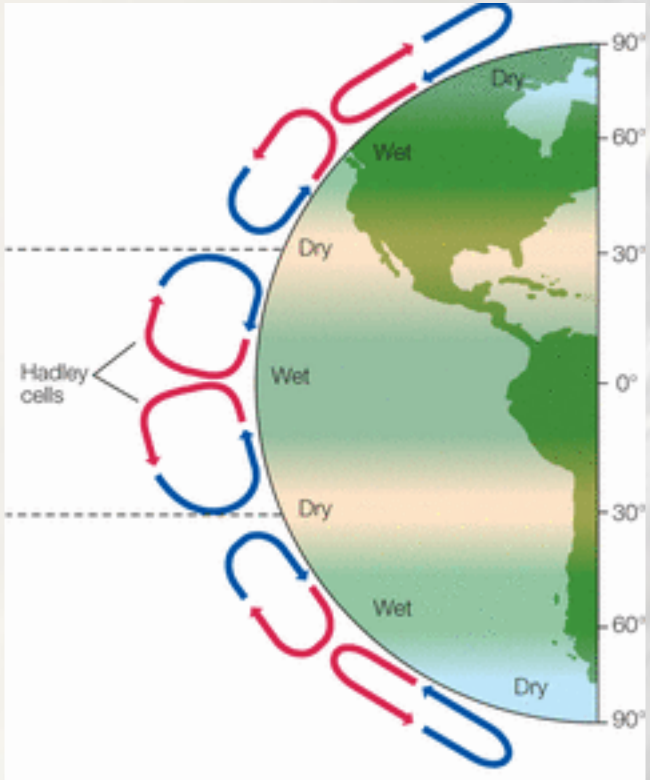
What are we missing?

→Latitudinal circulation!



→Convection cell.

In reality there are three cells:



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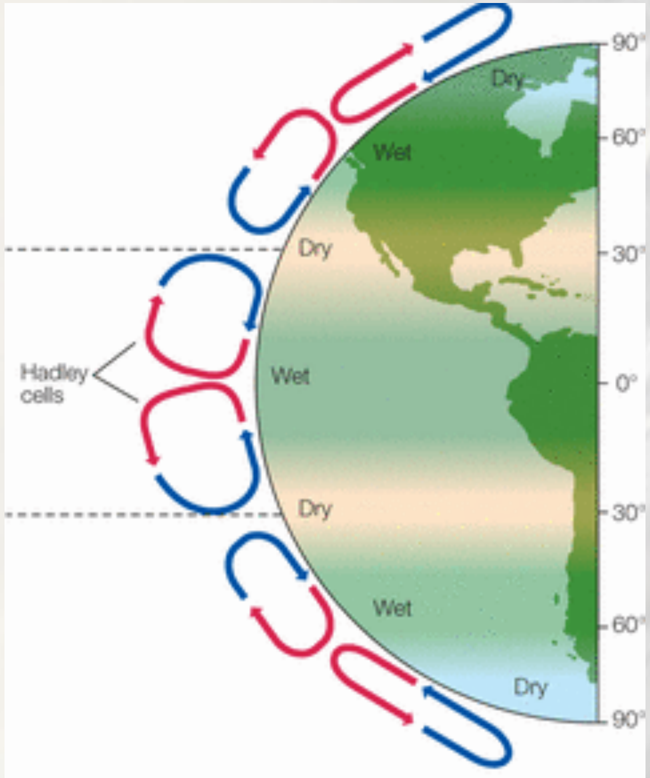
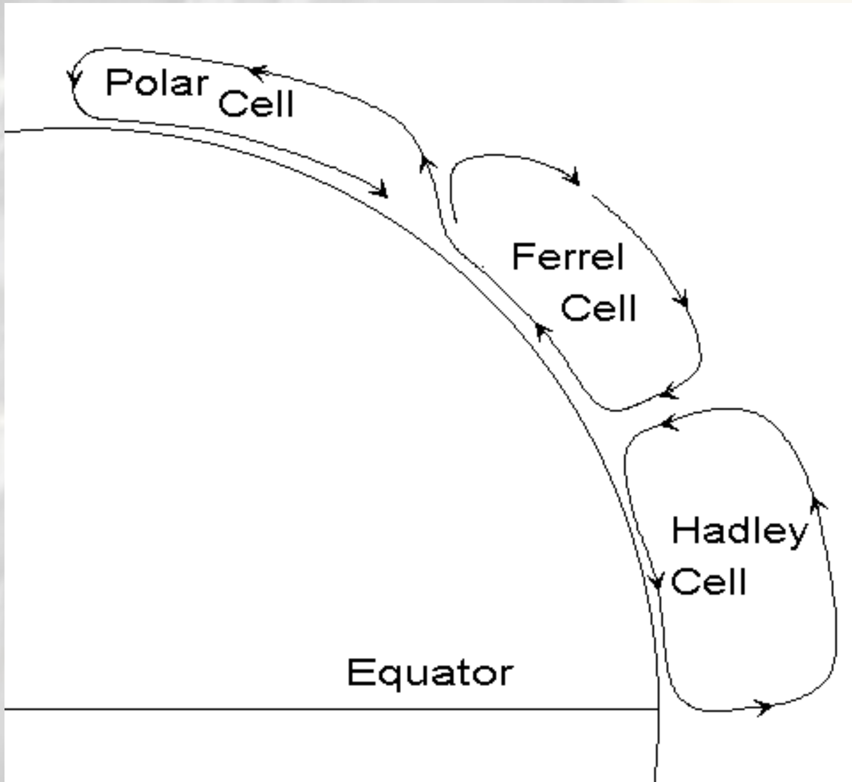
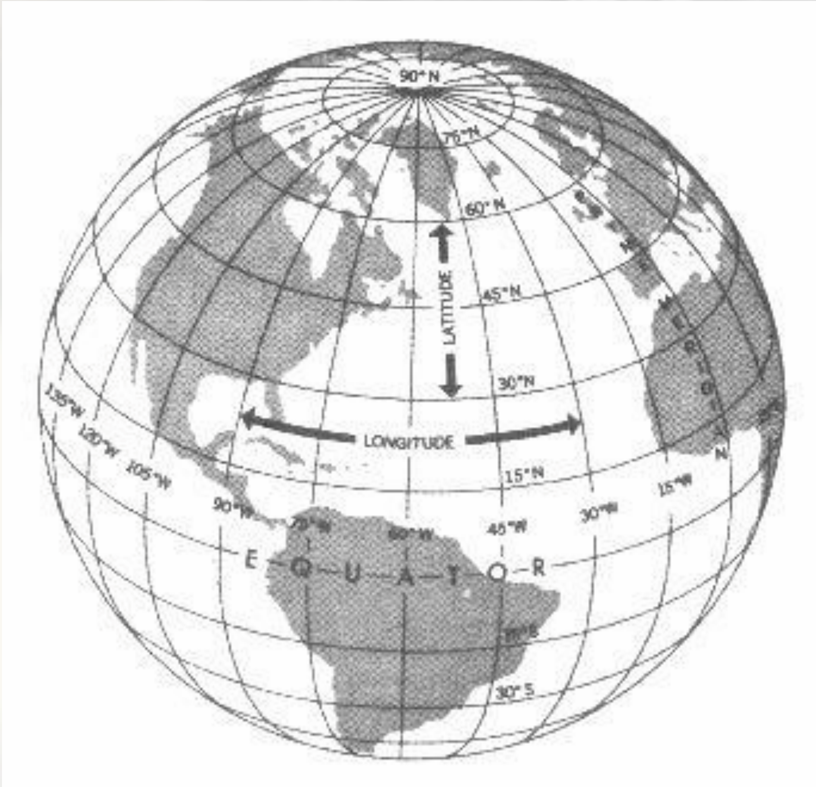


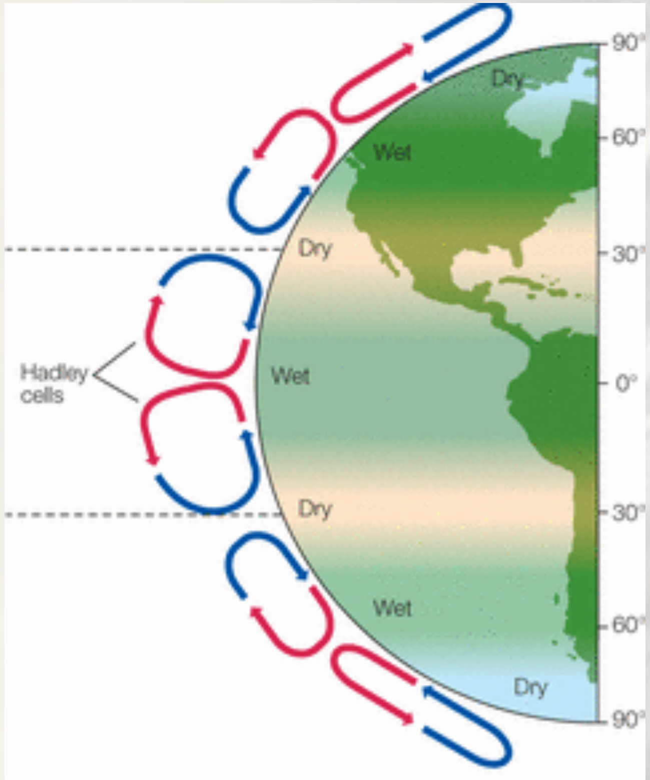


(b) Introduce a Longitudinal Dimension



We now allow motion both in latitudinal and longitudinal direction.

What happens?



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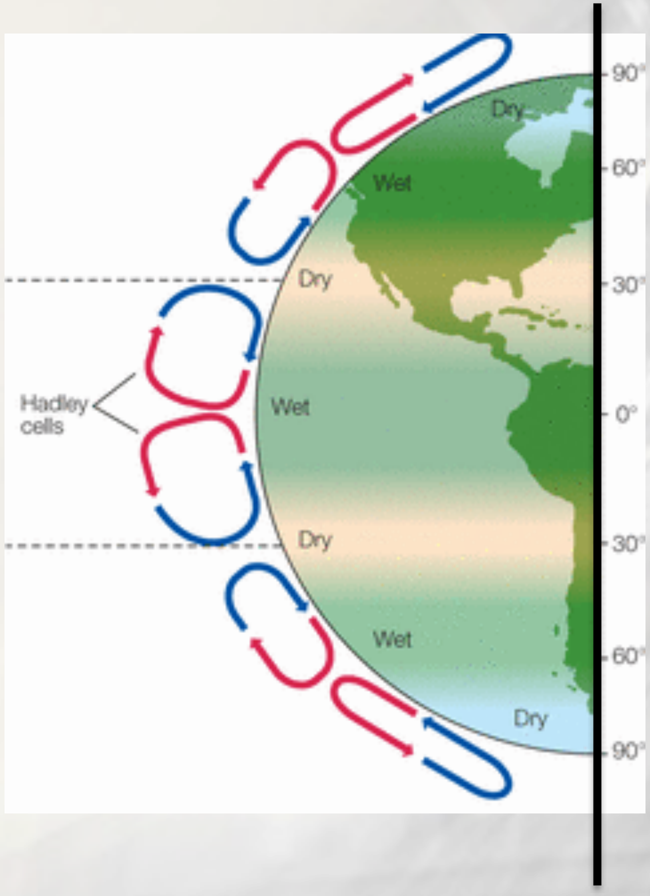
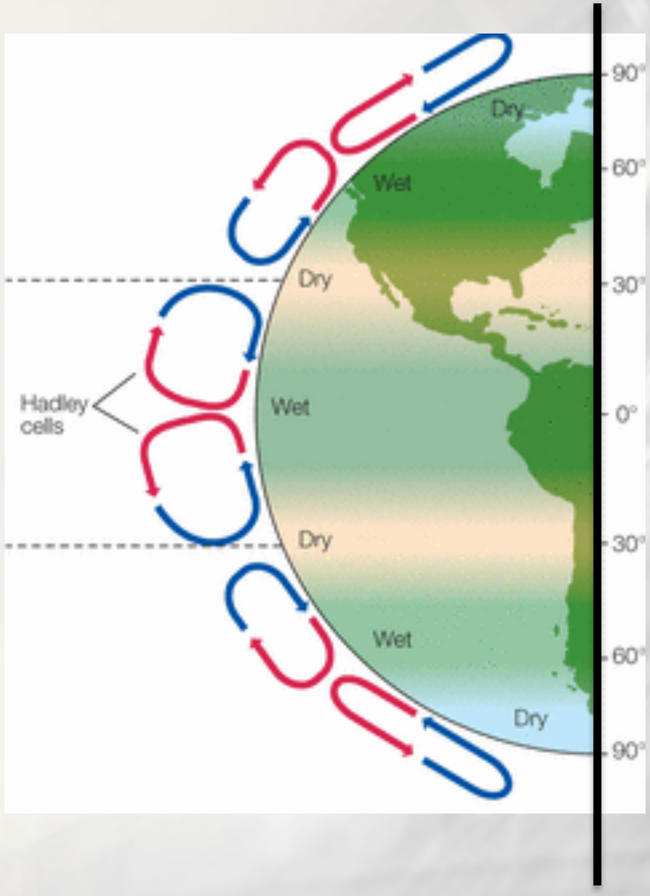


Crucial fact:
The earth is rotating!

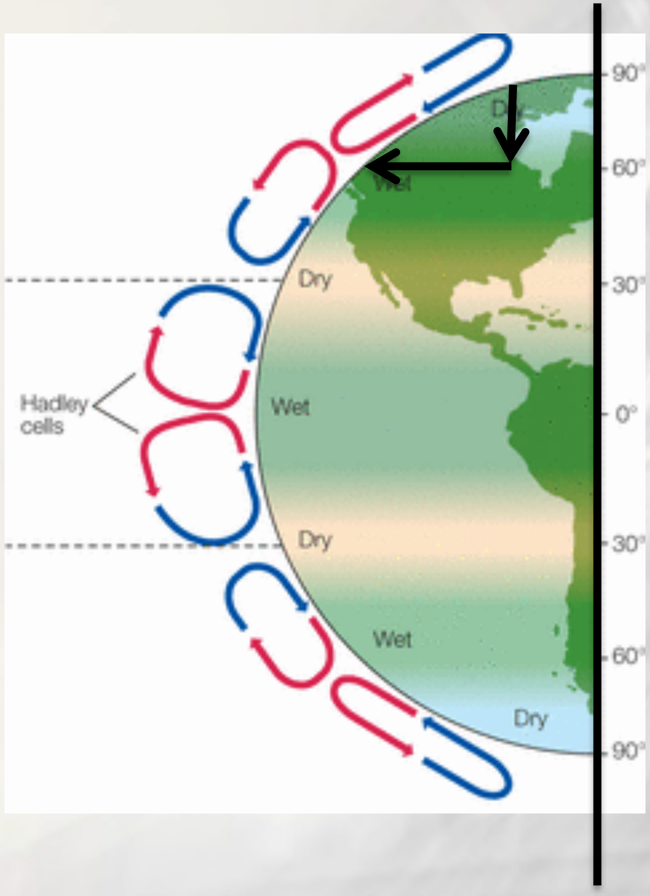
What happens?



Crucial fact:
The earth is rotating!

And:
We have a motion perpendicular to the axis of rotation.

What happens?



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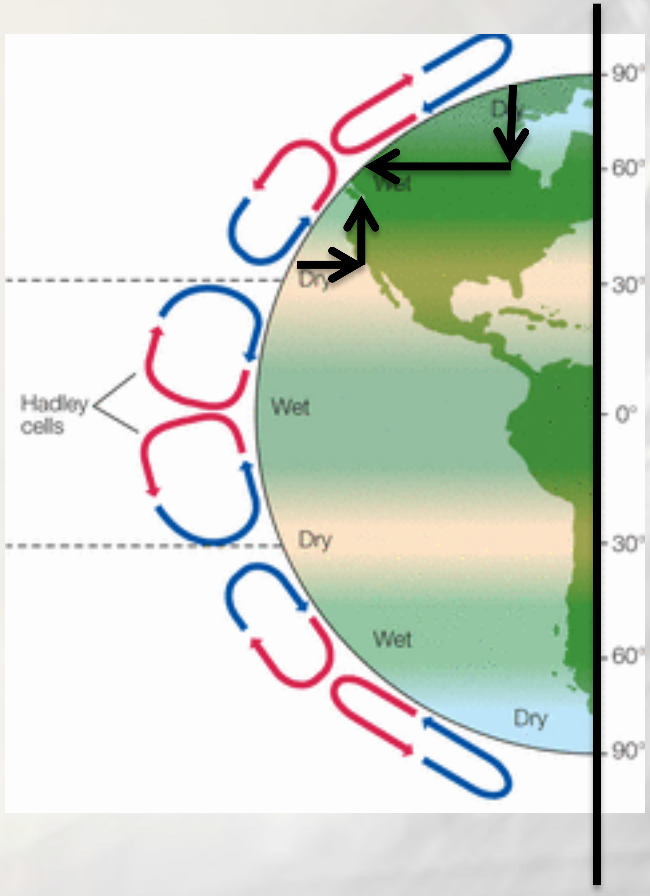

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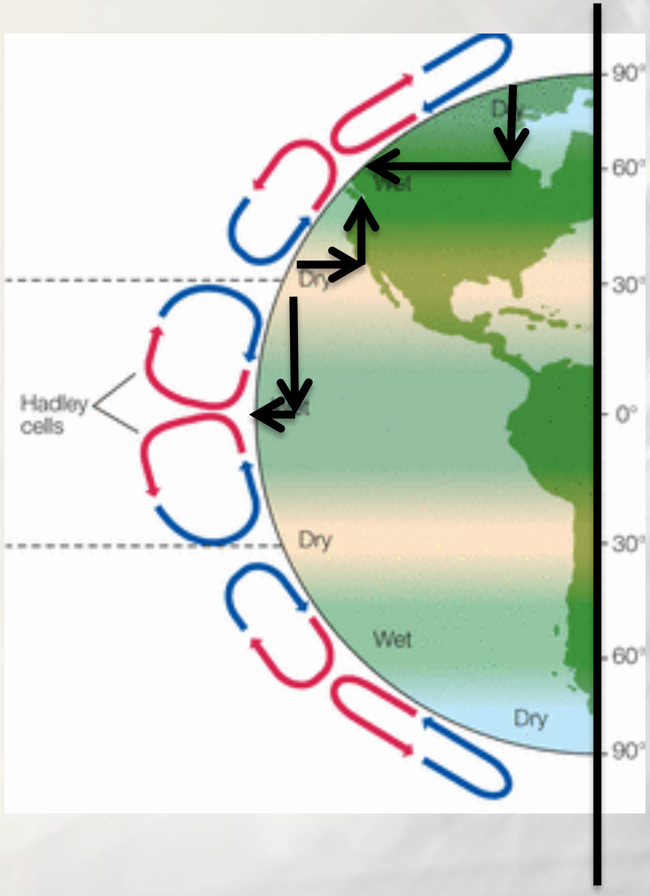

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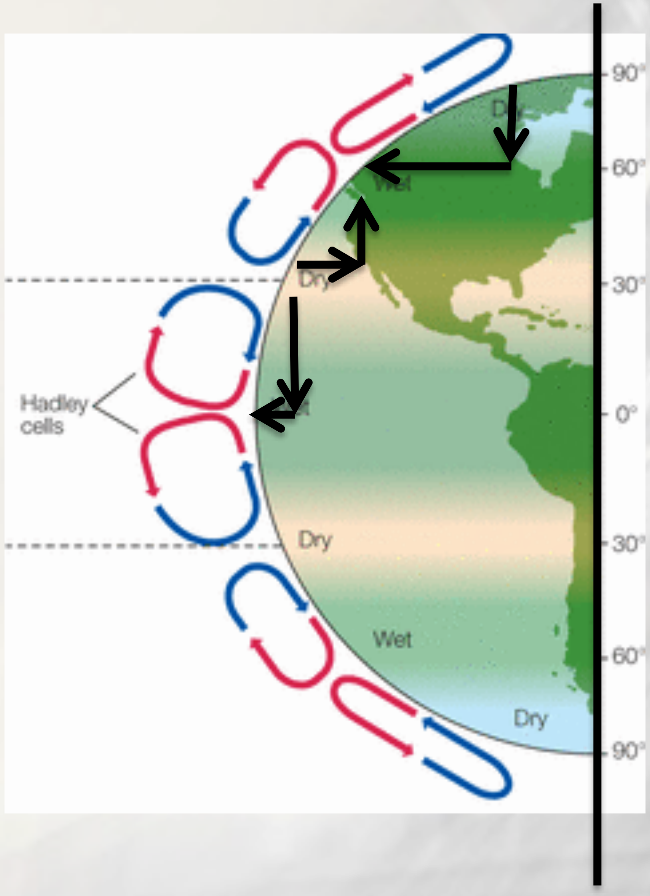

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→ **Coriolis Force**

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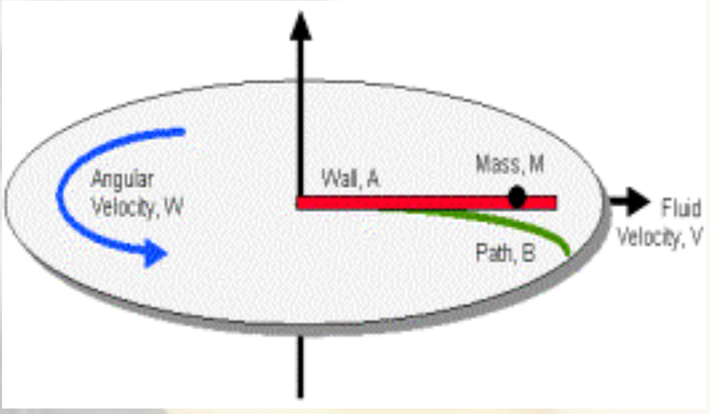
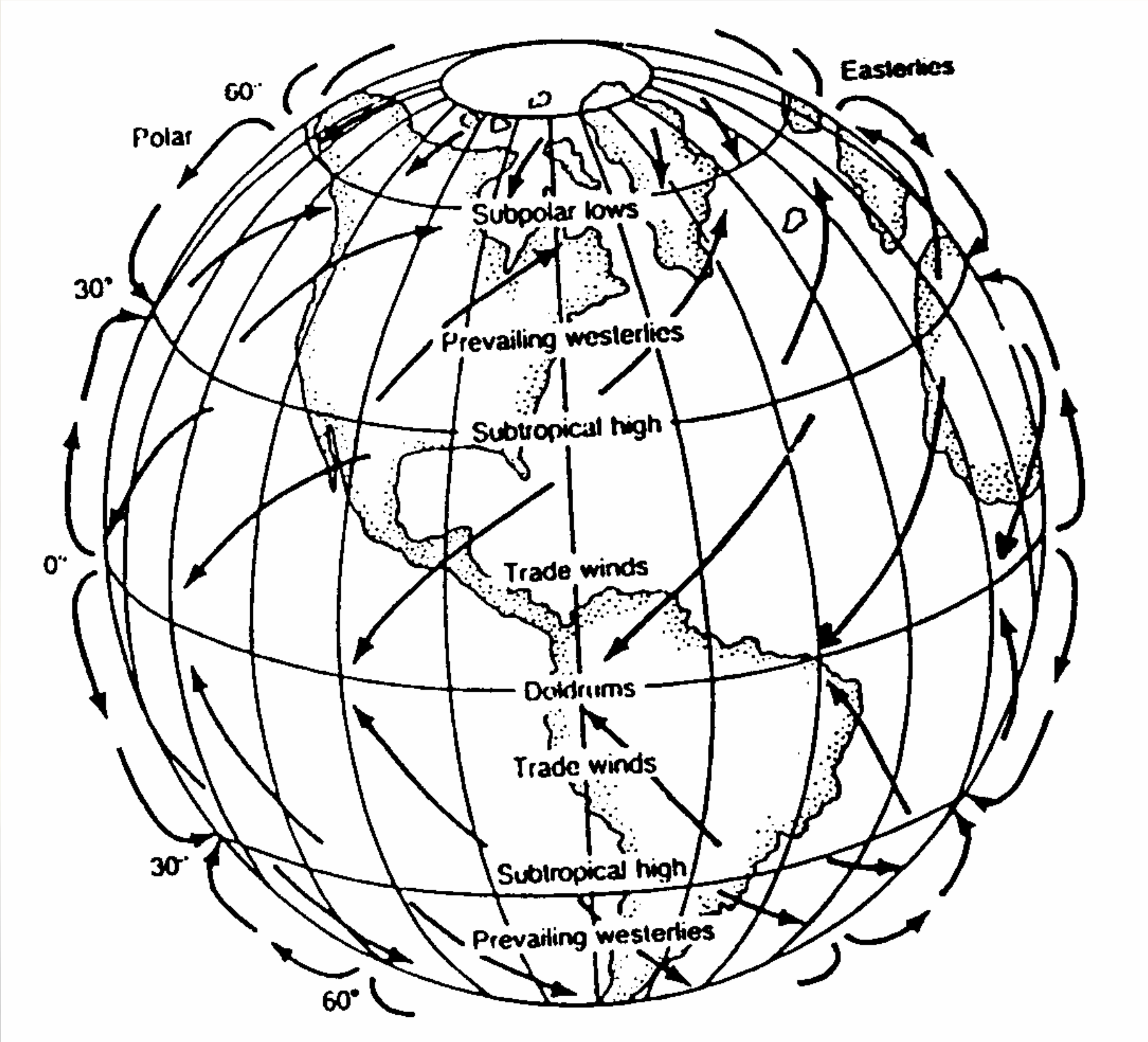


If you walk from the centre to the periphery, you are diverted.

→ **Left Hand rule!**


Easterlies
60°
Polar
Subpolar lows
30°
Prevailing westerlies
Subtropical high
0°
Trade winds
Doldrums
Trade winds
30°
Subtropical high
Prevailing westerlies
60°

- → These relatively simple considerations give the right overall pattern of global winds!
- → Simple example of a Radiative Convective Model (RCMs)

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→ Simple example of a Radiative Convective Model (RCMs)

Ways to refine our simple model:

- Differences in surface albedo
- Cloud albedo
- Heating rates of different atmospheric layers
- Topography of the earth!
- …

Missing altogether:

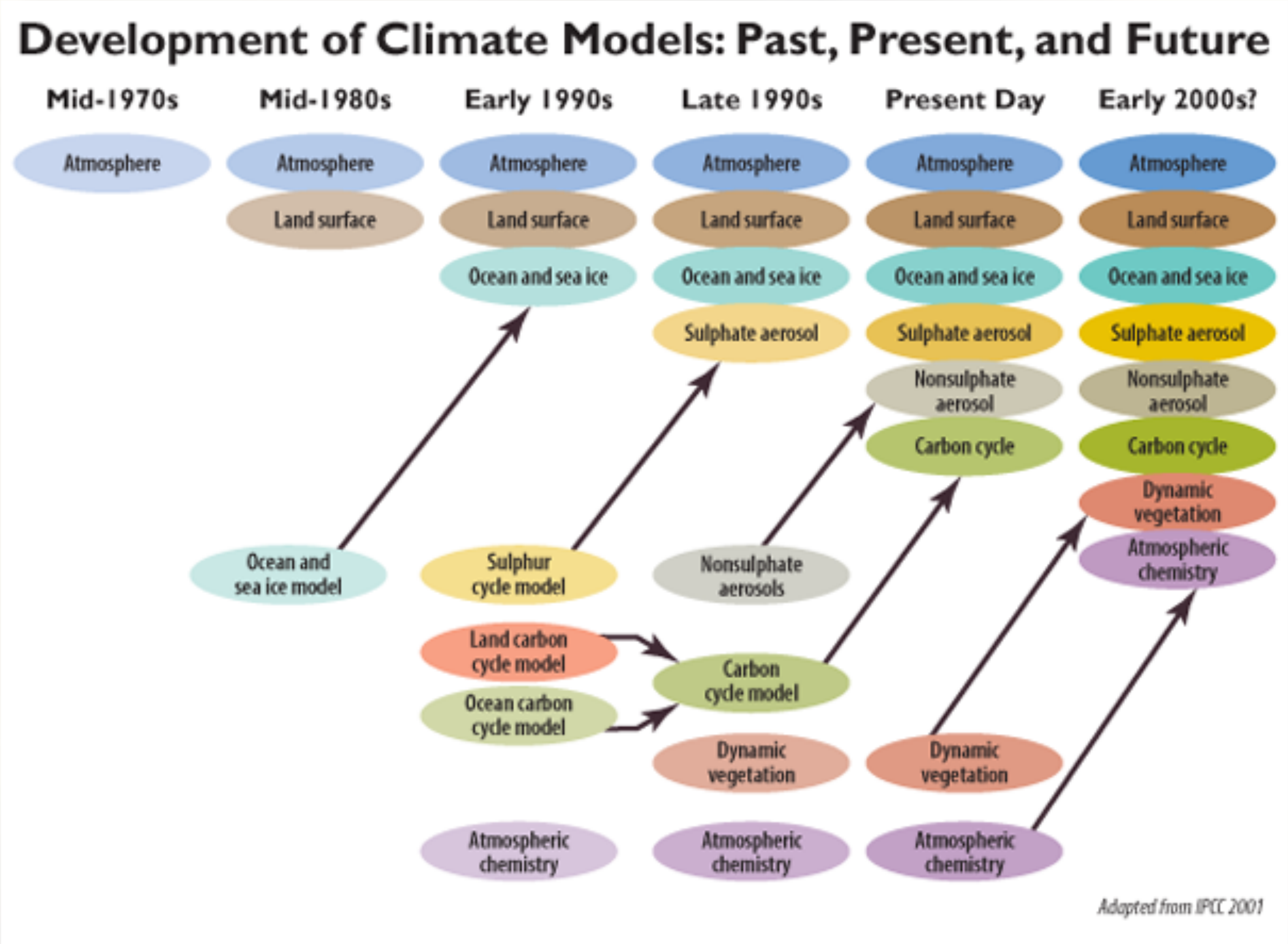
Ocean circulation!

This a crucial factor because the heat capacity of water is much higher than the heat capacity of air. Water and air *de facto* transport about the same amount of heat; water just does it much slower.

Integrating as many extra factors as possible leads to the construction of ever more complicated ***climate models***.

Historically this first happened in separate models, that then came together …

→ GCMs


Development of Climate Models: Past, Present, and Future
Mid-1970s
Mid-1980s
Early 1990s
Late 1990s
Present Day
Early 2000s?
Atmosphere
Atmosphere
Land surface
Atmosphere
Land surface
Ocean and sea ice
Atmosphere
Land surface
Ocean and sea ice
Sulphate aerosol
Atmosphere
Land surface
Ocean and sea ice
Sulphate aerosol
Nonsulphate aerosol
Carbon cycle
Atmosphere
Land surface
Ocean and sea ice
Sulphate aerosol
Nonsulphate aerosol
Carbon cycle
Dynamic vegetation
Atmospheric chemistry
Ocean and sea ice model
Sulphur cycle model
Nonsulphate aerosols
Land carbon cycle model
Ocean carbon cycle model
Carbon cycle model
Dynamic vegetation
Dynamic vegetation
Atmospheric chemistry
Atmospheric chemistry
Atmospheric chemistry
Adapted from IPCC 2001

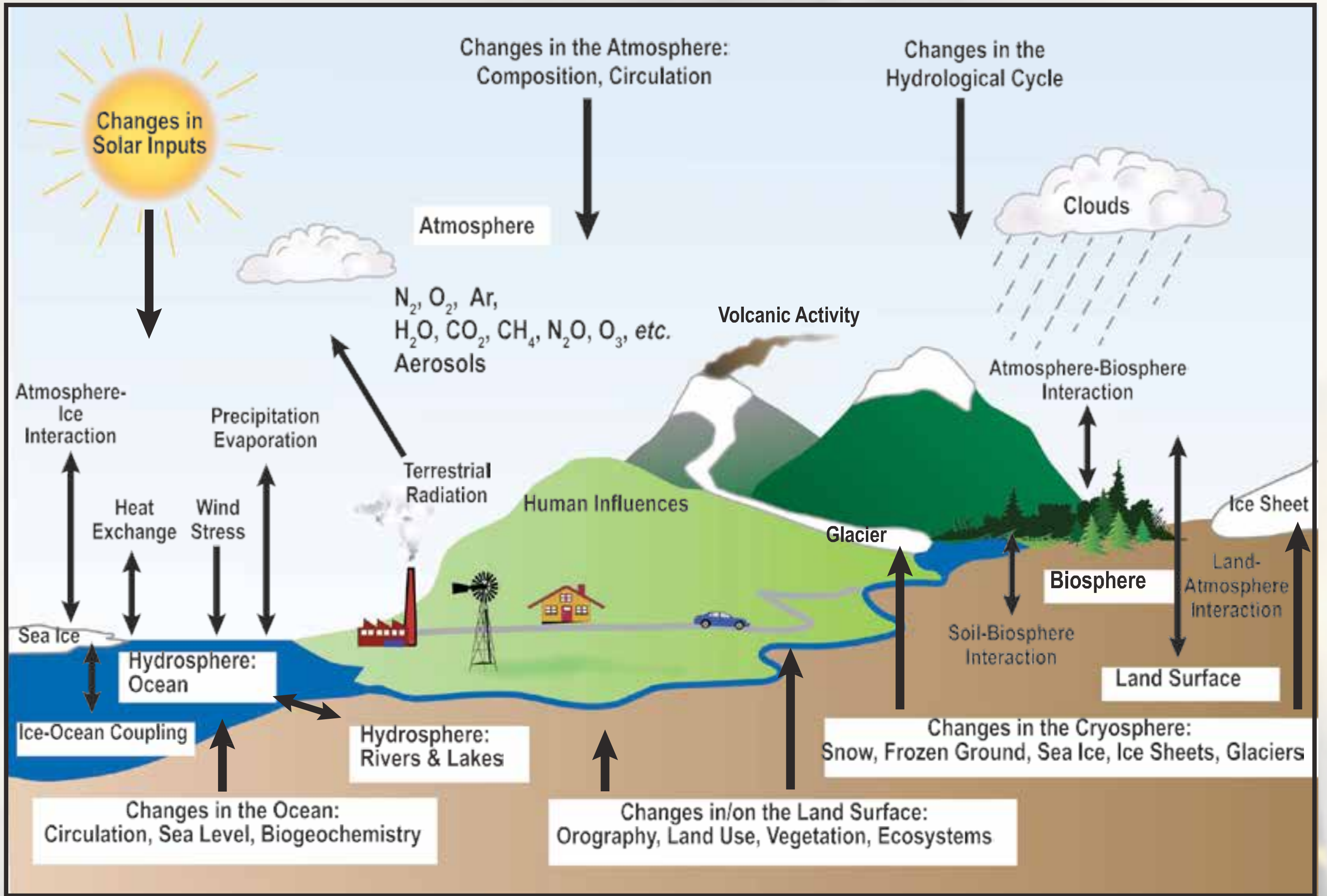
3. The Architectonic of a GCM

Dynamical core of a model: describes all the flows in the model.

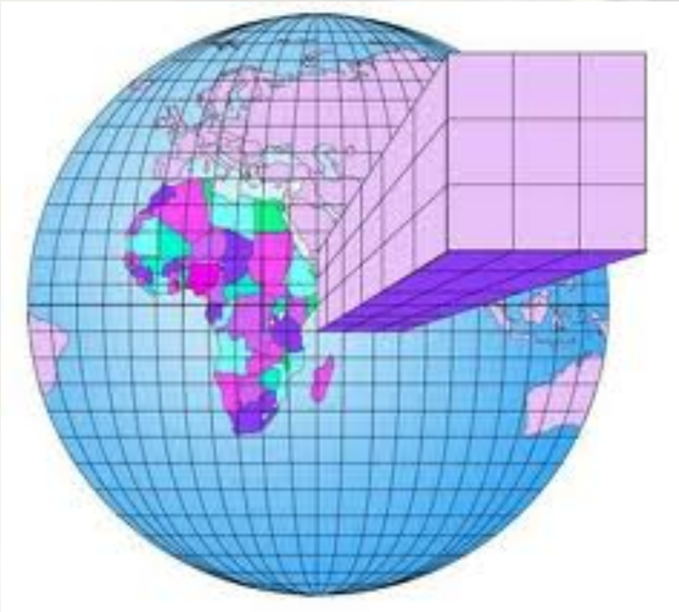
In theory these flows are completely described by the equations of fluid dynamics (the Navier-Stokes Equations).

In practice we usually can hardly write down these equations, and if we can we cannot solve them …

Reason: climate system is just too complex!


Changes in Solar Inputs
Changes in the Atmosphere: Composition, Circulation
Changes in the Hydrological Cycle
Atmosphere
Clouds
N_2, O_2, Ar, H_2O, CO_2, CH_4, N_2O, O_3, *etc.*
Aerosols
Volcanic Activity
Atmosphere-Biosphere Interaction
Atmosphere-Ice Interaction
Precipitation Evaporation
Terrestrial Radiation
Heat Exchange
Wind Stress
Human Influences
Glacier
Ice Sheet
Biosphere
Land-Atmosphere Interaction
Sea Ice
Hydrosphere: Ocean
Soil-Biosphere Interaction
Land Surface
Ice-Ocean Coupling
Hydrosphere: Rivers & Lakes
Changes in the Cryosphere: Snow, Frozen Ground, Sea Ice, Ice Sheets, Glaciers
Changes in the Ocean: Circulation, Sea Level, Biogeochemistry
Changes in/on the Land Surface: Orography, Land Use, Vegetation, Ecosystems

Simplification: grid



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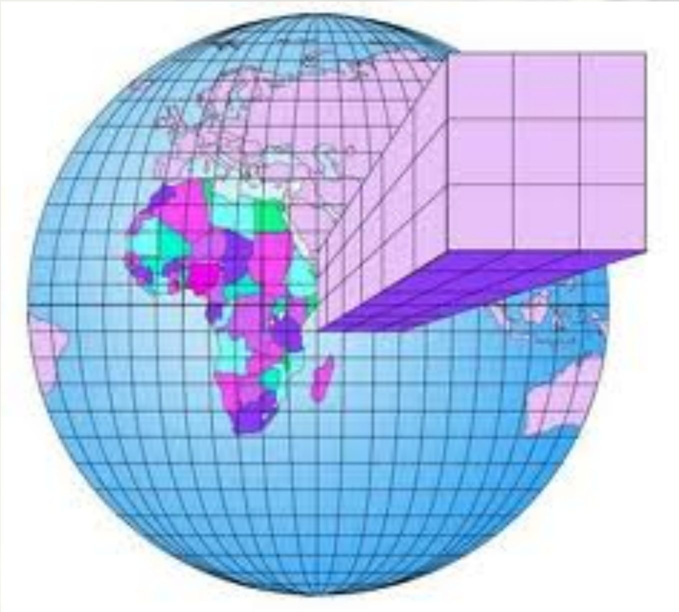

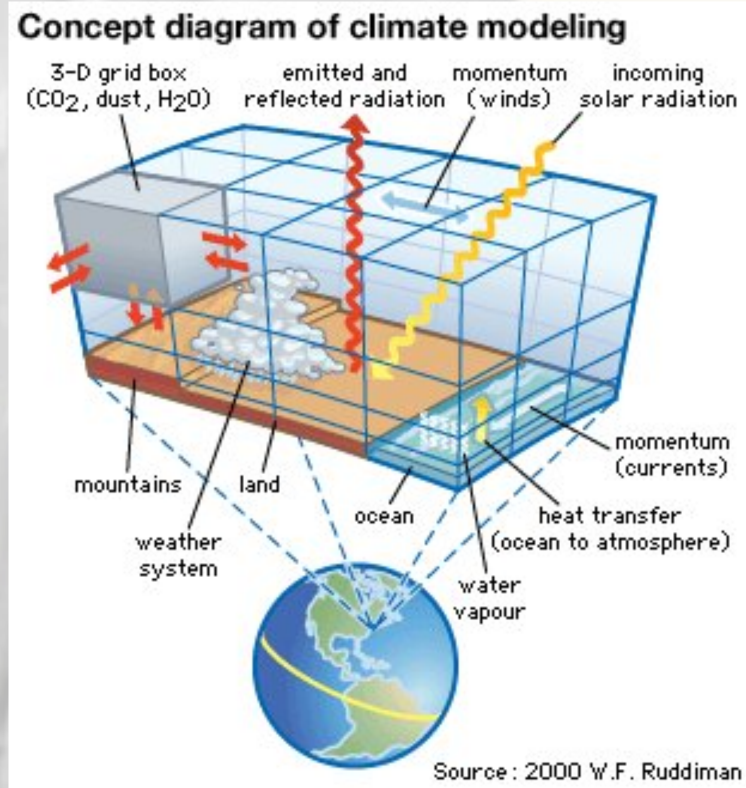

(Caveat: spectral models)

Example: HadCM3

"Hadley Centre Coupled Model Version 3"

- First unified model not to require flux adjustments (artificial adjustments applied to climate model simulations to prevent them drifting into unrealistic climate states).
- HadCM3 was one of the major models used in the IPCC Third and Fourth Assessments. Its good simulation of current climate without using flux adjustments was a major advance at the time it was developed and it still ranks highly compared to other models in this respect.

4 sub models: atmospheric, oceanic, sea ice, Land / ice sheets

Resolution:

- Atmospheric component: 19 levels with a horizontal resolution of 2.5 degrees of latitude by 3.75 degrees of longitude, which produces a global grid of 96 x 73 grid cells. This is equivalent to a surface resolution of about 417 km x 278 km at the Equator, reducing to 295 km x 278 km at 45 degrees of latitude.
- The oceanic component has 20 levels with a horizontal resolution of 1.25 x 1.25 degrees.

Why do we build GCMs?

- System not accessible to experimentation!
- Calculate global mean temperature increase
- Calculate climate sensitivity
- Understanding various parts of the climate system and their interplay.
- Make predictions about local impacts of climate change → Next lecture.
- …
- …

4. Uncertainty

There are number of factors that play a role in the model but which have uncertainties attached to them.

What are these and how can we understand them?

What are the impacts of these on model outputs?

<u>Brainstorming</u> about uncertainty

Processes smaller than the grid size is "invisible" to the model:

- Clouds
- Storms
- Ocean convection
- Ocean eddies
- Wind speed
- Most biological processes
- …

Reaction: “Parametrisations”, which describe processes not explicitly resolved in the model because they are below the model’s grid size. The aim is to include the *net effect* of sub-grid processes in the model.

Problem: key parametrisations (e.g. for clouds) have no firm theoretical basis and are at least to some degree arbitrary. This is worry since these parametrisations are crucial for model behavour.

Some go as far as saying that the are ad hoc.

And:

- Mountain ranges like the Andes are systematically too short
- The English Chanel
- Smaller volcanic islands chains with visible impacts on atmospheric circulation do not exist
- …

Furthermore:

- Not all processes can be taken into account
- Those that are taken into account are often described in an idealised way.
- Strength of feedback loops often unknown.
- Value of certain parameters are unknown (is there even anything like a true value?)
- Computer models are by necessity discrete and finite, but time in the world is continuous.
- Different machines

Reiterating the question: How can we systematise these uncertainties and assess their effects on the modelling enterprise?

→ What would be a suitable typology of uncertainty?

→ Neither the 2001 nor the 2007 IPCC reports have provided such a typology

This is an open question … but a good stab:

Petersen (2012)

Uncertainty Matrix		Sorts of Uncertainty						
		Nature of Uncertainty		Range of Uncertainty (Inexactness/Imprecision or Unreliability$_1$/Inaccuracy)		Recognised Ignorance	Methodological Unreliability (Unreliability$_2$) • Theoretical Basis • Empirical Basis • Comparison with Other Simulations • Peer Consensus	Value Diversity • General Epistemic • Discipline-Bound Epistemic • Sociopolitical • Practical
Location/Source of Uncertainty ↓		Epistemic Uncertainty	Ontic Uncertainty/ Indeterminacy	Statistical Uncertainty (Range + Chance)	Scenario Uncertainty (Range of 'What-If' Options)			
Conceptual model								
Mathematical model	**Model structure**							
	Model parameters							
Model inputs (input data, input scenarios)								
Technical model implementation (software and hardware implementation)								
Processed output data and their interpretation								

FIGURE 3.1
Typology of uncertainty in simulation.

Source: Petersen 2012, p. 51

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Typology of uncertainty in simulation.

Source: Petersen 2012, p. 51

Explaining Petersen's: vertical

→ Location of uncertainty

1. Conceptual model:
   - Do we get the physics right?
   - Do we take all relevant processes into account
   - Do we understand interactions correctly?
   - Feedback loops?
   - …

2. Mathematical model:

- Model structure: Do we have the right equations?
- Model parameters: We don't know what the correct value of certain model parameters is (worse: is there a true/correct value at all?)

3. Input uncertainty

- Data: initial conditions
- Scenarios: what will future emissions be?
- …

4. Technical Implementation

- Hardware: Does the computer function as it should
- Software: Do the programs do what they are expected to? Is the discretisation scheme working?
- …

5. Output data and their interpretation

- How do we interpret data
- For instance, do histograms give us probabilities?
- …

→ More about this in the next lecture

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Typology of uncertainty in simulation.

Source: Petersen 2012, p. 51

Explaining Petersen's matrix 2: horizontal

1. Nature of Uncertainty

   - Epistemic: is the uncertainty due to our lack of knowledge?

   - Ontic: is there an intrinsic indeterminacy? (Are things genuinely probabilistic? → 'aleatoric uncertainty')

→ Different consequences for reducing uncertainty.

2. Range of uncertainty

- Statistical uncertainty: expressible in terms of probabilities.
- Scenario uncertainty (‘what if’ uncertainties): not expressible as probabilities.
- … (?)

3. Recognised ignorance

'Recognised ignorance about a phenomenon we are interested in concerns those uncertainties that we realise – in one way or another – are present but for which we cannot establish any useful estimate.'

(Petersen 2012, 560)

Example: adequacy of software implementation: bugs can slip in but until they crop up one does not know where.

4. Methodological unreliability

- Theoretical basis: does an assumption have a firm theoretical basis?
- Empirical basis: does an assumption have a firm empirical basis?
- Comparison with other simulations: does a result agree with other similar results?
- Peer consensus: do peers consider a result reliable?

5. Value diversity

- General epistemic
- Discipline-bound epistemic
- Sociopolitical
- Practical

Rumsfeld/Cheney:

Known unknowns vs

Unknown unknowns

Uncertainty pertains to
know unknows …

Rumsfeld/Cheney:

Known unknowns vs

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Uncertainty pertains to

know unknows …

… but there are the

unknown unknowns!

1M$ question:

What is the effect of these uncertainties?

→ How worrisome are they?

→ What is their effect on our ability to predict the future?

→ What are the trade-offs between uncertainty in the modelling and the precision of the predictions?

… some reflections on these issues in the next lecture.

Often heard argument: we are so good about the past …

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… but can we really infer from the past to the future?

→ Hume's problem!

And more: there are good reasons to assume that in this particular case "more of the same" is not a good inference.

What is the effect of this?

Dutch meteorologist Henk Tenneke is sceptical:

"In practice a computer model always contains all sorts of tricks and empirical rules, no matter how many refinements are added. The [empirical content] contained in a computer model cannot be adjusted in advance; it is tuned by repeatedly checking against observations, until the model finally functions in a reliable way. [Since] the climate is a one-time experiment … the predictions of climatic models are always overtaken by the facts, regardless of how reliable the models are." (quoted in Petersen 2012, 109)

What uncertainties are there in CMs?

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Mathematical model	**Model structure**	1 2 3 4 5			1 3 4	1 2 3 4 5	1 3 4 5	1 3 4 5
	Model parameters	1 2 3 4 5			1 3 4	1 2 3 4 5	1 3 4 5	1 3 4 5
Model inputs (input data, input scenarios)		2 3 5		2 3	2 3	2 3 5	2 3 5	2 3 5
Technical model implementation (software and hardware implementation)								
Processed output data and their interpretation			1	1 4				1 4

The function of this matrix is to prioritise the uncertainty types that should receive priority in uncertainty assessment and communication by, for instance, the IPCC. The numbers refer to the sources of uncertainty listed in Table 6.1. The different fonts denote different levels of priority for assessing and communicating these uncertainties: *1* = important; 1 = very important; **1** = crucial. These levels have been assigned by the author.

FIGURE 6.4
Uncertainty matrix for simulation uncertainties in climate-change attribution.

Source: Petersen 2012, p. 134

Where:

1 = internal climate variablility

2 = natural forcing

3 = anthropogenic forcing

4 = response pattern to natural and anthropogenic forcing

5 = free atmosphere trends

5. Manifestations of Uncertainty

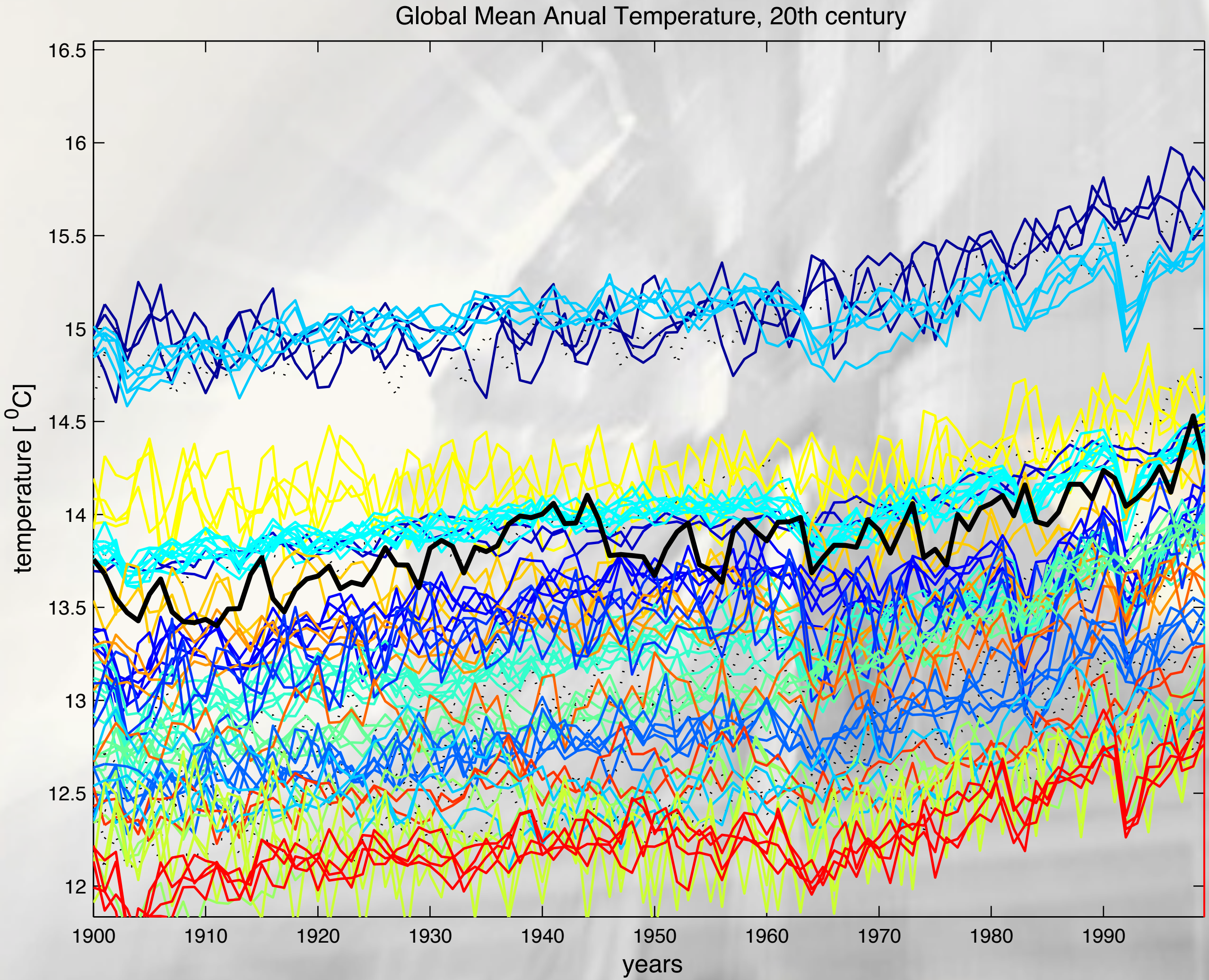
The uncertainties do matter in practice …

… they cannot be dismissed as academic hair-splitting!

Examples:

- Global mean temperature
- Relative changes in mean precipitation

Surface Warming over the last century



Thanks to Ana Lopez (CATS, LSE) for producing the graph

The figure shows model global mean temperatures over the last century of the 24 CMIP3 models (Coupled Model Intercomparison Project 3rd phase.)

All models show warming between 1900 and 2000, but their average temperatures vary tremendously …

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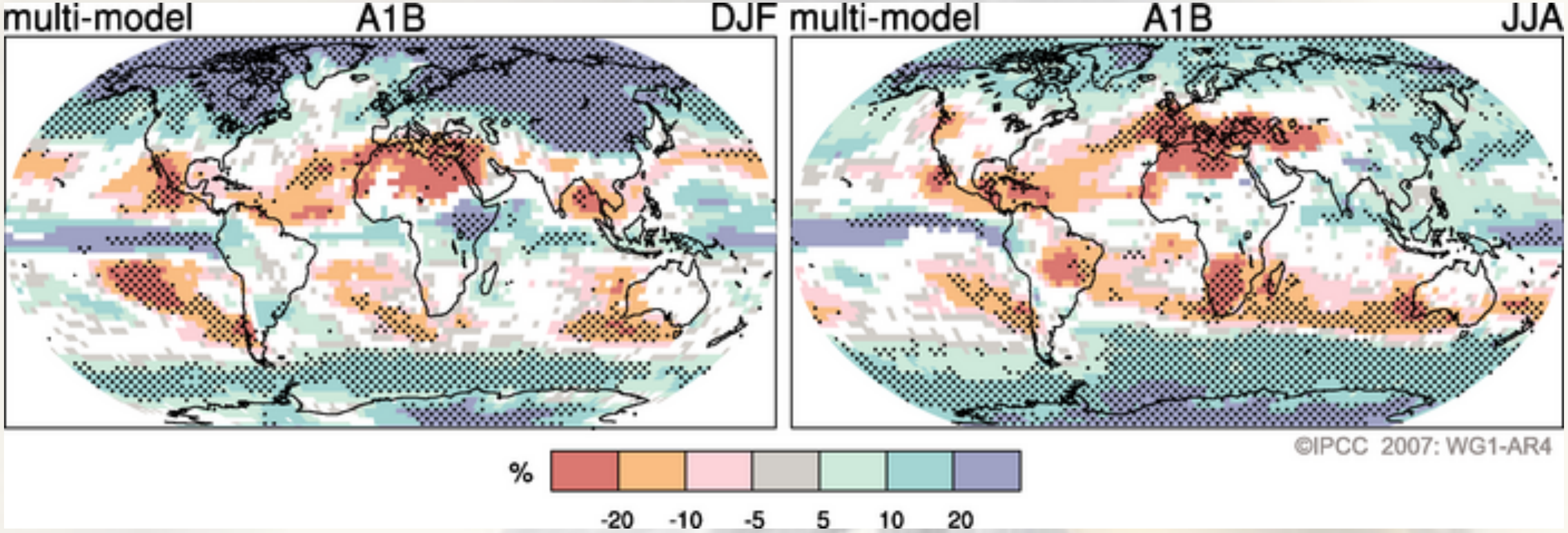
All models show warming between 1900 and 2000, but their average temperatures vary tremendously …

… and so do the average temperatures for the 21st century!

Predictions don't do better than retrodications!



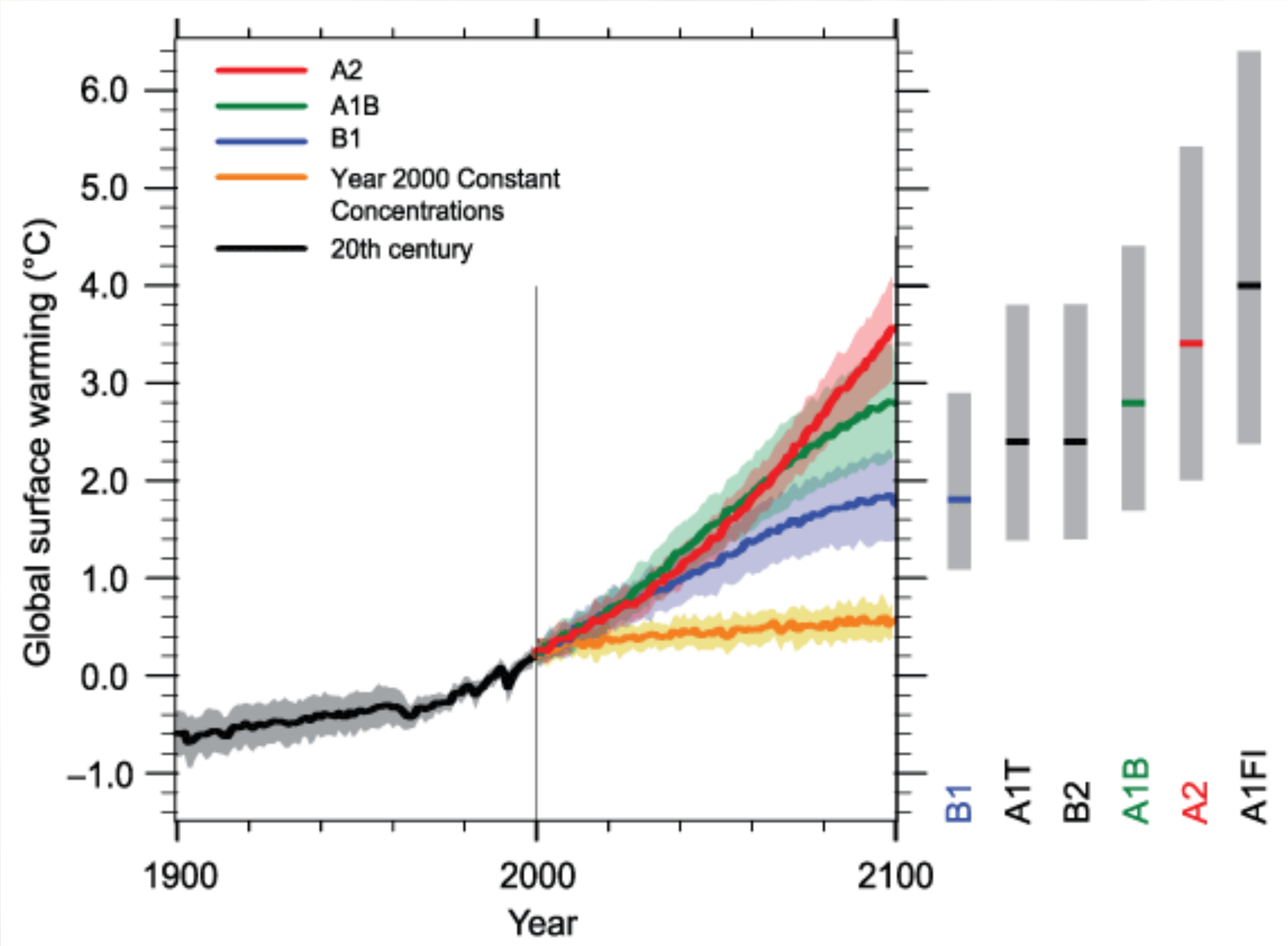
"Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. […] White areas are where less than 66% of the models agree in the ***sign of the change*** […]." (IPCC p. 16, emphasis added)

6. Multi Model Ensembles

Ensemble modeling approach: predictions of future climate conditions are produced with an ensemble of different climate models.

Increasingly, methods are used which assign probabilities to future changes on the basis of the set of projections in an ensemble.

Global surface warming (IPCC AR4)



23 GCM have been run to calculate the surface warming under different emission scenarios.

The IPCC report explains:

"The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints." (p. 14)

Intuition: agreement among ensemble members warrants increased confidence in the projected changes …

… and were we they don't agree we can use them to quantify uncertainty.

Question: what is the significance of agreement and how (if at all) can we use ensembles to quantify uncertainty?

The story of someone purchasing several copies of the same newspaper to check the details of one copy against another!

(Philosophical Investigations, sec. 256)

- The spread of an ensemble defines a range of changes that cannot yet be ruled out. This is known as ‘nondiscountable envelope’.
- Is there a reason to believe that future observed conditions will fall within the spread of the ensemble? If so, why?
- Does the envelope provide a lower bound on uncertainty?
- Do ensemble results translate into probabilistic estimates of uncertainty, or probability intervals?

7. Living with Uncertainty

- Is reducing uncertainty the only goal? The scientist may well not be to reduce uncertainty but classify it and communicate it clearly.
- Uncertainty provides no rational argument for inaction
- The challenge may well be the management of uncertainty rather than its reduction.

Further Reading

McGuffie, K. and A. Henderson-Sellers (2005). A Climate Modelling Primer. New Jersey Wiley.

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Bradley, S. (2011). "Scientific Uncertainty: A User's Guide." Grantham Institute on Climate Change Discussion Paper **56**(available at http://www2.lse.ac.uk/GranthamInstitute/publications/WorkingPapers/Abstracts/50-59/scientific-uncertainty-users-guide.aspx).

Parker, W. (2011). "When Climate Models Agree: The Significance of Robust Model Predictions." Philosophy of Science **78**(4): 579-600

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