Diversity in reanalysis products and opportunities for collaboration

Sergey Frolov

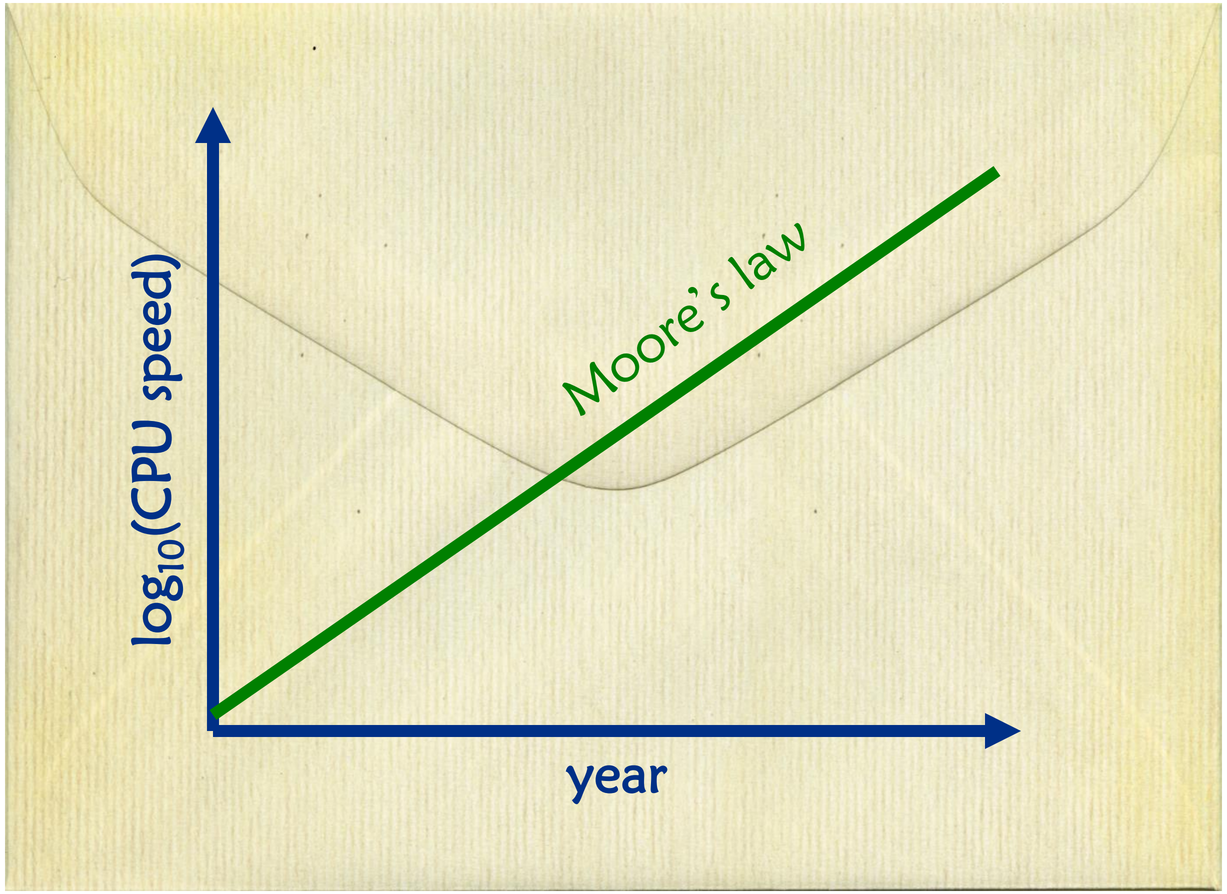
With gratitude to my colleagues

ECMWF Annual Seminar 2023

Outline

- **Historic diversity in reanalysis products**
- Focus on diversity in assimilation algorithms
- Next generation of reanalysis products
- Balancing competing need for cooperation and diversity

Putting diversity of atmospheric reanalysis in context



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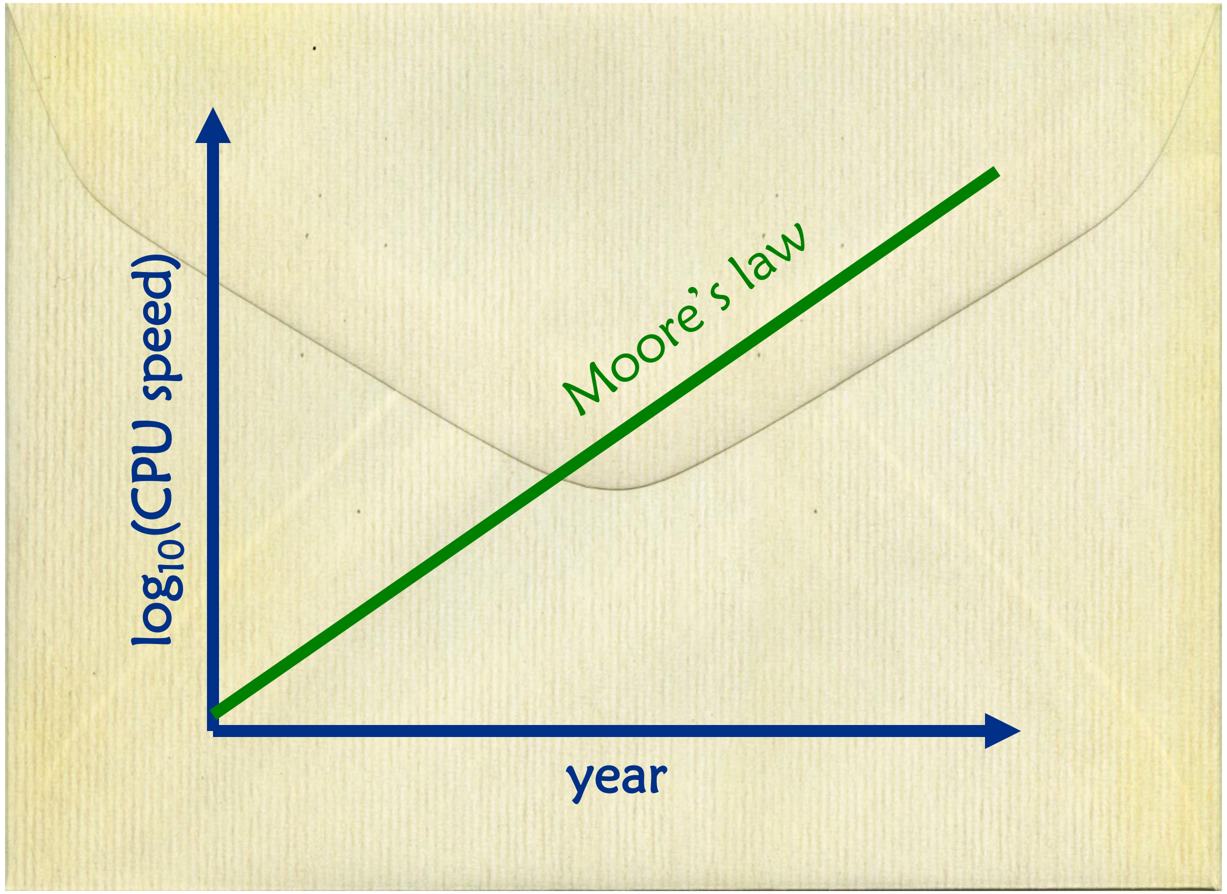
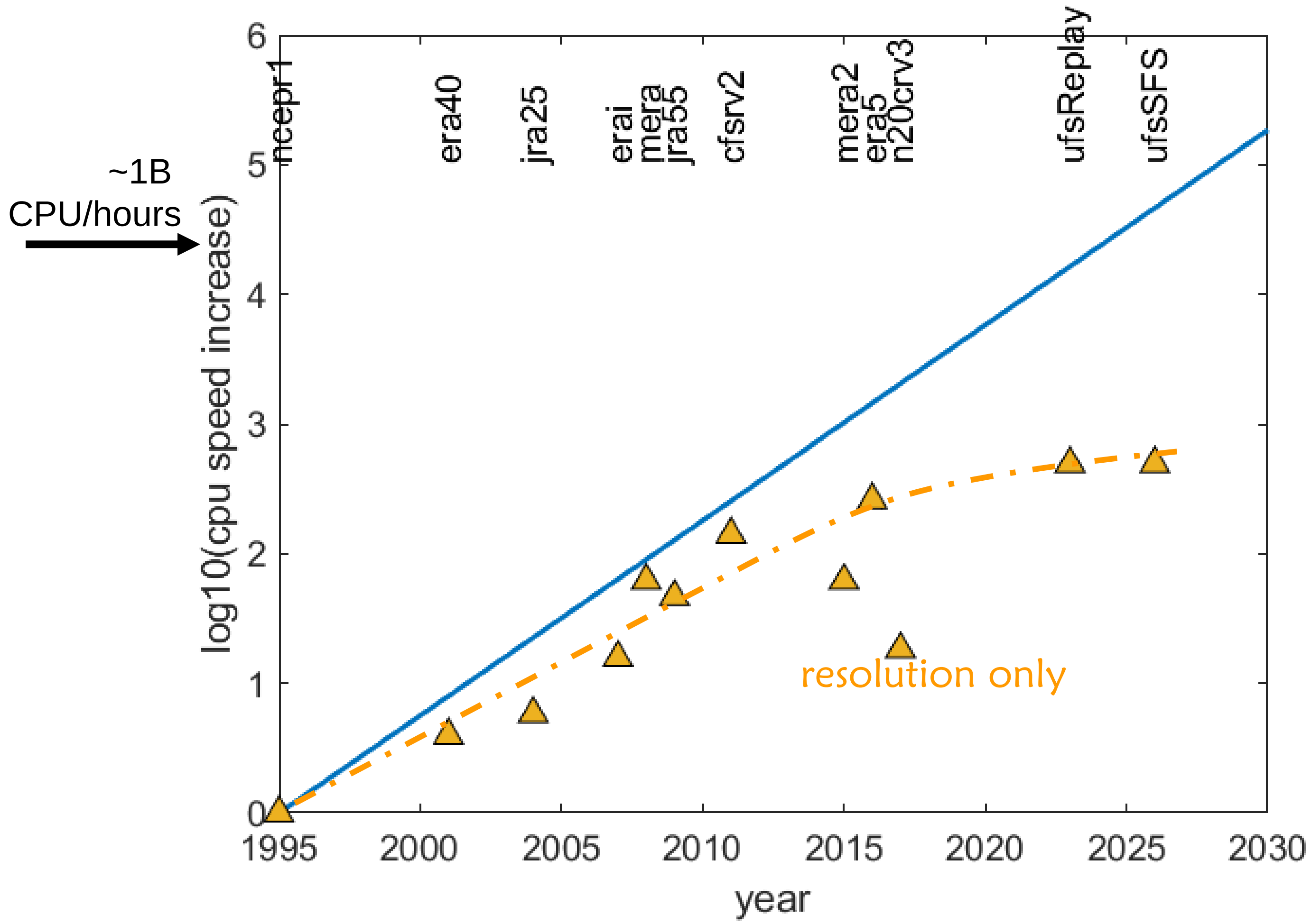


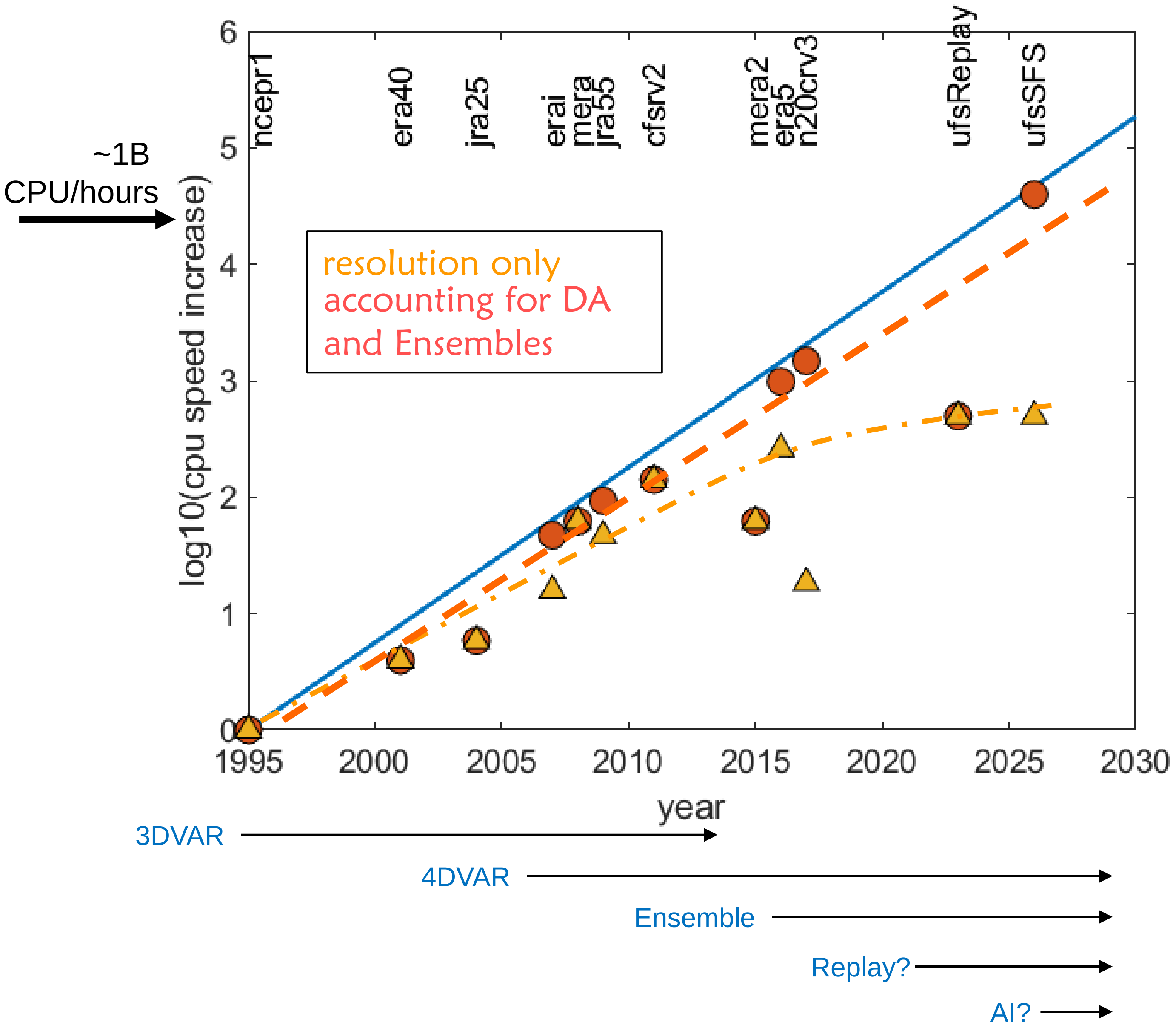
- Make basic assumptions:
  - Use log10 y axis to highlight changes in the order of magnitude.
  - Doubling of resolution leads to 8x increase in cost.
  - Cost of non-linear trajectory dominates cost of 4DVAR.
  - Cost of ensemble integration dominates the cost of EnKF.

Accounting for increase in resolution



- Historic increases in resolution of atmospheric reanalysis does not track increase in available CPU power.

Diversity of reanalysis driven by computational power increases



- Cost of reanalysis production tracks historic increases in computational power.
- Reanalysis costs increased due to combination of increase in:
  - Resolution;
  - Sophistication of DA algorithms (3DVAR->4DVAR);
  - Addition of model uncertainty (EDA, EnKF);
  - Sophistication of models (coupled, more physics, better numerics).

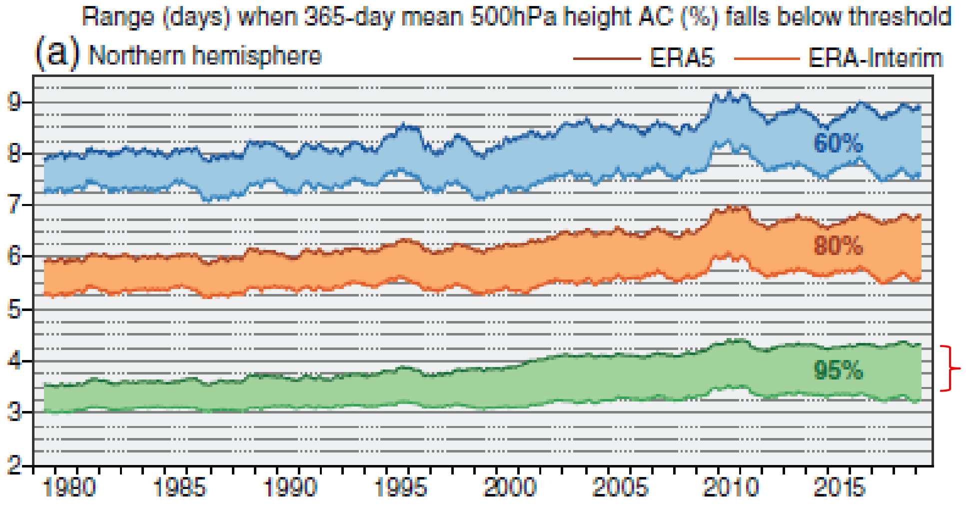
Aspects of diversity

product	Res.	DyCore	Physics	Coupled	DA	Obs	Ensemble
NCEPR1	200km	GFS	NOAA		OI/3DVAR	Conventi onal	1
ERAI	79km	IFS	ECWMF		4DVAR	ECWMF	1
MERA2	50km	FV3	NASA		3DVAR	NOAA/ NASA	1
CFSR	38km	GFS	NOAA	YES	3DVAR	NOAA	1
ERA5	31km	IFS	ECWMF		4DVAR	ECWMF	10
20CRv3	75km	GFS	NOAA		EnkF	Psurf	80
UFSreplay	25km	UFS	NOAA	YES	Replay	ERA5/ ORA5	1+

….

- Other aspects of diversity include:
  - Radiation, aerosols, chemistry, sea surface boundary conditions, radiation forcing, …

Increase in cost pays off



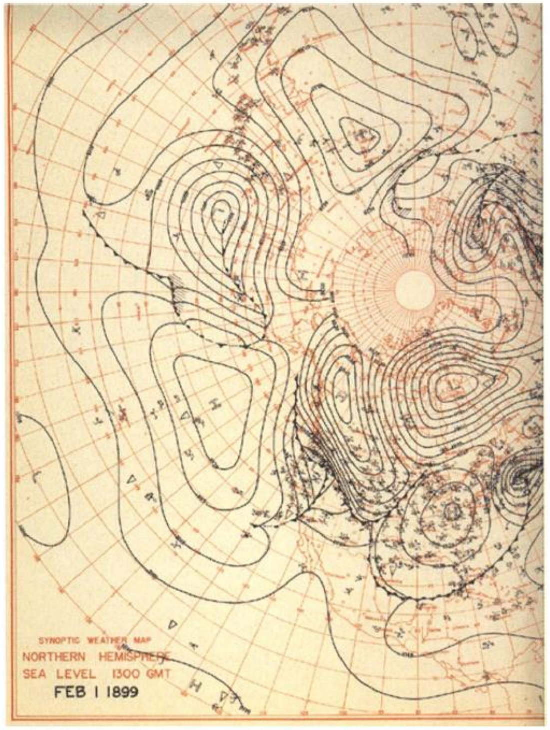
Improved short-range forecasts are mainly due to better I.C. in ERA5 compared to ERA-Interim

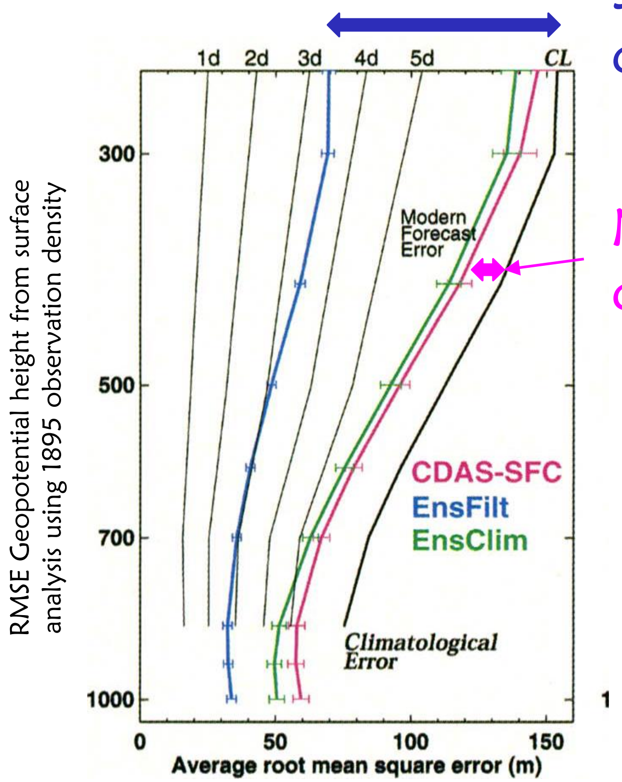
- A decade of development and computational power increase translates to better analysis and forecasts, as compared between ERA-Interim and ERA5.

DOI: 10.1002/qj.3803

Better algorithms pay off

Reconstructed weather in 1899





Substantial skill when flow-dependent covariances are used (EnKF, EDA)

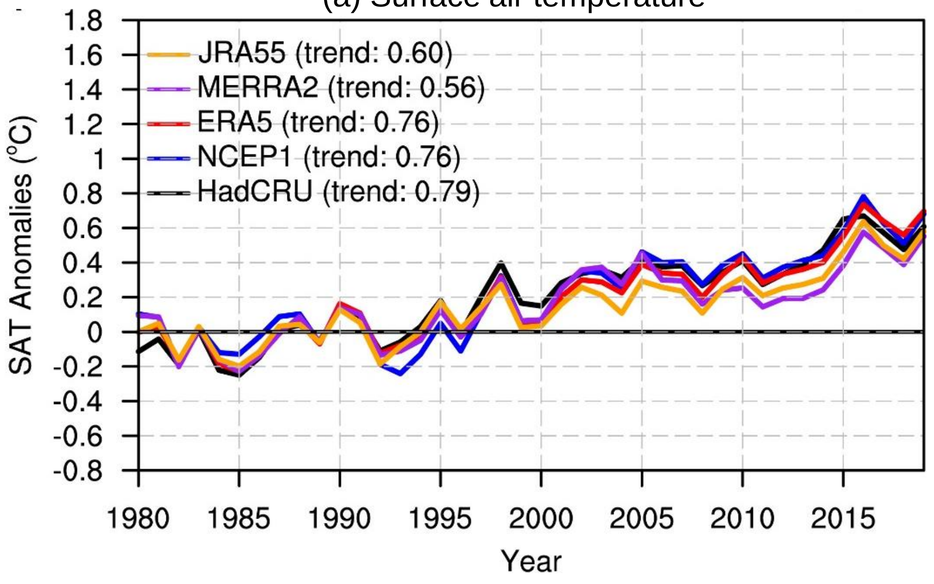
Marginal skill compared to climatology if static covariance is used (like 3DVAR, OI, EnsOI)

- Compo et.al. 2006 showed that it is essential to use flow-dependent covariances when assimilating sparse historical observations.

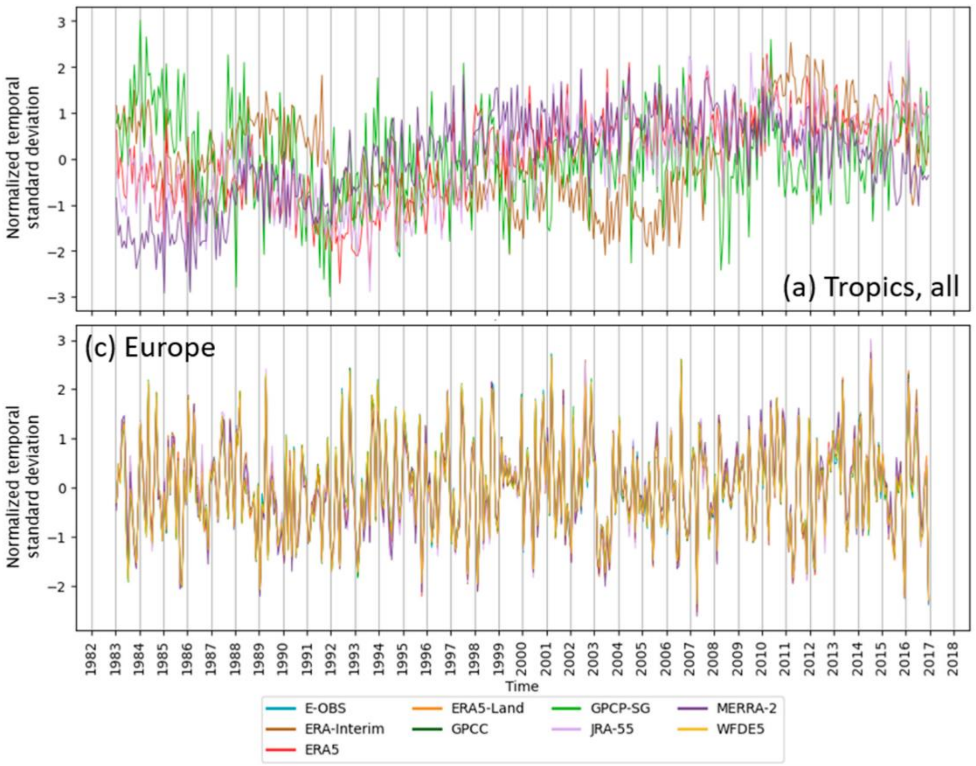
Compo et al. 2006 BAMS

Diversity of reanalysis pays off

(a) Surface air temperature



(b) Monthly mean anomalies of precipitation



- Diversity in reanalysis products provides essential confidence in our ability to represent trends and inter-seasonal patterns:
  - (a) all reanalysis capture positive trend in surface temperature but some do better than others.
  - (b) all reanalysis struggle to capture interannual variations in tropical precipitation but do well for precipitation over Europe.

https://doi.org/10.3390/atmos12111462
https://www.pnas.org/doi/10.1073/pnas.2117832119

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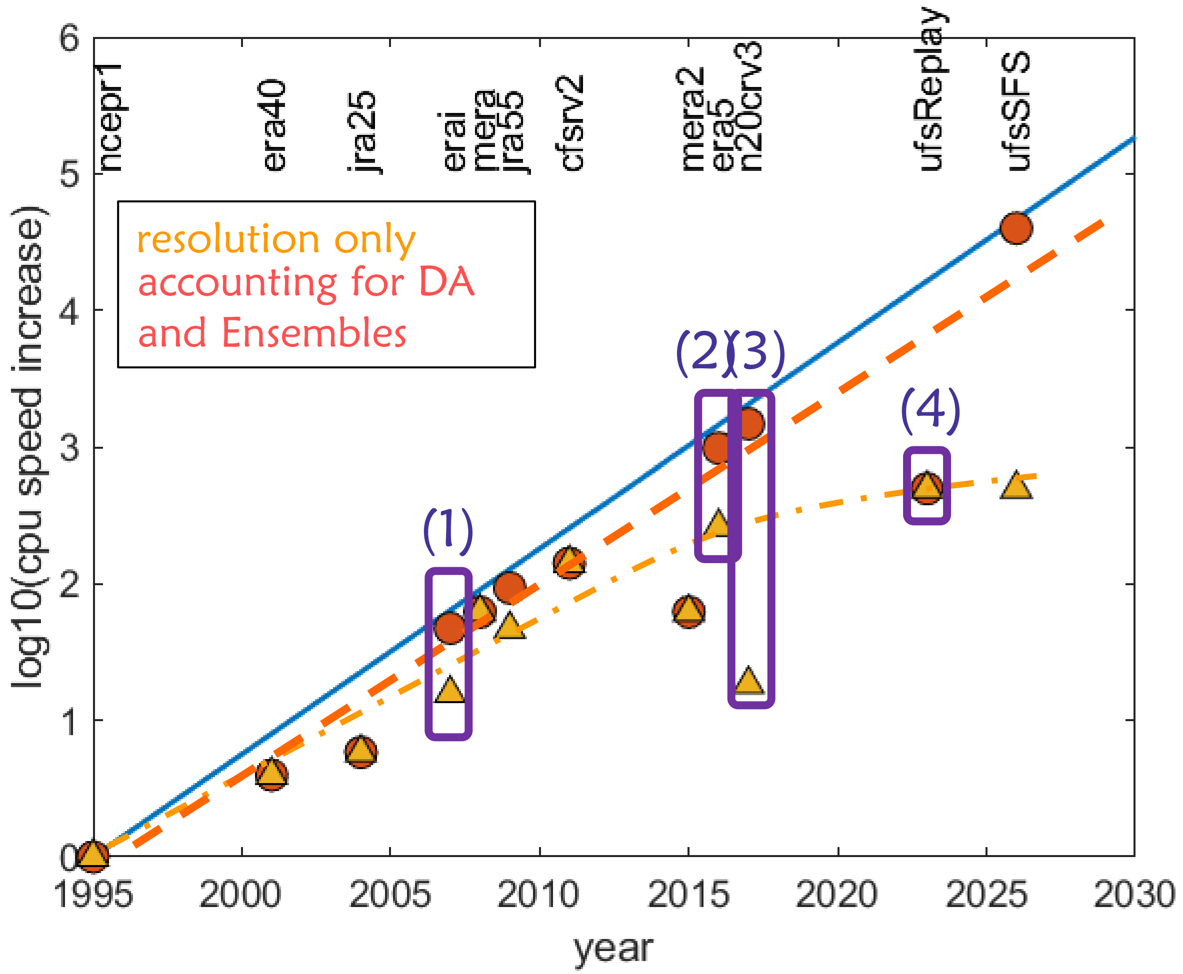
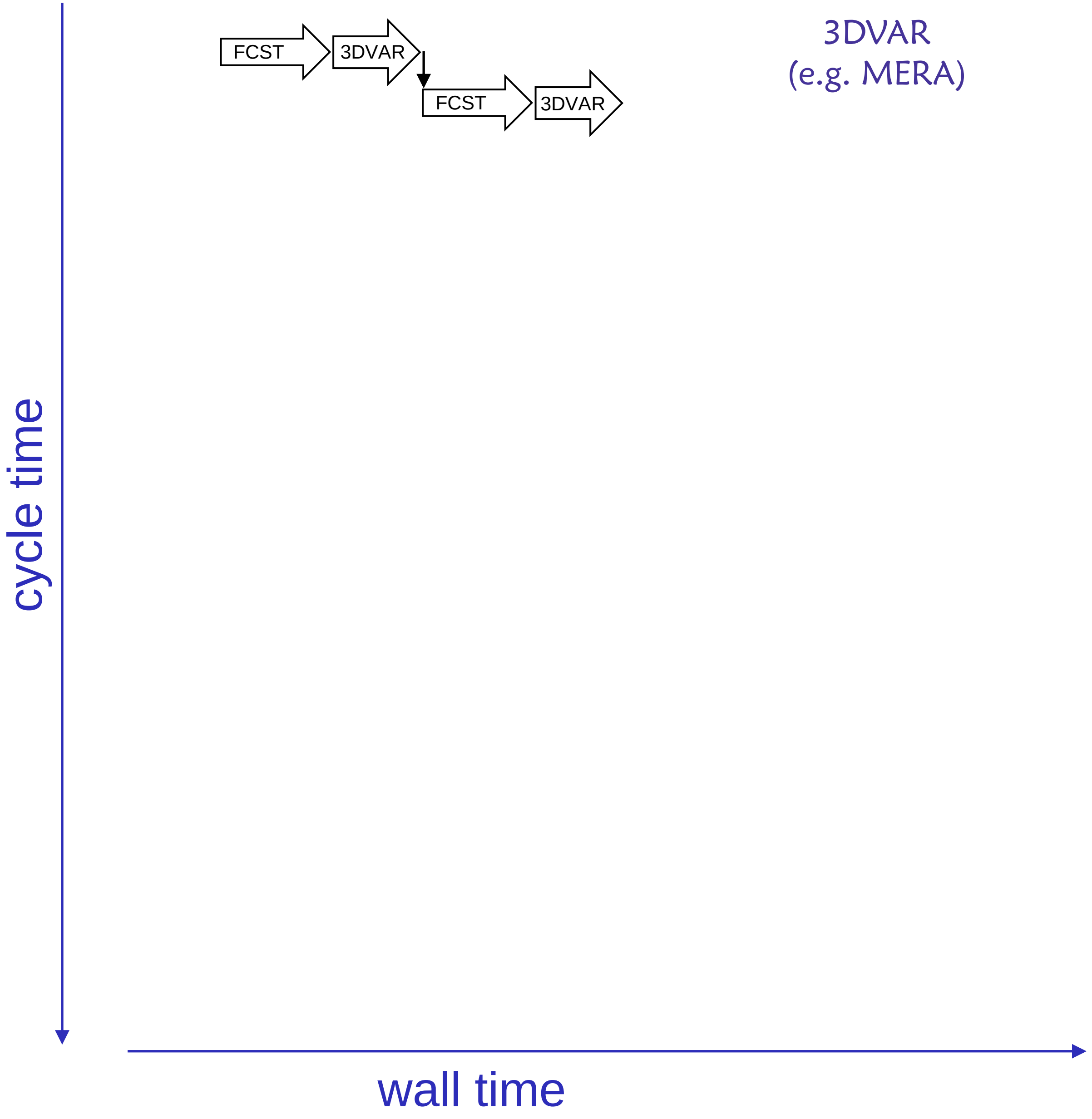
Focus on diversity in assimilation algorithms



1. Transition from 3DVAR to 4DVAR
2. Ensemble of 4DVARs (EDA)
3. EnKF compared to EDA
4. Replay compared to full reanalysis

Reanalysis: a balance of cost, throughput, and quality



- 3DVAR:
  - High throughput and low cost;
  - Inferior quality compared to 4DVAR/EnKF.

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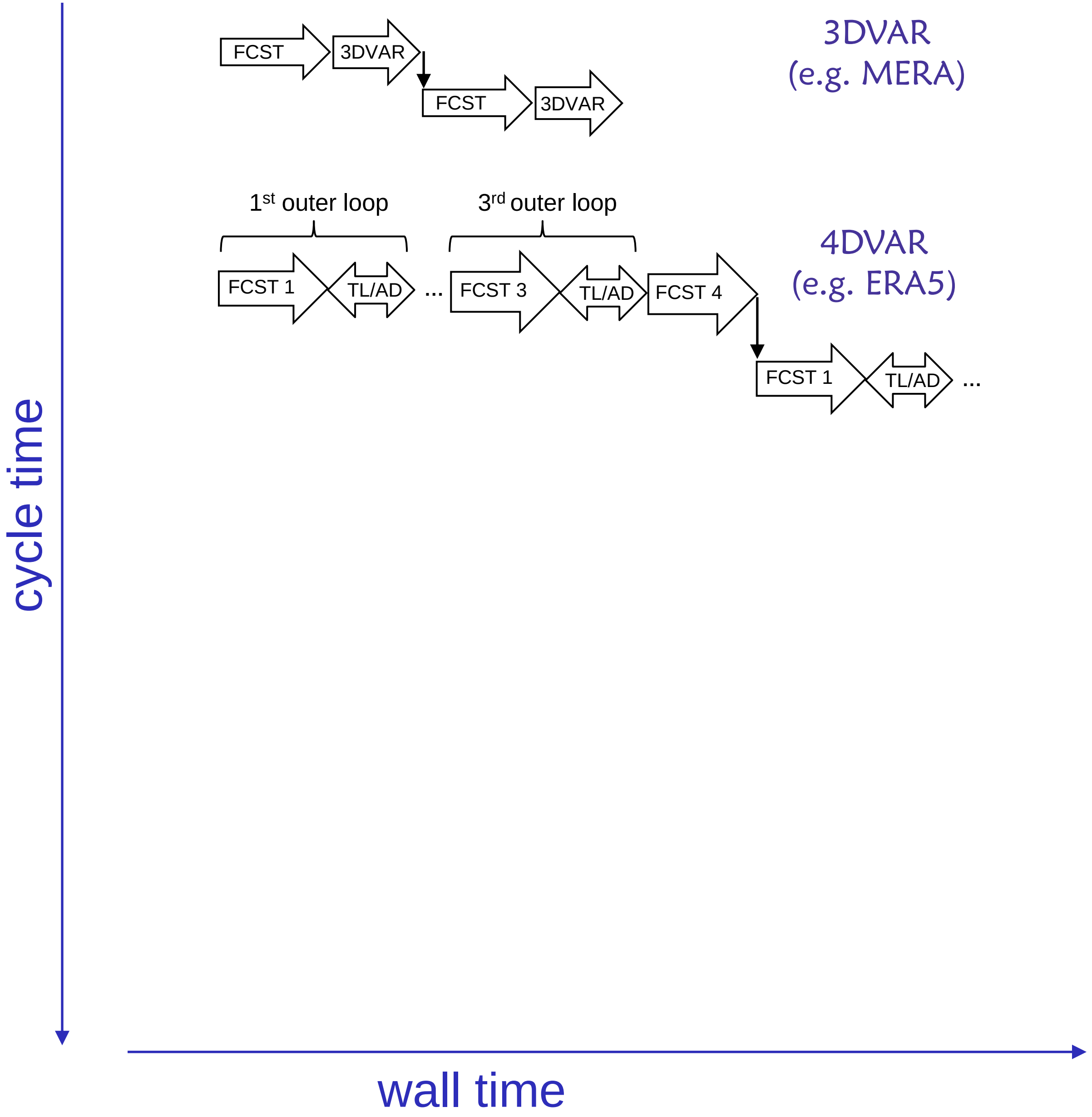

- 3DVAR:
  - High throughput and low cost;
  - Inferior quality compared to 4DVAR/EnKF.
- 4DVAR:
  - Throughput limited by sequential model integrations;
  - Very competitive quality especially when combined with EDA;
  - A lot of options for controlling total cost.

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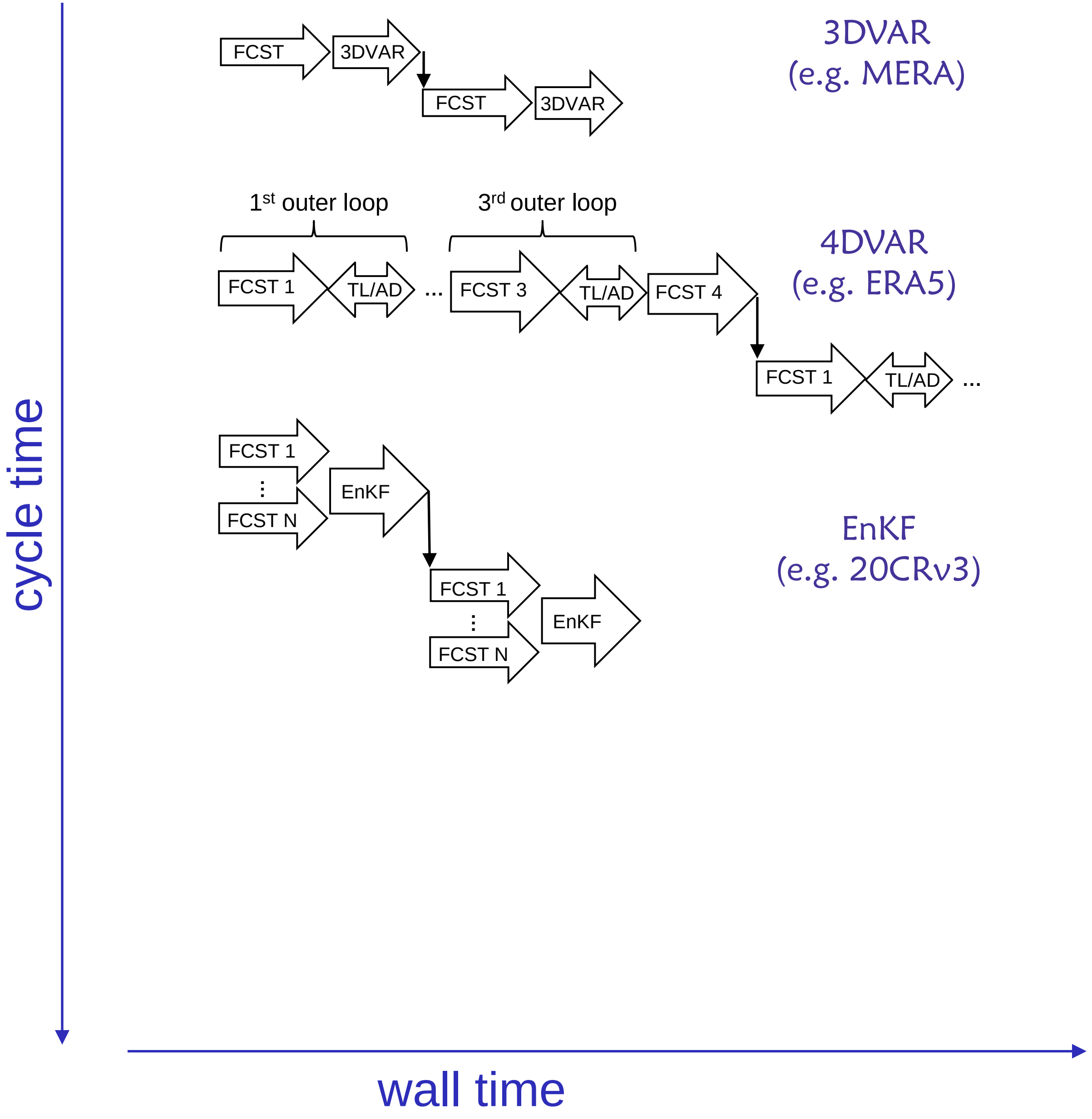

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  - High theoretical throughput;
  - High cost (~50-100 ensemble members);
  - Competitive quality.

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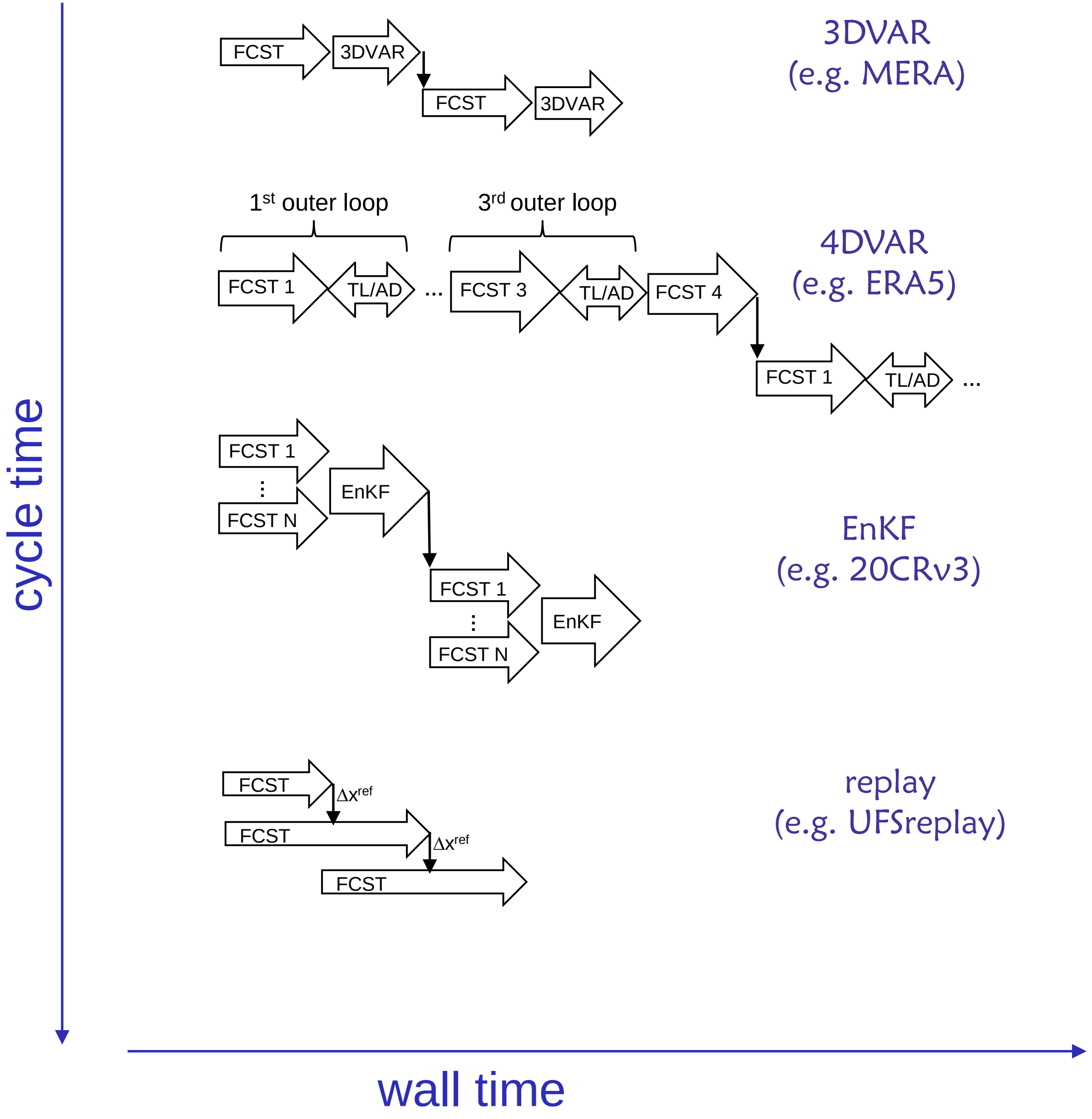

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- EnKF:
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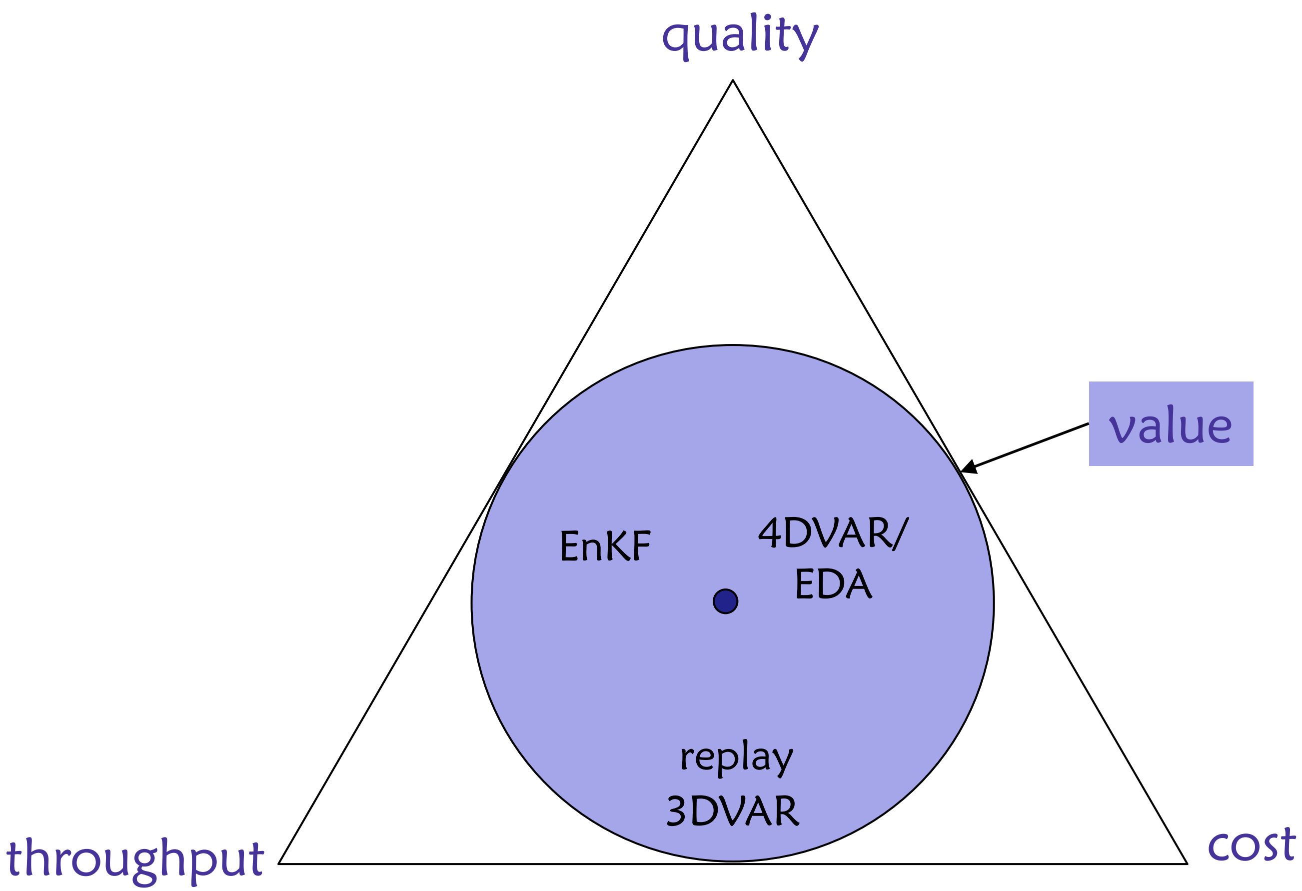
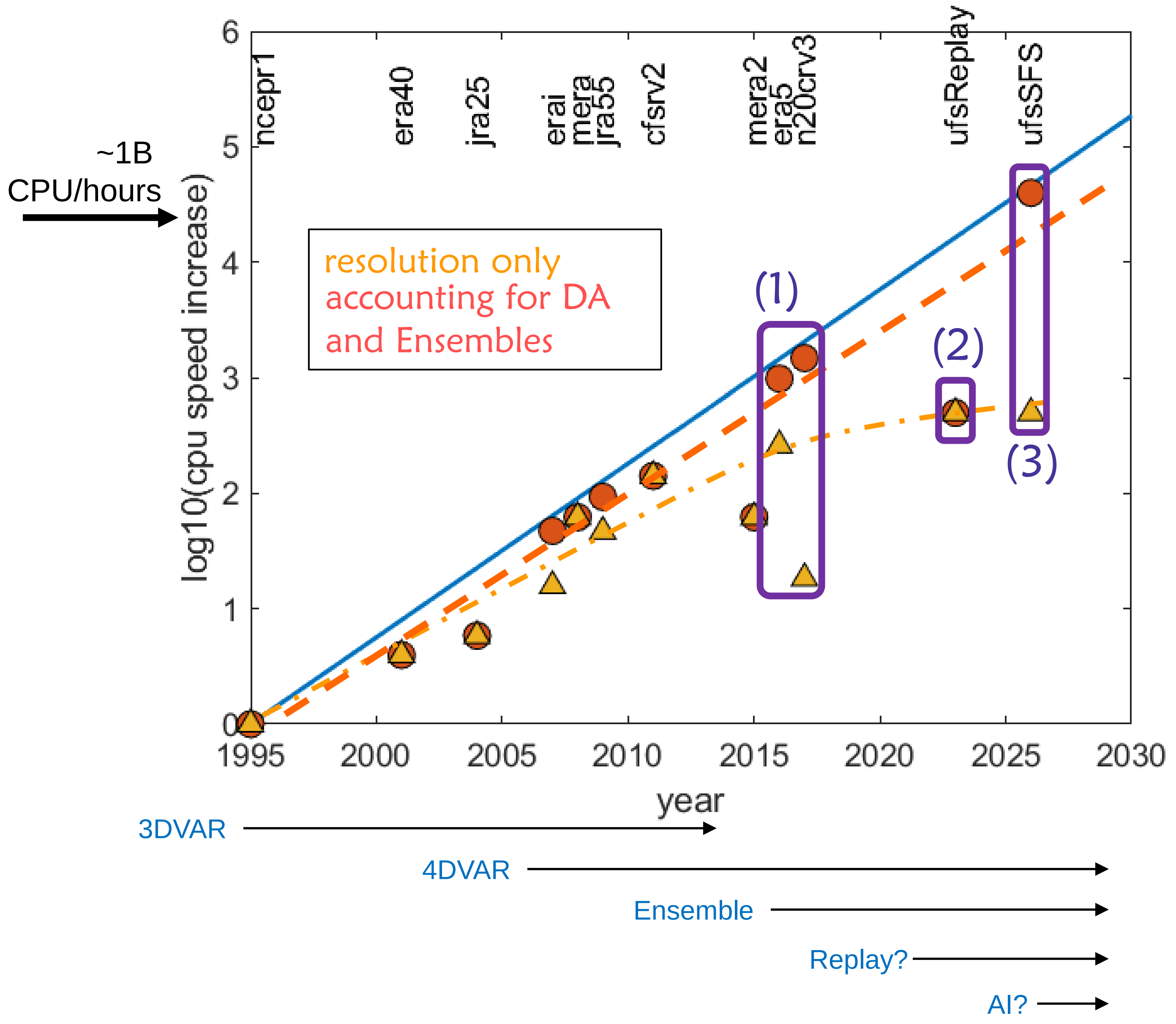
- Replay:
  - Low cost and very high throughput;
  - High quality (pegged to existing reference analysis like ERA5);
  - Limited utility.

Reanalysis: a balance of cost, throughput, and quality



- All reanalysis (independent of the method) yield value.
- Still more progress can be made to optimize for throughput, cost, quality, and (ultimately) value.

What is next for algorithms in reanalysis



(1) Use hybrid (multi-resolution) approaches and AI/ML to reduce cost of ensemble generation and uncertainty quantification for EnKF-based reanalysis.

(2) Exploit low cost of replay production to rapidly update reanalysis to reflect changes in model configurations,

(3) Exploit future advances in computing to increase:

- Sophistication of numerical models: e.g. coupled models.
- Data assimilation algorithms: e.g. model error estimation and strongly coupled DA,
- Resolution: e.g. high-resolution tiles within reanalysis configuration.

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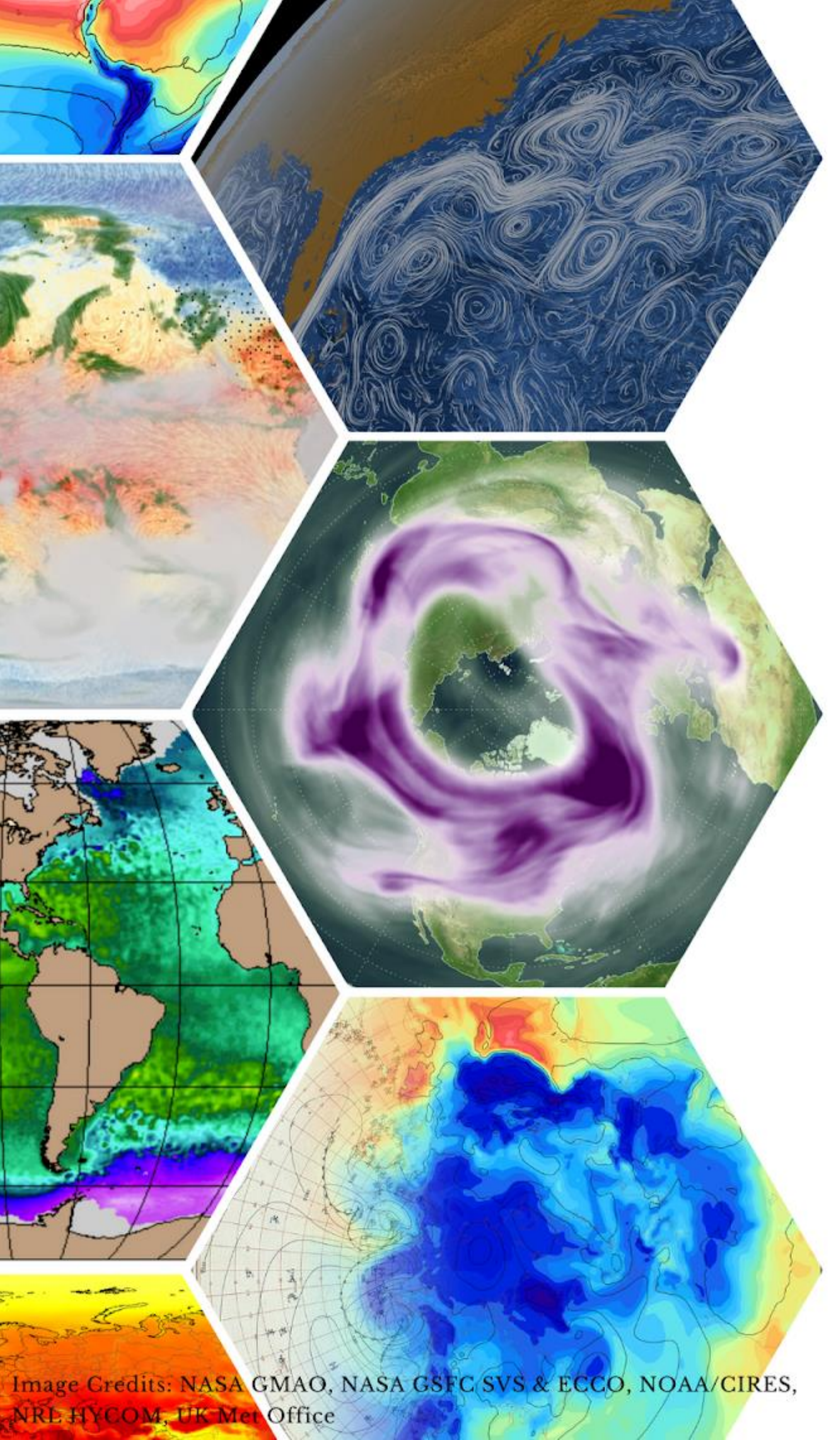

Image Credits: NASA GMAO, NASA GSFC SVS & ECCO, NOAA/CIRES, NRL HYCOM, UK Met Office

https://usclivar.org/meetings/reanalysis-2021

Workshop on Future US Earth System Reanalysis

MAY 16-18, 2022
BOULDER, CO & VIRTUAL

A workshop aimed at developing a shared scientific, technological, and application vision for the future of US reanalysis efforts.

Scientific Organizing Committee
Sergey Frolov, NOAA PSL (co-chair)
Cécile Rousseaux, NASA (co-chair)
Tom Auligne, JCSDA
Dick Dee, Planet A
Ron Gelaro, NASA GMAO
Patrick Heimbach, U. Texas
Isla Simpson, NCAR
Laura Slivinski, CIRES/NOAA PSL

Sponsored by

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Objectives

1. Identify **scientific goals** for the next generation of reanalysis from the atmospheric, oceanographic, and cryosphere perspectives.

2. Identify opportunities for **exploiting technological advancements** in Earth system models, data assimilation systems, observations, and computational infrastructure.

3. Identify priorities and **opportunities for tighter collaboration** between the US institutions, the US and the international reanalysis communities, and between reanalysis and observational communities.

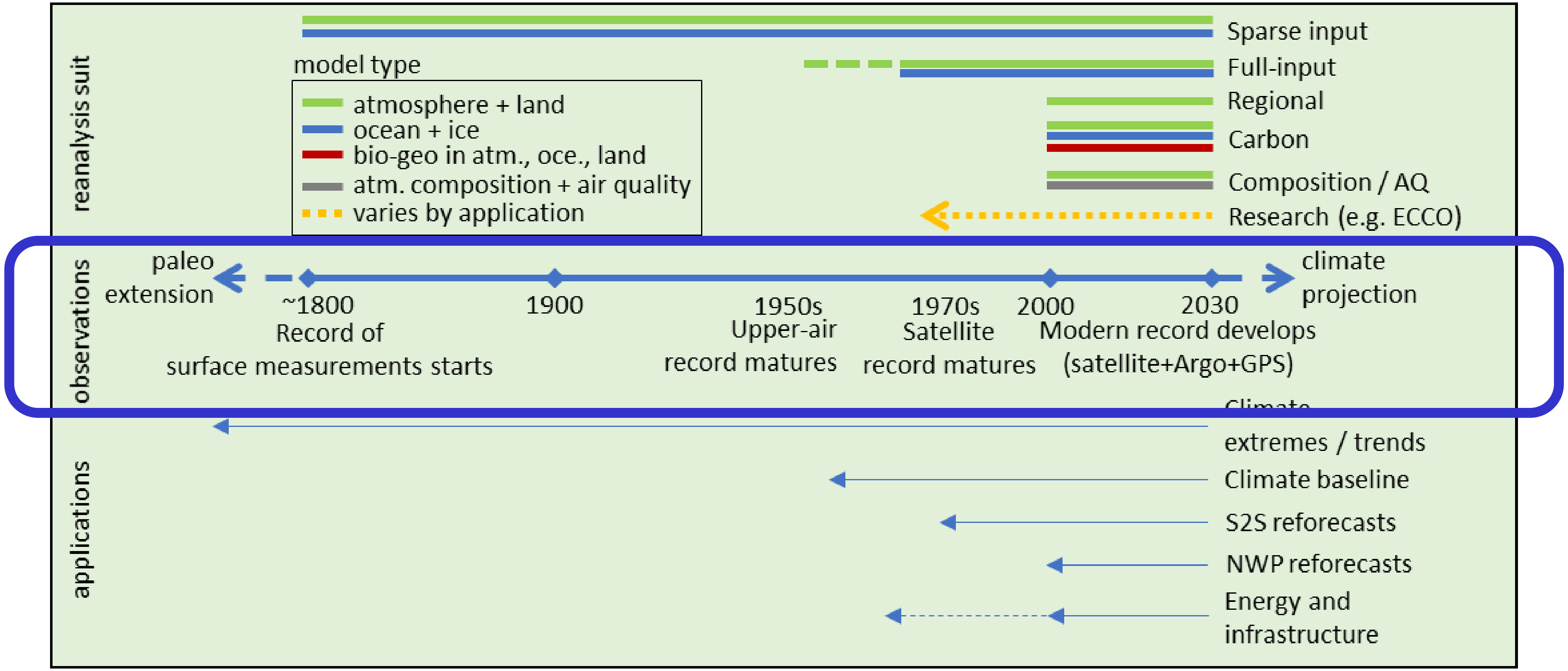
Cross cutting recommendation: 10-year vision of consistent reanalysis

- Consistent across multiple components of the Earth system:
  - Atmosphere, ocean, ice, land, carbon, air quality, hydrological cycle;
  - Fluxes across components; and
  - Start to close essential budgets of heat, water, and carbon.
- Consistent in representation of temporal trends:
  - Robust to changes in the observing system;
  - Estimates of uncertainty that reflect changes in the observing network.
- Colocation of compute and reanalysis product storage:
  - Consistent access across multiple reanalysis producers.
- Consistent/common error metrics and diagnostics that can guide development and evaluation of future products.

Do we need one reanalysis to rule them all?

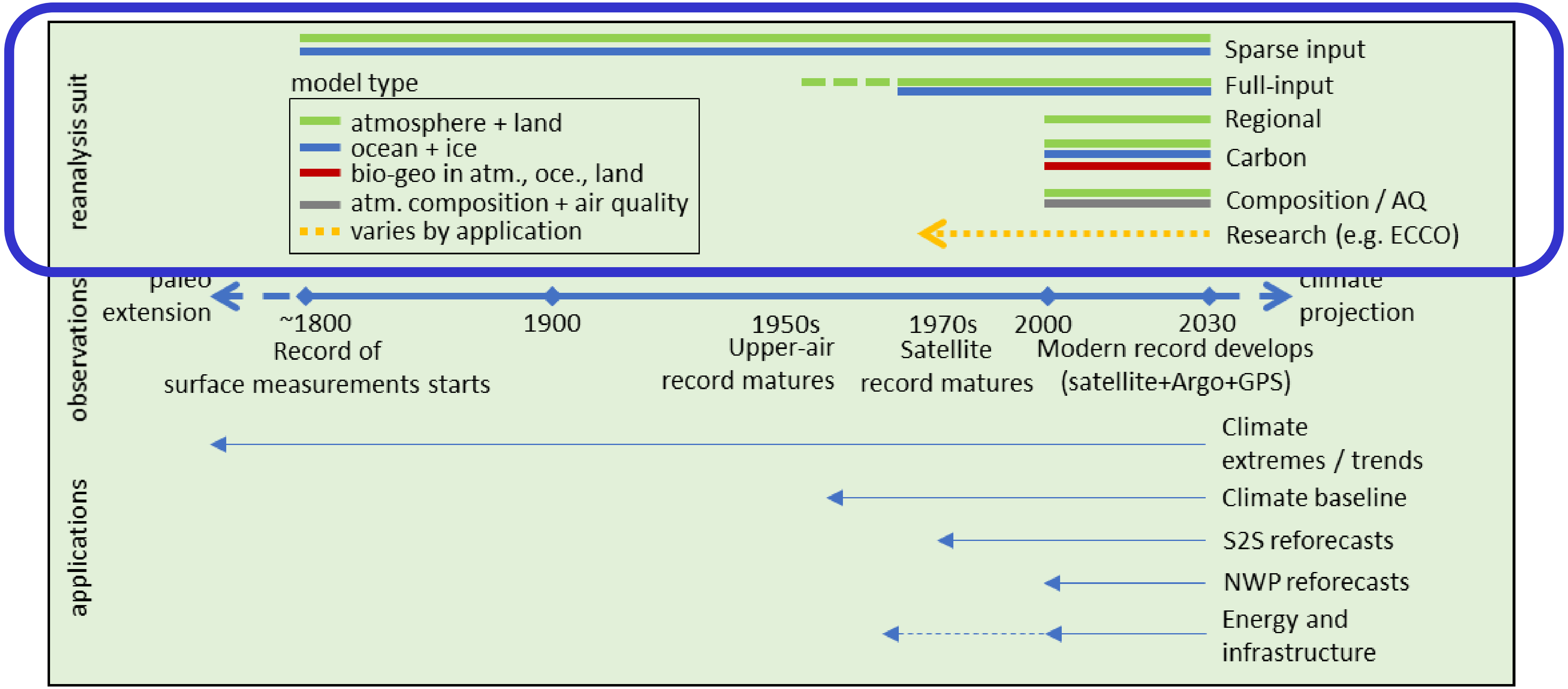
"A consensus was reached that striving for a single reanalysis product that integrates all components of the Earth system and satisfies the diverse user needs is infeasible and would likely degrade the accuracy of individual Earth System components."

Suite of reanalysis:
Strategy for development of consistent reanalysis products



Availability of historic data will dictate types of products that we can produce

Suite of reanalysis: Strategy for development of consistent reanalysis products



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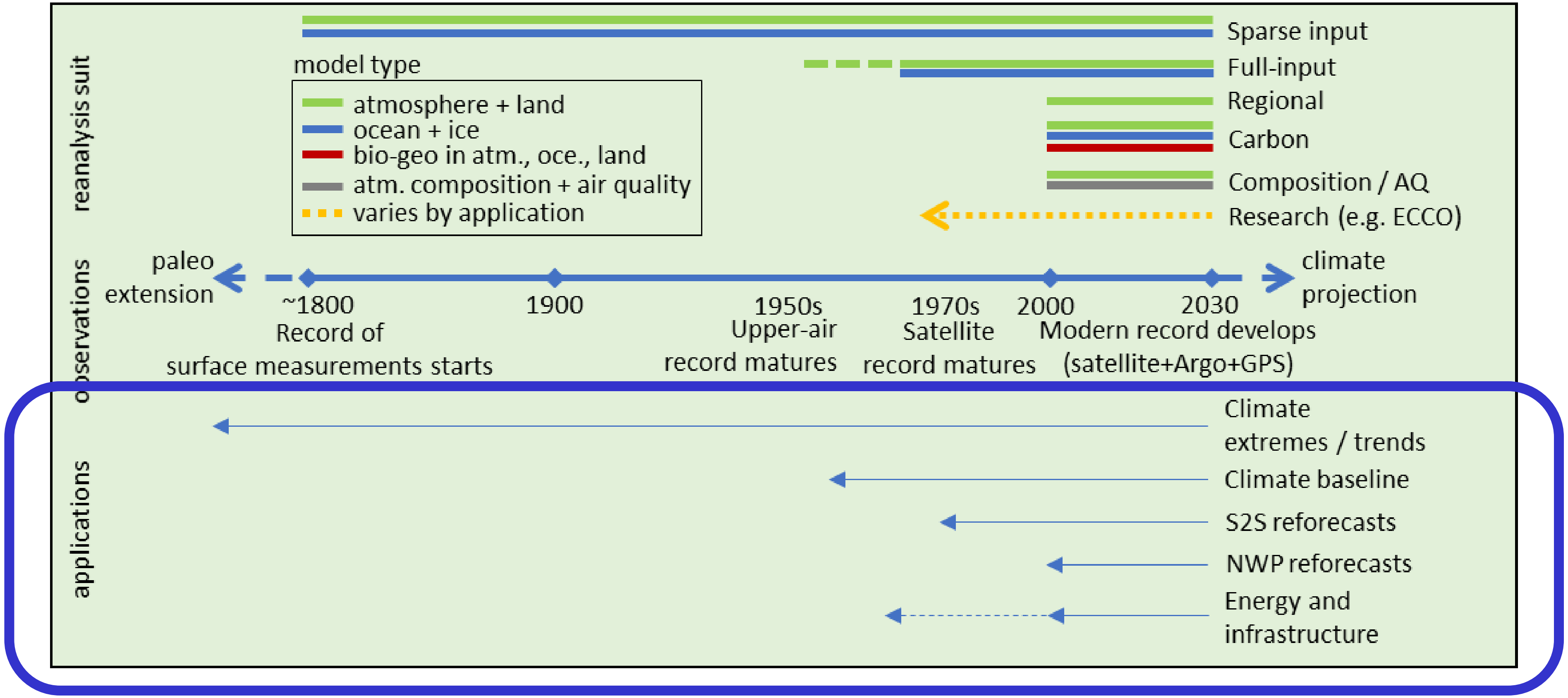
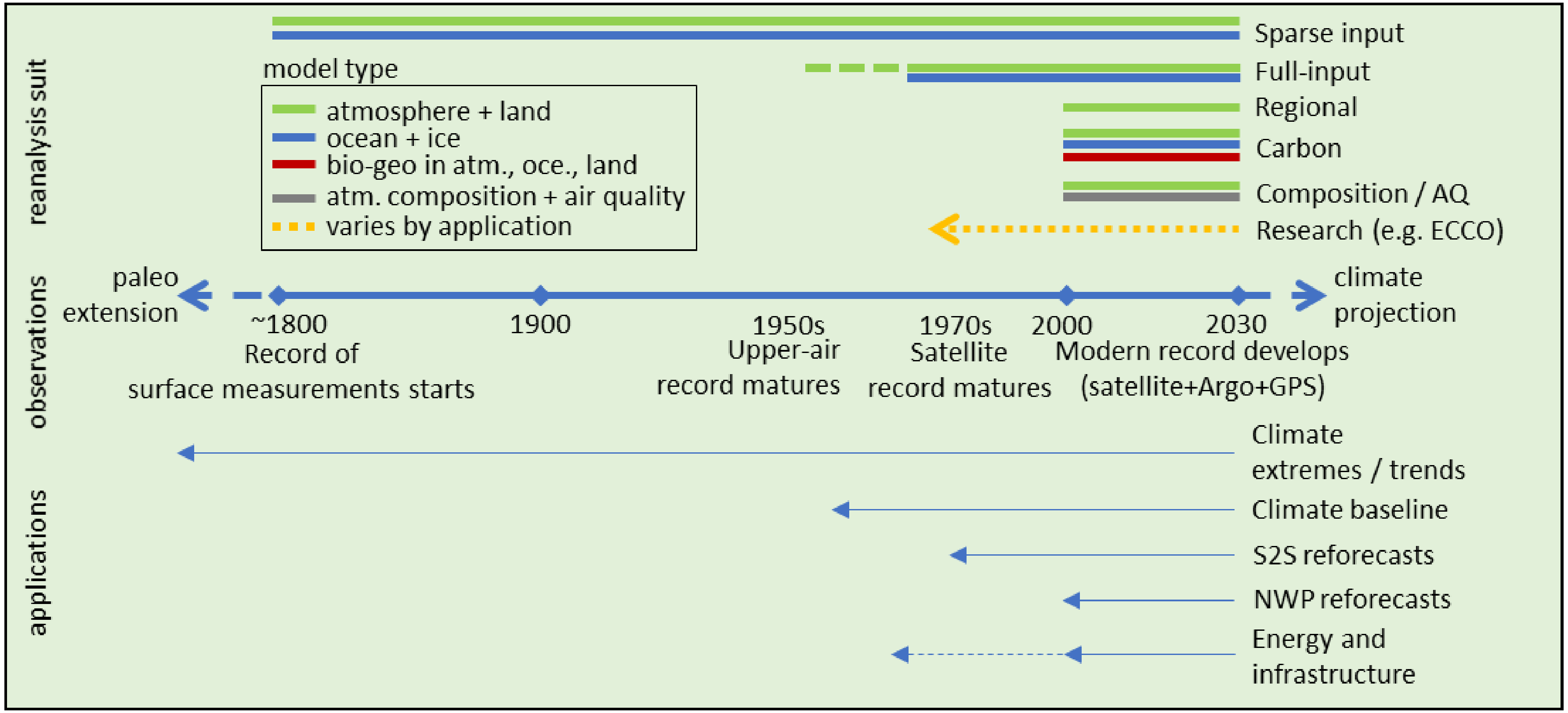


Proposed reanalysis suite projects on a wide range of applications and stakeholder needs.

Suite of reanalysis: Strategy for development of consistent reanalysis products



- Backbone reanalysis includes:
  - Sparse-input centennial reanalysis and
  - Full-input modern era reanalysis (all available data, including satellite record from late 1970s),
  - Each produced with state-of-the-art coupled atmosphere, ocean, ice, and land models.
- Backbone products will drive carbon stock, air quality, and hydrological reanalyses at global or regional scale.

Key scientific challenges

- Reanalysis with coupled models:
  - Reducing biases and closed budgets.
- Accounting for storage and fluxes of carbon:
  - Land modeling is a leading challenge.
- Representation of droughts, precipitation, water movement and storage between Earth system components.
- More realistic representation of tropospheric ozone in support of air quality reanalysis.
- Reduction of systematic model errors.
  - E.g. can we unify spares and full-input reanlaysis.

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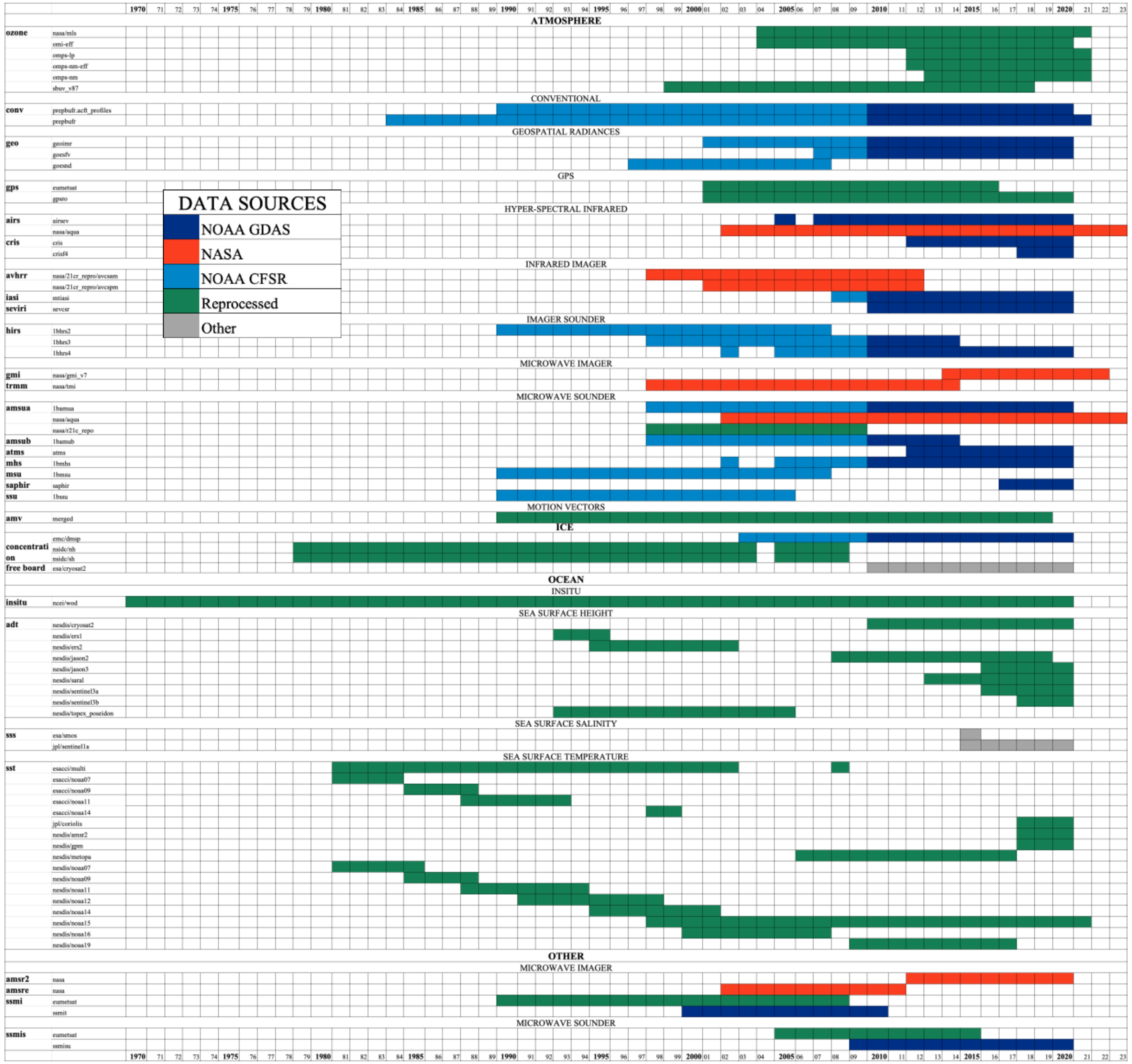
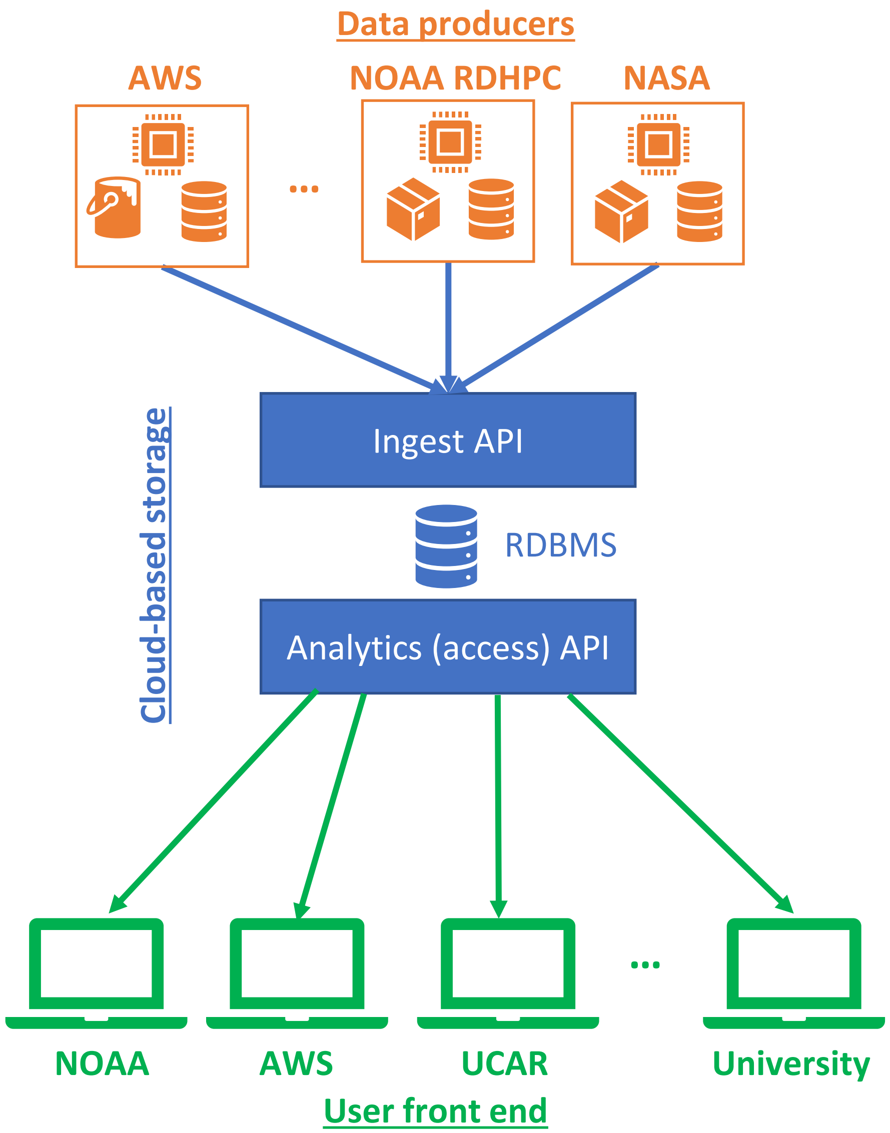
- Collaboration (especially within the U.S.) can lead to economies in reanalysis production and increase our ability to focus on science of reanalysis.
- To balance need for diversity with need to collaboration we (NOAA and NASA) choose to focus on mutualizing shared infrastructure and encouraging diversity in science.
- Mutual infrastructure:
  - DyCore: FV3, MOM6, CICE;
  - DA: JEDI-based infrastructure with variance in science choices;
  - Observations: shared archive of in-house and reprocessed obs.;
  - Diagnostics: shared diagnostic tools.

Improved collaboration: joint observational archive



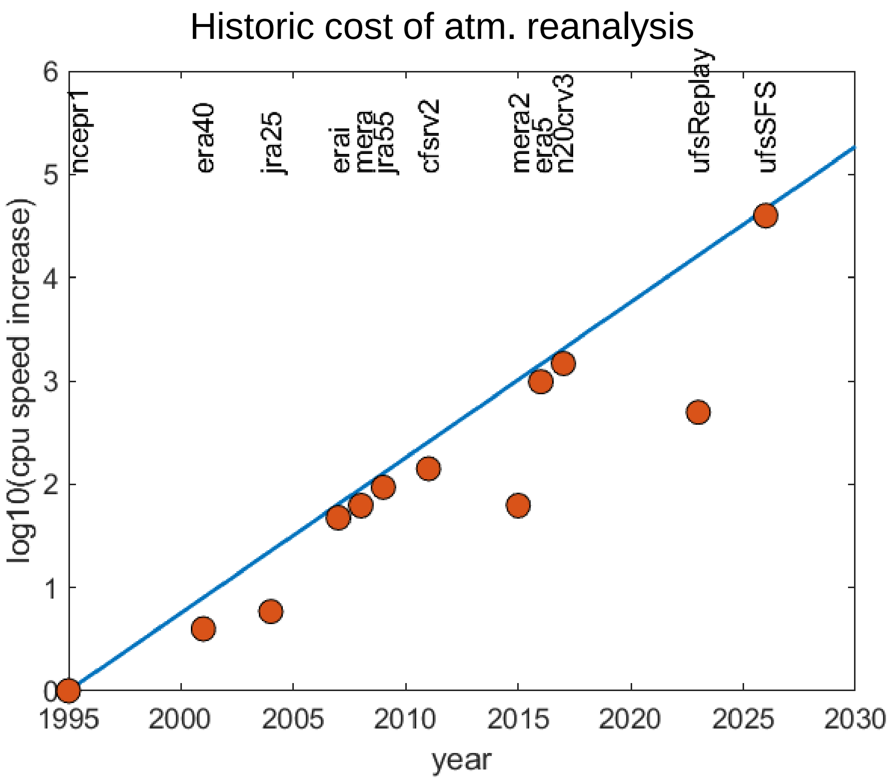
- Still incomplete but available on AWS S3
- Scope:
  - Ocean, atmosphere, ice, land.
  - Period: 1979-near real time.
  - Formats: bufr, prepbufr, iodav3
- Sources:
  - CFSR, NOAA ops, NASA ops., reprocessed (e.g. ESA, NCEI).
- Blacklist/whitelist/ error assignments.
- Coming: Tools for inventory and access to data.

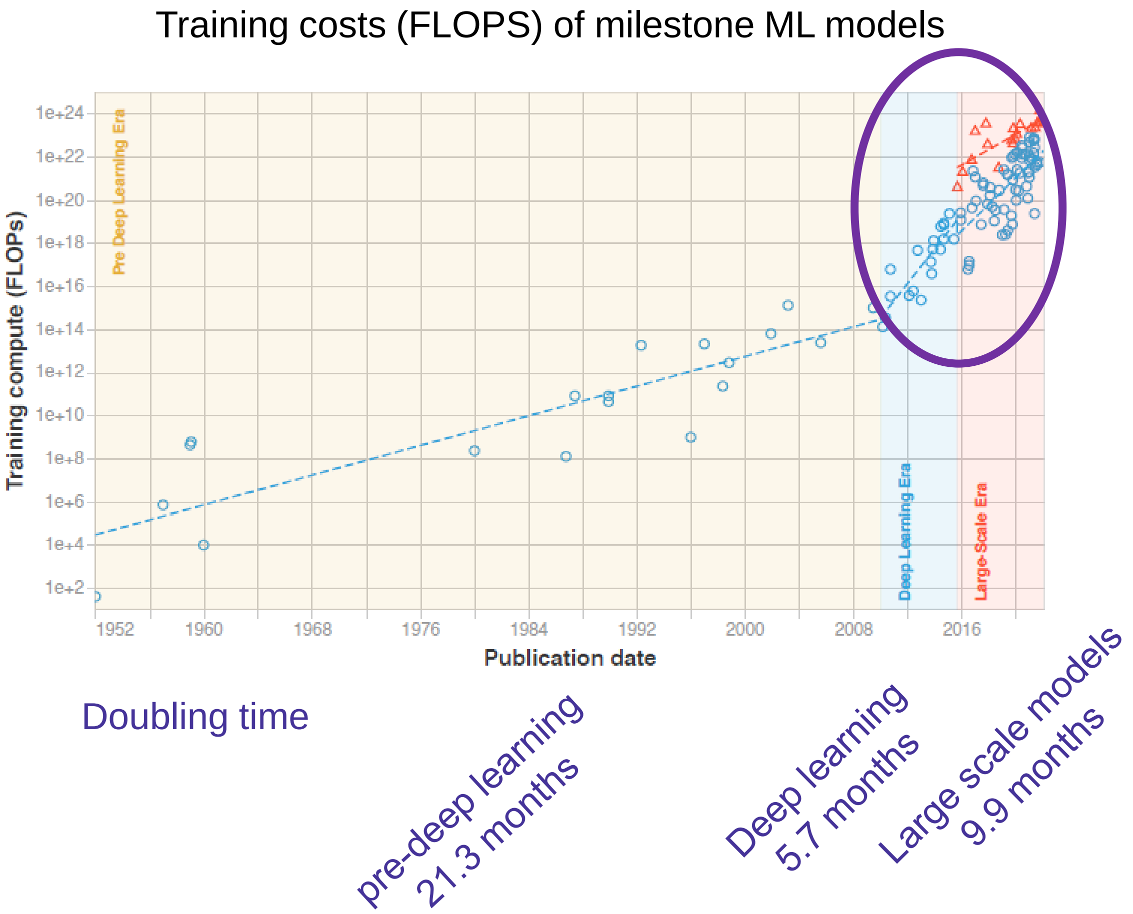
Improved collaboration: shared framework for diagnostics



- Need:
  - Experiments are produced at a variety of institutions.
  - Sharing of diagnostic files is cumbersome in terms of file formats and data transfer.
- Possible solution:
  - Ingest and store "headline" and climate scores in a cloud-hosted relational database.
- Current status:
  - Prototype is developed at NOAA PSL.
- Next steps:
  - Stress testing with NOAA scout runs and replay runs.
  - Integration with diagnostics developed at NASA GMAO and NOAA EMC.

Concluding thoughts

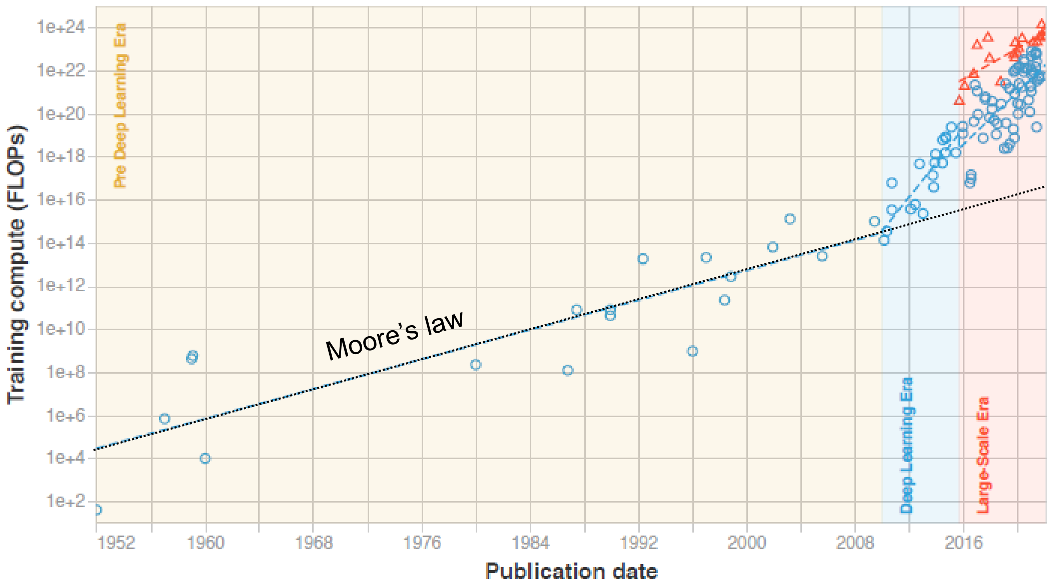




- To date, reanalysis development was constraint by Moore's law.
- **Combination of hardware, software, and science is accelerating ML development** significantly faster than the Moore's law.
- Can reanalysis and data assimilation for NWP benefit from the acceleration in ML science?

Concluding thoughts

Training costs (FLOPS) of milestone ML models



Doubling time

pre-deep learning 21.3 months

Deep learning 5.7 months

Large scale models 9.9 months

- How would the post AI future drive the diversity in reanalysis approaches?
  - Will all diversity collapse to ERA-X and we loose benefits of diversity in products?
  - Can we sustain existing diversity of approaches?

- Some hypothesis going forward:
  - New technology (AI/GPU) can increase diversity in reanalysis approaches by reducing the costs of reanalysis production.
  - Quality of reanalysis can increase if we mutualize infrastructure (observations, metrics, distribution) and diversify methods.

https://arxiv.org/pdf/2202.05924.pdf

End