Performance Analysis and Optimization of the Weather Research and Forecasting Model (WRF) Advection Schemes

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WRF is a numerical weather prediction system designed for both atmospheric research and operational forecasting.

Community model with **large user base**:

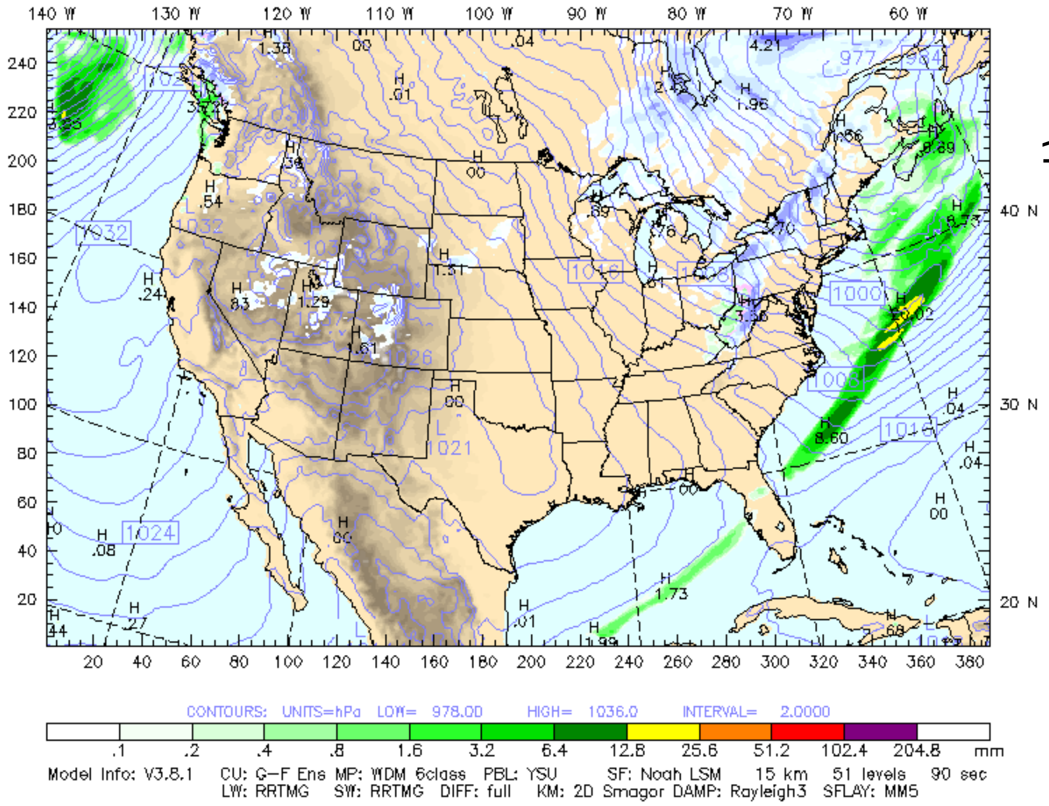
- More than 30,000 users in 150 countries

Research Goals

Goal 1. WRF scalability and comparison between MPI and hybrid parallelism

Goal2. Identify hotspots and potential areas for improvement in WRF

Goal3. Optimize the code to improve the performance of the hotspots



15 km X15 km

~2 million gridpoints

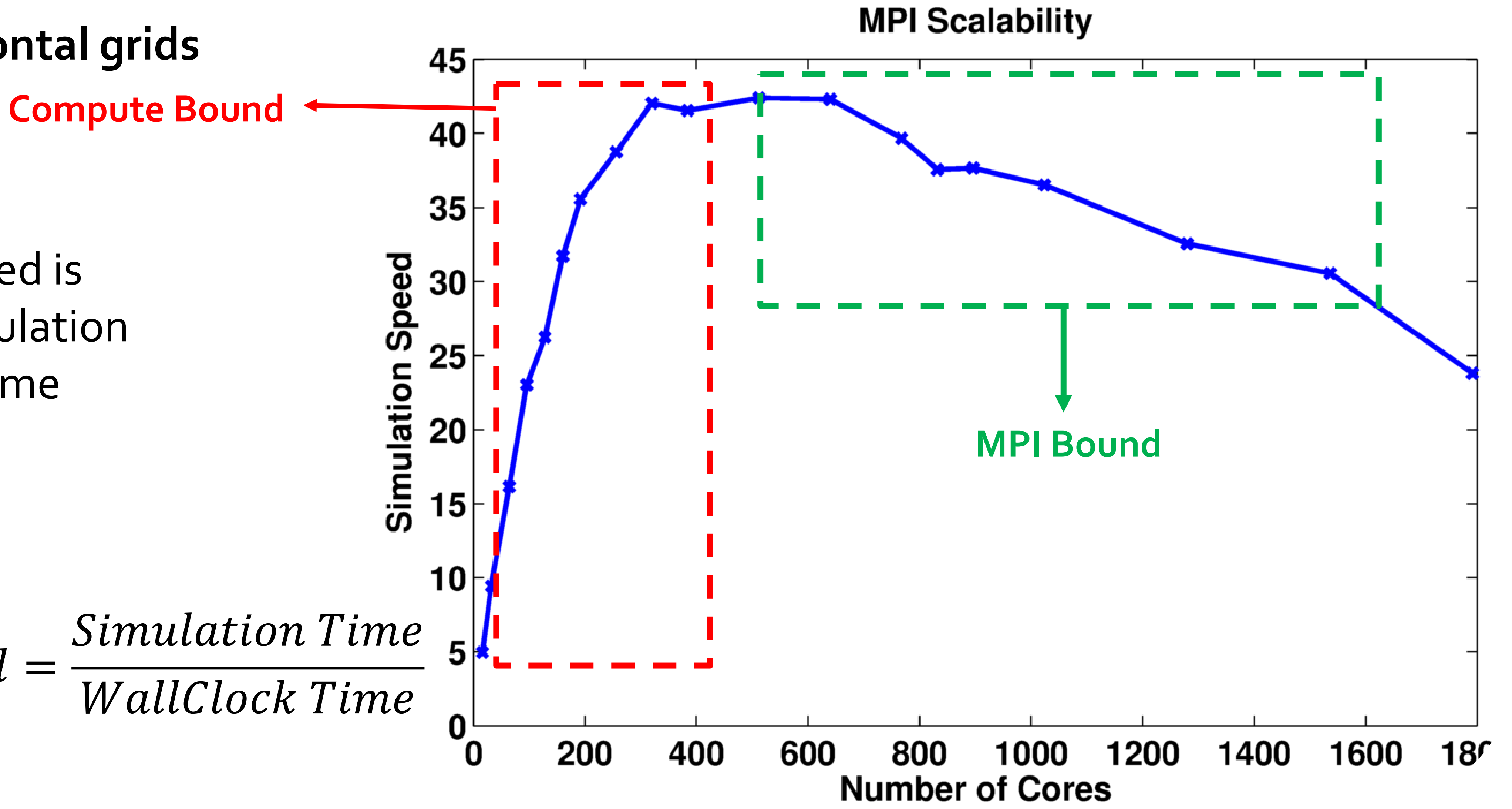
Higher resolutions???

Scalability Assessment (MPI Only)

500X500 horizontal grids

Simulation Speed is duration of simulation per wall clock time

$$Simulation\ Speed = \frac{Simulation\ Time}{WallClock\ Time}$$

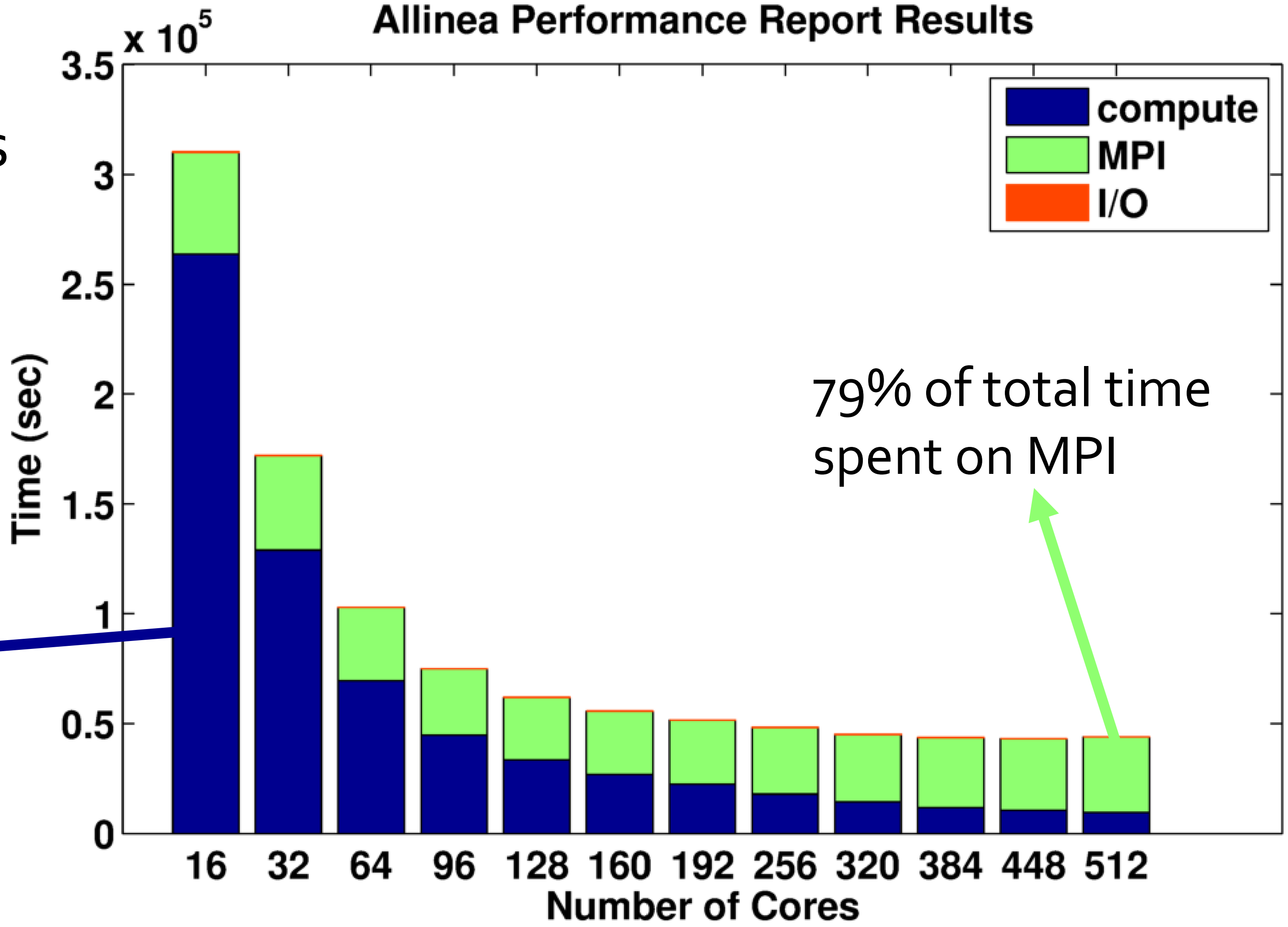


Scalability Assessment (MPI Only)

- Allinea Perfomance Reports
- Separate netcdf output file

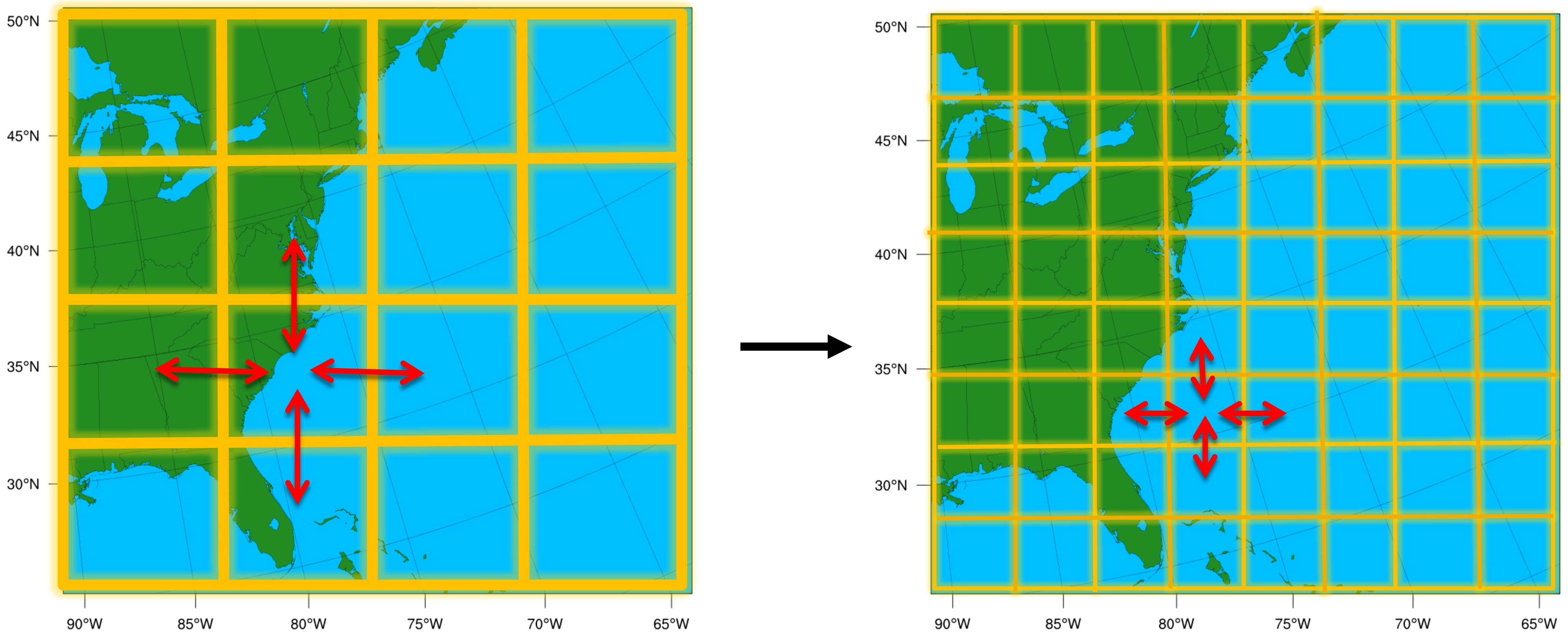
(io_form_history=102 in WRF namelist)

87% of total time spent on computation



79% of total time spent on MPI

Domain Decomposition (MPI only)



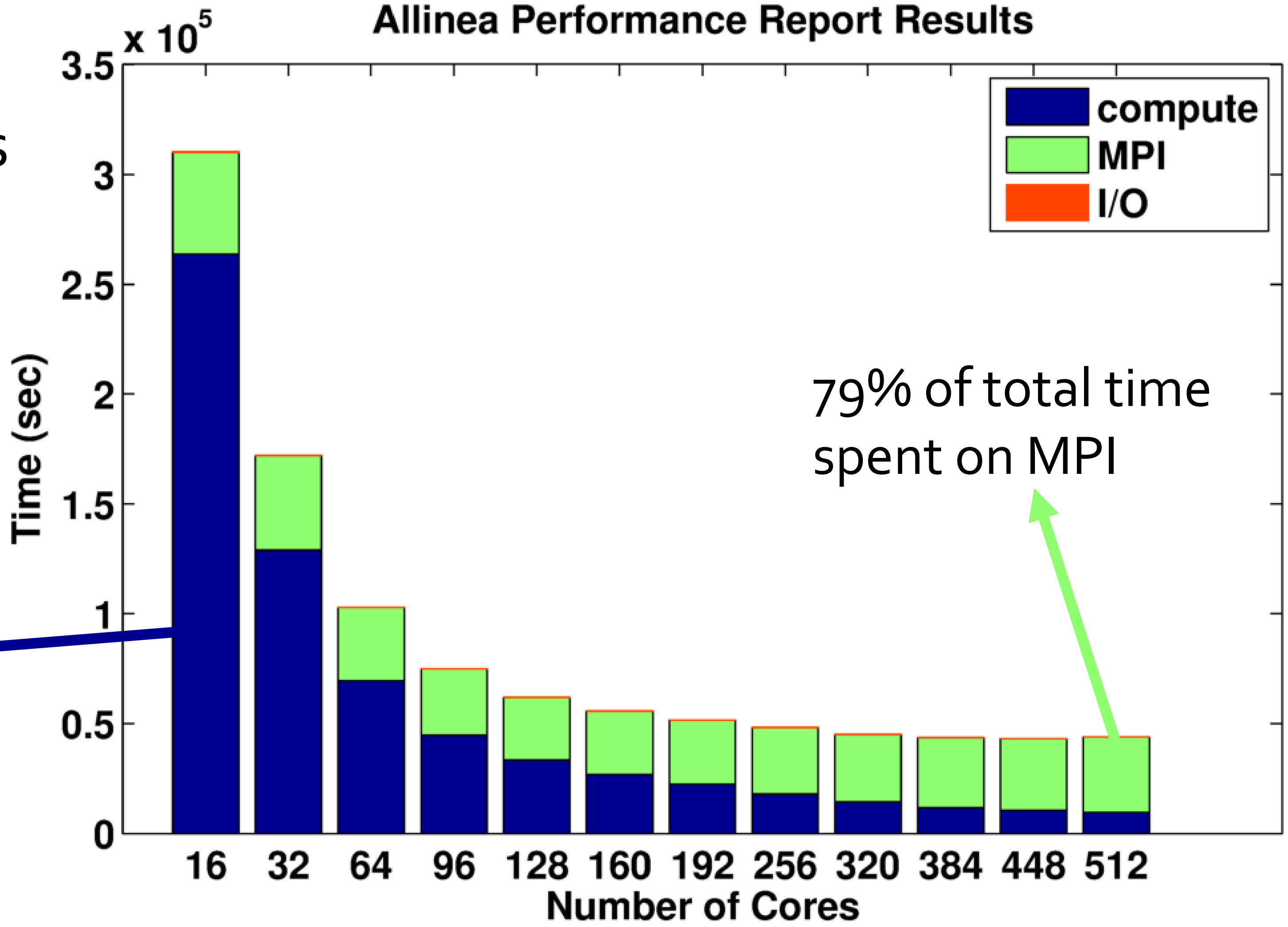
Per Grid :1/4 Computation and 1/2 MPI

Scalability Assessment (MPI Only)

- Allinea Perfomance Reports
- Separate netcdf output file

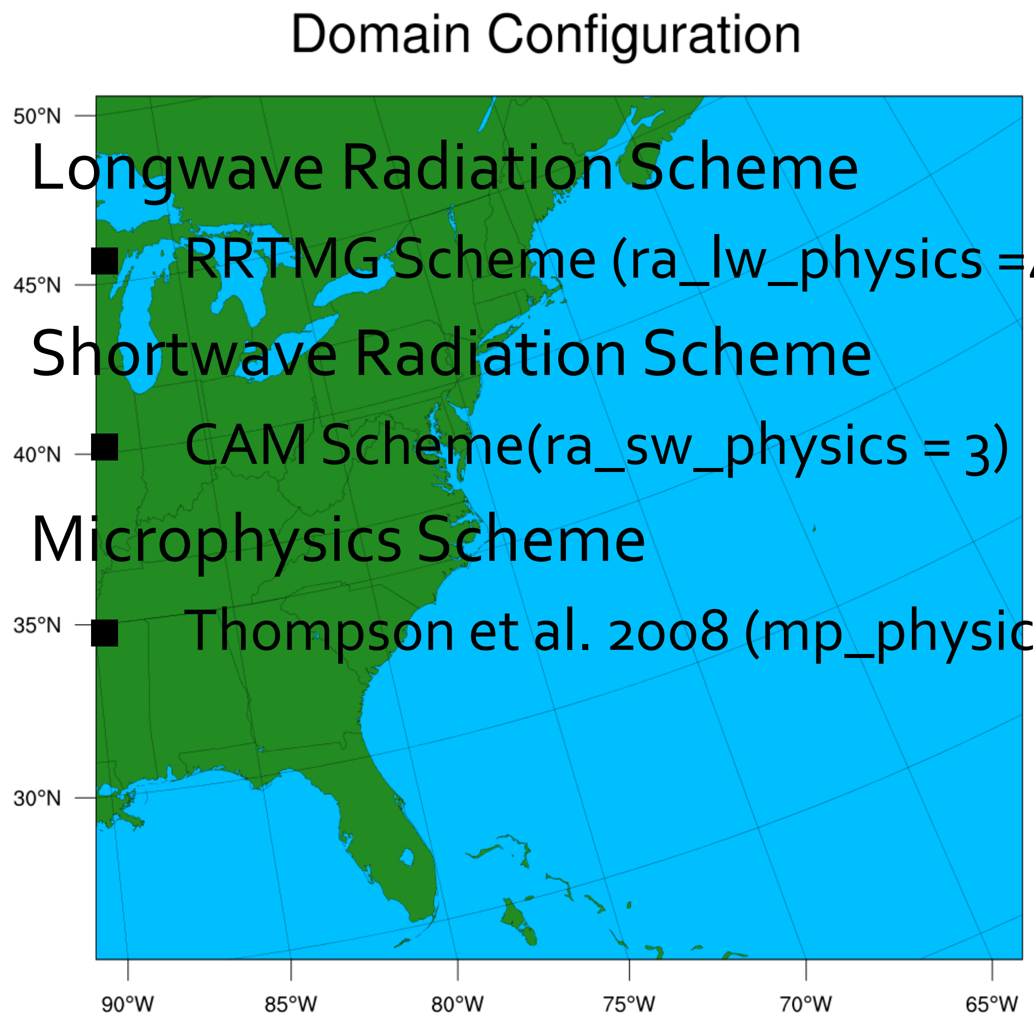
(io_form_history=102 in WRF namelist)

87% of total time spent on computation



Goal2.What does make WRF expensive?

Hurricane Sandy 4x4km case(500x500)



Longwave Radiation Scheme

- RRTMG Scheme (ra_lw_physics =4)

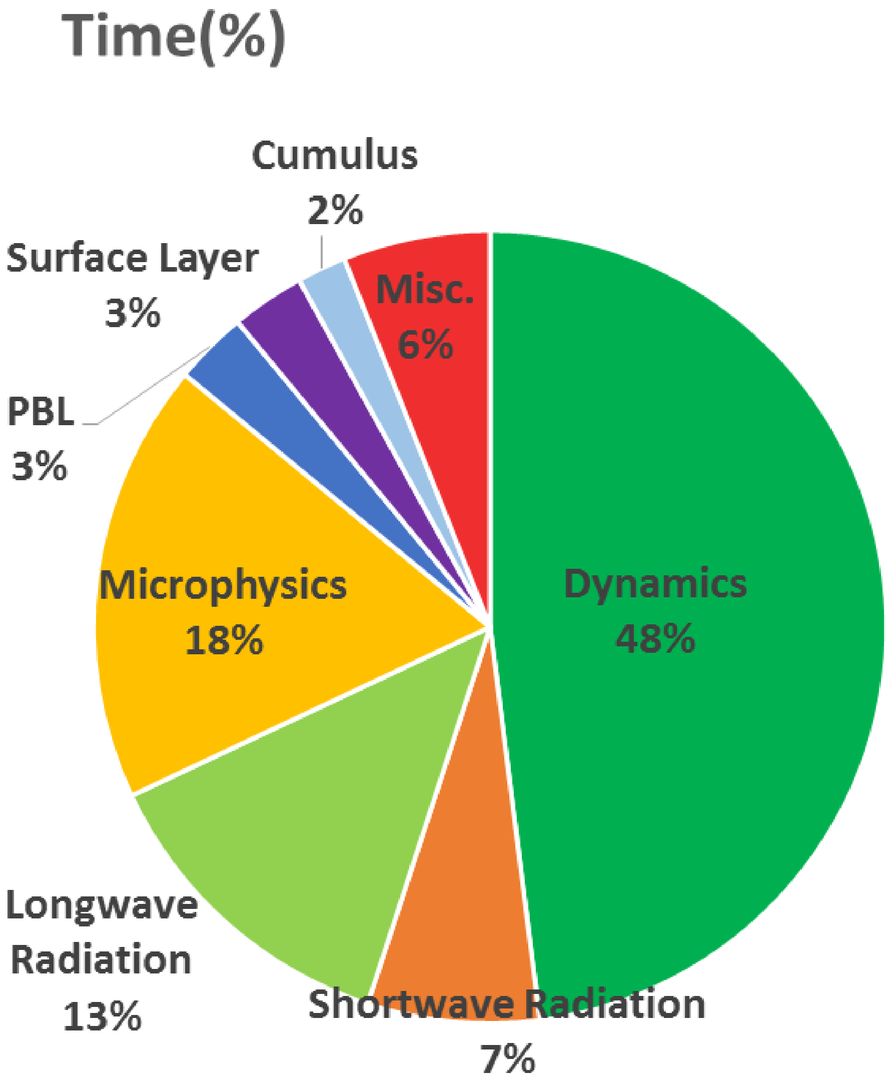
Shortwave Radiation Scheme

- CAM Scheme(ra_sw_physics = 3)

Microphysics Scheme

- Thompson et al. 2008 (mp_physics =8)

Intel Vtune Amplifier XE Results



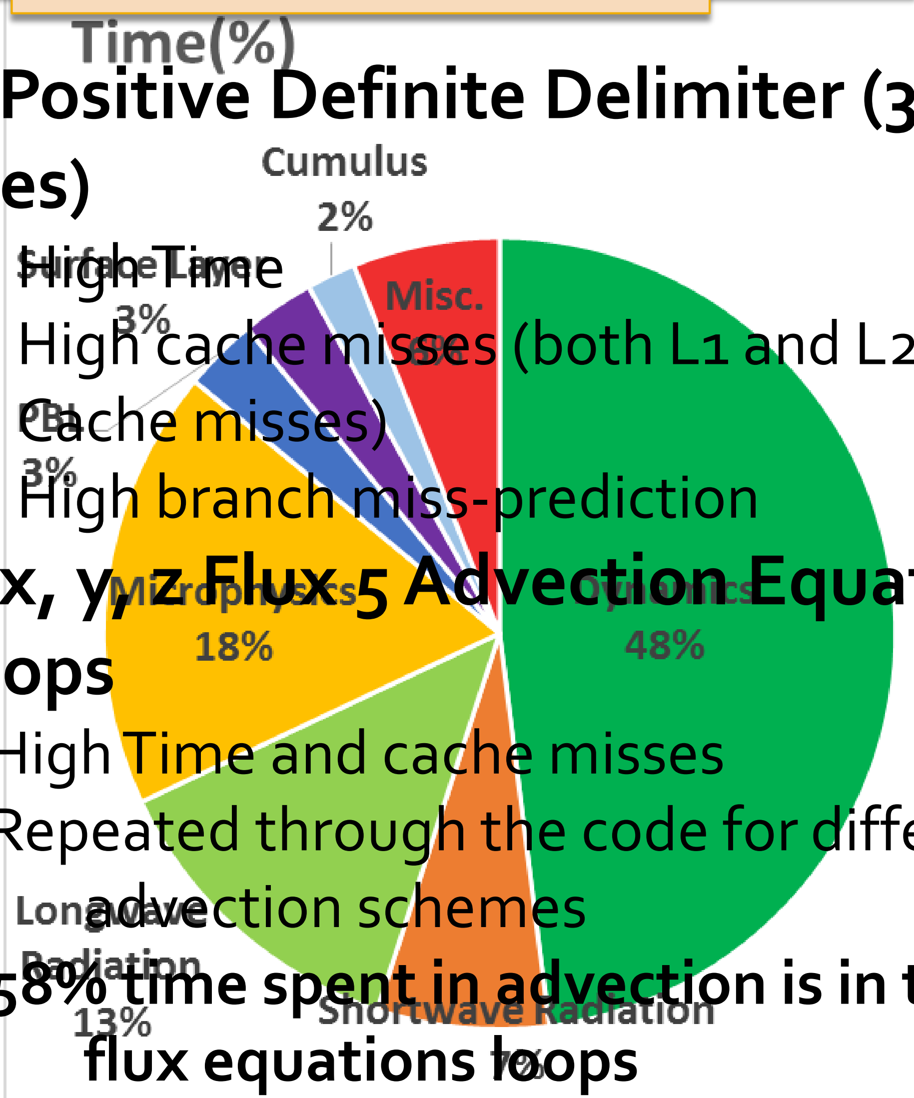
Identifying hotspots and potential areas for improvement in WRF

Detailed loop level high granularity analysis:

1- TAU tools

2- Allinea MAP

TAU/PAPI Tools Results



1- Positive Definite Delimiter (32 lines)

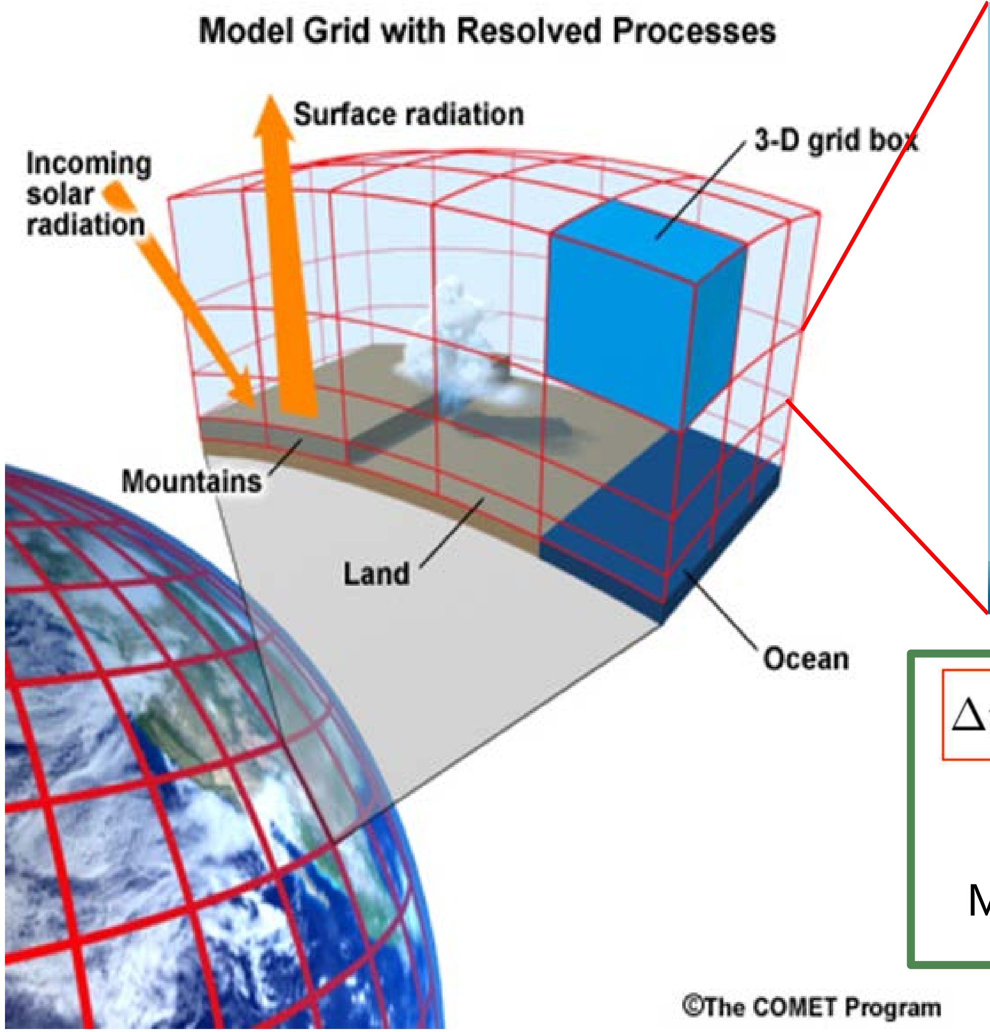
- High Time
- High cache misses (both L1 and L2 Cache misses)
- High branch miss-prediction

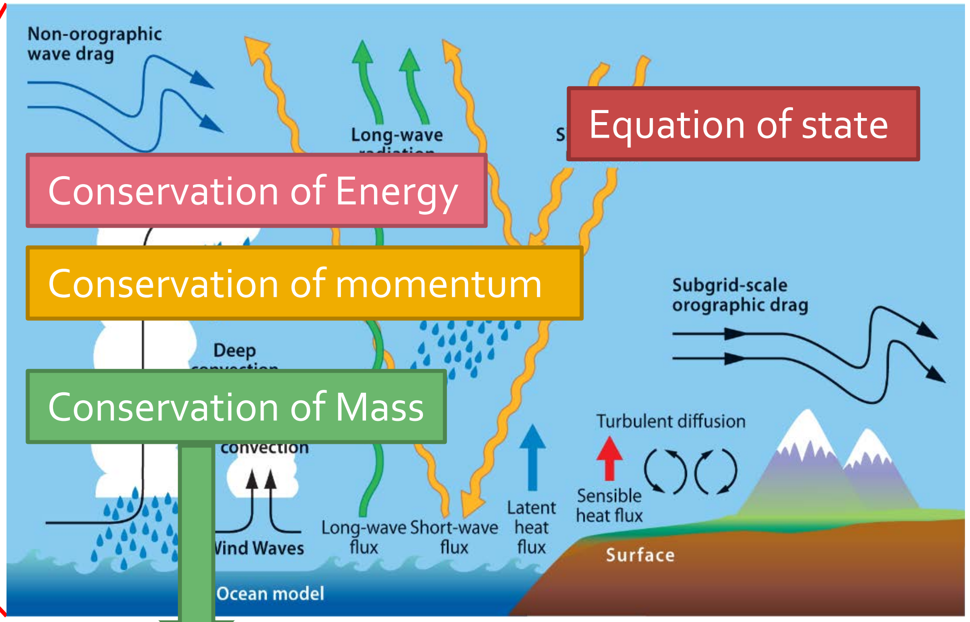
2- x, y, z Flux 5 Advection Equation Loops

- High Time and cache misses
- Repeated through the code for different advection schemes

58% time spent in advection is in these flux equations loops

Mass Conservation in the WRF Model





$$\Delta t^{-1}(\Delta x \Delta \eta)\cdot[(\mu)^{t+\Delta t}-(\mu)^{t})] = [(\mu u\Delta\eta)_{x-\Delta x/2,\eta} - (\mu u \Delta\eta)_{x+\Delta x/2,\eta})] + [(\mu\omega\Delta x)_{x,\eta-\Delta\eta/2} - (\mu\omega\Delta x)_{x,\eta+\Delta\eta/2})]$$

Mass change over a time step

Mass fluxes through control volume faces

Image adapted from UCAR COMET and NOAA

Moisture transport in ARW

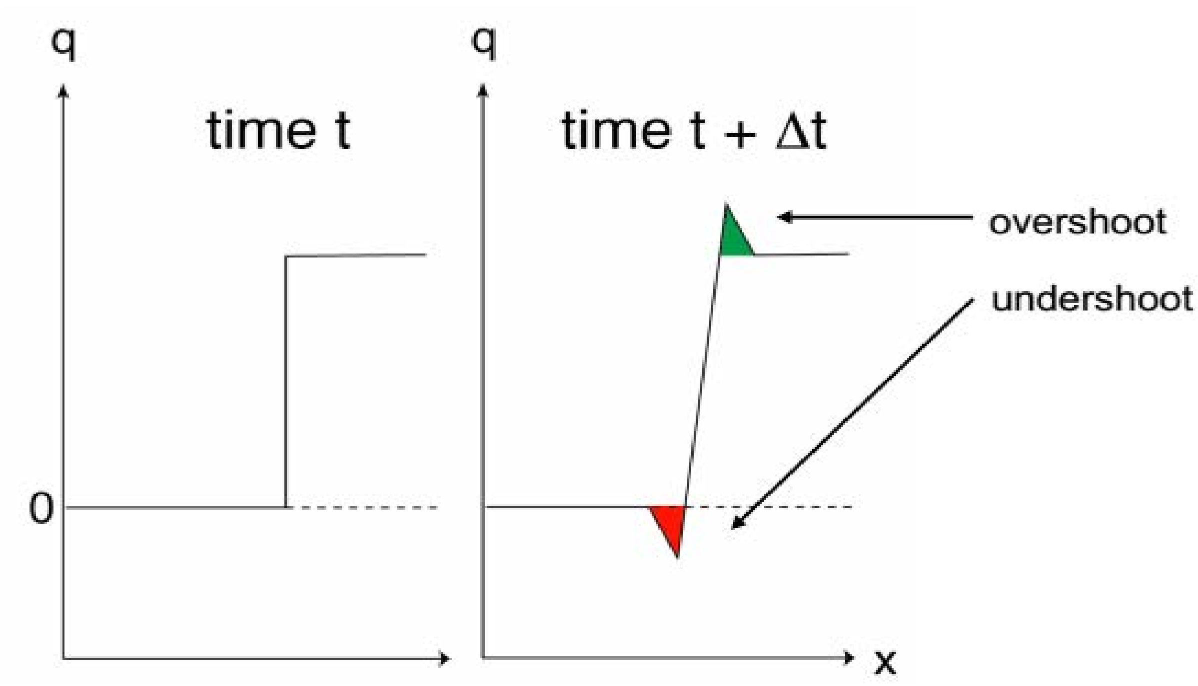
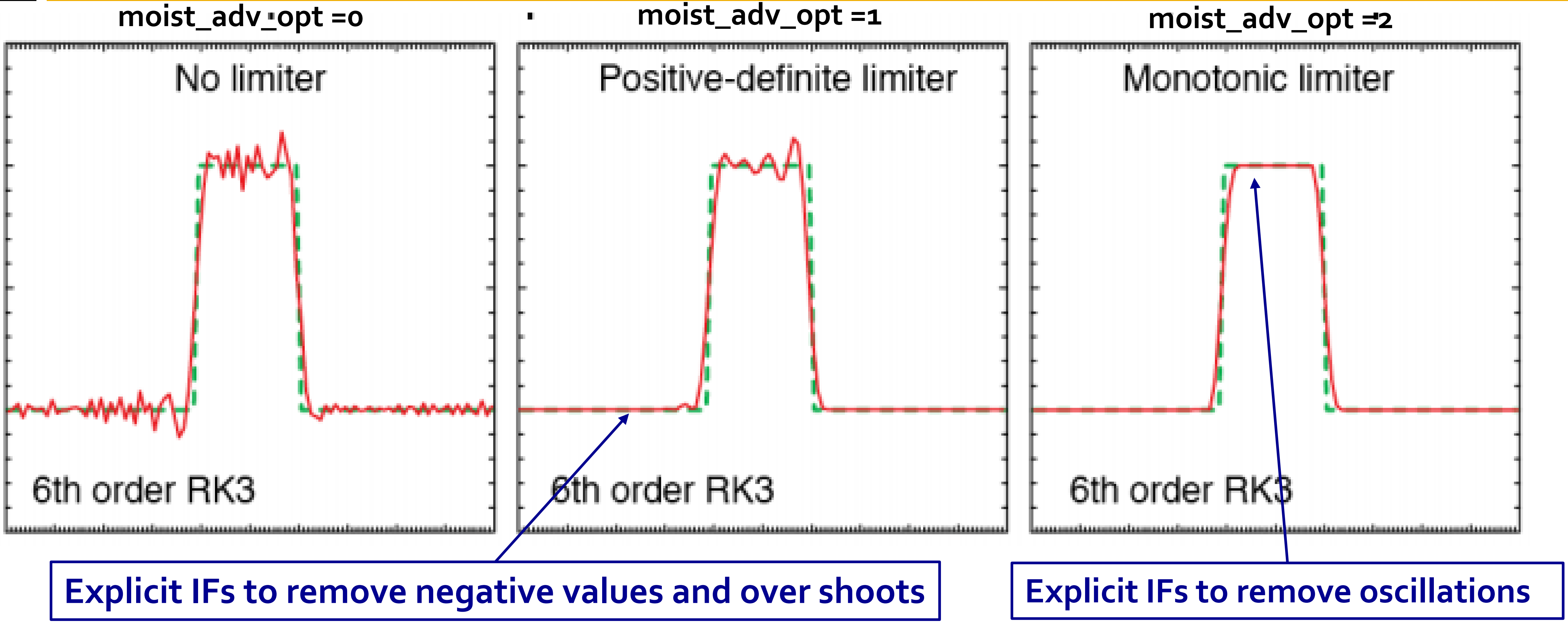


Figure from Skamarock and Dudhia 2012

- Until recently, many weather models did not conserve moisture because of the numerical challenges in advection schemes. → high bias in precipitation
- WRF-ARW is conservative but not all of the advection schemes are.
- This introduces new masses to the system.

Advection schemes can introduce both positive and negative errors particularly at sharp gradients.

Advection options in WRF

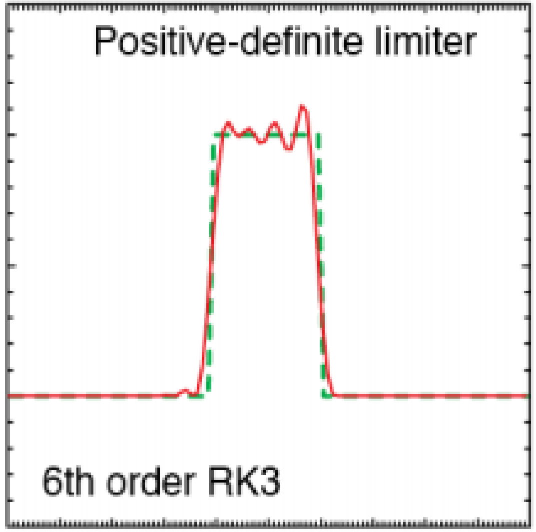


- **High number of explicit IFs are causing high branch mispredictions**

Figure from Skamarock and Dudhia 2012

Positive Define Advection Scheme

moist_adv_opt =1



Hotspot

Positive Definite Delimiter (32 lines)

- High Time
- High cache misses (both L1 and L2 Cache misses)
- High branch miss-prediction

Optimization Solution

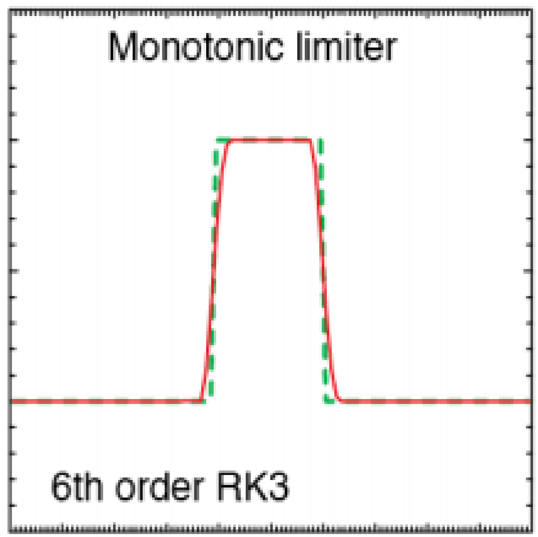
Restructure and split the PD delimiter loop

- Increase vectorization
- Reduce cache misses

Compiler	Optimization Flag	Loop Speed-up	Kernel Speed-up
Intel(v16.0.2)	-O3	100%	~17%
GNU (v6.1.0)	-Ofast	105%	~11%
PGI (v16.5)	-O3	35%	~4%

Monotonic Advection Scheme

moist_adv_opt =2



Validation Tests:
- **The results were bit-for-bit identical**
- **Regression tests with WTF (WRF Testing Framework).**

Hotspot

Monotonic Delimiter

High Time

High cache misses (both L1 and L2 Cache misses)

High branch miss-prediction

Optimization Solution

Increase vectorization

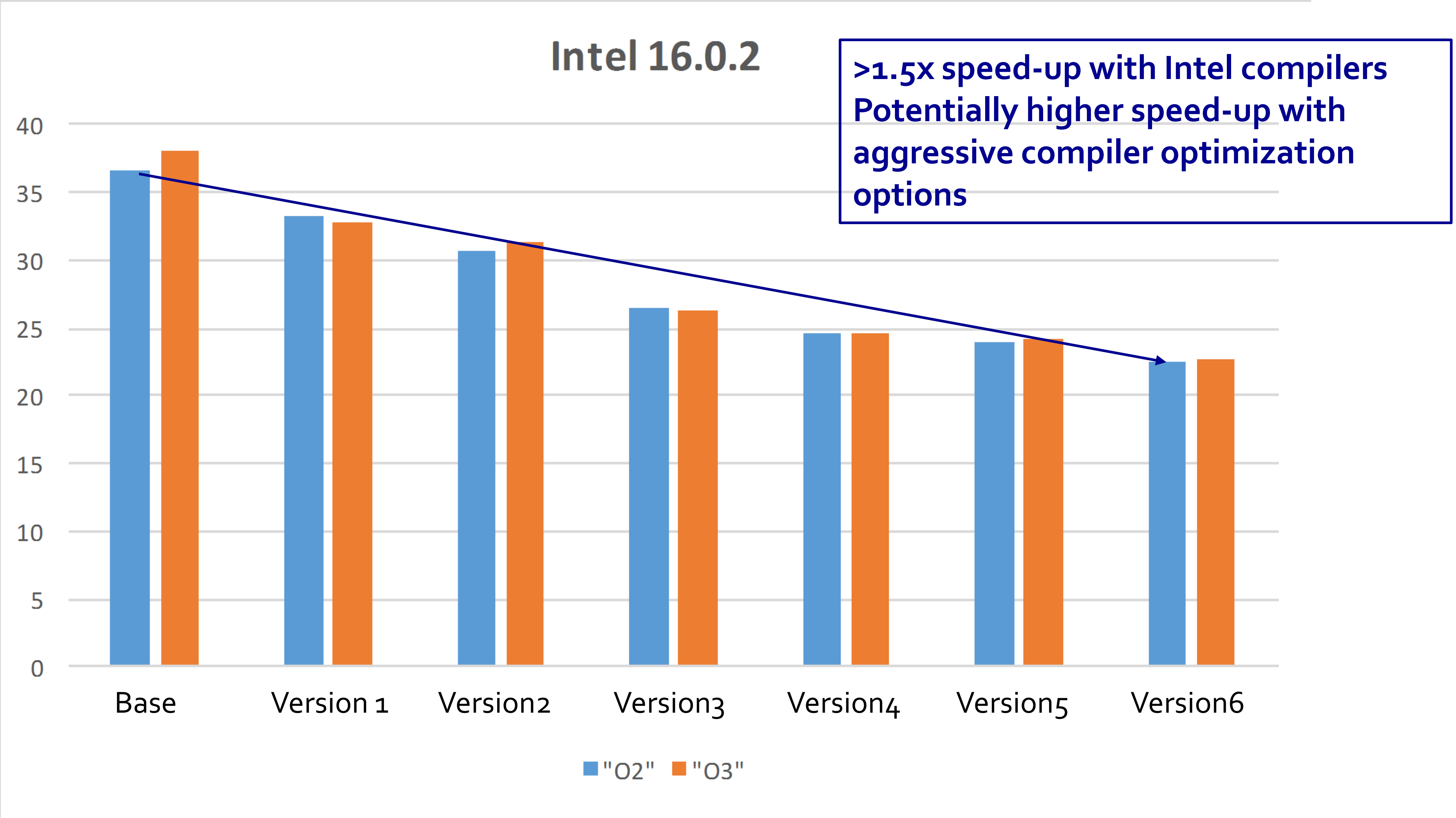
Reduce cache misses

Compiler	Optimization Flag	Whole Kernel Speed-up
Intel(v16.0.2)	-O3	~16%
GNU (v6.1.0)	-Ofast	~21%
PGI (v16.5)	-O3	~9%

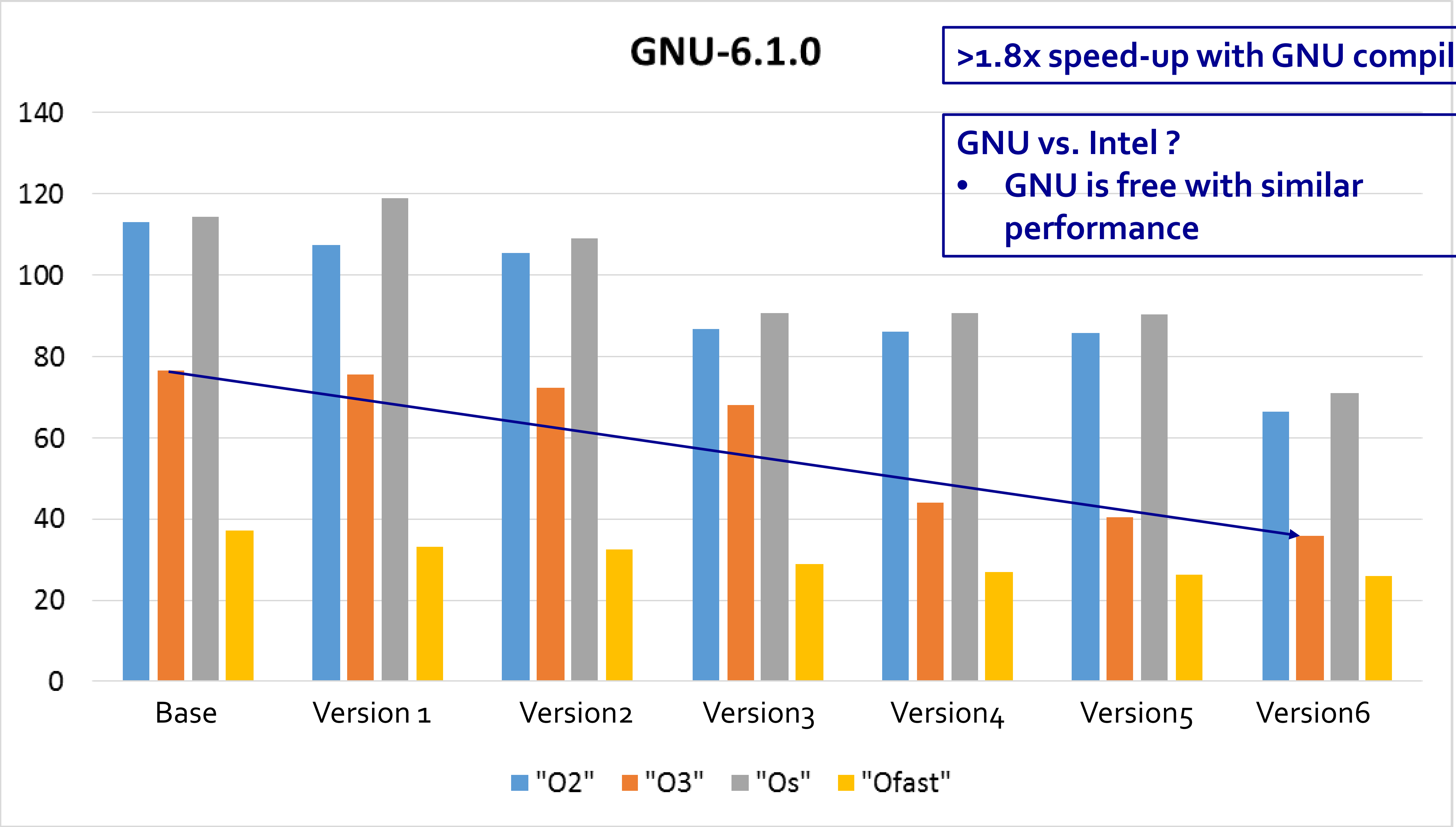
Optimization strategy

- **Expose more parallelism**
  - Push columns inside
  - Facilitates better vectorization
  - Facilitates cache blocking
- **Force vectorization** using SIMD & vector align directives
- **Replace:**
  - divisions with reciprocal multiplications
  - repeated indexed access with copies having coalesced access
  - assumed-shaped arrays (e.g. (:,:) with proper declarations)
- **Eliminate**:
  - unnecessary code, variables, initializations or copies

Positive Define Advection Scheme



Positive Define Advection Scheme

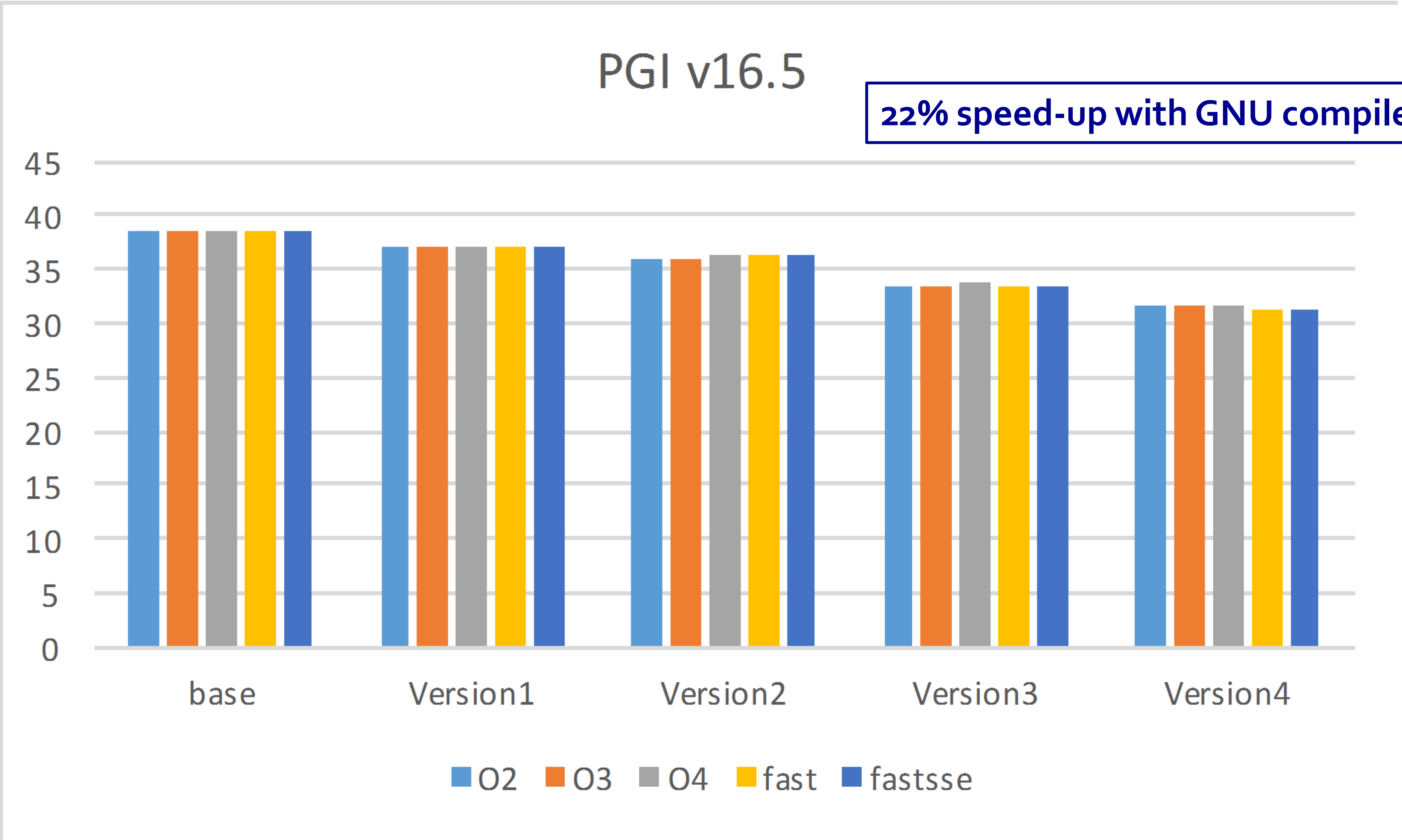


>1.8x speed-up with GNU compilers

GNU vs. Intel ?

- GNU is free with similar performance

Positive Define Advection Scheme



22% speed-up with GNU compilers

Conclusion

- **Profiling:** WRF with Intel Vtune XE, TAU tools, and Allinea MAP for identifying the hotspots of WRF
  - Dynamics is identified as the most expensive part of ARW
- **Optimizing:** the identified hotspots of different advection schemes for Intel, GNU , and PGI compilers
  - Significant speed-up of the advection schemes
- **Validating:** the results of the advection kernel
- **Integration**: The changes to WRF advection schemes are approved by the WRF committee and **integrated** in the main WRF repository.

Ongoing and Future Work

Performance Improvement of advection modules

- Reducing memory footprint by decreasing the number of temporary variables
- Increasing the advection module vectorization
- Analysis of hardware counters to fix branch mispredictions and cache misses

Future pull requests will provide up to 2.5x speed-up for advection schemes.

Acknowledgements

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NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NSF

CISL Computational & Information Systems Laboratory