

RO and the Two Weather Prediction Revolutions

Cliff Mass
University of Washington



Numerical Weather Prediction has experienced **two revolutions** during the past four decades



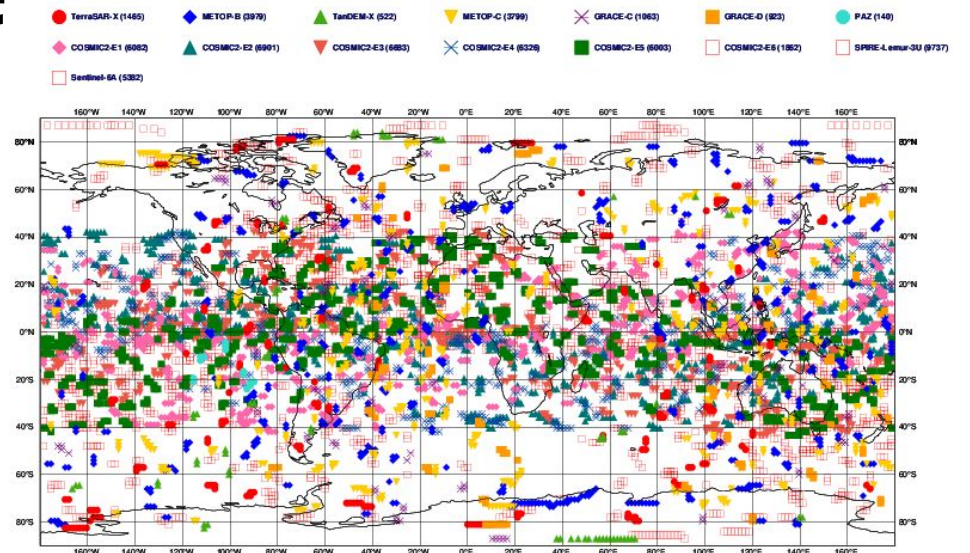
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The RO Community Has Played a Major Role in One of the Revolutions

Providing massive amounts of weather data that has revolutionized global observation and global we

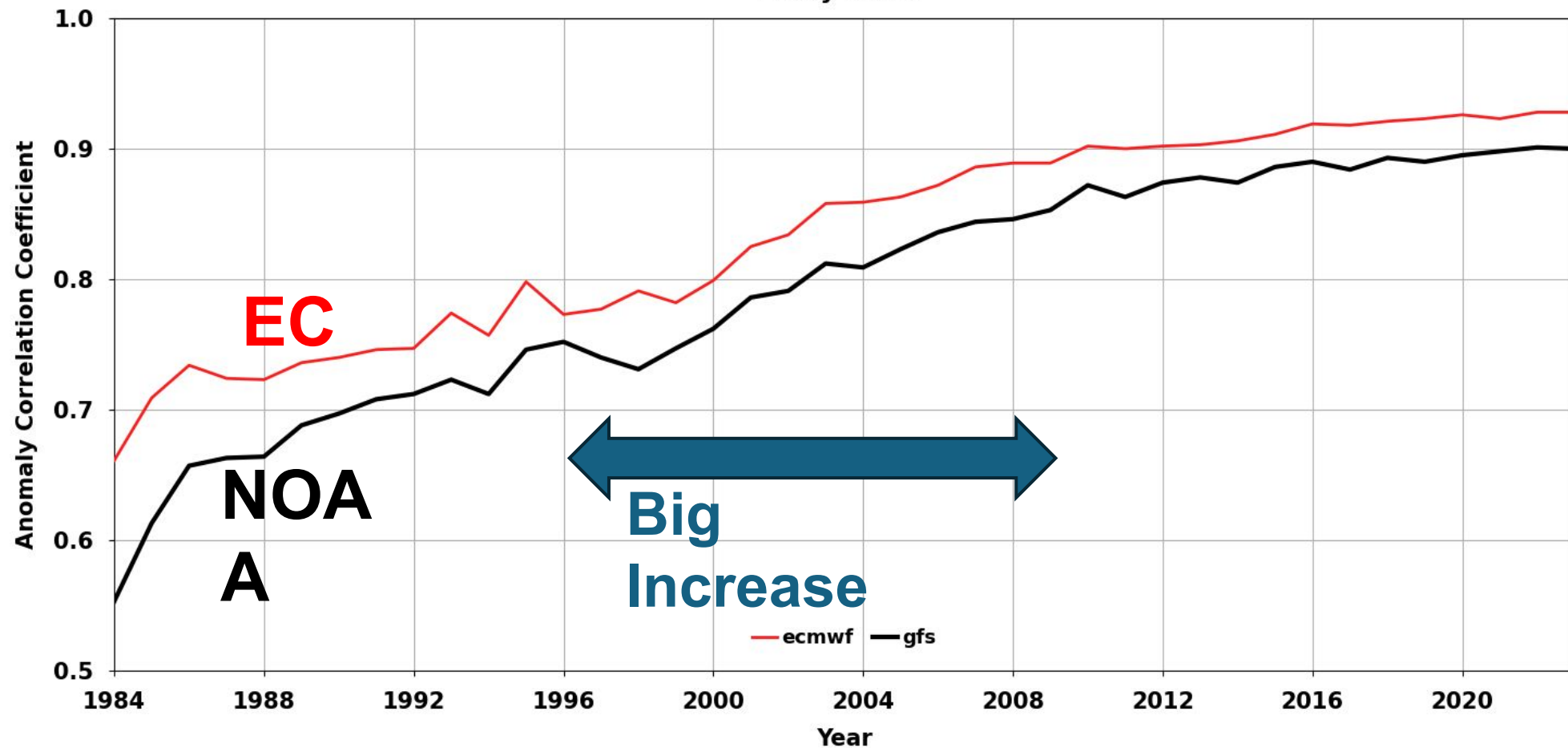
ECMWF data coverage (all observations) - GPSRO
2024082809 to 2024082815
Total number of obs = 60867



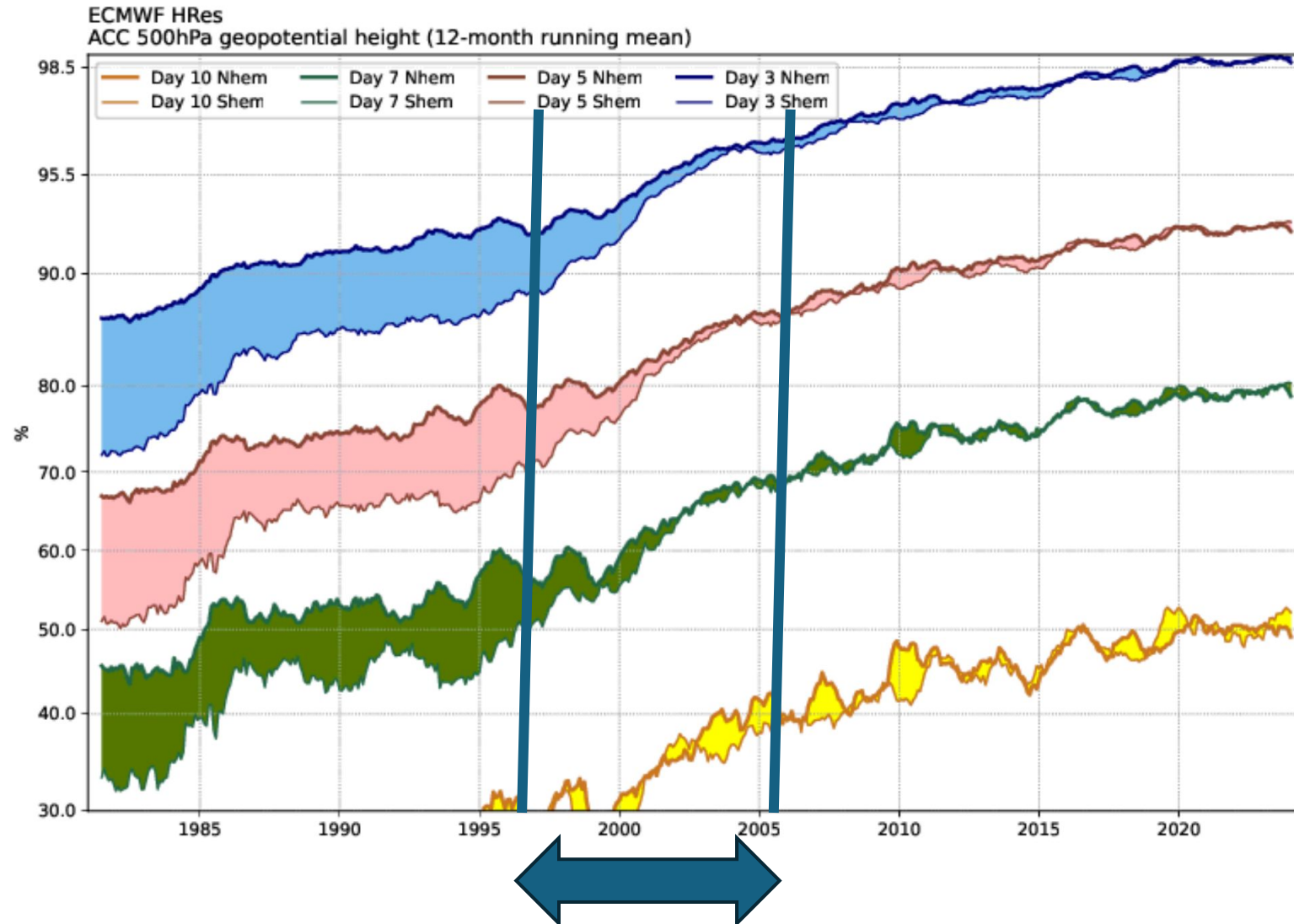
Large **Satellite-Driven** Increase in Global Forecast Skill from the mid-90s to ~2009



Anomaly Correlation Coefficient - G004/Northern Hemisphere 20N-80N
500 hPa Geopotential Height (gpm)
valid 1984-2023 valid 00Z, Forecast Day 5 (Hour 120)
Yearly Mean



During the satellite-data revolution the SH became as skillful at the NH



Same Story Regarding Skillful Lead Time

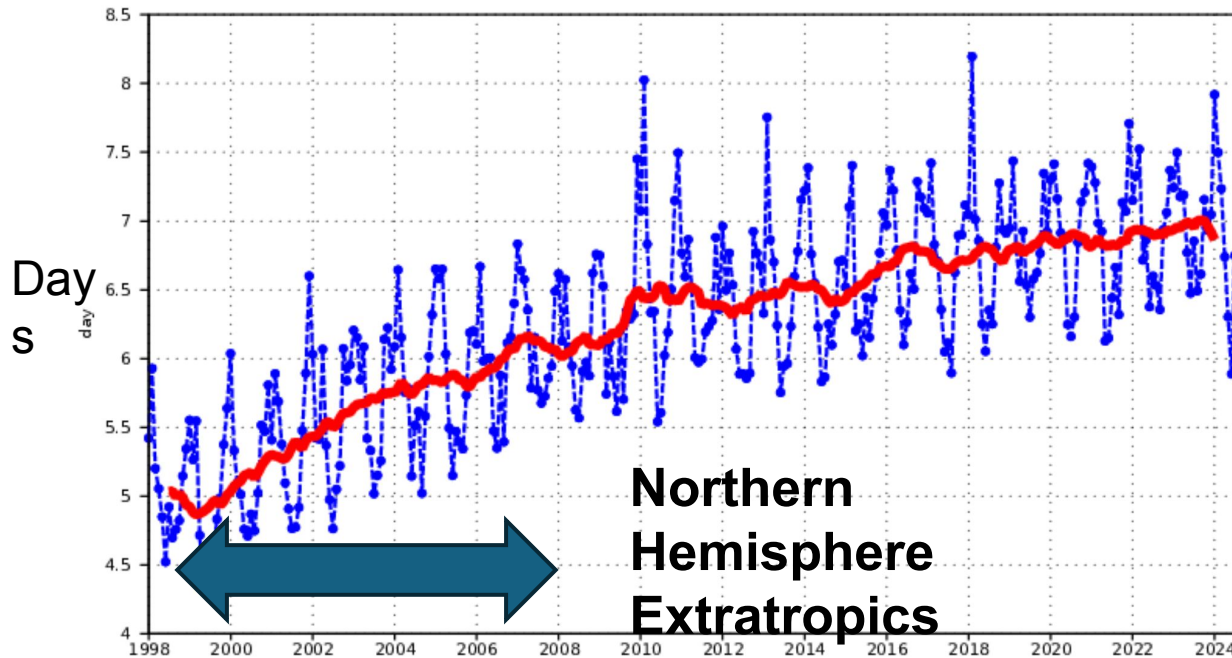
Lead time of anomaly correlation coefficient scores (ACC) of 500 hPa height falls to 80%

Lead time of anomaly correlation coefficient scores (ACC) of 500 hPa height falls to 80%

500hPa geopotential

Lead time of Anomaly correlation reaching 80%
NHem Extratropics

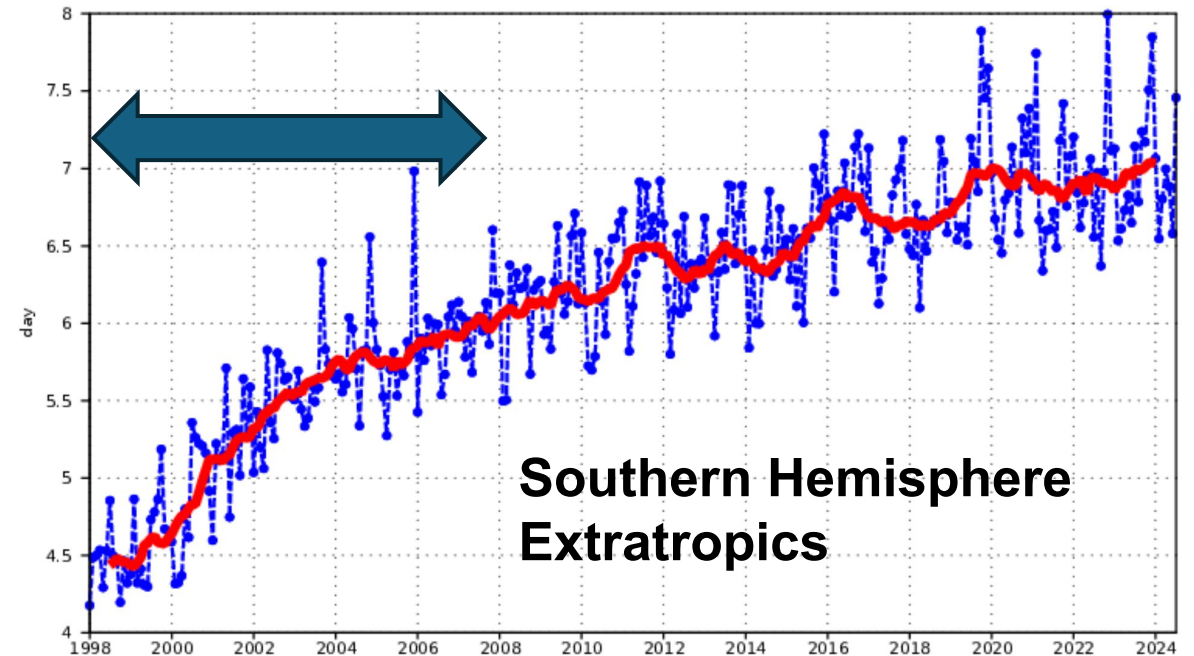
— acc 12m MA
—•• acc monthly mean



500hPa geopotential

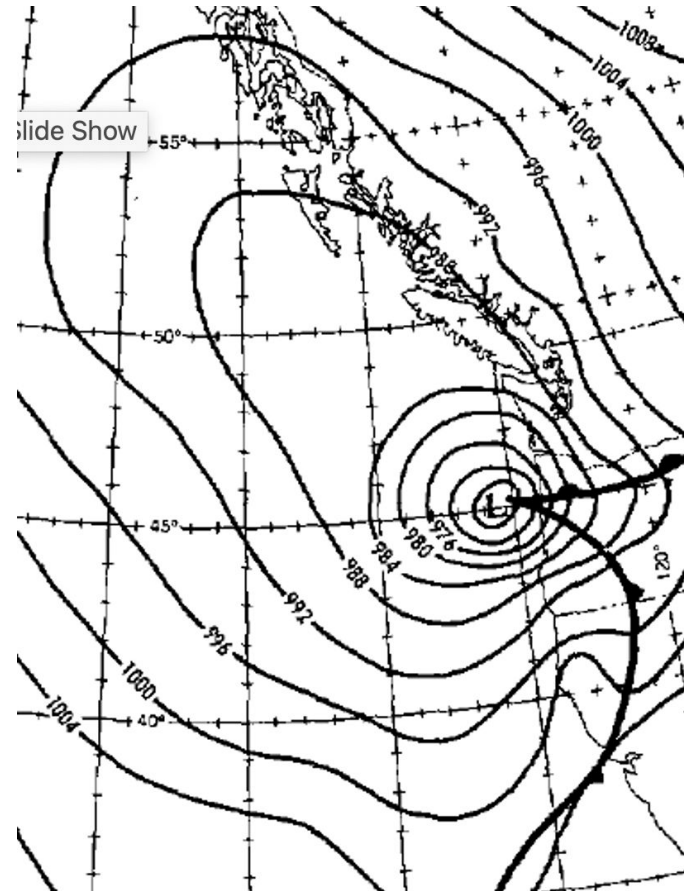
Lead time of Anomaly correlation reaching 80%
SHem Extratropics

— acc 12m MA
—•• acc monthly mean



The Impacts of Improved Global Data and Its Effective Assimilation Were Evident for Major Storms

On the West Coast, every major landfalling cyclone was poorly forecast before ~ 1990



Columbus Day Storm, Oct. 12, 1962

955 hPa low

October 11th Forecast: No Major Storm on October 12th!



Seattle Times

State Forecasts

Western Washington: Partly cloudy, with a few showers tonight and tomorrow. Snow on the mountain passes. High tomorrow, 46 to 54; low tonight, 35 to 45.

Mountain areas: Freezing level dropping to about 3,000 or 4,000 feet tonight and tomorrow, with rain changing to snow above 3,000 feet. Snow flurries on the east slopes of the Cascades.

Eastern Washington: Rain, beginning in the southwest, becoming general by tonight with increasing winds. Partly cloudy and cooler tomorrow, with snow flurries over the mountains. High tomorrow, 42 to 52; low tonight, 35 to 45.

Marine Warnings

Gale warnings were hoisted on the following waters:

- Inland—southeast winds 30 to 45 knots, diminishing tonight.
- Strait—northeast winds 35 to 45 knots, shifting to southwest or west and diminishing tonight.
- Whole-gale warnings were displayed on the coast from Tatoosh to Astoria for southeast winds 50 to 60 knots, diminishing to 34 to 46 tonight and 23 to 34 tomorrow.

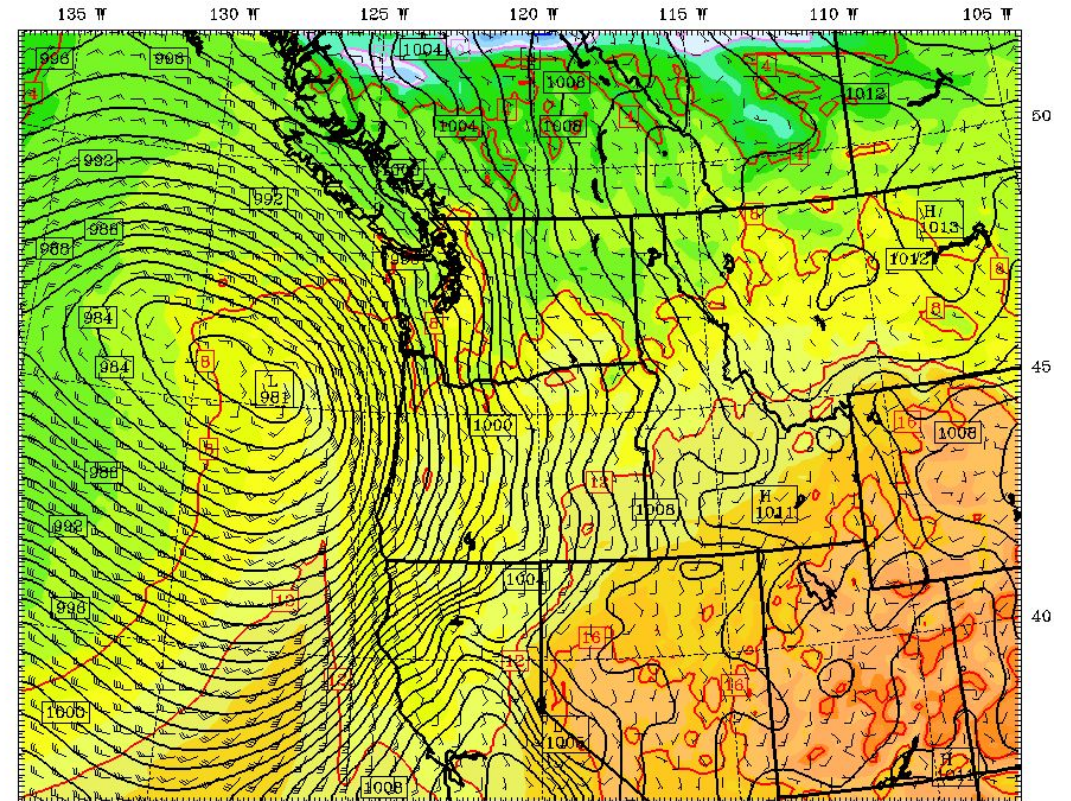
Attempts to simulate with modern models and data assimilation failed

Clearly there was a problem with the initial state over the Pacific (and other oceans) before the satellite era.

Observations were inadequate

UW WRF-GFS 12km Domain
Fest: 15 h
Temperature at 925 mb (°C)
Sea Level Pressure (hPa)
Wind at 10m (full barb = 10kts)

Init: 00 UTC Thu 11 Oct 62
Valid: 15 UTC Thu 11 Oct 62 (08 PDT Thu 11 Oct 62)



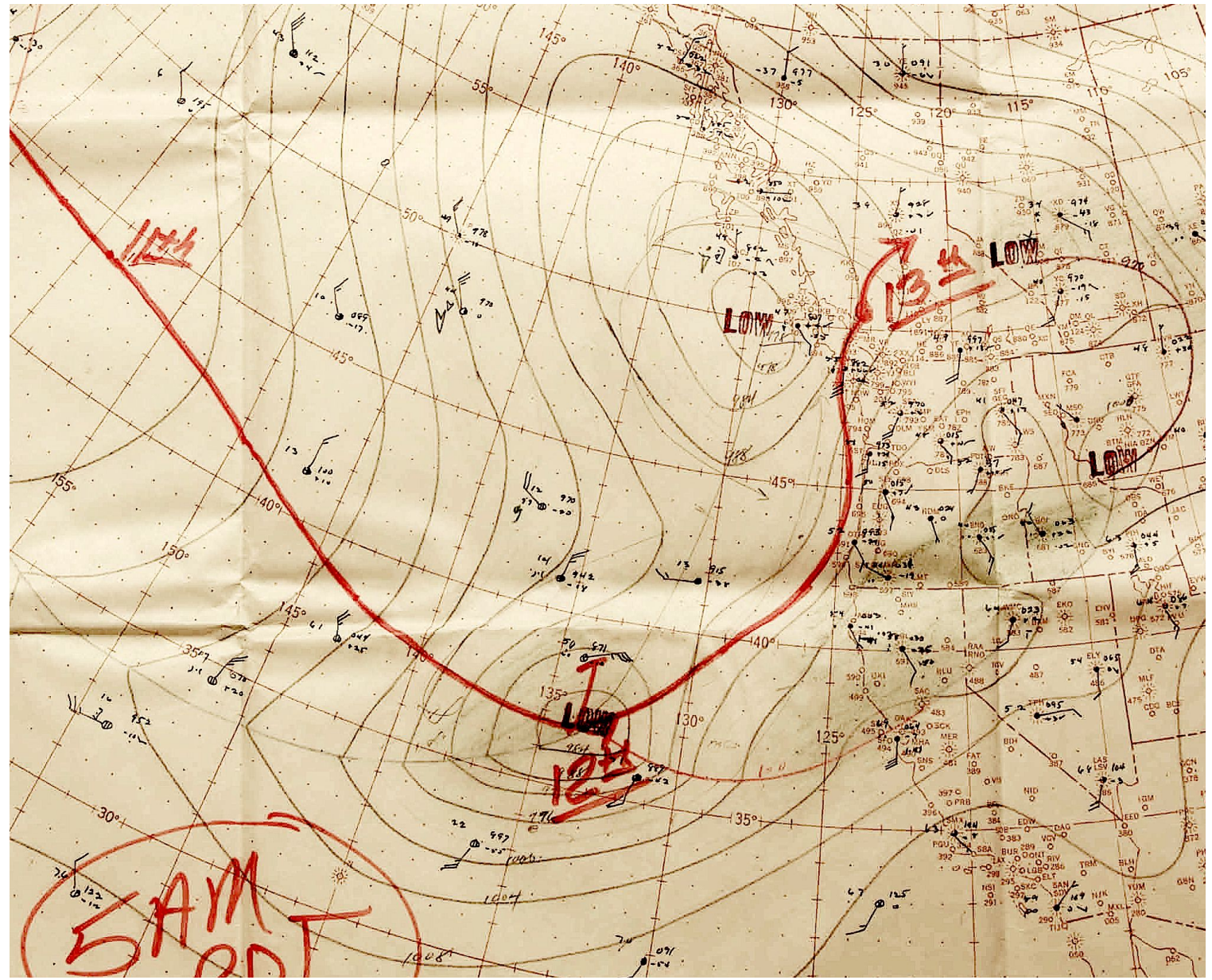
CONTOURS: UNITS=hPa LOW= 982.00 HIGH= 1014.0 INTERVAL= 1.0000
CONTOURS: UNITS=°C LOW= -4.0000 HIGH= 20.000 INTERVAL= 4.0000

-31.5 -27 -22.5 -18 -13.5 -9 -4.5 0 4.5 9 13.5 18 22.5 27 31.5 36 °C

Model Info: V4.1.3 G-D Ens YSU PBL Thompson Noah-MP 12 km, 37 levels, 72 sec
LW: RRTMG SW: RRTMG DIFF: full KM: ED Smagor

Not deep enough, too far offshore

Only
some
ships
and
island
station
s
offshor
e

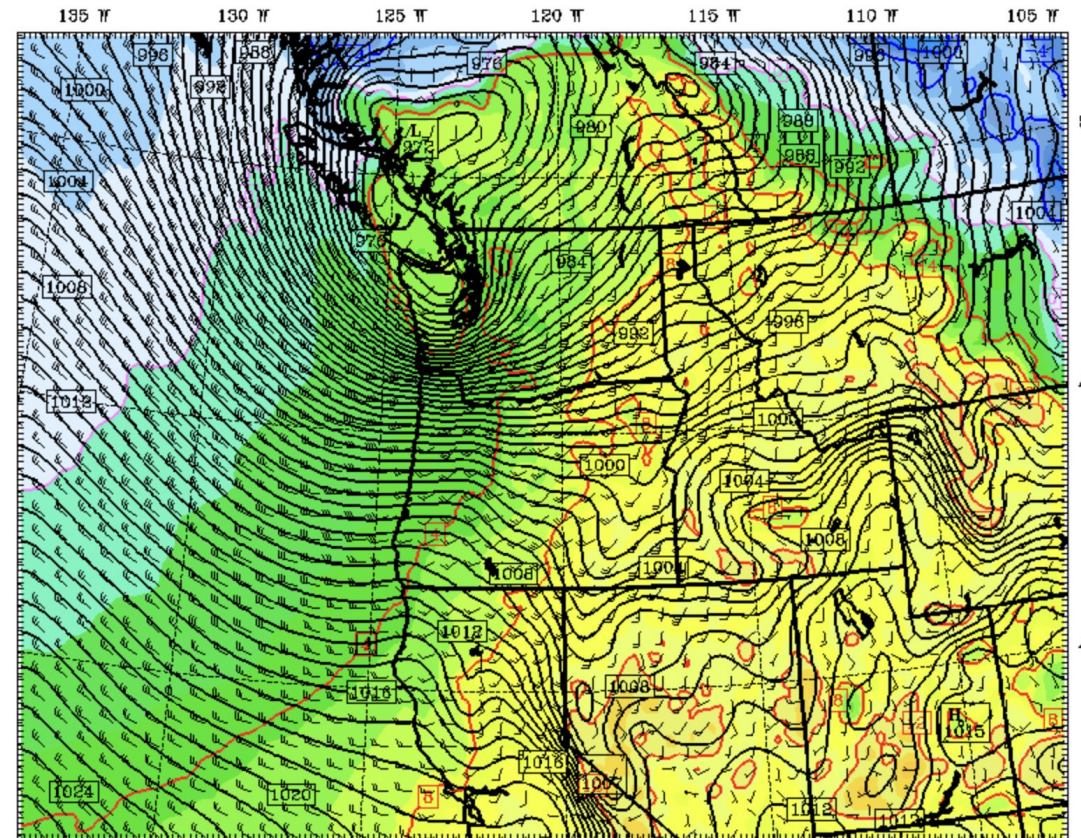


After ~1995 With Satellite Observations All Major Storms Were Predicted Skillfully for Days 1-3

**Chanukah Eve
Storm: 18-h
forecast for 10
PM December
14, 2006**

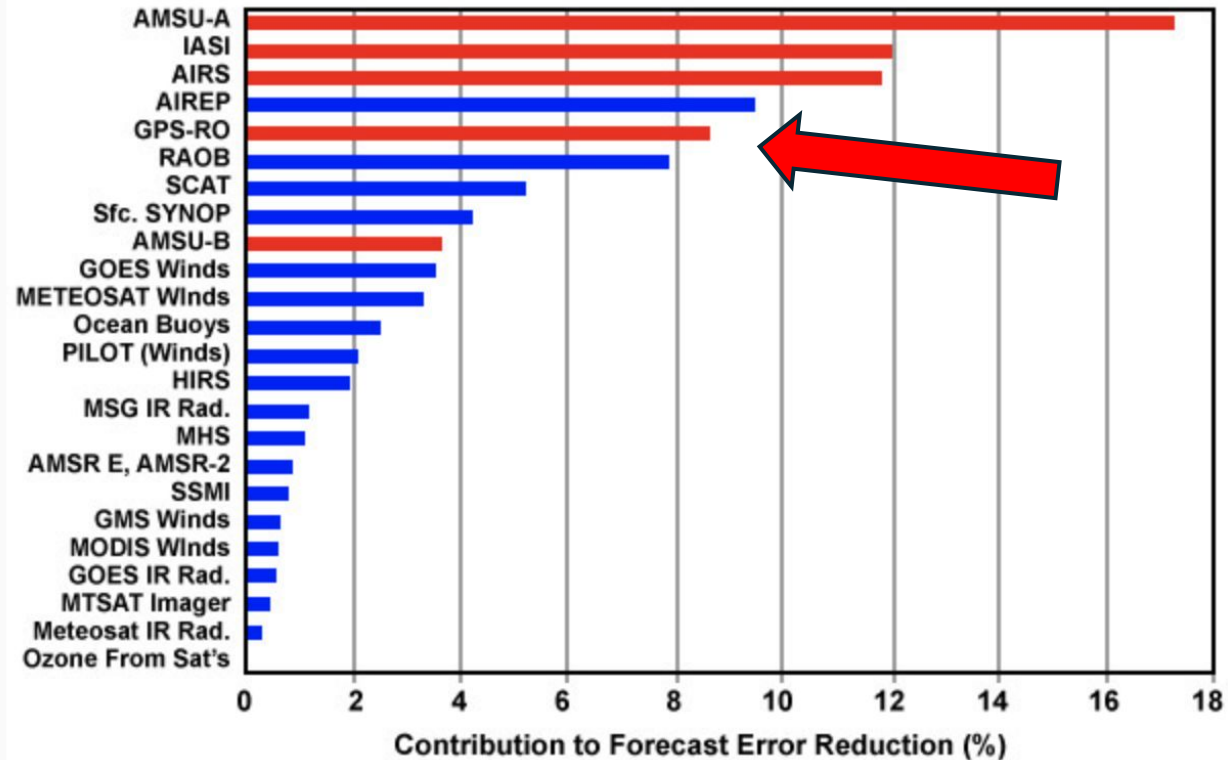
UW WRF-GFS 12km Domain
Fcst: 33 h
Temperature at 925 mb (°C)
Sea Level Pressure (hPa)
Wind at 10m (full barb = 10kts)

Init: 00 UTC Thu 14 Dec 06
Valid: 09 UTC Fri 15 Dec 06 (01 PST Fri 15 Dec 06)



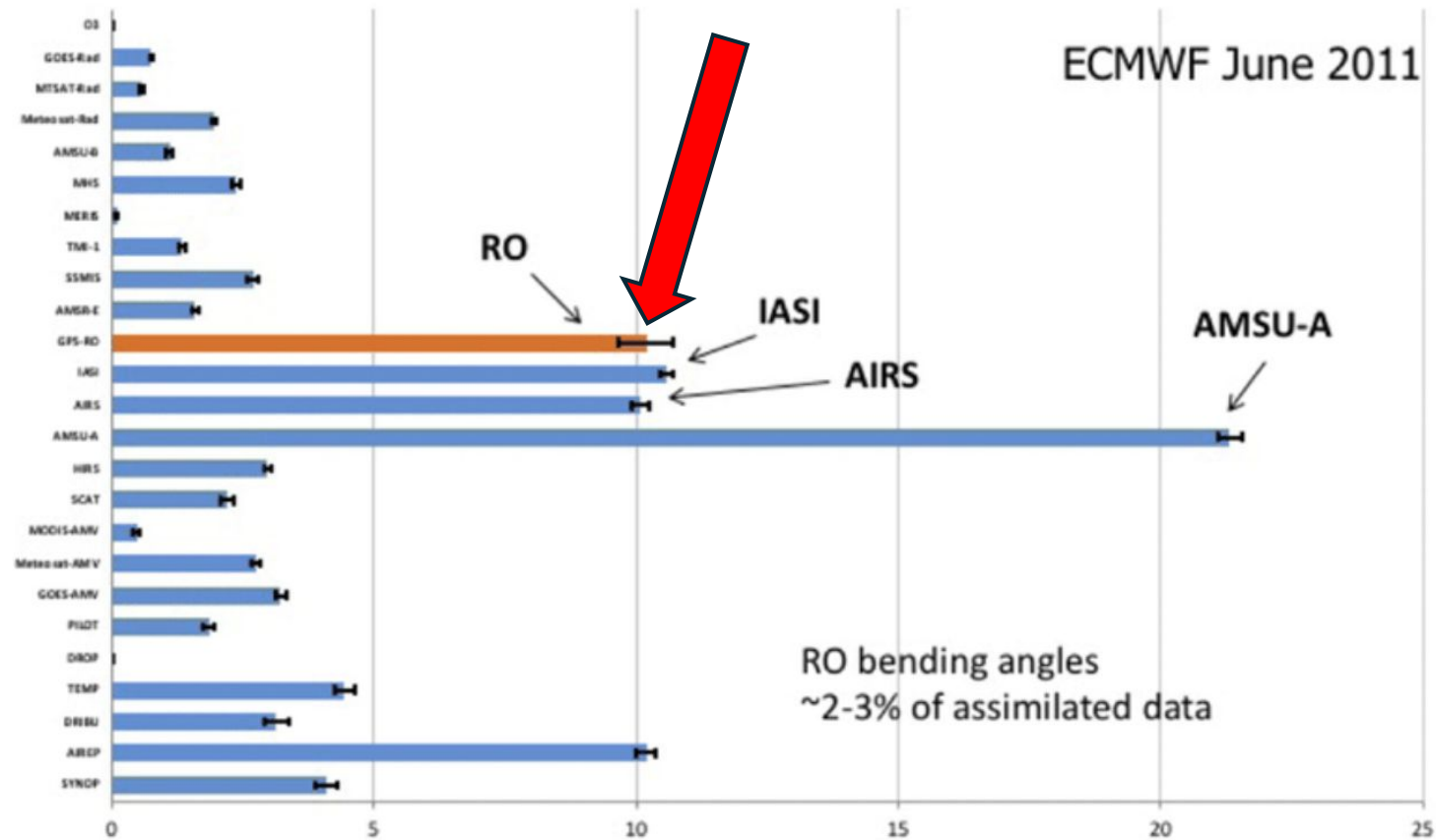
RO Satellites Played A Critical Role in This Revolution After ~2007

Percent Contribution of Different Observations to Forecast Error Reduction
in the Operational ECWTF System From Sep to Dec 2008
Averaged Over All Model Layers and the Entire Global Atmosphere



RO Satellites Played A Critical Role

Contributions to forecast accuracy by observing system



The Improvement of NWP by RO Data is Documented in Many Papers and Reports

Journal of Geophysical Research: Atmospheres / Volume 129, Issue 14 / e2024JD041709

Research Article

Impact of Varying Number of Radio Occultation Observations on Regional Weather Prediction Over India During the Summer Monsoon Season

Randhir Singh , Satya P. Ojha, Richard Anthes

First published: 11 July 2024

Geophysical Research Letters / Volume 50, Issue 5 / e2021GL096750

Research Letter |  Open Access |    

Potential Impacts of Radio Occultation Data Assimilation on Forecast Skill of Tropical Cyclone Formation in the Western North Pacific

Hsu-Feng Teng , Ying-Hwa Kuo, James M. Done

Contract Report to the European Space Agency

Final Technical Note of "Impact assessment of commercial GNSS-RO data"

Katrin Lonitz*, Christian Marquardt\$, Neill Bowler⁺
and Sean Healy*

* ECMWF \$ EUMETSAT + UK Met Office


November 15, 2021





Even AI Concurs


Does RO data improve weather forecasts?

Show drafts 

Yes, Radio Occultation (RO) data significantly improves weather forecasts. 

RO data provides high-resolution vertical profiles of atmospheric temperature, pressure, and humidity. These profiles are crucial for accurate weather prediction models. Here's why: 

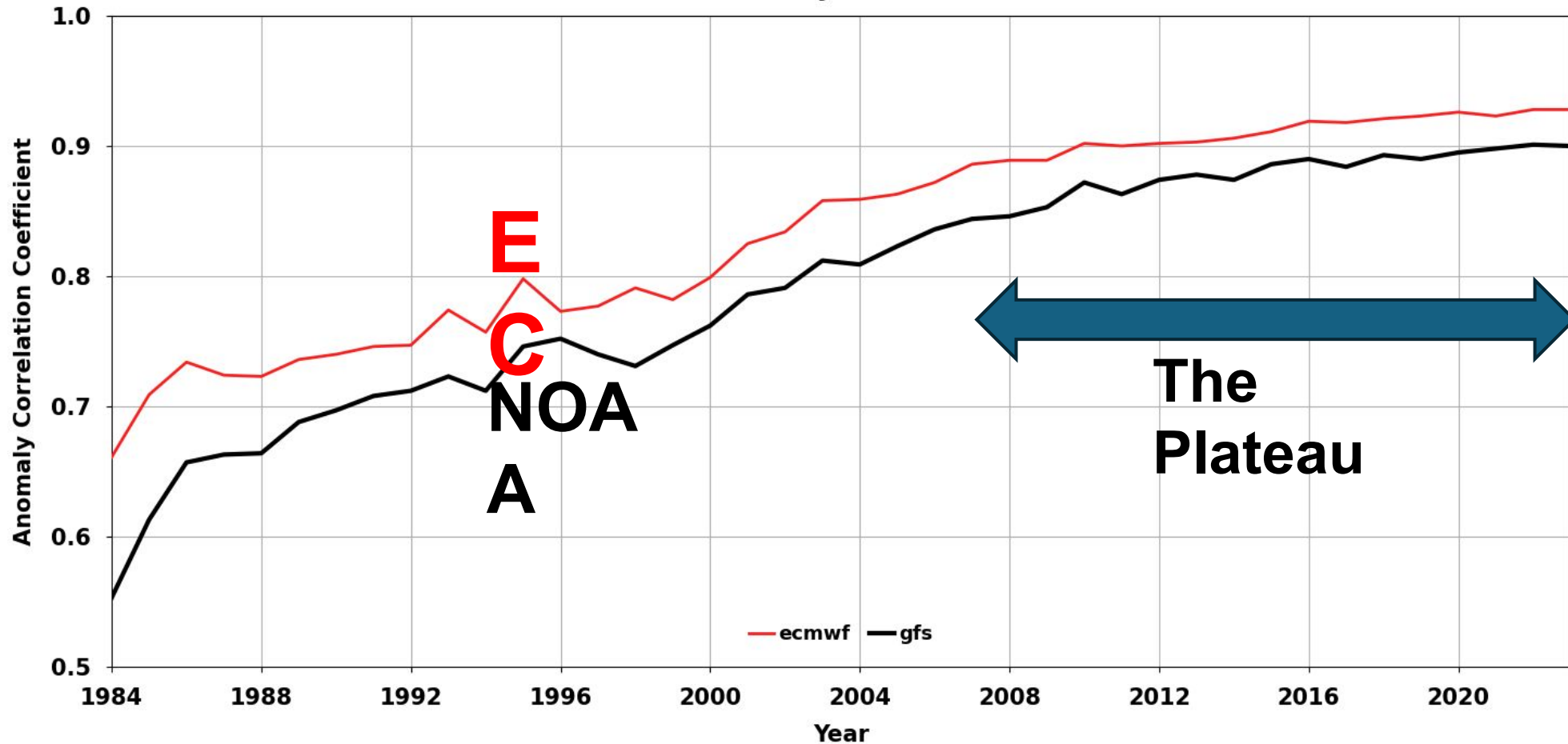
- **Improved understanding of atmospheric structure:** RO data helps meteorologists better understand the vertical structure of the atmosphere, including the boundary layer, troposphere, stratosphere, and mesosphere. 
- **Enhanced tropical cyclone forecasts:** RO data has been shown to improve forecasts of tropical cyclone intensity and track. 
- **Better prediction of extreme weather events:** By providing more accurate atmospheric data, RO can help improve predictions of severe weather events like hurricanes, thunderstorms, and heavy rainfall. 
- **Real-time monitoring of atmospheric conditions:** RO data can be collected in real-time, providing meteorologists with up-to-date information for making timely weather forecasts and warnings. 

In essence, RO data offers a valuable tool for improving weather prediction capabilities and ensuring public safety. 

Major improvement (1995-2008) following by the **great plateau in large-scale forecast skill**



Anomaly Correlation Coefficient - G004/Northern Hemisphere 20N-80N
500 hPa Geopotential Height (gpm)
valid 1984-2023 valid 00Z, Forecast Day 5 (Hour 120)
Yearly Mean



Does the “great plateau” mean that actual forecast skill has stagnated?



The Answer is No



Why? Because of ANOTHER NWP revolution that occurred as the great plateau become evident

RO and Satellite
Observations



+



?

A Revolution That Would Allow Mesoscale/Local Forecast Skill to Increase Even as Large-Scale Skill Stagnated ?

RO and Satellite Observations



+

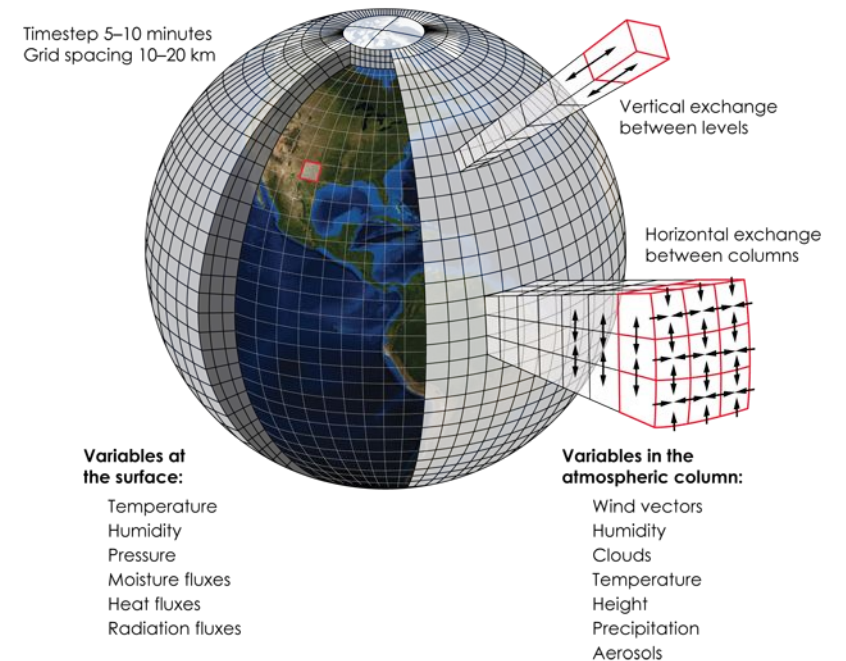


**Hint: Bill
Kuo and
Rick Anthes
Played a
Major Role
in Both
Revolutions**



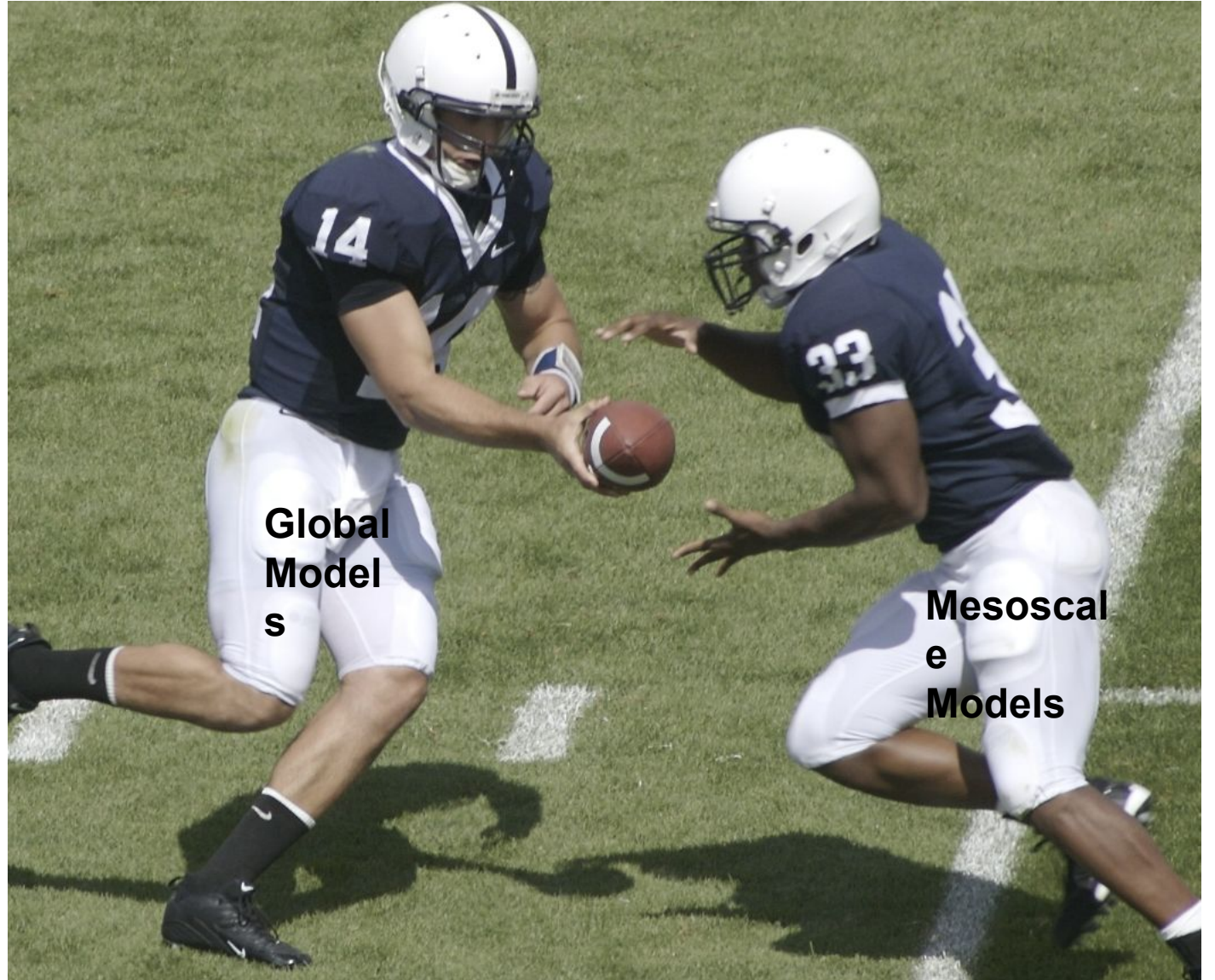
The High-Resolution Prediction Revolution

- During the past two decades, model resolution and physics improved substantially, allowing more accurate simulation of critical mesoscale features.
- In the U.S., global models went from ~ 100 km grid spacing in 1995 to 13 km in ~2020. National and regional models went from ~50 to ~4 km during the same period.

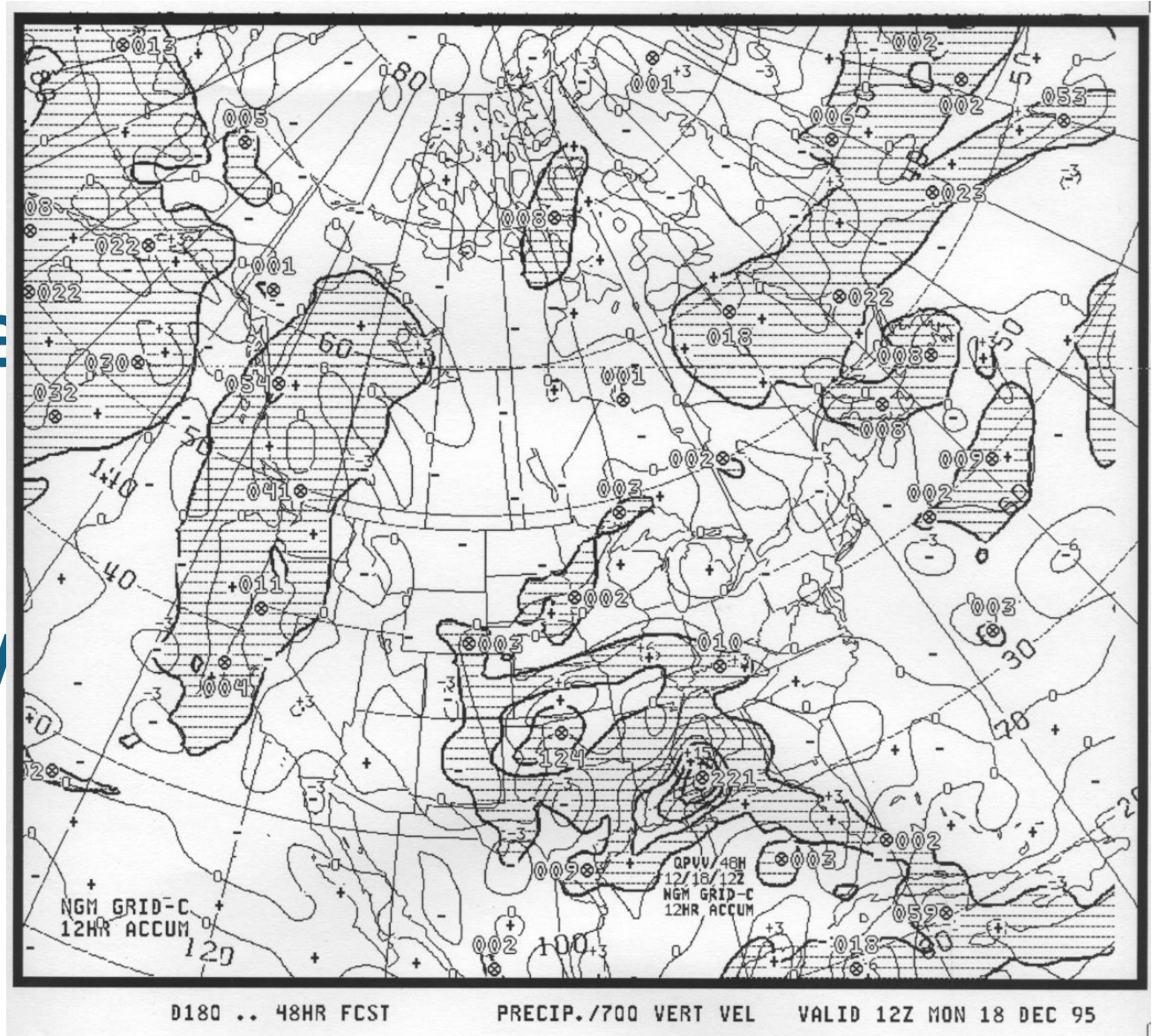


The Hand Off

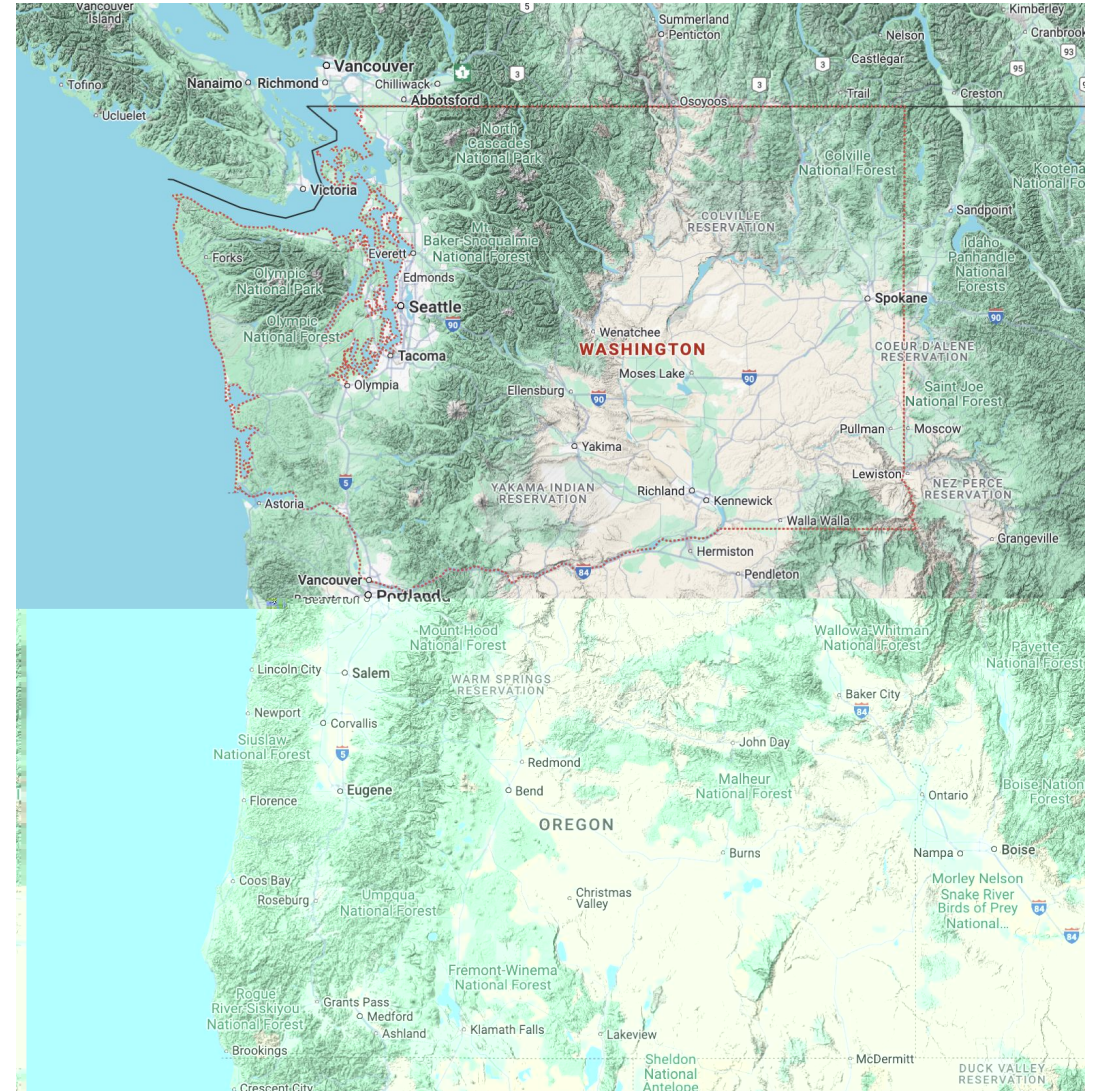
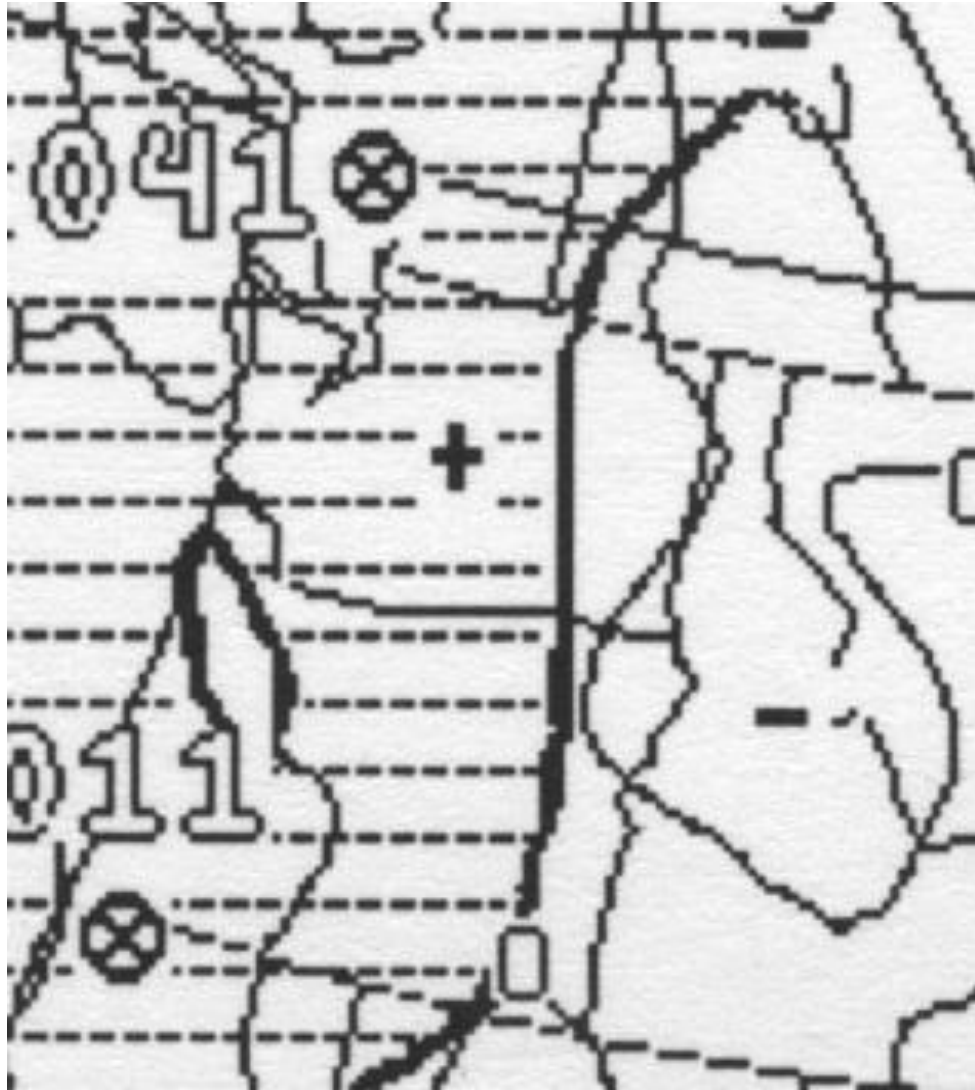
Using improved global data assimilation and prediction as a starting point, high resolution prediction provided increasingly skillful downscaling of global forecasts.



1995 State of the Art Operational Prediction: the NOAA/NWS NGM Model

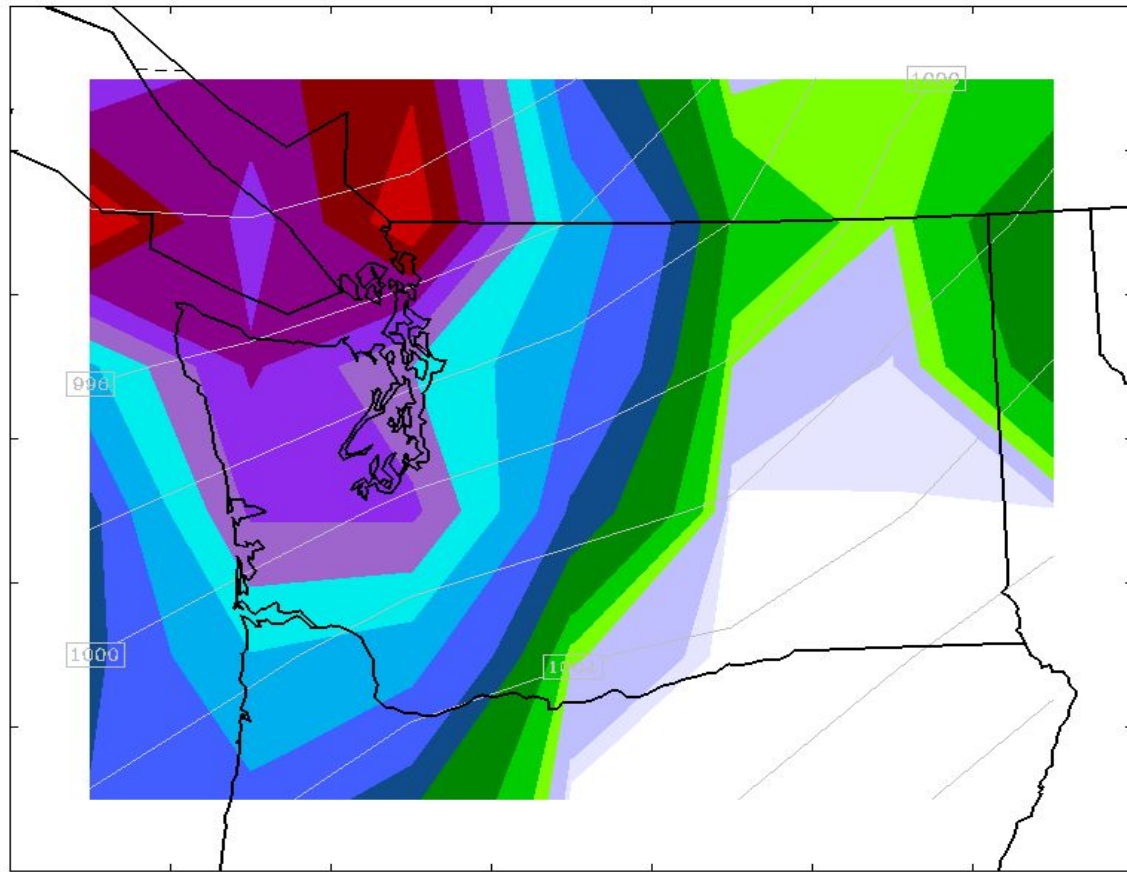


No Mesoscale Structures

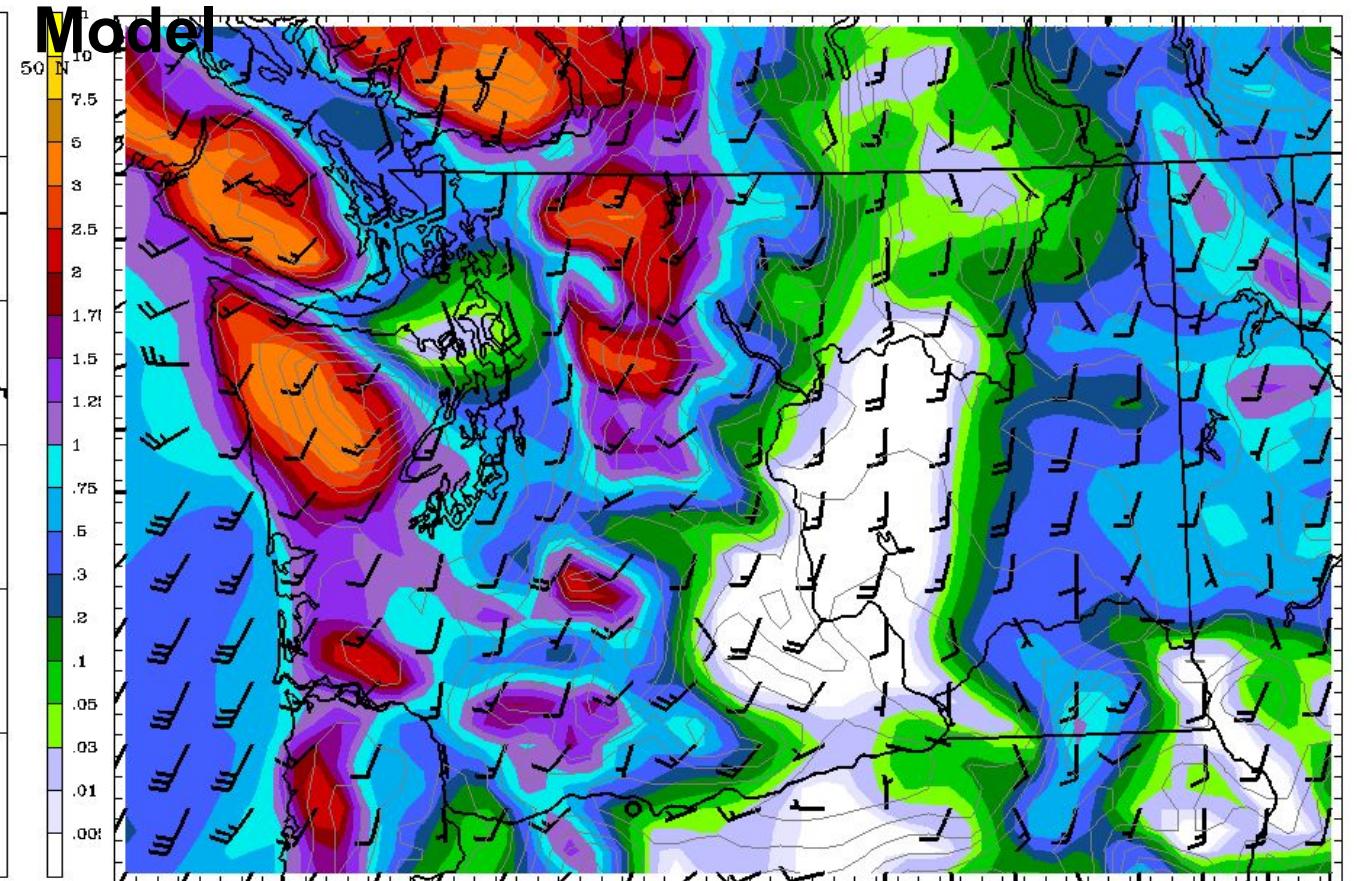


When grid spacings declined to ~15 km amazing things happened. Example: mesoscale terrain effects

24-h Precipitation ending 00 UTC 23 February 2024 WRF



100-km Grid Spacing

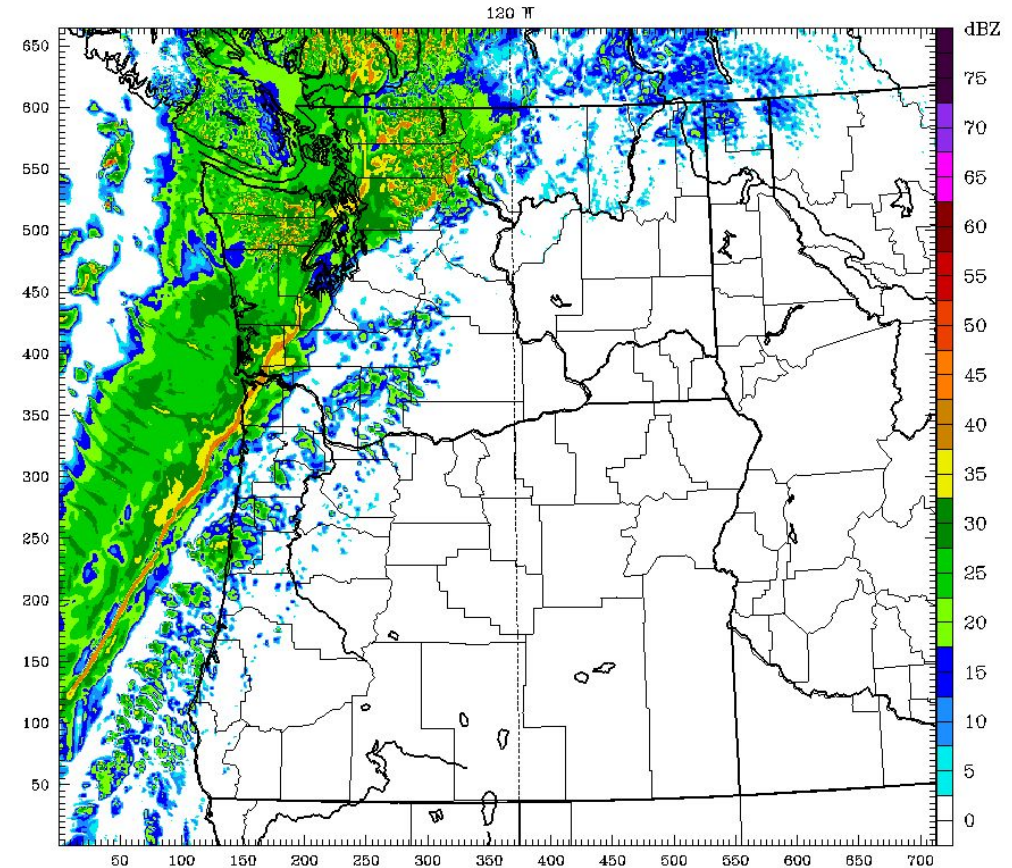


12-km Grid Spacing

But it was more than that.. At higher resolution...

- Frontal collapse and frontal circulations become resolved
- Downslope windstorms were simulated
- Convection increasingly resolved
- Diurnal circulations were simulated
- And much more...

UW WRF-GFS 1.33km Domain Init: 12 UTC Tue 24 Nov 20
Fest: 11.00 h Valid: 23 UTC Tue 24 Nov 20 (15 PST Tue 24 Nov 20)
Radar reflectivity (lamda = 10 cm) at k-index = 37

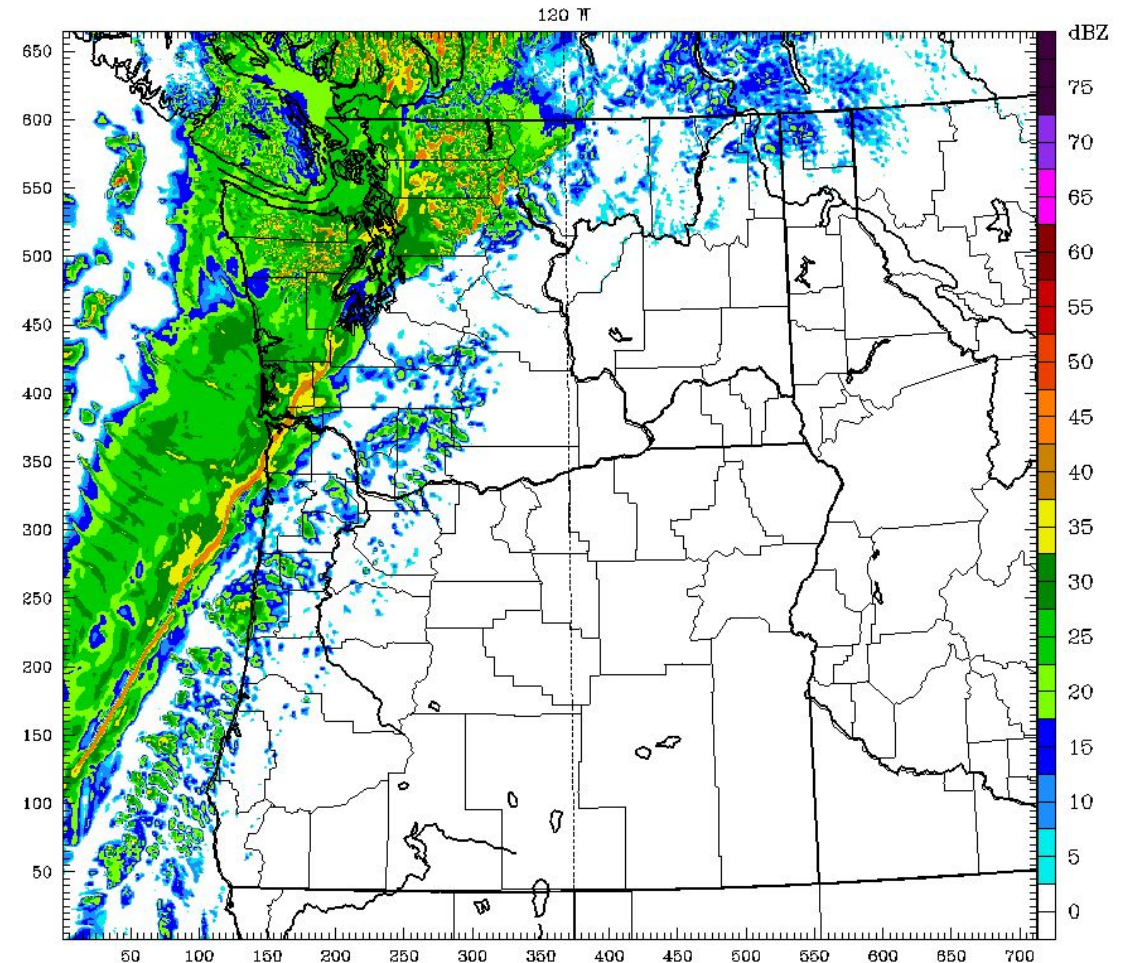
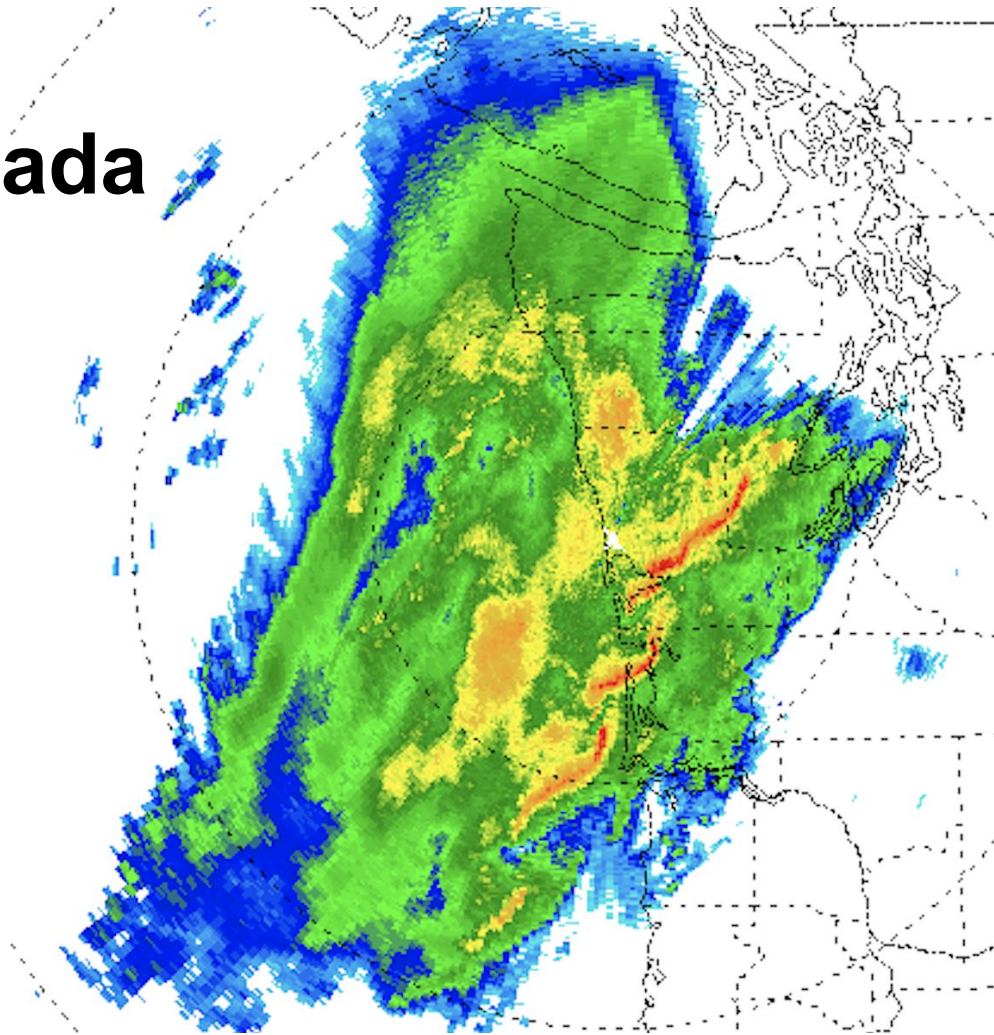


Model Info: V4.1.3 No Cu YSU PBL Thompson Noah-MP 1.3 km, 37 levels, 8 sec
LW: RRTMG SW: RRTMG DIFF: full KM: 2D Smagor INIT: RAP+GFS

Cold Front and Narrow Cold Frontal Rainbands

UW WRF-GFS 1.33km Domain
Init: 12 UTC Tue 24 Nov 20
Fcst: 11.00 h Valid: 23 UTC Tue 24 Nov 20 (15 PST Tue 24 Nov 20)
Radar reflectivity ($\lambda = 10$ cm) at k-index = 37

Rada
r



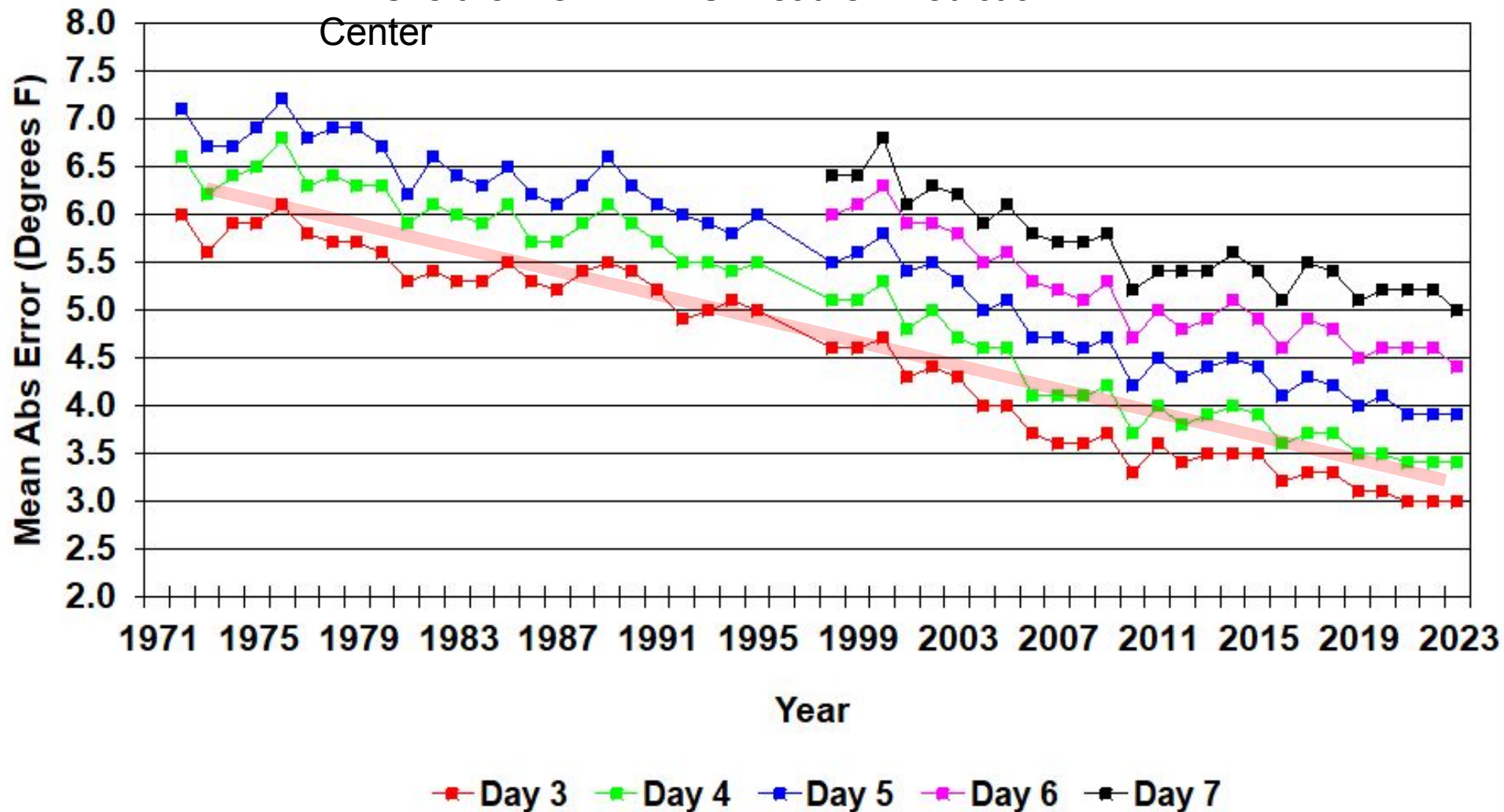
Model Info: V4.1.3 No Cu YSU PBL Thompson Noah-MP 1.3 km, 37 levels, 6 sec
LW: RRTMG SW: RRTMG DIFF: full KM: 2D Smagor INIT: RAP+GFS

**Objective
Verification
of the
Second
Revolution**



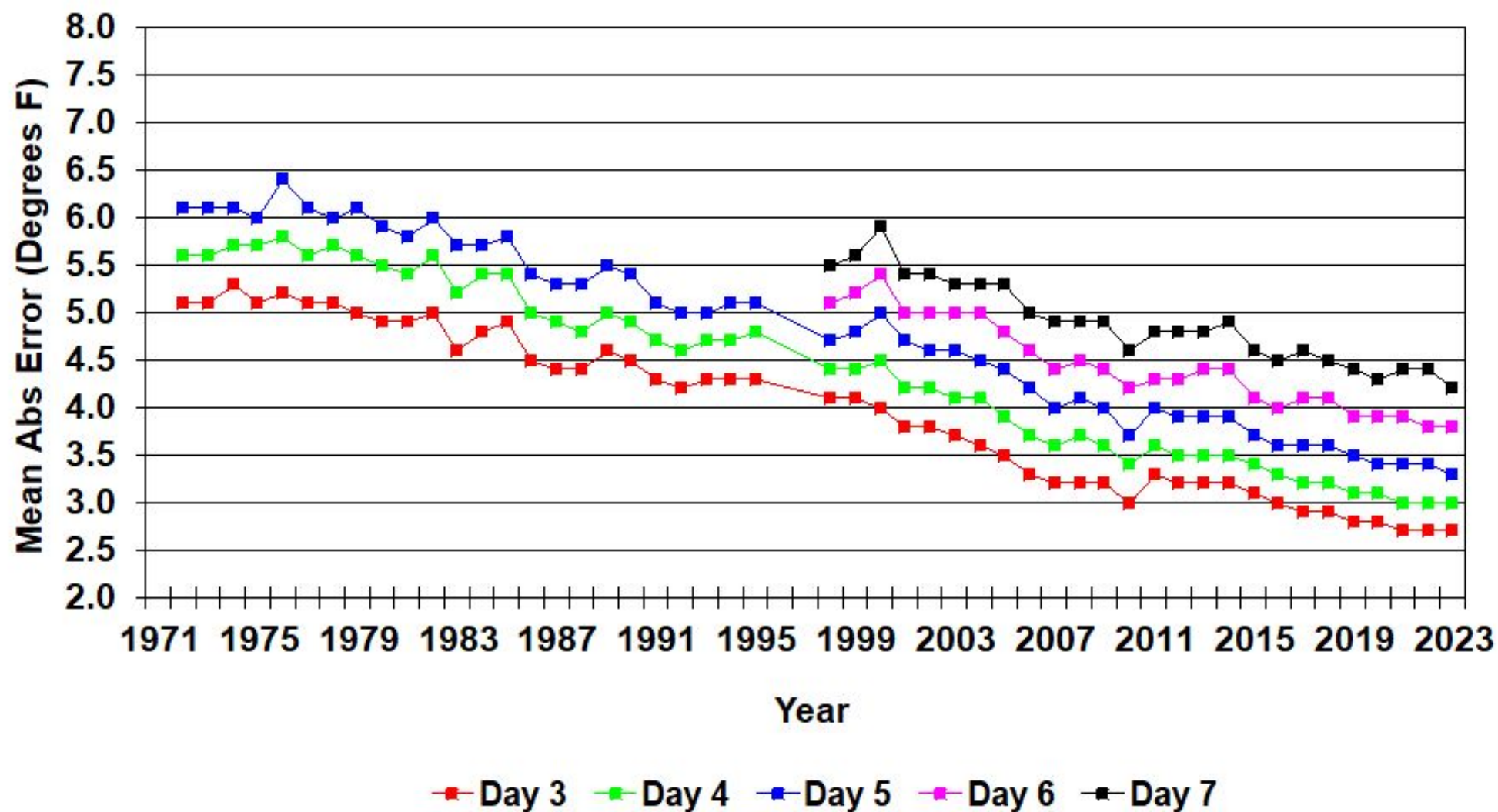
Annual WPC Mean Absolute Errors Maximum Temperatures

WPC is the NOAA/NWS Weather Prediction
Center

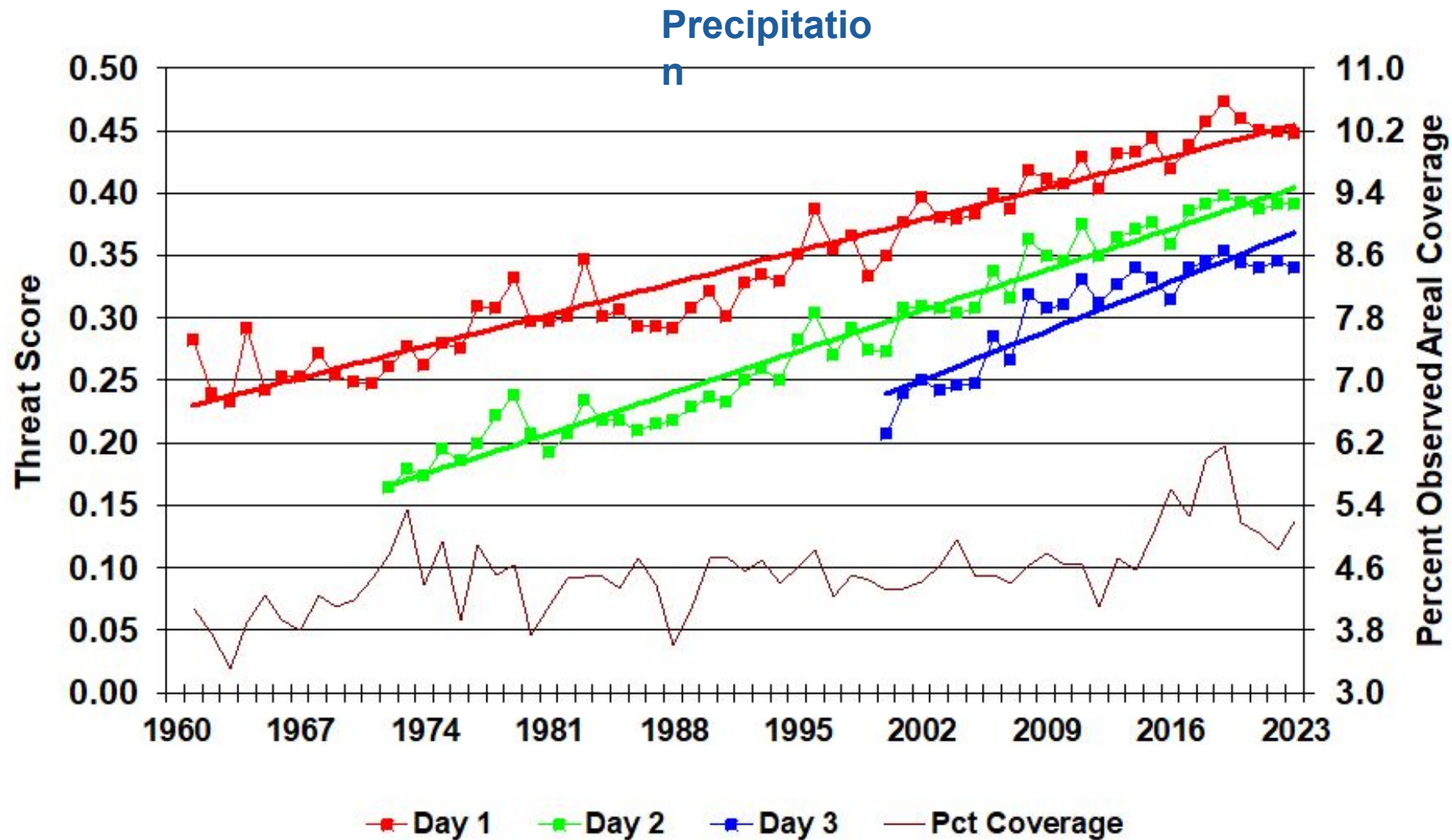


Skill trend
Maintained
No
Plateau

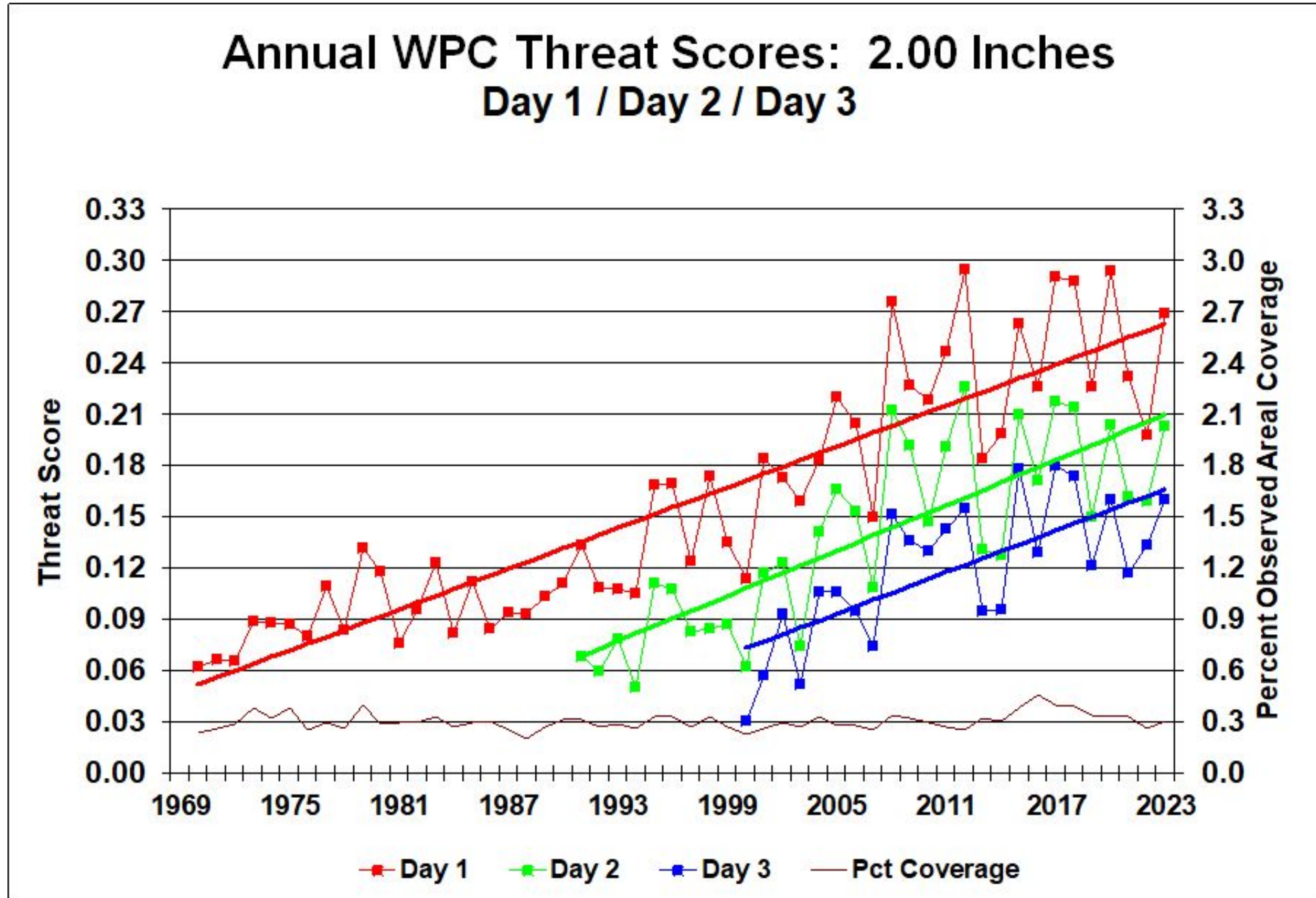
Annual WPC Mean Absolute Errors Minimum Temperatures



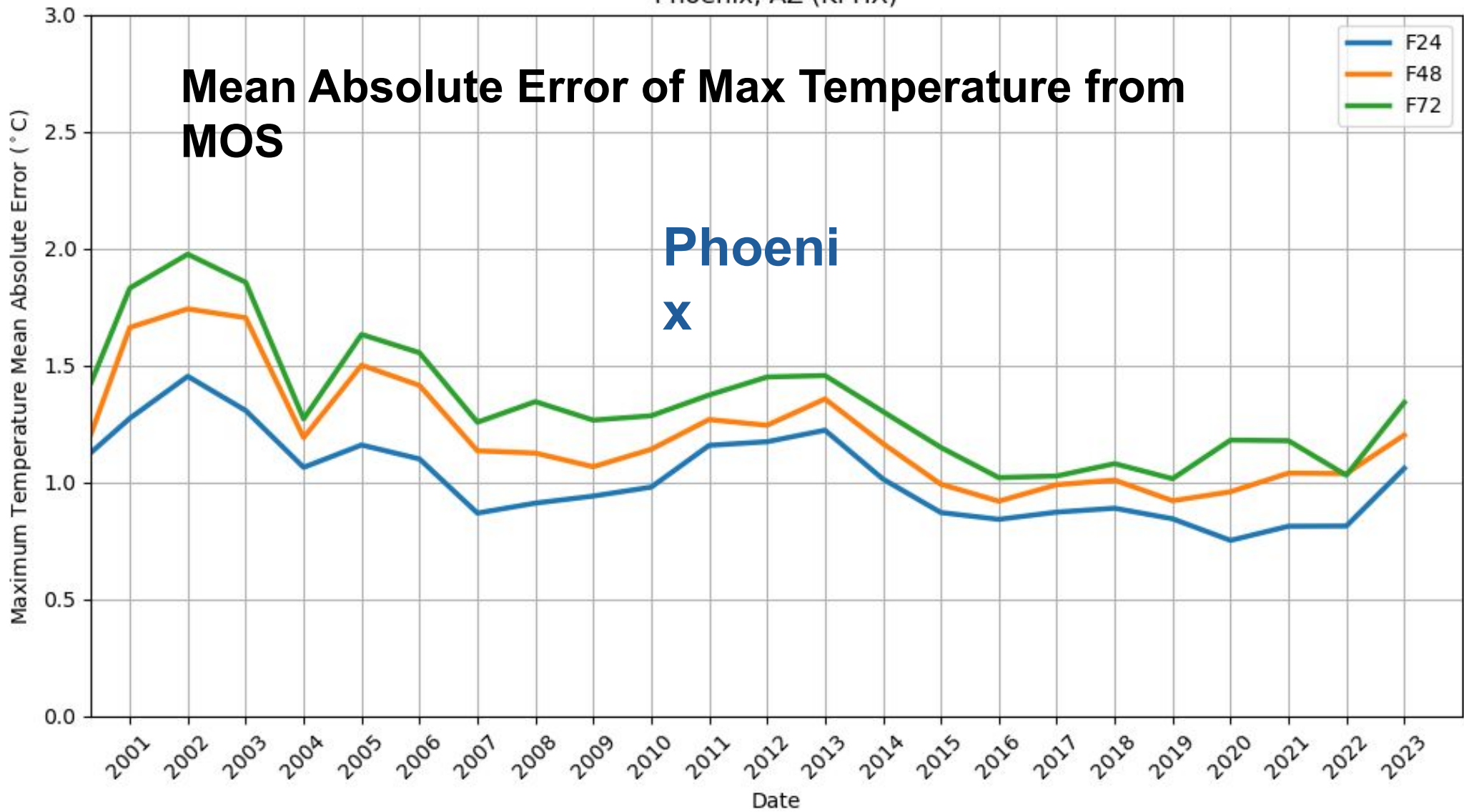
Annual WPC Threat Scores: 0.50 Inch Day 1 / Day 2 / Day 3



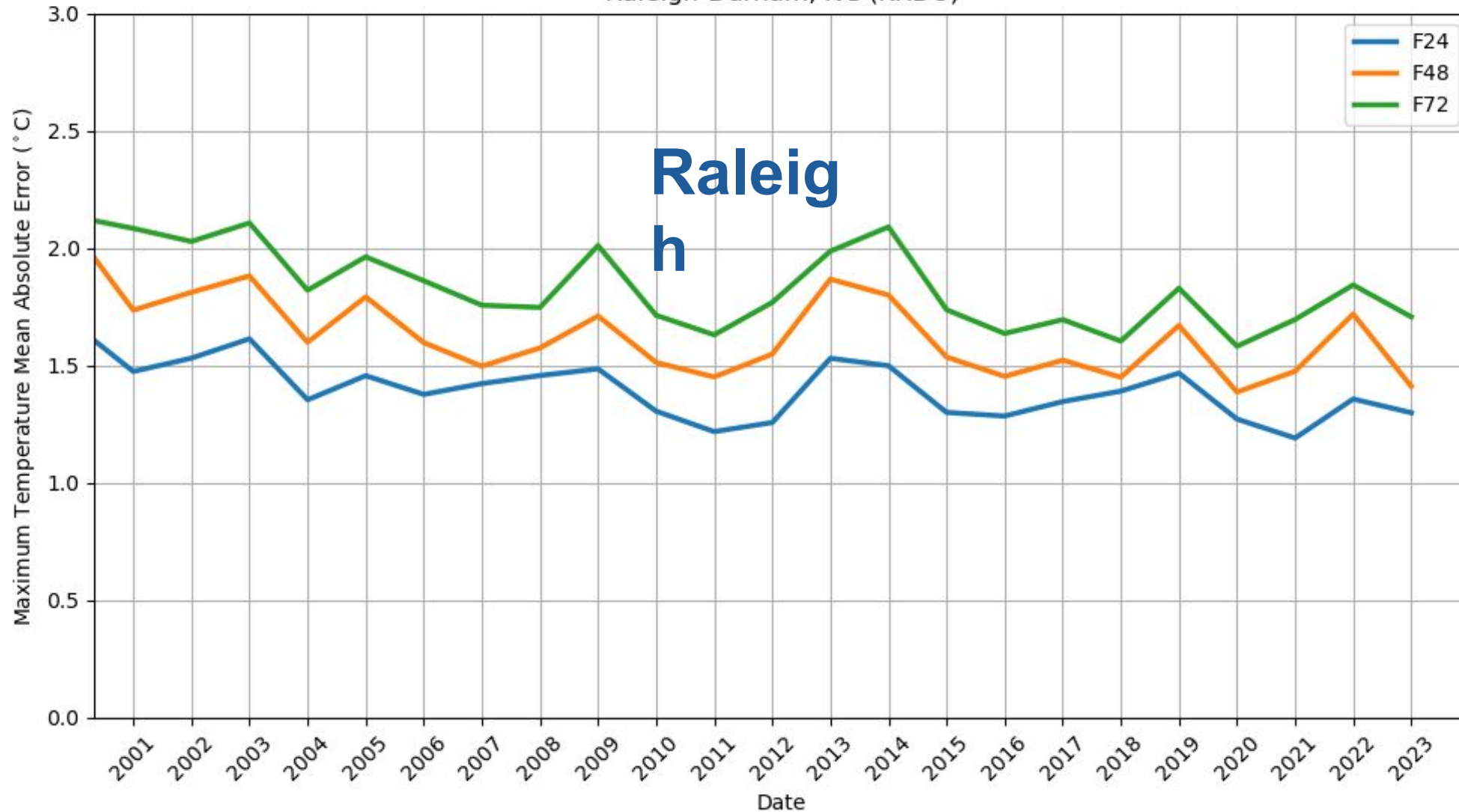
Heavy Precipitation



MAE, MOS, 00Z , Maximum Temperature , 2000 - 2023
Phoenix, AZ (KPHX)



MAE, MOS, 00Z , Maximum Temperature , 2000 - 2023
Raleigh-Durham, NC (KRDU)



A Stunning Example of Progress

On August 8, 2023, large wildfires hit western and central Maui, killing at least 100 people and resulting in 3-6 billion dollars of damage



The Maui Wildfire Event Was Associated with Very Strong Downslope Winds

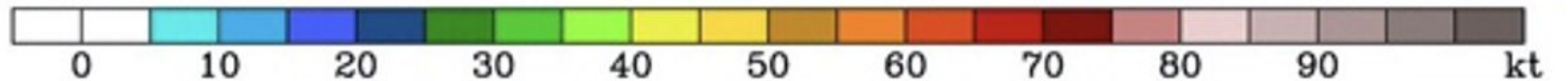
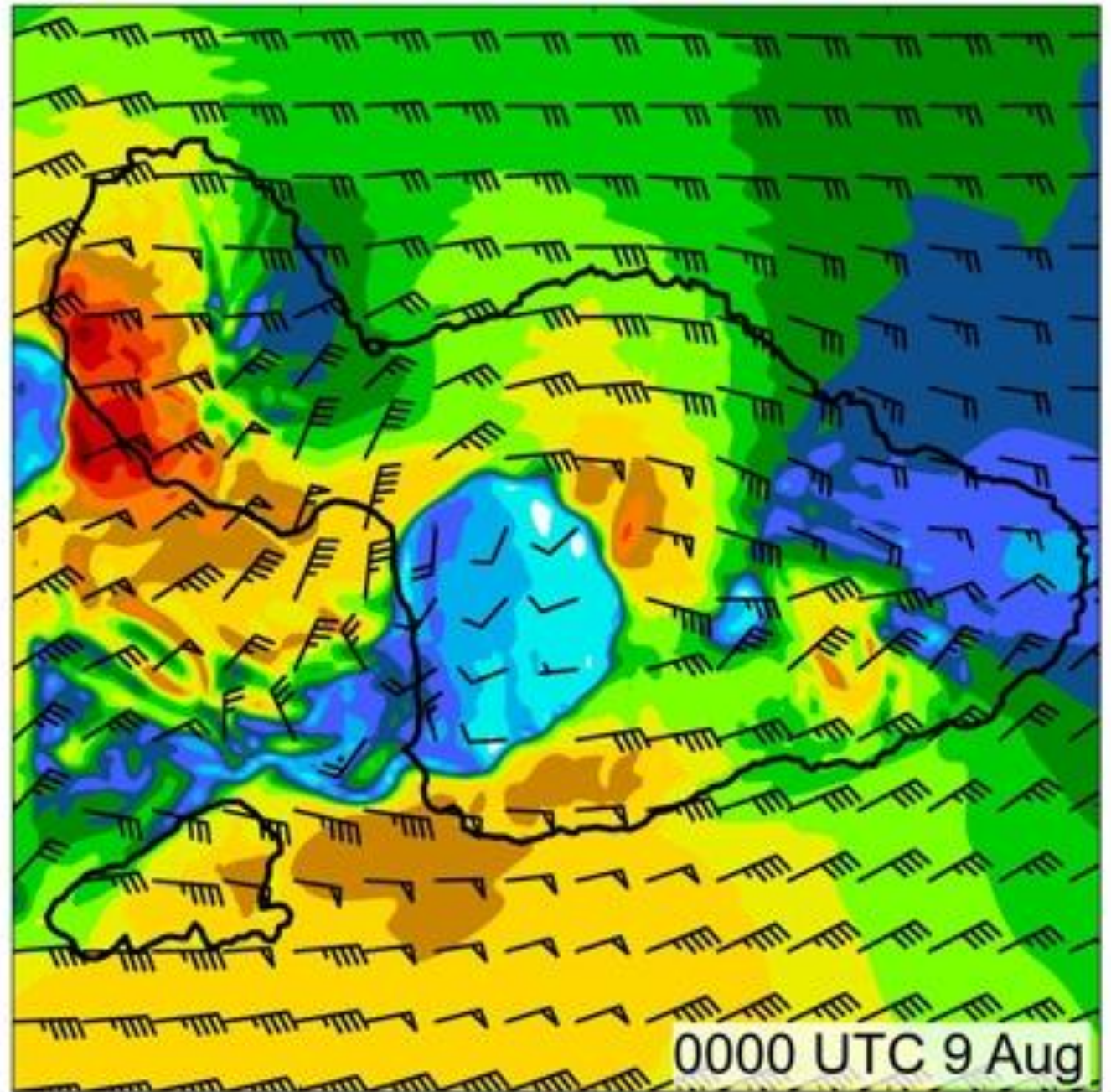
Based on damage and limited wind observations, estimated winds gusted to 60-80 kt in and east of Lahaina

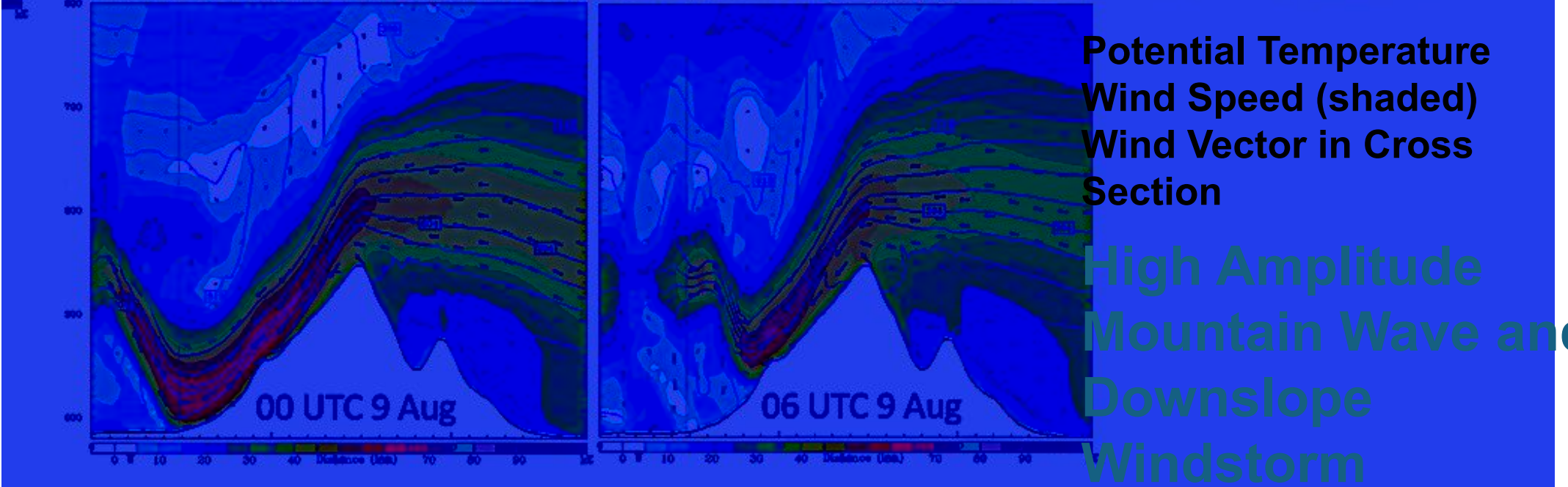
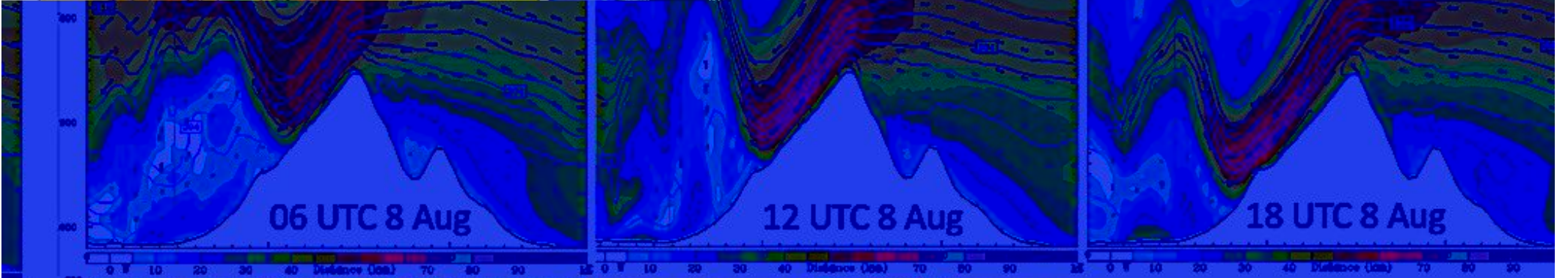
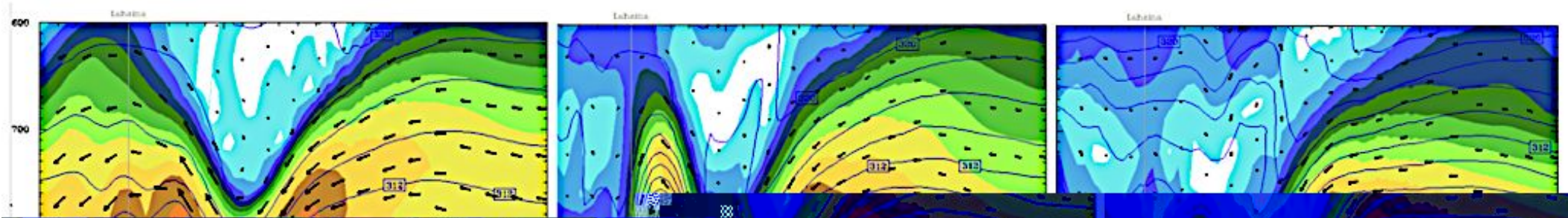


24-h forecast was excellent

WRF
Model
Forecast
Wind
Gusts (kt)

Initialized 0000 UTC
8 August

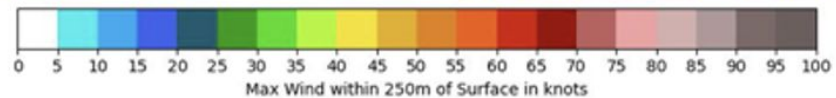
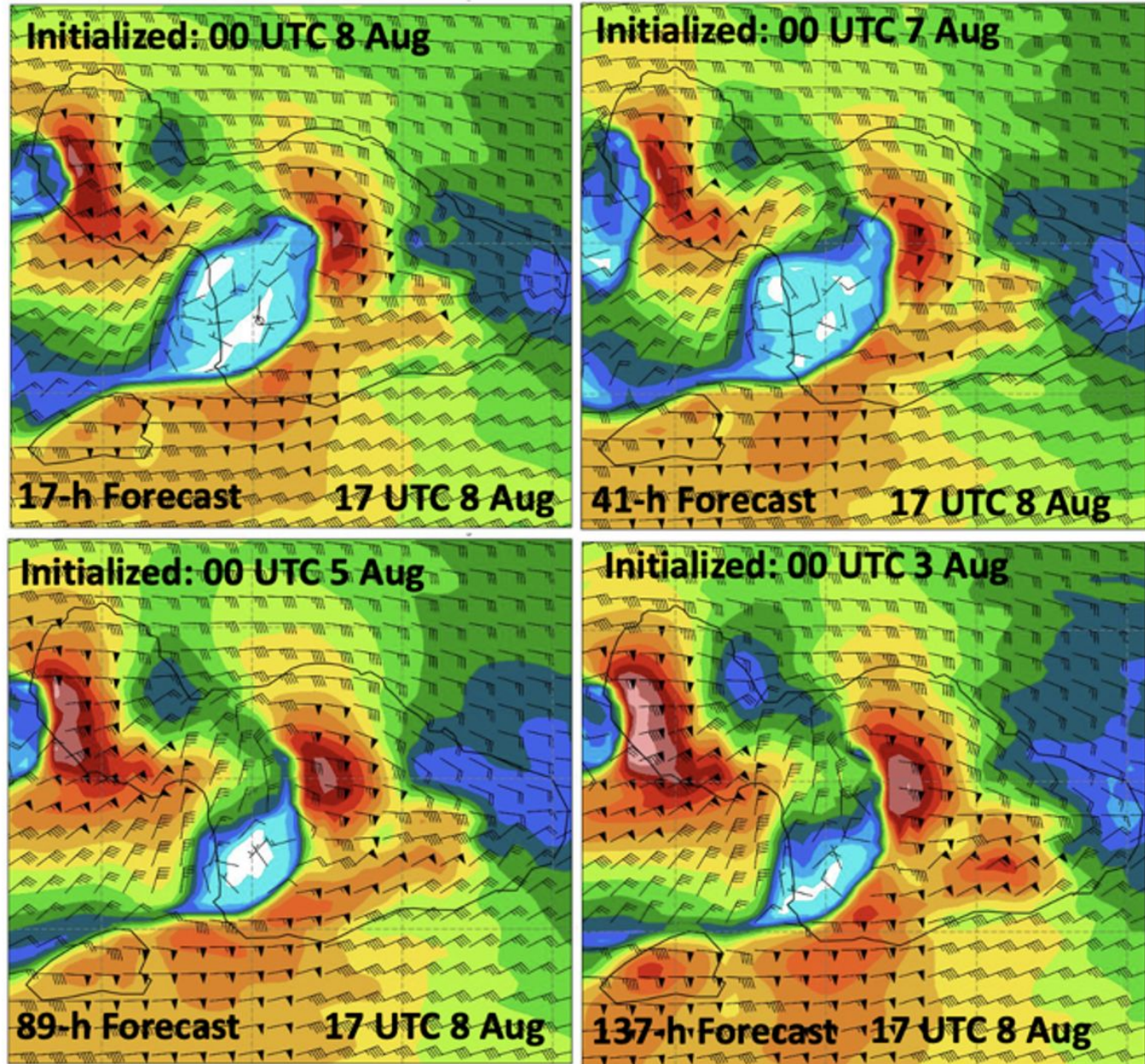




Potential Temperature
 Wind Speed (shaded)
 Wind Vector in Cross
 Section

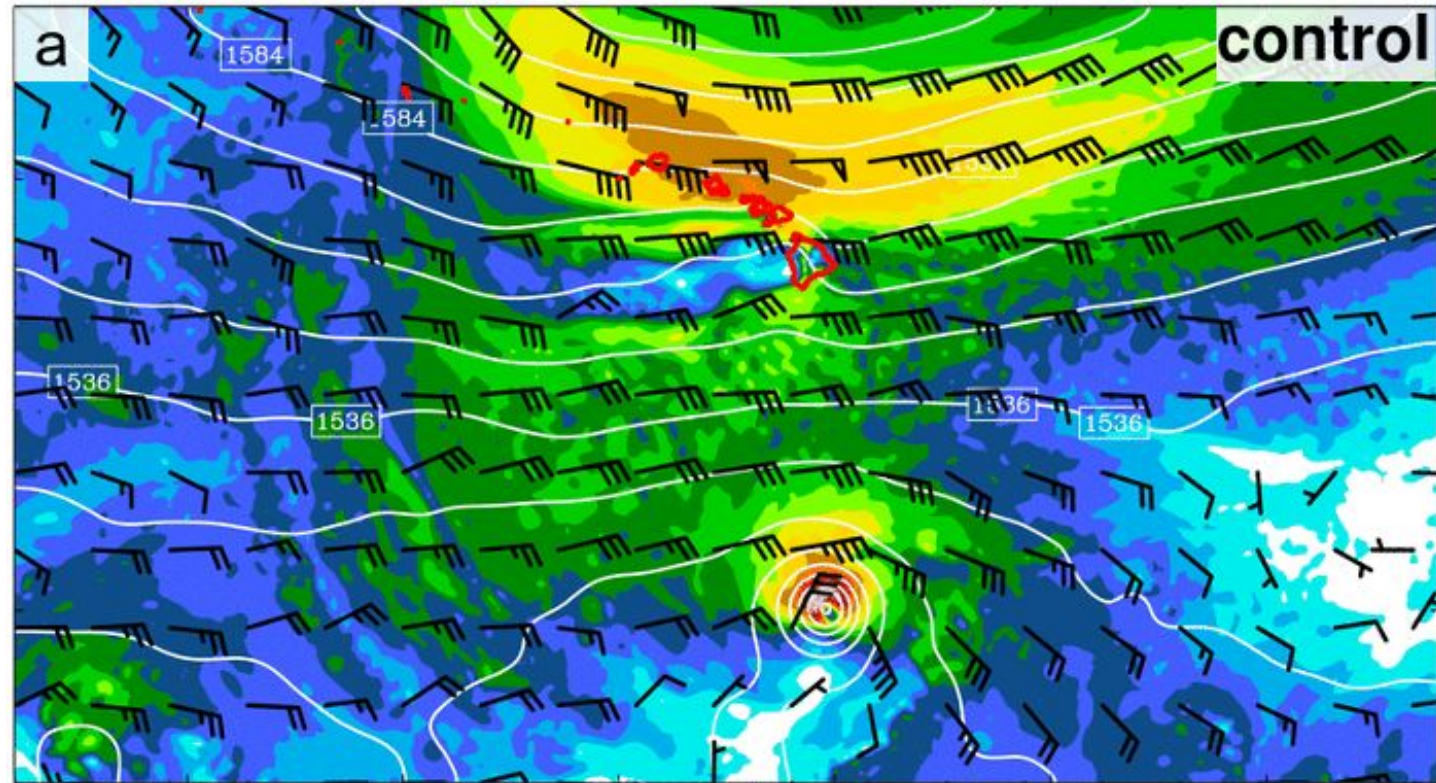
High Amplitude
 Mountain Wave and
 Downslope
 Windstorm

**Almost no
loss of skill
through 137
h (nearly 6
days!)**



The Two Revolutions Made This Happen

- Excellent large-scale initialization over the vast Pacific from satellite assets
- Excellent downscaling to the mesoscale by high-resolution NWP models, such as WRF.



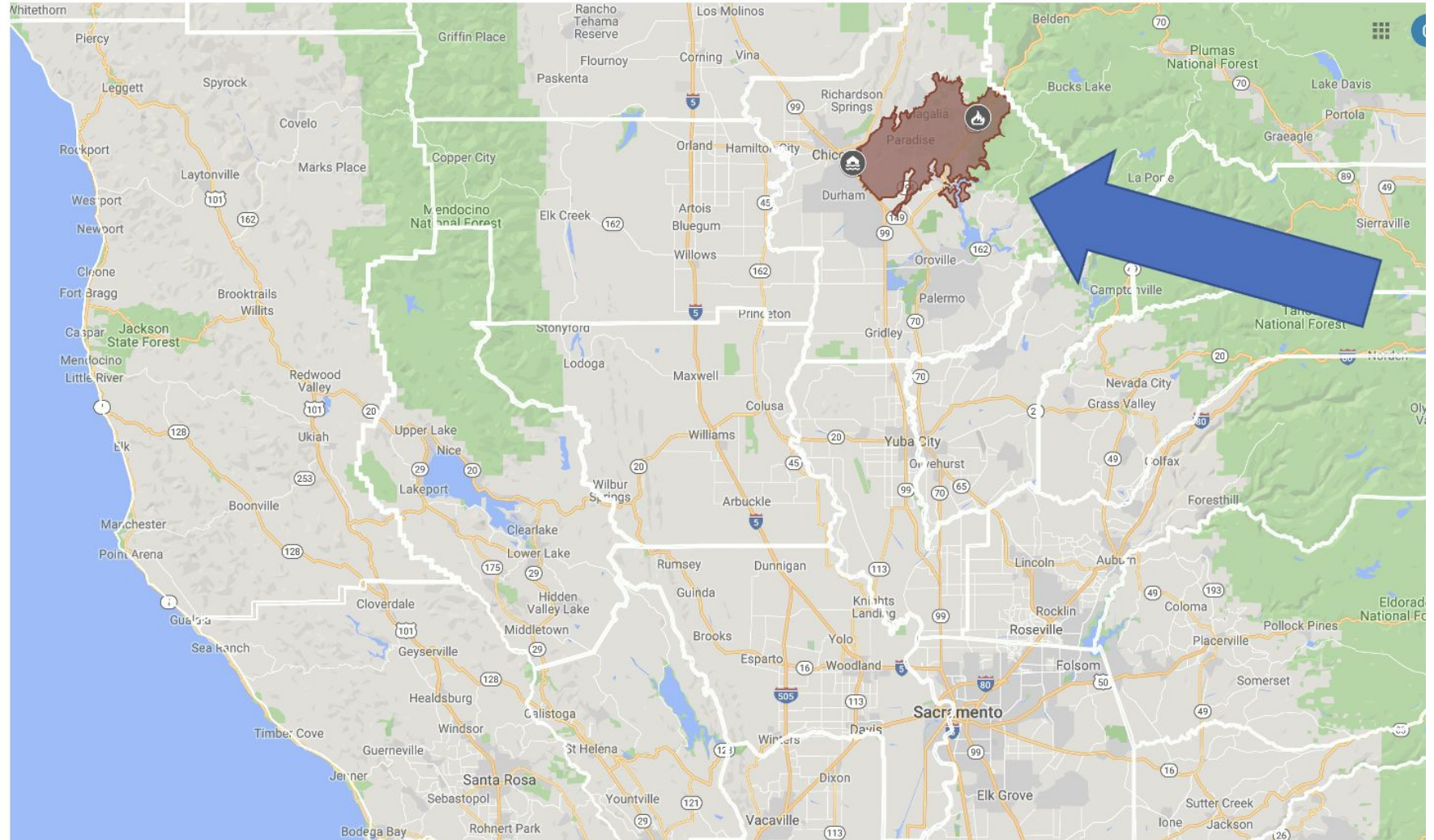
850 hPa Heights and Wind Anomalies

This case was not exceptional: similarly skillful forecasts have occurred time and time again

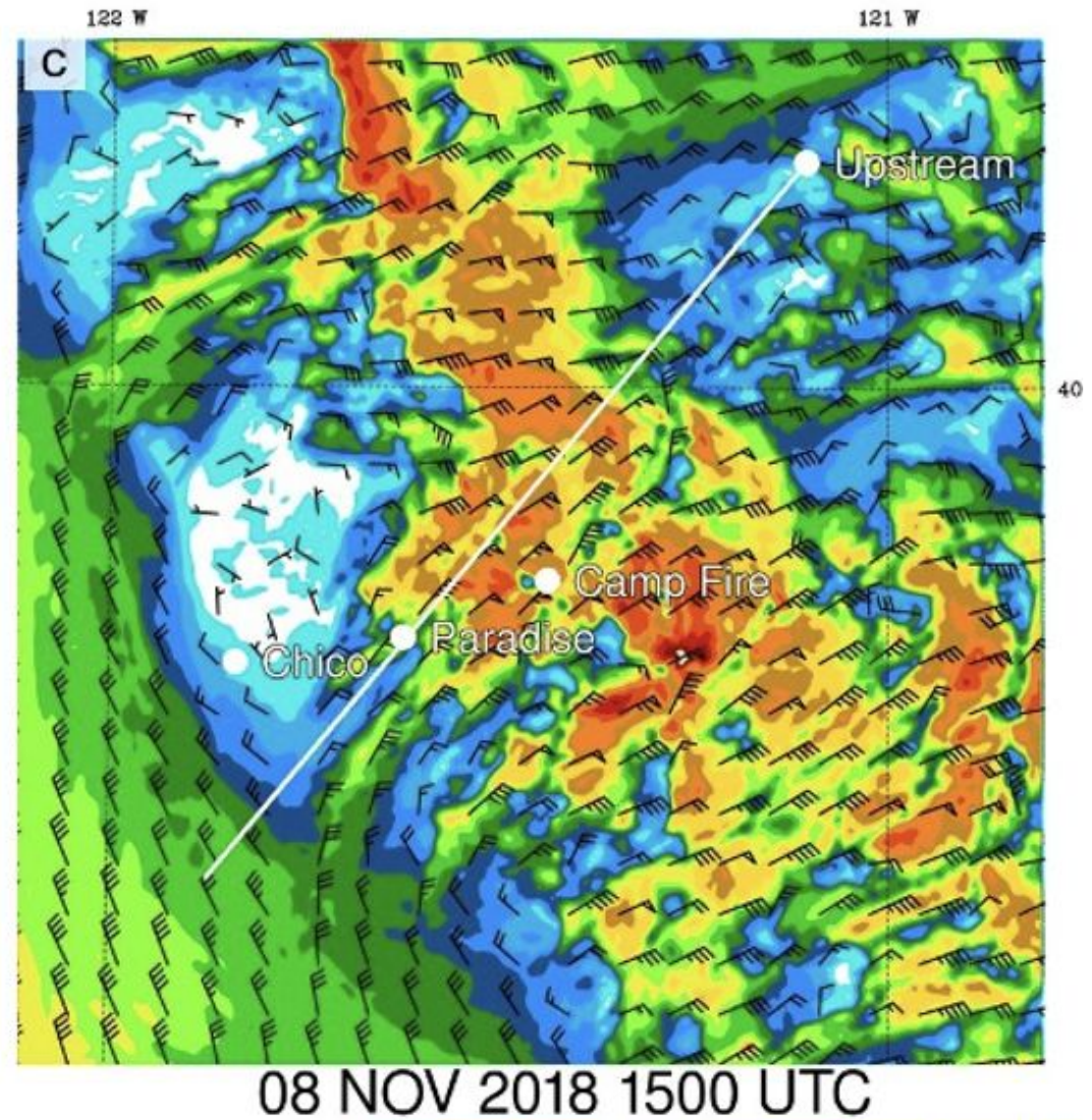


**The
Meteorology
of the Camp
Fire**

Camp Fire Location



Near Perfect Forecasts of the Event



Looking into the Future



The NWP modeling community has **not** caught up with the improved global analyses and data assimilation made possible by the RO community and others.

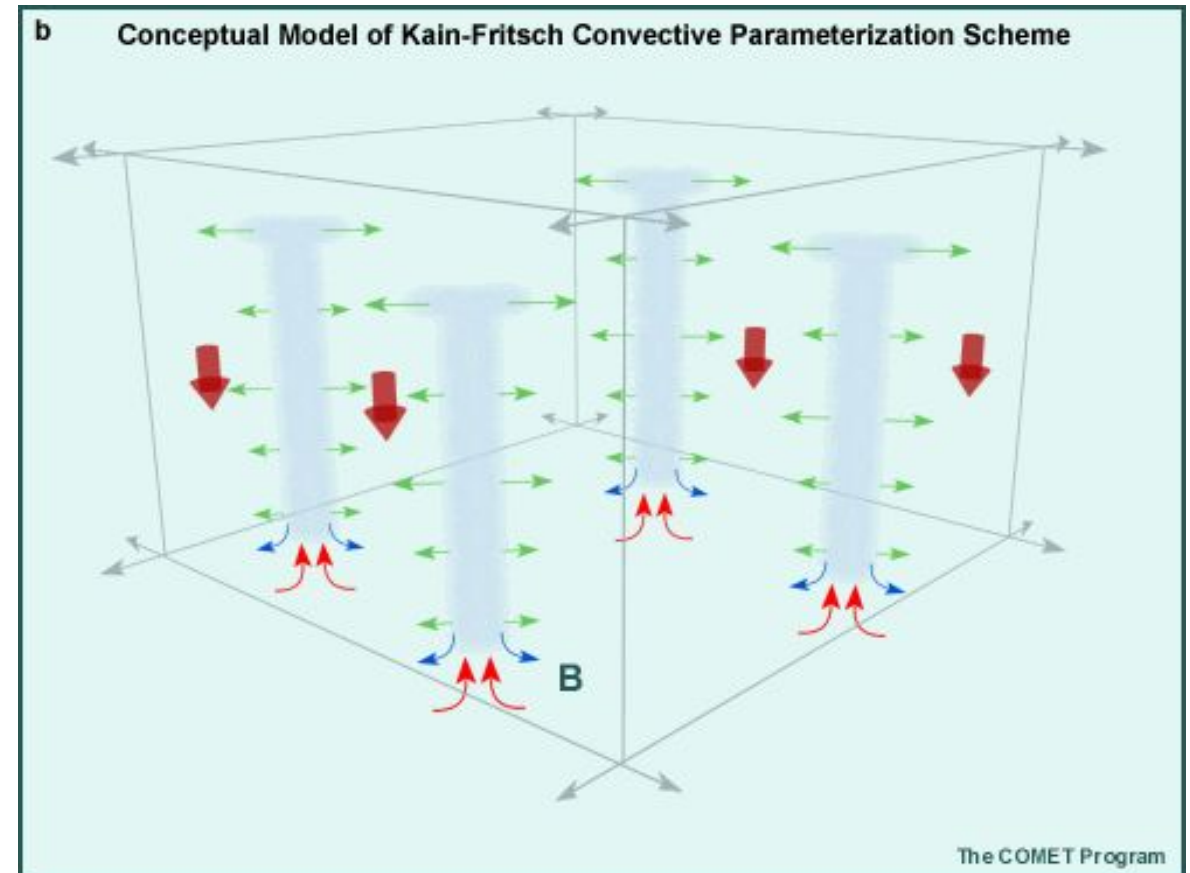


Why are modelers behind you?



One Reason: Most global models parameterize convection

- Convective parameterizations are **all** problematic and inadequate
- There is **extensive evidence** that convective-allowing resolution in global models, with convection simulated explicitly, is MUCH more skillful.



Convection Permitting Global Prediction: Evaluation for Operational Application

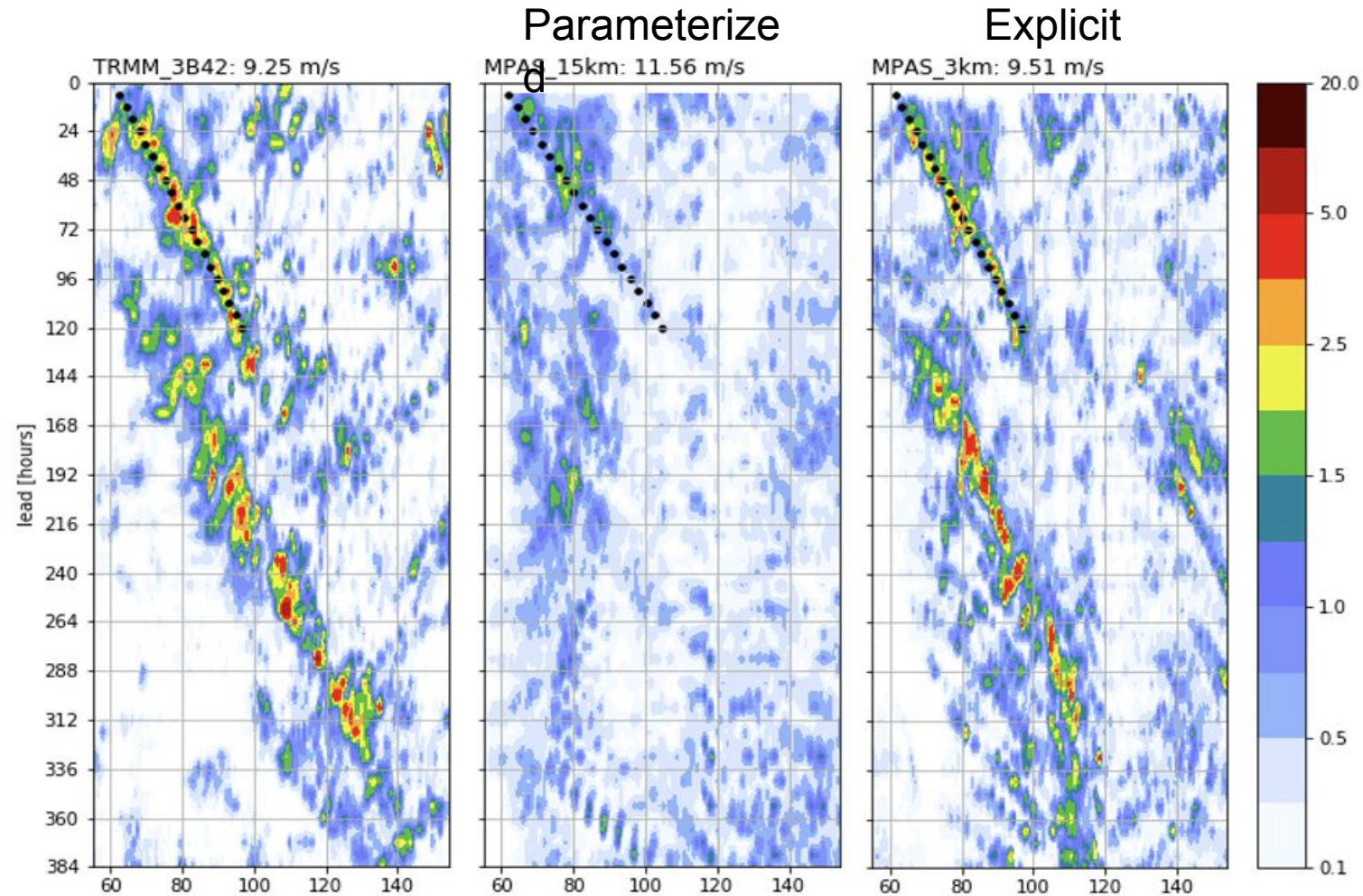
Cliff Mass

Nick Weber

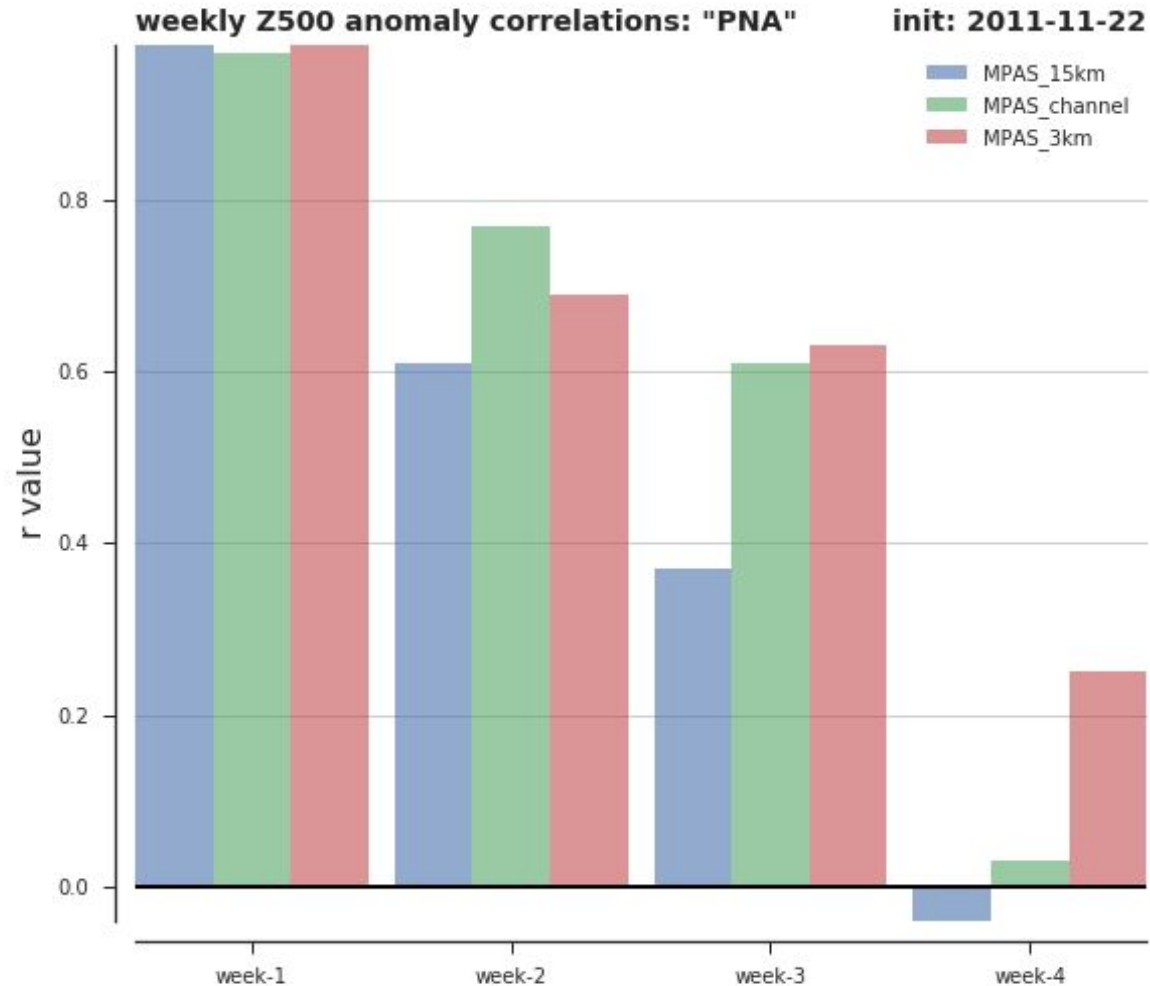
**One-month global forecasts
at 3-km grid spacing (MPAS)**



Major Improvements in Tropical Convective Wave Propagation (MJO propagation)



Major Increases in Week 3-4 Forecast Skill With Explicit Conversion



**Only a matter of time before
all global NWP models are
run at convection-allowing
resolution with explicitly
modeled convection**

**Forecast skill will increase,
with better use of the
potential of satellite-based
data**



But there is something else.....

More proof that current models are not taking advantage of all the potential skill in current analyses/initializations



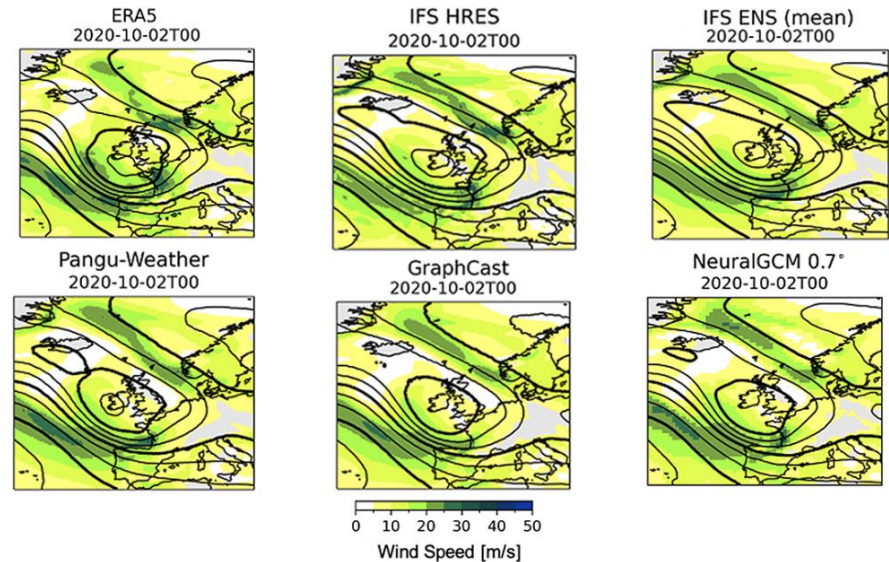
The Implications of Machine Learning NWP

Machine Learning Masters Weather Prediction

Community datasets and evaluation standards are needed to further advance machine learning for weather prediction.

By Hannah Christensen

10 July 2024

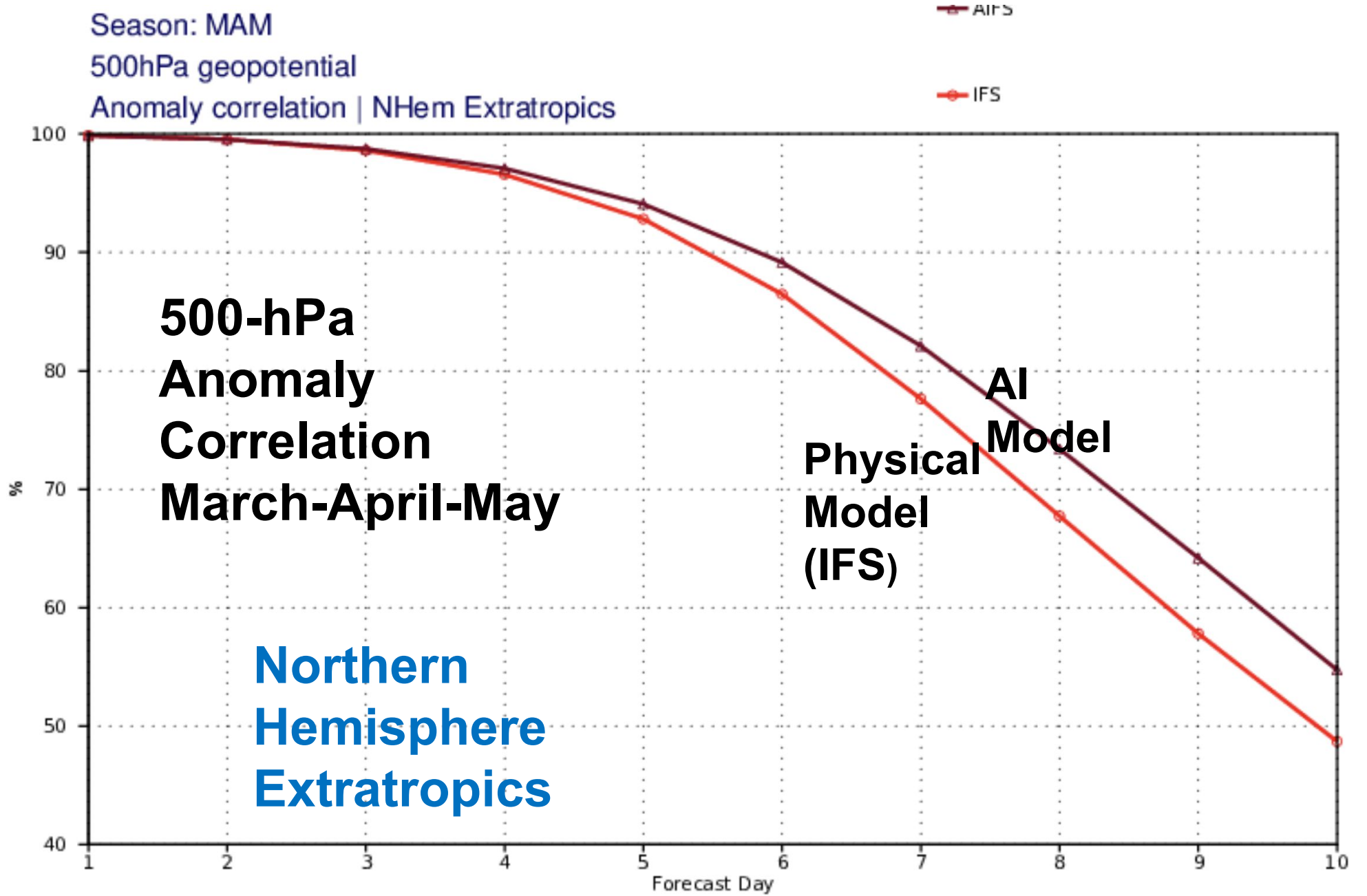


Machine Learning Appears to be More Skillful than Traditional Global NWP Models

Implications:

- There is a a lot more skill that be squeezed out of our current initial conditions!
- Today's physical global models have deficiencies that have prevented them from deriving maximum skill from improved descriptions of the initial state

EC



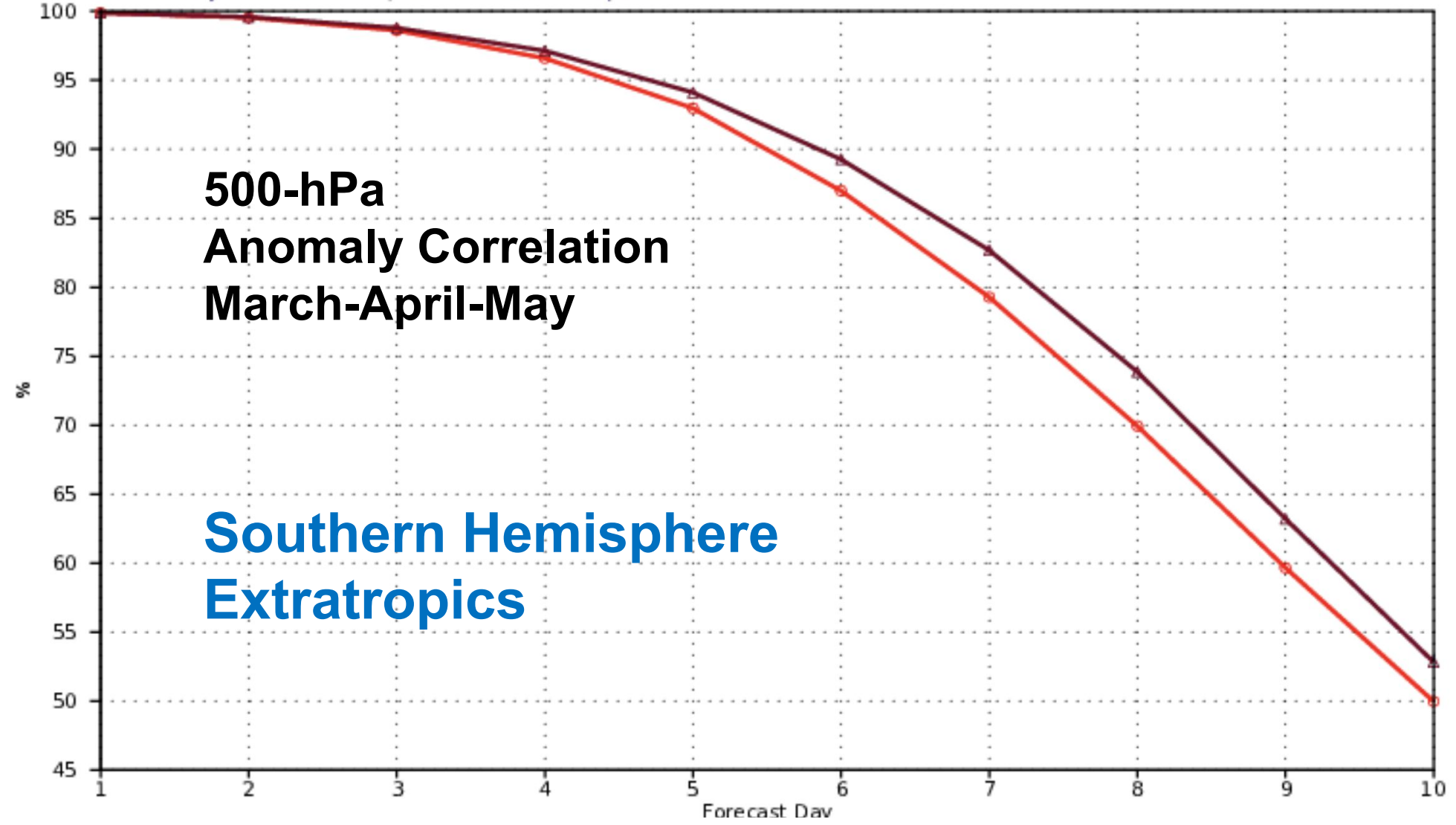
Season: MAM

500hPa geopotential

Anomaly correlation | SHem Extratropics

IFS

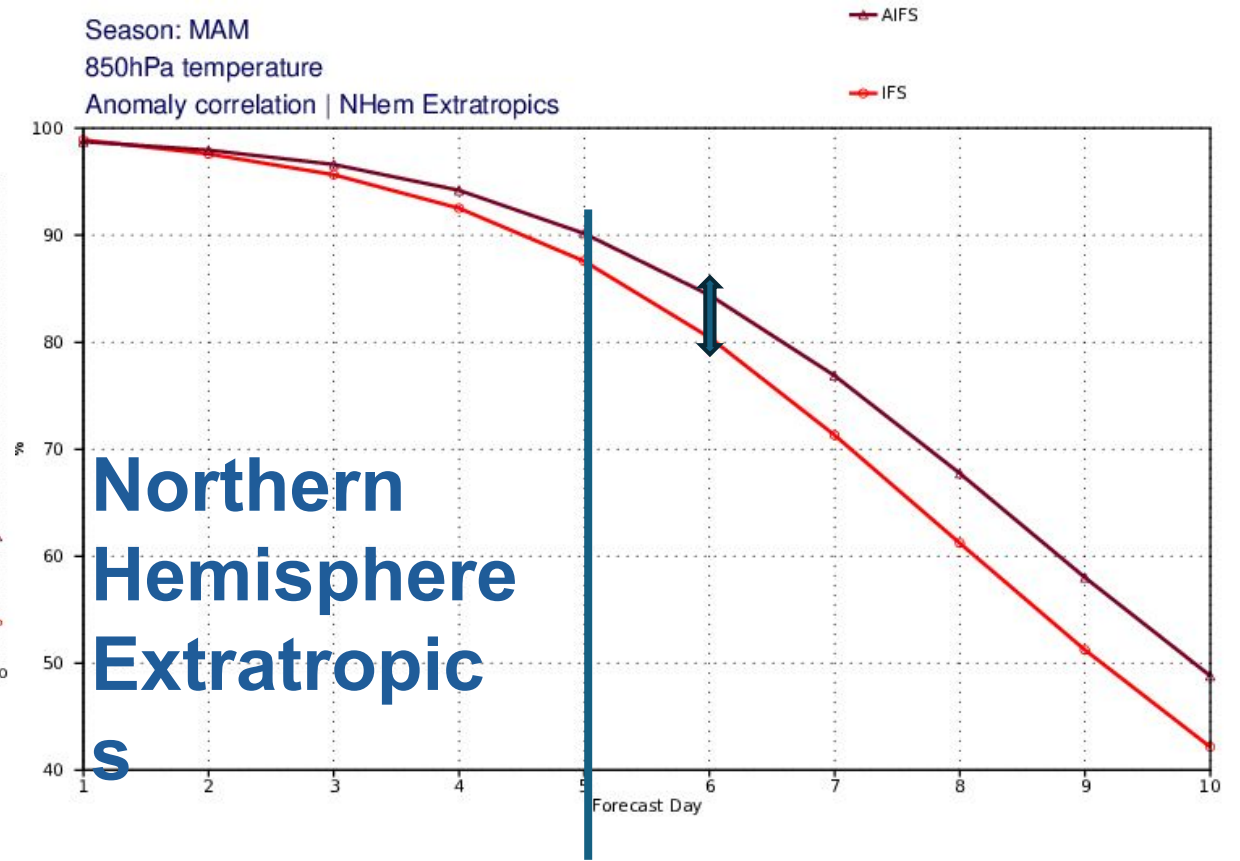
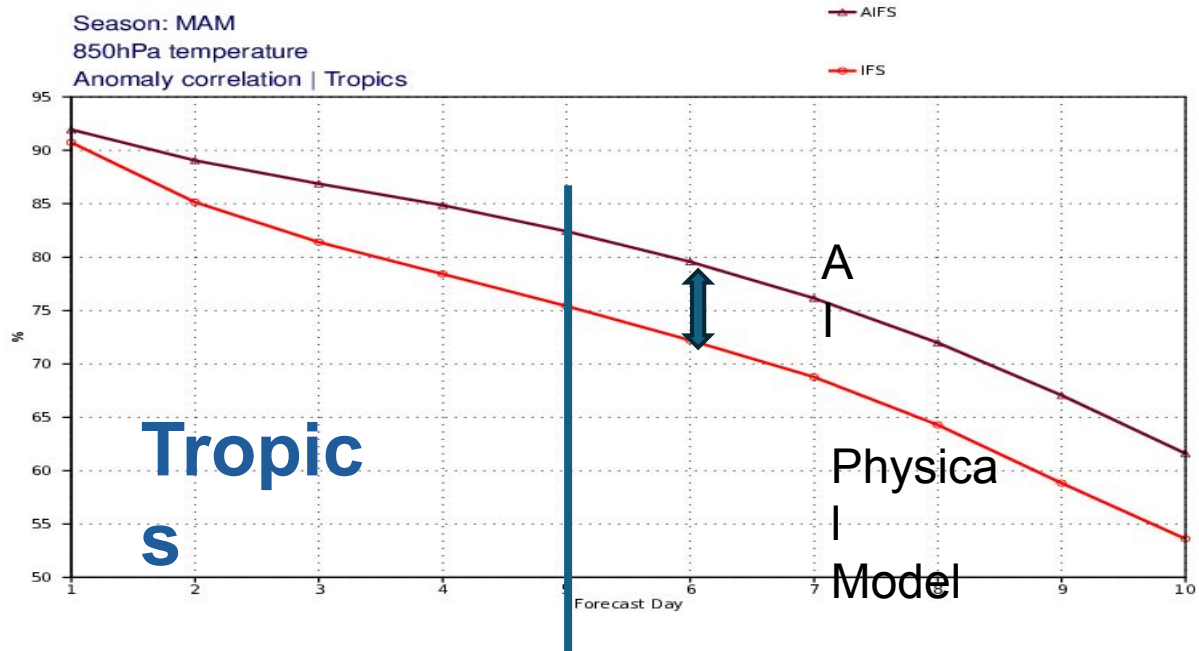
IFS



**500-hPa
Anomaly Correlation
March-April-May**

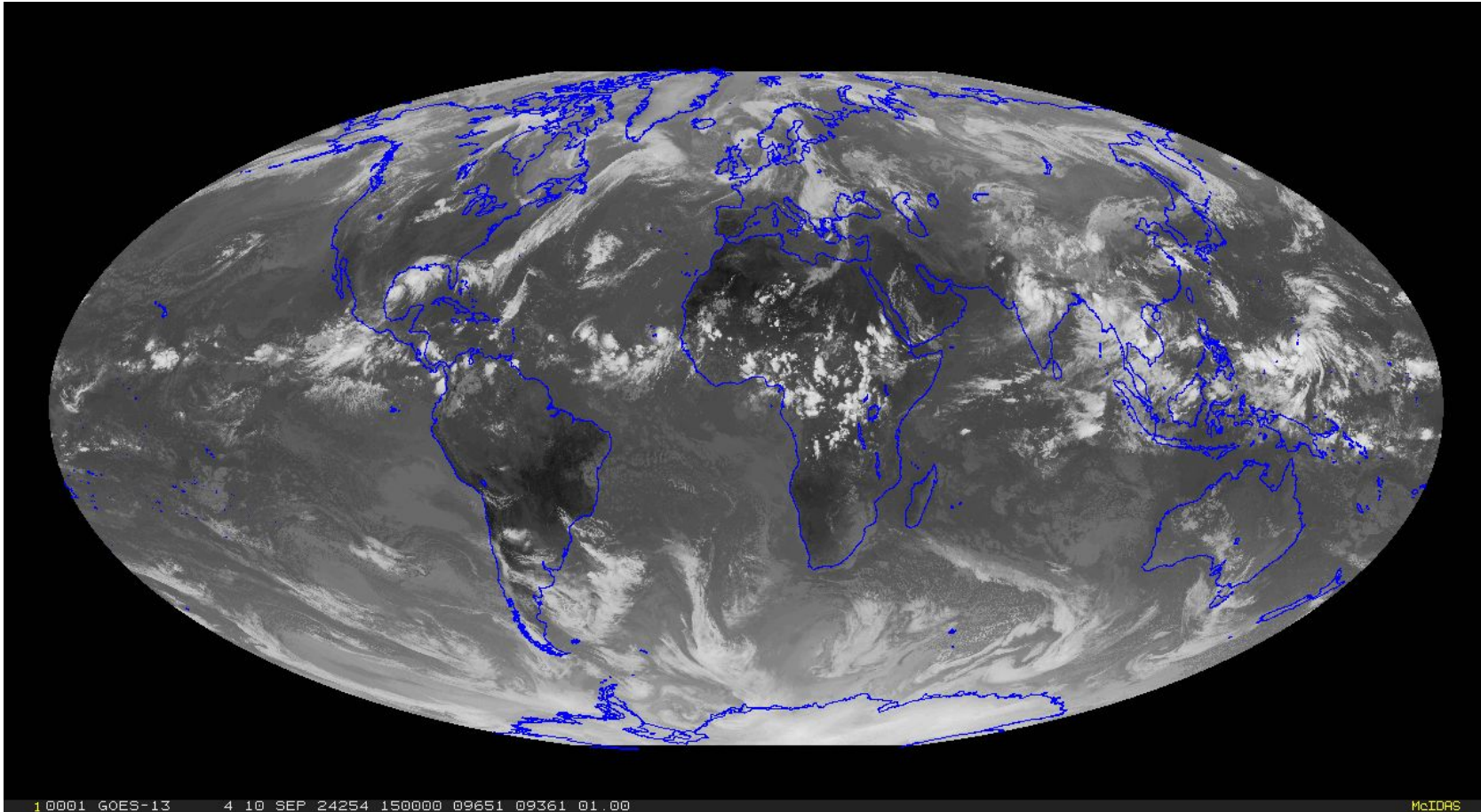
**Southern Hemisphere
Extratropics**

The Tropics Versus Northern Hemisphere: 850 hPa temperature



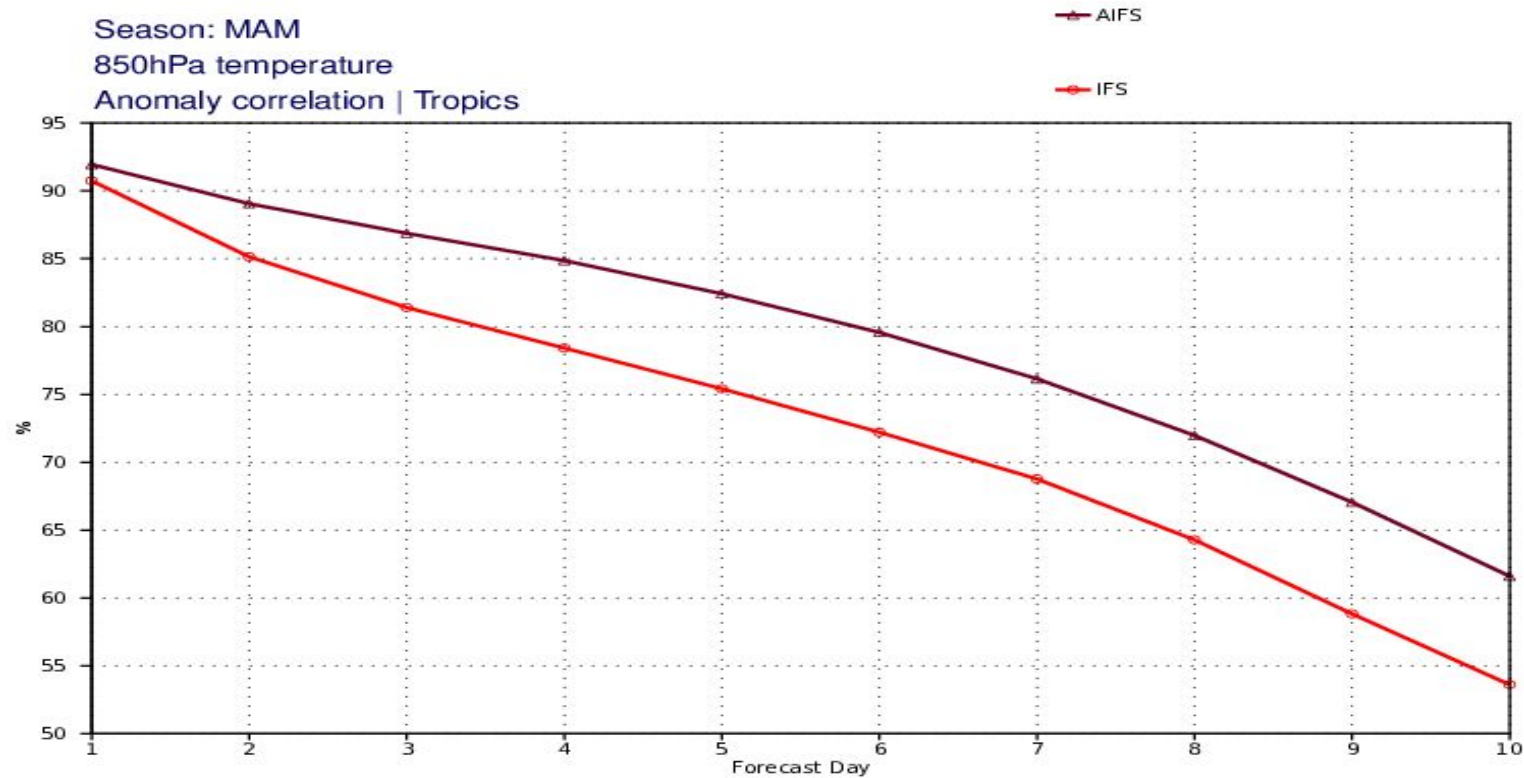
AI NWP is relatively far more skillful in tropics compared to traditional models.

Could this be true because convection is far more important in the tropics?



Possible implication: AI is doing better with the aggregate effects of convection

Tropics

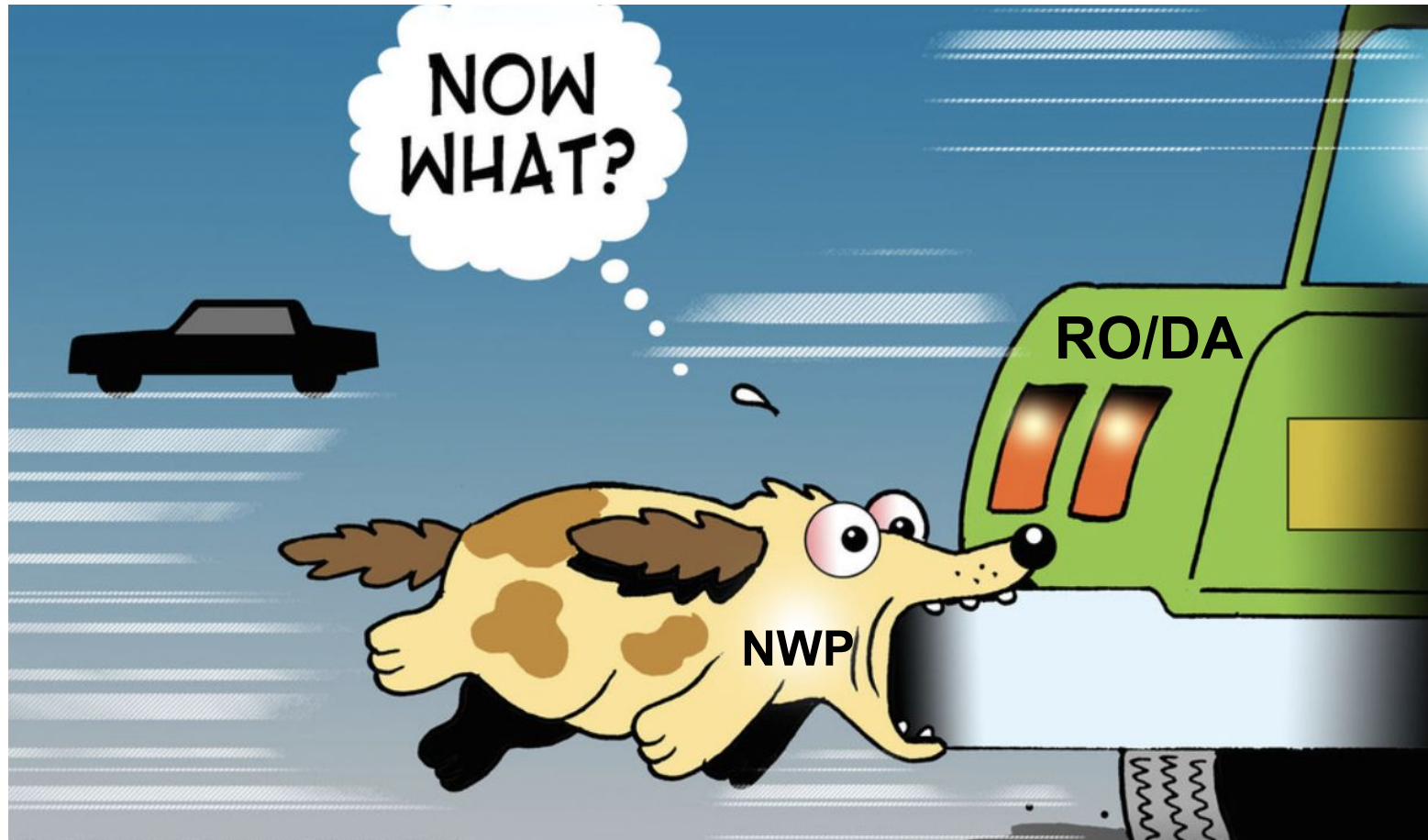


Important Point

Either convection-allowing global physical models or AI models will allow global NWP to make better use of the improved initial state that the RO and satellite community are providing

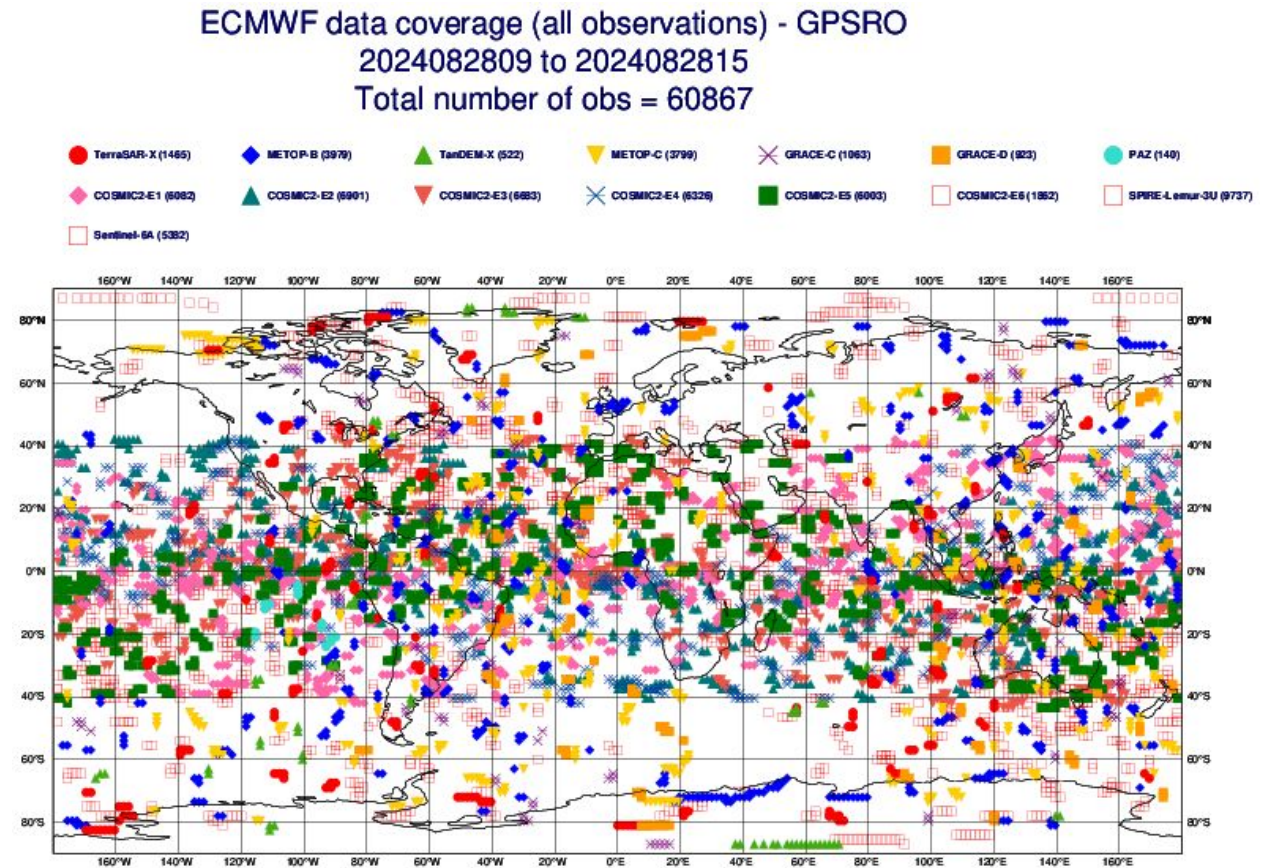
There is substantial room for improvement

Eventually, the modeling community will catch up to you....so the RO and DA communities need to keep ahead



One final note

- Current AI NWP is trained on analyses, such as ERA-5
- If observations are dense enough from RO and other satellite sensors, could AI-NWP be trained directly on observations or gridded versions of observations?



Summary

- **Increased satellite assets, such as RO, have led to a rapid increase in large-scale forecast skill in NWP during approximately 1995-2008, followed by a subsequent leveling off**
- **Mesoscale forecasting skill continued to increase rapidly due to increasing resolution and improved physics.**
- **Operational NWP has not not caught up to the potential of current global analyses.**
- **Convection-allowing global modeling and AI NWP are two approaches to “catch up” and greatly improve forecast skill.**



“NOW THIS IS NOT THE
END. IT IS NOT EVEN
THE BEGINNING OF
THE END. BUT IT IS,
PERHAPS, THE END OF
THE BEGINNING.”

Winston Churchill