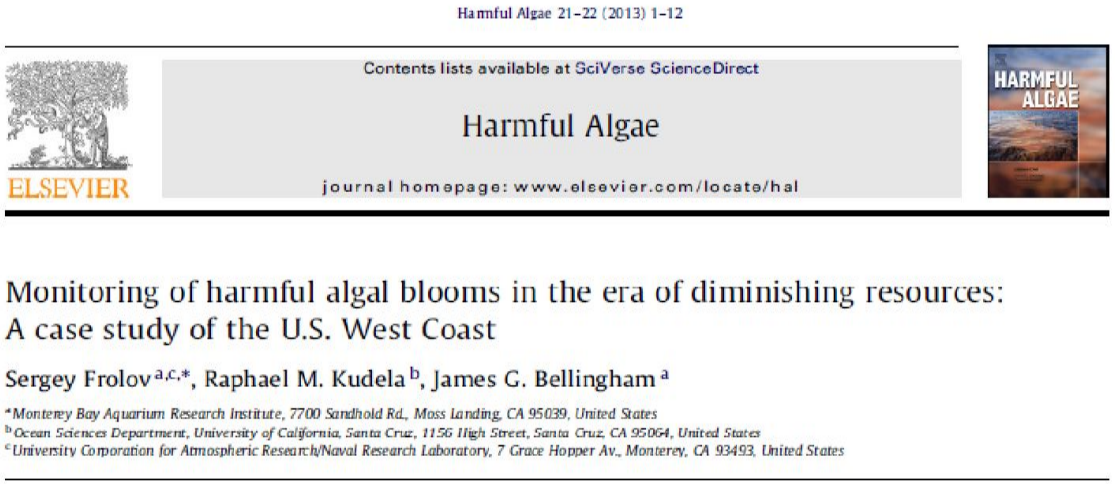
How do we determine an ideal observing system?

Sergey Frolov

With gratitude to so many in our community

Presented at:
CLIVAR bi-annual meeting,
Boulder, CO July 2025

There is never enough money for observations



Harmful Algae 21–22 (2013) 1–12

Contents lists available at SciVerse ScienceDirect

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Monitoring of harmful algal blooms in the era of diminishing resources: A case study of the U.S. West Coast

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[b] Ocean Sciences Department, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, United States
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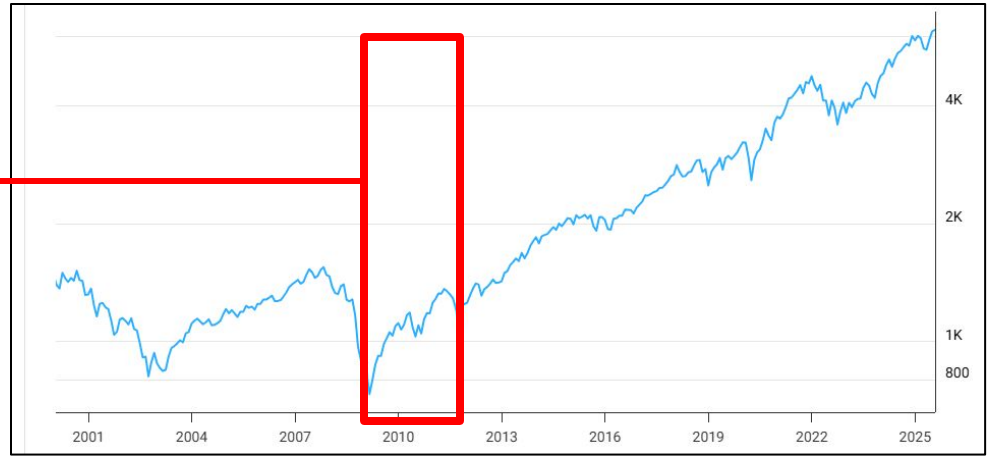
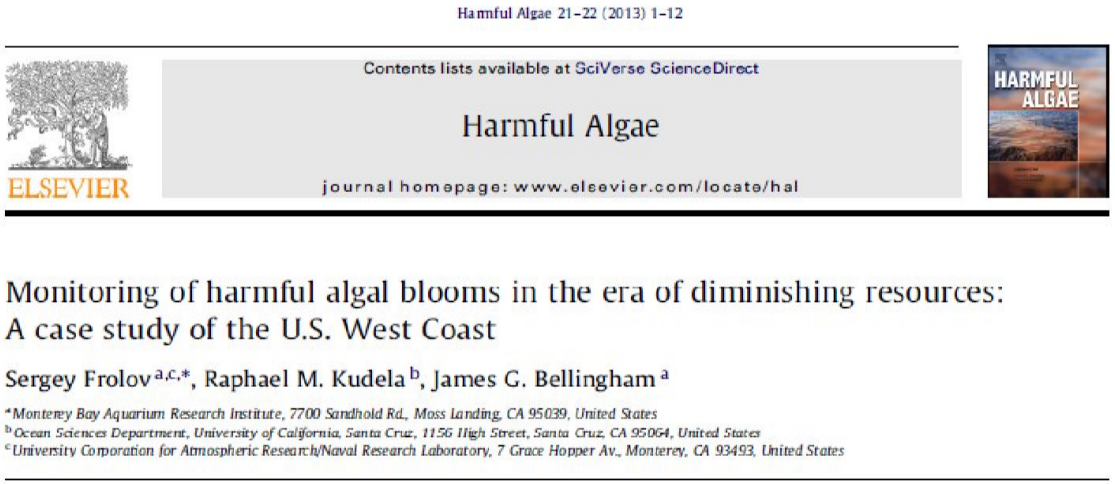


- [left] During the Great Recession, we wondered how to best use limited resources to observe the ocean.

There is never enough money for observations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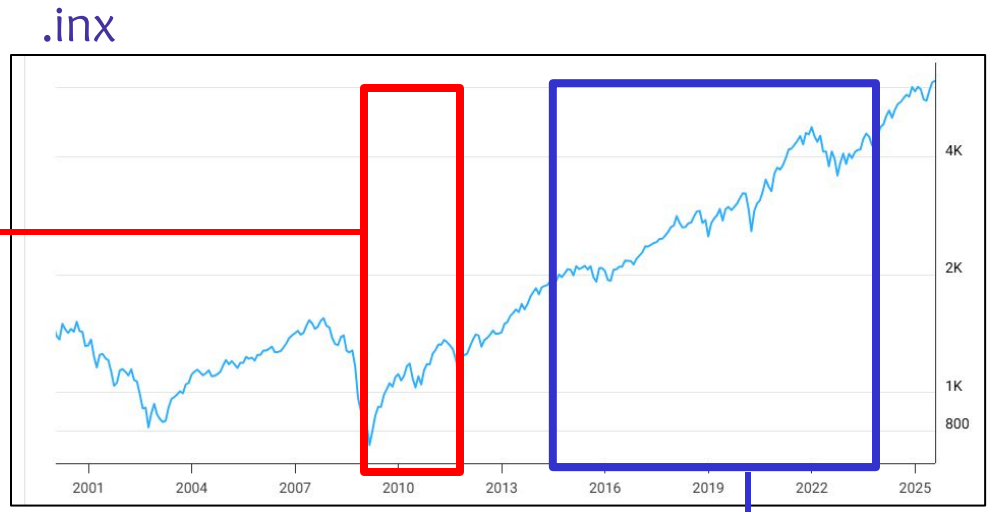
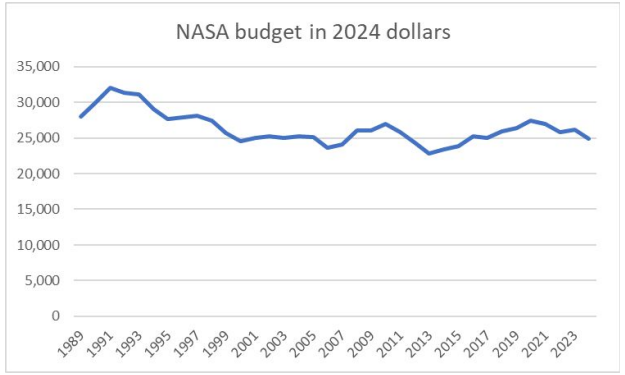
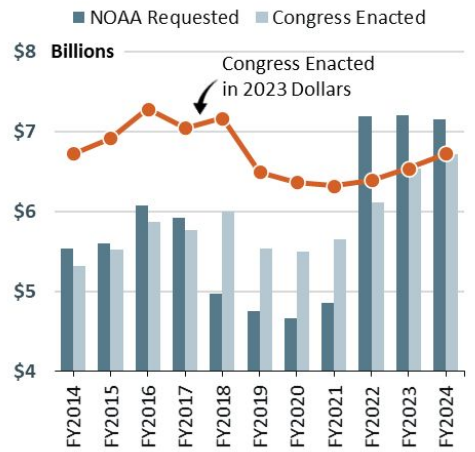


- [left] During the Great recession, we wondered how to best use limited resources to observe the ocean.
- [bottom] Later we found that market performance is not correlated with the investment in Earth science

Take home message: we will always need to be efficient with our observational investments.





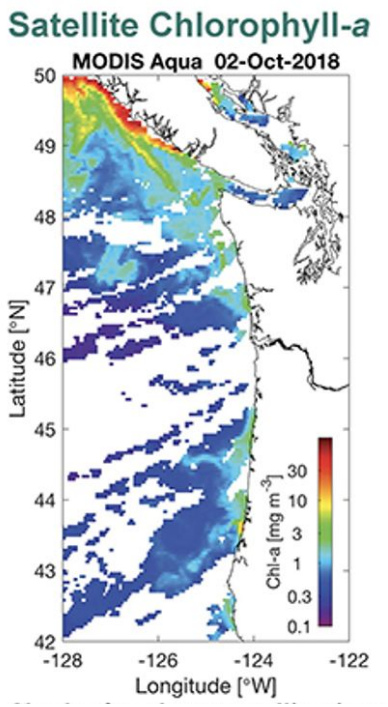
Outline

- Use the HAB example to break down the assessment of the observing strategy into intuitive steps.

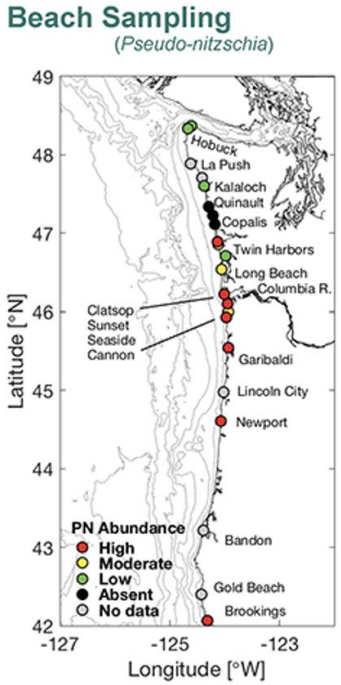
- Review the state of the art in observing system assessments

- Take a pick into the AI-powered future

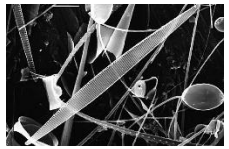
Quick primer on HABs

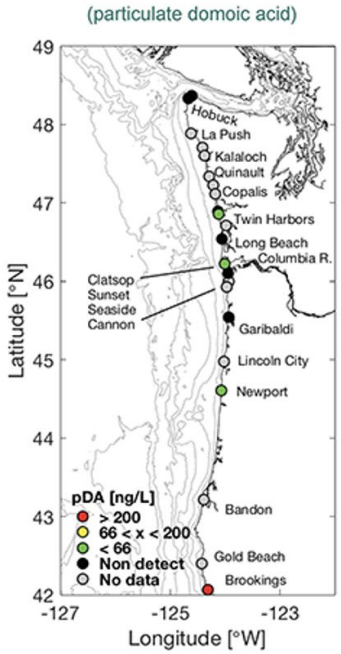


Satellite can sense “bulk” phytoplankton presence but it is often obscured by clouds. Chl-a imagery is not sufficient to detect presence of “toxic” event.

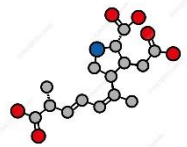


From the beach water samples, we can detect “toxic” species of the phytoplankton.





From the beach water samples, we can measure the actual levels of toxins.

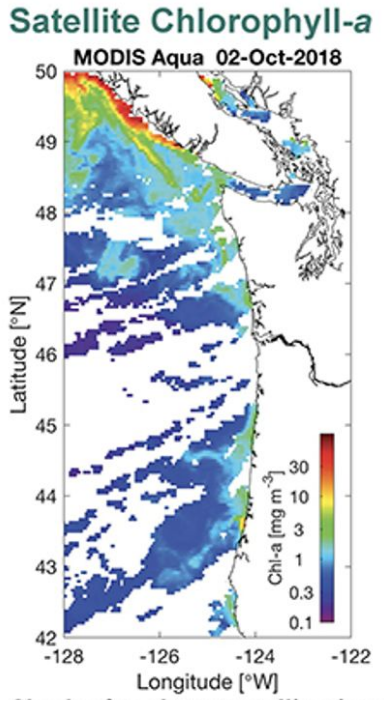


Kathy Ponting, a volunteer at The Marine Mammal Center's San Luis Obispo Operations based in Morro Bay, California, administers bagged fluids to California sea lion patients impacted by domoic acid poisoning on August 5, 2024. Photo: Giancarlo Rulli © The Marine Mammal Center

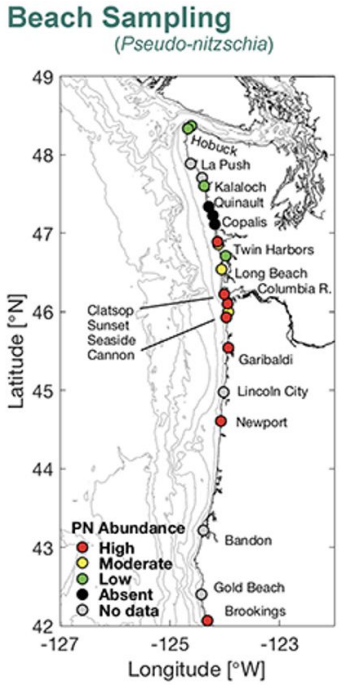
High levels of domoic acid can lead to marine mammal mortality (image above does not correspond to the specific event on the left)

Trainer et.al 2020. NOAA Fisheries.

Key questions



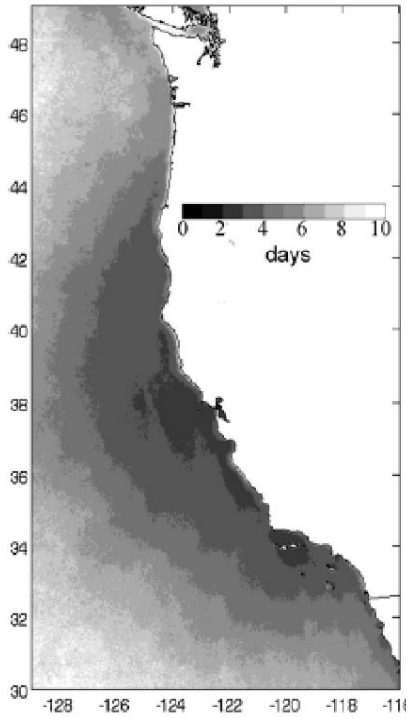
How reliable is the satellite imagery for bloom detection?



How representative is shore sampling of the off-shore conditions?

Using time correlations to quantify value of the satellite imagery

Mean days between consecutive MODIS pixels



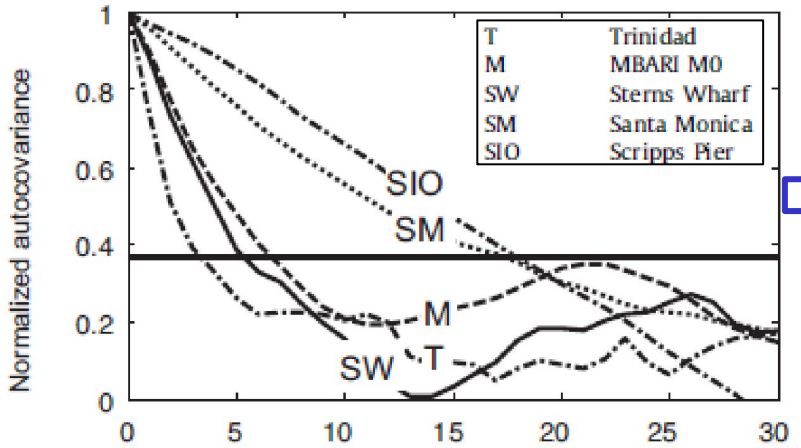
T: Trinidad

+

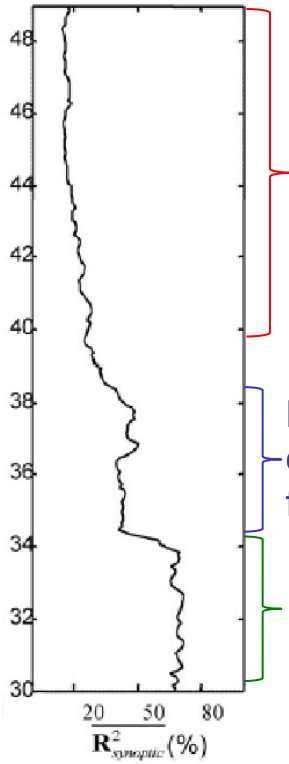
M: Monterey

SM: Santa Monica
SIO: Scripps

Chl-a temporal correlation from automated sensors installed on wharfs



R^2 statistics for MODIS effectiveness



OR/WA are poorly observed: Fast bloom dynamics, cloudy skys.

Northern California is still well observed: faster blooms, still frequent imagery.

Southern California is well observed: slow blooms, frequent imagery.

Description of the observing system

Description of the process statistics (usually as correlation functions)

Some measure of fitness for purpose: e.g. [forecast error with obs]/[forecast error no obs]

Frolov et.al 2012.

Zoom in 2025

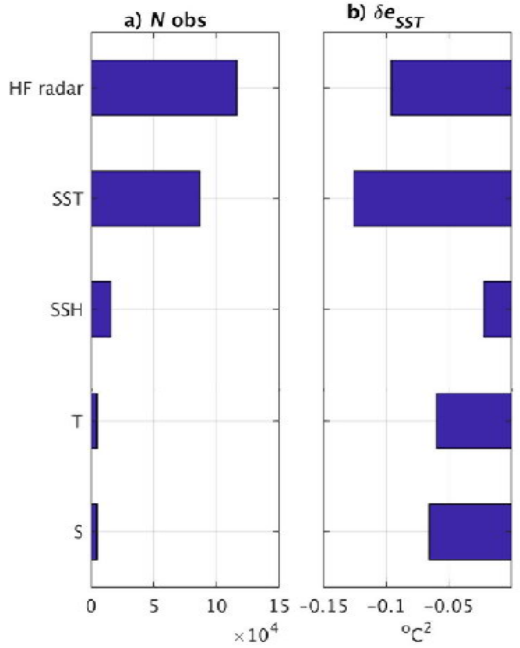
IPhone 5

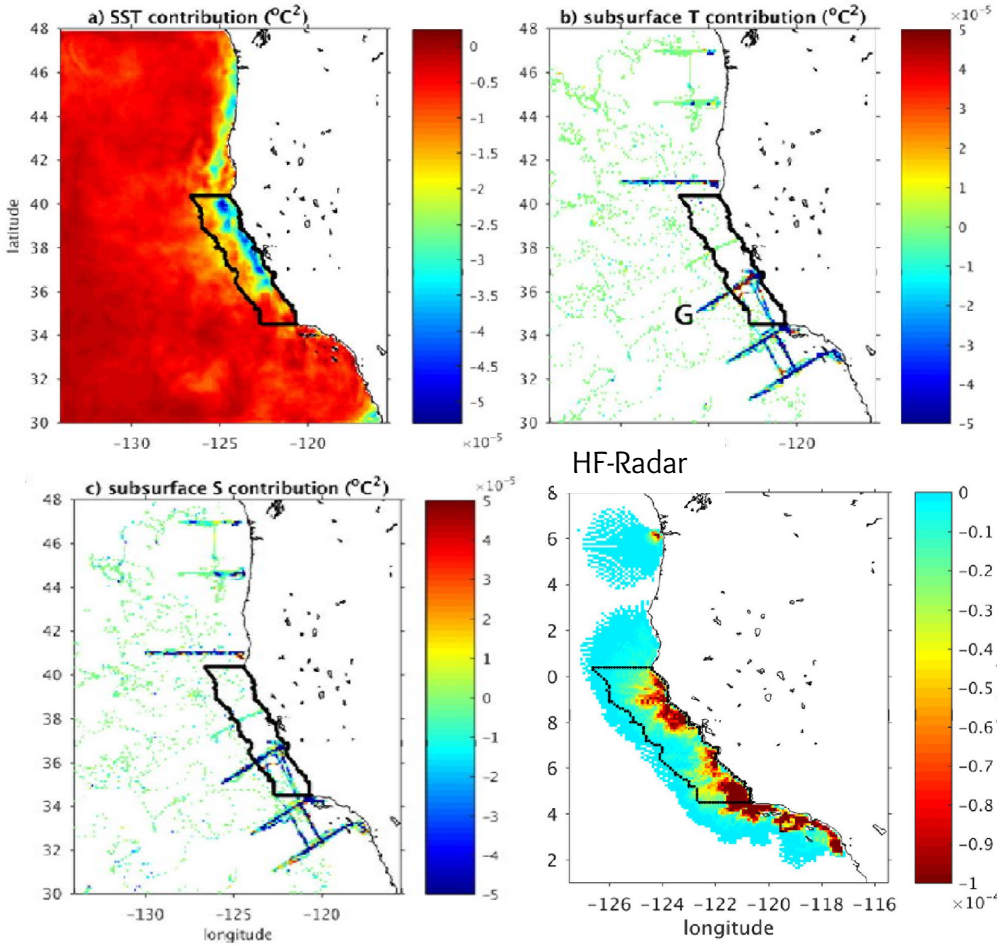
IPhone 15

Most of the core observing system evaluation theory was developed in early 2000s.
Now we finally have the tools to apply it at scale

https://www.digitaltrends.com/

Scaling this up to 2025: FSOI

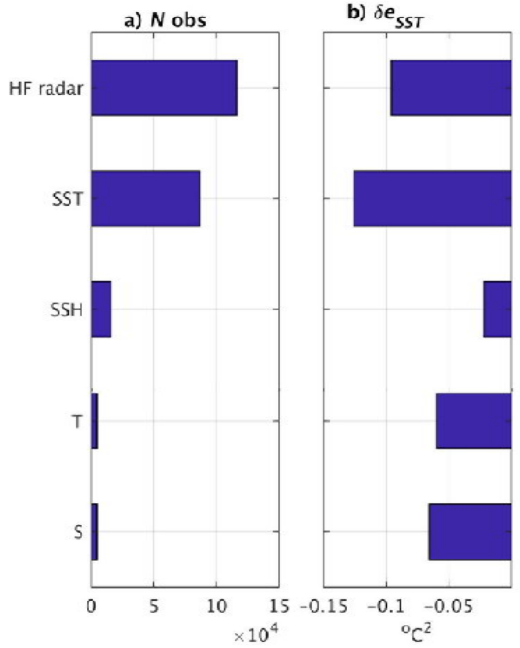


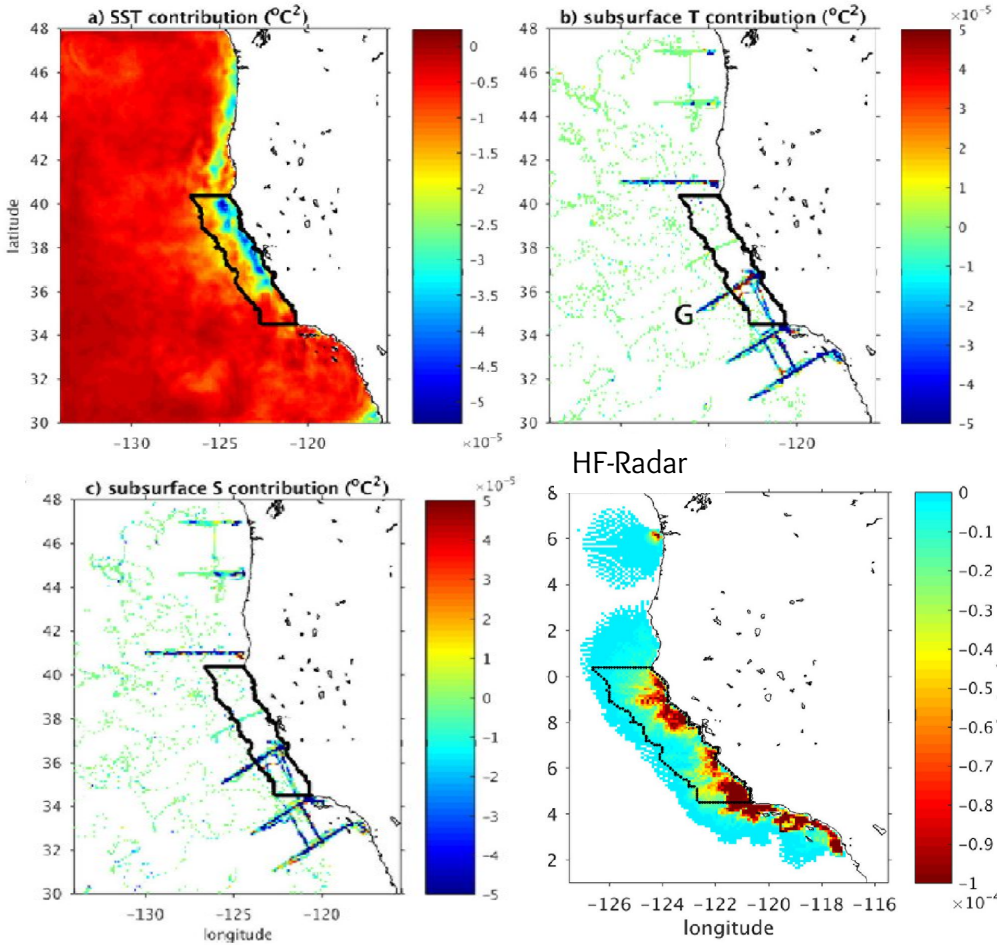


- Modern data assimilation machinery can quantify value of each individual observation:
  - Value is defined by reduction of errors in future forecasts.

Drake et.al 2023

Scaling this up to 2025: FSOI



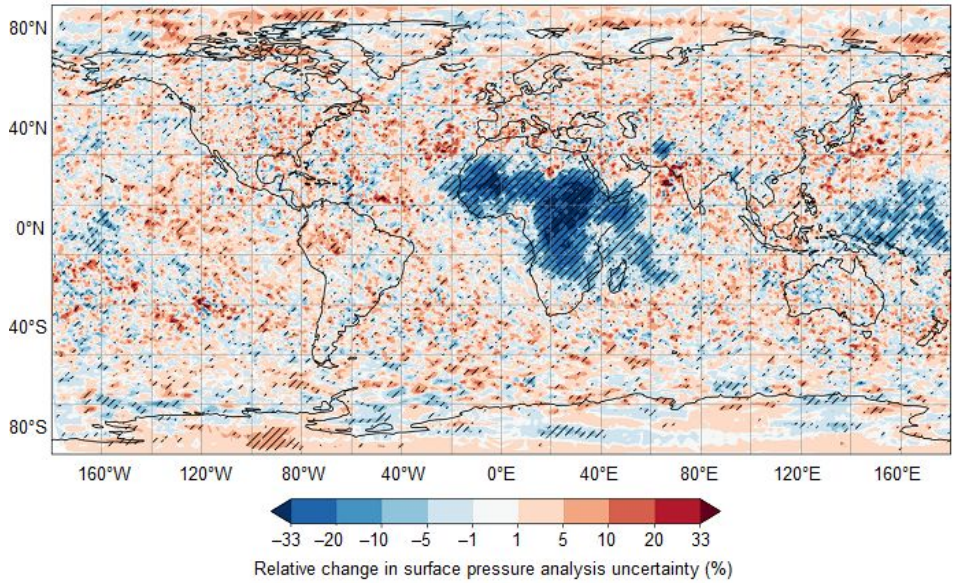


- Modern data assimilation machinery can quantify value of each individual observation:
  - Value is defined by reduction of errors in future forecasts.
  - Could be computed for complex cost functions (e.g. upwelling, water vapor flux, etc.)
  - Works best for well tuned "operational" suite of observations.
  - Accounts for all interactions between components of the observing system.
  - Tricky to extend to "hypothetical" observations.
  - Different implementation of data assimilation systems might give slightly different answers.

Drake et.al 2023: Coastal California

Scaling this up to 2025: Value of hypothetical observations

ECMWF/WMO 2025: impact of additional surface and upper air observations on reduction in analysis uncertainty



- Systematic Observation Financing Facility (WMO/UNDP) requested ECMWF to quantify value of additional conventional observations in least developed countries.
- ECMWF found significant added value of observations in:
  - Africa.
  - Small island nations.
- This was relatively easy to do for "conventional" observations.
- A shortcut was taking for looking at analysis skill vs forecast skill (e.g. no need for an expensive Nature Run).

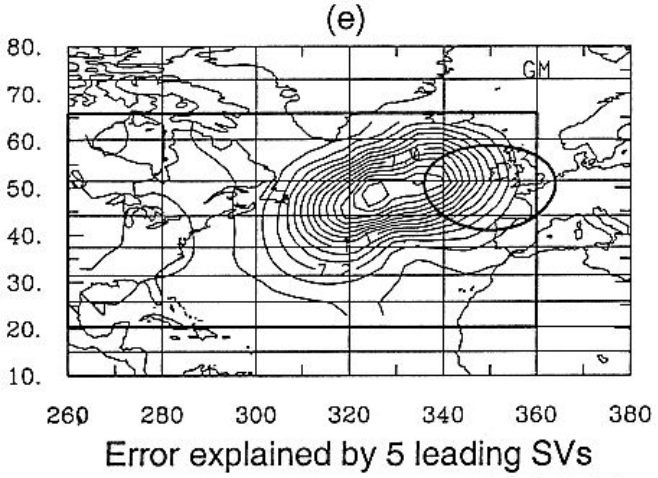
What have we learned so far

- Mathematics and mechanics of assessing value of observations is relatively well understood:
  - Best done using a well-tuned data assimilation and forecast system.
  - Best done for well understood observations.

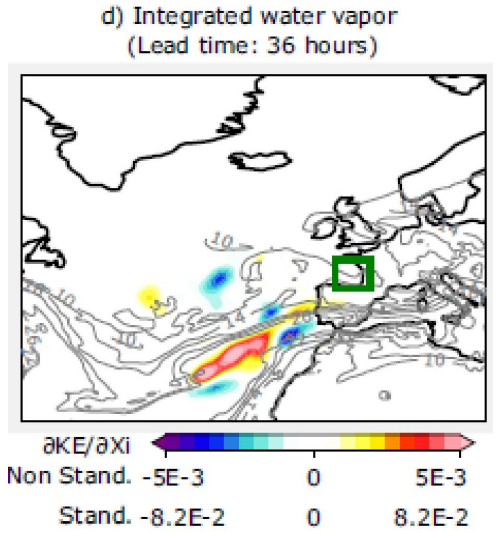
- Difference between evaluating
  - Existing observations (OSE, FSOI) and
  - Novel observations (OSSE).

- But what about:
  - Very complex forecast cost functions and
  - Very complex observations?

Scaling beyond 2025: complex cost functions



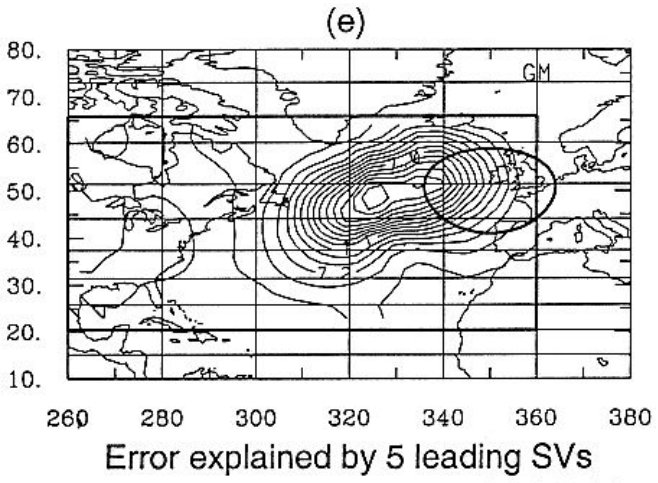
Bishop and Toth 1999



Bano-Medina et.al 2025

- [left] In 1990th Bishop pioneered the idea of targeted observations for winter storm forecasts.
  - His results very large scale and the targeted flight program has been terminated after a decade.
- [right] Modern tools can be based on AI model adjoints and are much more precise (targeting frontal features)
  - Flights have resumes to improve forecast of Atmospheric rivers over CA.

Scaling beyond 2025: complex cost functions



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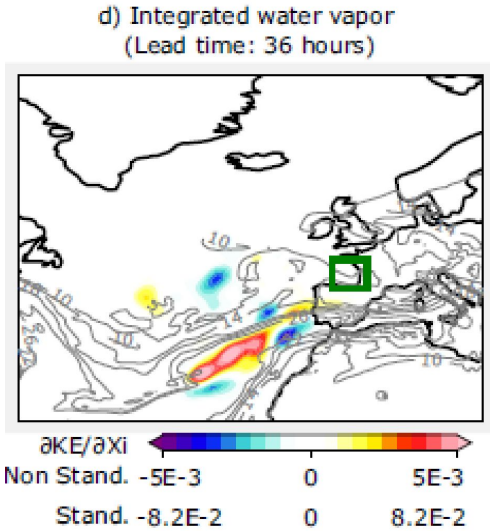
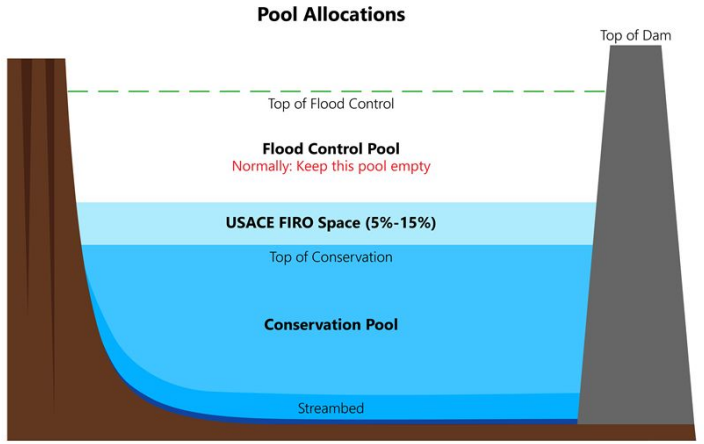


Bano-Medina et.al 2025

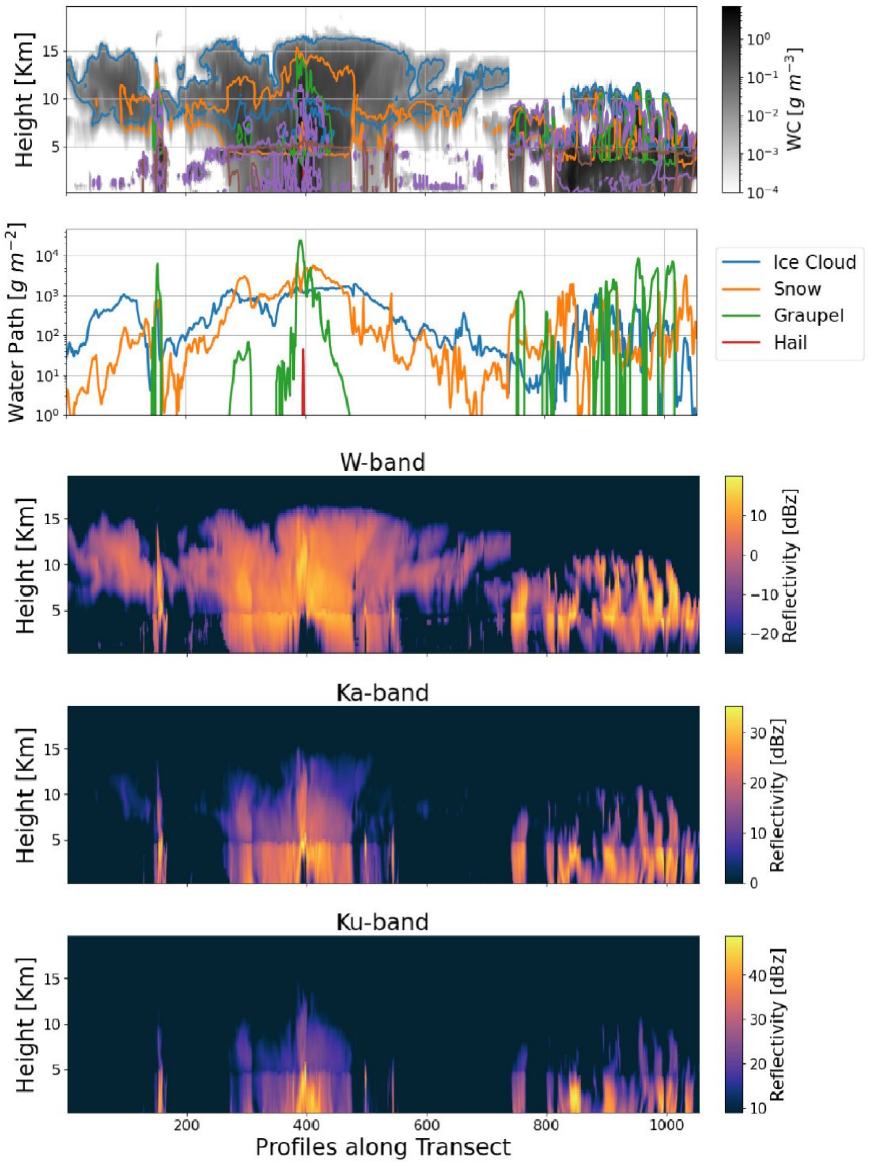


Forecast Informed Reservoir operations

- [right] As end-to-end AI models expand, they could include such complex factors as reservoir storage and runoff.

Damage to the Oroville dam spillway in 2017

Scaling beyond 2025: novel observations



- Understanding the value of novel observations requires:
  1. Expensive nature runs.
  2. Observations operator for novel observations.
  3. Optimal data assimilation for novel observations.
- [left] study by Liu et.al 2022 on the potential satellite observing system for ice cloud microphysics.
  - Required significant investment into development of novel data assimilation methods.
- New AI-based capabilities can rapidly train/develop optimal DA system from (1) and (2) above.

Summary

- Quantifying value of observing systems is a mature field and is routinely used to fly targeted sampling and design future satellite missions.

- However, application of optimal design had a high start up cost (e.g. access to a well tuned data assimilation system)

- Upcoming AI methods will significantly reduce the cost of designing optimal experimental strategies.