Climbing down Charney's Ladder

UFS Webinar Series

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14 April 2022

Outline

1. Climate science and climate models
   - Weather and climate
   - Radiative balance and dynamical response
   - The "infinite forecast"
2. Computational climate science
   - Model evolution, from the Charney Report to the IPCC
   - The end of Dennard scaling
   - What computers are good at: Machine Learning
   - Learning from models, learning from observations
   - Learning the physics of fine scales
3. Summary: Climbing Down Charney's Ladder

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3. Summary: Climbing Down Charney's Ladder

What is climate?

- Climate is what you expect, weather is what you get
- ... but we are going to have to change our expectations! See NOAA new normals, 4 May 2021.
- What you perceive is the difference between the weather and the climate.
- The climate record is based on careful removal of weather “noise” from observations to see the climate “signal”: the residuals are small compared to the observed quantities.
- Fluctuations, feedbacks and forcings at all scales: minutes to millennia, microbes to megacontinents.
- Solving the climate problem implicates any field of science or engineering you can imagine: fluid mechanics, radiative transfer, chemistry, biology, mathematics, statistics, algorithms, computing hardware, materials science, ... please join the fun!

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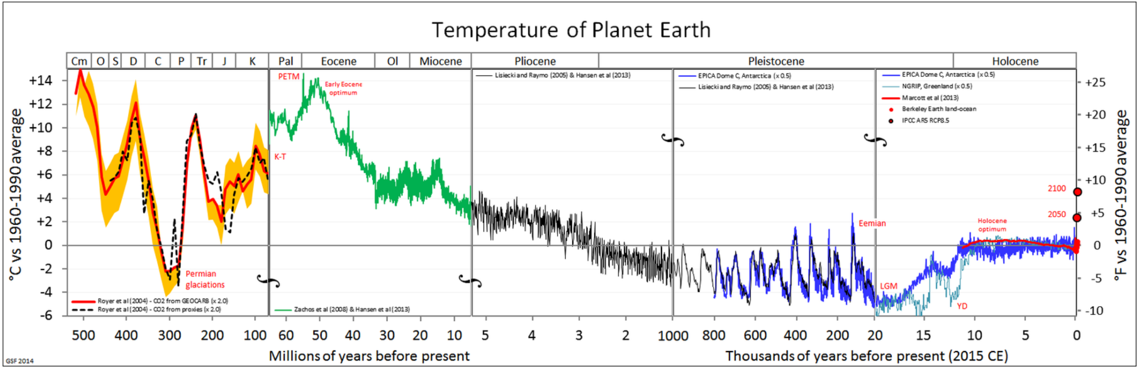
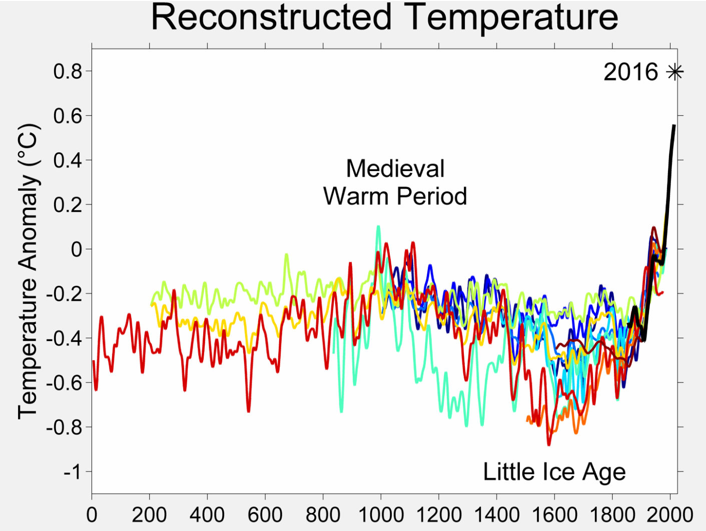
Earth's Temperature History: observations

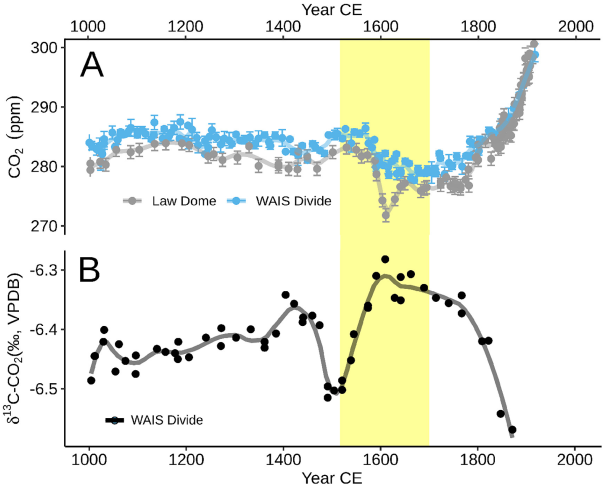


From Wikipedia.



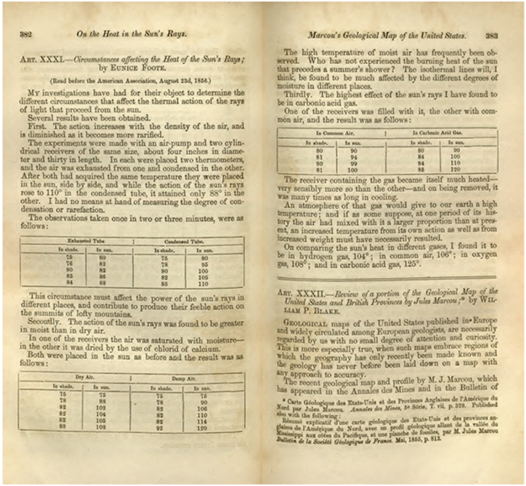
- 1000-year reconstructions from tree rings and ice cores.
- The Mediæval warm period and the Little Ice Age may be only regional signals
- The current warming has a global signature
- From Wikipedia

The Great Dying in the Americas



From Koch et al (2019). Global impact of depopulation in the Americas, c. 1600 CE.

Eunice Foote discovers the greenhouse effect, 1857



382 *On the Heat in the Sun's Rays.*

ART. XXXI.—*Circumstances affecting the Heat of the Sun's Rays;* by EUNICE FOOTE.

(Read before the American Association, August 23d, 1856.)

MY investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun.

Several results have been obtained.

First. The action increases with the density of the air, and is diminished as it becomes more rarified.

The experiments were made with an air-pump and two cylindrical receivers of the same size, about four inches in diameter and thirty in length. In each were placed two thermometers, and the air was exhausted from one and condensed in the other. After both had acquired the same temperature they were placed in the sun, side by side, and while the action of the sun's rays rose to 110° in the condensed tube, it attained only 88° in the other. I had no means at hand of measuring the degree of condensation or rarefaction.

The observations taken once in two or three minutes, were as follows:

Exhausted Tube		Condensed Tube.	
In shade.	In sun.	In shade.	In sun.
75	80	75	80
76	82	78	95
80	82	80	100
83	86	82	105
84	88	85	110

This circumstance must affect the power of the sun's rays in different places, and contribute to produce their feeble action on the summits of lofty mountains.

Secondly. The action of the sun's rays was found to be greater in moist than in dry air.

In one of the receivers the air was saturated with moisture—in the other it was dried by the use of chlorid of calcium.

Both were placed in the sun as before and the result was as follows:

Dry Air.		Damp Air.	
In shade.	In sun.	In shade.	In sun.
75	75	75	75
78	88	78	90
82	102	82	106
82	104	82	110
82	105	82	114
88	108	92	120

Marcou's Geological Map of the United States. 383

The high temperature of moist air has frequently been observed. Who has not experienced the burning heat of the sun that precedes a summer's shower? The isothermal lines will, I think, be found to be much affected by the different degrees of moisture in different places.

Thirdly. The highest effect of the sun's rays I have found to be in carbonic acid gas.

One of the receivers was filled with it, the other with common air, and the result was as follows:

In Common Air.		In Carbonic Acid Gas.	
In shade.	In sun.	In shade.	In sun.
80	90	80	90
81	94	84	100
80	99	84	110
81	100	85	120

The receiver containing the gas became itself much heated—very sensibly more so than the other—and on being removed, it was many times as long in cooling.

An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.

On comparing the sun's heat in different gases, I found it to be in hydrogen gas, 104°; in common air, 106°; in oxygen gas, 108°; and in carbonic acid gas, 125°.

ART. XXXII.—*Review of a portion of the Geological Map of the United States and British Provinces by Jules Marcou;** by WILLIAM P. BLAKE.

GEOLOGICAL maps of the United States published in Europe and widely circulated among European geologists, are necessarily regarded by us with no small degree of attention and curiosity. This is more especially true, when such maps embrace regions of which the geography has only recently been made known and the geology has never before been laid down on a map with any approach to accuracy.

The recent geological map and profile by M. J. Marcou, which has appeared in the Annales des Mines and in the Bulletin of

* Carte Géologique des Etats-Unis et des Provinces Anglaises de l'Amérique du Nord par Jules Marcou. *Annales des Mines,* 5e Série, T. vii, p. 329. Published also with the following:

Résumé explicatif d'une carte géologique des Etats-Unis et des provinces anglaises de l'Amérique du Nord, avec un profil géologique allant de la vallée du Mississippi aux côtes du Pacifique, et une planche de fossiles, par M. Jules Marcou *Bulletin de la Société Géologique de France.* Mai, 1855, p. 813.

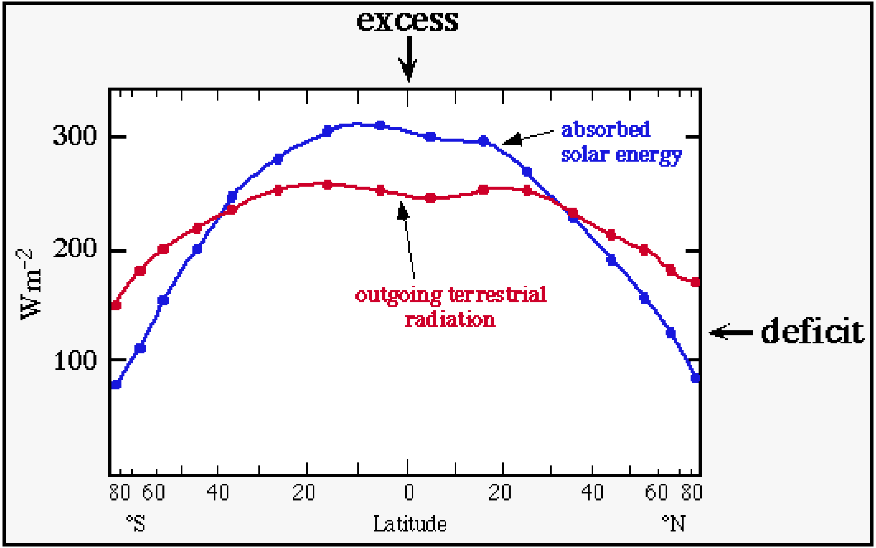
"An atmosphere of that gas would give to our earth a high temperature". From climate.gov.

Bjerknes and modern weather forecasting

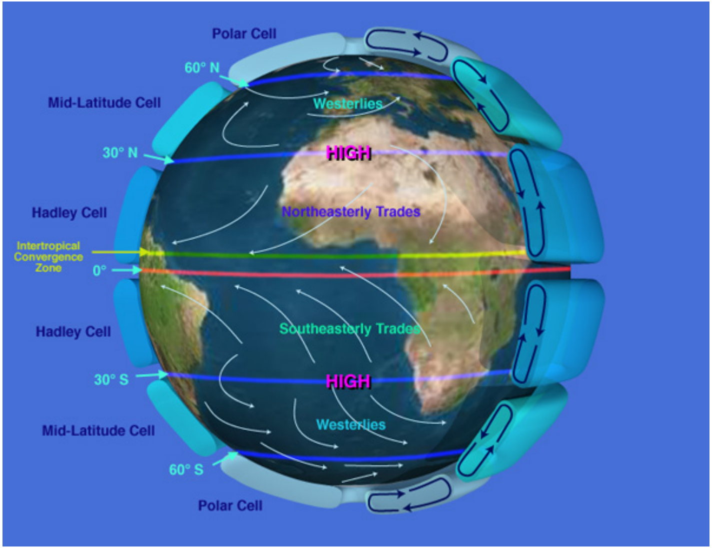
- V. Bjerknes first formulated the primitive equations for the general circulation (1904).
- Unable to find a practical way to integrate them forward in time, he attempts a graphical calculus on hand-drawn contour maps
- Finally resorts to empirical methods based on libraries of contour maps

Bjerknes develops the foundations of dynamical meteorology but in the end, performs forecasting using methods "that were neither algorithmic nor based on the laws of physics", *Calculating the weather*, Nebeker (1995).

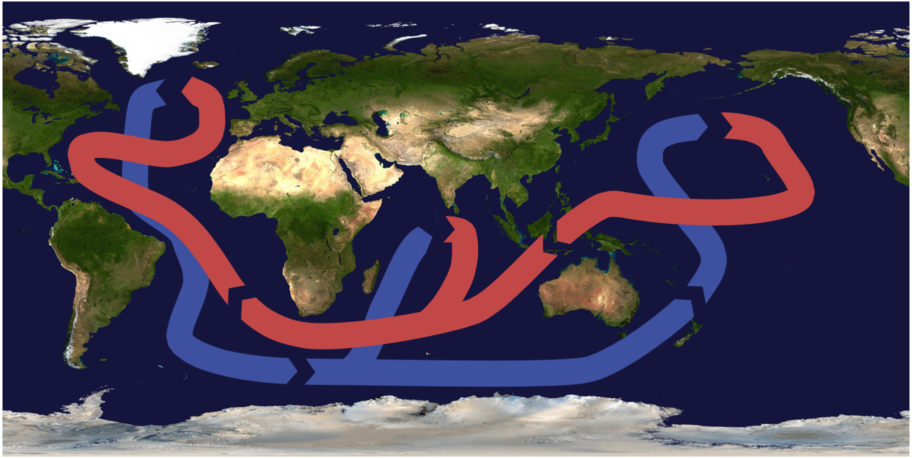
The Earth's radiation budget



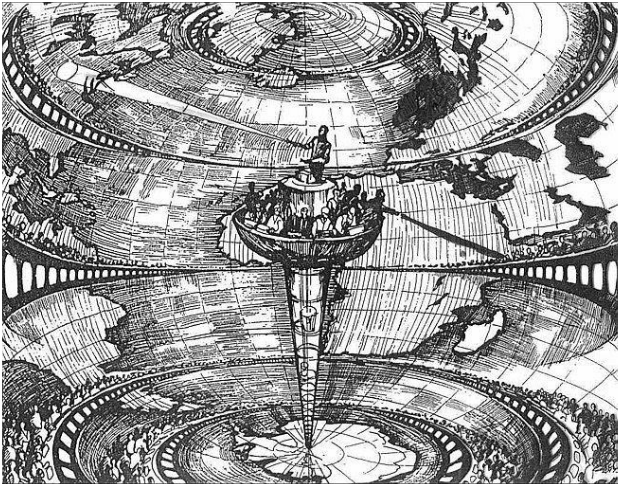
Global atmospheric circulation



Global oceanic circulation



Richardson’s failed attempt to compute the general circulation, 1922



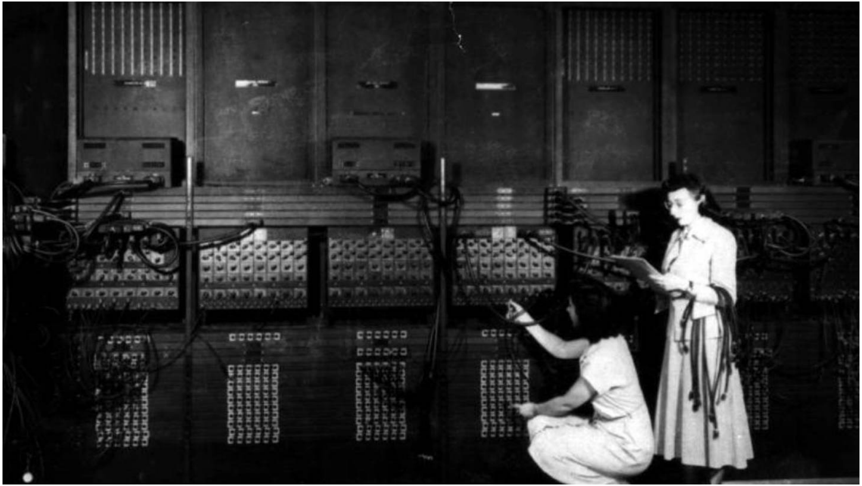
From A Vast Machine, Edwards 2010.

The dawn of digital computing at the IAS

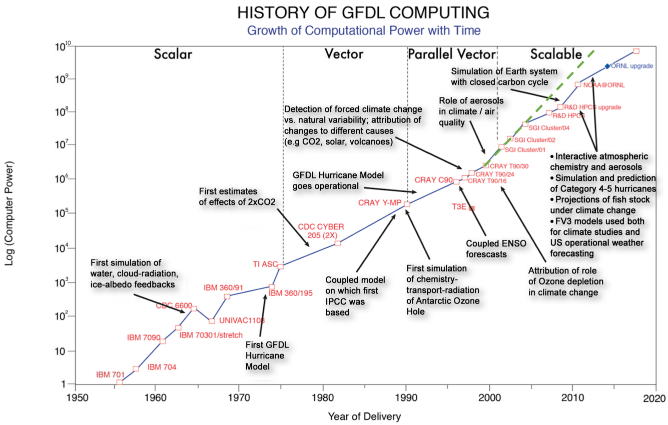
FIG. 2. Some of the members of the IAS Meteorology Group in 1952. Left to right: J. G Charney, N. A. Phillips, G. Lewis, N. Gilbarg, G. W. Platzman (behind the camera: J Smagorinsky). The IAS Computer is in the background.

From Climbing down Charney's ladder, Balaji (2021). Picture by Joe Smagorinsky.

Programming the ENIAC



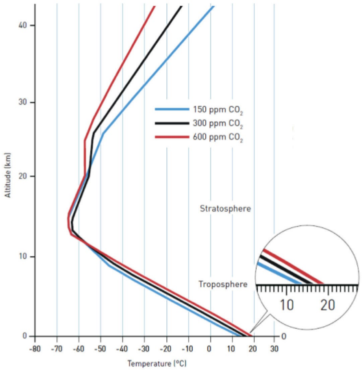
History of GFDL Computing



- John von Neumann birthed programs in the 1950s for weather forecasting, and climate (the “infinite forecast”).
- From Climbing down Charney’s ladder, Balaji (2021). Credit: Youngrak Cho, NOAA/GFDL.

Outline

Manabe and Wetherald (1967): 1D model response to CO_2 doubling

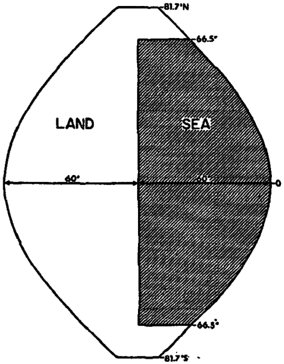


Source: Manabe and Wetherald (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity, *Journal of the atmospheric sciences*, Vol. 24, Nr 3, May.

"Radiative convective equilibrium of the atmosphere with a given distribution of relative humidity is computed as the asymptotic state of an initial value problem.". Syukuro Manabe won the Nobel Prize in Physics, 2021.

Manabe and Bryan (1969)

- Recognized as a “milestone in scientific computing”, Nature (2006).
- Sector model of 120°
- 1 atmospheric year coupled to 100 ocean years
- 1200h for 1 simulated year (0.02 SYPD) on Univac 1108



Atmospheric response to doubled CO_2

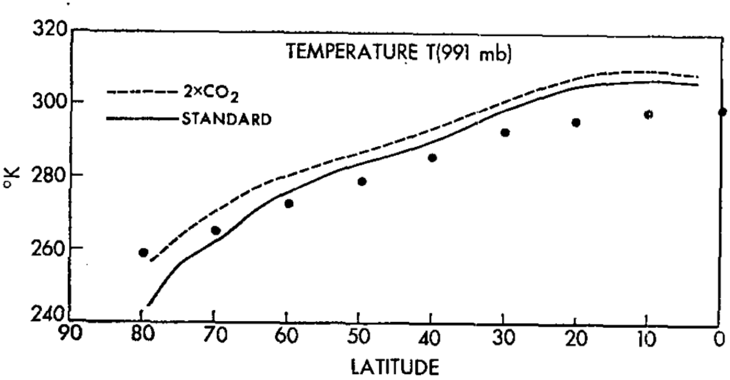


Fig 5 from Manabe and Wetherald (1975), equilibrium response to doubled CO_2.

Atmospheric response to doubled CO_2

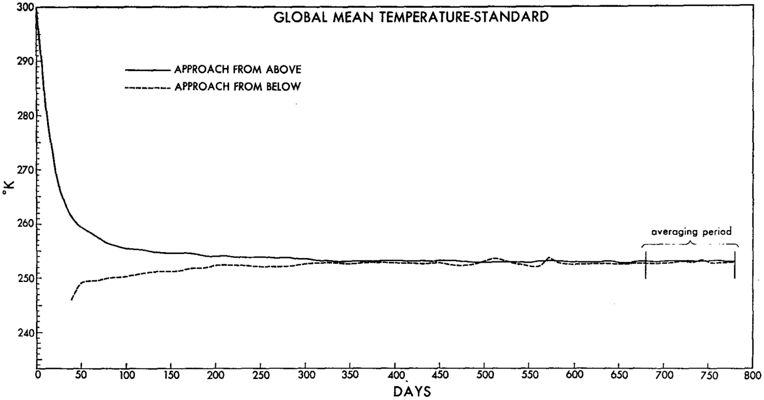
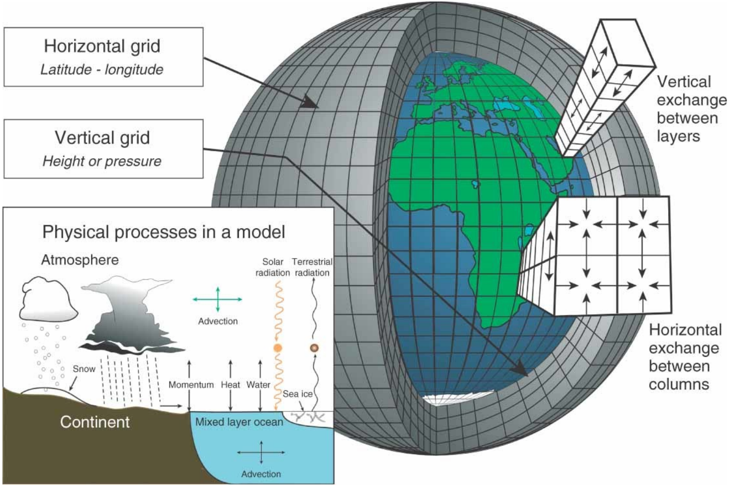


Fig 3 from Manabe and Wetherald (1975), equilibrium response to doubled CO_2. Spinup times in modern GCMs can be $\mathcal{O}(1000 \text{ years})$.

The structure of a GCM, from Manabe to present day



From Edwards (2011). $\mathcal{O}(10X)$ increase in resolution from Manabe and Bryan to CMIP6.

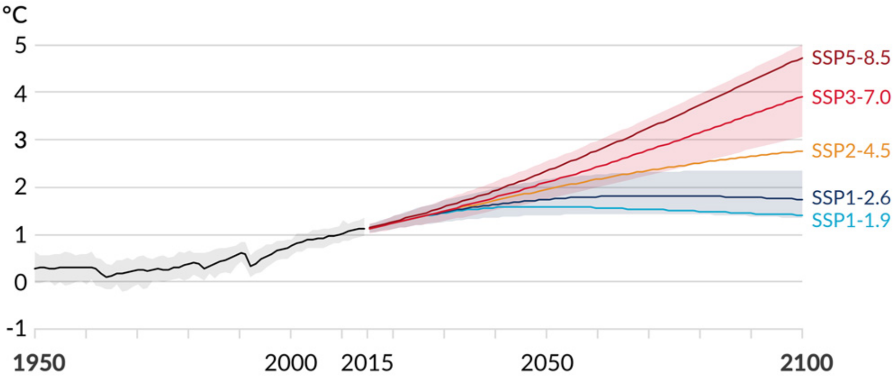
The Charney Report (1979)

"Carbon dioxide and climate: A Scientific Assessment."

- Precursor to the IPCC Assessment Reports.
- Based on 5 model runs: 3 from Manabe (GFDL), 2 from Hansen (GISS).
- Conclusions:
  - Direct radiative effects due to doubling of CO_2: ~ 4 W/m^2
  - Feedbacks: water vapour (Clausius-Clapeyron), snow-ice albedo feedback.
  - Cloud effects: "How important the cloud effects are, is, however, an extremely difficult question to answer. The cloud distribution is a property of the entire climate system, in which many other feedbacks are involved."
  - "We believe, therefore, that the equilibrium surface warming will be in the range of 1.5-4.5°C, with the most probable value near 3°C."

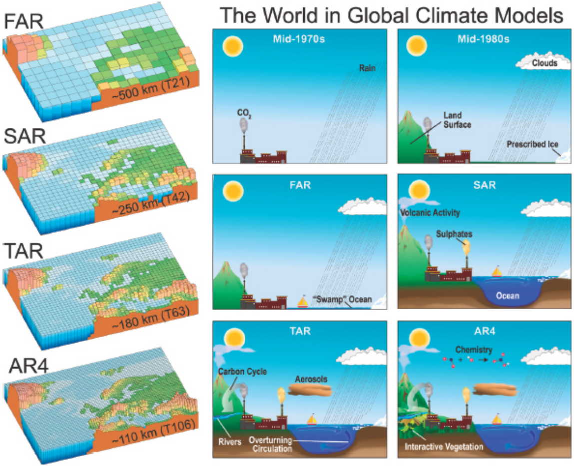
Very nice reassessment of the Charney Report: Bony et al (2013).

... to IPCC AR6



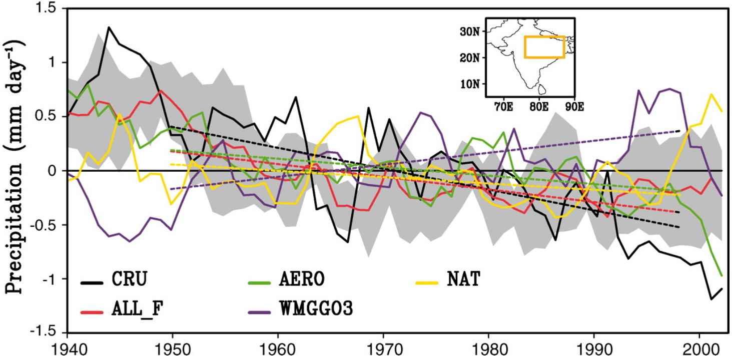
Courtesy IPCC AR6 (2021), Fig 8a from Summary for Policymakers. Based on 114 models from 44 institutions.

Models add detail



Models grow in resolution and complexity. Courtesy IPCC AR4 report. A typical IPCC model today has 25-100 km resolution and $\mathcal{O}(100)$ variables.

Attribution: data from alternate Earths



- Cloud-aerosol feedbacks induce a weakening of the Indian monsoon Bollasina et al., *Science* 2011.
- We can now "attribute" individual events.

Dennard Scaling

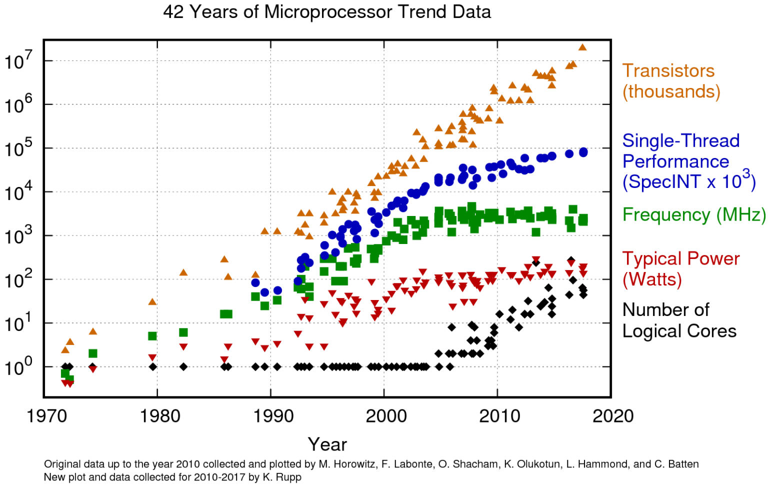
TABLE I

SCALING RESULTS FOR CIRCUIT PERFORMANCE

Device or Circuit Parameter	Scaling Factor
Device dimension t_{ox}, L, W	$1/\kappa$
Doping concentration N_a	κ
Voltage V	$1/\kappa$
Current I	$1/\kappa$
Capacitance $\epsilon A/t$	$1/\kappa$
Delay time/circuit VC/I	$1/\kappa$
Power dissipation/circuit VI	$1/\kappa^2$
Power density VI/A	1

Table 1 from Dennard (1974). Shows scaling of various quantities when transistor dimension is reduced by factor κ.

End of Dennard scaling



From 42 Years of Microprocessor Trend Data, courtesy Karl Rupp.

All algorithms are not created equal

- Real codes often gated by memory bandwidth.
- Roofline model:

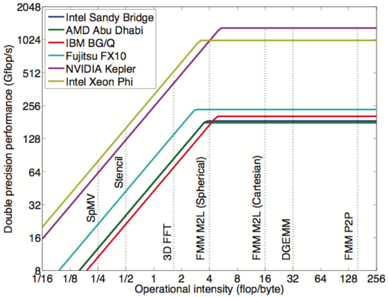
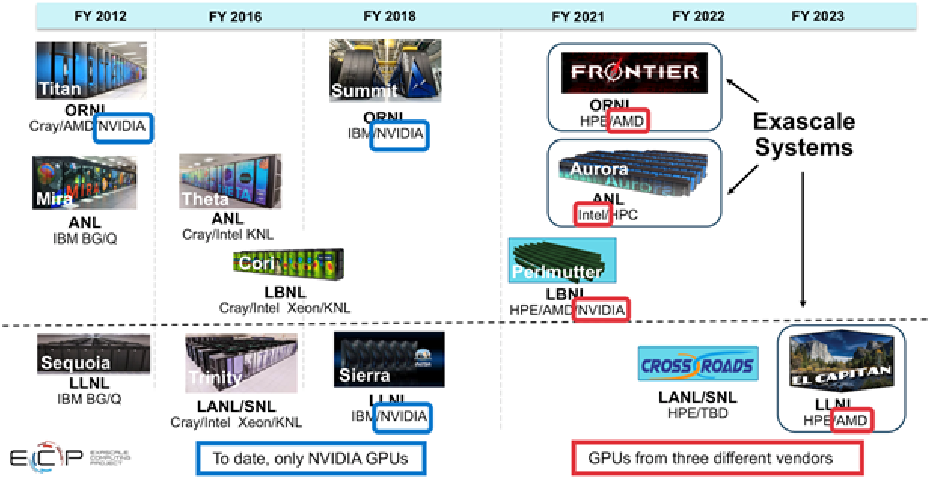


Figure courtesy Barba and Yokota *SIAM News* 2013.

US Exascale Roadmap



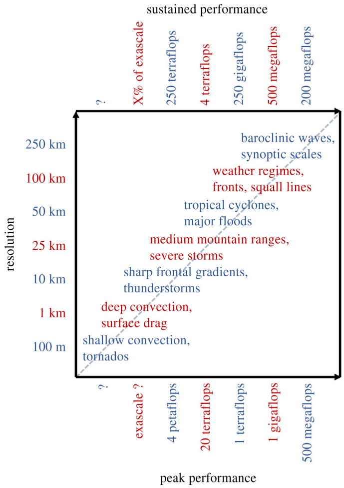
From DOE Exascale Computing Project, via Travis Linderman's blog, Oct 2020.

EU and Japan moving forward with ARM

From European Exascale Project, via EE News, April 2020.

What can we expect at an exaflop?

Will exascale be the rescue? Neumann et al (2019).



Hypothesis: vastly reduced uncertainty at 1 km.

- ICON projects that a 1 km global model will run at 0.06 SYPD on "pre-exascale" technology: 17X improvement needed for 1 SYPD.
- This will be on 200,000 nodes (roughly 2xGaea).
- DECK: 1000 SY.
- A full suite of hindcasts for seasonal forecasting: 10,000 SY.
- Ocean state needed for monsoon prediction as well!

The carbon cost of climate modeling

is-enes
INFRASTRUCTURE FOR THE EUROPEAN NETWORK FOR EARTH SYSTEM MODELLING

CMIP6 Summary

IS-ENES3 1st General Assembly
25-27th March 2020
Toulouse, France

CMIP6 Experiments: Institutions/Models	Useful SY	Total SY	Useful Data Produced	Total Data Produced	Useful CH (Mh)	Total CH (Mh)	Total Energy Cost (Joules)	Carbon Footprint (CO2/KWh)
EC-Earth	17,5[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	41.8	1.27×10^{12}	162.6t
CNRM-CERFACS	23,6[illegible]	[illegible]	[illegible]	[illegible]	[illegible]06.4	325	3.13E+12	49.5t
IPSL	53,0[illegible]	[illegible]	[illegible]	[illegible]	100	270	6.16E+12	122t
CMCC	96[illegible]	[illegible]	[illegible]	[illegible]	1.99	NA	1.61E+12	
UKMO	23,4[illegible]	[illegible]	[illegible]	[illegible]	473	NA	1.76E+13	572.5t
DKRZ	1,2[illegible]	[illegible]	[illegible]	[illegible]	5.52	5.90	4.09E+11	24.8t
NCC-NORESM2	6,484	NA	0.297	NA	11.7	NA	4.75E+11	
NERC	640	NA	0.460	NA	55.497	NA	2.17E+12	
MPI	24,175	35,000	1.9	NA	968.116	NA	6.20E+11	37.6t

Please take these numbers as first (and not accurate) approximation

- Total Energy cost is calculated multiplying useful SY and the proportional average of JPSY for the set of CMIP6 experiment per institution.
- CO2 is calculated using factor conversion and PUE, proposed by carbon footprint group and yet in discussion.

* We have also Useful SY, Useful Data and Useful CH per CMIP6 experiment

The IS-ENES3 project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824084

From CPMIP Project (Balaji et al, GMD 2017), courtesy Mario Acosta, BSC.

The climate Turing test

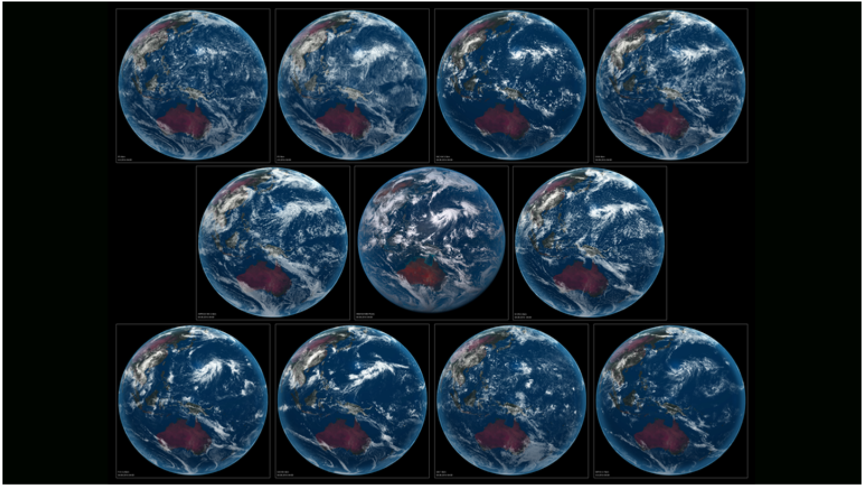
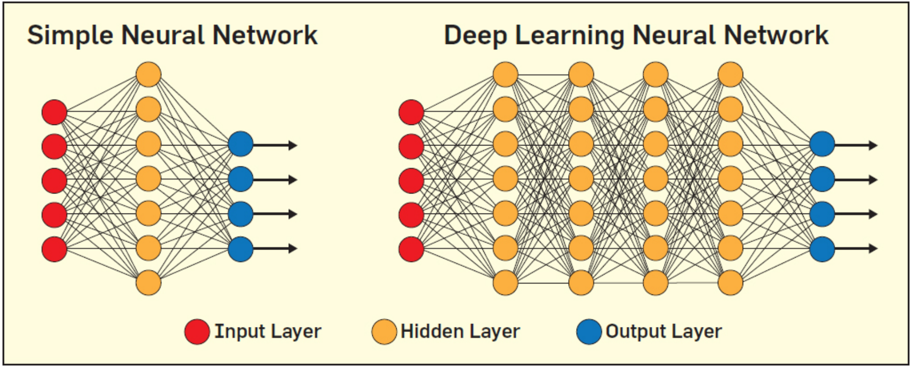


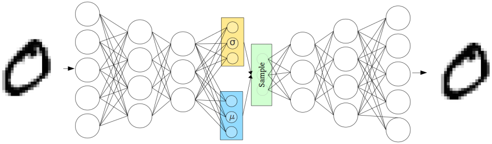
Figure courtesy the DYAMOND initiative.

Deep Learning



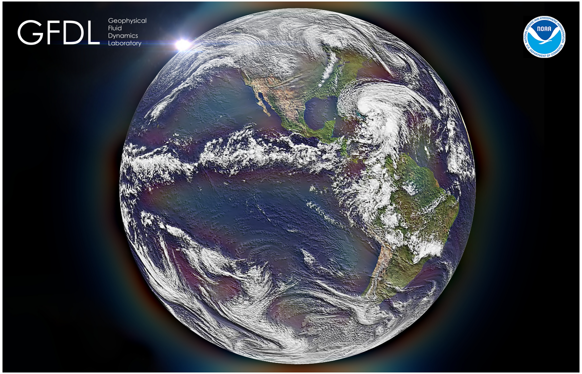
From Edwards (2018), ACM.

The ML approach: finding the essence

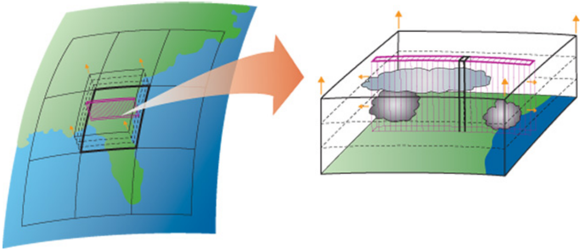


From "features" make new instances that capture the essence. Angles and Mallat (2018)

Coarse-graining using ML



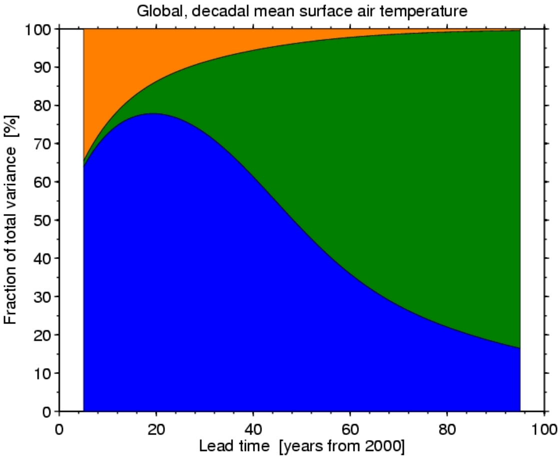
(Courtesy: S-J Lin, NOAA/GFDL).



(Courtesy: D. Randall, CSU; CMMAP).

- From global cloud-resolving models, can we learn the statistical aggregate of small scales? See Schneider et al 2017, Gentine et al (2018), O'Gorman and Dwyer (2018), Bolton and Zanna (2019), ...

Science requires going beyond observations

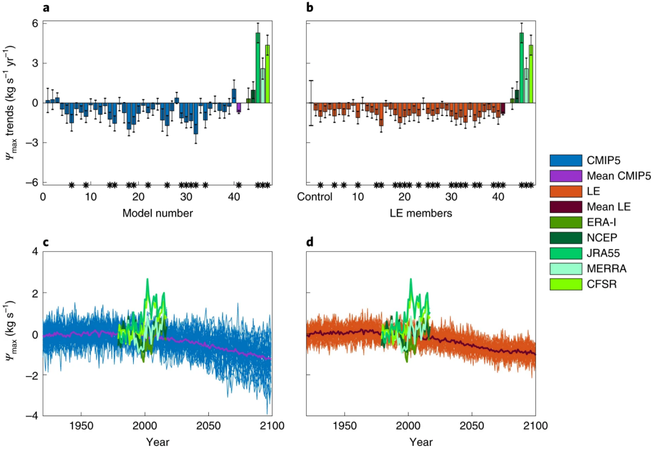


Sources of uncertainty in weather and climate simulation:

- *chaotic uncertainty* or internal variability
- *scenario uncertainty* dependent on policy and human actions.
- *structural/epistemic uncertainty* or imperfect understanding.

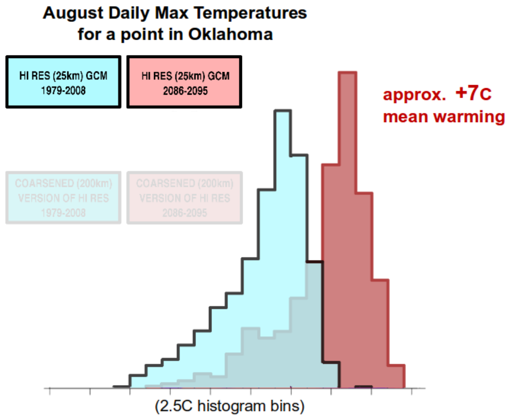
Models must also generate counterfactual values! From Hawkins and Sutton (2009).

Models or observations?



Hadley cell strength is likely correct in models and not in "observations"!
From Chemke and Polvani (2019).

Error patterns associated with stationarity assumption



Errors can be traced with warming outside the temperature distribution of the training period. Caution needed at distribution tails ("extreme events"). Dixon et al (2016).

Where models and data are both weak...

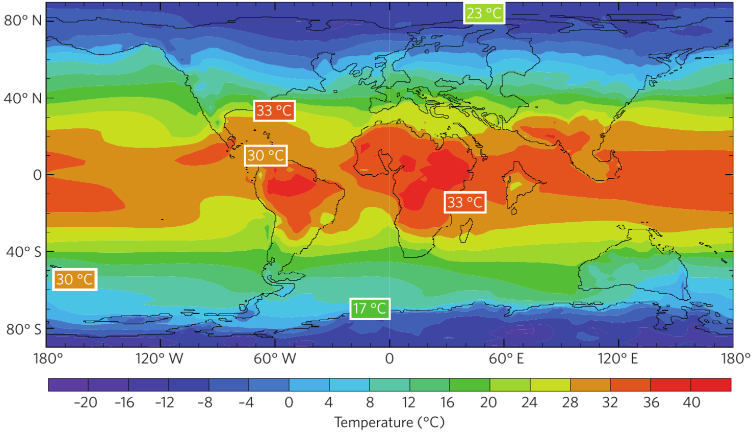
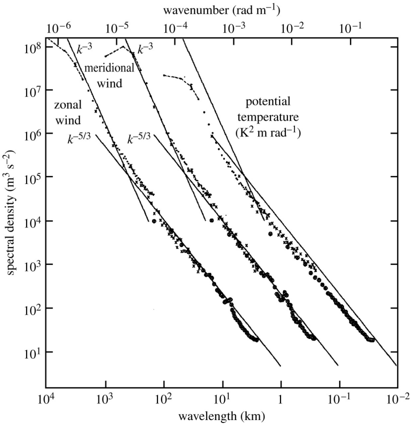


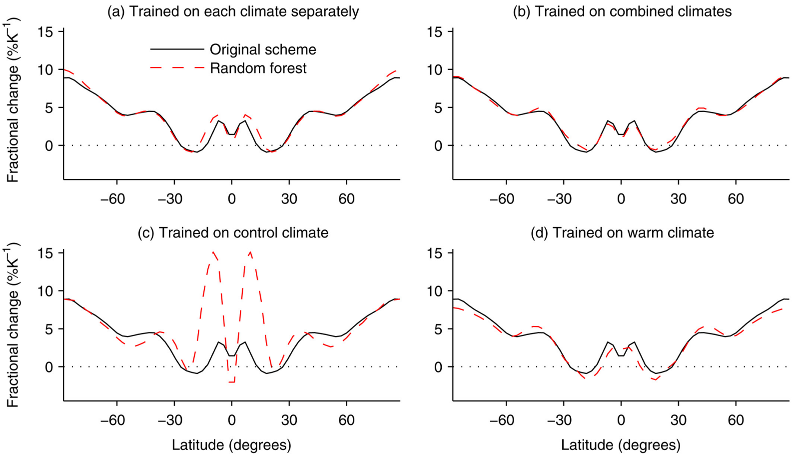
Fig 1 from Valdes (2011). GCMs are unable to simulate the Paleocene-Eocene climate of 55 My ago.

No separation of "large" and "small" scales



Nastrom and Gage (1985). More model fidelity, more complexity over time in small scales ("physics"). The backscatter idea (Jansen and Held 2014) provides an energetically consistent framework for SGS.

Replacing a parameterization with DL



From O'Gorman and Dwyer (2018). Limitations of training on short non-stationary time series. See also Dixon et al (2016).

Learning sub-gridscale turbulence

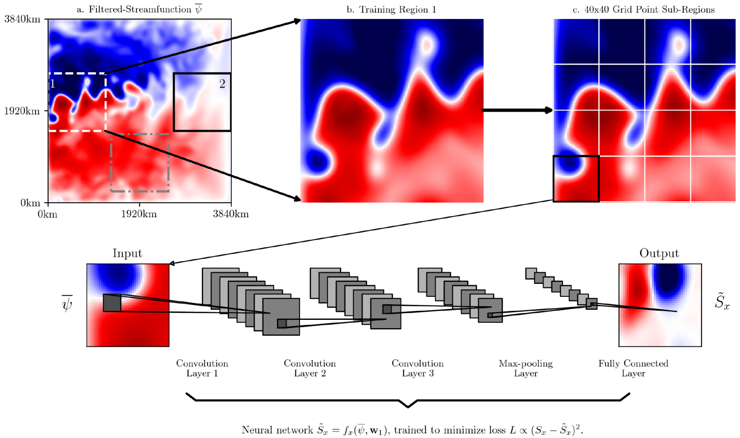
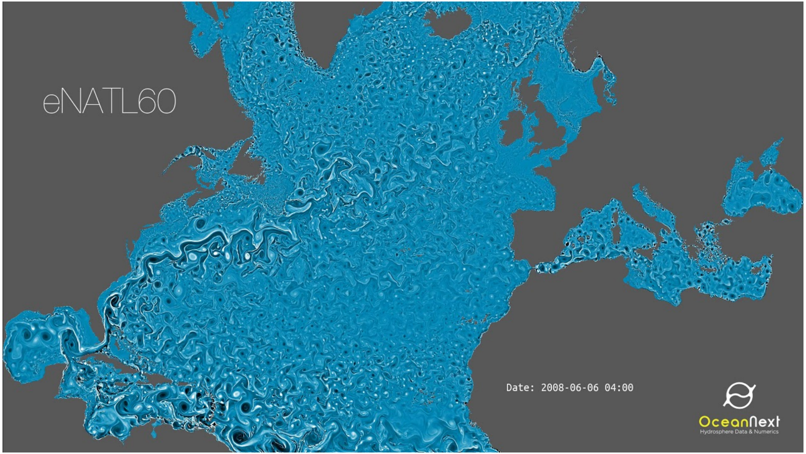


Fig 1 from Bolton and Zanna (2019).

Coarse-graining without scale separation



eNATL60 dataset courtesy Julien le Sommer and collaborators. Can we assume a structure for learning. e.g "GM+E" Bachman 2019. See Sommer et al AGU 2019.

Distilling Free-Form Natural Laws from Experimental Data

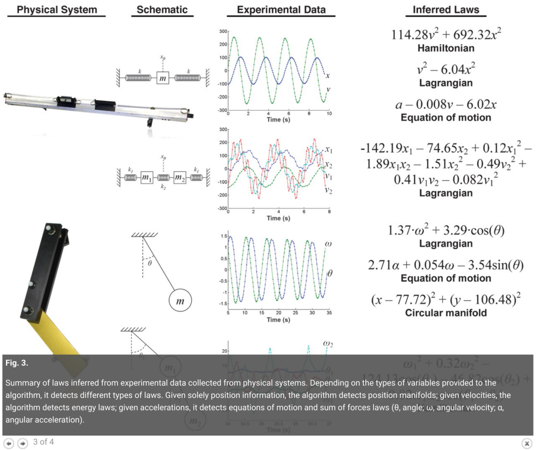
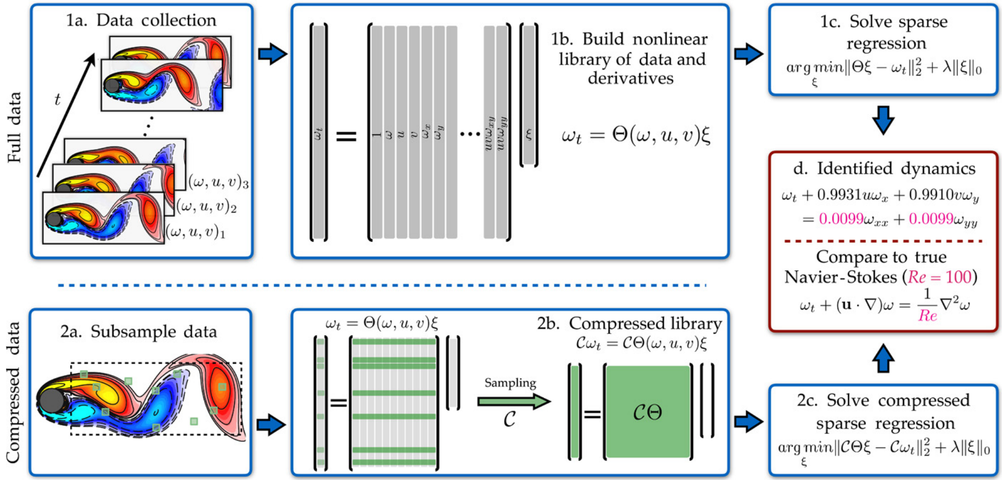


Fig. 3.

Summary of laws inferred from experimental data collected from physical systems. Depending on the types of variables provided to the algorithm, it detects different types of laws. Given solely position information, the algorithm detects position manifolds; given velocities, the algorithm detects energy laws; given accelerations, it detects equations of motion and sum of forces laws (θ, angle; ω, angular velocity; α, angular acceleration).

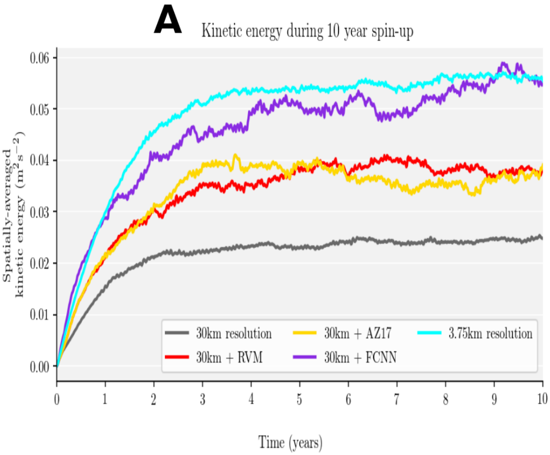
From Schmidt and Lipson, *Science*, 2009. My little *hommage*, Gaitán et al (2016), *Can we obtain viable alternatives to Manning's equation using genetic programming?*

Navier-Stokes from data



From Rudy et al (2017).

Discovering subgrid momentum closures



Zanna and Bolton 2020 builds on work previously shown, and returns a closed-form expression for subgrid momentum closures:

$$\mathbf{S_u} = (\overline{\mathbf{u}}.\nabla)\overline{\mathbf{u}} - \overline{\mathbf{u}.\nabla\mathbf{u}}$$

where *relevance vector machine* techniques yield a representation similar in form to Anstey and Zanna (2017).

Outline

Summary: where is climate modeling headed?

- Models today embody a dizzyingly detailed Earth system. Trust comes from fidelity to individual processes and feedbacks, fidelity relative to other lines of evidence. But there is the Borges conundrum (see "On exactitude in science", and Lewis Carroll's "Sylvie and Bruno").
- Would you trust "model-free" simulations from an AI?
- Machine learning and "AI" still is in the positive phase of a hype cycle (publication bias, reproducibility crisis) but it isn't *all* hype. Dominating the hardware market.
- ML-derived models must be capable of going outside observational bounds
- Imperative to derive hierarchies of simple models from expensive ones.
- Energy and carbon cost of computing must be factored into model development and experiment design: carbon-intensive data must be maximally utilized by the community.
- Survey paper: *Climbing down Charney's ladder*, Balaji *Phil Trans* Feb 2021.
- Disclaimer: views expressed here are my own!