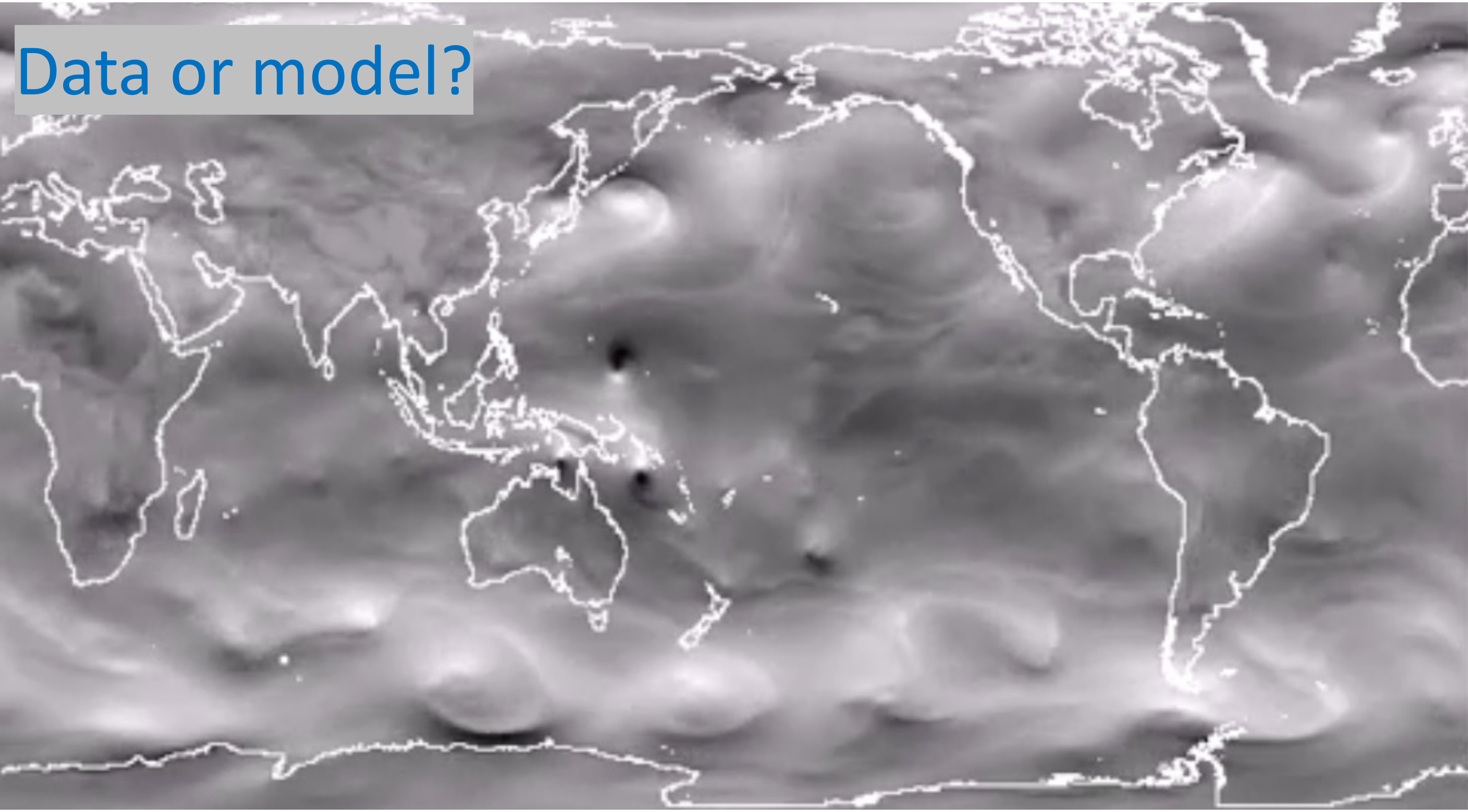
Are climate models any good or useful at all?



https://www.gfdl.noaa.gov/visualizations-hurricanes/

Common thoughts about modeling

1. The goal of modeling is to reproduce data
2. If a model doesn't fit the data, the model is useless (…and modeler also)
3. Since modelers don't measure anything, they don't know anything about data or care about them
4. Measurement(s) of "X" can be used to better constrain climate models
5. Process "W" is not explicitly implemented in the model, hence the model cannot model the effect of the "Z" on climate as "W" has or may have an (unquantified) effect of the "Z" and "~" may effect CO_2 or T, etc. … therefore models are useless

Some propositions to feel better

1. All models are "wrong" and "incomplete"

   (modeling with the sole goal of fitting data can be futile)

   (state-or-the-art models have many free parameters, uniqueness of the fit/solution is not guaranteed anyways – fit for wrong reason possible)

2. Models have the merit of being internally consistent and possess fundamental conservation properties (mass, momentum, energy) that arm-wavy arguments do not have

   (It's much easier to explain data with arm-wavy arguments)

   (…but models can provide means to test hypotheses)

3. Models can be wrong in many different ways

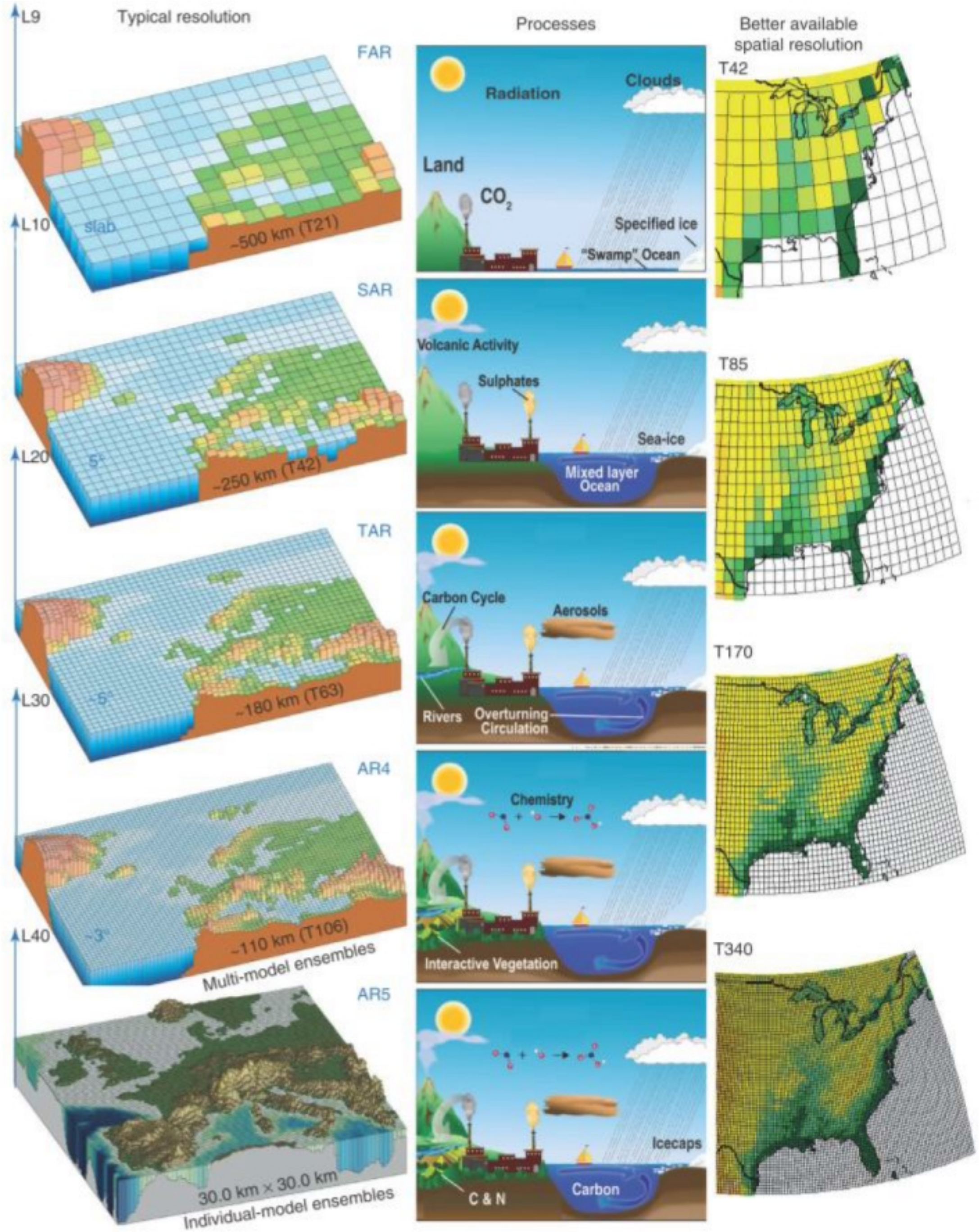
   (figuring out why they are wrong is where learning occurs)

   (data come in to inform parameterizations and testing simulations)

4. The skill of a "modeler/analyst" is less in knowing how to model (i.e math, computer science) and more in how to make useful sense of incomplete/uncertain results and design meaningful experiments

Model resolution

Increasing spatial resolution
…also means increasing temporal resolution to maintain numerical stability
(i.e. decrease time step)



Huge cost of resolution:
2x increase resolution in all dimensions means
8x more computations
8x more memory
8x more time

With decreased time-step
>16x slower and more demanding

Benefits of improving resolution?

- Better numerical accuracy in solving dynamical equations
  - Smaller discretization steps
- Better representation of topography/bathymetry (mountains, islands, seamounts…)
  - Grid-boxes have vertical walls!
- Explicit inclusion of subgrid-scale processes
  - Parameterizing vs. resolving (e.g. eddies, overflows, etc)
- Property gradients can be larger
  - Affects pressure gradients (i.e. velocity of currents)
  - Model becomes more advective and less diffusive
  - Exchange-processes that depend on gradient become stronger (strong exchange, although on shorter spatial scales, e.g. air-sea heat fluxes)
- Better agreement with the way data are collected (i.e. what observations mean)
  - Averaging over space/time and variability

https://www.gfdl.noaa.gov/climate-modeling/

Gulf Stream

Labrador Sea

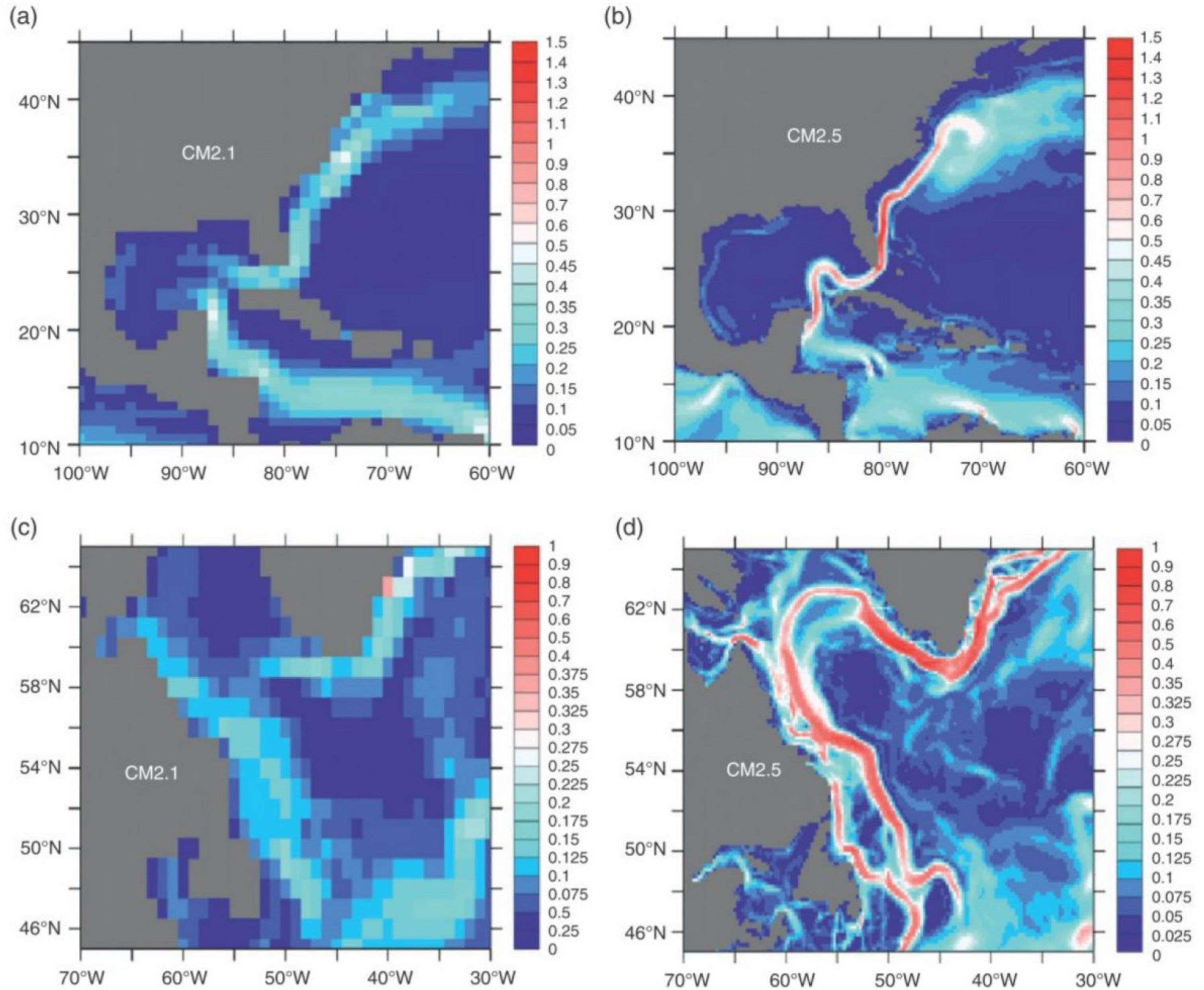


Figure 5.4 Improvement in depiction of ocean surface current (m s^{-1}) as a function of the model's spatial resolution and parameterisation improvements over 6 years seen in 100 year annual means for two model resolutions: coarse (CM2.1 ca.2006) and improved (CM2.5 ca.2012) and for the Gulf Stream (a) and (b) and the Labrador Sea (c) and (d). Source: After Delworth et al. (2012). Reproduced with permission of the American Meteorological Society.

Ocean resolution: 2 cases resolving eddies (the ocean’ storms)

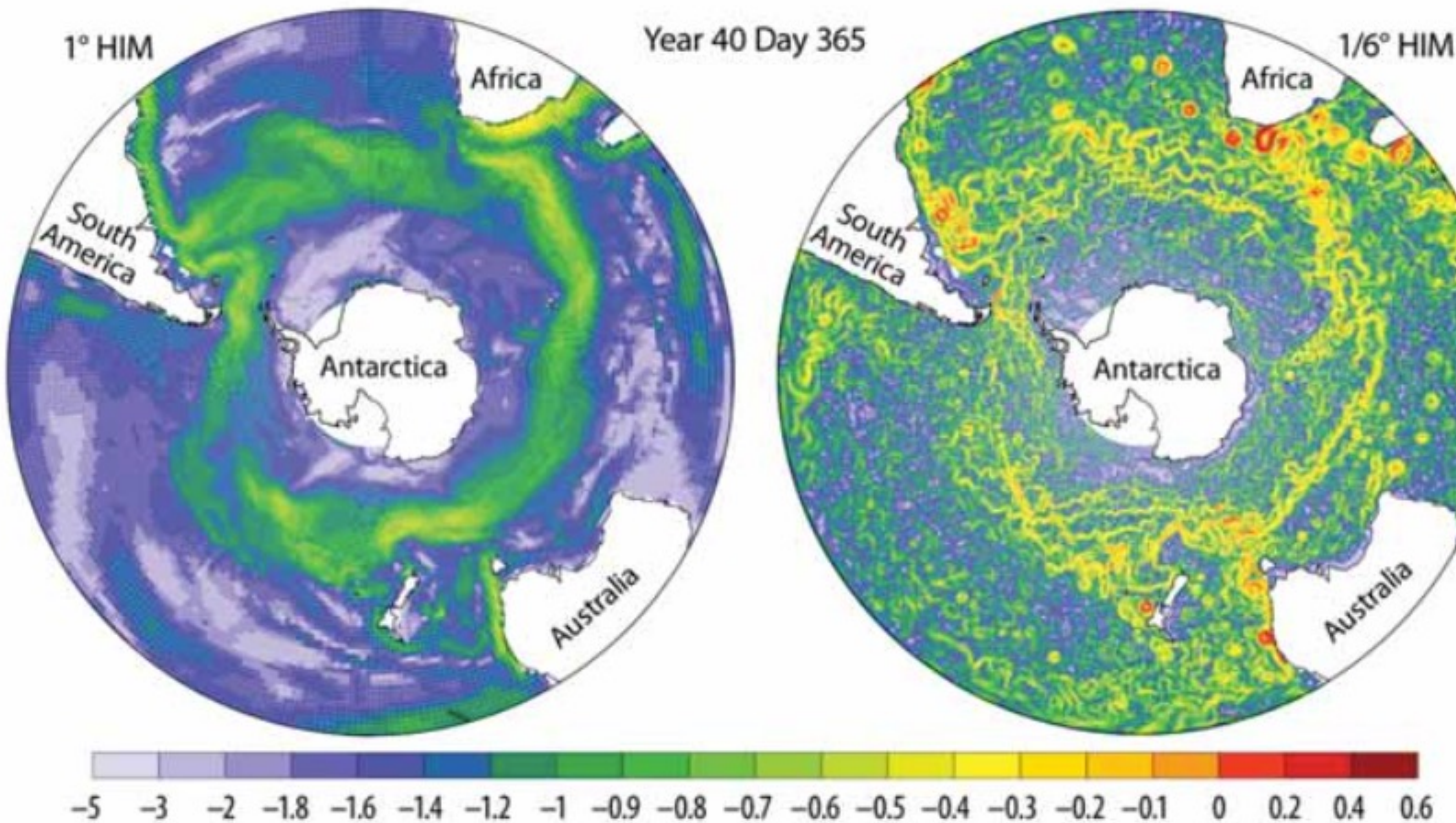
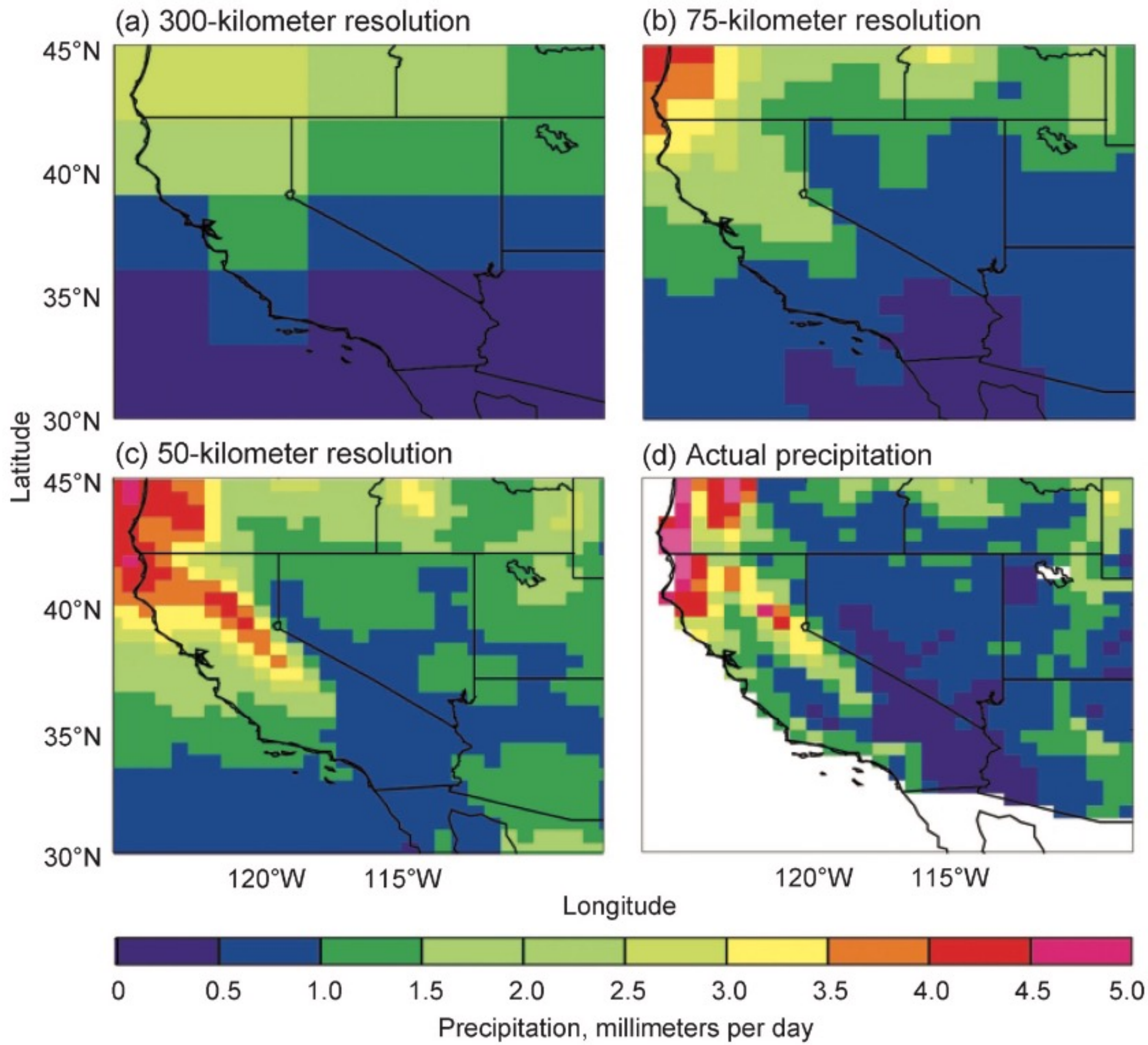


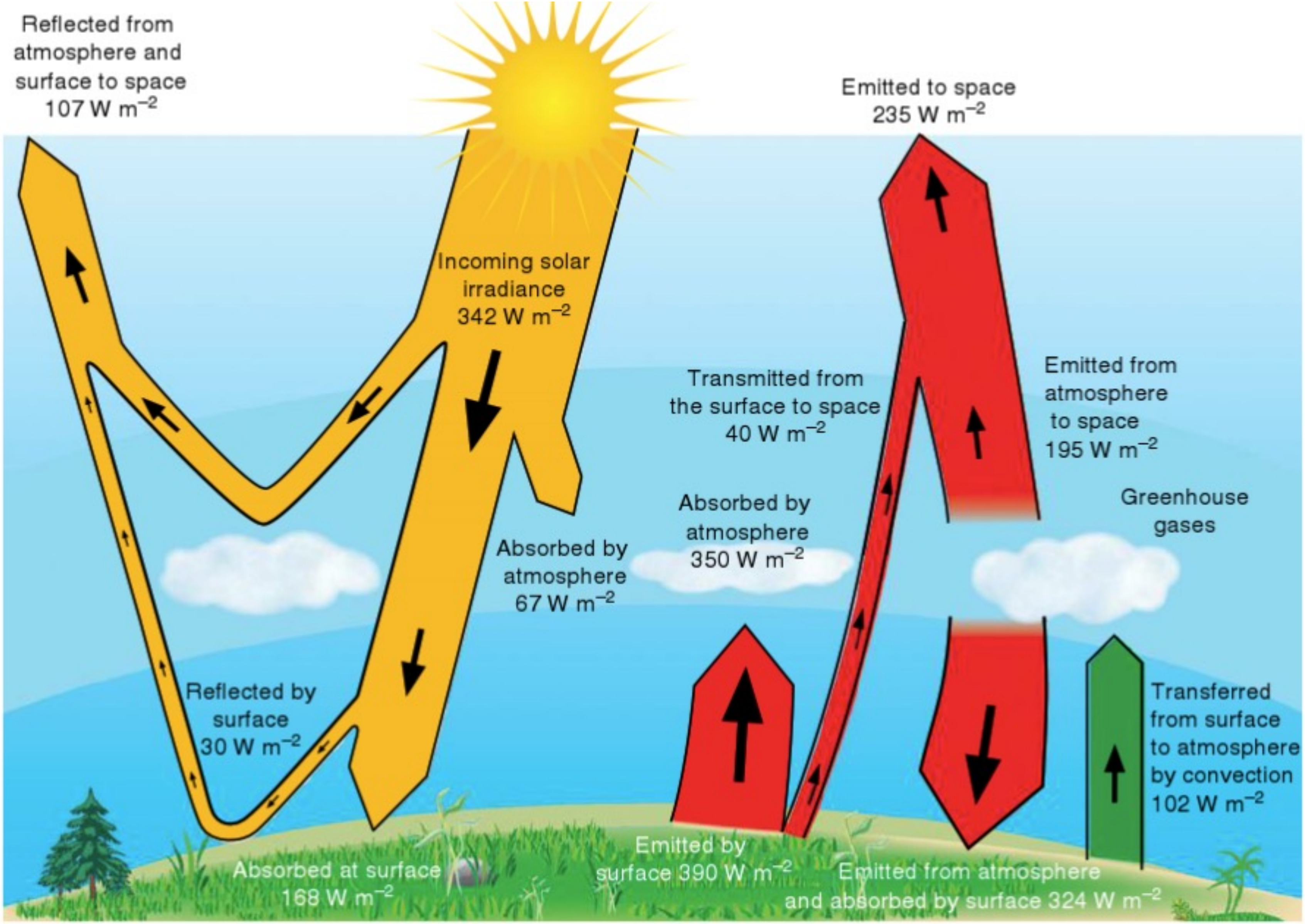
Figure 6.1. Surface-Current Speed in Two Simulations of the Southern Ocean in Low- and High-Resolution Ocean Models.
[From Fig. 6 in R. Hallberg and A. Gnanadesikam 2006:The role of eddies in determining the structure and response of the wind-driven Southern Hemisphere overturning: Results from the modeling eddies in the Southern Ocean (MESO) project. *J. Physical Oceanography*, **36**, 2232–2252. Reproduced by permission of the American Meteorological Society (AMS).]

Atmospheric resolution: 3 cases



The atmosphere matters … **a lot**!

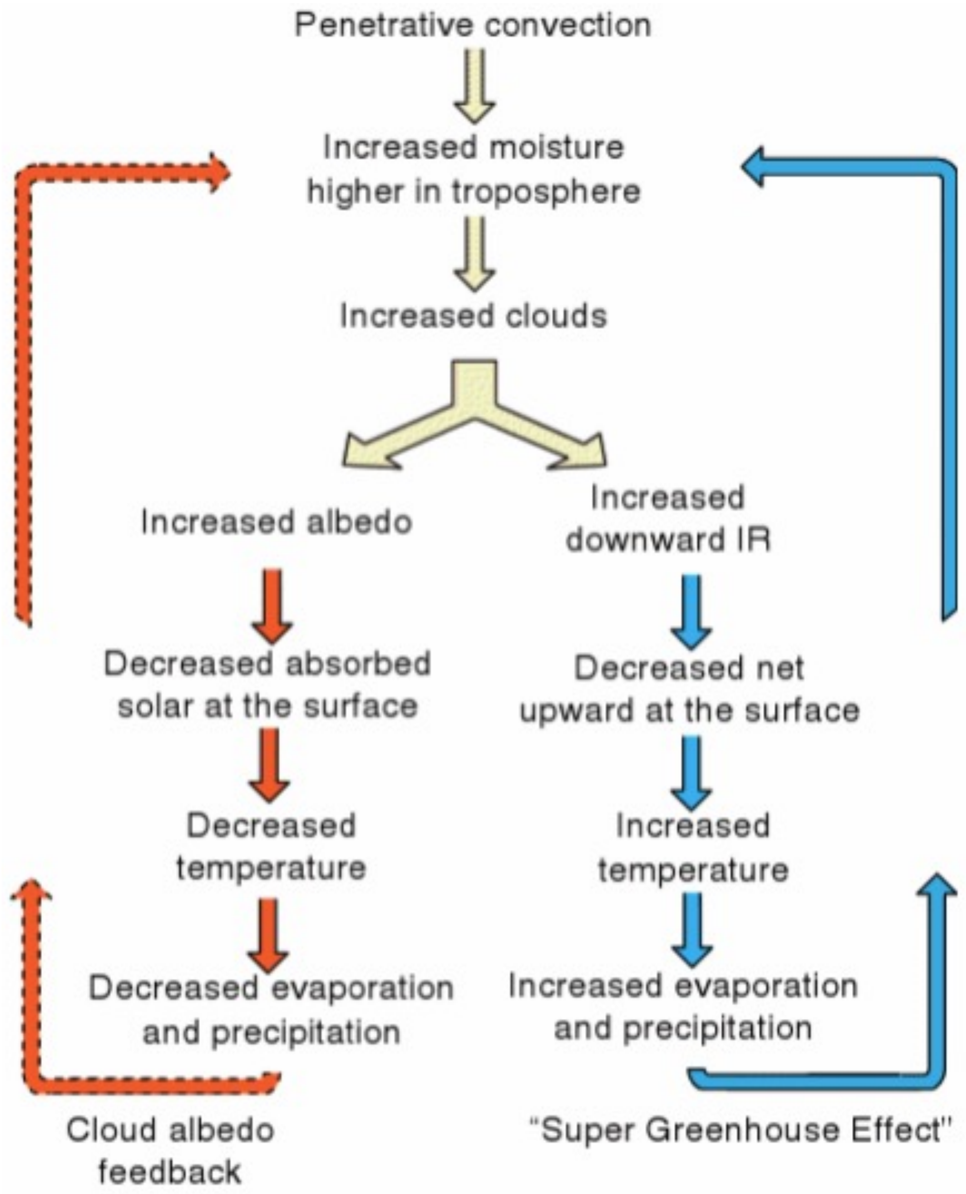
Radiative-convective equilibrium



The hydrologic cycle challenge and **Relative humidity** (h)

- It is the ratio of partial pressure of water vapor to the equilibrium partial pressure
  - "the salinity of the atmosphere"
- Relative humidity decreases as T increases
  - Warm air can hold more water
    - More water = more clouds?
    - More low clouds = more albedo?
    - More high clouds = more greenhouse?
  - Question: If T increases and air can hold more water, what happens over deserts?

The “**clouds**” challenge



Clouds can both cool and warm the climate

The microphysics responsible for cloud formation is not well understood

The grid cells in models are much much bigger than time/space scales relevant for cloud physics

⇒ **Magnitude/location of rain events is hard to predict well**

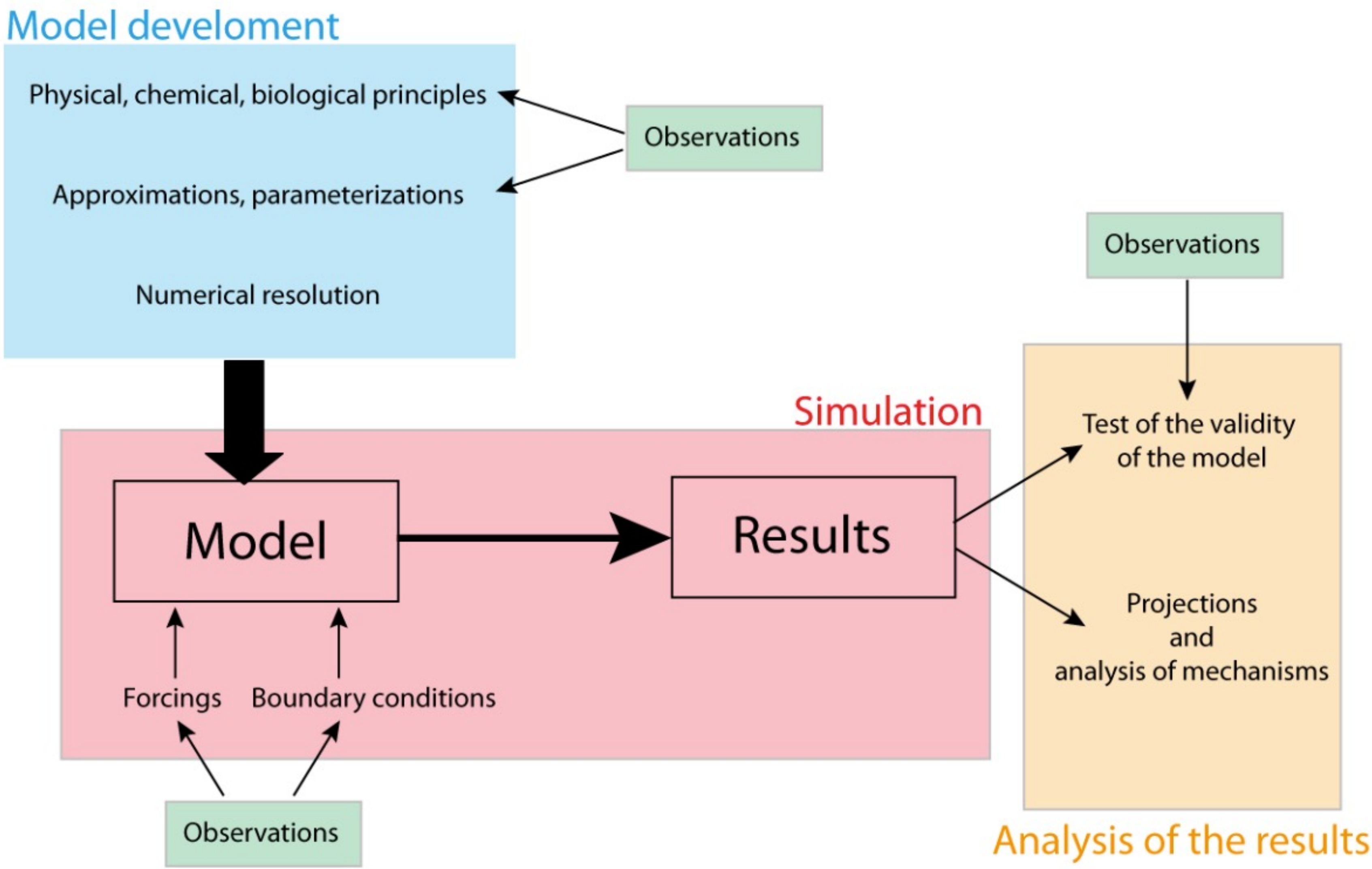
⇒ **That information is useful though!**

Figure 4.13 Feedback loops associated with including penetrative convection in a global climate model. The right-hand loop (*blue*) results in increased sensitivity of the system through enhanced circulation of moisture, whereas the left-hand loop (*red*) results in a decrease in sensitivity due to the increased cloud albedo. Source: After Meehl and Washington (1995). Reproduced with permission of Springer Science+Business Media.

Comparing models with data

- What is a data point? Observation vs model result
- Are model solutions at a point similar to a data point (i.e. observational sample)?
  - Spatially?
  - Temporally?
- Using data well is not a trivial task. It requires understanding the model well and the data well
  - A trend towards "Observational System Simulation Experiments" (OSSE)
  - data assimilation (e.g. 4DVAR)

The role of **observations** in modeling



http://www.climate.be/textbook/pdf/Chapter_3.pdf

Models vs observations

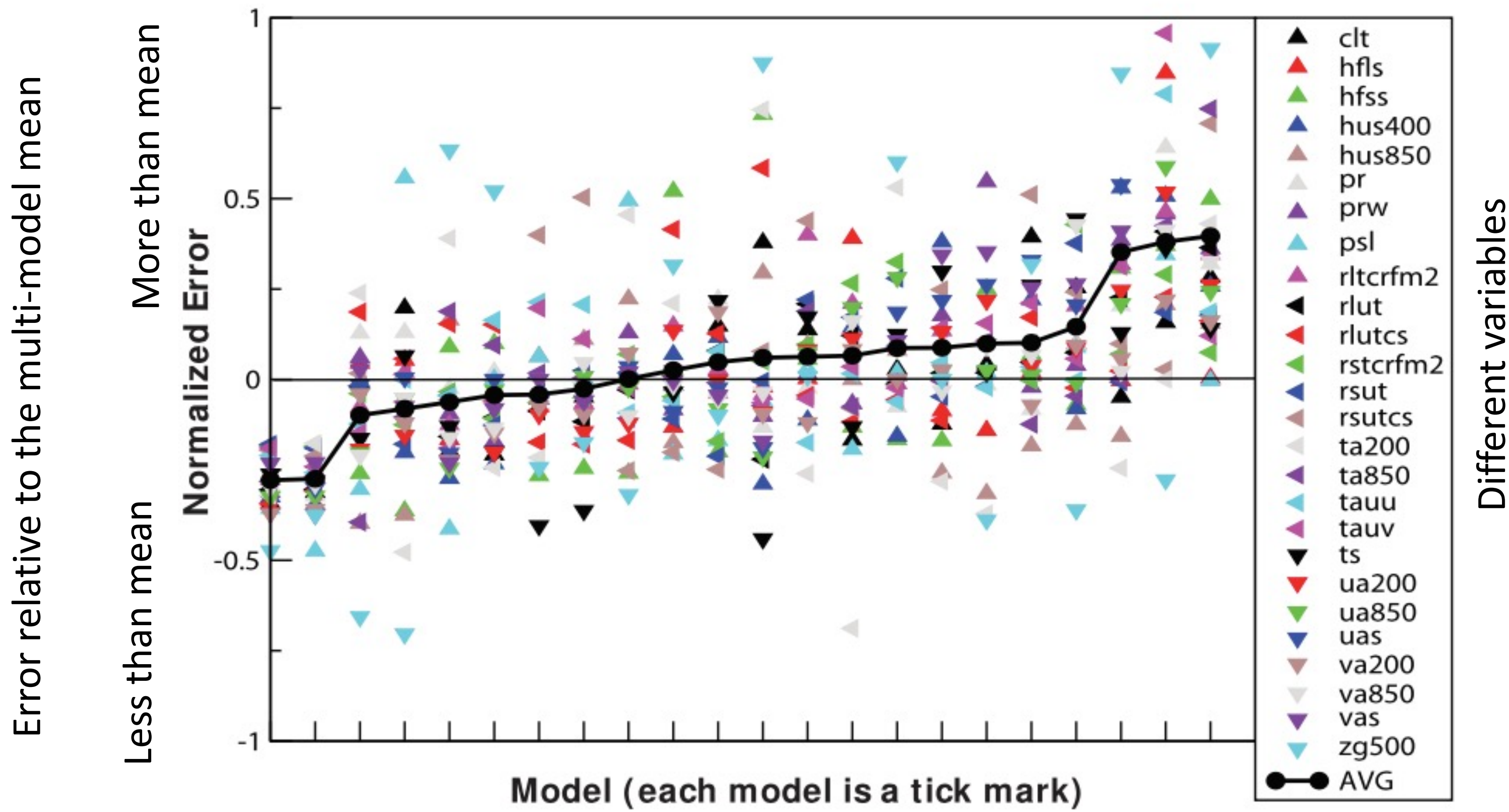
- There are data that are ’just’ observations
- There are models that are ‘just’ models
- There are models that are ‘assimilated with data’
  - Often called ‘Reanalysis Products’
    - (also used in weather forecasting, obviously)
  - These are models that are ‘fitted’ to data
    - Some model parameters are tuned to fit
      - Question is what to fit/how? (Data assimilation, 4DVAR)
  - Provide best gridded high-resolution spatio-temporal product available … but:
    - they are still model results
      - Fitting a bad/wrong model still is a bad results
    - they only exist for the period when data exist
      - so cannot be used for forecasting
      - But extremely useful to understand past/current climate patterns/variability

Are models ever “right”?

- Since models are incomplete by construction, what does “right” even mean?
- What do we do if one model can represent a variable better but another variable worst?
- A model can reproduce the mean state well but not the variability. Is it a “good” model?
- What if model solution shows spatial and temporal patterns well, but is consistently offset?
- Embrace/accept that sometimes the best we can do is to provide a probabilistic answer to questions

Model performance and deciding which is the best model?

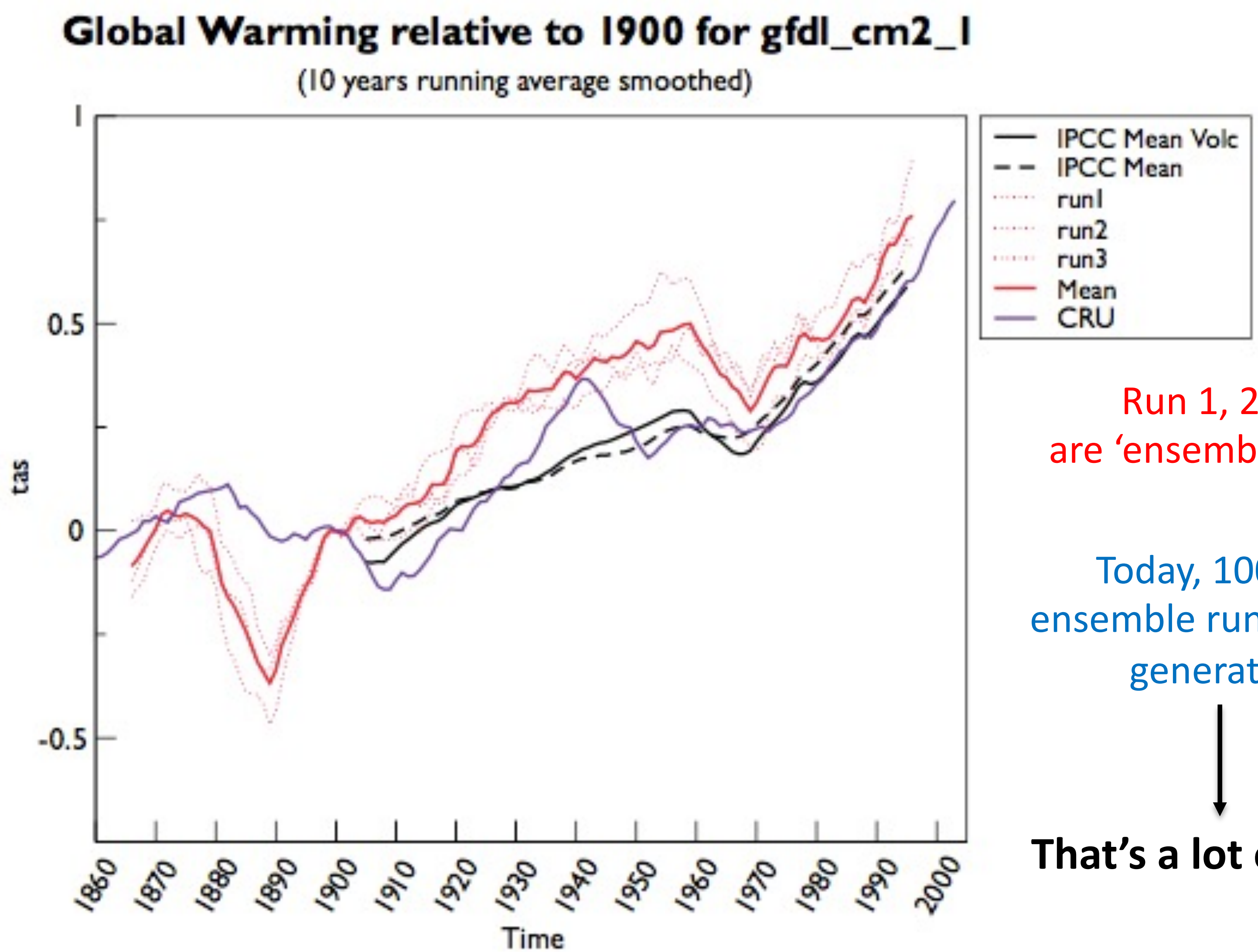
Which is the best "Metric" - a judgment call?



Different models

Internal variability vs “forced” response?

Ensemble simulations



Run 1, 2, 3
are ‘ensemble’ runs

Today, 100s of ensemble runs can be generated

That’s a lot of data!

What model for what process, for what analysis?

Choosing the best model product for the job

If simple works, go simple! (less data to process) – not everything has to be coupled all the time!

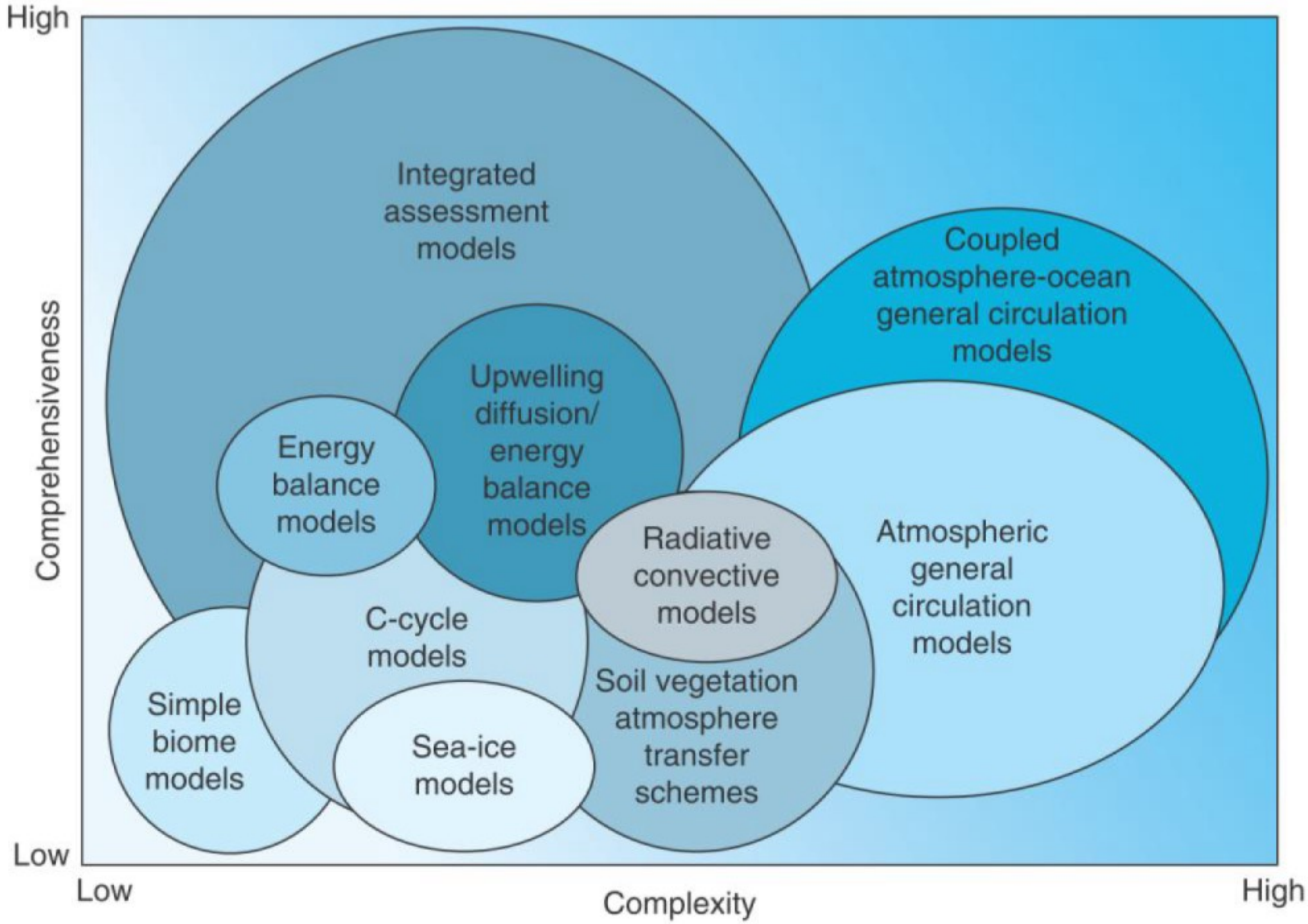


Figure 1.26 Comparison of the comprehensiveness and complexity of a variety of climate model types (C-cycle is carbon cycle). This straightforward plot can be compared with the two diagrammatic categorisations of climate models shown in Figure 1.22. Source: After Houghton et al. (1997). Reproduced with permission of the IPCC.

Can one model do it all?

Processes operate on various time/space scales

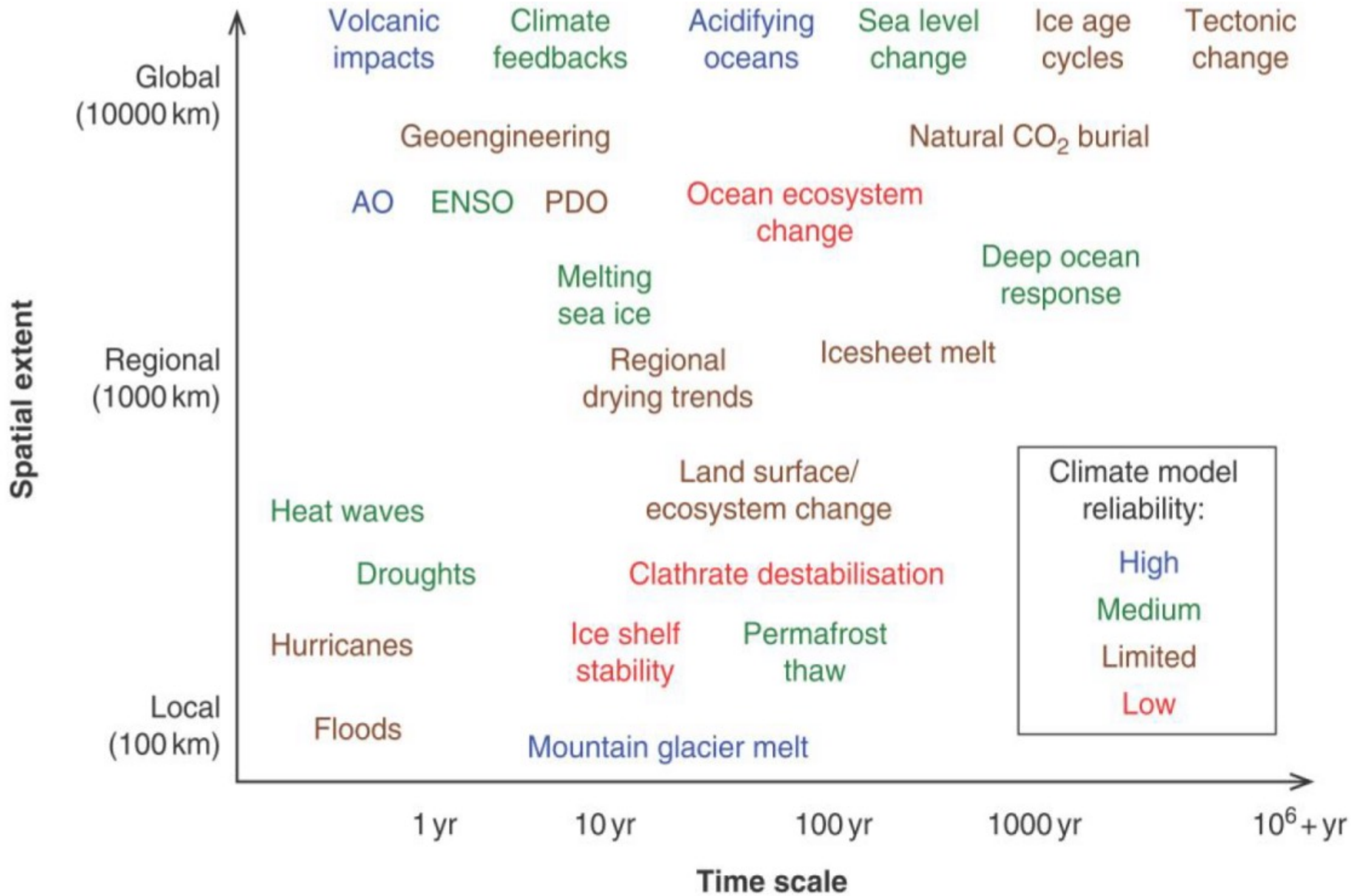
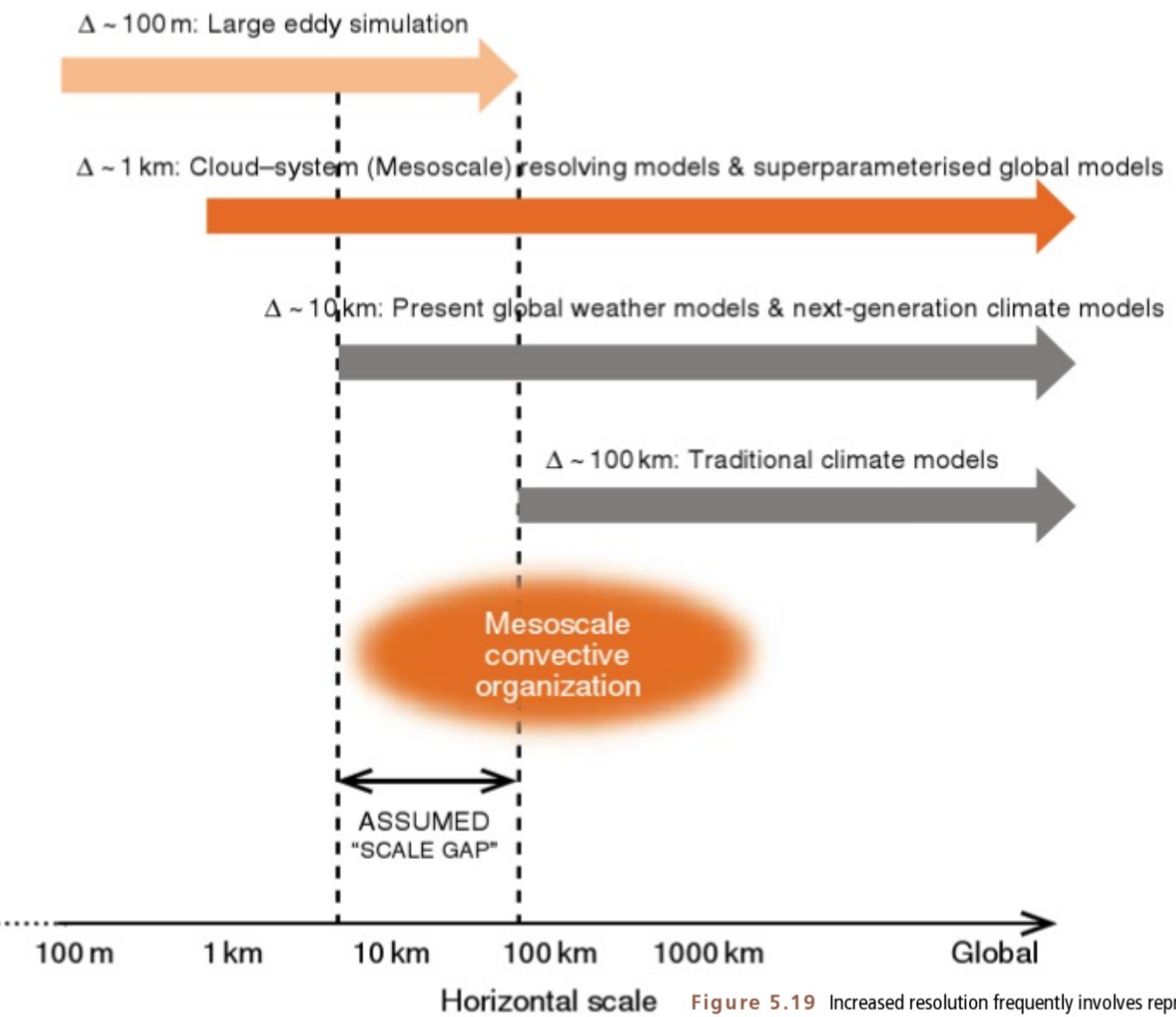


Figure 2.13 Time and space scales of key climate phenomena coloured according to the reliability of (as perceived by authors of a US national report) or confidence in simulations of their prediction by climate models in 2012. Source: National Academy of Science (2012). Reproduced with permission of the National Academies Press.



Higher resolution

- (more data)
- (local extremes)
- (shorter simulation)
- (no/few ensembles)

Lower resolution

- (fewer data)
- (longer simulation)
- (many ensembles)

Figure 5.19 Increased resolution frequently involves representation of additional aspects of climate, for example mesoscale convection. Mesoscale convective systems are not represented in most climate models because their computational grid is too coarse and organised convection is not parameterised. Such additions can bring benefits as well as challenges. Here, the upscale effects previously neglected can be incorporated into a higher resolution model. (a) Up-scaling and down-scaling of weather-climate relationships. (b) Mesoscale convective organisation bridges the scale gap often presumed in convective parameterisation. Source: Moncrieff et al. (2012). Reproduced with permission of the American Meteorological Society.

Take home messages

- Models will always be imperfect (accept this!)
  - the challenge is to **make them useful** by keeping them as simple as possible in spite of their limitations
    - very difficult in practice, requires deep scientific knowledge
    - Understanding of the question and of the tools available
  - The **skill of the analyst is to know how far to push the interpretation** and to select the correct model/simulations for the right question
- Main sources of uncertainties to consider
    - Numerics and choice of equations/implementation
    - Resolution
    - Parameterizations
    - Boundary conditions and forcing
    - Internal dynamics
- **Influence of uncertainties on final conclusions** of analysis must be considered