

# FV3-Powered Research and Developments for DYAMOND in the Era of E-Class HPCs

Xi Chen<sup>1,2</sup>, Shian-Jiann Lin<sup>2</sup>, and the FV3 Team

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Mainz, Germany

<sup>1</sup>Atmospheric Oceanic Sciences, Princeton University, Princeton, NJ USA

<sup>2</sup>NOAA's Geophysical Fluid Dynamics Lab, Princeton, NJ USA



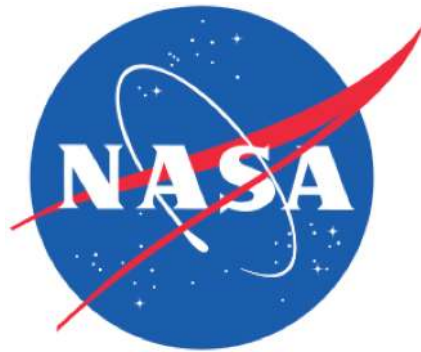
# Main Topics

- What is FV3 and how it works
- Current state of the NWP and FV3
- Beyond software adaptation – Numerics for modern computing architectures
- FV3 in DYAMOND – a bold future of NWP

What is FV3 and how FV3 works



AM/CM/ESM 2/3/4  
HIRAM, fvGFS  
FLOR, HiFLOR, SPEAR

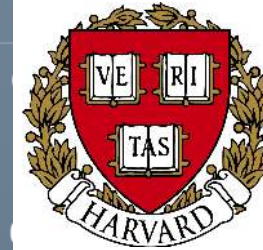


GEOS, DAS, MMF, MERRA(2)  
GISS Model E  
Ames Mars model



Operational  
USA weather  
Forecast  
(12 Jun 2019)

FV3-powered GFS, GEFS, CFS  
FV3-based regional model for HREF and HRRR



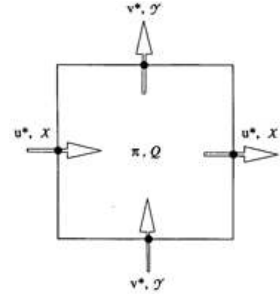
GEOS Chem  
GCHP



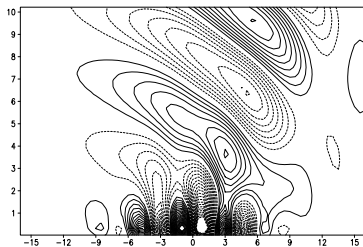
LASG FAMIL

# Why FV3 – key algorithms

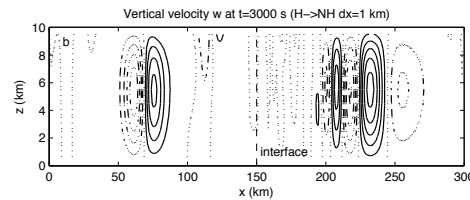
Lin & Rood 1996  
 - Efficient 2D high order FV transport



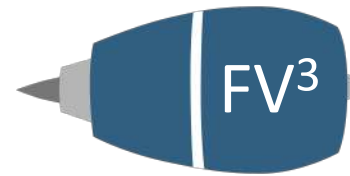
Lin 2004  
 - “Floating” vertical Lagrangian coordinate



FV to FV3  
 - Non-hyd extension

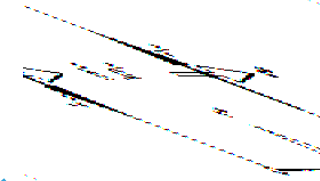


Chen 2013  
 - Consistent/seamless Hyd-nonhyd transport



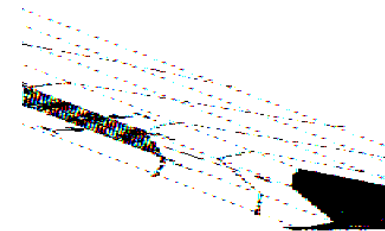
Lin & Rood 1997

- Implicitly making absolute vorticity the first class citizen



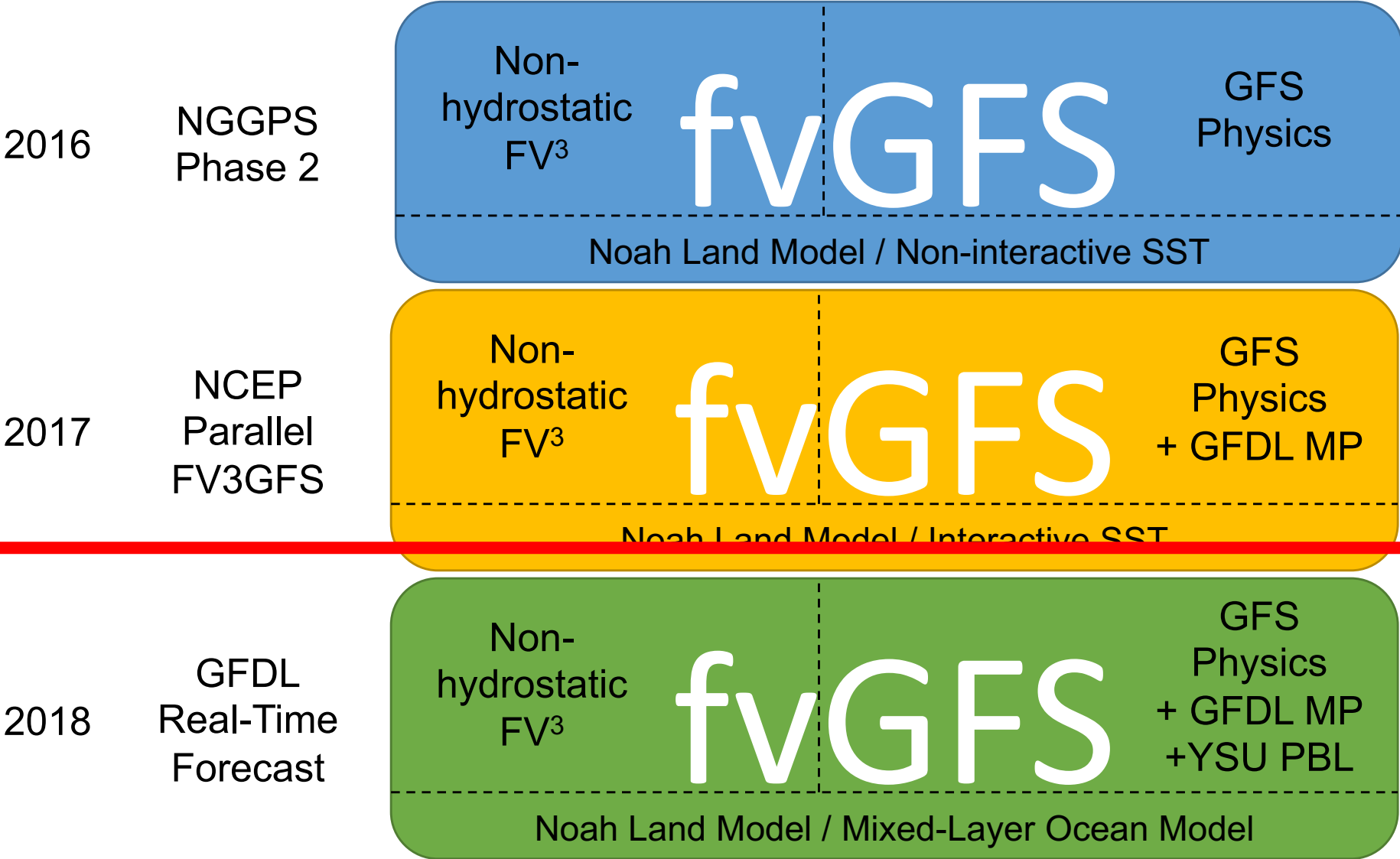
Lin 1997

- Efficient high-order PGF for non-orthogonal shape



FV3’s innovations respect the nature of the atmosphere, and rarely follow the “traditional” thinking

# Next Generation Global Prediction System (NGGPS) – fvGFS



Source: Hazelton et al., 2018ab; Chen et al., 2018; Zhou et al., 2019; Chen et al., 2019ab; Magnusson et al., 2019; Harris et al., 2019

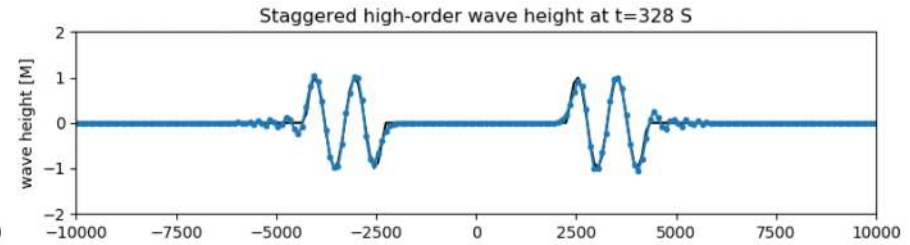
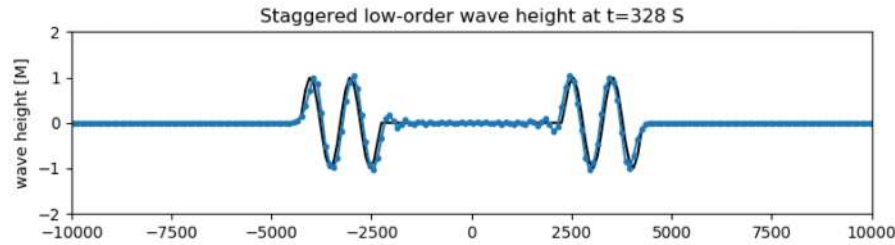
Courtesy to Linjong Zhou

# Dispersion in staggering vs. order of accuracy

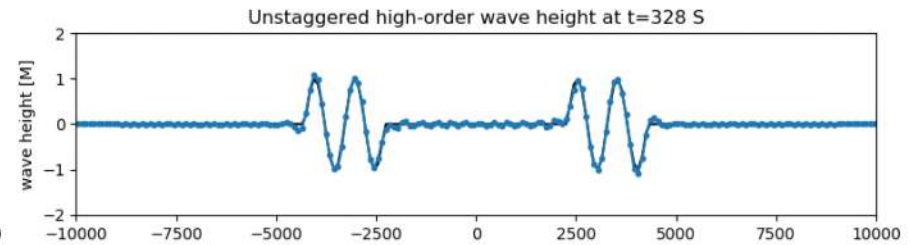
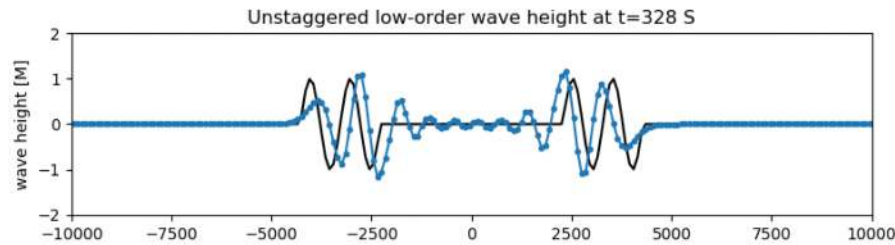
Low-order: staggering matters, diffusion is usually excessive

High-order: staggering effects are comparable, diffusion alters dispersion properties

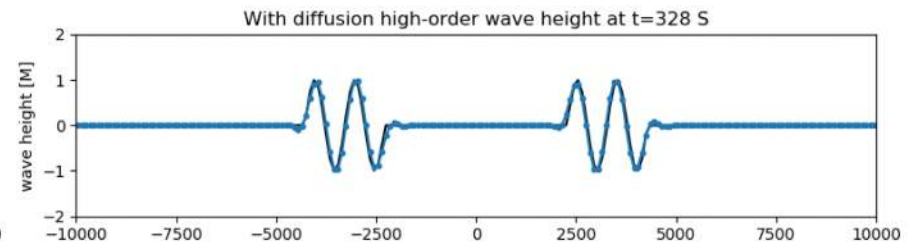
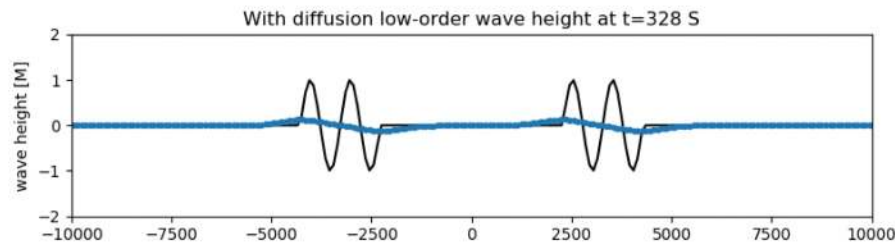
Staggered



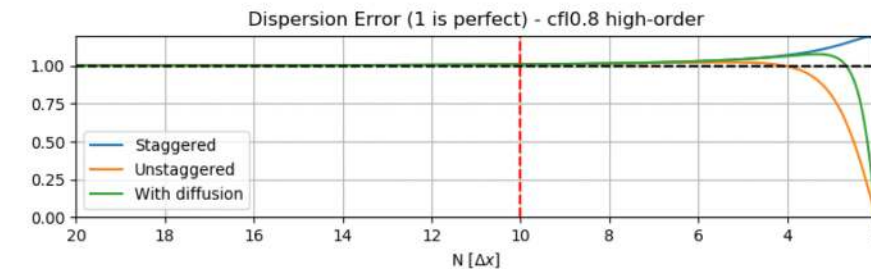
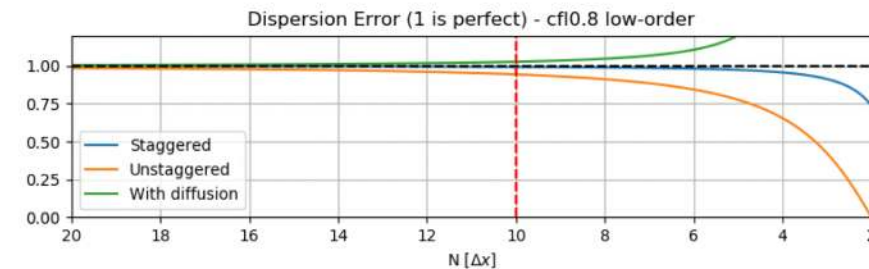
Unstaggered



Unstaggered w/ diffusion



Dispersion errors

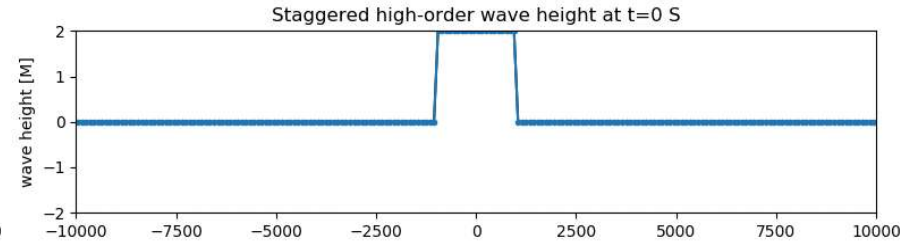
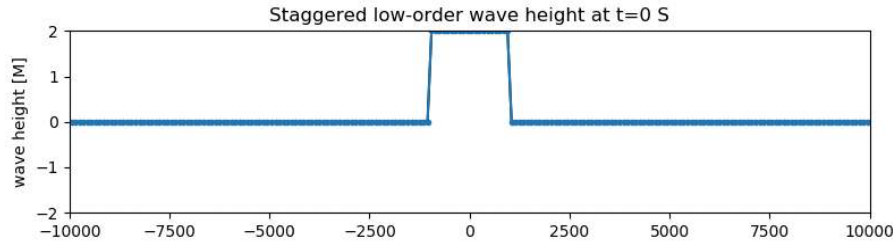


# High-resolution leads to stronger gradient

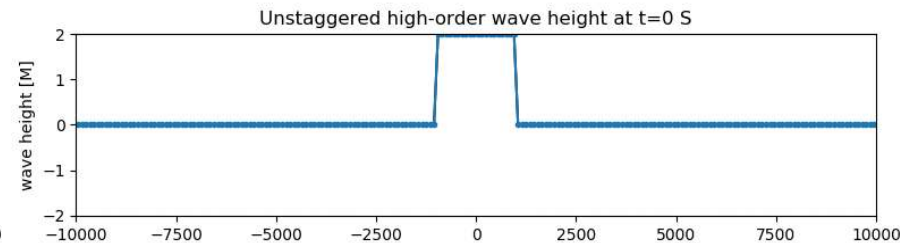
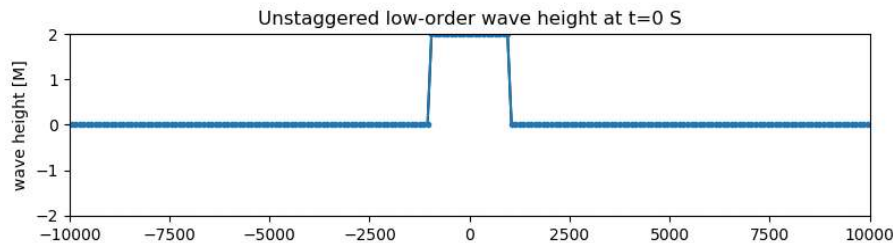
Low-order: no option is effective with sharp gradient

High-order: diffusion is critical, short waves needs to be removed

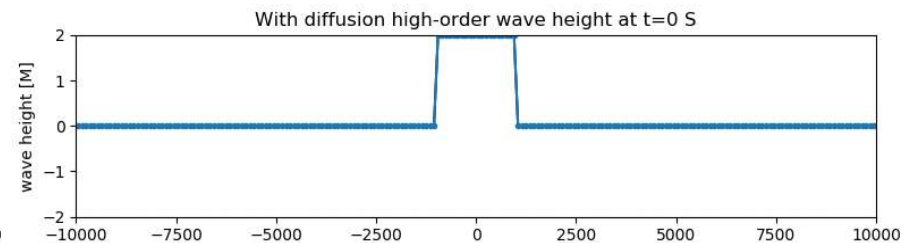
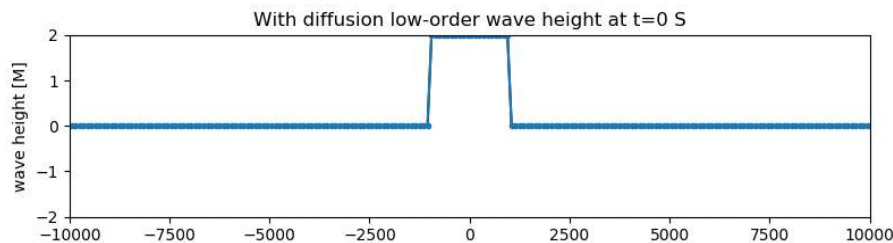
Staggered



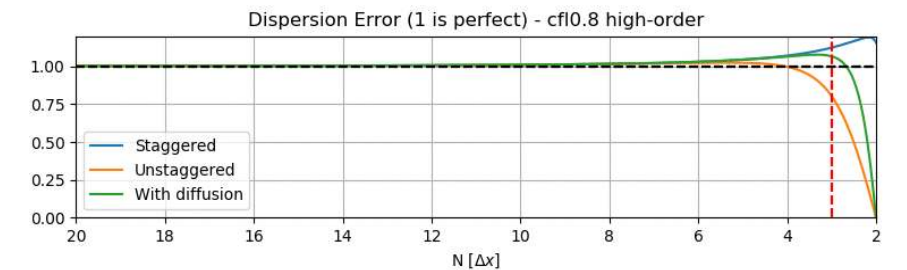
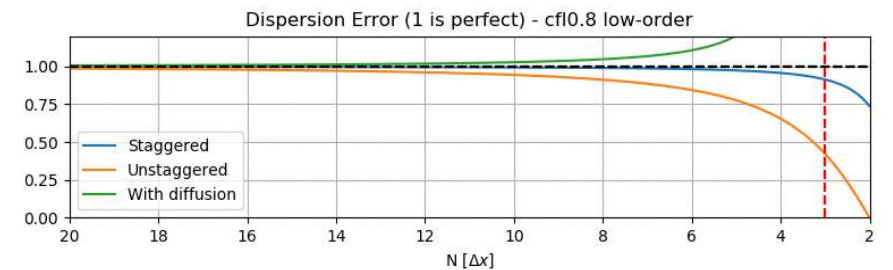
Unstaggered



Unstaggered w/ diffusion



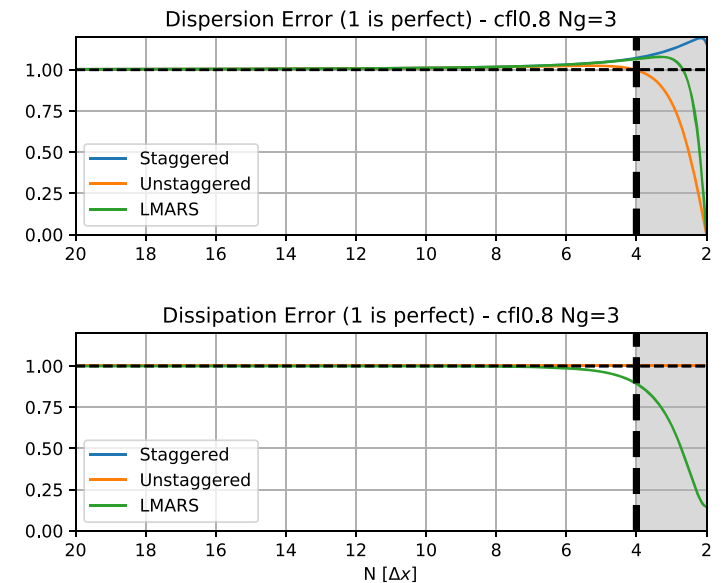
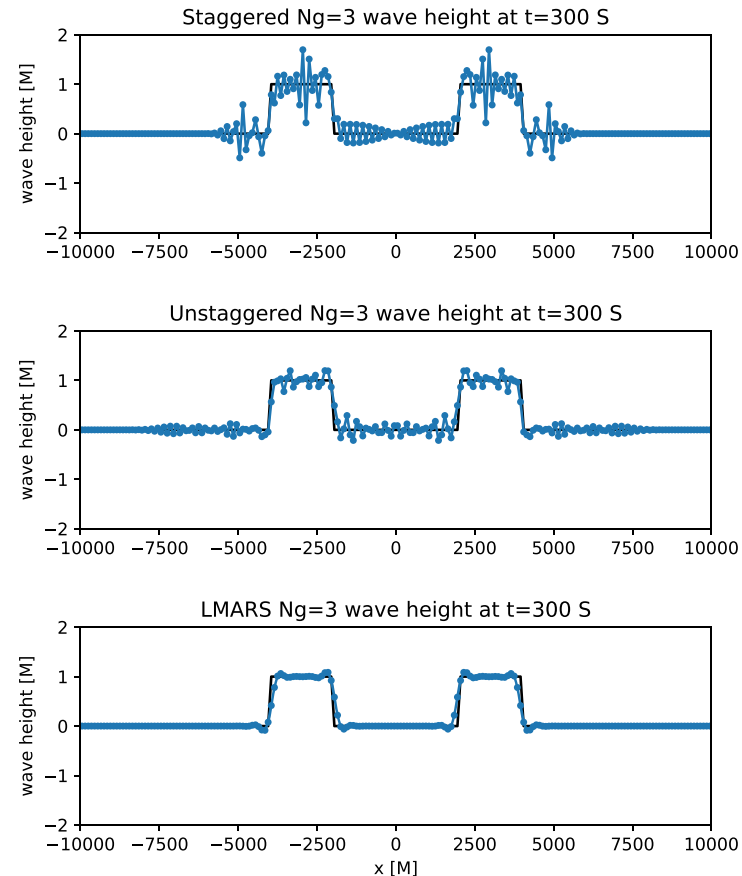
Dispersion errors



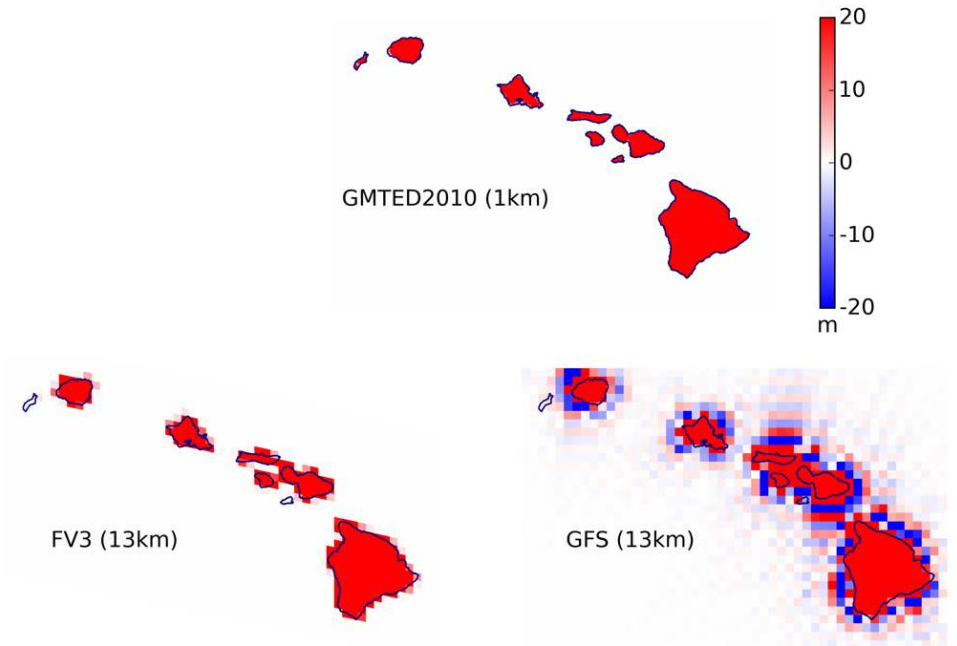
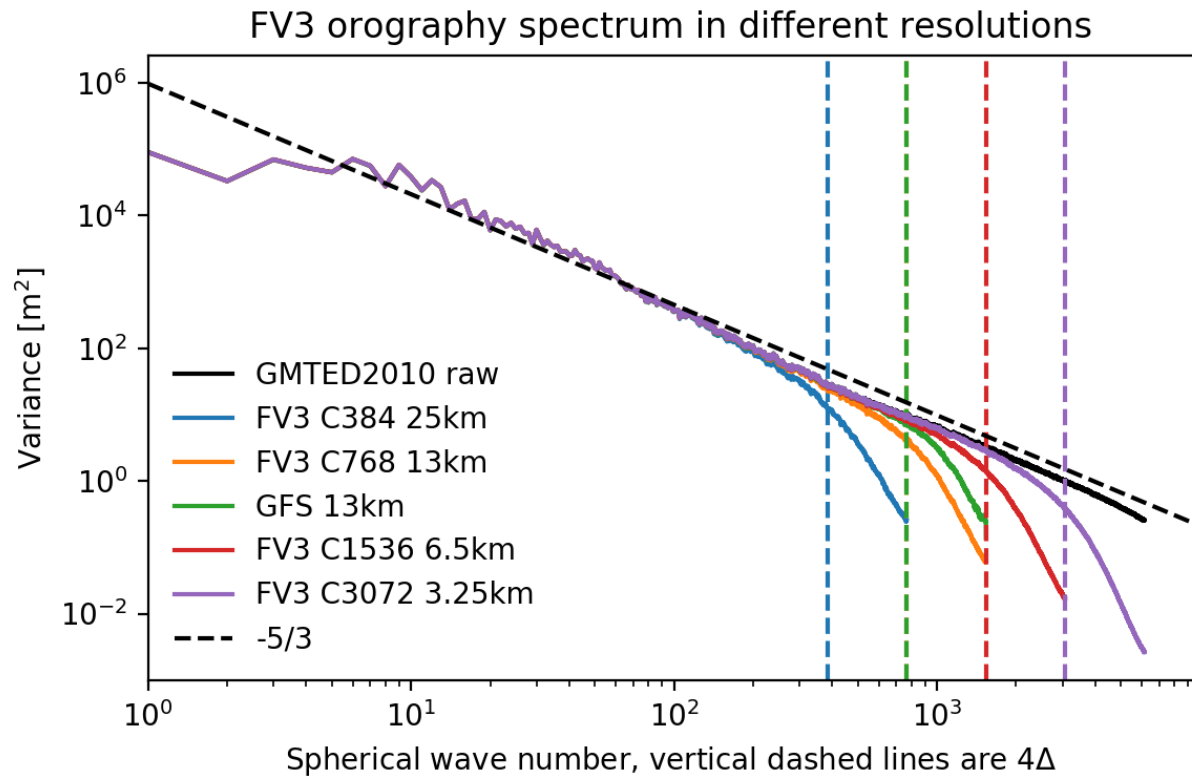


# Matching dissipation and dispersion

- If the solution contains discontinuities, the noise is most likely in the 2-delta to 6-delta range.
- The noise is indistinguishable from the actual information at the similar wavelengths.
- It is crucial that the dissipation curve tightly “wraps” the dispersion curve

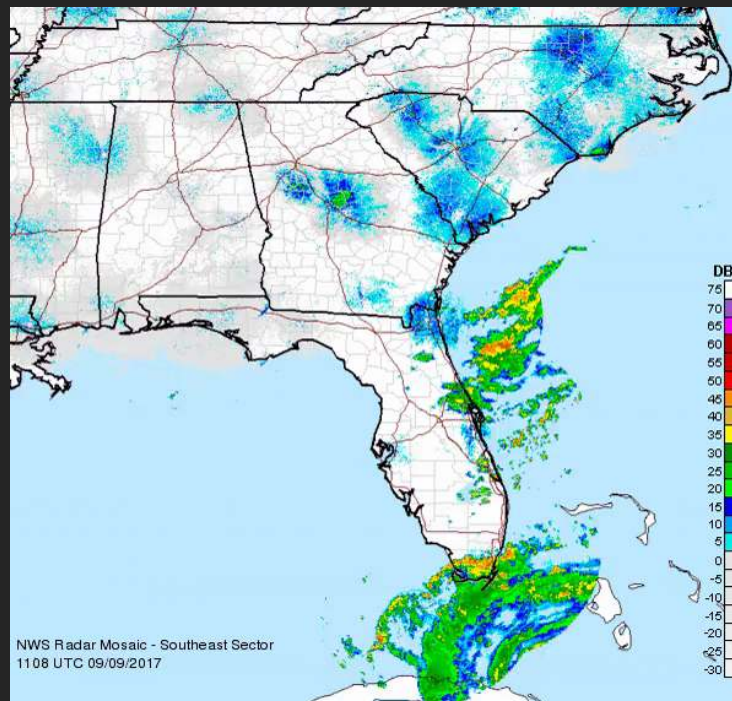


# FV3 integrated design for best consistency

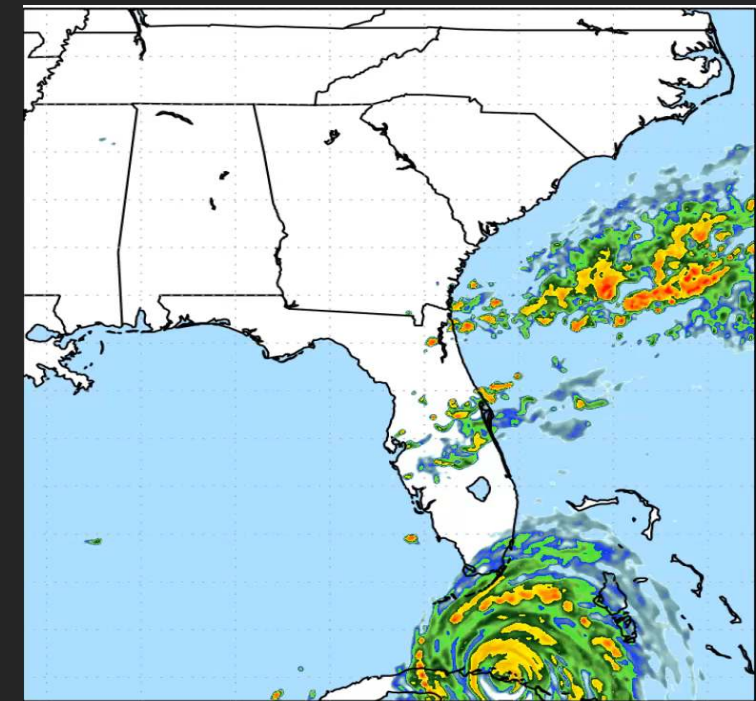


# Current progress of FV3 in NWP

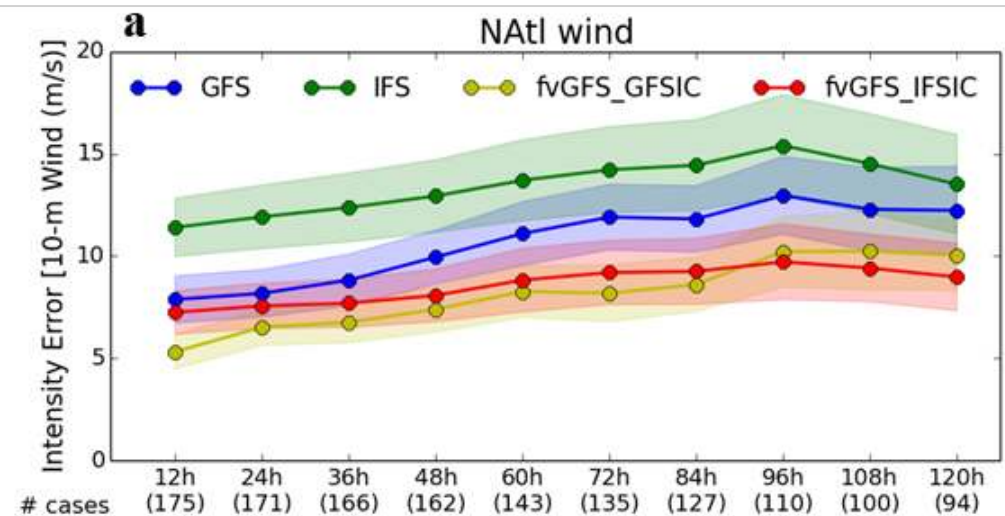
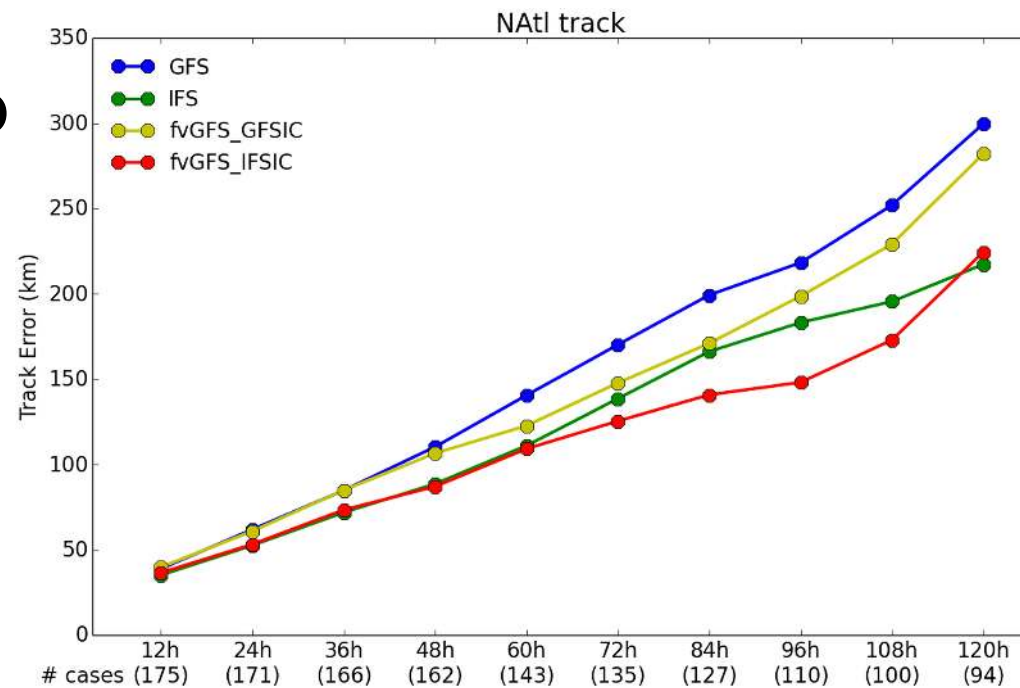
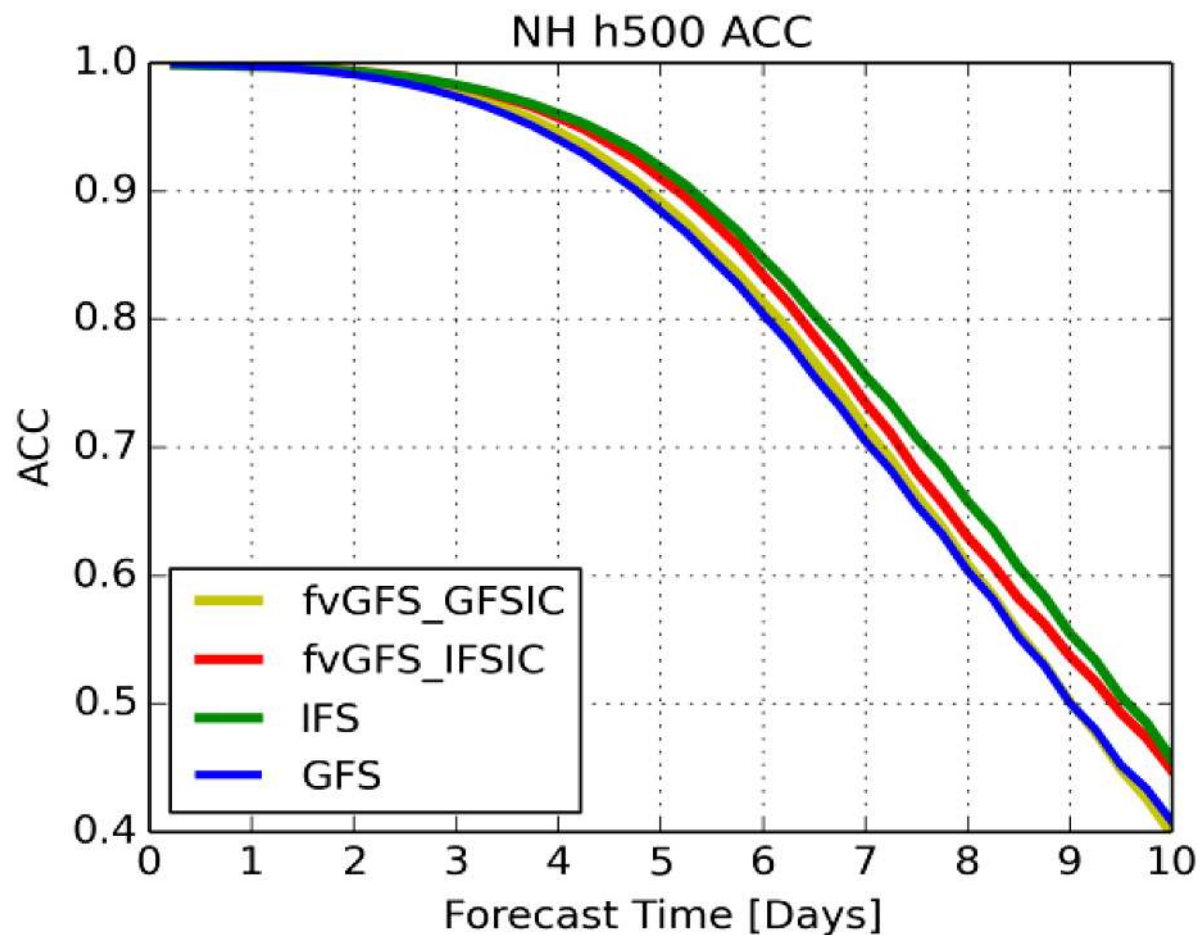
Observed radar image (Brian McNoldy)



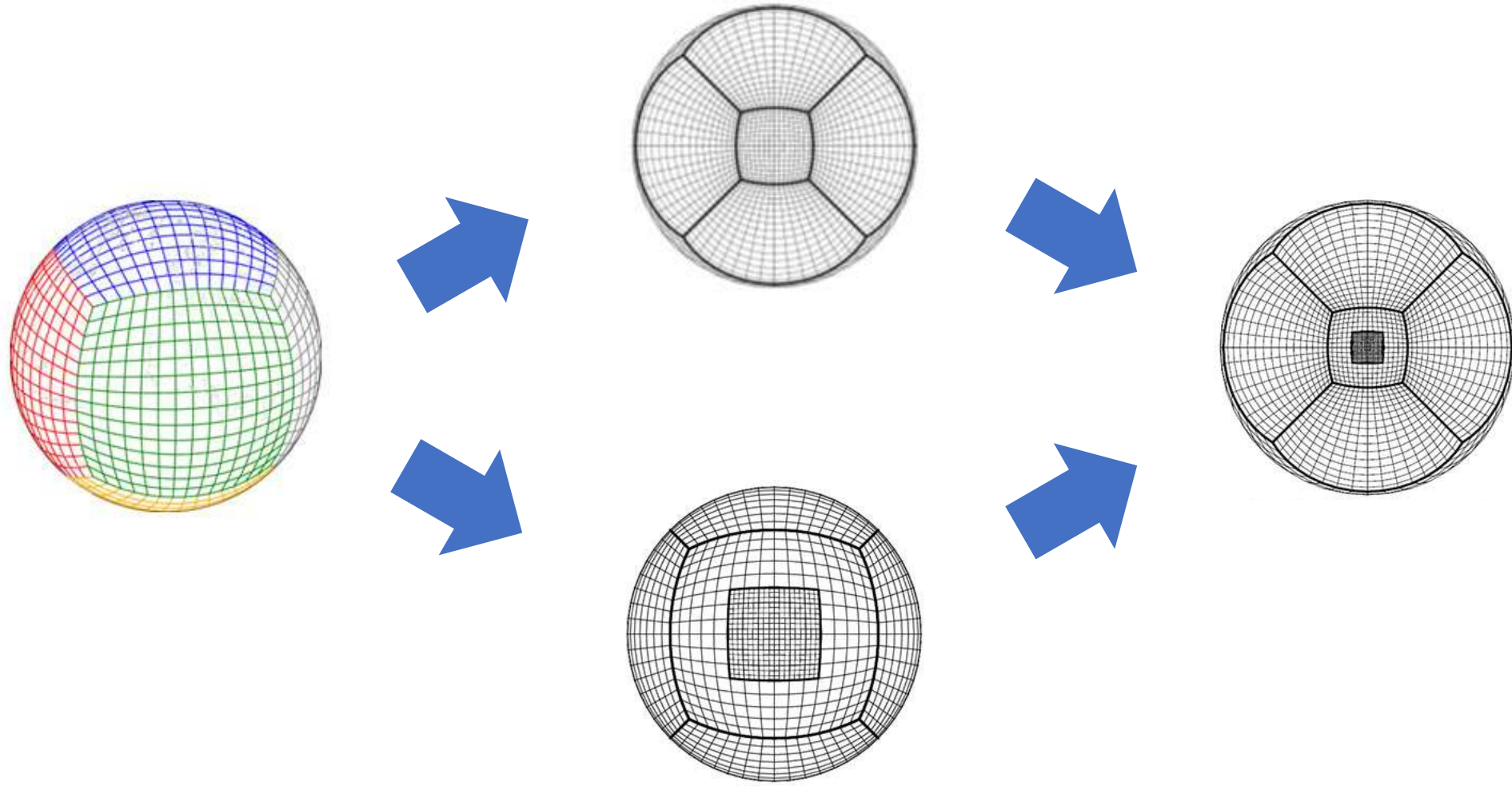
Nested FV3 forecast from 0906  
(Andrew.Hazelton@GFDL)



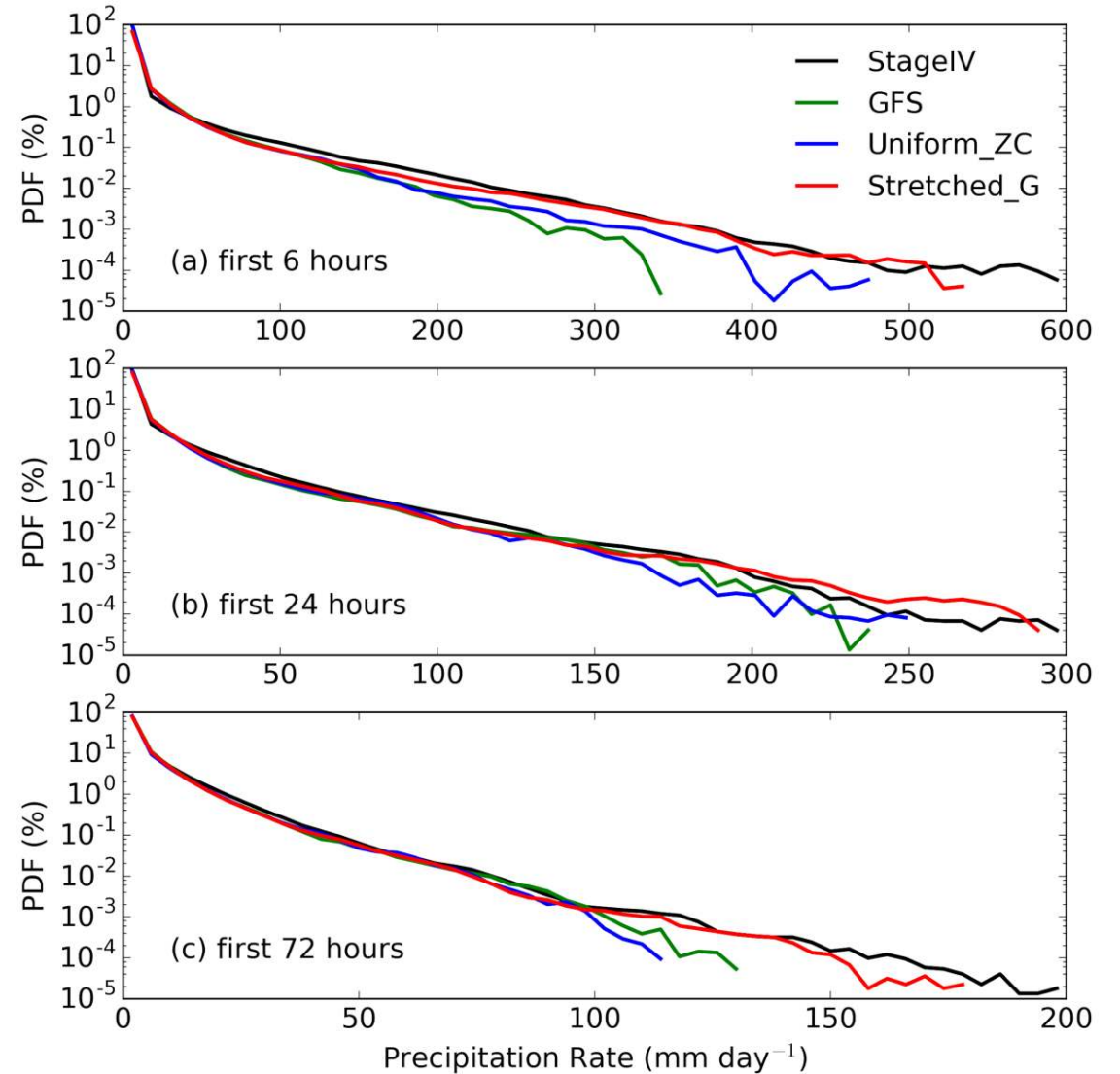
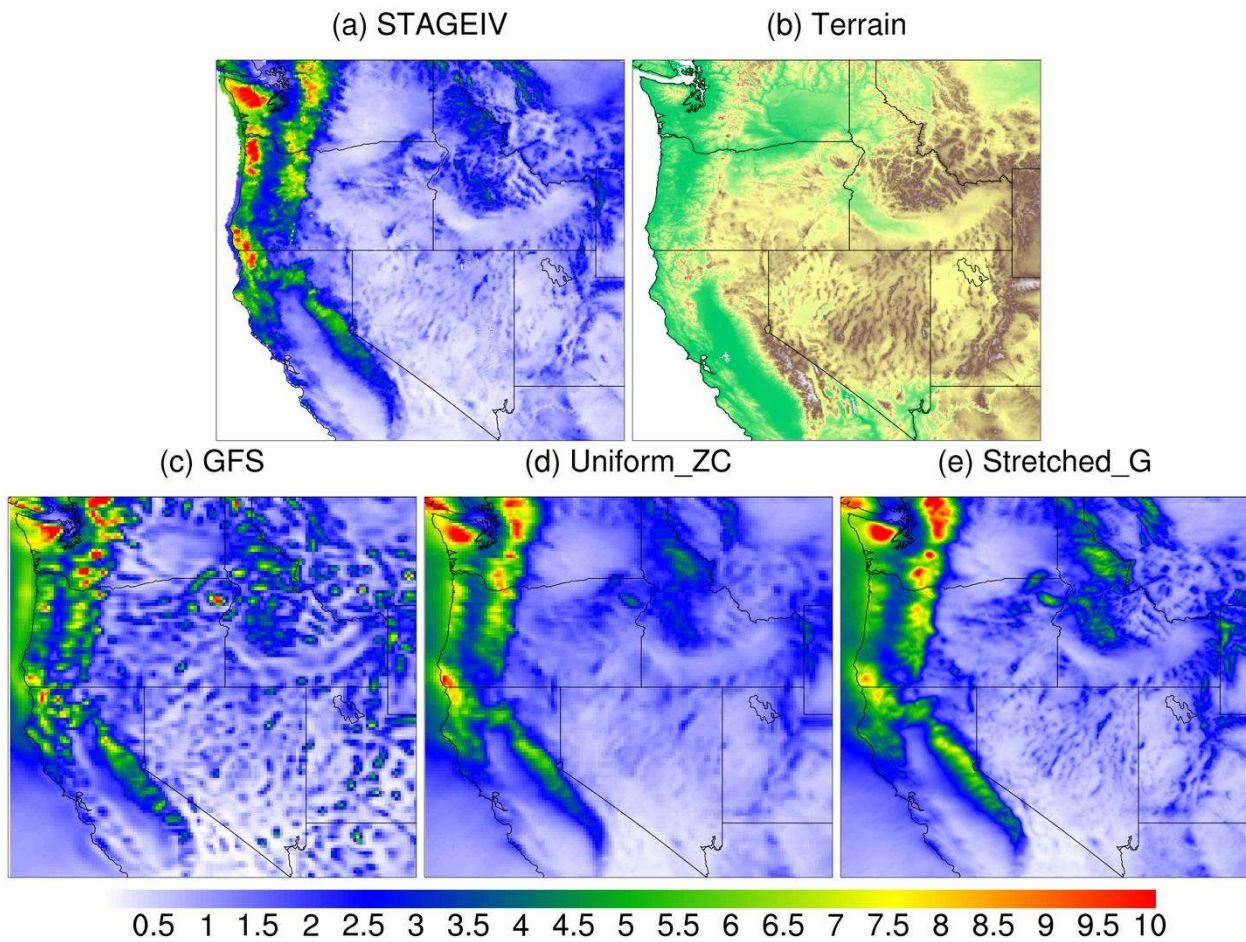
# Uniform grid FV3 NWP



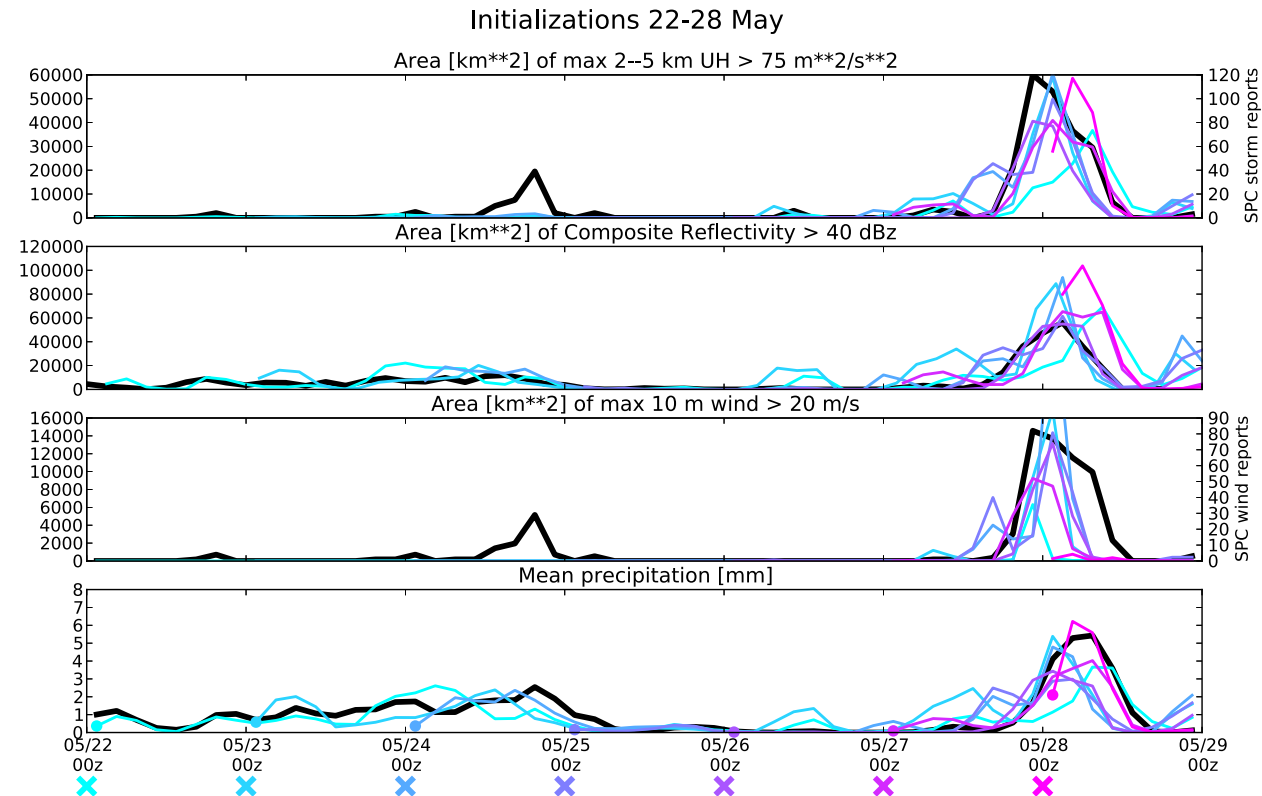
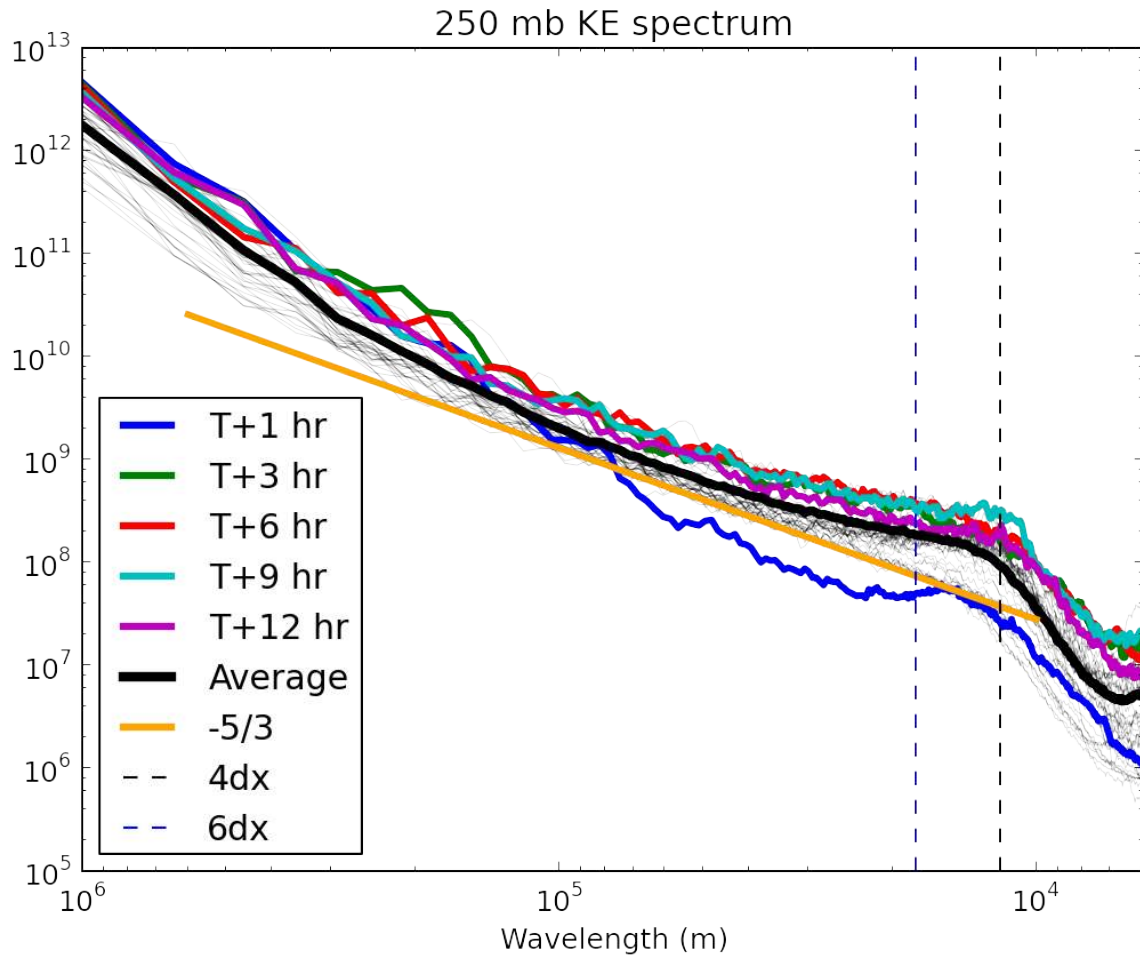
# Variable resolution FV3 applications



# Stretched grid FV3 NWP



# Nested grid FV3 NWP



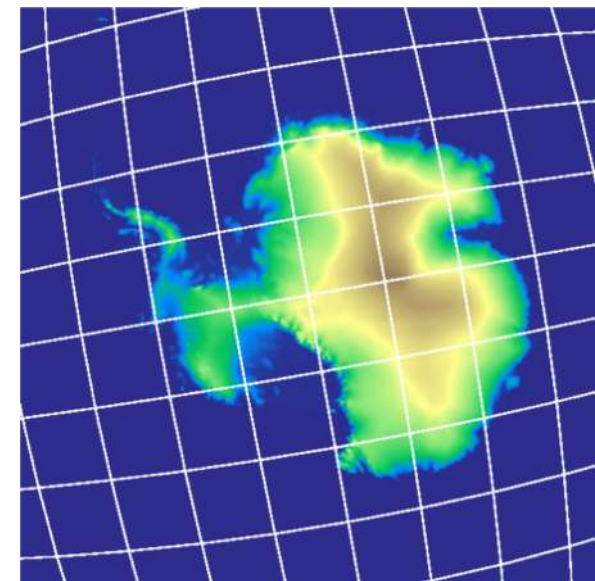
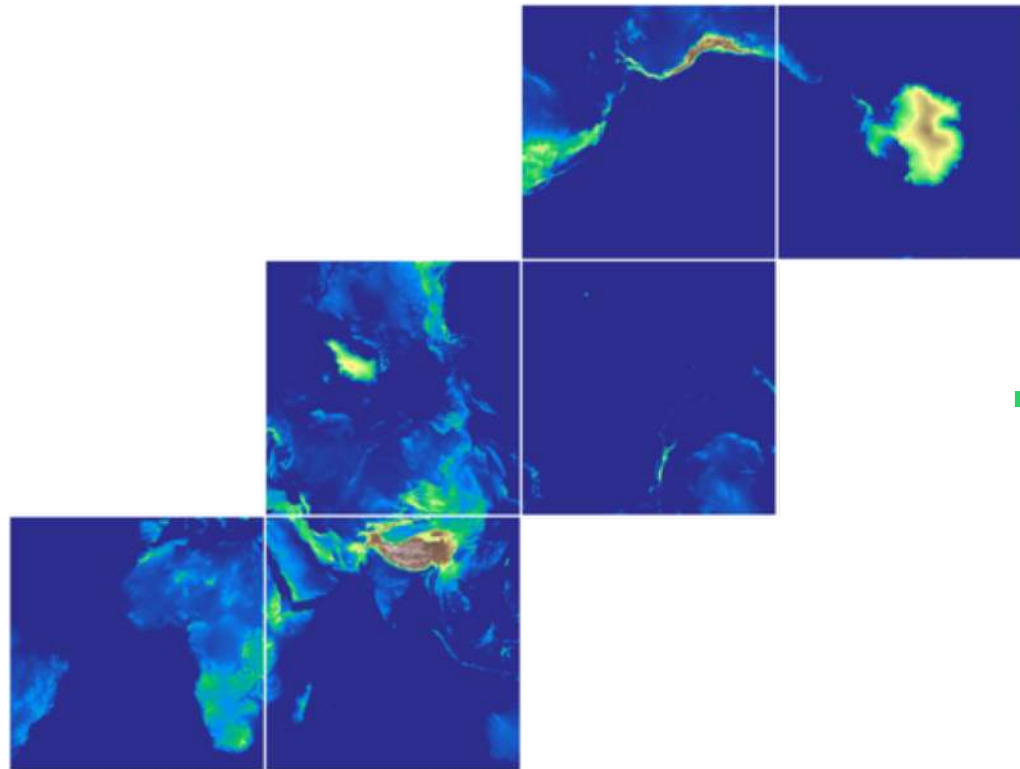
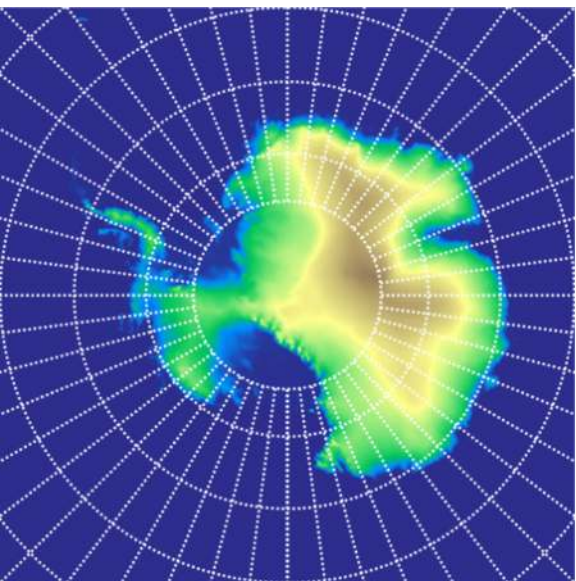
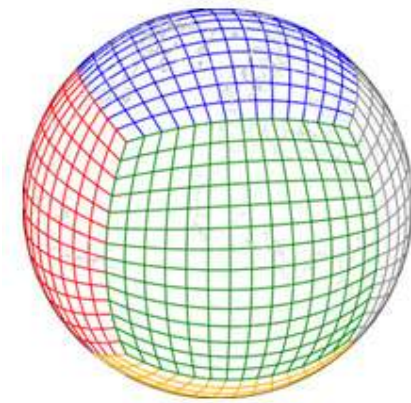


# Beyond software adaptation

- Numerics for modern computing architectures



|  $[FV]^3$  is for cubed-sphere



# Extra dimension for optimization

- Discretization with computing architecture in mind
- Extra dimension and direct access of i-j-k or i-k-j loops
- **10% CPU peak performance** (courtesy to Mark Govett)

## Structure of Atmospheric Dynamical Core

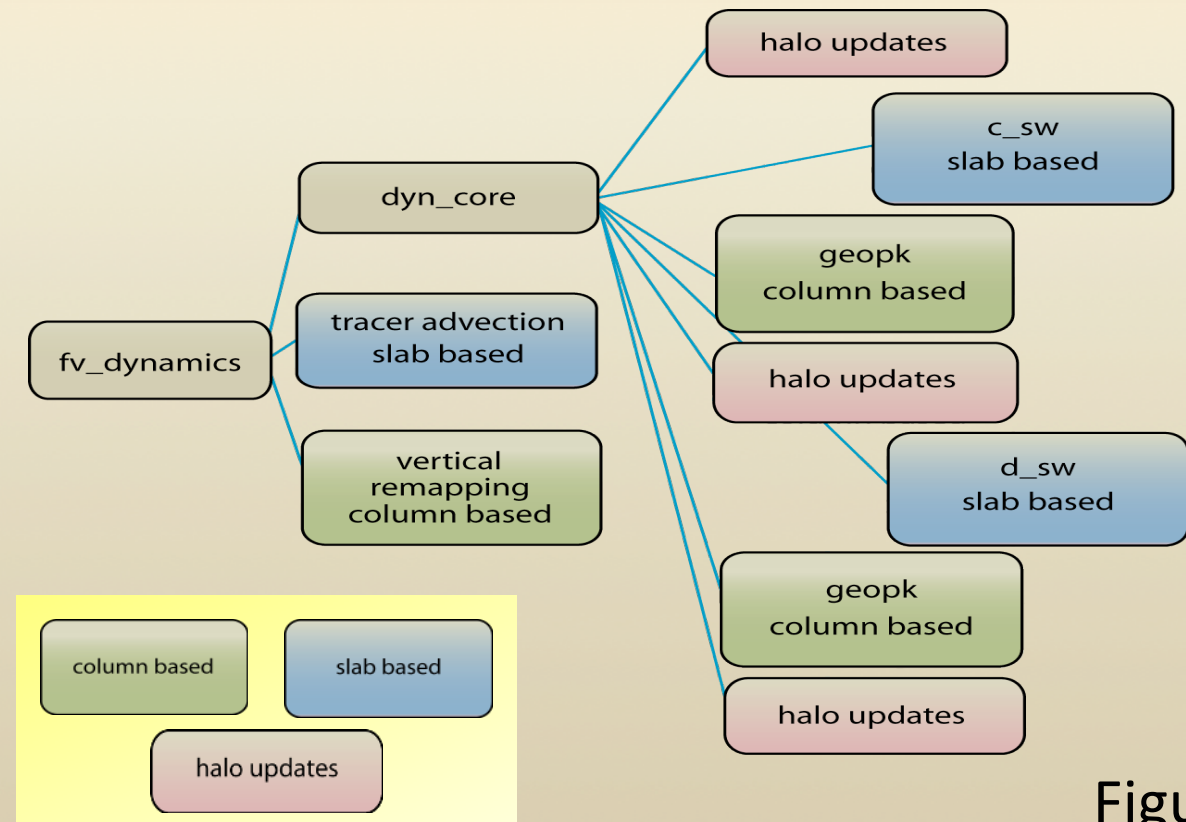


Figure 1

# The densest FV3 loops for GPU Dev

- D\_SW – horizontal 2D
- RS – vertical 2D
- MAPZ – vertical 2D
- C\_SW – horizontal 2D

# FV3 GPU development status and external collaborations

- OpenACC + Cuda
  - In house
- GridTools/Kokkos
  - Swiss National Supercomputing Centre (CSCS)
  - Vulcan Group
  - DOE/NASA

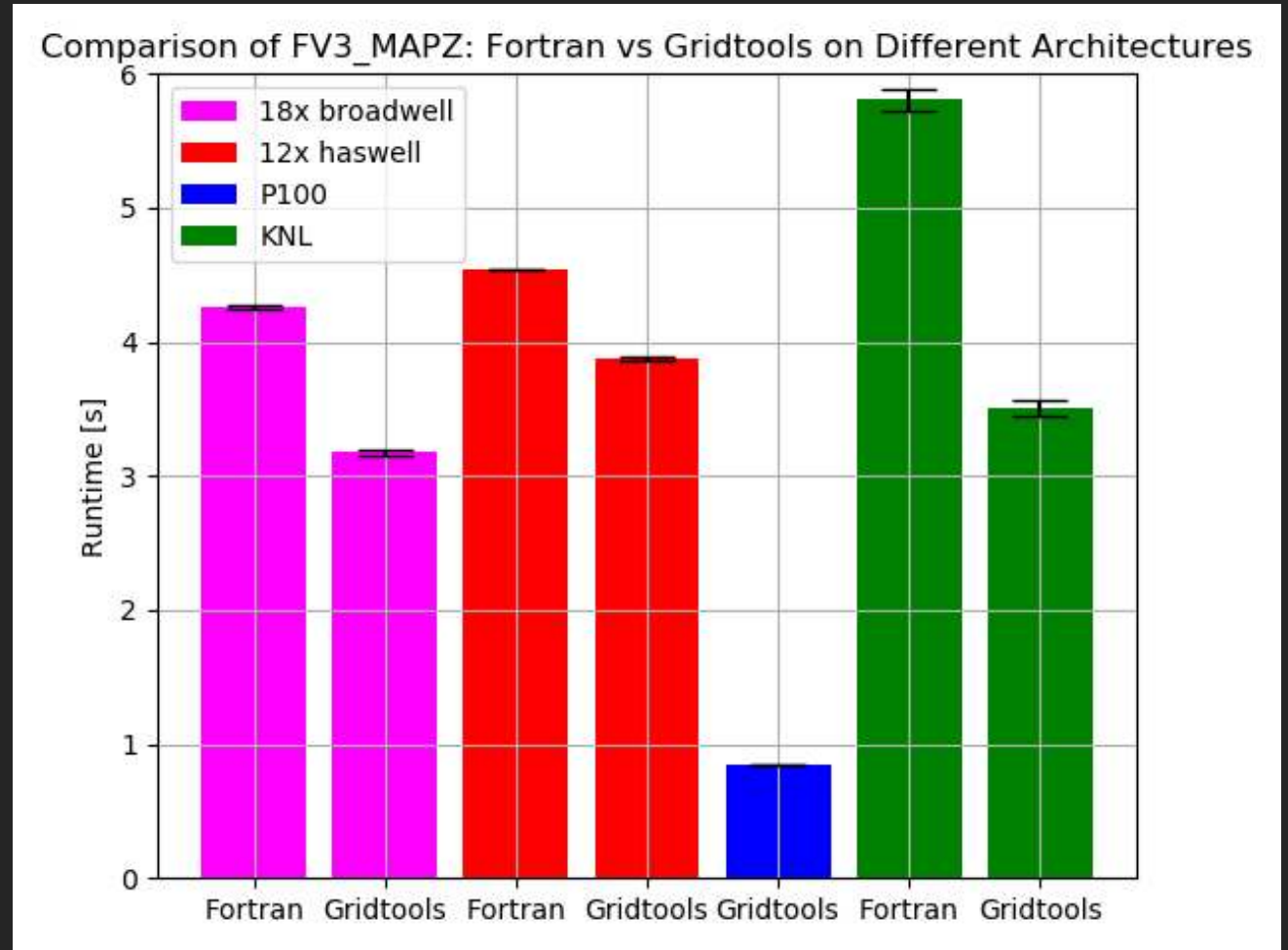
# Optimization results (extremely preliminary)

In House Zhi.Liang@GFDL (Fortran + OpenACC/Cuda):

- RS and fyppm (key component of D\_SW) achieved about 30x compared to single CPU core
  - CPU: Intel Haswell 3.5 GHz
  - GPU: Nvidia Tesla V100

CSCS (GridTools):

- MAPZ speed up about 5x compared to 12x Haswell
  - CPU: Intel Haswell 2.6 GHz
  - GPU: Nvidia Tesla P100



# Beyond dynamics

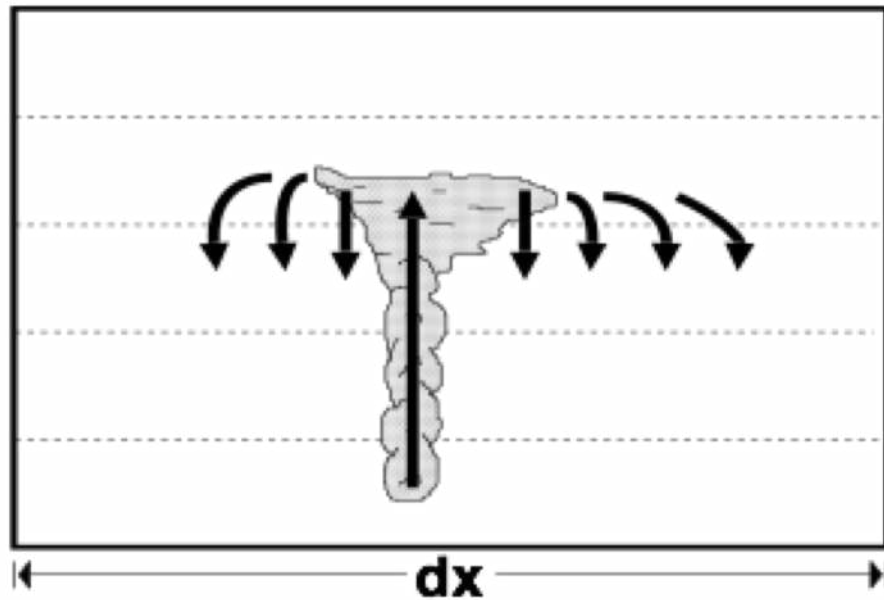
- Physics parameterizations is a significant consumer of computational resources.  
Traditional approach: column based, (i, j) independent
- Scientific challenges in the E-Class HPC era
  - Nonhydrostatic physics – need to re-evaluate the processes and assumptions
  - Parameterize or direct/partially resolve
- Computational challenges in the E-Class HPC era
  - Good for CPU OpenMP optimization
  - Dependency in k-dimension, prevent good GPU optimization. Therefore, need to rearrange the code.

# New scientific challenges (opportunities) with higher resolution

## classical schemes

grid size  $> 20\text{...}50$  km:

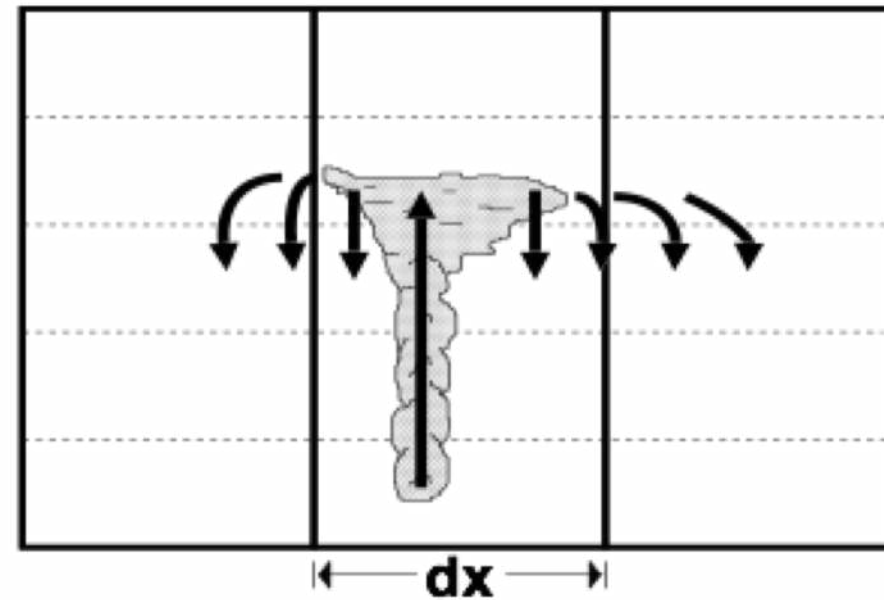
conv. **entirely subgrid scale**



## new scheme

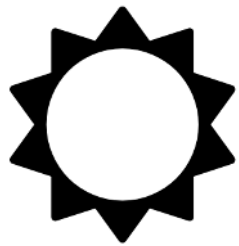
grid size  $\approx 1\text{...}20$  km:

convection **partially resolvable**



# Breaking the boundary between “physics” and “dynamics”

- Remove some parameterizations and (partially) resolve them! It’s also good for GPU as it is consistent with the “dynamics” code structure



Slow  
Processes

## PHYSICS

Para. Update

- Radiation
- Cloud MP
- Pollutant Source/Sink
- Sub-Grid-Orog. effects
- PBL, etc.



Intermediate  
Processes



Fast  
Processes

## DYNAMICS

Tracers Update

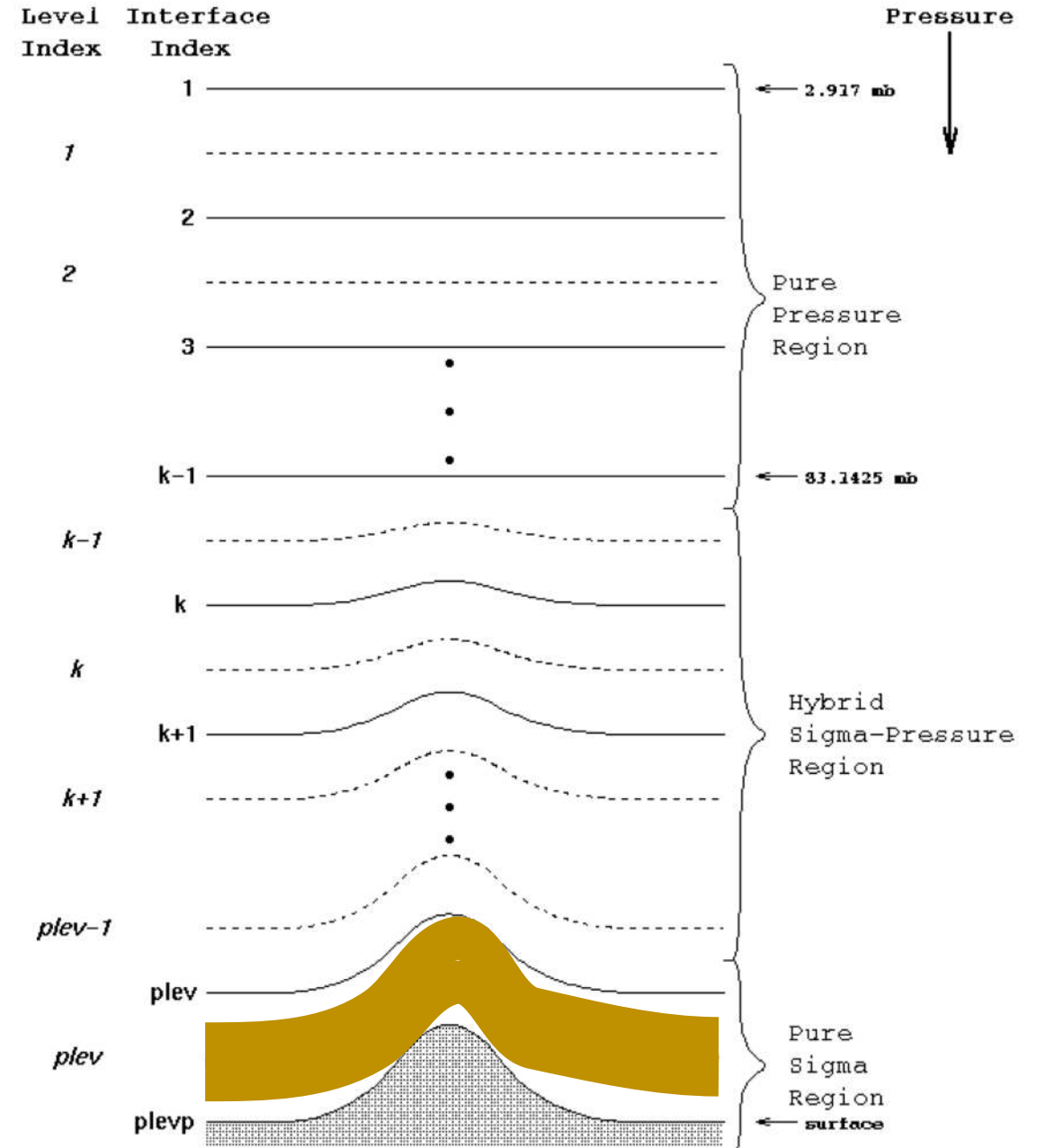
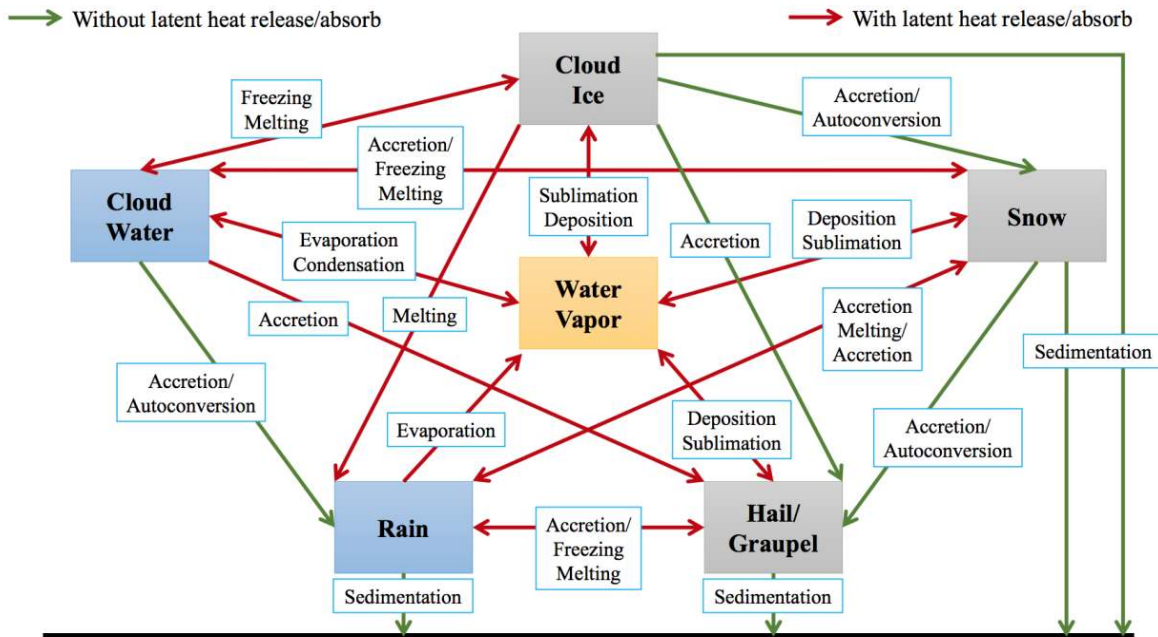
Prog. Vars. Update



# Consistent Phys-Dynamics Coupling in Next-Gen FV3

- GFDL cloud microphysics
- Pollution/Aerosol emission (On going work with the help from Dr. Paul Ginoux)

## GFDL cloud microphysics (6 species)





# FV3 as a (chemical) particle-transport forecasting model

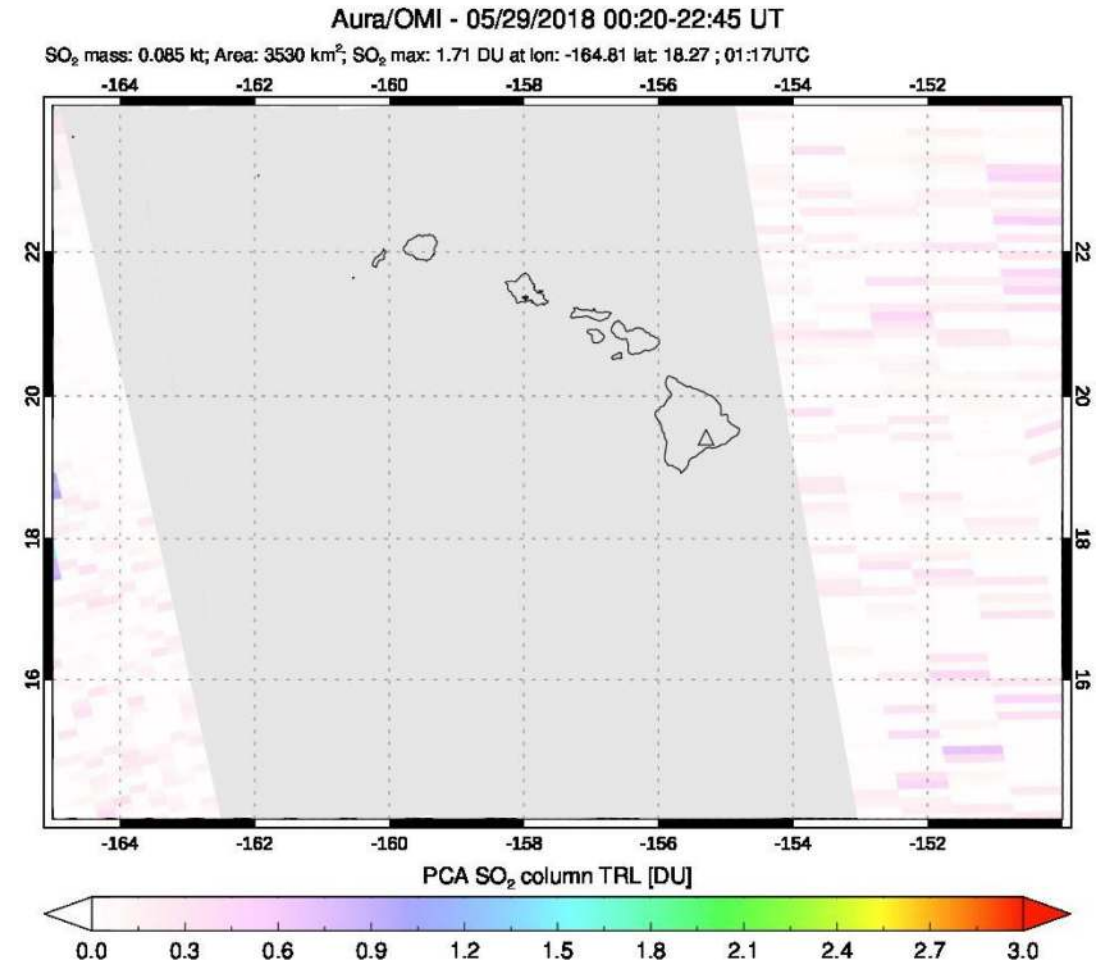
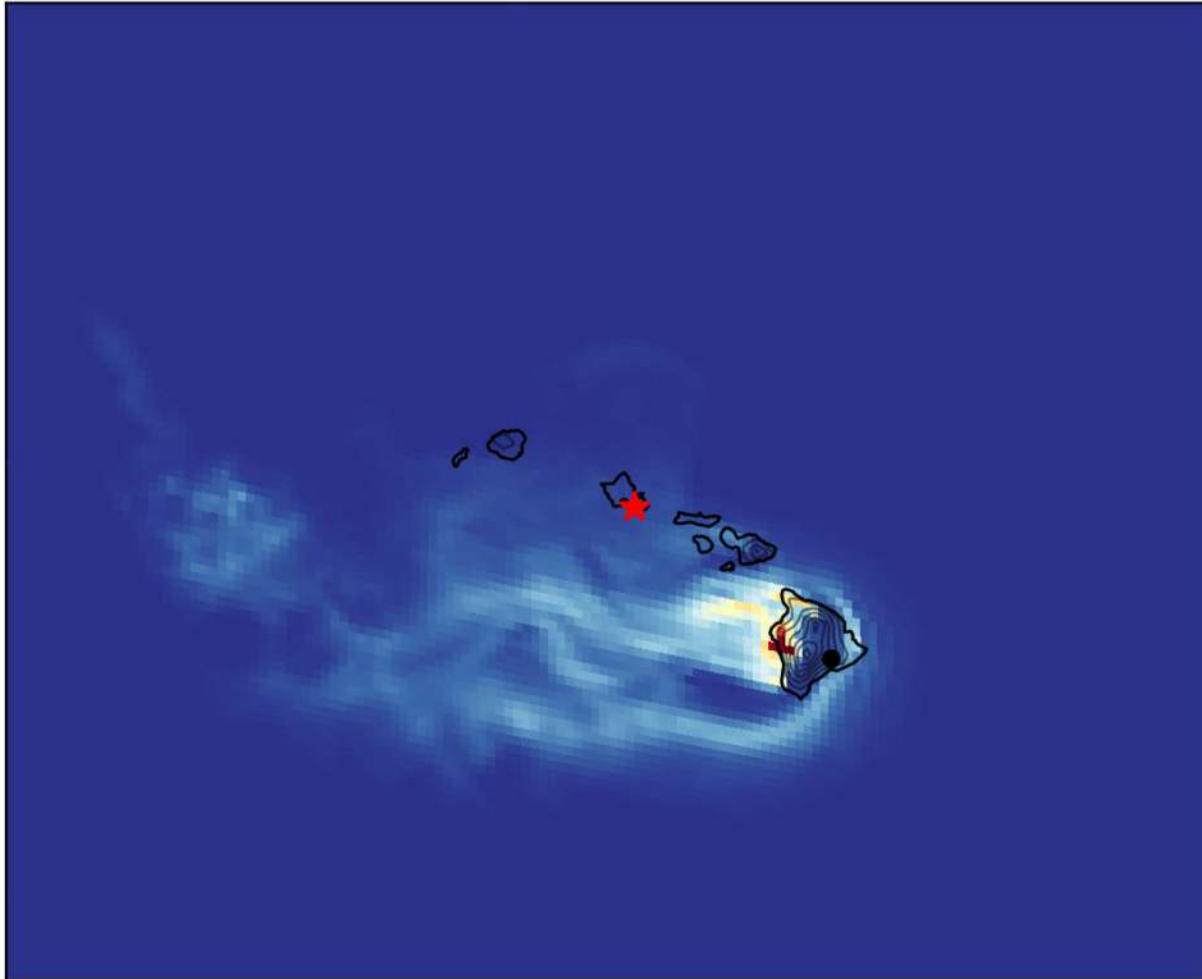
2018-05-29 01:00Z  
001 Forecast Hours  
FV3 13km

Visualization  
Xi Chen@FV3 team

Day-1

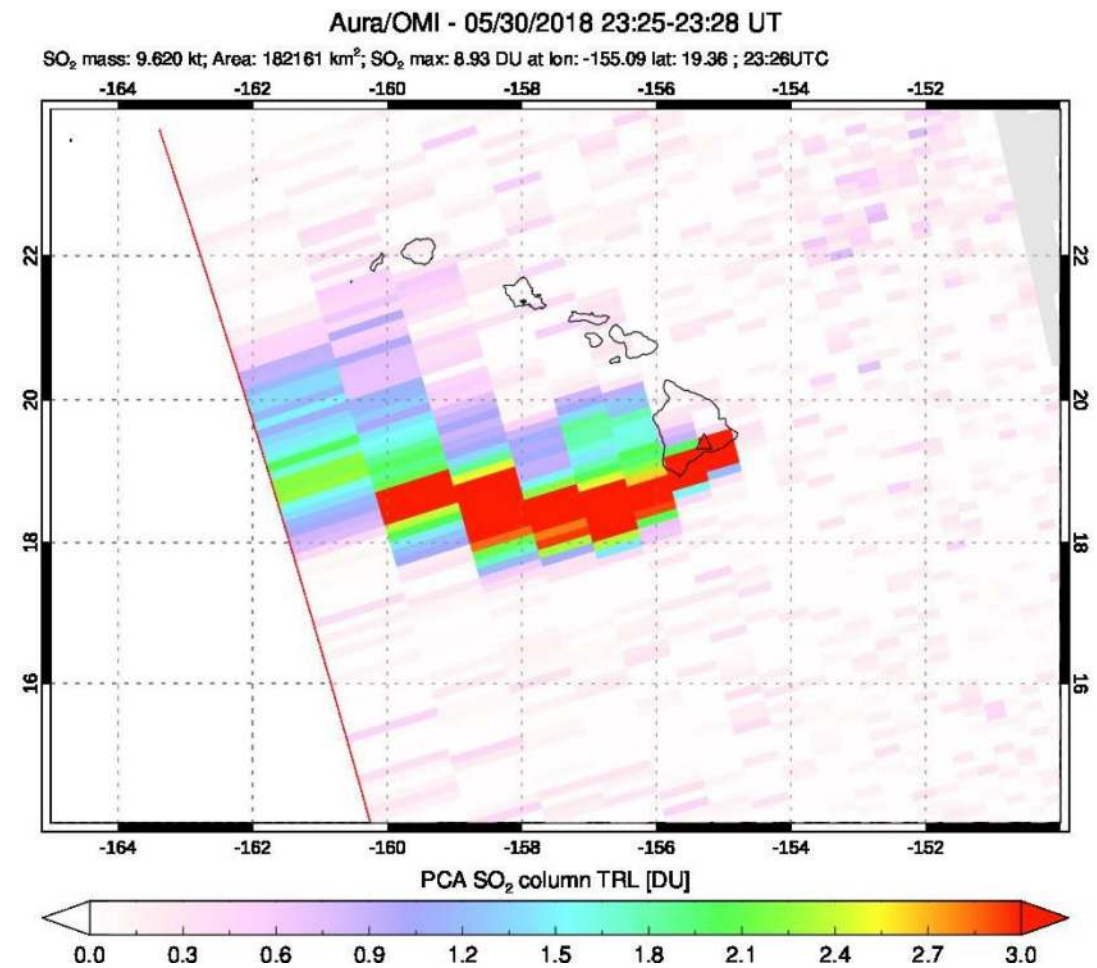
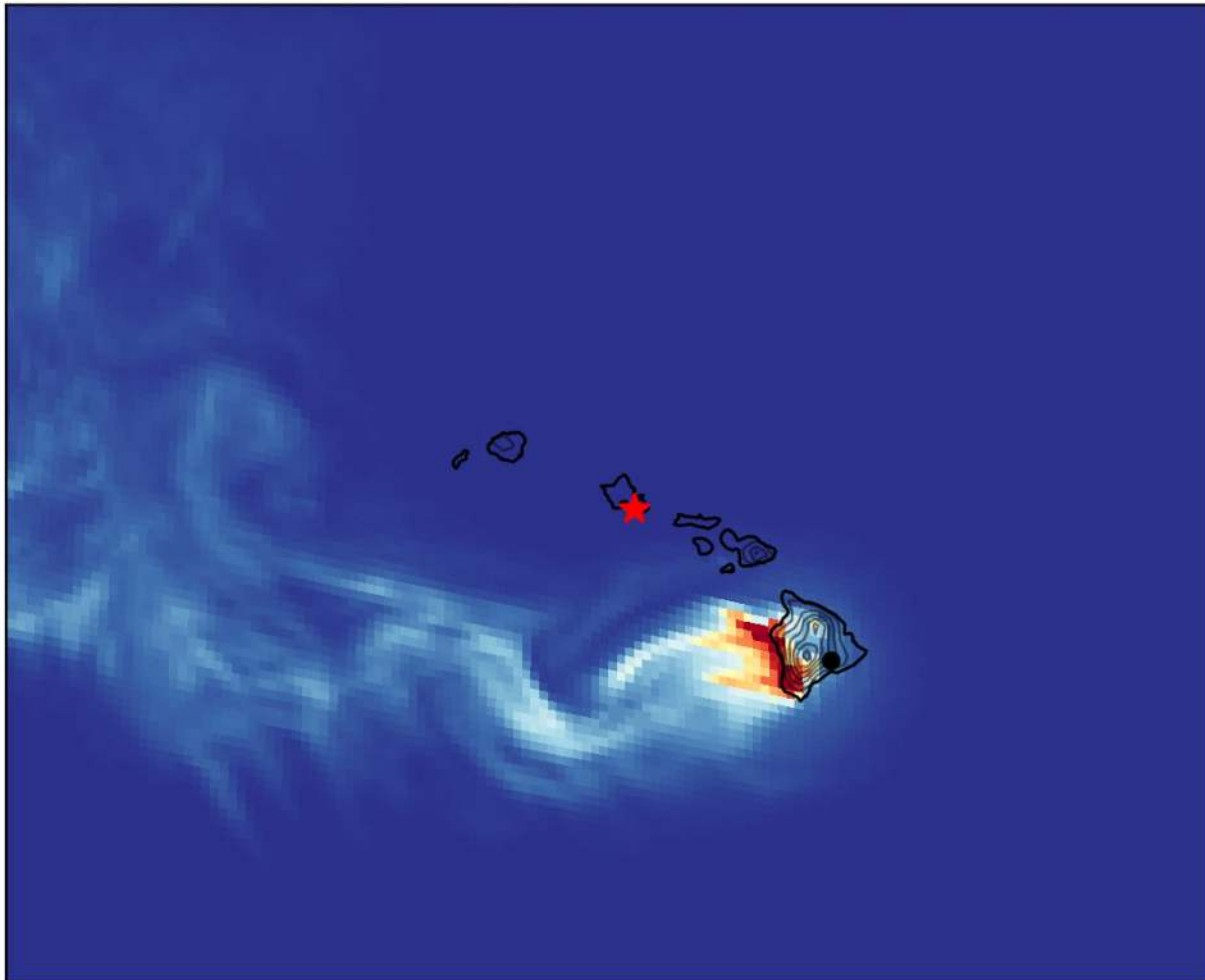
Observation: <https://so2.gsfc.nasa.gov/>

FV3 Kilauea Emission transport FCST at 2018-05-30 00:00Z



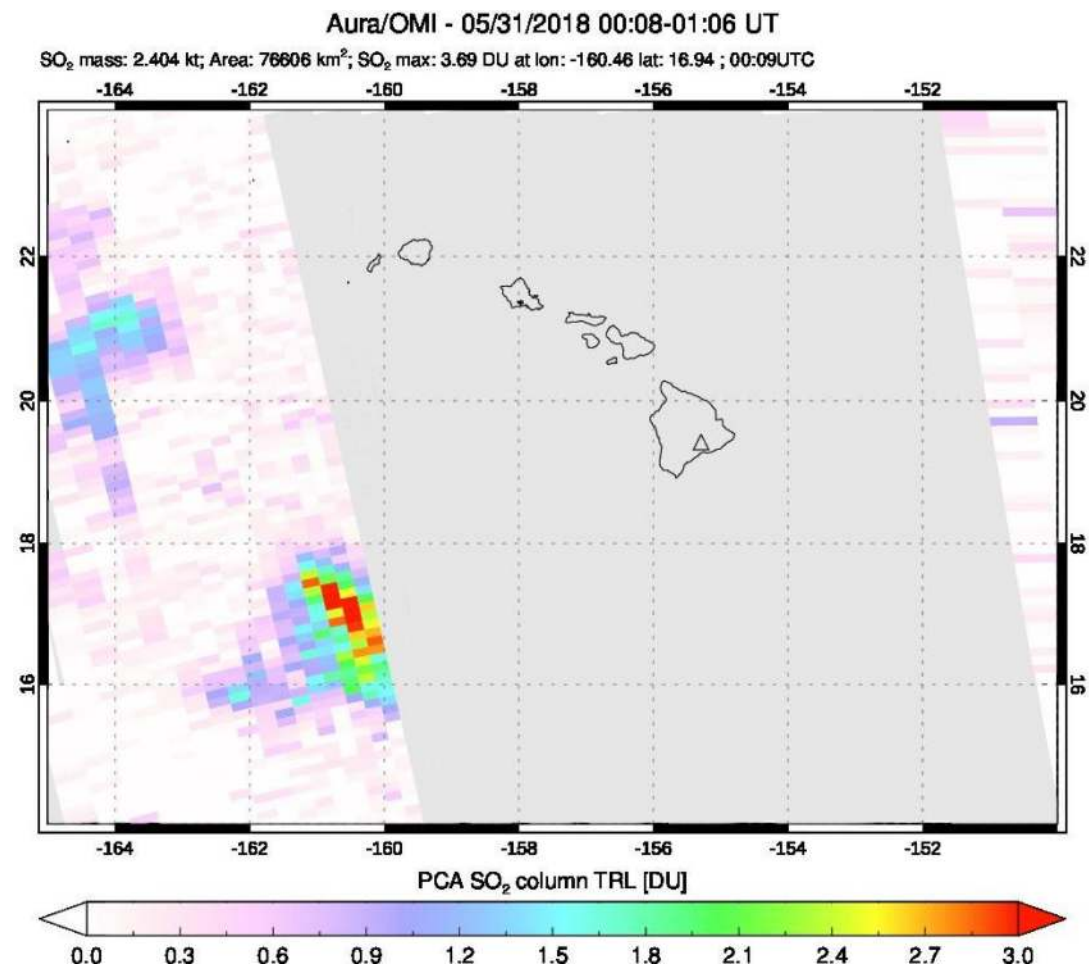
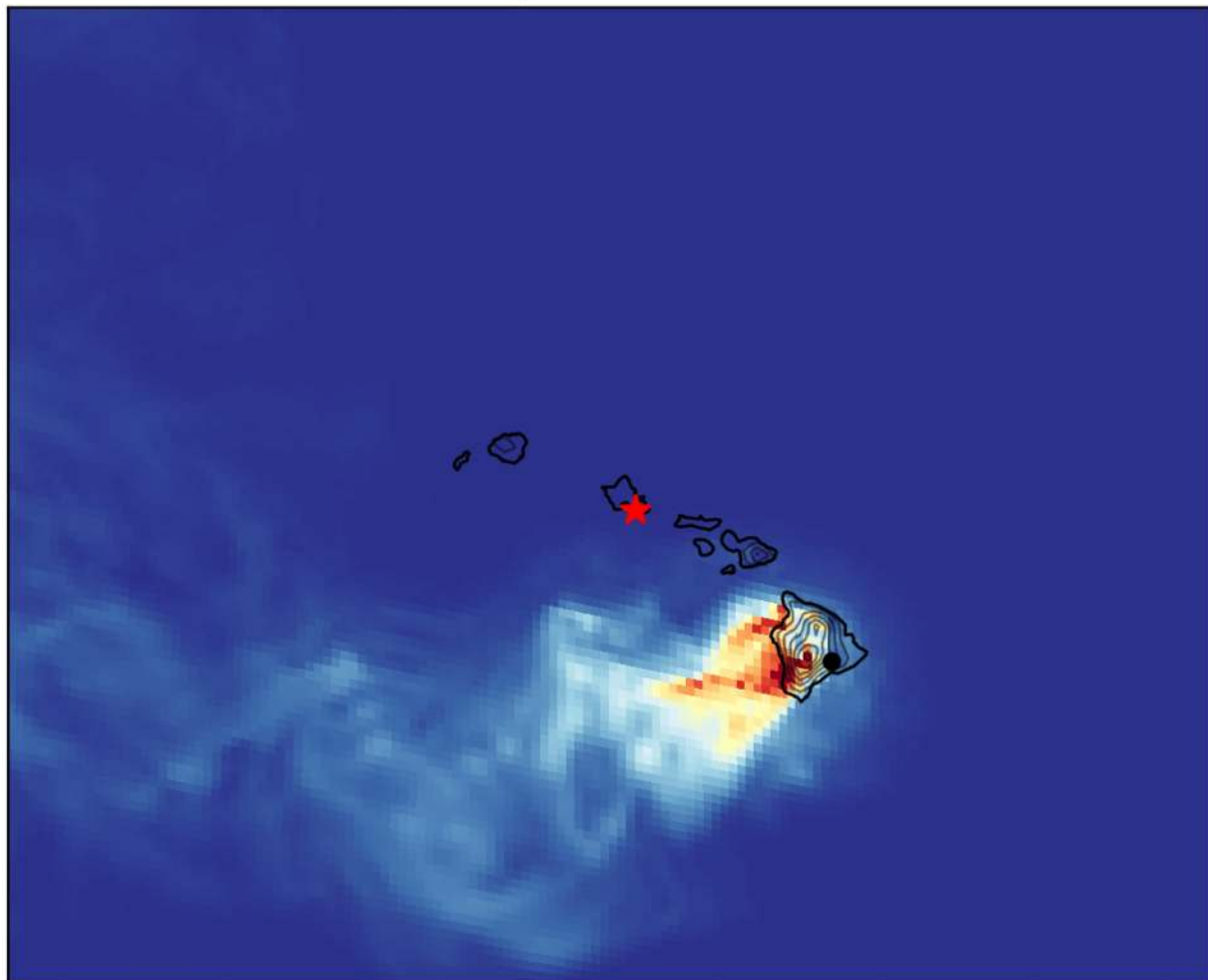
# Day-2

FV3 Kilauea Emission transport FCST at 2018-05-31 00:00Z



Day-3

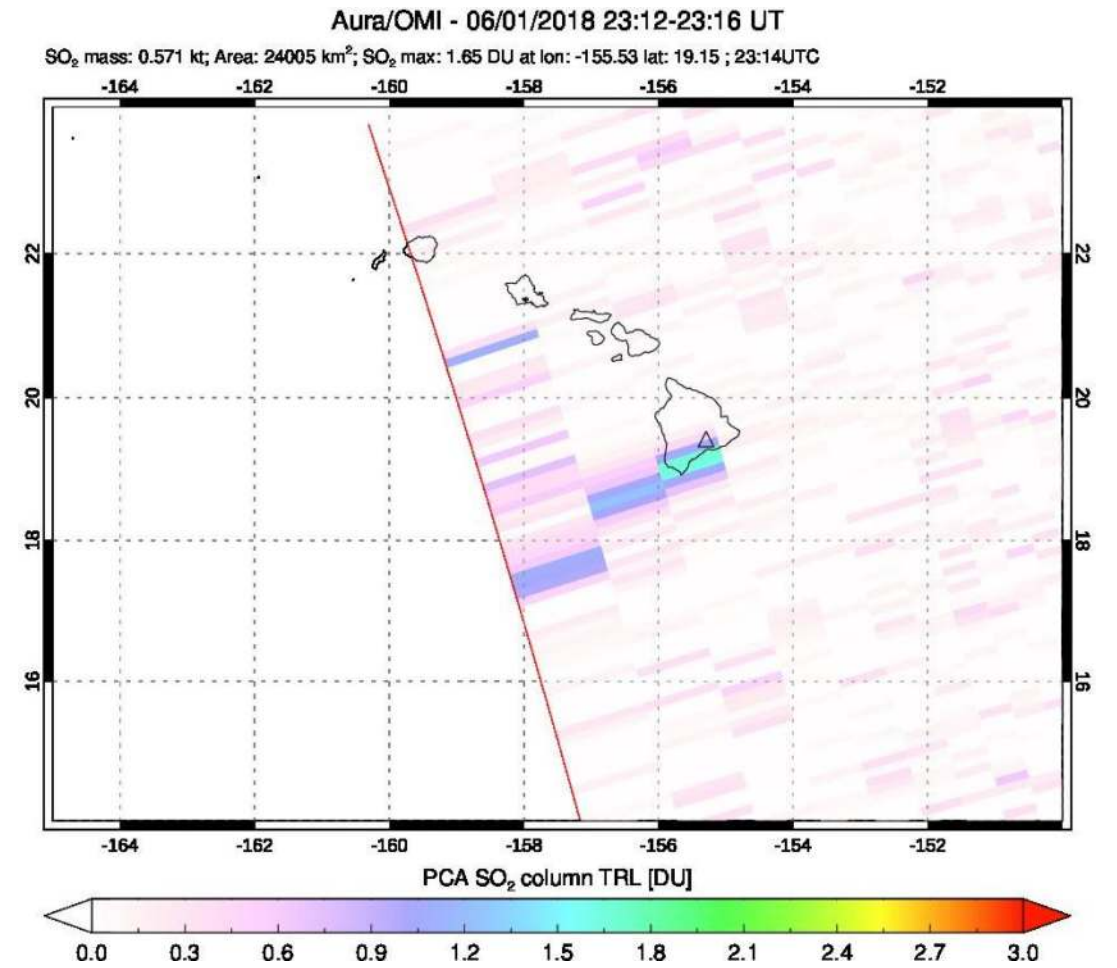
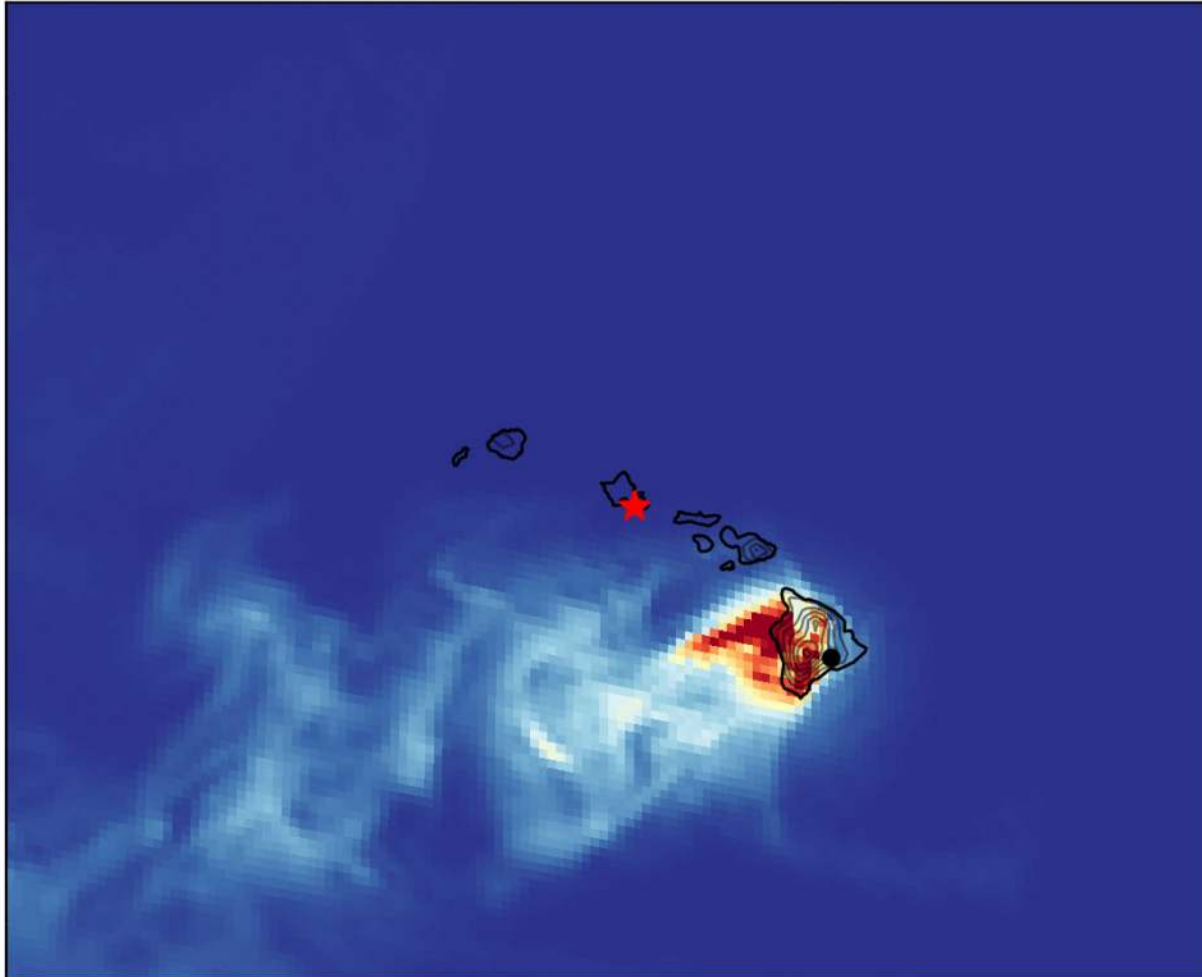
FV3 Kilauea Emission transport FCST at 2018-06-01 00:00Z



Day-4

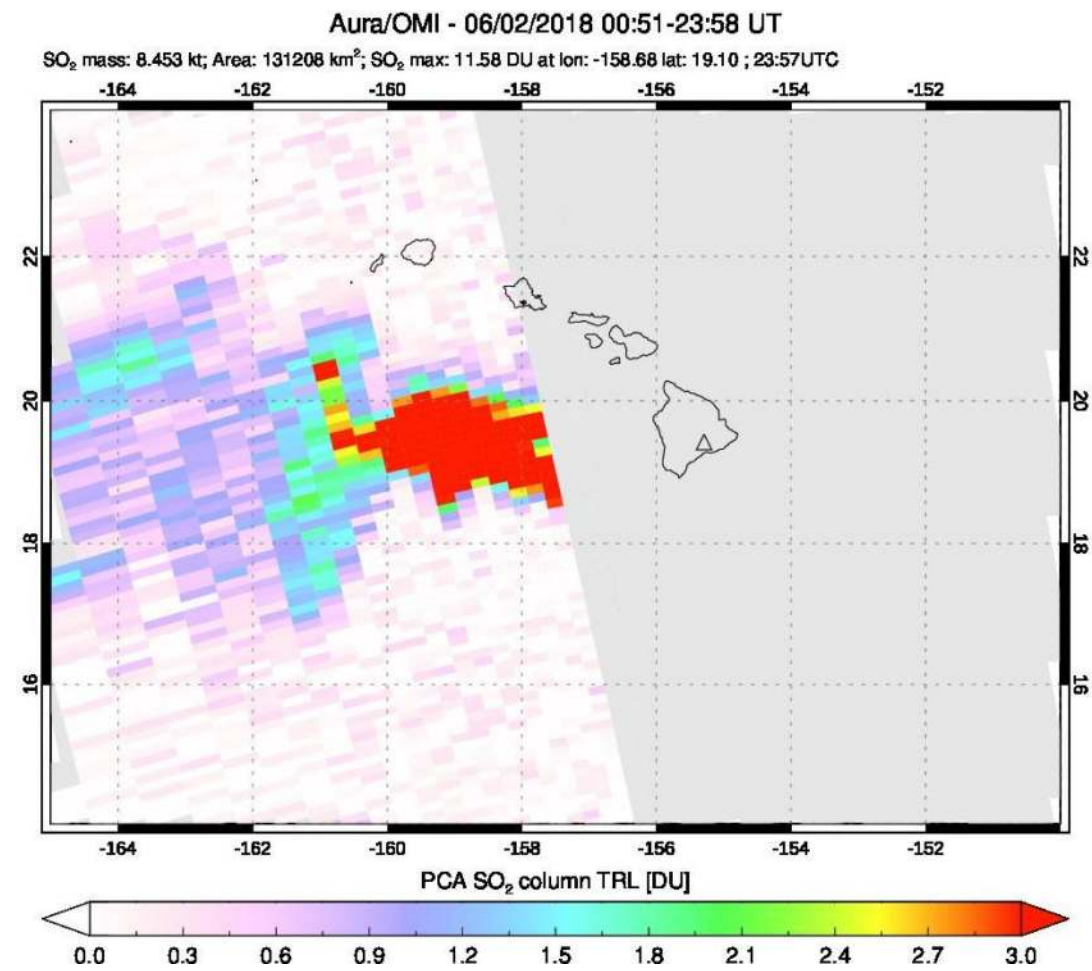
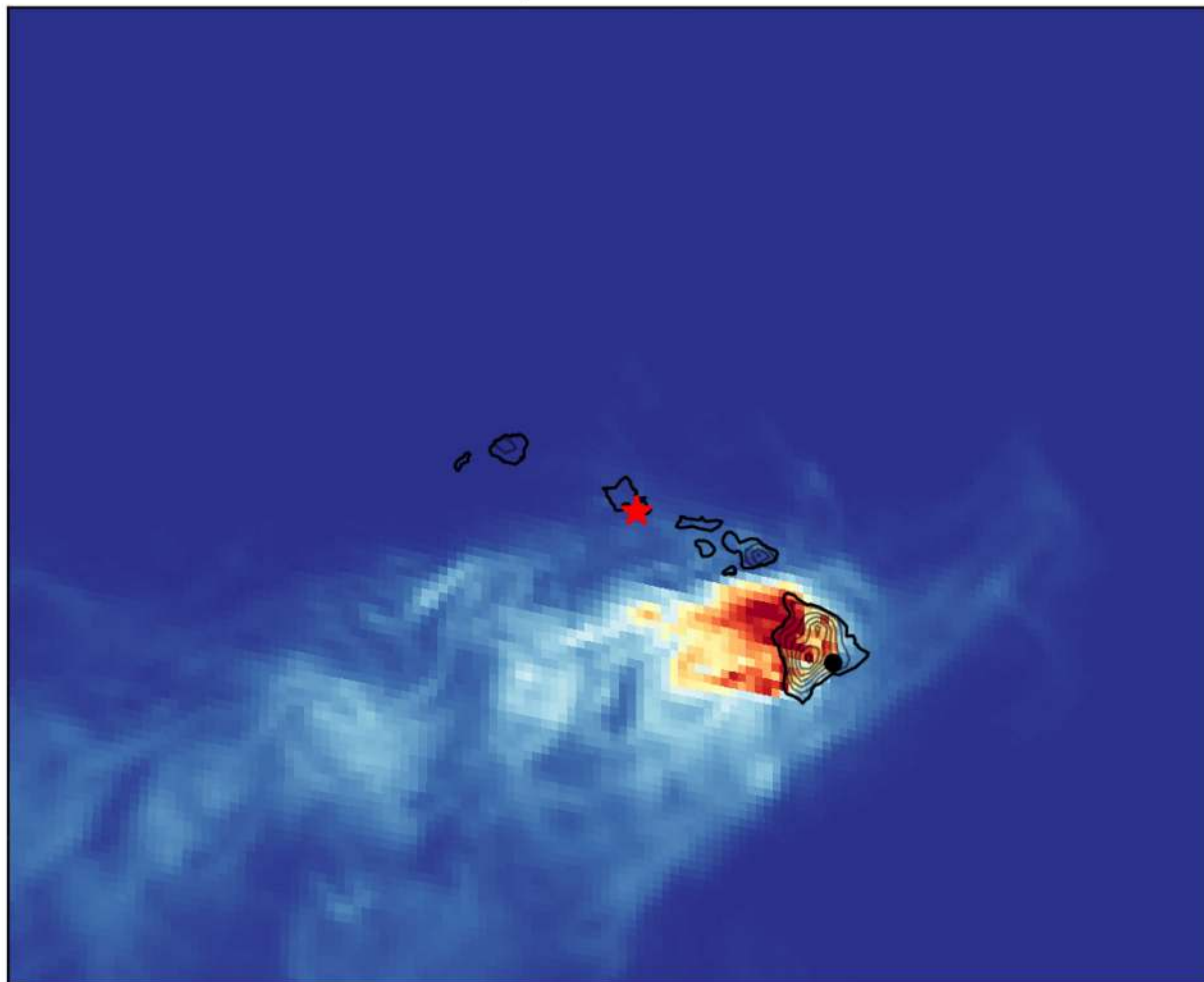
(observation malfunction or volcano lack of activity?)

FV3 Kilauea Emission transport FCST at 2018-06-02 00:00Z



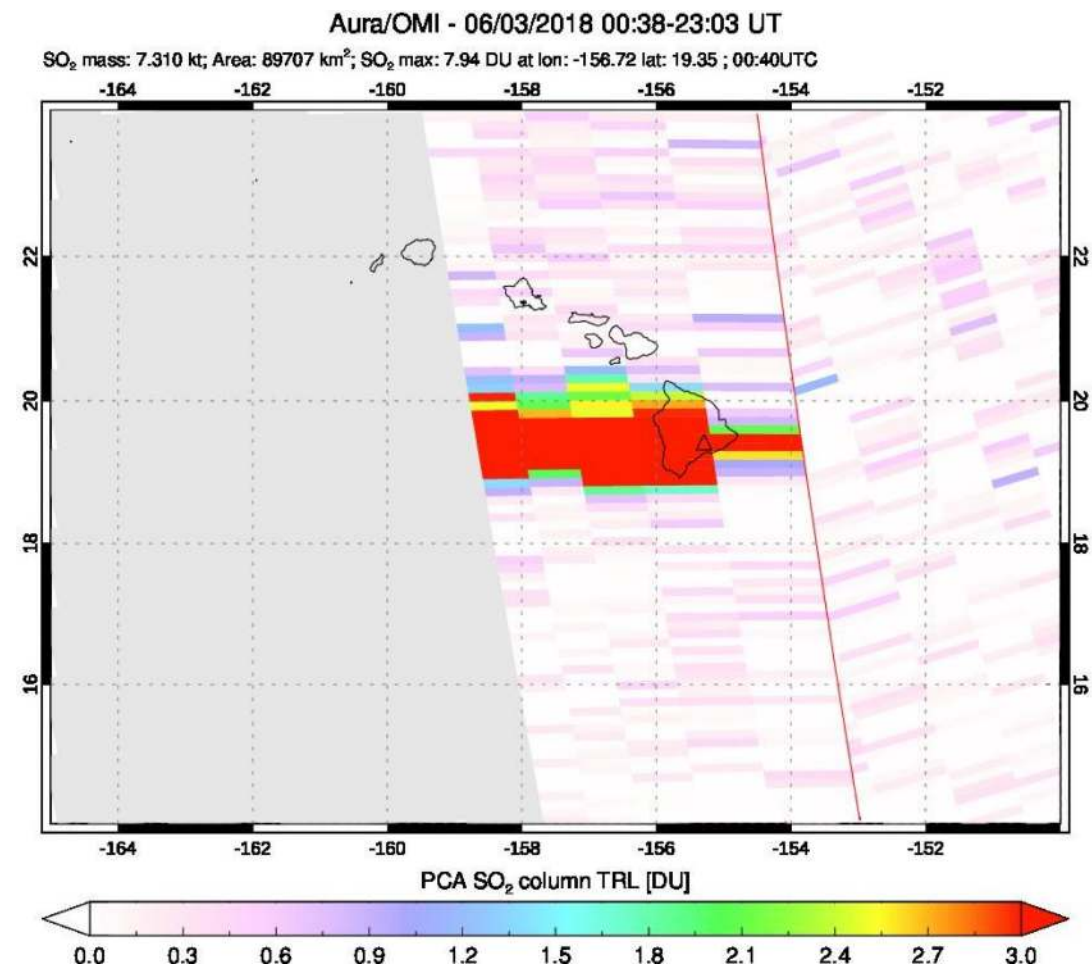
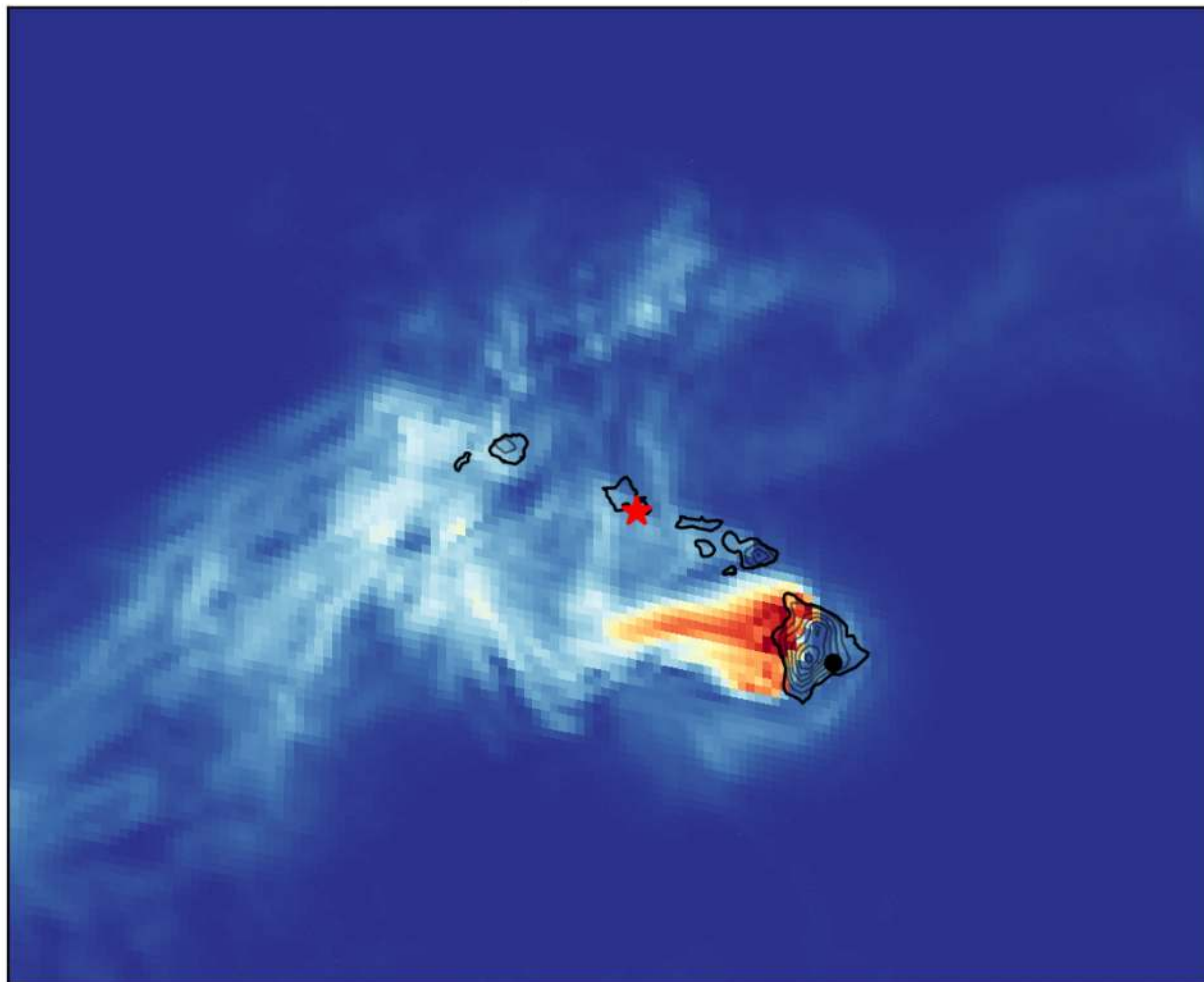
Day-5

FV3 Kilauea Emission transport FCST at 2018-06-03 00:00Z



# Day-6

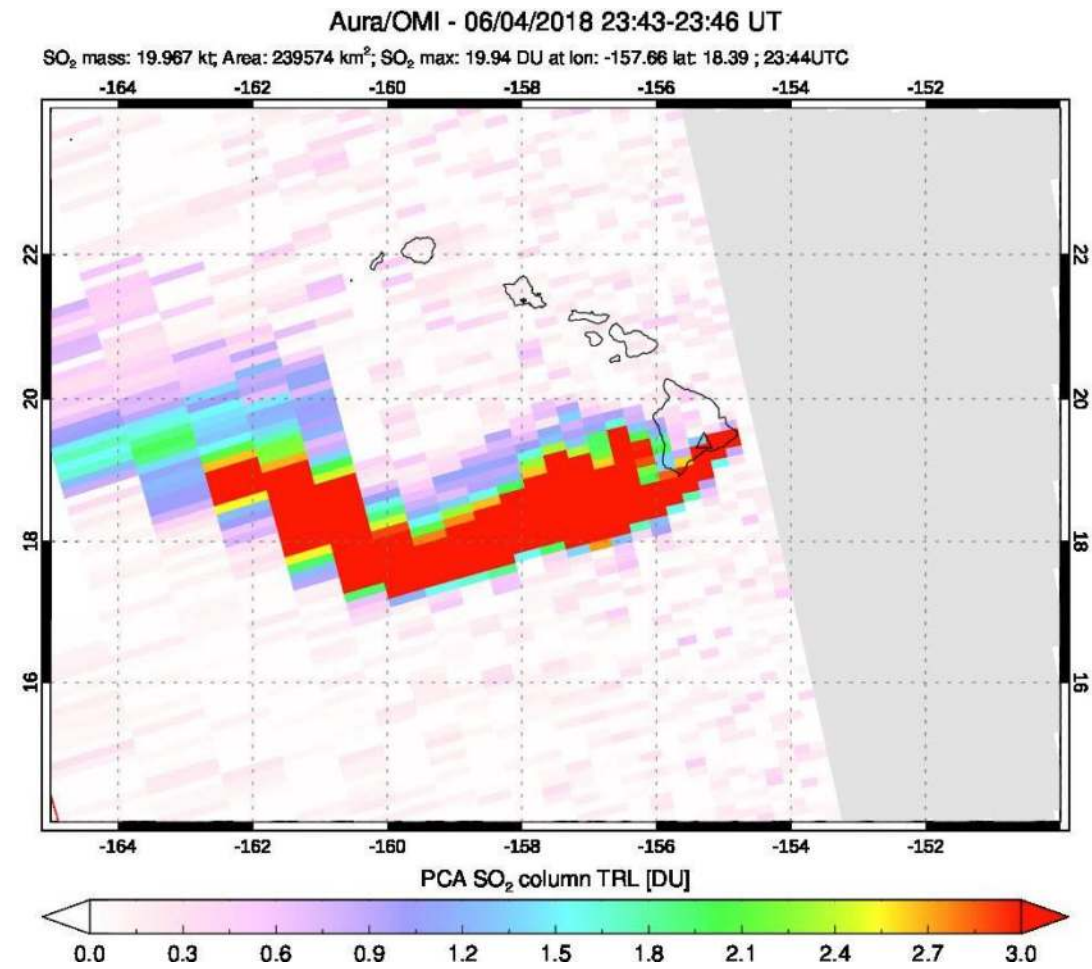
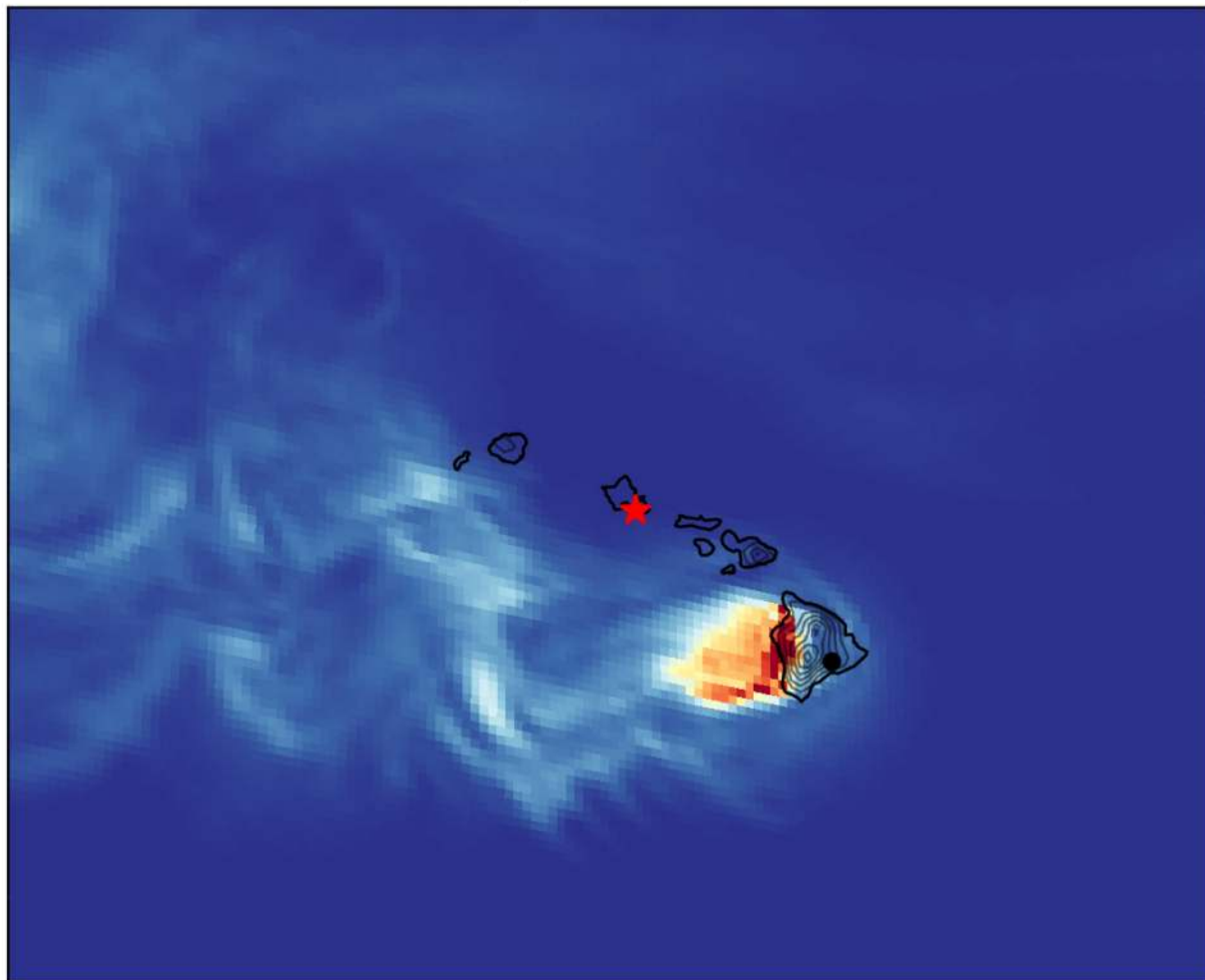
FV3 Kilauea Emission transport FCST at 2018-06-04 00:00Z





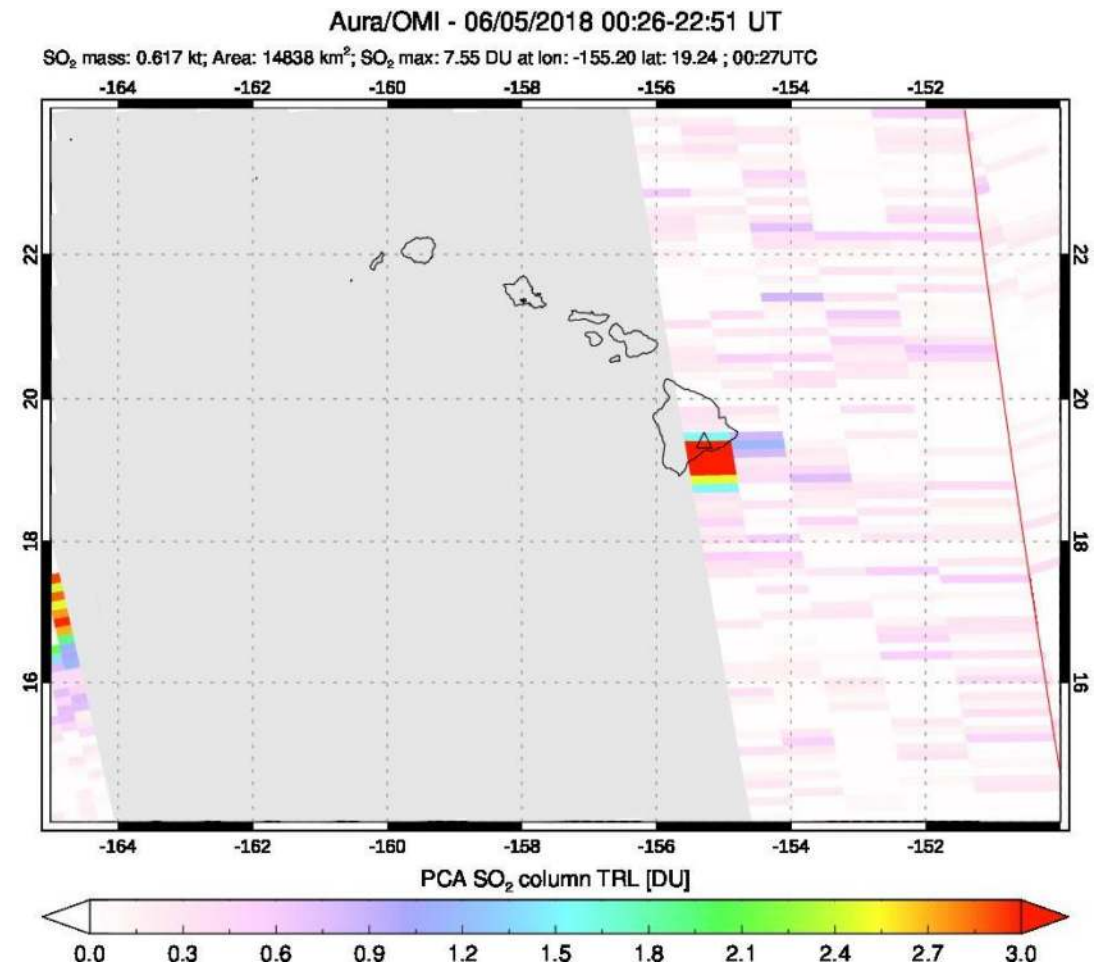
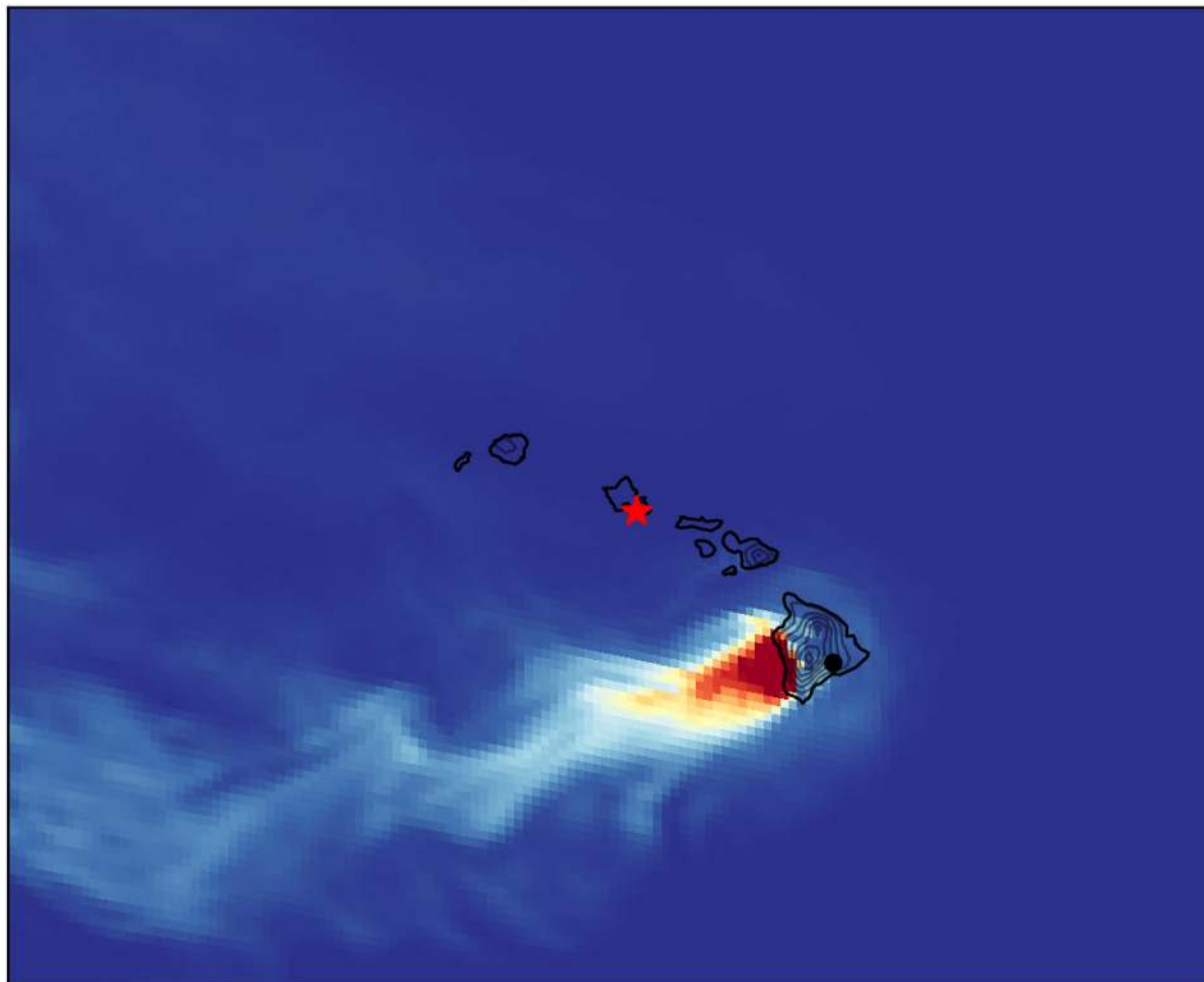
Day-7

FV3 Kilauea Emission transport FCST at 2018-06-05 00:00Z



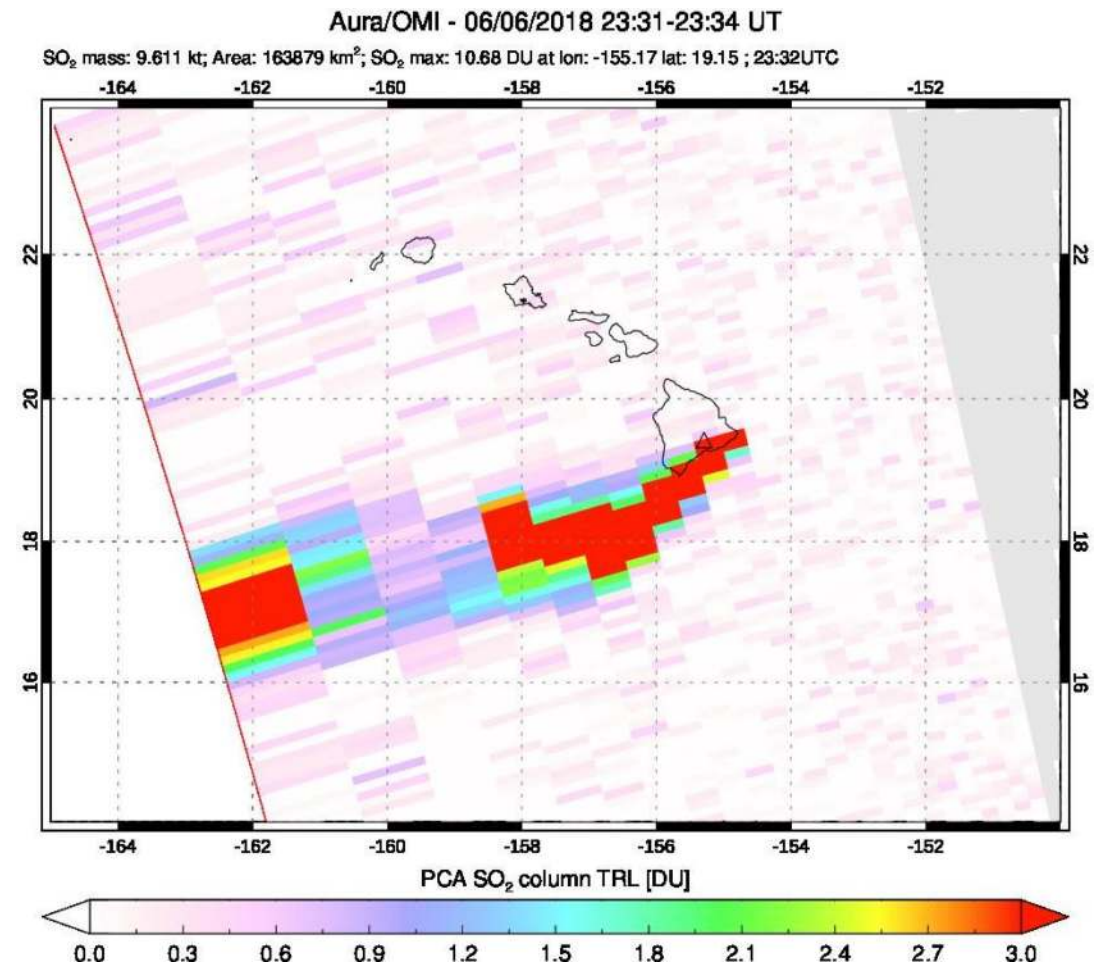
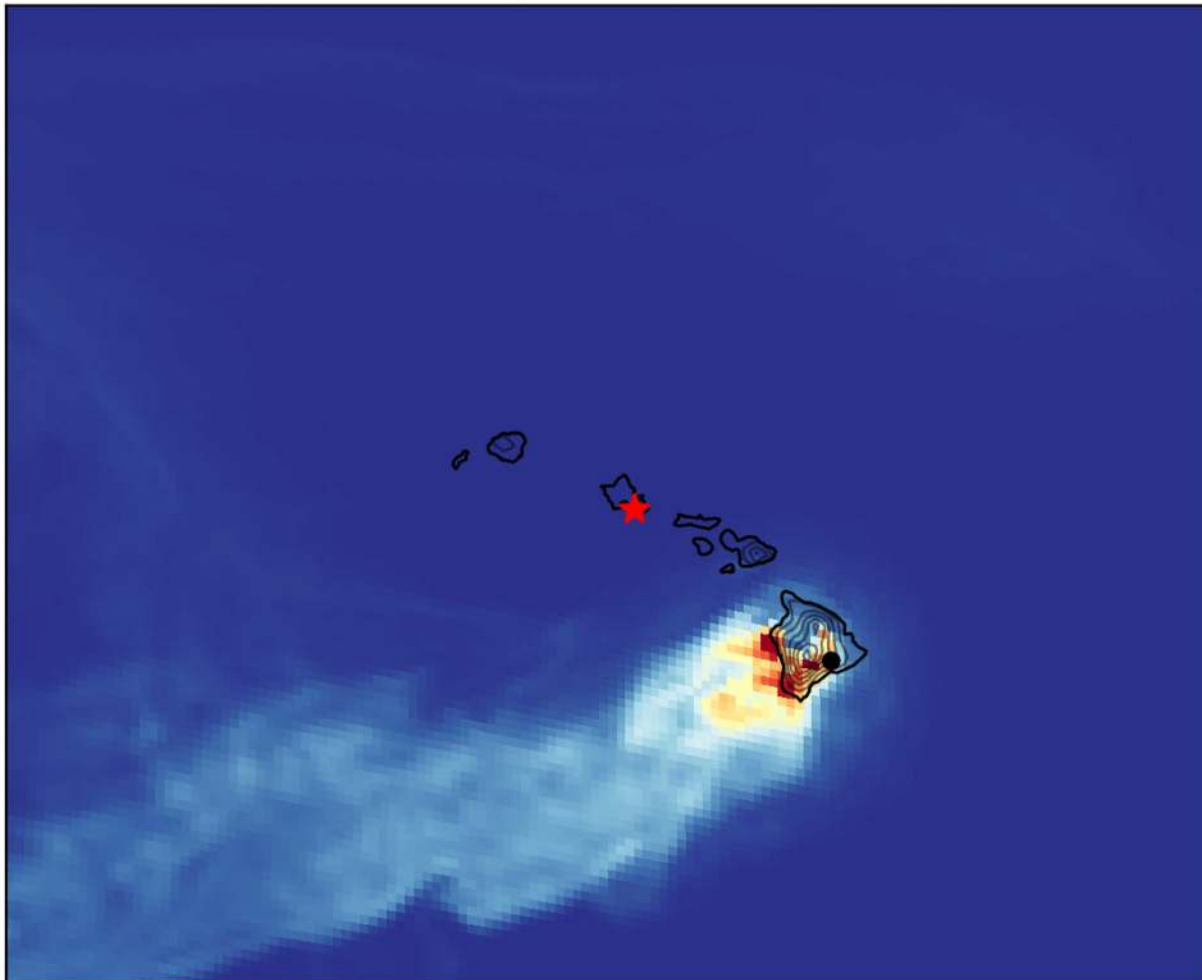
# Day-8

FV3 Kilauea Emission transport FCST at 2018-06-06 00:00Z



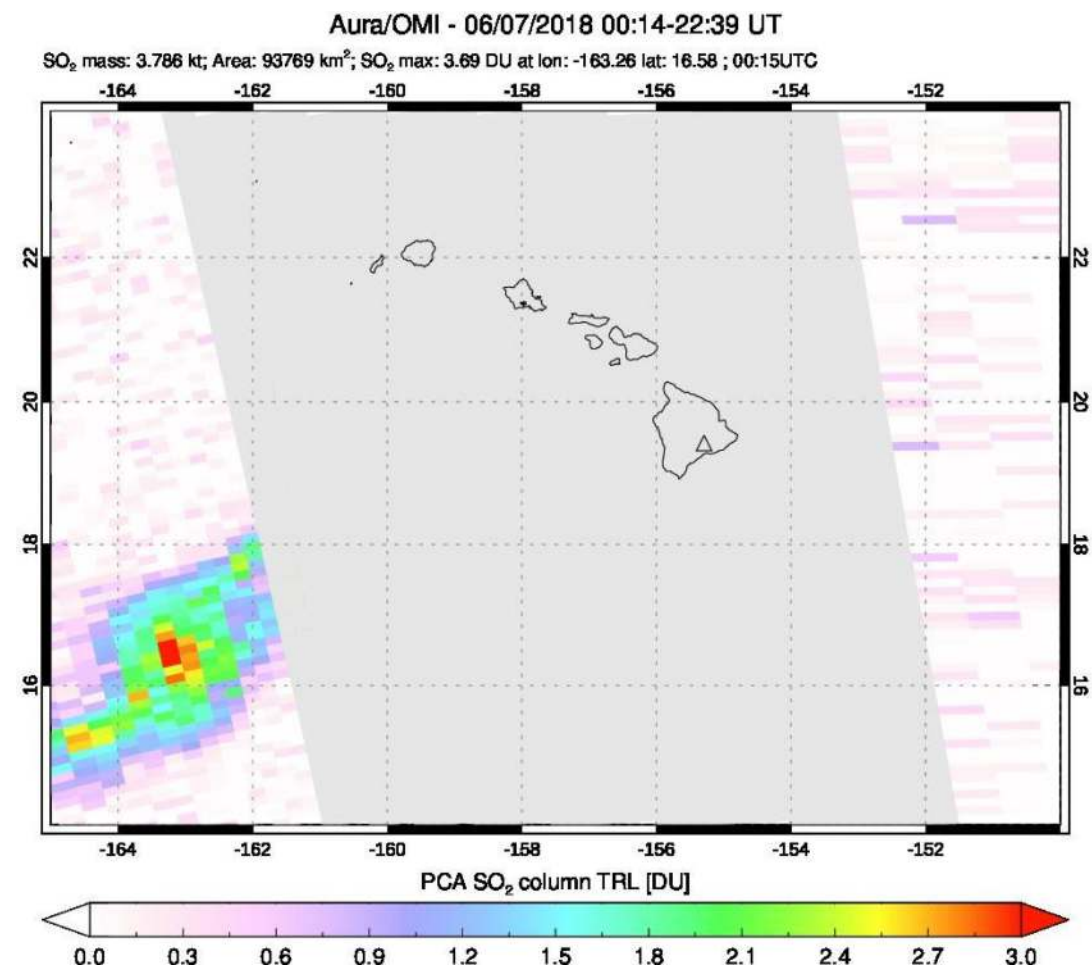
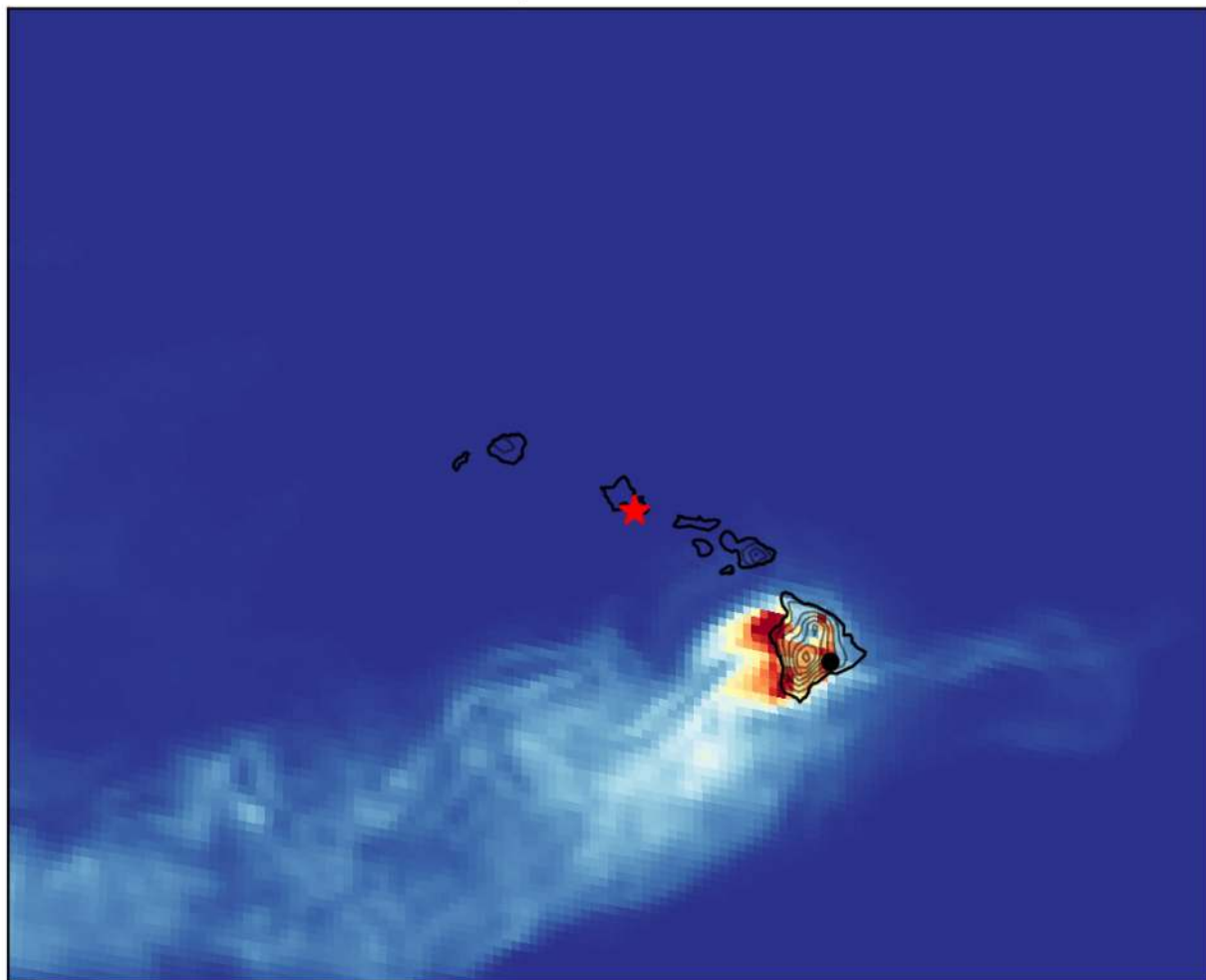
Day-9

FV3 Kilauea Emission transport FCST at 2018-06-07 00:00Z



# Day-10

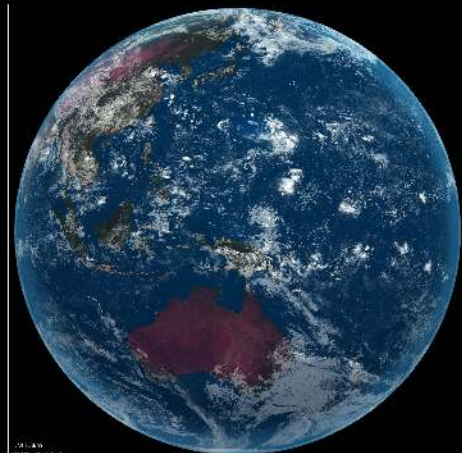
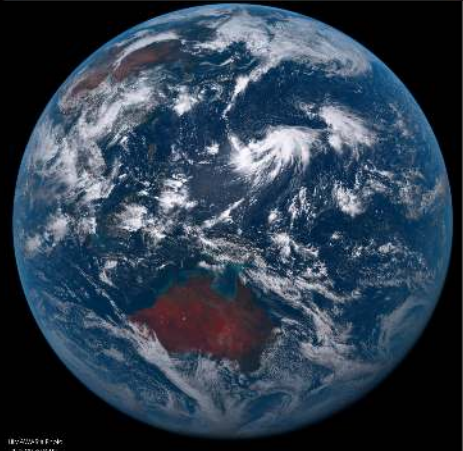
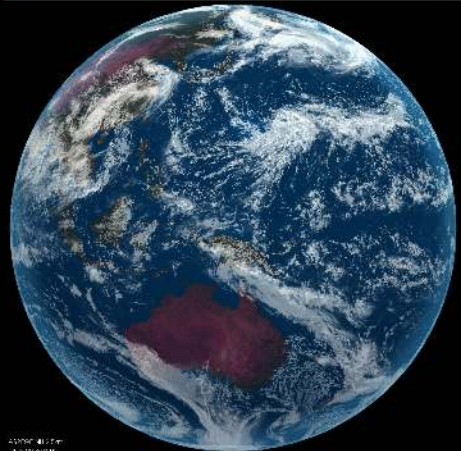
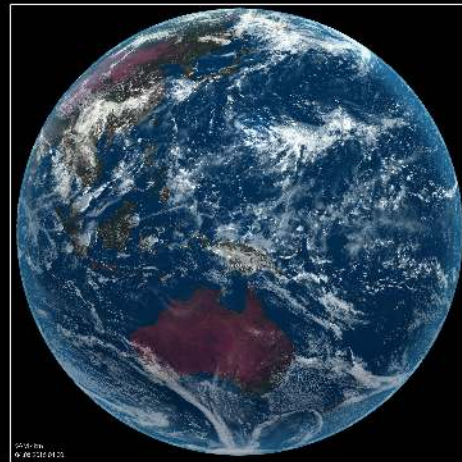
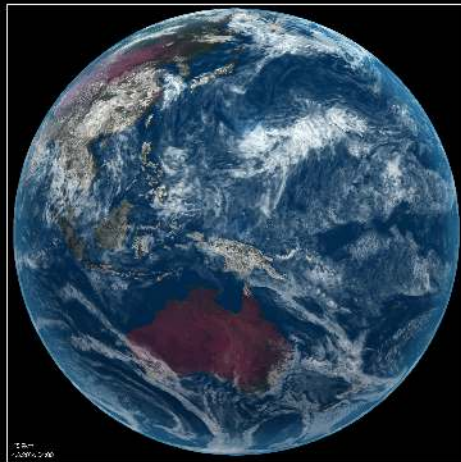
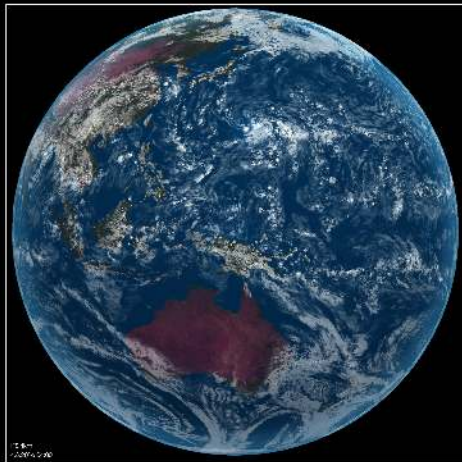
FV3 Kilauea Emission transport FCST at 2018-06-08 00:00Z



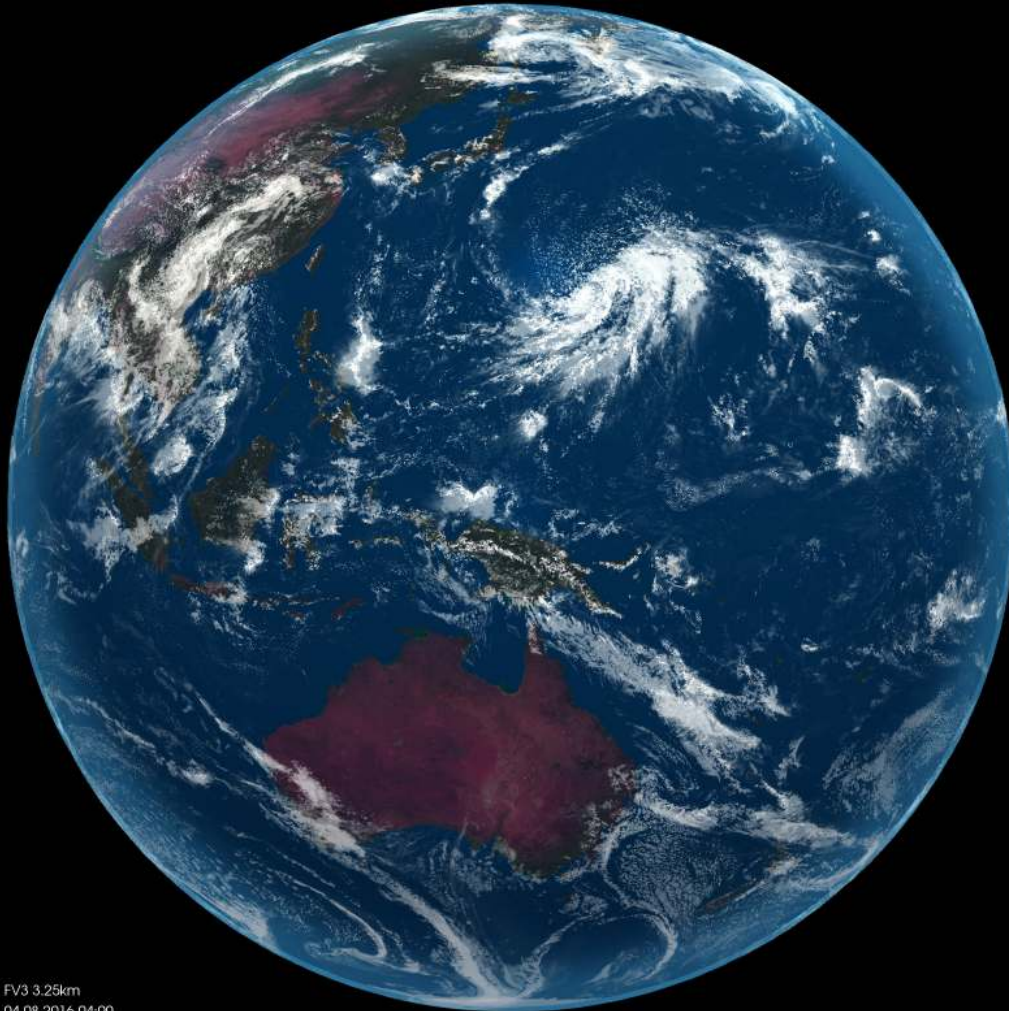


# FV3 in DYAMOND

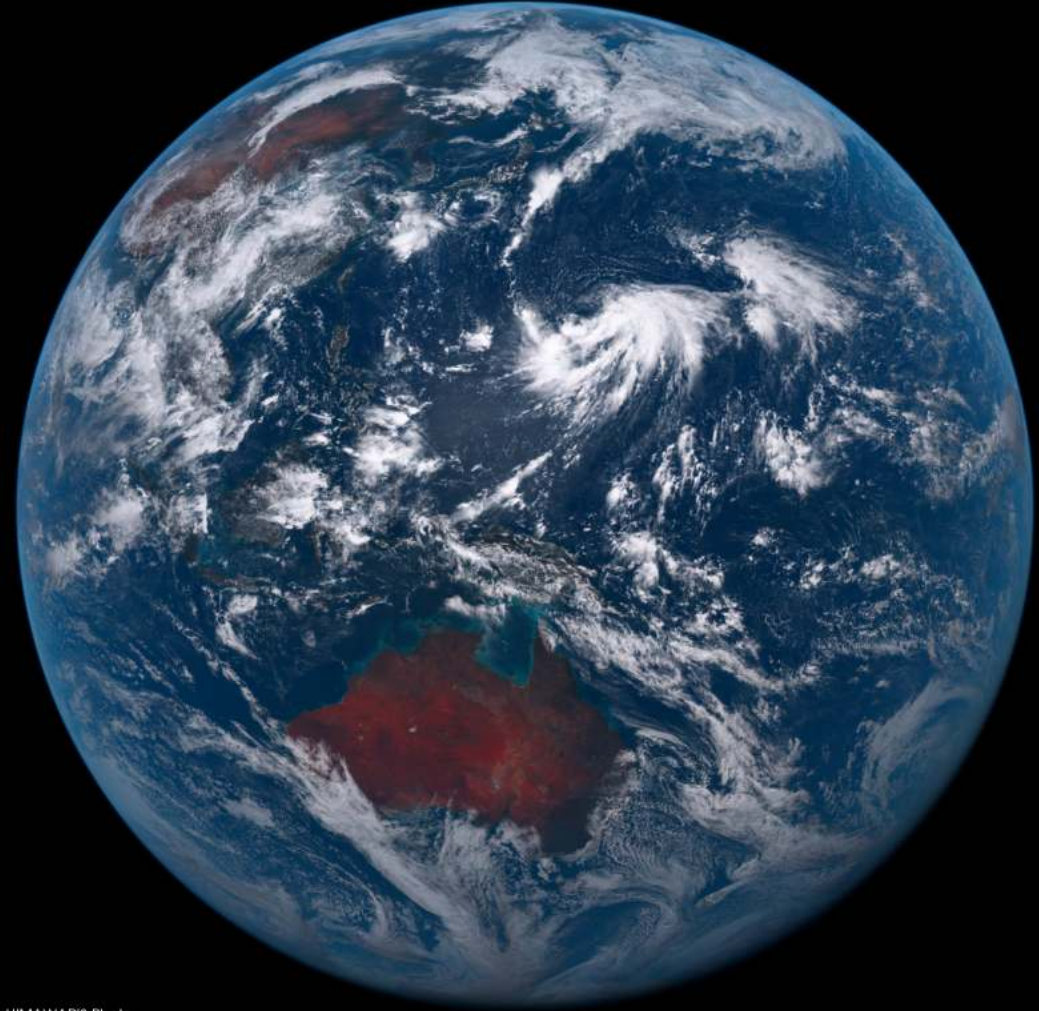
- a bold future of NWP



# | A Bold Future of NWP



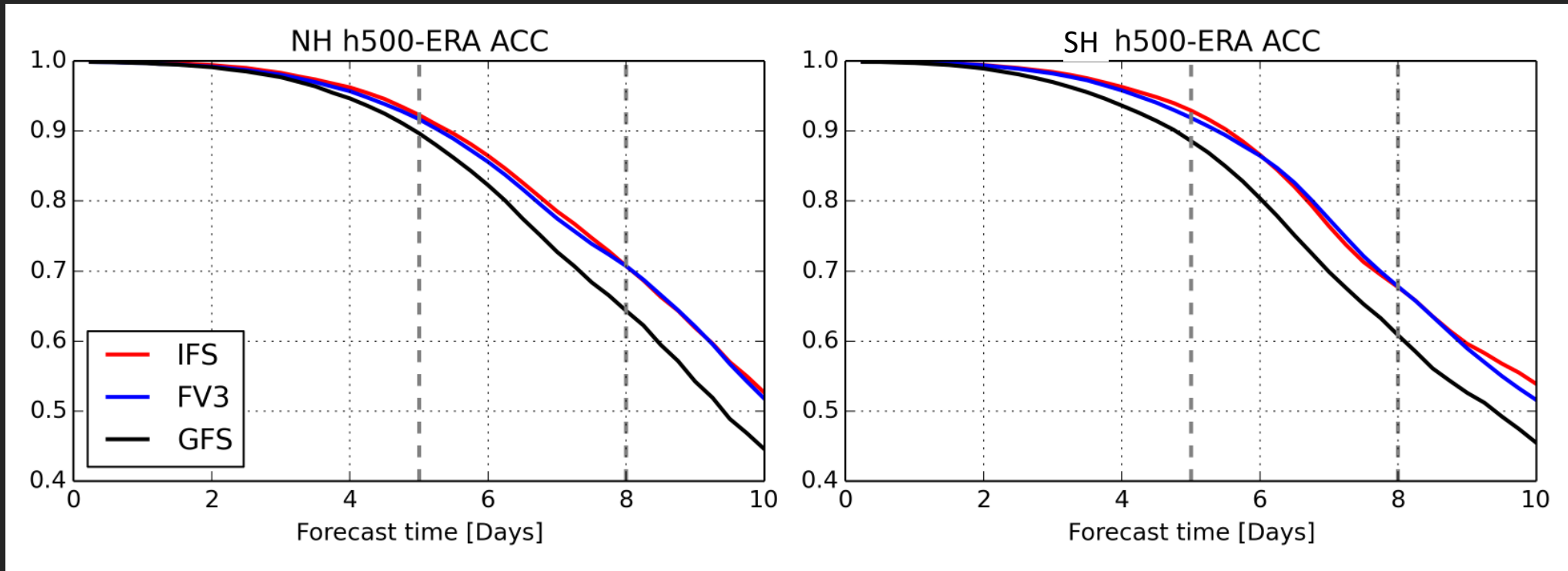
FV3 3.25km  
04.08.2016 04:00



HIMAWARIB Photo  
04.08.2016 04:00

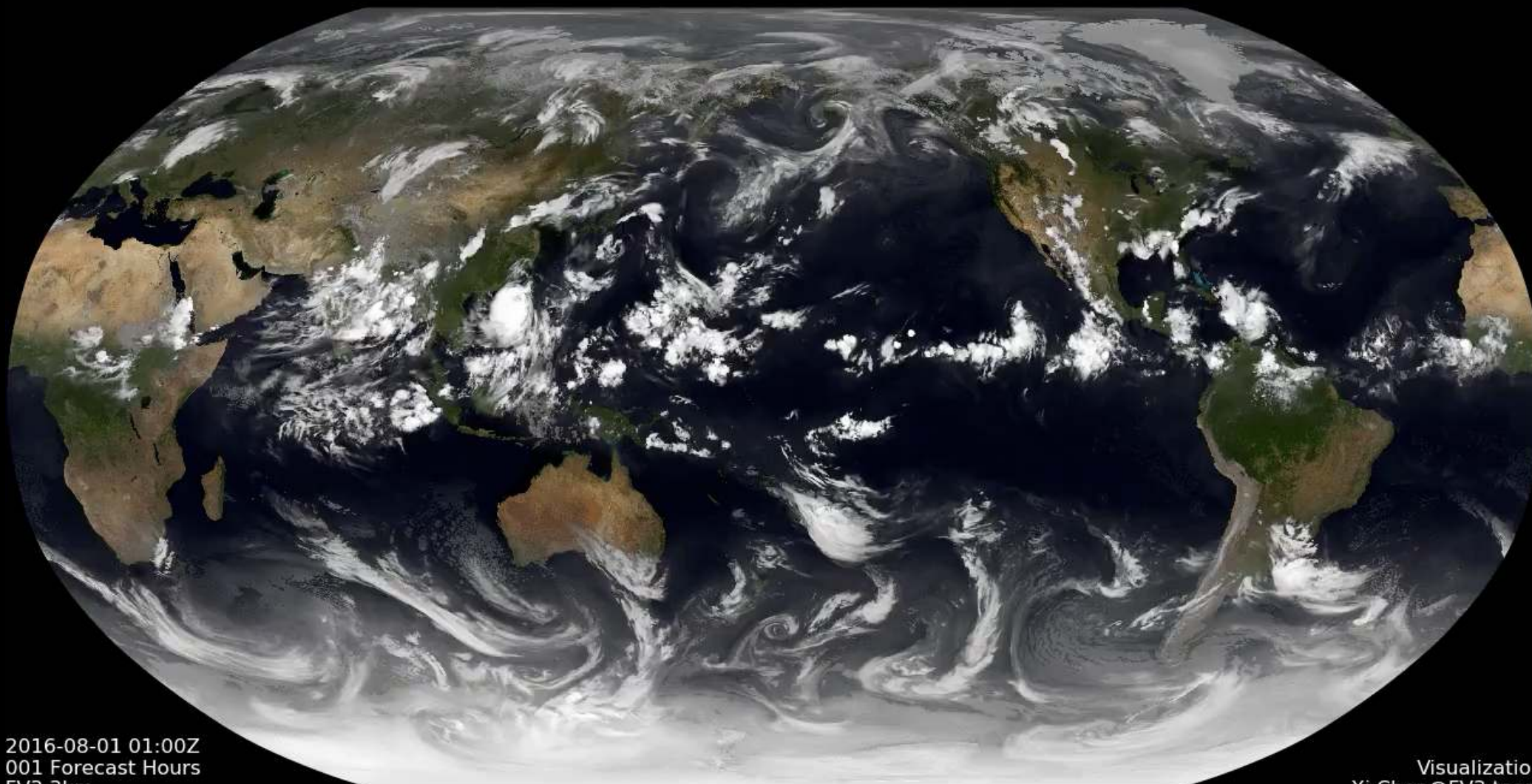
# FV3 with consistent PDC maintains good NWP skills

- FV3-GFS (3-km) vs. NCEP-GFS (13-km) vs. IFS (9-km)
- 24 cases, twice per month for a full year, ACC of h500





# Beyond NWP – (almost) Everything under the sun

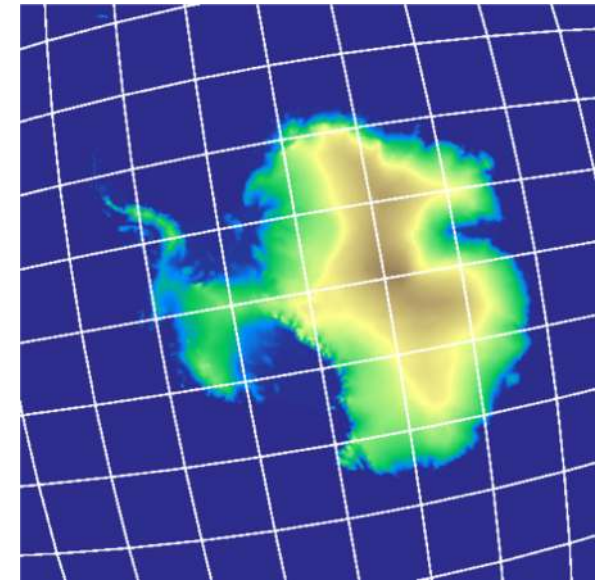
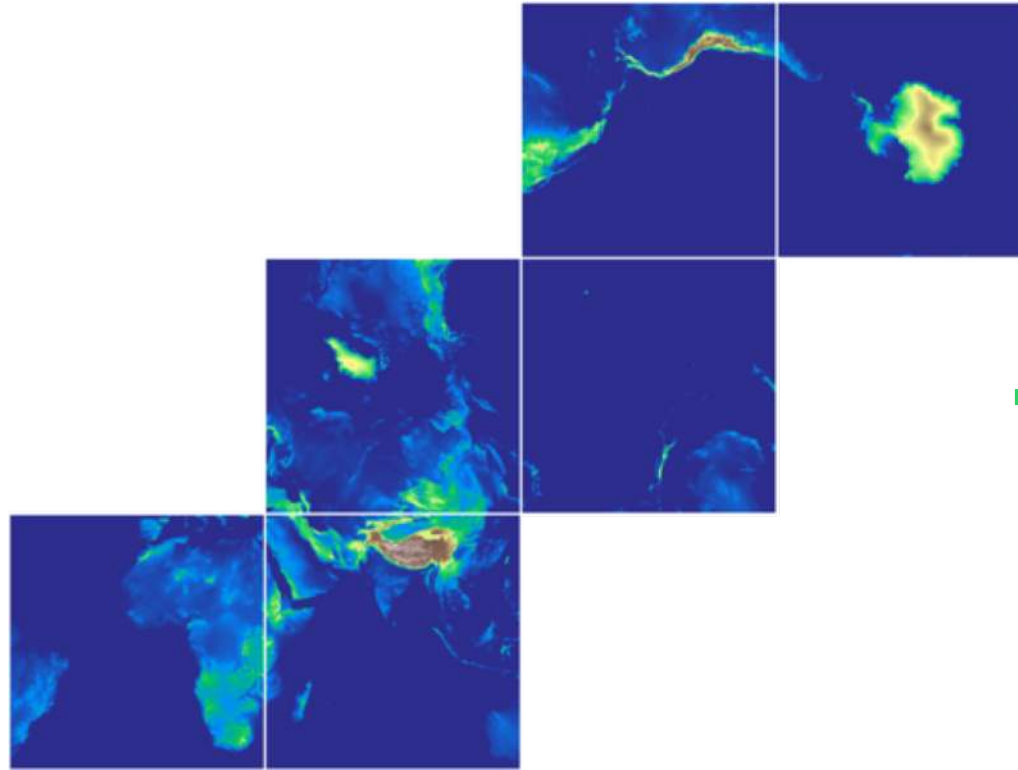
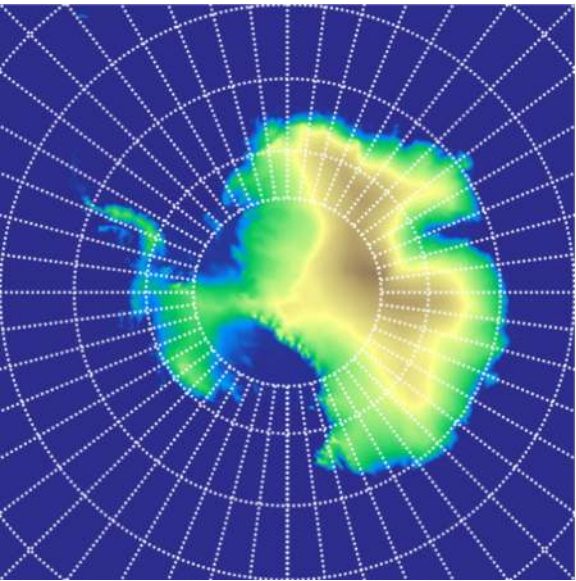
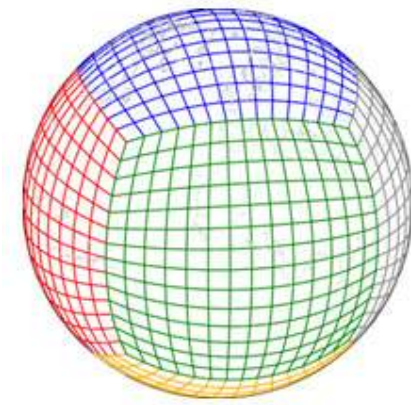


2016-08-01 01:00Z  
001 Forecast Hours  
FV3 3km

Visualization  
Xi Chen@FV3 team

# FV3 data description

native and regridded



# FV3 data description

- Four 10-day segments: 201608?1 – YYYYMMDD
- Native files: [var\_name]\_[15min/3hr].tile[1-6].nc
- RegridDED: [var\_name]\_C3072\_[nlon]x[nlat].fre.nc
- The DYAMOND standardized
  - Units, format, grid, etc.
  - Kudos to Daniel Klocke
- Variable list: <https://www.esiwace.eu/services/dyiamond/dyiamond-specific-pages-and-material/fv3>
- Fv3py => DYAMONDpy

# GFDL FV3 development – SHiELD

System for High-resolution prediction on Earth-to-Local Domain.  
Advances in SHiELD will benefit other UFS applications as well as other FV3-based models.

- SHiELD – 13km/9.5km
- S-SHiELD – 25km S2S/climate
- T-SHiELD – 3km (convective scale) nest tropical
- C-SHiELD – 3km (convective scale) nest continental
- R-ShiELD – standalone regional
- x-ShiELD – 3km global cloud resolving

A satellite image of Earth showing a large hurricane over the Atlantic Ocean. The hurricane is a prominent white spiral with a clear eye, surrounded by dense white clouds. The surrounding ocean is dark, and the landmasses of North and South America are visible in the lower-left corner. The overall scene is a high-contrast, black and white representation of the planet's weather patterns.

## X-SHiELD exploration

- A demonstration of GFDL GCRM and unified weather-climate model capabilities
- A platform for new scientific and computational model advances
- A tool for weather and climate research from the general circulation to convective-scales
- A means to leverage GCRM simulations to improve lower-resolution models