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Optimization strategy for MASNUM surface wave model

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Center at FIO

Outline

- ❖ Brief Introduction Intel[®] PCC at FIO
- ❖ Background
- ❖ Optimization strategy
- ❖ Future work

Introduction of FIO

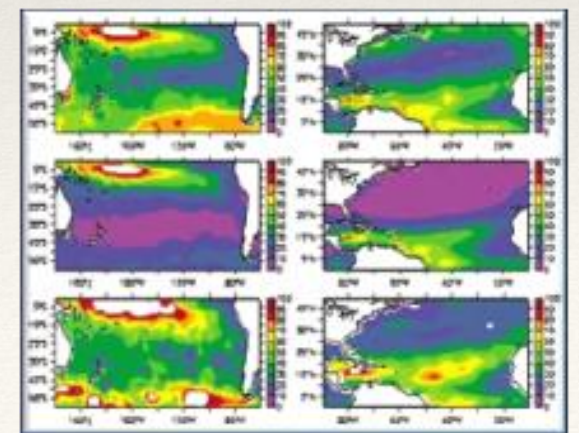
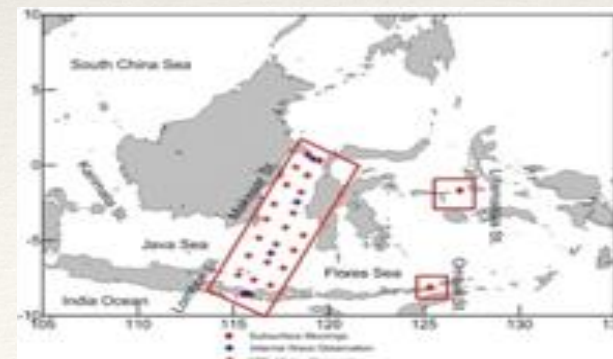
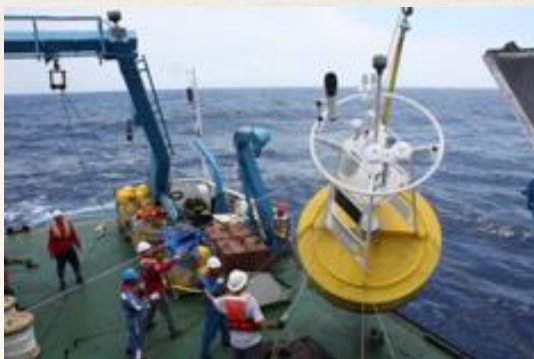
- ❖ SOA Headquarters, Beijing
- ❖ 4 Research Institute
 - **FIO, Qingdao**
 - SIO, Hangzhou
 - TIO, Xiamen
 - 4IO, Beihai (being built)
- ❖ 8 Operational Centers
 - NMEFC, NMEMC, NMDIS...
- ❖ 3 Branches
 - North Sea, East Sea, South Sea



Introduction of FIO

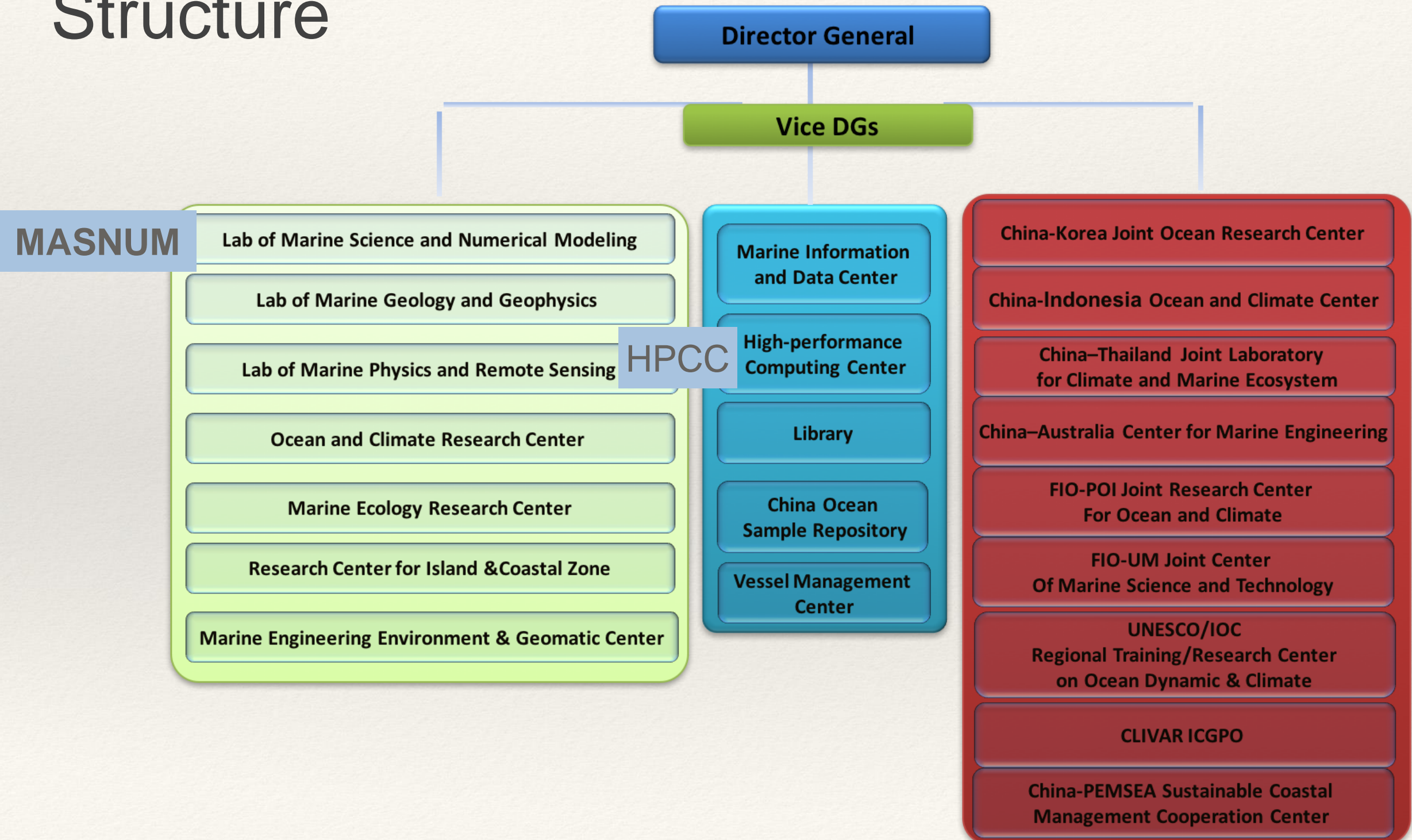
Mission

- ❖ Basic and applied research in oceanography, marine science and technology.
- ❖ Technical support and research service to the development of high-tech industries, marine resources management, marine environment protection, public service, marine safety, etc.
- ❖ Major research priorities: Marine Geology/Geophysics, Physical Oceanography, Sea-Air Interaction, Marine Ecology, Marine Engineering, Remote Sensing, Marine Policy, etc.



Introduction of FIO

Structure



Introduction of FIO

MASNUM Major Research Fields

- ❖ Oceanography dynamics in the Chinese offshore area, polar region and global oceans
 - Formation and variation mechanisms of major marine phenomena and circulation systems in the Chinese offshore area, polar region and global oceans
 - General ocean circulation, mass transport and its ecological effect
 - Land-sea-air interaction and climate changes
- ❖ Ocean survey and experiment techniques
 - Sound, light and electricity measurement techniques
 - Wave tank and physical model experiments
 - Survey technique application and data process in oceanography
- ❖ **Ocean numerical modeling**
 - **Numerical computing scheme and data analysis**
 - **Wind-wave-current interaction mechanism and coupled numerical model**
 - **Application systems including database and data assimilation technique**
- ❖ Marine information system
 - Database, visualization and system integration techniques
 - Application information systems in climate forecast, disaster prediction, engineering oceanography and military security

Intel® PCC at FIO

Large-Scale and Highly-Effective Numerical Simulation of Marine Environment with Global Surface Waves Model



Fangli Qiao



Zhenya Song



Xiaomeng Huang

- ❖ **Optimize the MASNUM wave model**
 - **Computing performance——Better Scalability and simulation faster**
 - **Simulation ability——More accuracy by using deep learning**
- ❖ **Release the code to the ocean community worldwide**
- ❖ **Publish papers in SCI/EI journal**
- ❖ **Training course, and workshop of best known method sharing**



Zhe Wang



Yanguo Yang



Shan Zhou



Haifeng Lv

Intel® PCC at FIO

Large-Scale and Highly-Effective Numerical Simulation of Marine Environment with Global Surface Waves Model



- ❖ **Project period**
 - July 1, 2018—June 30, 2020
- ❖ **Unveiling ceremony on July 28, 2018, Qingdao**
- ❖ **First one in Chinese ocean fields**

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Ocean surface wave model

Ocean surface wave

- ❖ Occur in the ocean surface driven by winds
- ❖ Wave height range from several centimeters to tens meters



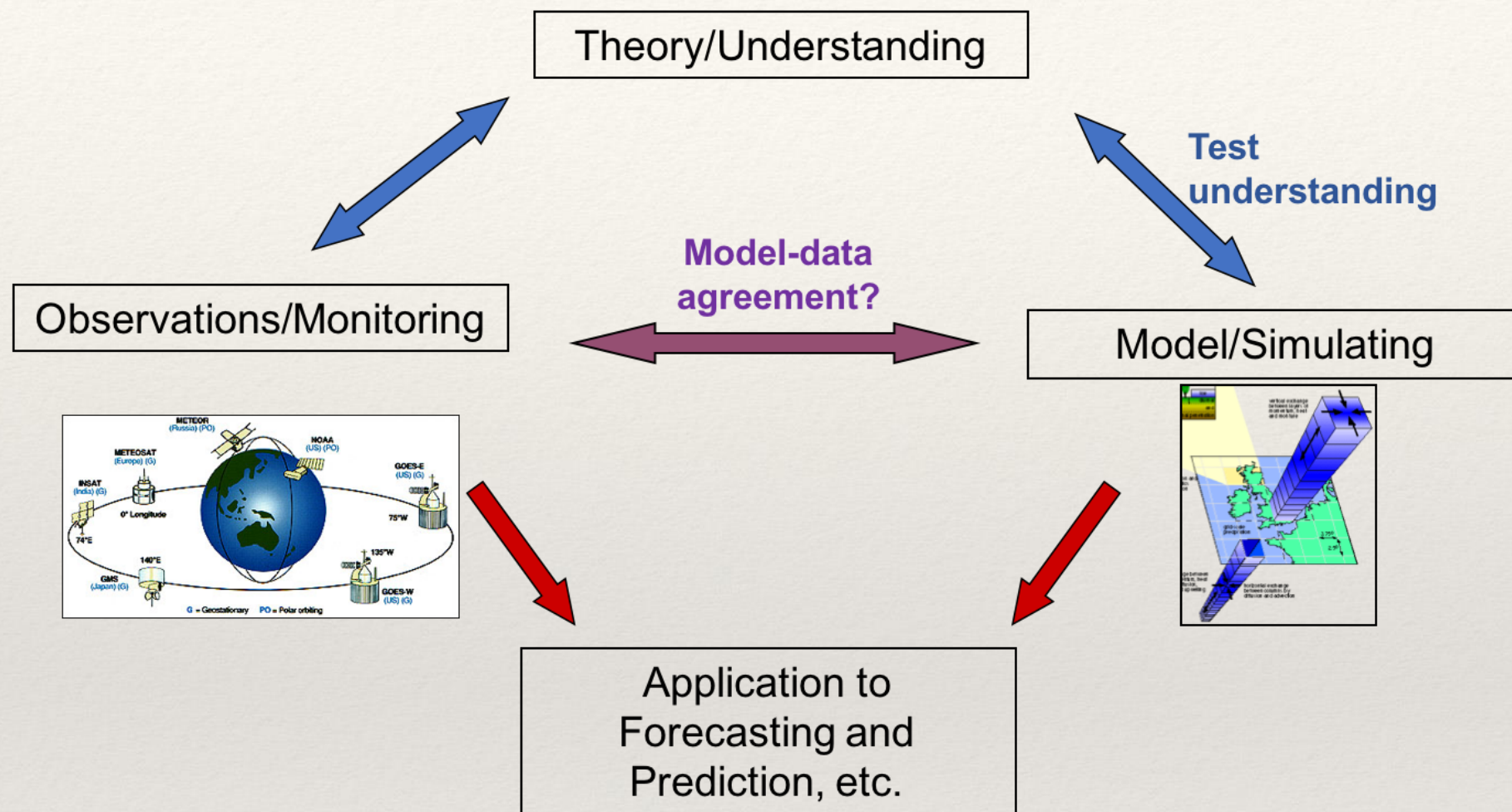
Ocean surface wave model

Importance of ocean surface wave



- ❖ Ocean surface wave is important for navigation.
- ❖ Ocean surface wave is important for ocean engineering

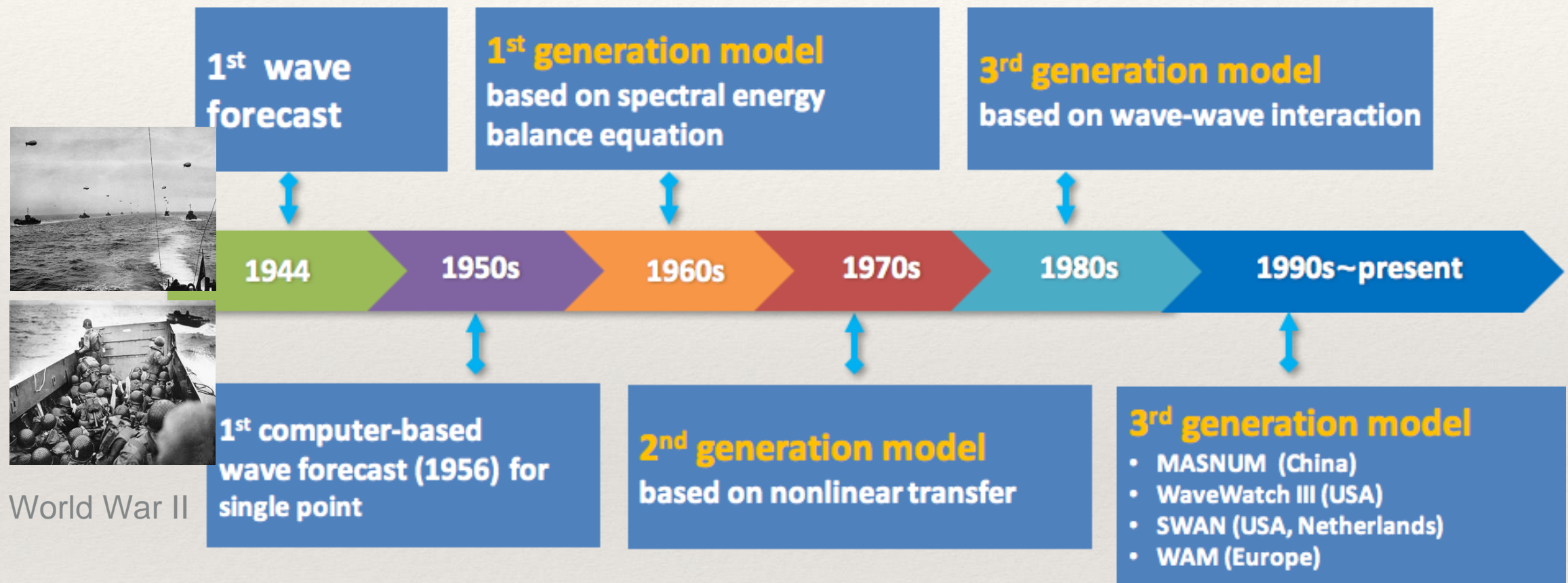
Ocean surface wave model



- ❖ Three methods: Theoretical research, Lab experiments and Observation, and Numerical simulation
- ❖ Model is the key tool for forecasting and prediction

Ocean surface wave model

History of ocean surface wave model



- ❖ First ocean surface wave forecasting during World War II (1944)
- ❖ Ocean surface wave model is the key tool to wave forecasting
- ❖ Accurately ocean surface wave forecasting is still a challenge

Ocean surface wave model

Model equation

Equation

$$\frac{\partial E}{\partial t} + \left(\frac{C_{g\lambda} + U_\lambda}{R \cos \phi} \right) \frac{\partial E}{\partial \lambda} + \left(\frac{C_{g\phi} + U_\phi}{R} \right) \frac{\partial E}{\partial \phi} - \frac{(C_{g\phi} + U_\phi) \tan \phi}{R} E = SS(E)$$

Source functions

$SS(E) = S_{in}$ Wind input source function
+ S_{ds} Dissipation source function
+ S_{bo} Bottom friction source function
+ S_{nl} Nonlinear interaction source function
+ S_{cu} Current-wave interaction

$E = E(K, \lambda, \phi, t)$ Wave-number spectrum
 $\vec{K} = (k_\lambda, k_\phi)$ Wave-number
 $\vec{U} = (U_\lambda, U_\phi)$ Background current
 $\vec{C}_g = (C_{g\lambda}, C_{g\phi})$ Group velocity

- ✓ 5D problem = 2D geographic space + 2D spectrum space + 1D time
- ✓ Bottlenecks :
 - ✓ Huge computation cost for source functions
 - ✓ Data commutation due to propagation

- ✓ Fortran 90 + MPI
- ✓ Double precision
- ✓ Explicit numerical method

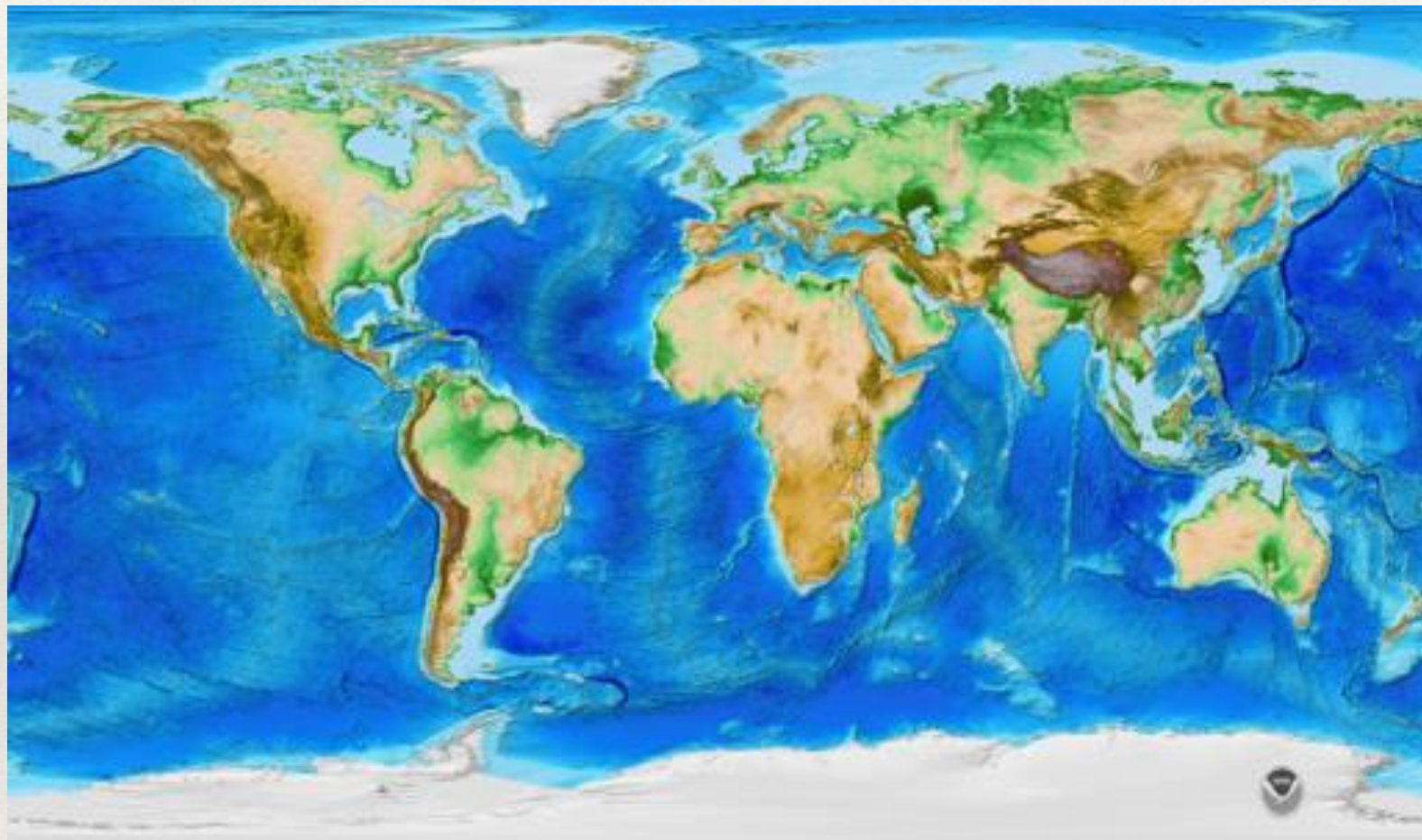
Ocean surface wave model

Evolution of MASNUM wave model

1990s	Early 2000s	Late 2000s	Early 2010s	Present
<ul style="list-style-type: none">• LAGFD• Serial• Regional	<ul style="list-style-type: none">• MASNUM• Serial• Regional/ Global• Coupled to OGCMs	<ul style="list-style-type: none">• MASNUM• 128 cores in parallel (2007)• Regional/ Global• Coupled to OGCMs	<ul style="list-style-type: none">• MASNUM• 130,000 cores (2014)• Regional/ Global• Coupled to OGCMs• Coupled to ESM	<ul style="list-style-type: none">• MASNUM• 10,649,600 cores (2016)• Regional/ Global• Coupled to OGCMs• Coupled to ESM• Ultra-high resolution

Ocean surface wave model

Milestone 1: Irregular quasi-rectangular domain decomposition (2014)



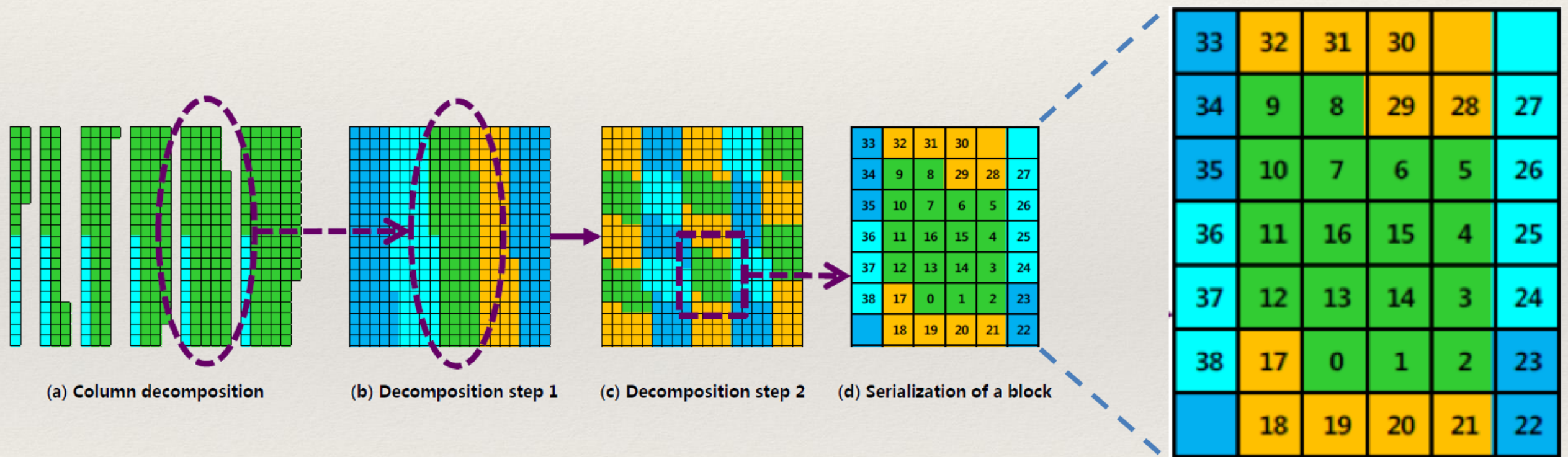
About 30% land
points in global
domain

Problem: In order to keep load balance, we should eliminate the land points.

Ocean surface wave model

Milestone 1: Irregular quasi-rectangular domain decomposition (2014)

An interesting mathematical game : Transforming a 2D plane into an 1D line.



Comparing with the method of space filling curve, we keep the quasi-rectangular shape to simplify the implementation of communication and maintain good data locality.

Ocean surface wave model

Milestone 1: Irregular quasi-rectangular domain decomposition (2014)

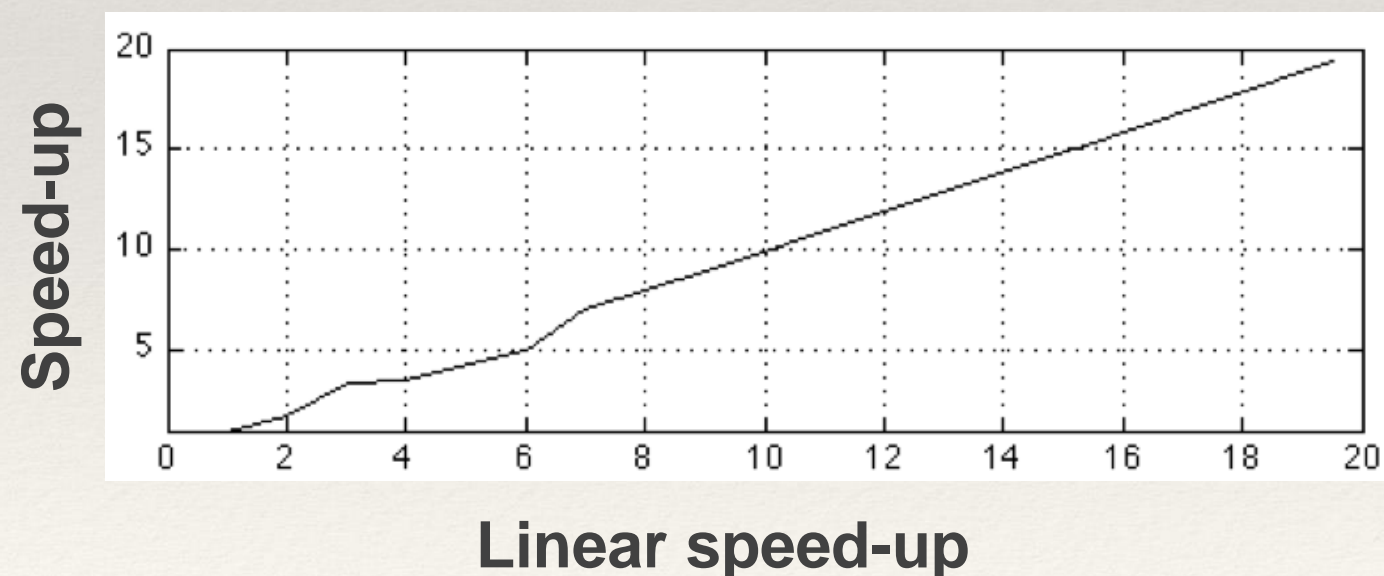
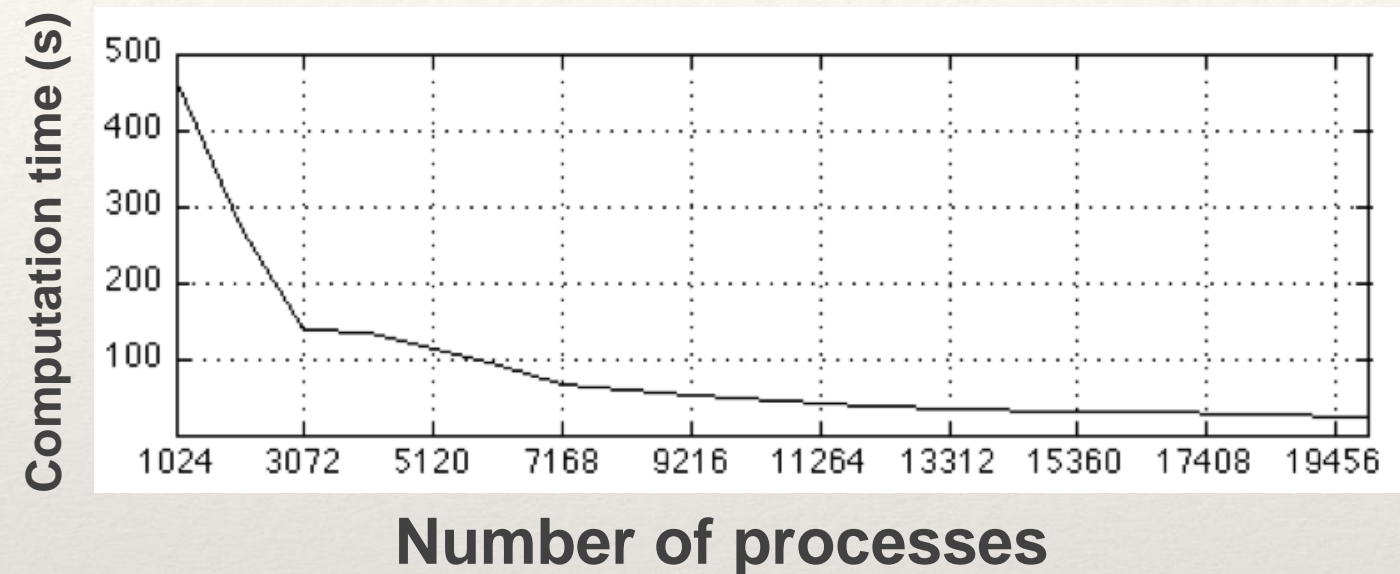


TIANHE-1A (National SuperComputer Center in Tianjin)

CPU	2* Intel Xeon X5670@2.93GHz + Tesla M2050
Memory	24 GB/node
OS	RedHat
Fortran/C Compiler	Intel Compiler v12
MPI	
Network	40 Gbps

Ocean surface wave model

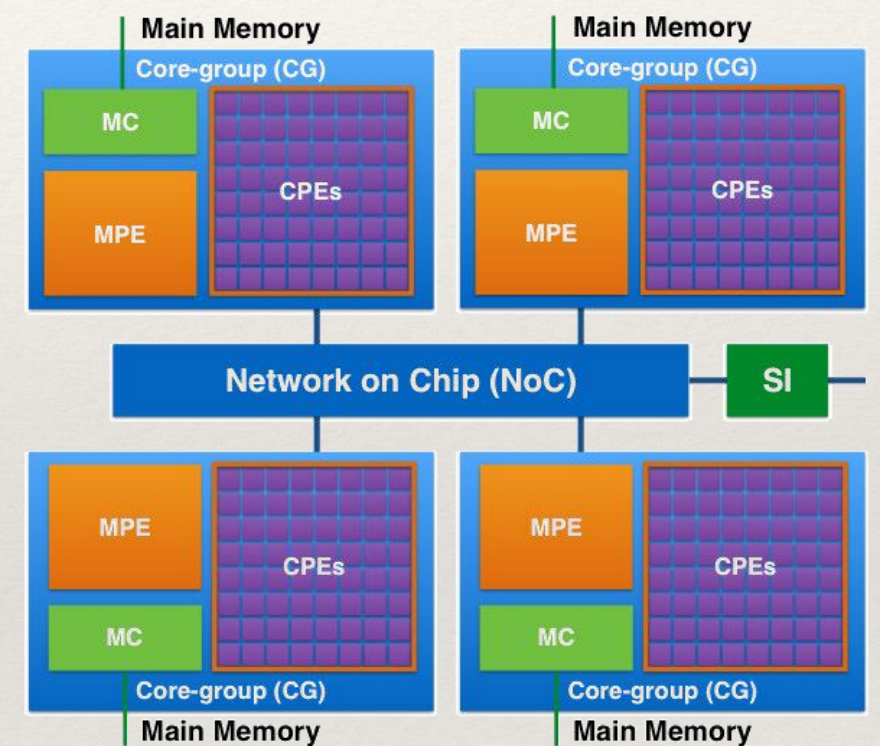
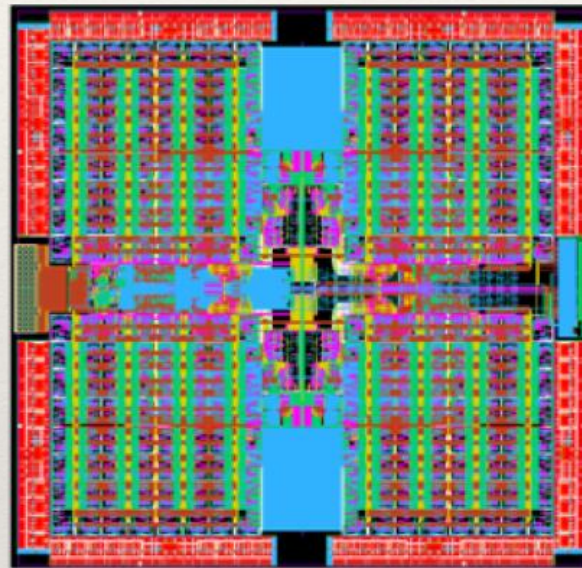
Milestone 1: Irregular quasi-rectangular domain decomposition (2014)



Upper: Computation time (minutes); Lower: Speed-up

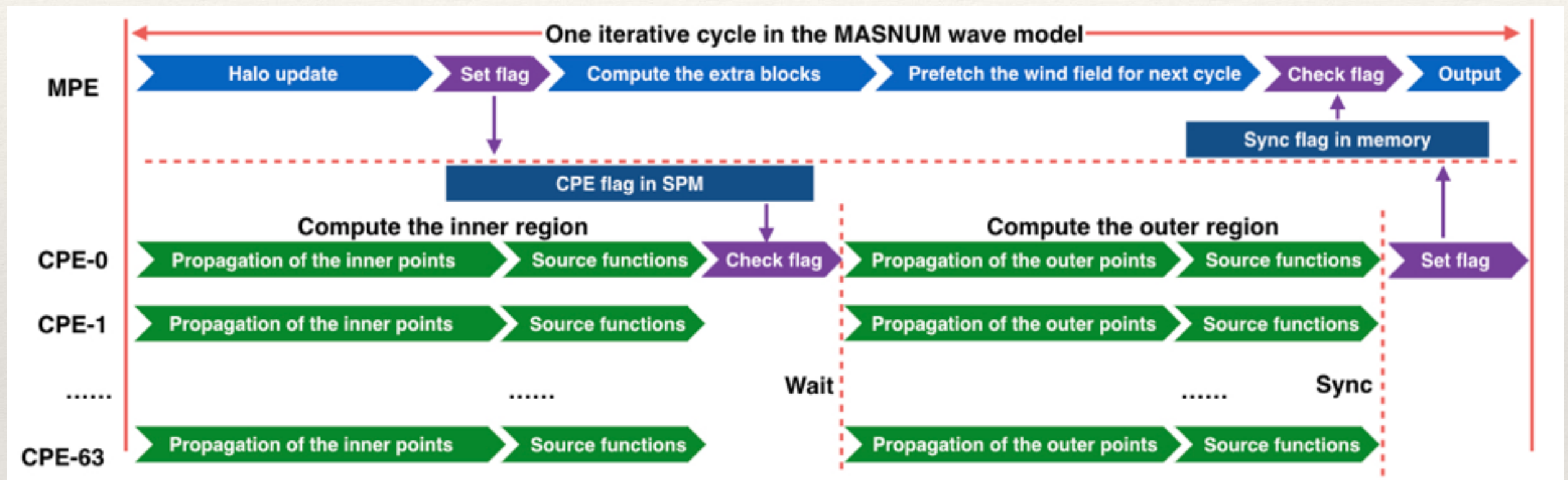
Ocean surface wave model

Milestone 2: Master-slave cooperative computing workflow(2016)



Ocean surface wave model

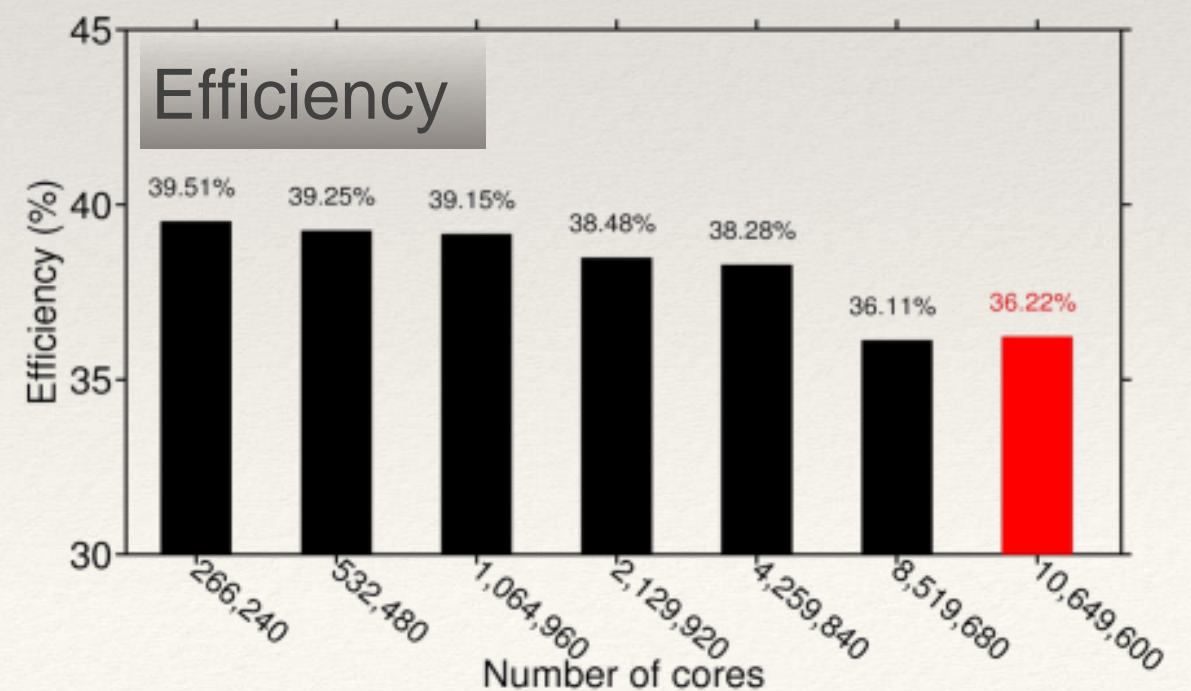
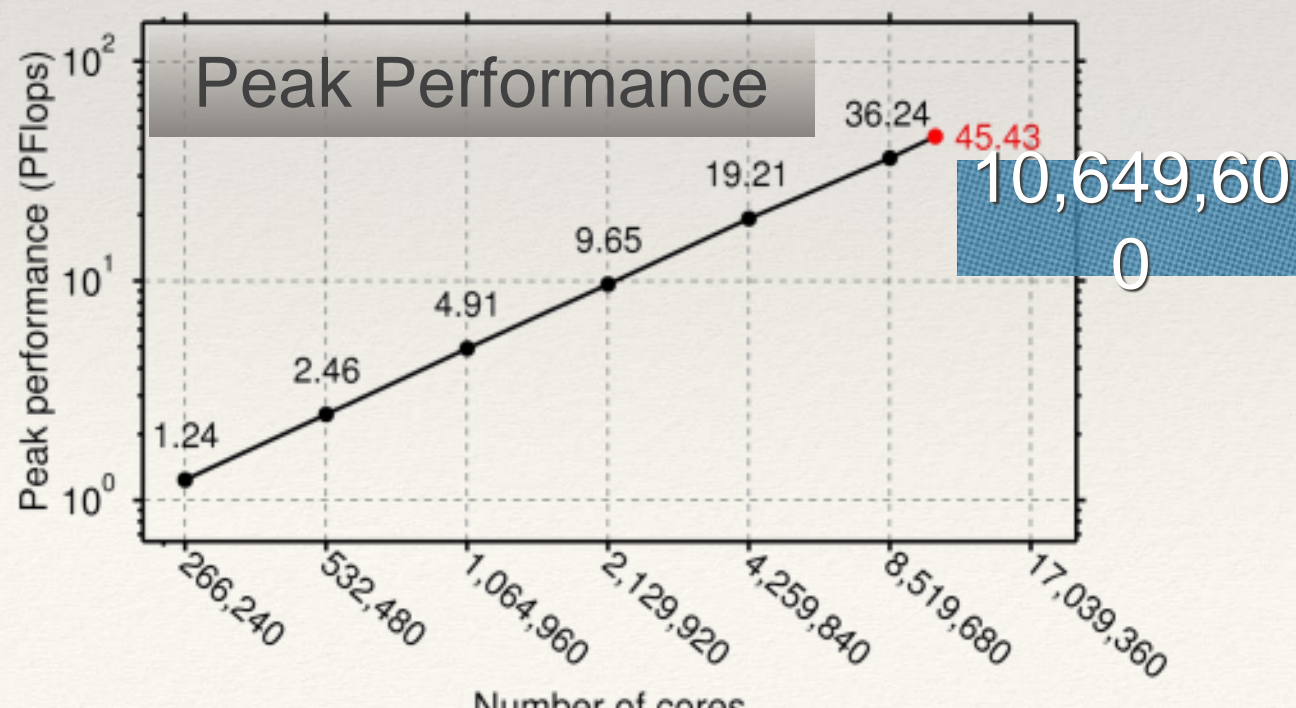
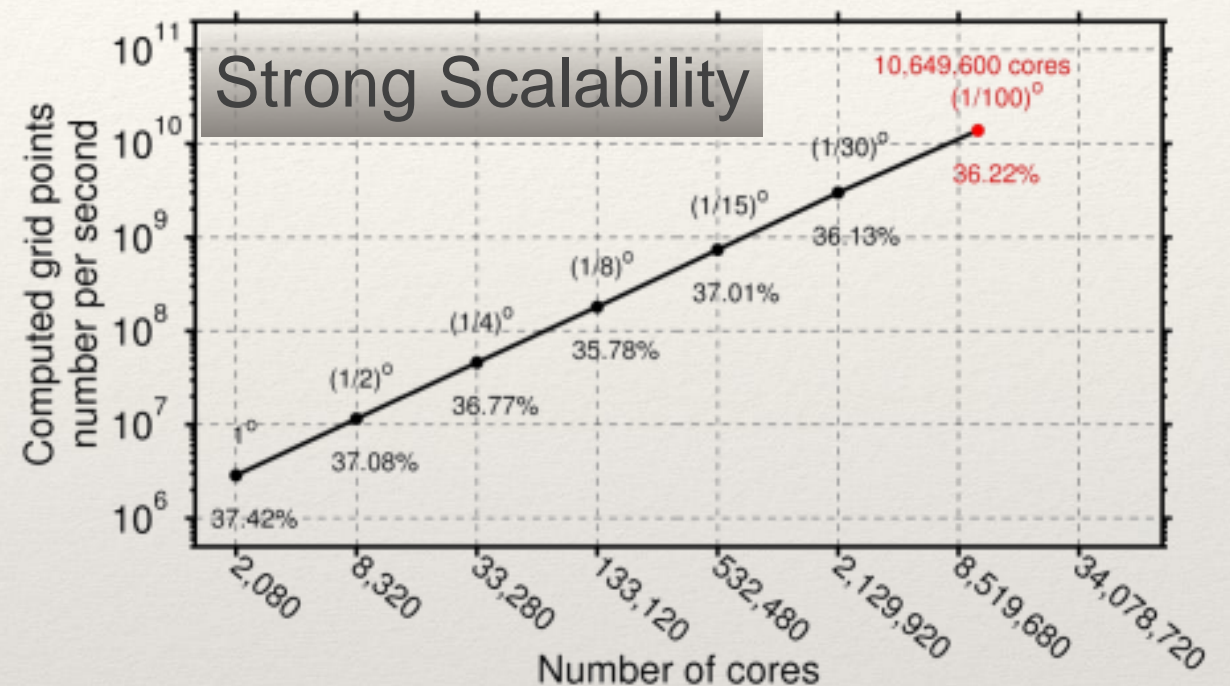
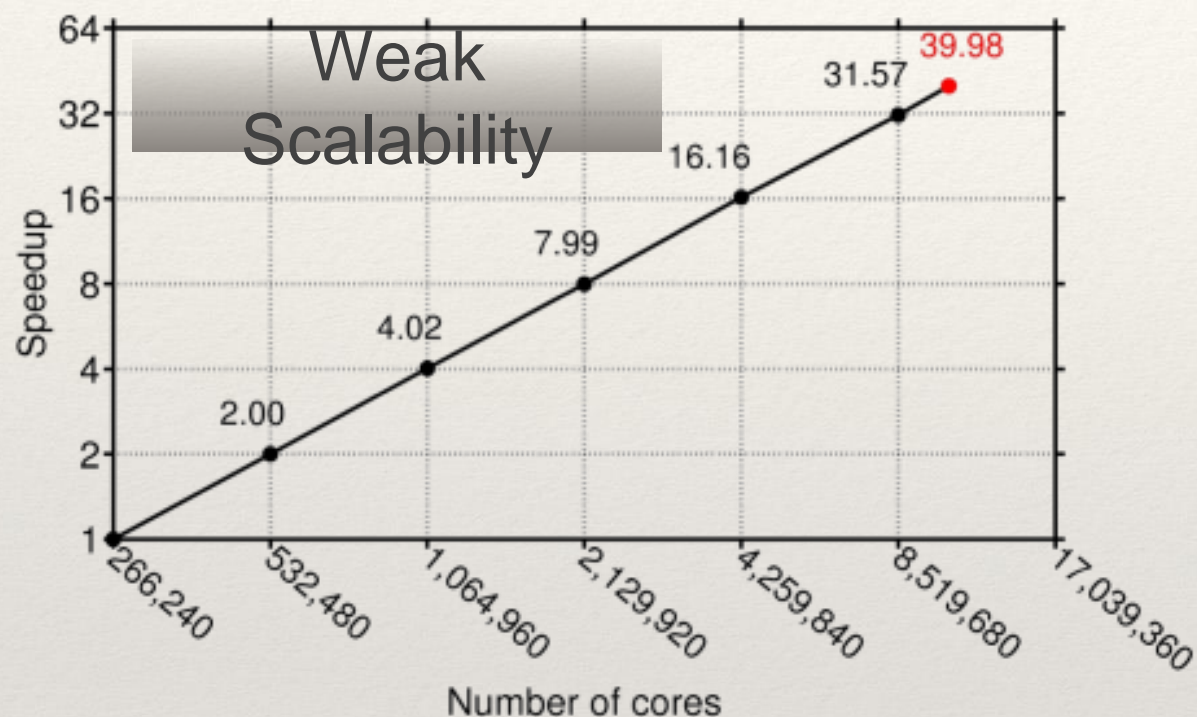
Milestone 2: Master-slave cooperative computing workflow(2016)



- ❖ **Cooperation:** overlapping of communication and computing; data prefetching
- ❖ **Synchronization :** highly efficient synchronization among CPEs
- ❖ **Memory utilization:** fully applied the local memory in CPEs (64KB)

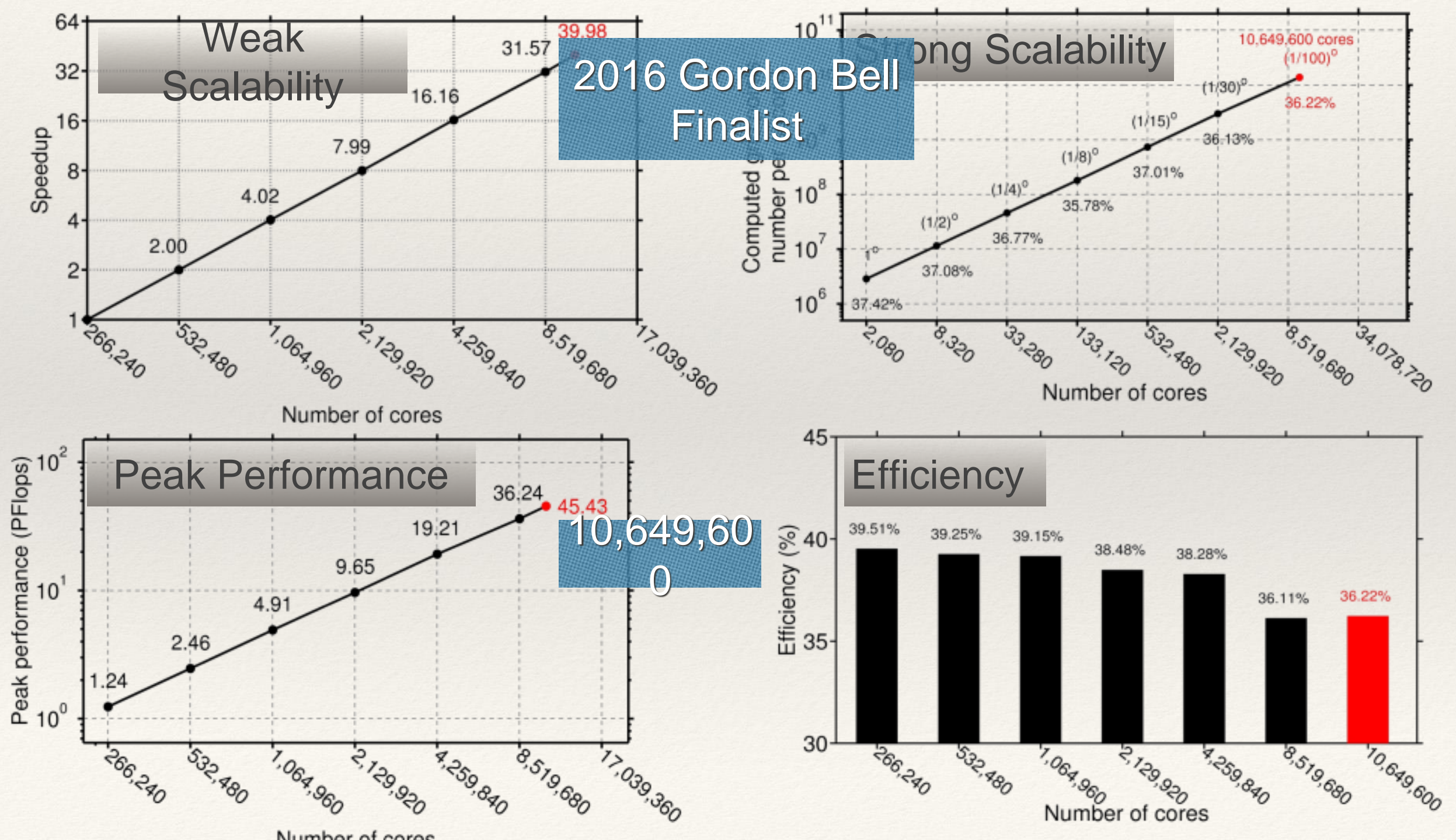
Ocean surface wave model

Milestone 2: Master-slave cooperative computing workflow(2016)



Ocean surface wave model

Milestone 2: Master-slave cooperative computing workflow(2016)



Operational forecasting system

OSF for ocean: Global Ocean Environment Forecasting Systems

❖ 1st generation OFS

- POM + MASNUM
- Assimilation: Nudging
- HR with 50 km

○ 2nd generation OFS

- MOM + SIS + MASNUM
- Assimilation: Ensemble adjust Kalman Filter
- HR with 10 km



National Marine
Environment Forecasting
Center, OSF2

East China Sea Marine
Environment Forecasting
Center, OSF1

Xiamen Marine
Environment Forecasting
Station, OSF1

UNESCO/IOC Ocean
Forecasting
demonstration System in
the Southeast Asian Sea,
OSF1

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Optimization strategy

Based on Code Modernization Optimization

- Define the hotspots using Intel® VTune™ Amplifier
- Guarantee the load balance using Intel® Trace Analyzer & Collector

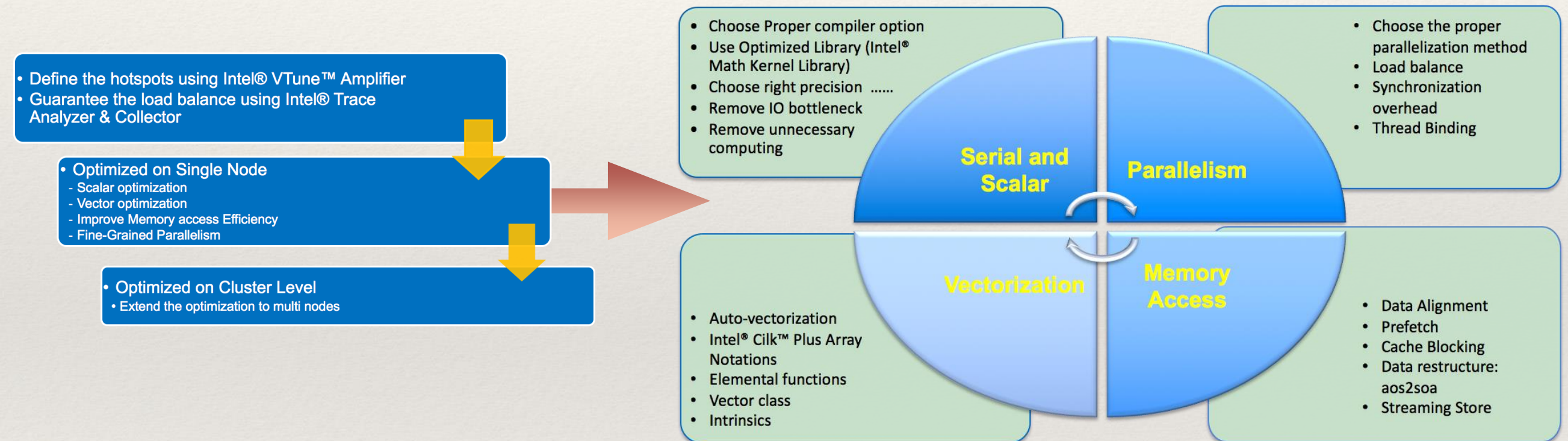
- Optimized on Single Node
 - Scalar optimization
 - Vector optimization
 - Improve Memory access Efficiency
 - Fine-Grained Parallelism

- Optimized on Cluster Level
 - Extend the optimization to multi nodes

Optimization Methodology

Optimization strategy

Based on Code Modernization Optimization



Optimization Methodology

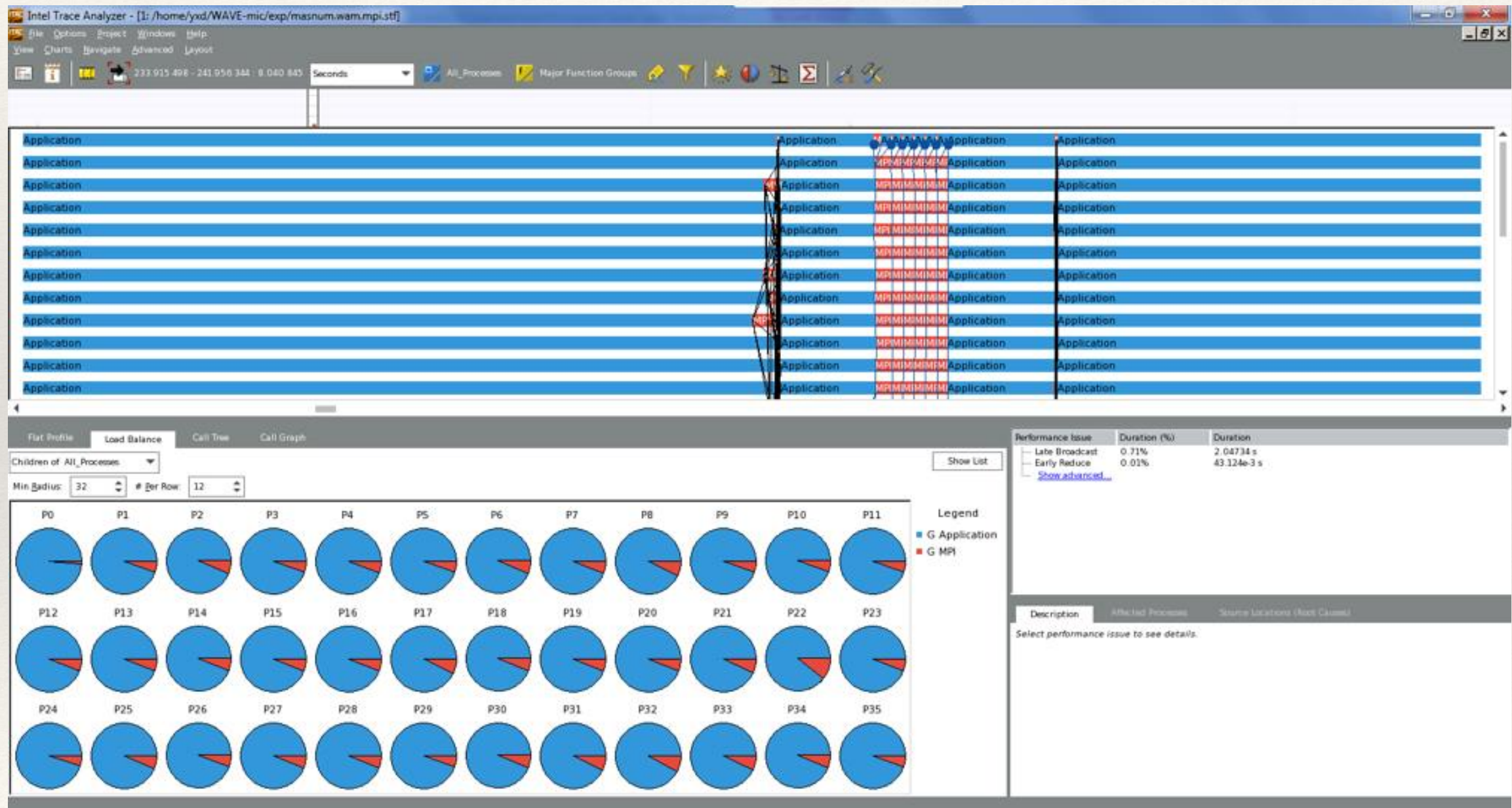
Optimization strategy

Optimization of MASNUM surface wave model on Xeon

	Xeon
CPU	Intel Xeon E5 2699 v3, 18 cores
amount	2 way in single node
Nodes	7 nodes, 252 cores in total
Frequency	2.3 GHz
Memory	128 GB
OS	RHEL 6.5
Compiler	Intel Compiler 16.0
MPI	Intel MPI 5.4.4

Optimization strategy

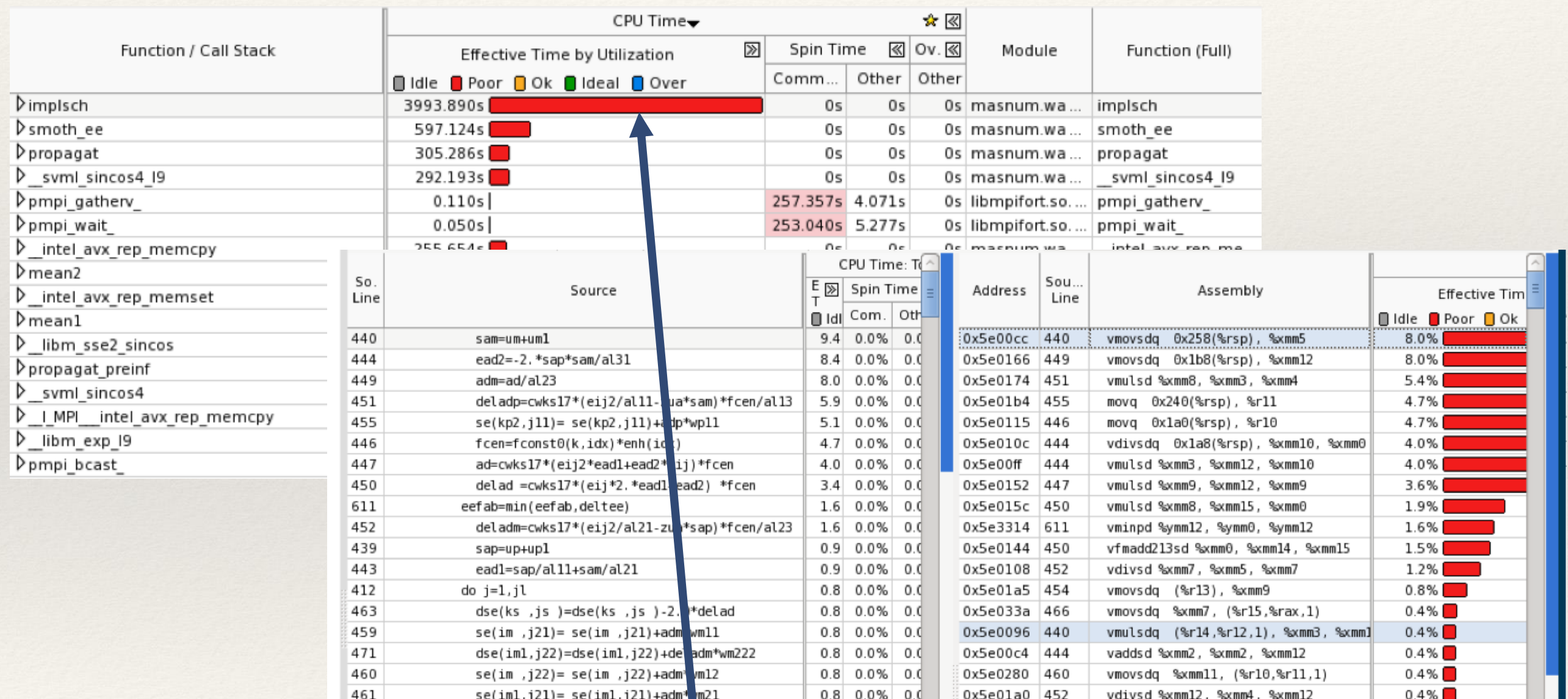
Step 1.1: Analysis Load-balance with ITAC



Load-balance is good!

Optimization strategy

Step 1.2: Analysis Hotspots on Single Model with Intel Vtune

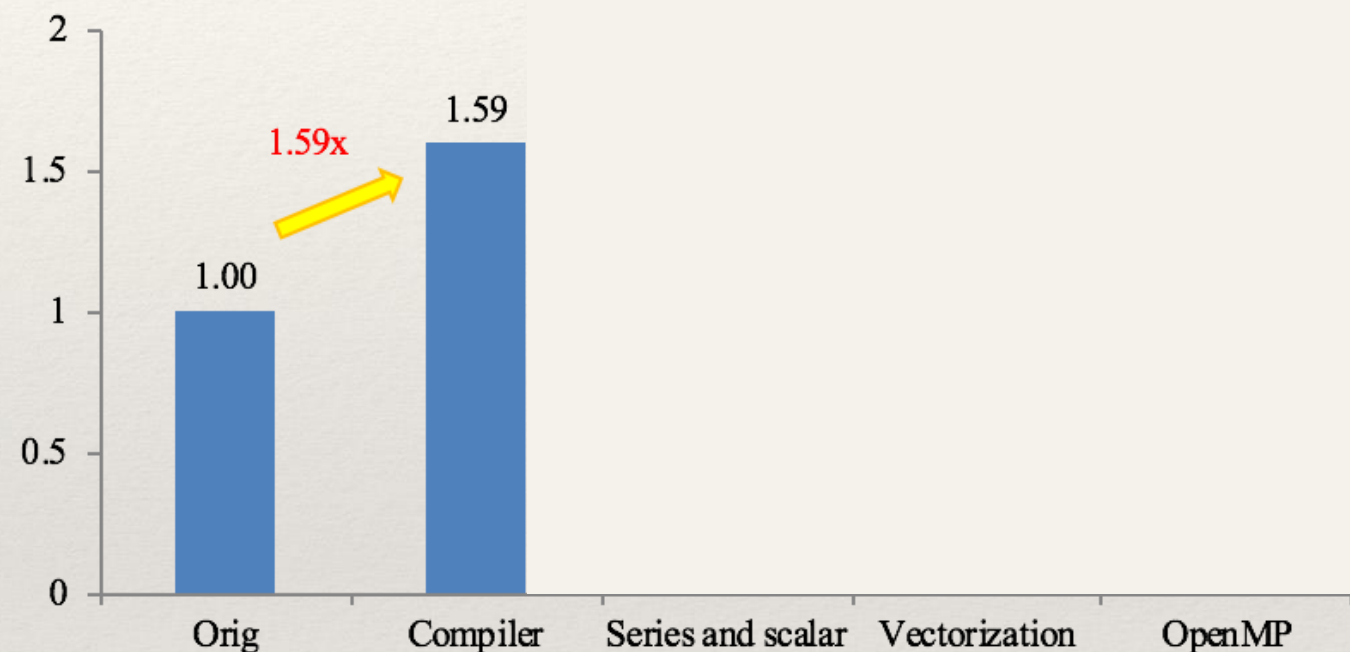
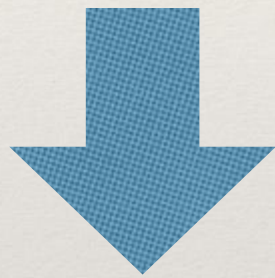


implsch is the hotspot!

Optimization strategy

Step 2.1: Best Compiler Option before optimized on Single Node

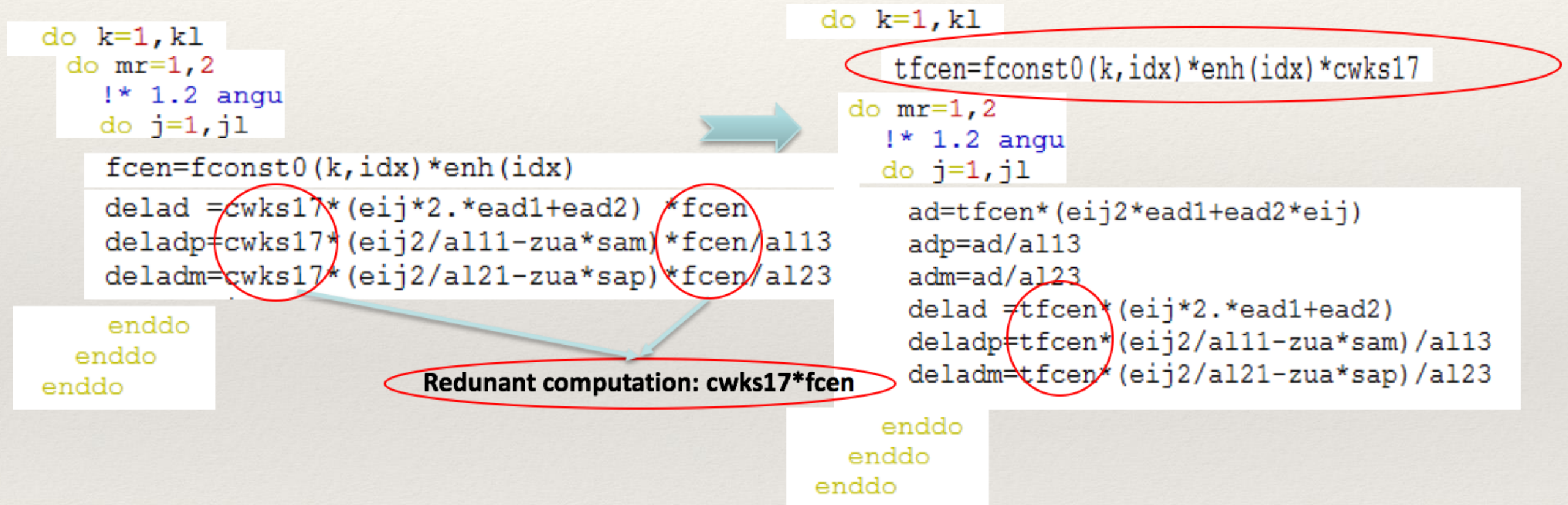
Default



-O3 -xHost -align array32byte -no-prec-div

Optimization strategy

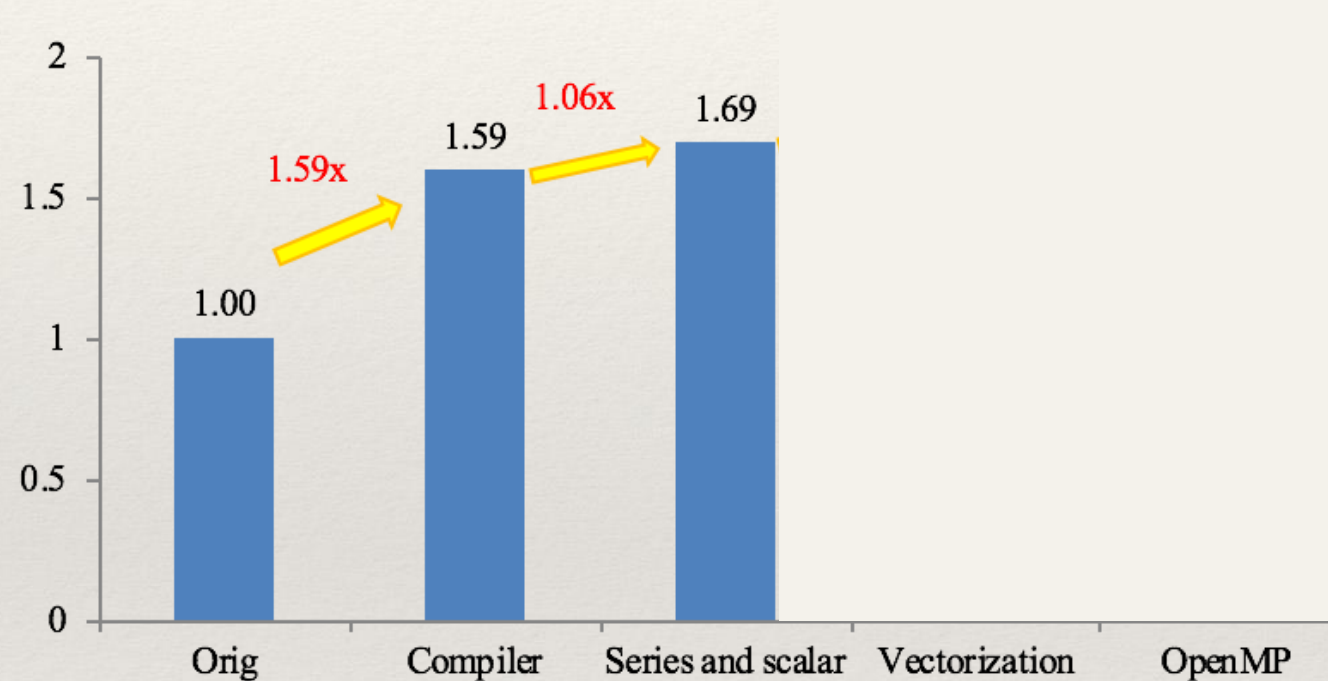
Step 2.2: Serial and Scalar Optimization



Reduce the redundant computations

Optimization strategy

Step 2.2: Serial and Scalar Optimization



Reduce the redundant computations

Optimization strategy

Step 2.3: Vectorization Optimization

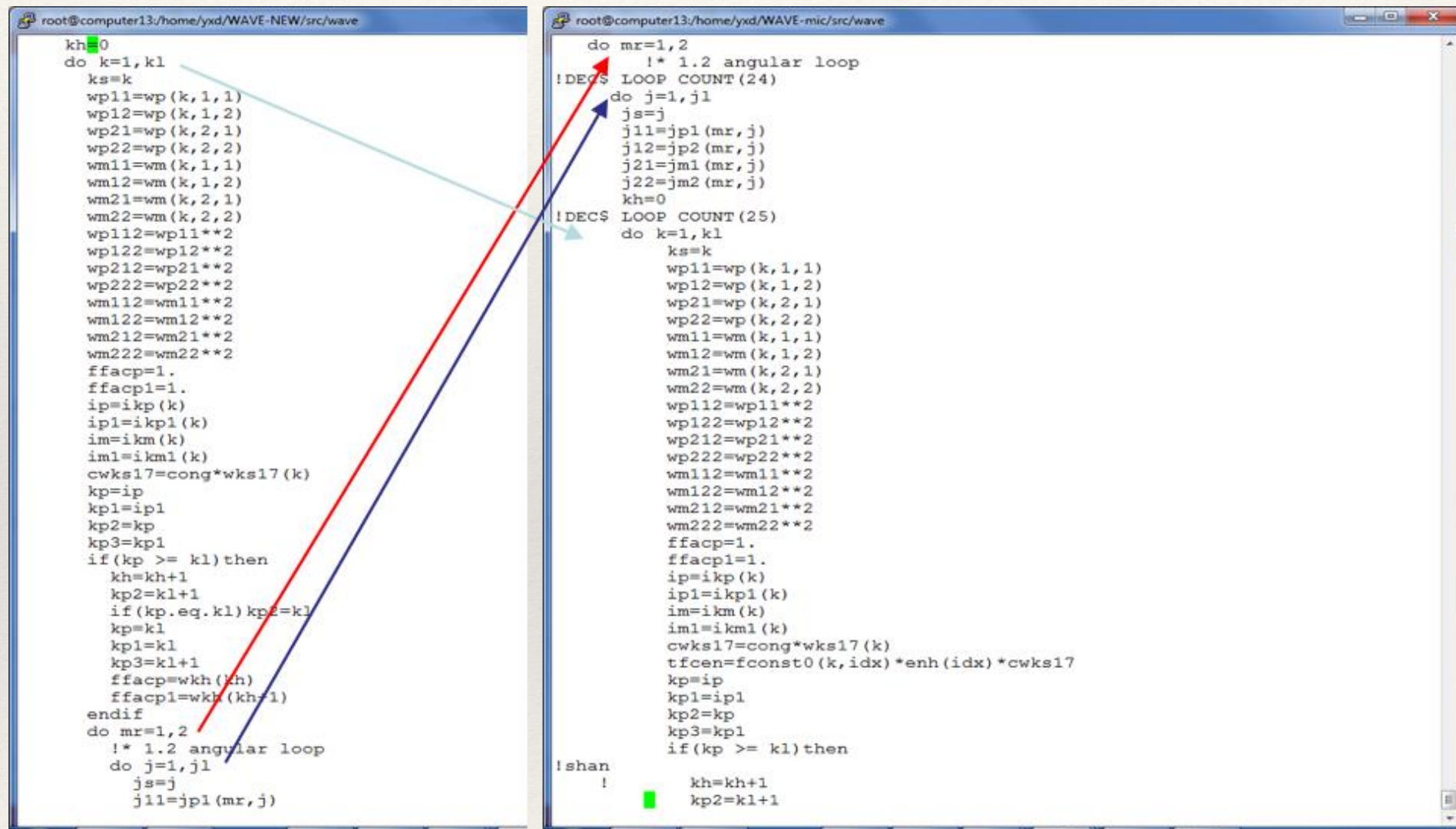
```
LOOP BEGIN at ../src/wave/wamcor_mod.f90(410,7)
  remark #15344: loop was not vectorized: vector dependence prevents vectorization
  remark #15346: vector dependence: assumed OUTPUT dependence between wamvar_mod_mp_se_line 454 and wamvar_mod_mp_se_line 462
  remark #15346: vector dependence: assumed OUTPUT dependence between wamvar_mod_mp_se_line 462 and wamvar_mod_mp_se_line 454
  LOOP BEGIN at ../src/wave/wamcor_mod.f90(412,9)
    remark #15344: loop was not vectorized: vector dependence prevents vectorization
    remark #15346: vector dependence: assumed OUTPUT dependence between wamvar_mod_mp_se_line 454 and wamvar_mod_mp_se_line 462
    remark #15346: vector dependence: assumed OUTPUT dependence between wamvar_mod_mp_se_line 462 and wamvar_mod_mp_se_line 454
    LOOP END
  LOOP END
LOOP END
```

```
410      do mr=1,2
411        !* 1.2 angular loop
412        do j=1,jl
413          js=j
414          j11=jp1(mr,j)
415          j12=jp2(mr,j)
416          j21=jm1(mr,j)
417          j22=jm2(mr,j)
447          ad=cwks17*(eij2*ead1+ead2*eij)*fcen
448          adp=ad/al13
449          adm=ad/al23
450          delad=cwks17*(eij*2.*ead1+ead2)*fcen
451          deladp=cwks17*(eij2/al11-zua*sam)*fcen/al13
452          deladm=cwks17*(eij2/al21-zua*sap)*fcen/al23
454          se(ks,js)=se(ks,js)-2.0*ad
455          se(kp2,j11)=se(kp2,j11)+adp*wp11
456          se(kp2,j12)=se(kp2,j12)+adp*wp12
457          se(kp3,j11)=se(kp3,j11)+adp*wp21
458          se(kp3,j12)=se(kp3,j12)+adp*wp22
459          se(im,j21)=se(im,j21)+adm*wm11
460          se(im,j22)=se(im,j22)+adm*wm12
461          se(im1,j21)=se(im1,j21)+adm*wm21
462          se(im1,j22)=se(im1,j22)+adm*wm22
```

Analyze by using compiler option “-qopt-report=5”

Optimization strategy

Step 2.3: Vectorization Optimization

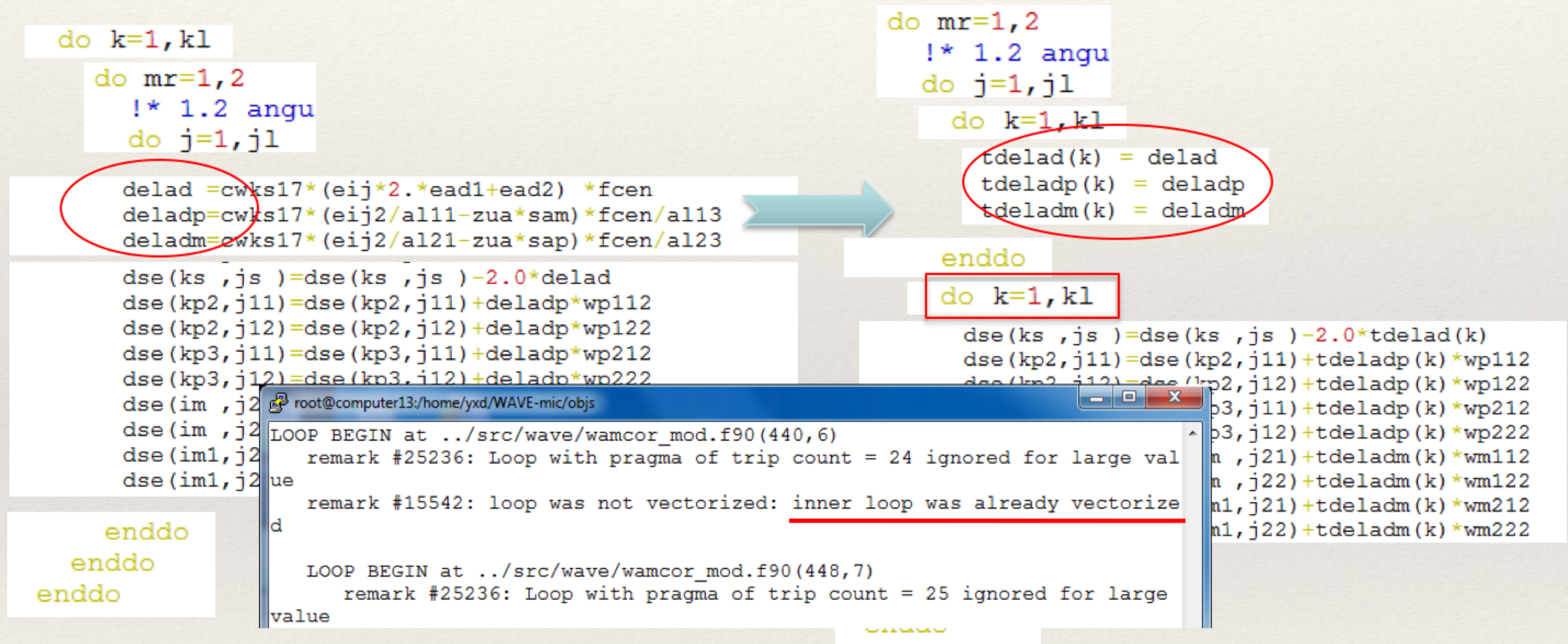


```
kh=0
do k=1,kl
  ks=k
  wp11=wp(k,1,1)
  wp12=wp(k,1,2)
  wp21=wp(k,2,1)
  wp22=wp(k,2,2)
  wm11=wm(k,1,1)
  wm12=wm(k,1,2)
  wm21=wm(k,2,1)
  wm22=wm(k,2,2)
  wp112=wp11**2
  wp122=wp12**2
  wp212=wp21**2
  wp222=wp22**2
  wm112=wm11**2
  wm122=wm12**2
  wm212=wm21**2
  wm222=wm22**2
  ffacp=1.
  ffacp1=1.
  ip=ikp(k)
  ip1=ikp1(k)
  im=ikm(k)
  im1=ikm1(k)
  cwks17=cong*wks17(k)
  kp=ip
  kp1=ip1
  kp2=kp
  kp3=kp1
  if(kp >= kl) then
    kh=kh+1
    kp2=kl+1
    if(kp.eq.kl) kp2=kl
    kp=k1
    kp1=k1
    kp3=kl+1
    ffacp=wkh(kh)
    ffacp1=wkh(kh-1)
  endif
  do mr=1,2
    !* 1.2 angular loop
    do j=1,jl
      js=j
      j11=jp1(mr,j)
      j12=jp2(mr,j)
      j21=jm1(mr,j)
      j22=jm2(mr,j)
      kh=0
      !DECS LOOP COUNT(24)
      do k=1,kl
        ks=k
        wp11=wp(k,1,1)
        wp12=wp(k,1,2)
        wp21=wp(k,2,1)
        wp22=wp(k,2,2)
        wm11=wm(k,1,1)
        wm12=wm(k,1,2)
        wm21=wm(k,2,1)
        wm22=wm(k,2,2)
        wp112=wp11**2
        wp122=wp12**2
        wp212=wp21**2
        wp222=wp22**2
        wm112=wm11**2
        wm122=wm12**2
        wm212=wm21**2
        wm222=wm22**2
        ffacp=1.
        ffacp1=1.
        ip=ikp(k)
        ip1=ikp1(k)
        im=ikm(k)
        im1=ikm1(k)
        cwks17=cong*wks17(k)
        tfcen=fconst0(k,idx)*enh(idx)*cwks17
        kp=ip
        kp1=ip1
        kp2=kp
        kp3=kp1
        if(kp >= kl) then
          kh=kh+1
          kp2=kl+1
        endif
      enddo
    enddo
  enddo
enddo
```

Exchange the Loop sequence

Optimization strategy

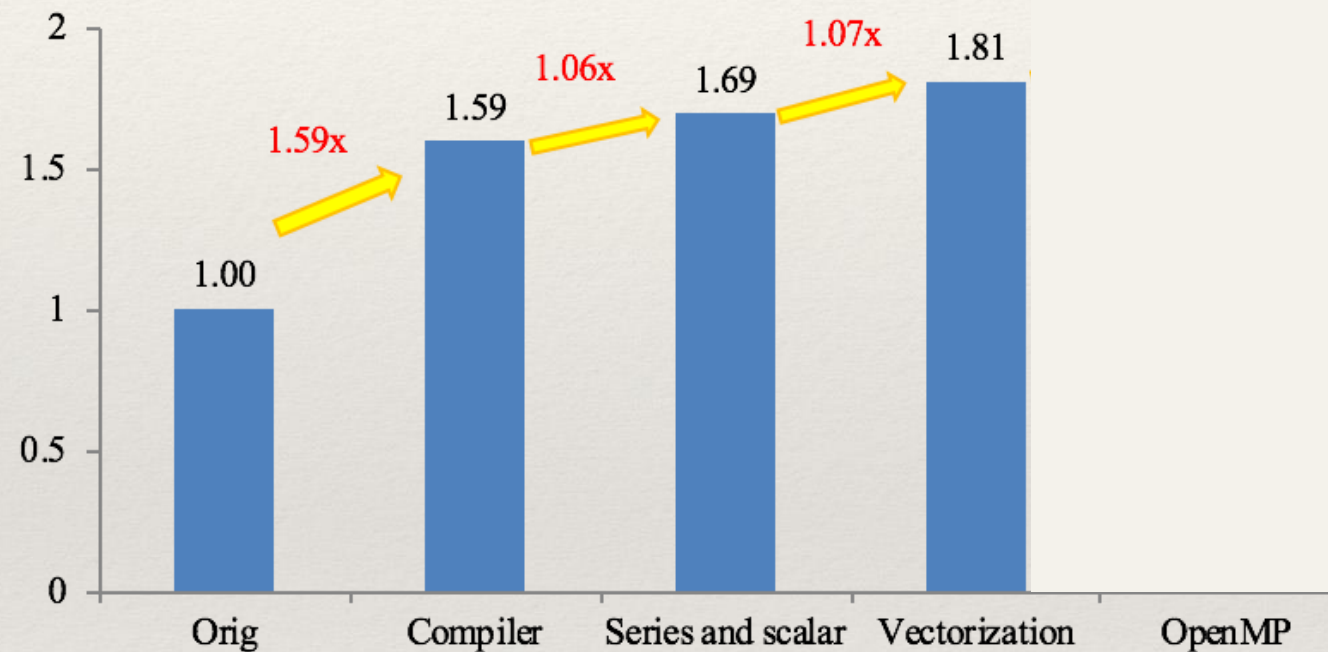
Step 2.3: Vectorization Optimization



Remove the dependence

Optimization strategy

Step 2.3: Vectorization Optimization

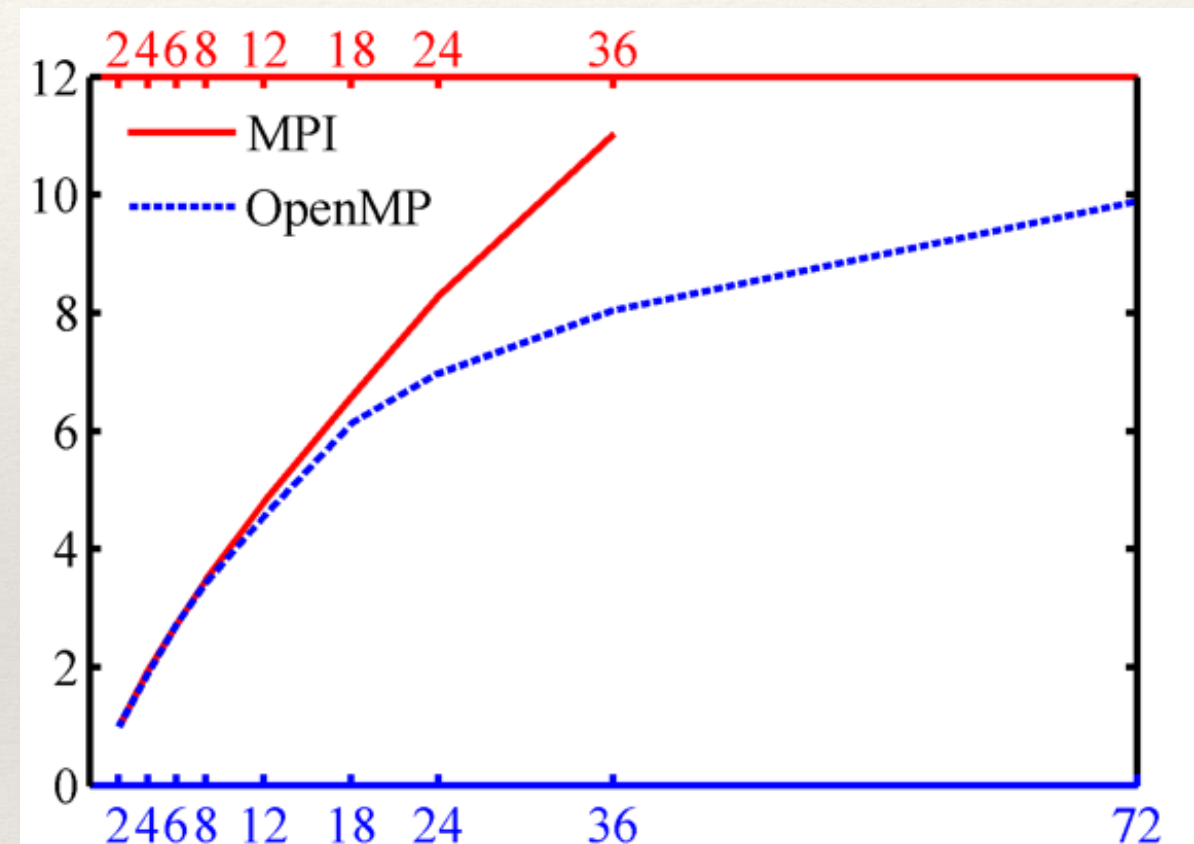


Optimization strategy

Step 2.4: Fine-Grained Parallism

```
!$OMP PARALLELDO PRIVATE(idx)
do idx=1,np
call mean2(idx)
enddo

allocate(tad(klp1) )
allocate(tadp(klp1) )
allocate(tadm(klp1) )
allocate(tdelad(klp1))
allocate(tdeladm(klp1))
allocate(tdeladp(klp1))
allocate(tkh(klp1))
!$OMP PARALLELDO DEFAULT(NONE) SHARED(pein,peds,pebo,nsp,awk,wx,wy) &
!$OMP SHARED(kpmt0,kakt0,fconst0,wf,d,enh,e,ee,w,ks0) &
!$OMP SHARED(wk,ikp,jp1,jp2,jm1,jm2,wp,wm,ikp1,ikm,ikm1,wks17) &
!$OMP SHARED(wkh,tkh,presin,precos,grolim) &
!$OMP SHARED(awf,asi,ark,ae,uxx,uxy,uyx,uyy,ccg) &
!$OMP SHARED(cong,np,alog10pwk,al31,al11,al12,al21,al13,al23,dwk,deltt,deltt5)
&
!$OMP PRIVATE(awkss,vx,vy,ww,wkpm,wkpmt,wakt,beta) &
!$OMP PRIVATE(xx,wp11,wp12,wp21,wp22,wm11,wm12,wm21,wm22) &
!$OMP PRIVATE(wp112,wp122,wp212,wp222,wm112,wm122,wm212,wm222,ffacp,ffacp1) &
!$OMP PRIVATE(cwks17,rij,eij,ea1,ea2,ea3,ea4,ea5,ea6,ea7,ea8,up,up1) &
!$OMP PRIVATE(um,um1,sap,sam,eij2,zua,ead1,ead2,fcen,ad,adp,adm,delad) &
!$OMP PRIVATE(deladm,cd,theta0,coth,sinth,wl,wlstar,wk0,wf0,ws0,bett) &
!$OMP PRIVATE(awfss,arkss,aess,eks,ekspm,sds,asiss,ssds,d0,dk,ssbo,duxdx0) &
!$OMP PRIVATE(duydx0,duydy0,th0,coth2,sinth2,cg,cp,cgdc,cu1,cu2,cu3,sscu) &
!$OMP PRIVATE(wstar,delte,eef,gadiag,eefab,sig,deladp,duxdy0,sbo) &
!$OMP PRIVATE(kpmt,kakt,ks1,ks,ksp1,k,j,kh,ip,ip1,im,im1) &
!$OMP PRIVATE(kp,kp1,kp2,kp3,mr,js,j11,j12,j21,j22,i) &
!$OMP PRIVATE(tfcen,tasds,tad,tadm,tadp,tdeladp,tdeladm,tdelad) & !shan
!$OMP PRIVATE(se,dse,sein,seds,sebo) SCHEDULE(GUIDED,7)
```

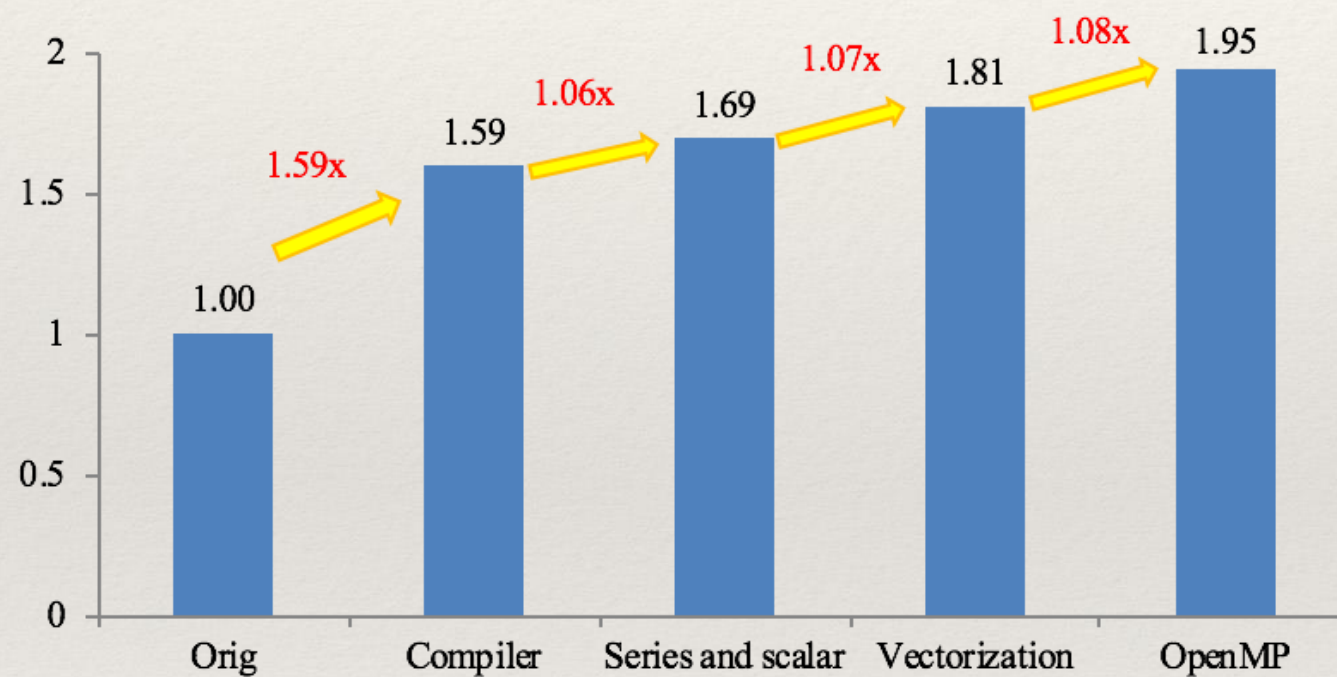


Red: MPI; Blue: OpenMP

use Open MP “!\$OMP PARALLELDO” for parallelization

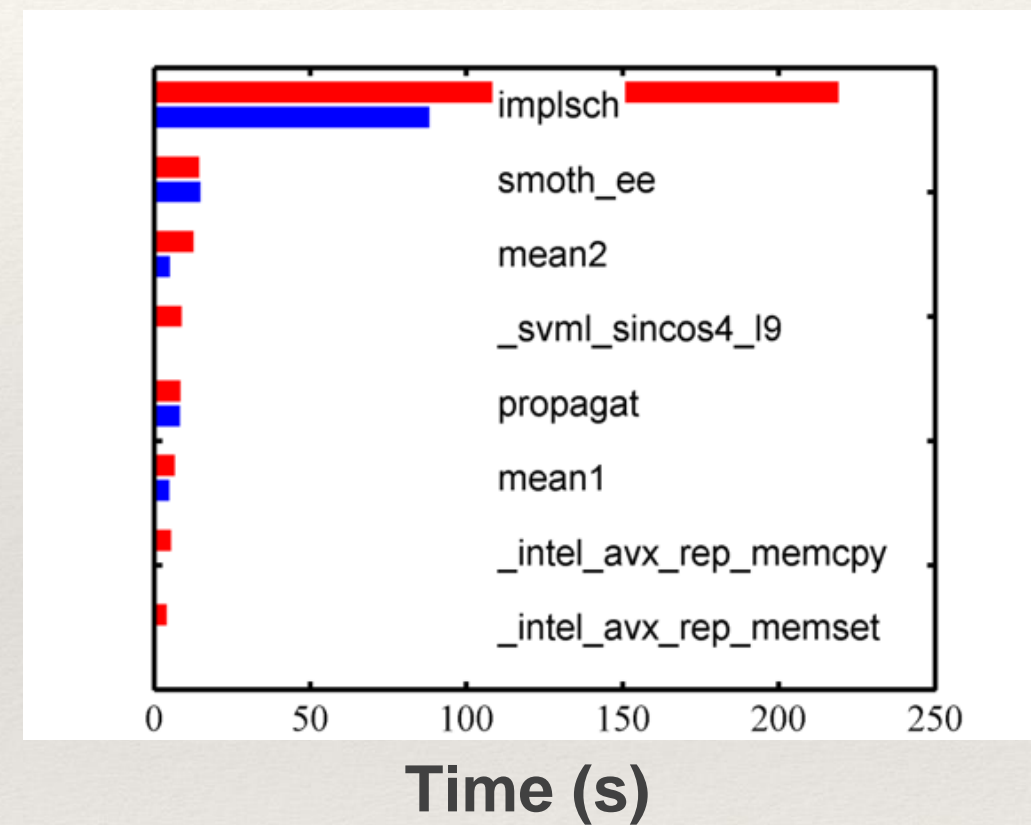
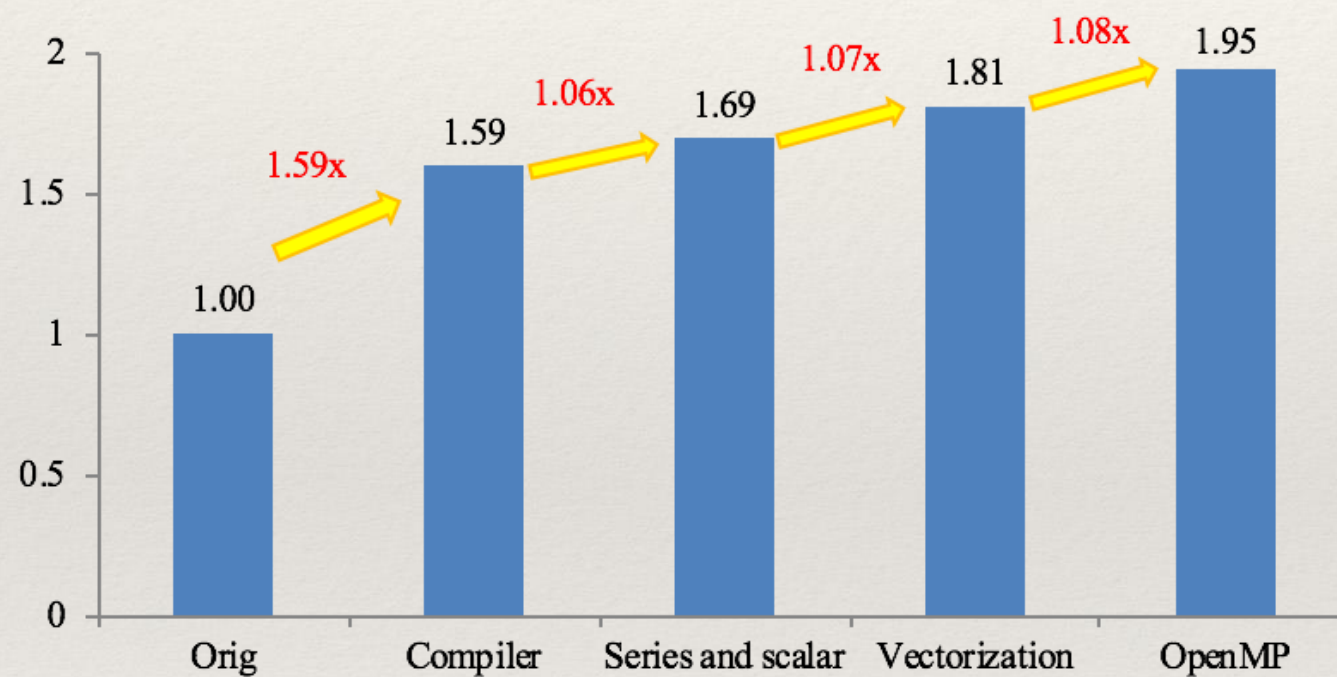
Optimization strategy

Step 2.4: Fine-Grained Parallism



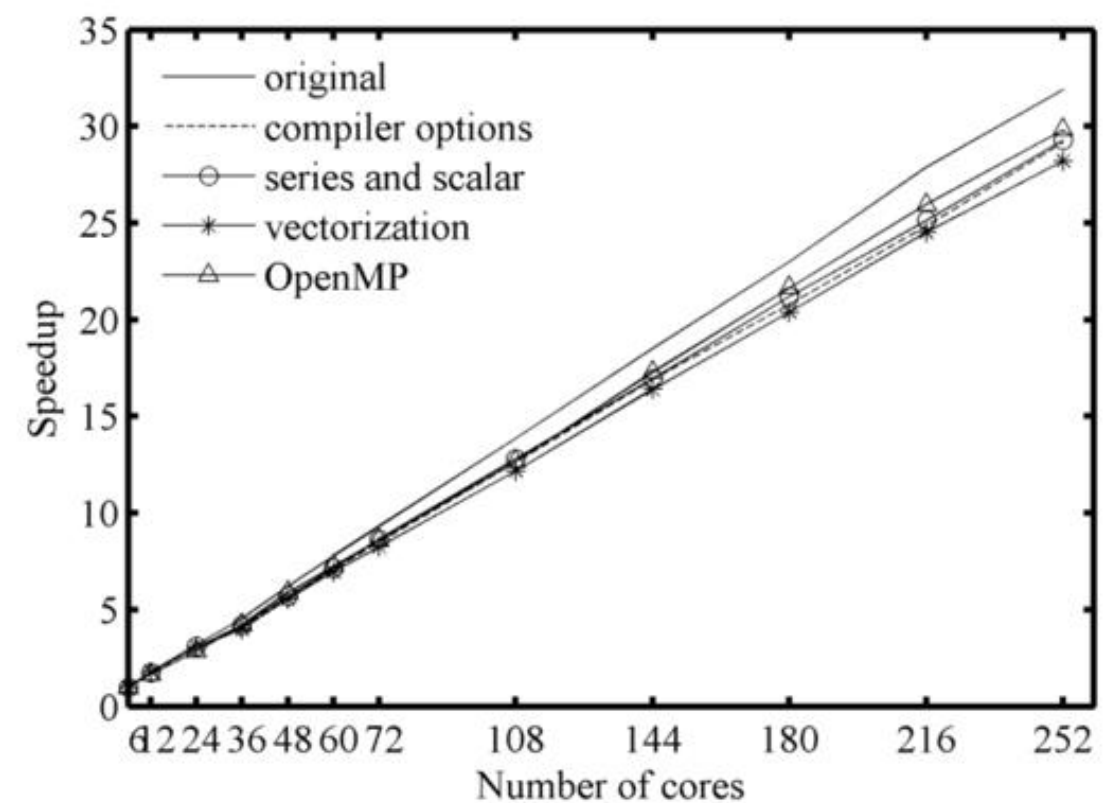
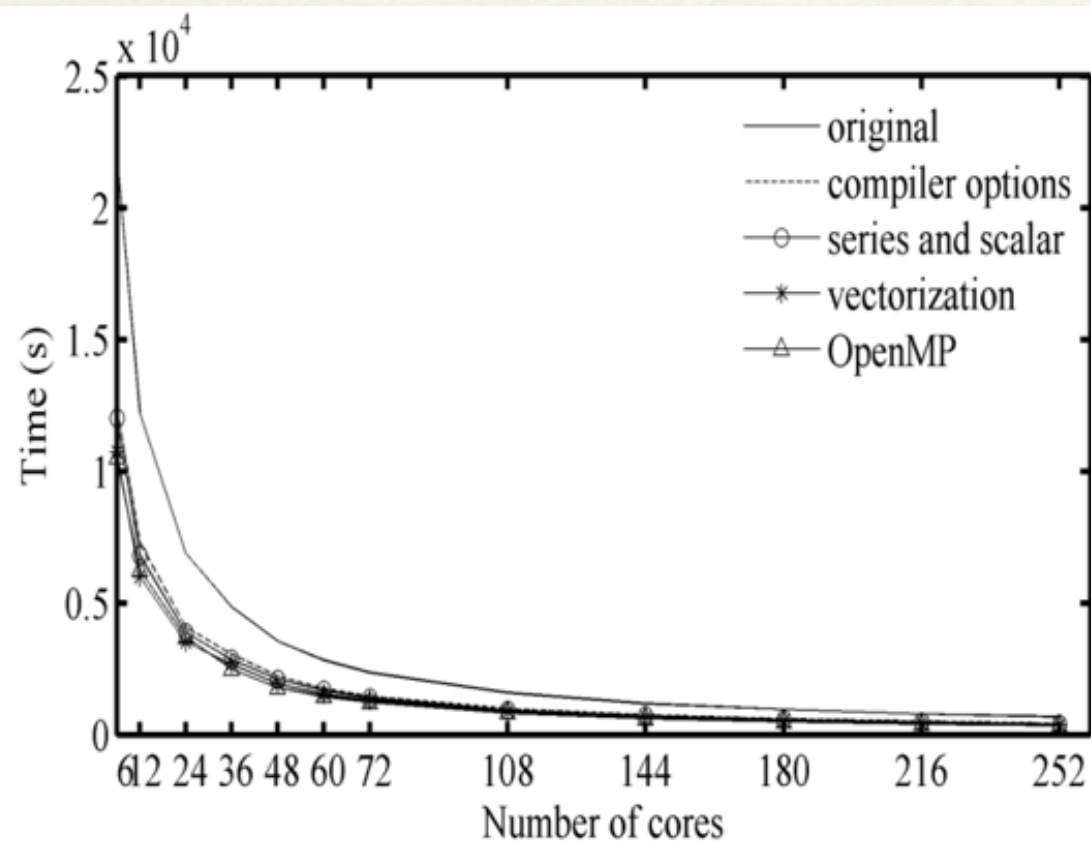
Optimization strategy

Step 2.4: Fine-Grained Parallism



Optimization strategy

Step 3: Optimization on multi-nodes



Outline

- ❖ Brief Introduction of Intel[®] PCC at FIO
- ❖ Background
- ❖ Optimization strategy
- ❖ Future work

Future work

❖ MPI+OpenMP load balance

- ▶ Single node: 36 MPI + 2 OpenMP
- ▶ Multi nodes: 12 MPI + 6 OpenMP

Can we find an algorithm?
 $f = (\text{workload}, \text{cpu}, \text{network})$

Future work

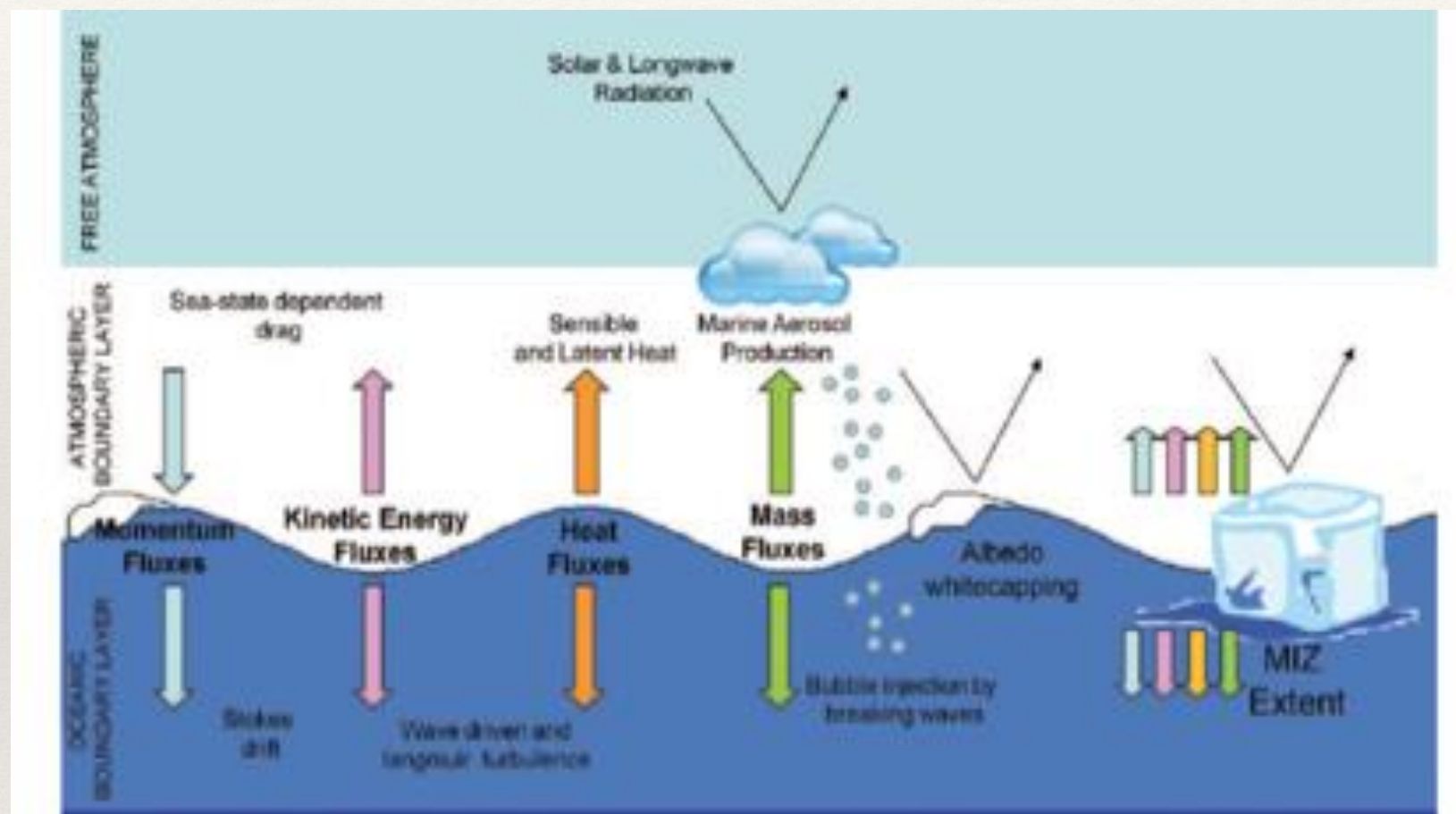
- ❖ MPI+OpenMP load balance
- ❖ Optimize on the new Intel Architecture (wider vector length)
- ❖ Optimize the MASNUM surface wave model on large-scale cluster
- ❖ Try to apply the optimization strategy to other ocean and atmosphere models

IMPROVE RESEARCH CAPACITY
BOOST COLLABORATION BETWEEN HPC AND OCEAN
RESEARCH
MAXIMISE APPLICATION AND COMMERCIALISATION OF
RESEARCH OUTCOMES

THANK FOR YOUR ATTENTION

Coupled models by incorporated ocean surface wave model

Importance of ocean surface wave

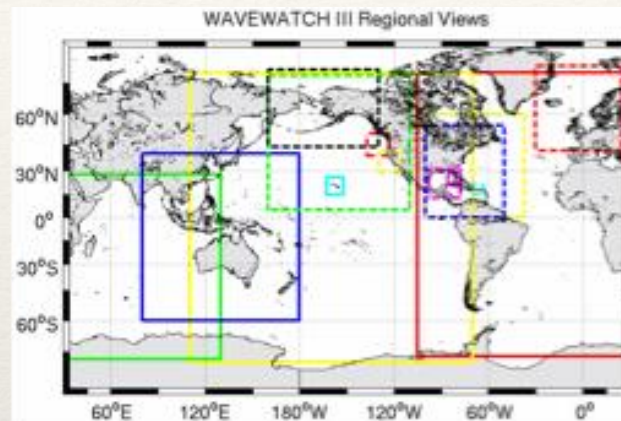


- ❖ Ocean surface wave is also important in the ocean and climate system.
- ❖ Coupled with ocean surface wave model is a way to accurately simulating and forecasting for ocean and climate

Intel® PCC at FIO

T1: Model computing performance——simulating faster

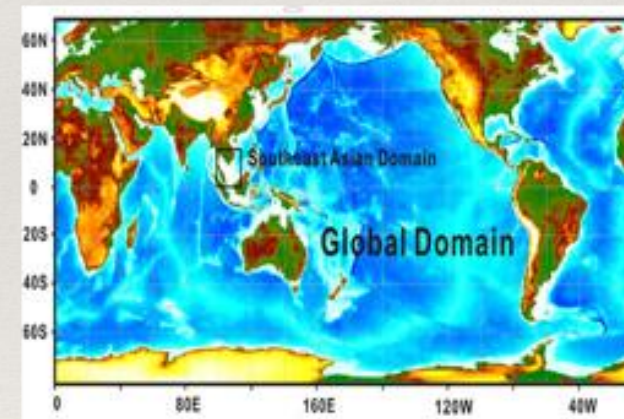
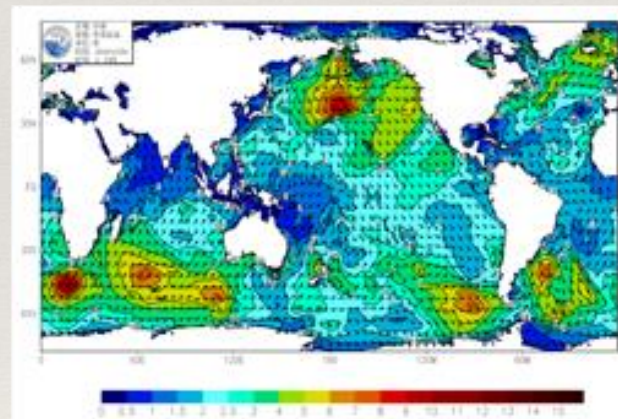
NCEP (USA),
WaveWatch III
Global: $1.25 \times 1.00^\circ$
Region: $0.25 \times 0.25^\circ$



ECMWF (Europe),
WAM, Global
7-day: $0.125 \times 0.125^\circ$
15-day: $0.25 \times 0.25^\circ$

State-of-the-art of wave forecasting

NMEFC (China),
SWAM
Global: $0.5 \times 0.5^\circ$
Region: $0.125 \times 0.125^\circ$

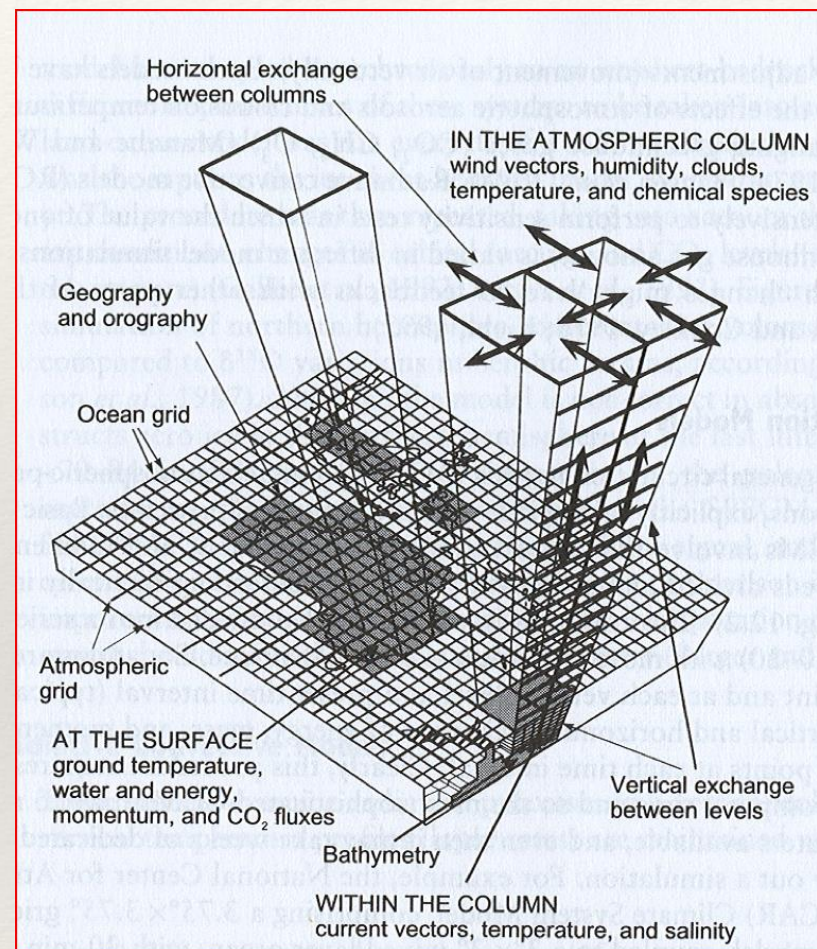
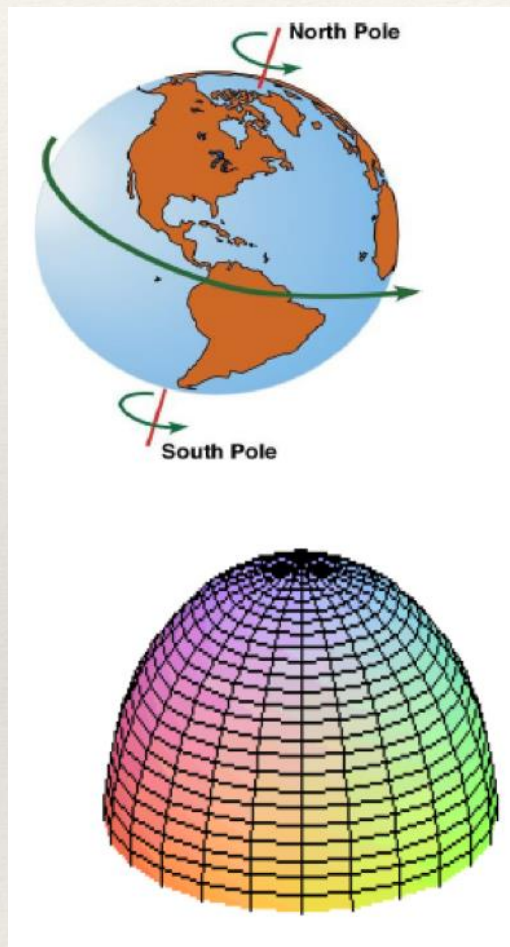


IOC/WESTPAC,
MASNUM
Global: $0.5 \times 0.5^\circ$
Region: $0.125 \times 0.125^\circ$

- ❖ 7-days forecasting within 90 minutes
- ❖ Resolution finer, simulation ability better
- ❖ Fine-resolution is still a challenge

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T2: Model simulation ability——more accurate



Parameterization:
unsolved physical
process due to
resolution

- ❖ Model tuning: a hard work, depending on modeler empirically
- ❖ Parameter optimization: by using deep learning