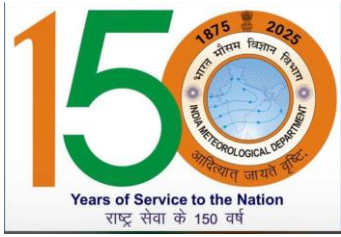
Future Technologies for Weather and Climate Services: Advanced Earth System Modeling and Emerging trends in Data Driven Models

NATIONAL WEATHER SERVICE

Brian Gross, Director, Environmental Modeling Center, NOAA/NWS/NCEP

Celebration of IMD@150: Past, Present and Future, January 15, 2024

Huge Congratulations to India Meteorological Department



- 150 years of unparalleled service
- Successful collaborations between NOAA and IMD/MOES for more than three decades

- 30+ years of GFS and GDAS
- 20+ years of CFS & GEFS
- 10+ years of HWRF/HyCOM/WaveWatchIII

Monsoon Desk at NCEP: Established in 2010

New U.S. - India 'Monsoon Agreement' to Improve Global Seasonal Climate Forecasts

President Obama and India's Prime Minister Singh will enter into a new collaborative agreement between NOAA and the India Ministry of Earth Sciences that aims to improve India's monsoon forecasts. The agreement is part of a series of food security agreements formalized this week during the president's visit.

Under the agreement, the U.S. will create a monsoon forecast desk at the National Centers for Environmental Prediction, part of NOAA's National Weather Service in Camp Springs, Md. Visiting atmospheric scientists from India's Ministry of Earth Sciences will collaborate with NOAA scientists to share knowledge and skills to improve the Climate Forecast System (CFS) for long-range forecasts of the monsoon.

Source: NOAA

U.S., India Join to Improve Monsoon Forecasts

OurAmazingPlanet Staff | November 11, 2010 06:28pm ET

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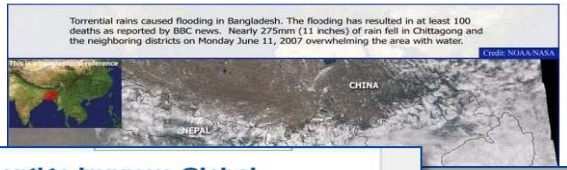

The United States and India are teaming up to improve India's forecasts of th intense rainy season that strikes every year, the U.S. National Oceanic and Atmospheric Administration (NOAA) announced yesterday (Nov. 11).

To improve monsoon forecasts, President Barack Obama and Indian Prime Minister Manmohan Singh will join forces between NOAA and the Indian Ministry of Earth Sciences. The agreement is part of a series of food security agreements formalized this week during the president's visit.

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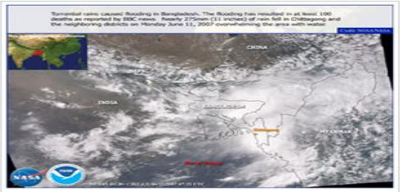
Media Contact
Susan Buchanan
301-713-0622

New U.S. - India 'Monsoon Agreement' to Improve Global Seasonal Climate Forecasts

November 10, 2010

President Obama and India's Prime Minister Singh will enter into a new collaborative agreement between NOAA and the India Ministry of Earth Sciences that aims to improve India's monsoon forecasts. The agreement is part of a series of food security agreements formalized this week during the president's visit.

India experiences monsoon weather, typically resulting in six months of rain beginning in early June. But it is difficult to predict when the monsoon will begin, how strong it will be or when it will end – information that can help plan for seasonal crops and project surface water supplies. In addition to the regional impacts, the



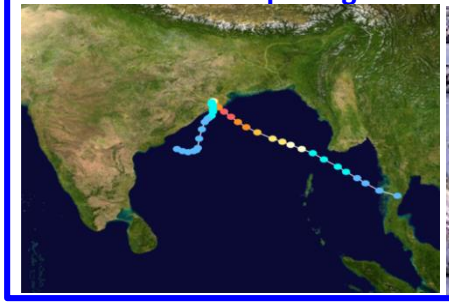
- **Monsoon Desk IA Extended for five more years (2024-2028)**

Advancing Operational Tropical Cyclone Forecasts for the North Indian Ocean Region

A Success Story Demonstrated through Better Preparedness and Reduced Loss of Life for Tropical Cyclone Phailin (2013)

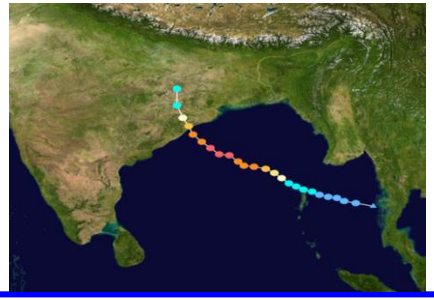
1999 Orissa Cyclone

- Deadliest storm since 1971
- 155 mph winds and 8m (26 ft) storm surge at landfall
- ***10000 casualties, damages ~5 Billion USD***
- Operational NWP at IMD based on 24-hr forecasts from NCEP QLM
- Accurate 48-hr forecast lead time for tracks, no skill for intensity forecasts
- Inadequate guidance on storm surge, rain & flood



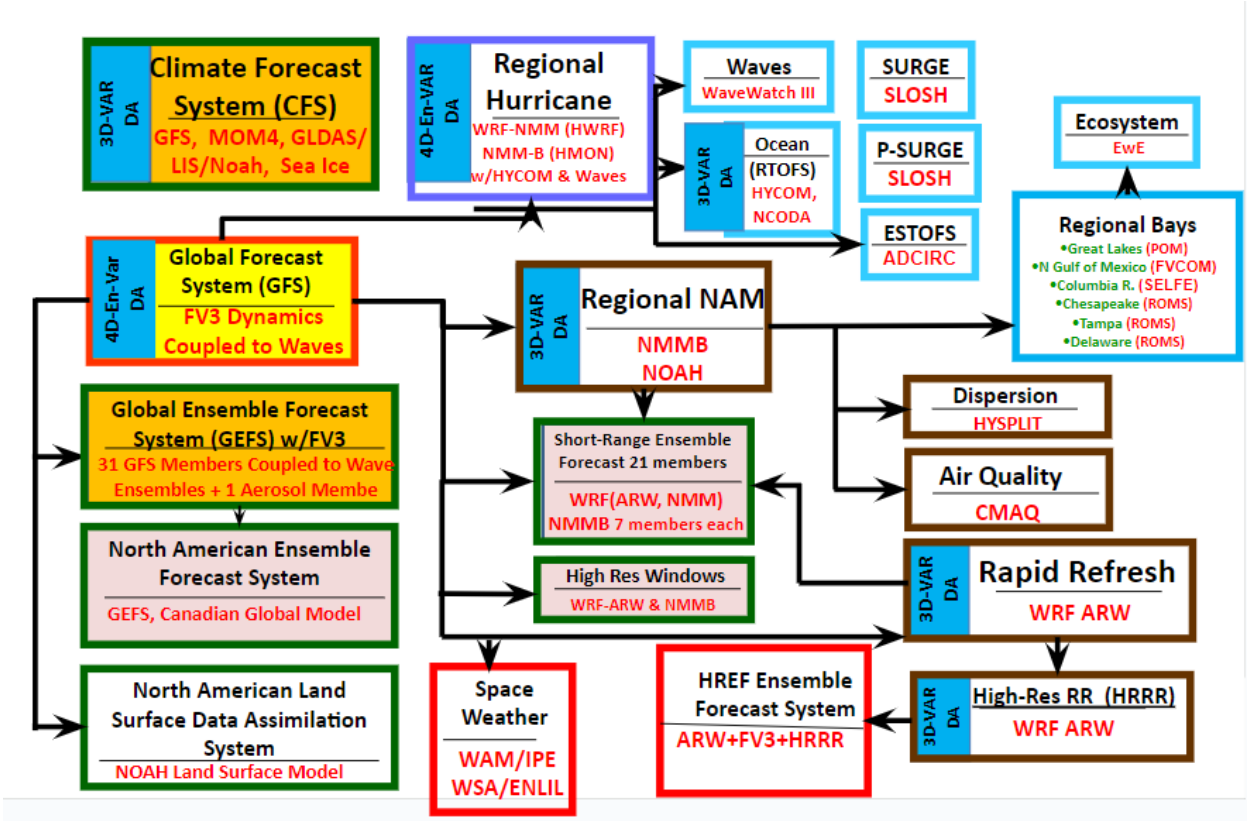
2013 Orissa Cyclone (Phailin)

- Deadliest storm since 1999
- 160 mph peak intensity, 115-30 mph at landfall,
- and 3m (18 ft) storm surge at landfall
- ***36 casualties, damages ~0.7 Billion USD***
- Operational NWP at IMD based on 126-hr forecasts from IMD versions of NCEP GFS and HWRF models
- ***Accurate 96-hr forecast lead time for tracks, intensity, structure, size, landfall time and location, rainfall, flood potential, wave height and storm***

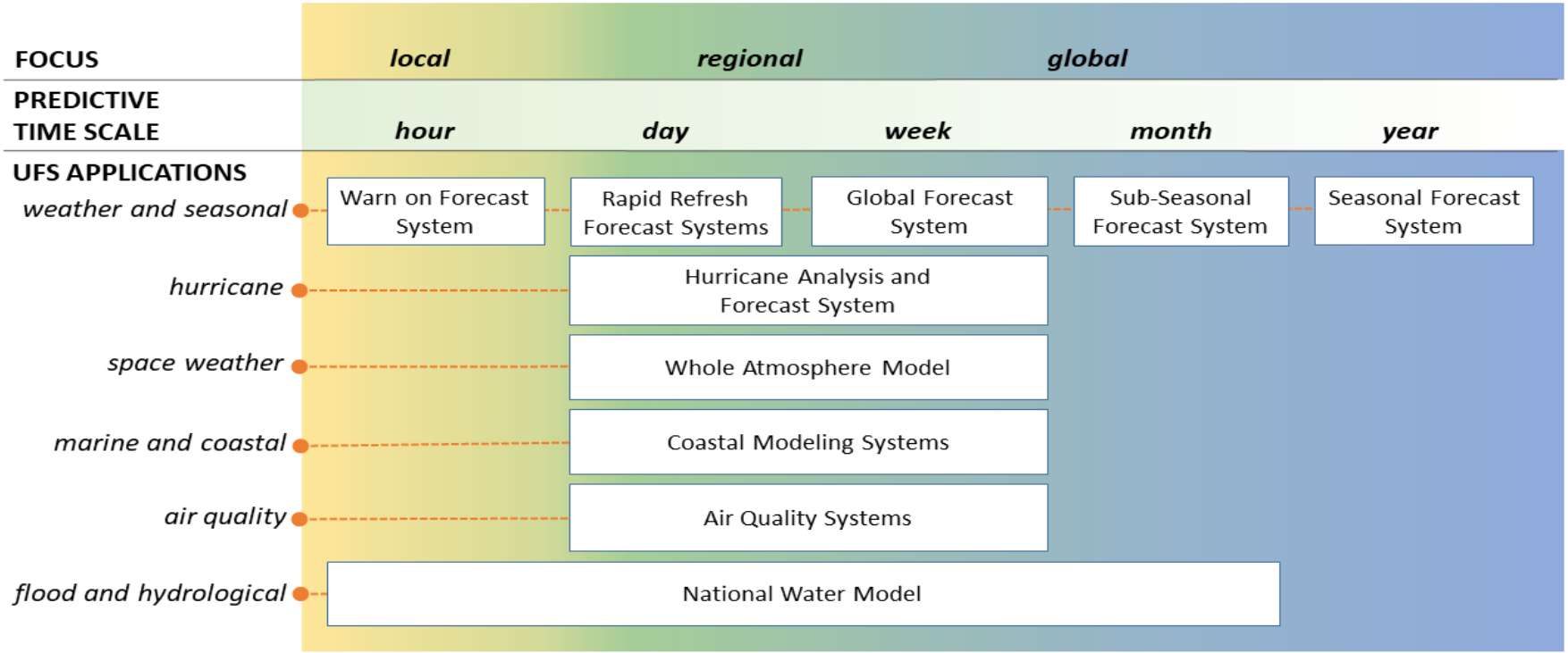


NCEP GFS and the high-resolution HWRF modeling systems have directly contributed towards dissemination of more accurate watches and warnings for Tropical Cyclone Phailin with more than 96-hr lead time

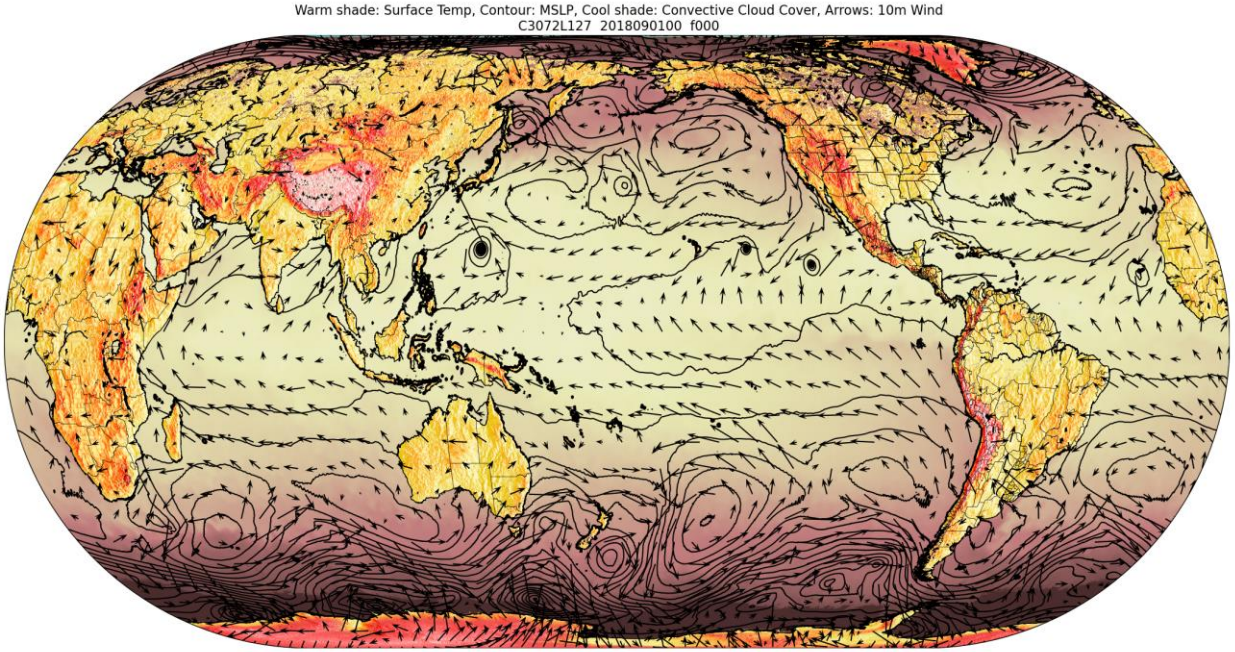
NOAA's Current Production Suite: The "quilt"



NOAA's Goal: Transition to Earth System Modeling for all Operational Applications using the Unified Forecast System



MRW/S2S: Building a Six-Way Global Coupled Unified Forecast System For future GFS, GEFS and SFS



UFS Earth System Model Components:

- FV3 (Atmosphere)
- MOM6 (Ocean)
- CICE6 (Sea Ice)
- WW3 (Waves)
- NOAH-MP (Land)
- GOCART (Aerosols)

A fully coupled UFS serves as a foundation for future operational global forecast systems at NOAA/NWS/NCEP ranging from weather to subseasonal to seasonal scales.

Global Forecast System v17 Upgrade

EMC Implementation Plan FY23-27

	GFSv16 to GFSv17: Target Implementation Mar 2026
Model	FV3/Noah_MP MOM6/CICE6/WW3 (two-way coupling)
Resolution	C786L127 or C1152L127 (13km or 9km, 80km top)
Physics	Thompson MP, CA, UGWD, tuning of convection, surface and PBL physics schemes, MERRA-2 aerosol climatology
Deterministic Forecast (up to 16 days)	GSI, JEDI Ocean/Sea Ice, JEDI Snow 16 days from 00Z, 06Z, 12Z and 18Z
Evaluation	2 year retrospective and real-time runs MEG Group, Field evaluation focusing on hurricane, winter storms, severe weather, extreme temp and prec., sea ice, ocean Evaluation of impacts on downstream models

Global Ensemble Forecast System v13 Upgrade

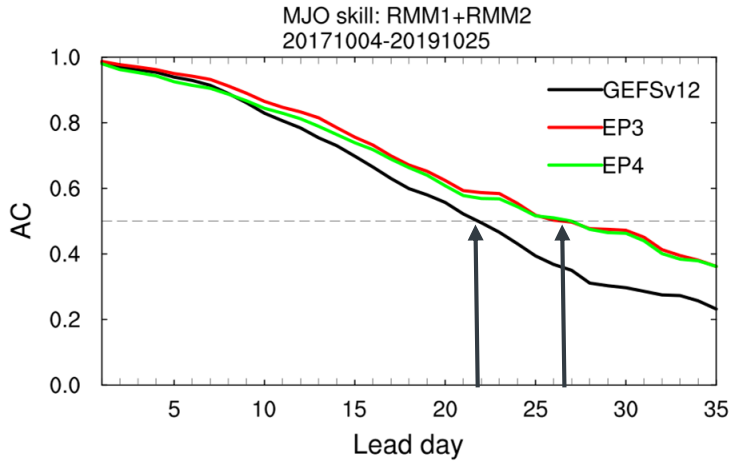
EMC Implementation Plan FY23-27

	GEFSv13: Target Implementation Mar 2026
Model	FV3/Noah_MP MOM6/CICE6/WW3/GOCART (two-way coupling)
Resolution	C384L127 (~25km, 80km top)
Physics	GFSv17 physics + Stochastic physics (SPPT, SKEB, ocean)
Ensemble Forecast - Realtime	GSI, JEDI Ocean/Sea Ice, JEDI Snow 16 days (06Z, 12Z and 18Z), 31 members 48 days (00Z), 31 members
Ensemble Forecast - 31-years Reforecast	Replay to ERA5 Atmos, ORAS5 Ocean/Sea Ice, Noah_MP spin up, snow DA in 1994-2024 16 days, every day, 6 members 48 days, every Monday, Thursday, 11 members
Evaluation	Weather/hurricane/waves: 2.5 year retrospective experiments Subseasonal: 31-year reforecasts

Fully Coupled Global Ensemble Forecast System (GEFSv13)

- 1st fully-coupled global ensemble forecast system including coupling between ATM-LSM-OCN-ICE-CHM-WAV
- Model vertical resolution increase from 64 to 127 layers with a model top of 80km.
- Thompson microphysics scheme replacing GFDL microphysics scheme, NOAH-MP replacing NOAH LSM and other ATM physics updates
- Adding ocean stochastic physics to represent uncertainties from ocean prediction
- Forecast length increases from 35 days to 48 days

Four Ensemble Prototypes (EP1 - EP4) completed, preliminary results are encouraging.



EP3 and EP4 both have higher MJO skill (RMM1+RMM2) than GEFSv12 for longer lead times (extend skill for 4-5 days).

NOAA's Seasonal Forecast System (SFS) to replace CFS

GOALS:

- **Balanced initializations across interfaces**
- **Minimize systematic drift from initial conditions**
- **Best estimation of uncertainties in ensemble forecasts**
- **Reduce systematic biases and improve forecast skill**
- **SFS infrastructure should provide critical support**

SFS will be:

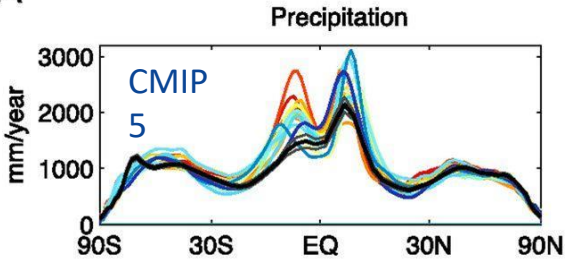
- **Enabled to run in the cloud**
- **Incorporated into UFS repositories**
- **Provided to community through the Earth Prediction Innovation Center (EPIC)**

- Develop SFSv1 as a **replacement** of Climate Forecast System version 2 **(CFSv2)**, a decade-old system
- **Address common errors** in CFSv2 and NMME
  - MJO propagation across Maritime Continent
  - False ENSO alarms
  - Positive SST trend errors in tropical Pacific
  - Too frequent above-normal temperature forecast
  - Too infrequent below-normal temperature forecast

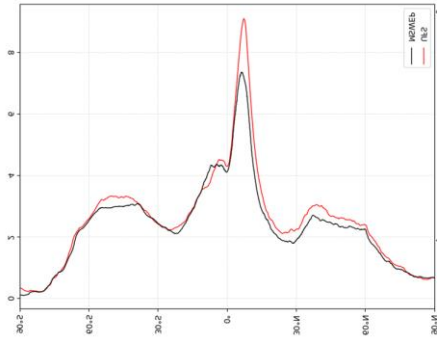
SFSv1 Early Results

No Double ITCZ in UFS climate run

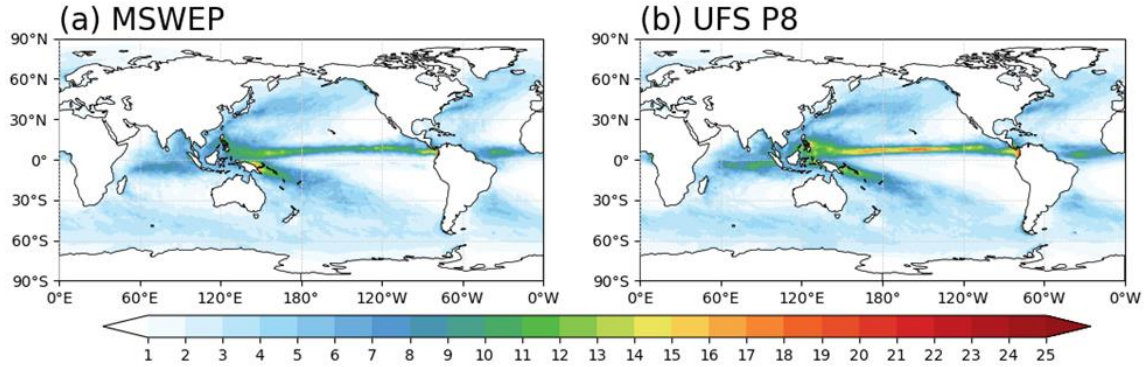
A



[Hwang and Frierson, 2013, PNAS]

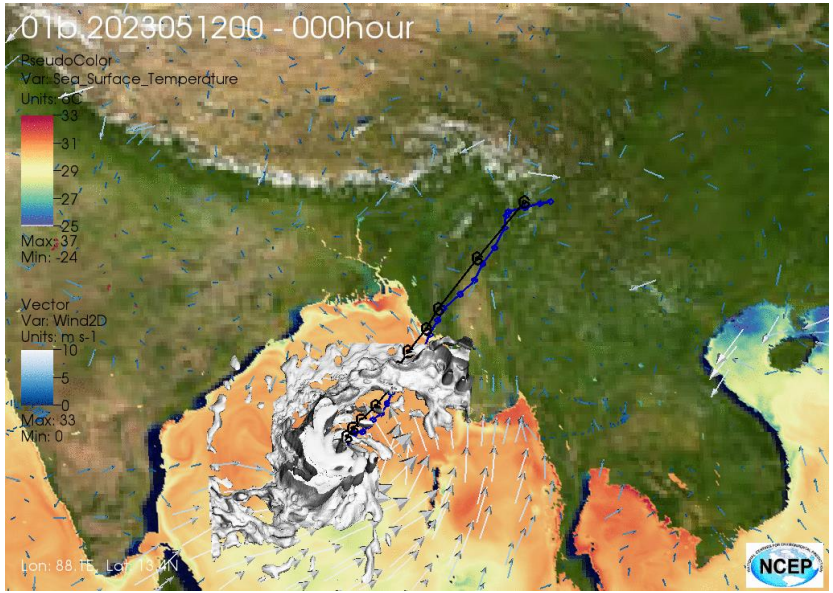


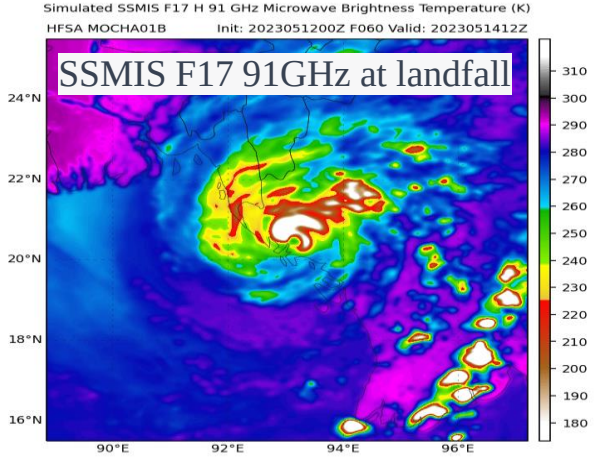
UFS P8 overestimates ITCZ, but doesn't show double ITCZ

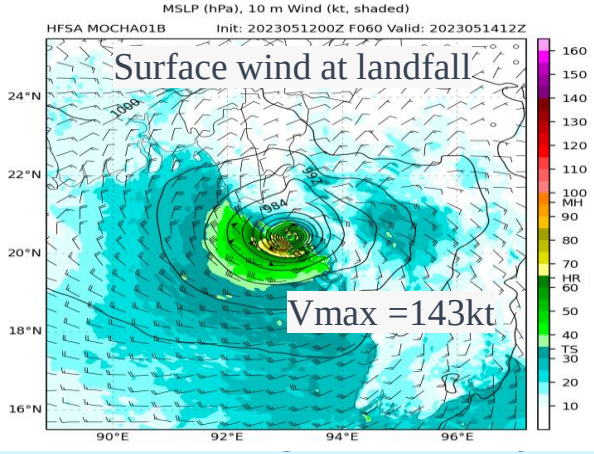


HFSA predicted clouds, SSMIS and surface wind

SST(shaded), wind 10m(vector) and clouds (3D)

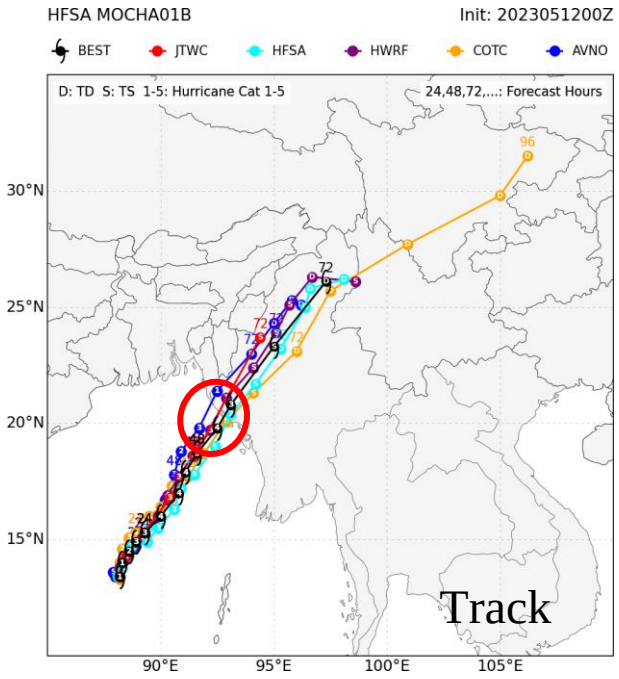


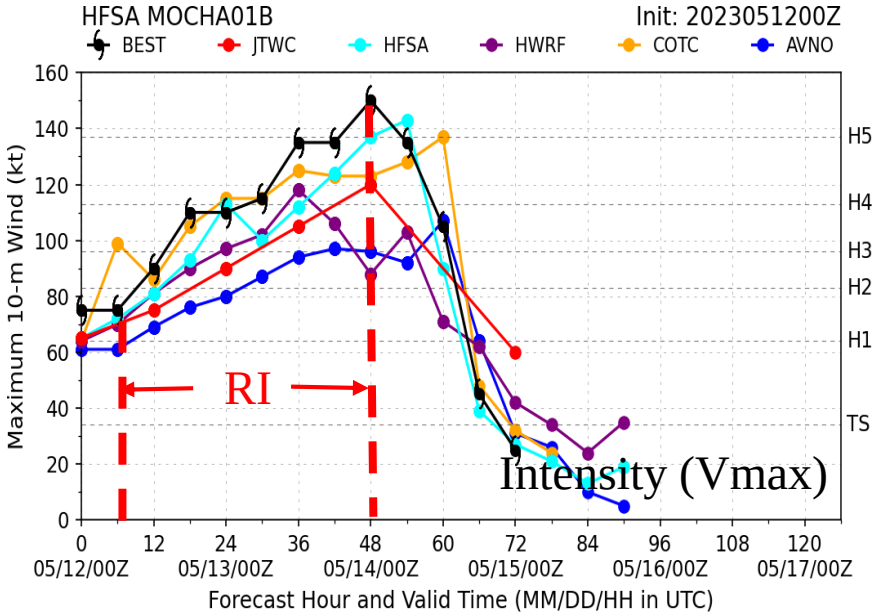




HFSA accurately predicted Mocha's landfall location and Category 5 intensity 60 hours before landfall.

The cycle of Mocha 01B 2023: initialized at 60 hours prior to landfall





HFSA accurately predicted Mocha's landfall location, captured its rapid intensification, and successfully predicted the storm reaching Category 5 intensity.

Joint Effort for Data assimilation Integration

Infrastructure for Unified Data Assimilation

GSI in operations since 2007, but portions of the code are 30+ years old

JEDI is a project within the Joint Center for Satellite Data Assimilation (JCSDA)

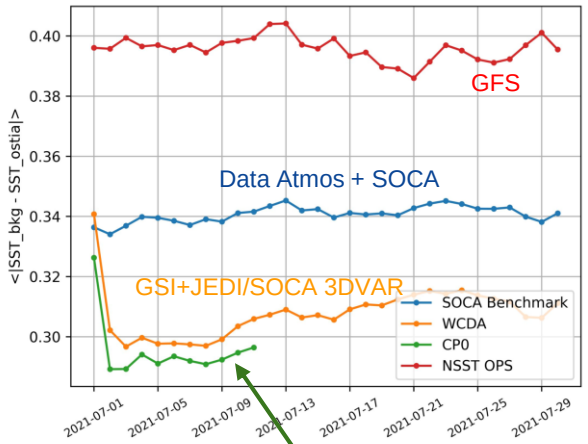
JEDI provides a software infrastructure for DA that:

- is model agnostic (but requires an interface to models!)
- is generic and portable
- does not impose specific methodologies or algorithms
- allows to share efforts (new observation types, etc.) across different orgs.

JEDI will allow us to have one shared codebase for all DA,
from global to regional, and for all Earth-system components

Weakly Coupled Data Assimilation preliminary results: SST

comparison against OSTIA

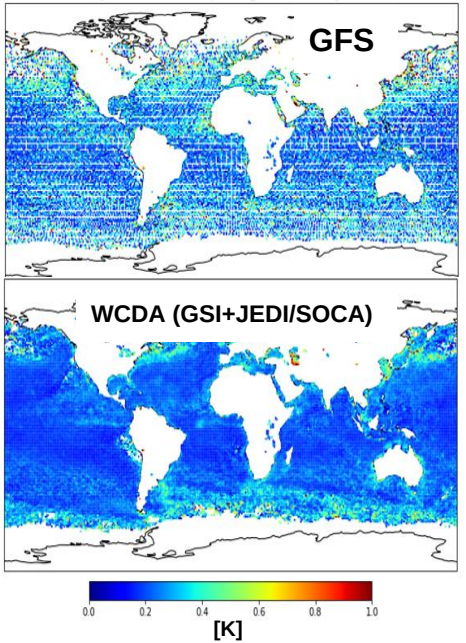


GSI+JEDI/SOCA Hybrid EnVAR

cp0: Status as of 07-11-2023. Ocean & sea ice hybrid EnVAR with 30 offline members

Better estimate of the foundation temperature leads to better simulation of radiances sensitive to SST.

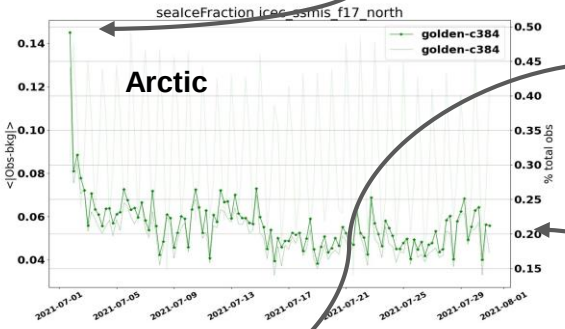
AVHRR NOAA-18, channel 3 <|Obs-Bkg|>

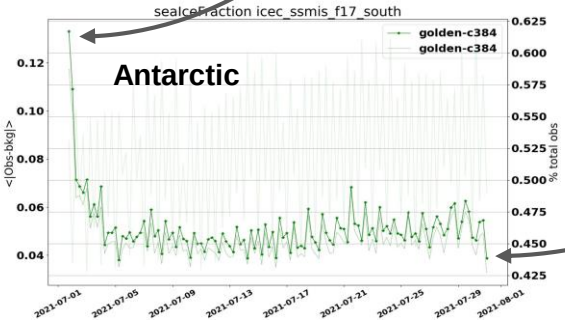


- More obs passed the GSI QC
- Smaller O-B almost everywhere

Weakly Coupled Data Assimilation preliminary results: Sea ice

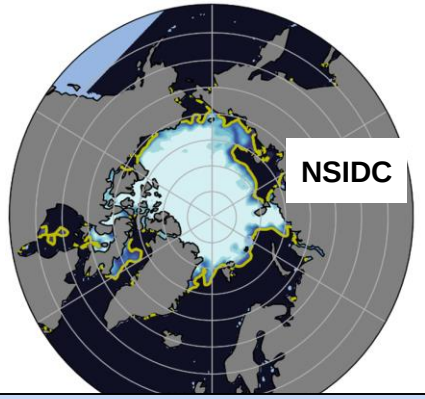
Sea ice concentration OMB statistics



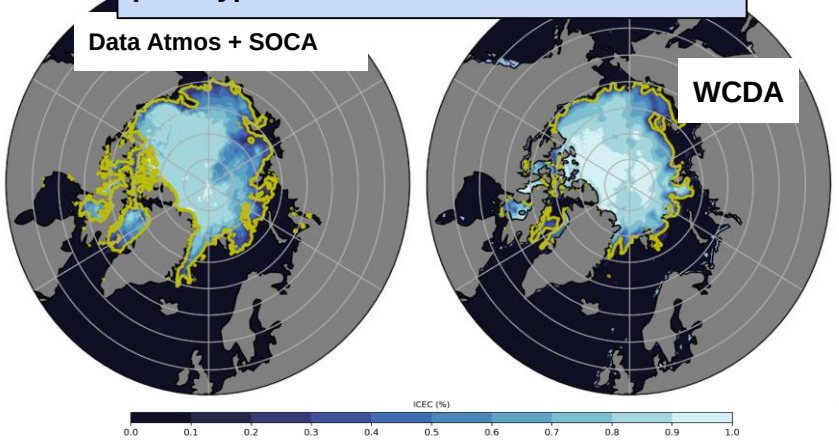


Started from a benchmark SOCA based short reanalysis (~6 months)

Significant error reduction in the WCDA system

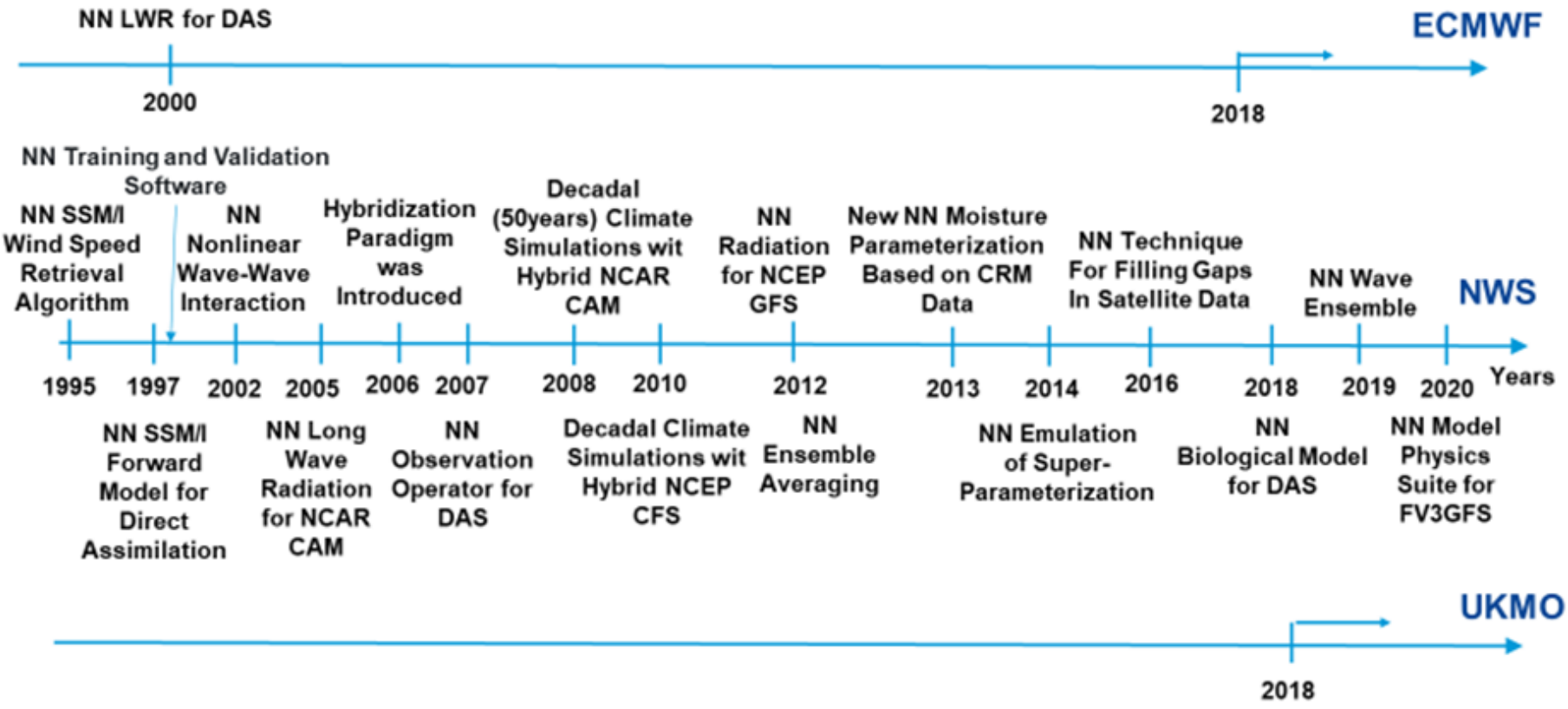


Better sea ice extent in the WCDA prototype



Emerging Trends in Operational Weather and Climate Predictions: Application of AI/ML

EMC Developments in ML for NWP & Climate

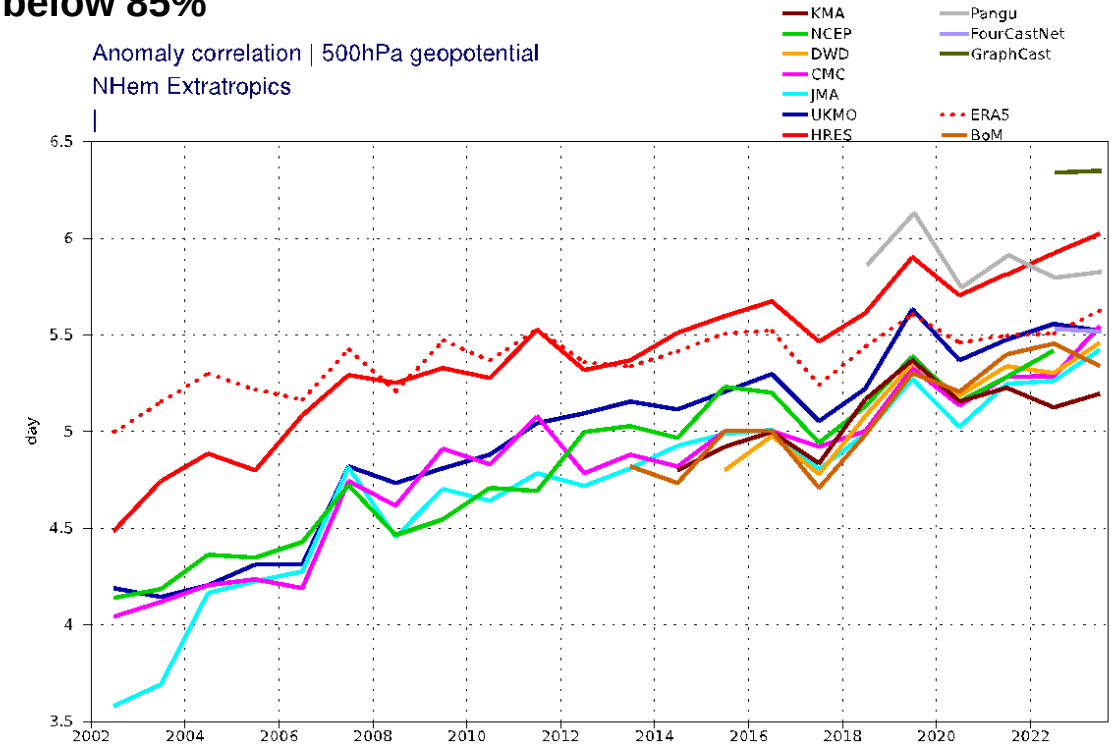


Current/Planned AI/ML Activities at NCEP/EMC

Observations	Data Assimilation	Forecast	Post/Product
Radiosonde processing	Physics emulation	AC Accelerated Transport	Wave Systems
Satellite Thinning	Improved Background	Atmospheric Chemistry Emulator	Air Quality Bias Correction
AMV super-observations and error estimation	Background Error Covariances	Physics Suite Emulation	Sub-Seasonal/ Seasonal forecast products
Conventional / Aircraft quality control	CRTM emissivity modeling	Radiation Parameterizations	
Observation Anomaly Detection	High-resolution background downscaling and emulation	Ensemble Forecasting / Forecast Model Emulation	
	Radiance bias correction	Fire emissions for sub-seasonal to seasonal predictions	

What results are showing
Headline score - 500hPa geopotential

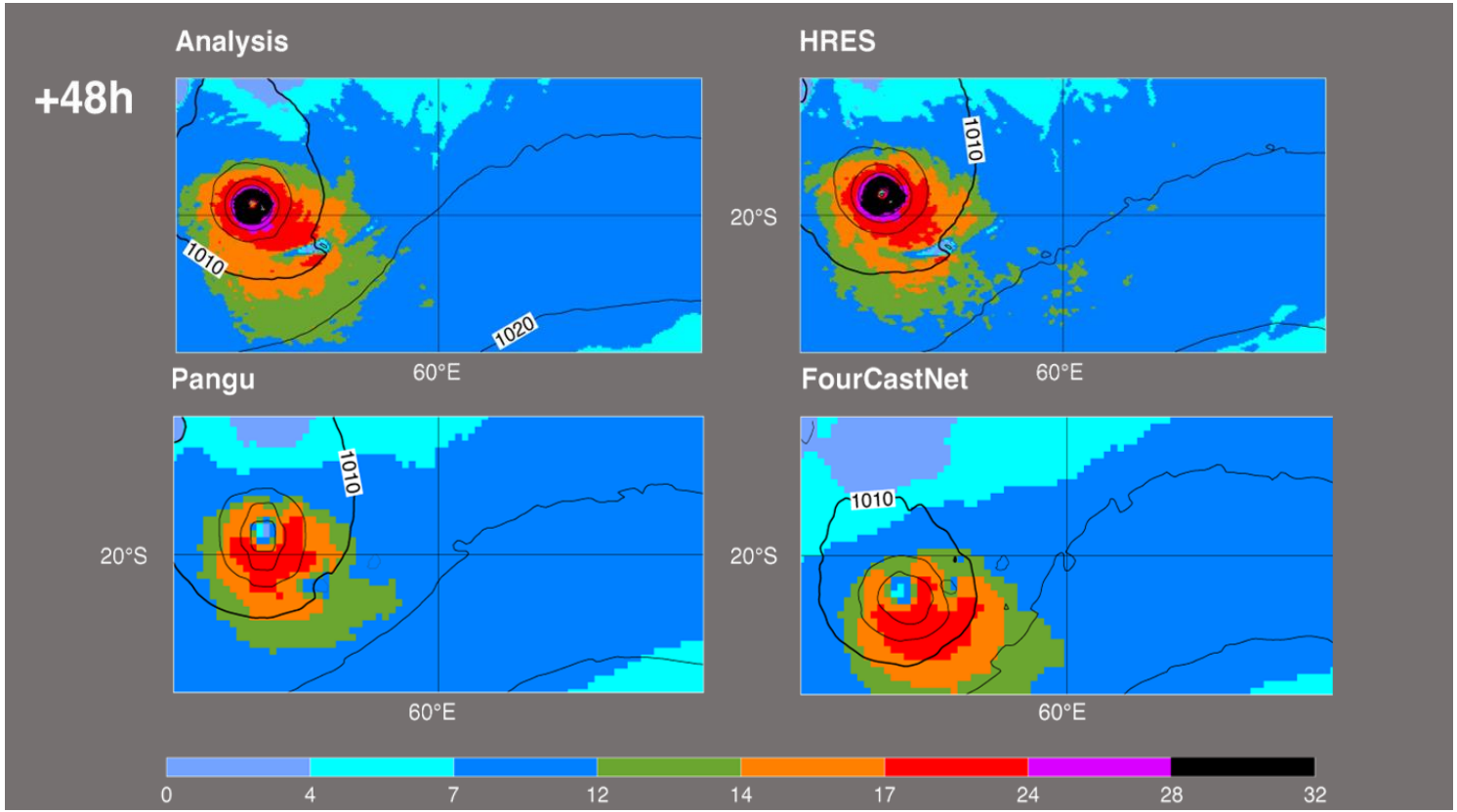
Anomaly correlation of 500hPa geopotential over Northern Hemisphere Extratropics, falling below 85%



ML models (initialised with ECMWF HRES analysis)

What results are showing

Tropical cyclone FREDDY – 18 February 2023, 00UTC



Real Time forecasts using Google deepmind Graphcast ML model emulator

Evaluation results of GraphCast, a high-resolution model presented by *Lam et al., 2023* (0.25 degree resolution, 37 pressure levels), trained on ERA5 data from 1979 to 2017.

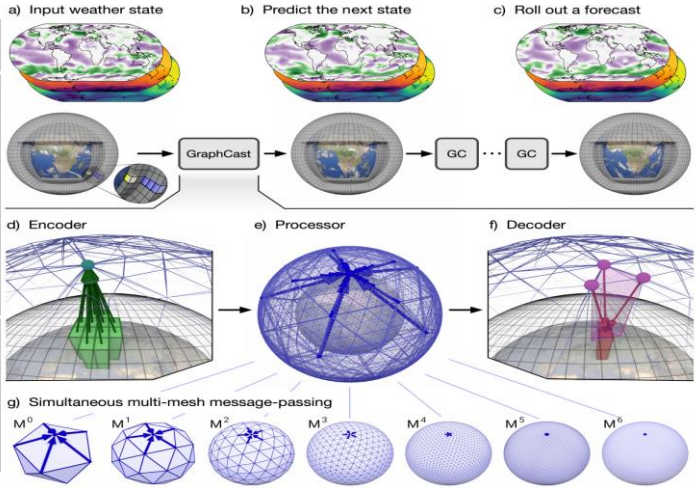
Status:

- Able to run GraphCast with ERA5 data on NOAA cloud

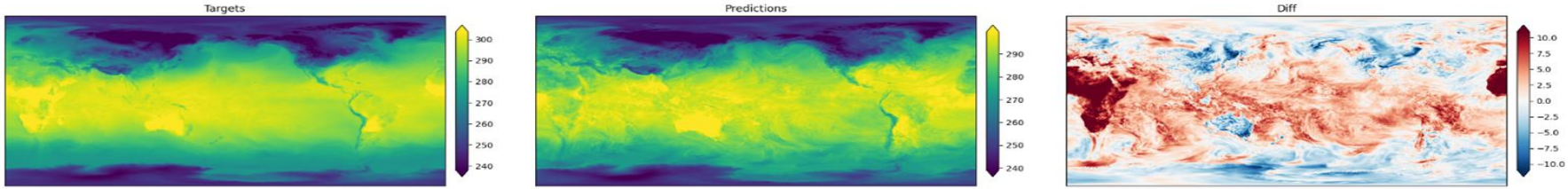
EMC's Plan:

- Run GraphCast in real time with GDAS analysis
- Train GraphCast with GEFSv12 reanalysis and run ensemble forecast.

Variable name	Role (accumulation period, if applicable)
Geopotential	Input/Predicted
Specific humidity	Input/Predicted
Temperature	Input/Predicted
U component of wind	Input/Predicted
V component of wind	Input/Predicted
Vertical velocity	Input/Predicted
2 metre temperature	Input/Predicted
10 metre u wind component	Input/Predicted
10 metre v wind component	Input/Predicted
Mean sea level pressure	Input/Predicted
Total precipitation	Input/Predicted (6h)
TOA incident solar radiation	Input (1h)
Geopotential at surface	Input
Land-sea mask	Input
Latitude	Input
Longitude	Input
Local time of day	Input
Elapsed year progress	Input



2m_temperature, 6:00:00



How AI fits into future operational NWP?

Up till now, improvements in **NWP forecasts** have come from

- Improvements in ***forecast model resolution and physics*** (by increasing compute power and utilizing observations to improve process understanding, translating to better representation in models).
- Improvements in ***observation networks, DA algorithms*** to better initialize the models.

Recent rapid improvements in **AI forecasts** have come from

- Better utilization of ***training datasets*** (reanalyses).
- Better, more efficient ***deep learning methods***.
- Efficient workflows for training that leverage the power of ***GPU***s.

To be addressed

- Prediction of extremes in a nonstationary climate
- Construction of representative ensembles
- Capturing predictability limits

Imagine a World ….

- Operational Production Suite backbone of continuously assimilating comprehensive coupled Earth System Model
  - “Digital Twin” - constant update of global state and innovation of training data
- Regular prediction systems (e.g., 2/day global, hourly CAM) and ad hoc (hurricane, fire, dispersion, etc)
- Variety of approaches - deterministic, ensemble-based, surrogate systems trained on reanalysis and backbone
- Cloud-based systems to accommodate HPC requirements as-needed

Thank you!

Questions?