C2SM
Center for Climate Systems Modeling

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Adapting Numerical Weather Prediction codes to heterogeneous architectures: porting the COSMO model to GPUs

O. Fuhrer, T. Gysi, **X. Lapillonne**, C. Osuna, T. Dimanti, T. Schultess and the HP2C team

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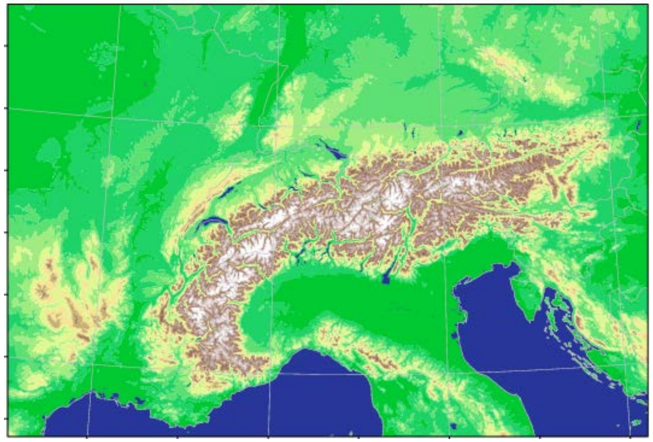
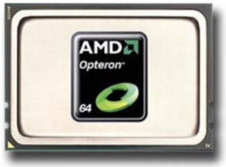
The COSMO model



- **Limited-area** model
- Run operationally by several National Weather Service within the Consortium for Small Scale Modelling: Germany, Switzerland, Italy, Poland, Greece, Rumania, Russia.
- Used for climate research in several academics institutions

Why using Graphical Processor Units ?

- Higher peak performance at lower cost / power consumption
- High memory bandwidth

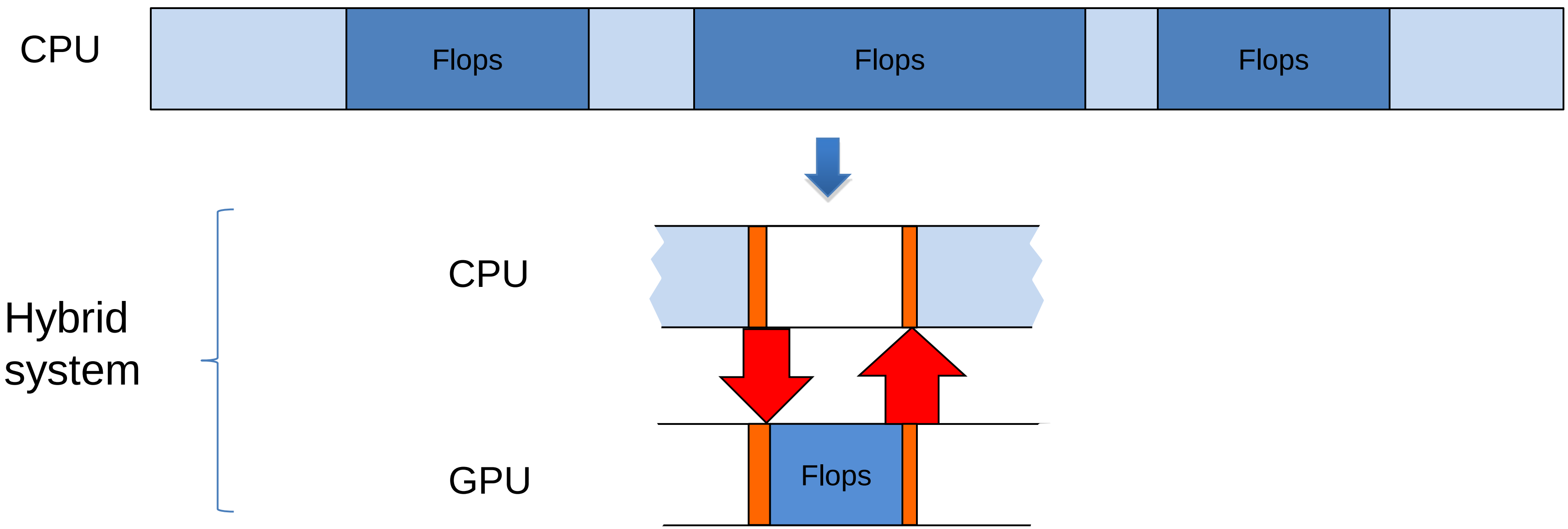


	Cores	Freq. (GHz)	Peak Perf. S.P. (GFLOPs)	Peak Perf. D.P. (GFLOPs)	Memory Bandwith (GB/sec)	Power Cons. (W)
CPU: AMD Opteron (Interlagos)	16	2.1	268	134	57	115
GPU: Fermi X2090	512	1.3	1330	665	155	225

X 5 X 3

Using GPUs : the accelerator approach

- CPU and GPU have different memories



- Most intensive parts are ported to GPU, data is copied back and forth between the GPU and the CPU between each accelerated part.

What does this mean for NWP application ?

- Low FLOP count per load/store (stencil computation)
- Example with COSMO-2 (operational configuration at MeteoSwiss) :

*

Part	Time/Δt
Dynamics	**172 ms**
Physics	**36 ms**
Total	**253 ms**

vs

§

Transfer of ten prognostic variables

118 ms

CPU-GPU data transfer time is large with respect to computation time:

Accelerator approach might not be optimal

* CPU measurements: Cray XT6, Magny-Cours, 45 nodes, COSMO-2

§ GPU measurements: PCIe 8x, HP SL390, 2 GB/s one way, 8 sub-domains

Our strategy : full GPU port

- **All code which uses grid data fields at every time step is ported to GPU**

Input/Setup → keep on CPU / copy to GPU

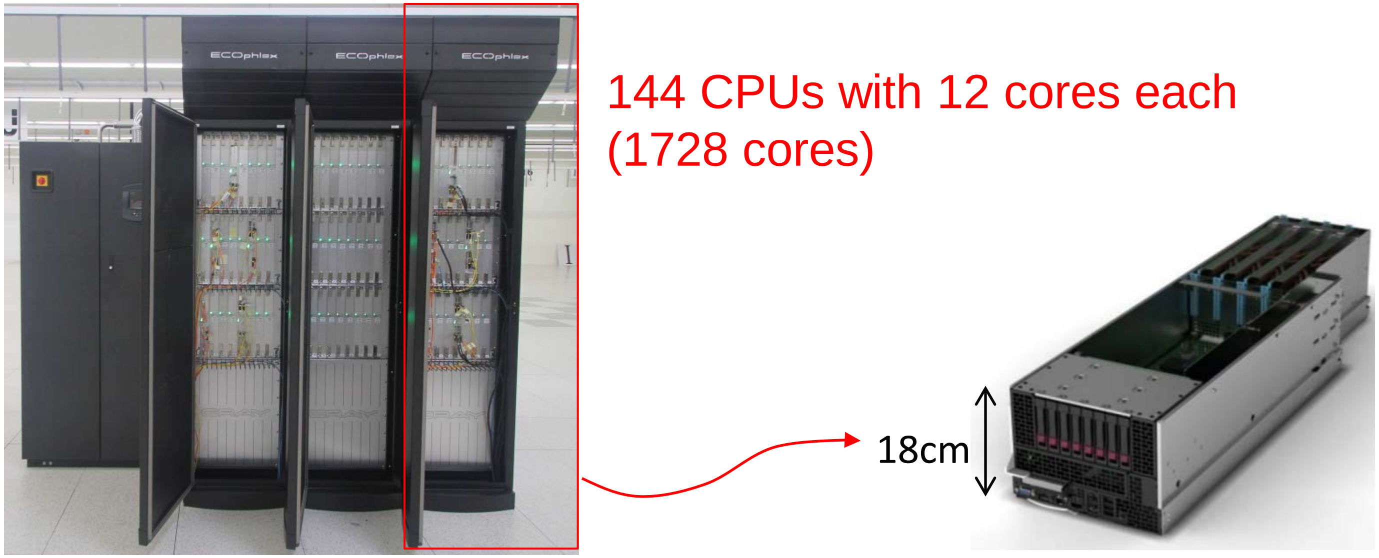
Δt

- **Initialize timestep** → OpenACC directives
- **Physics** → OpenACC directives
- **Dynamics** → C++ rewrite (uses CUDA)
- **Assimilation** → OpenACC directive (part on CPU)
- **Halo-update** → GPU-GPU communication library (GCL)
- **Diagnostics** → OpenACC directives
- **Output** → keep on CPU / copy from GPU

Finalize

The HPCC OPCODE project

- Part of the Swiss High Performance High Productivity initiative
- Prototype implementation of the COSMO production suite of MeteoSwiss making aggressive use of GPU technology
- Same time-to-solution on substantially cheaper hardware:



1 cabinet Cray XE5

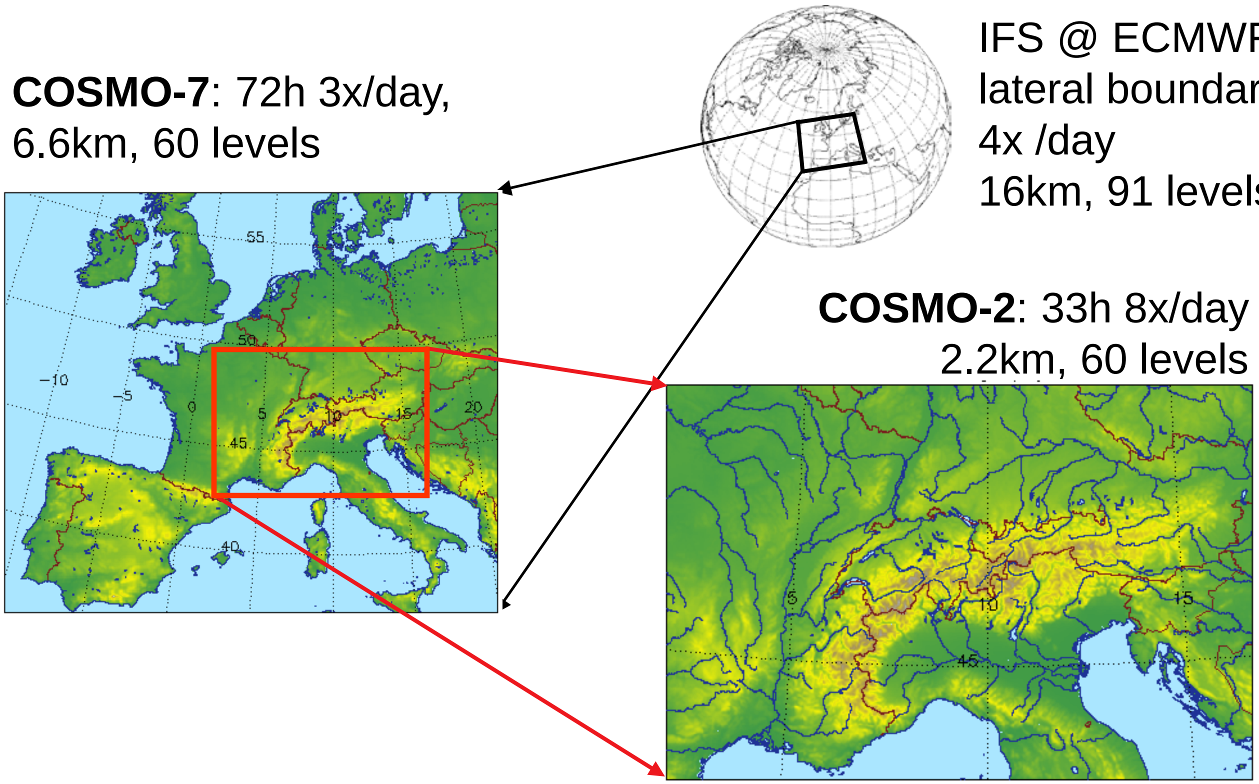
GPU based hardware

- OPCODE prototype code should be running by end 2012
- These developments are part of the priority project POMPA within the COSMO consortium : preoperational GPU-version of COSMO for 2014

MeteoSwiss COSMO-7 and COSMO-2

COSMO-7: 72h 3x/day,
6.6km, 60 levels

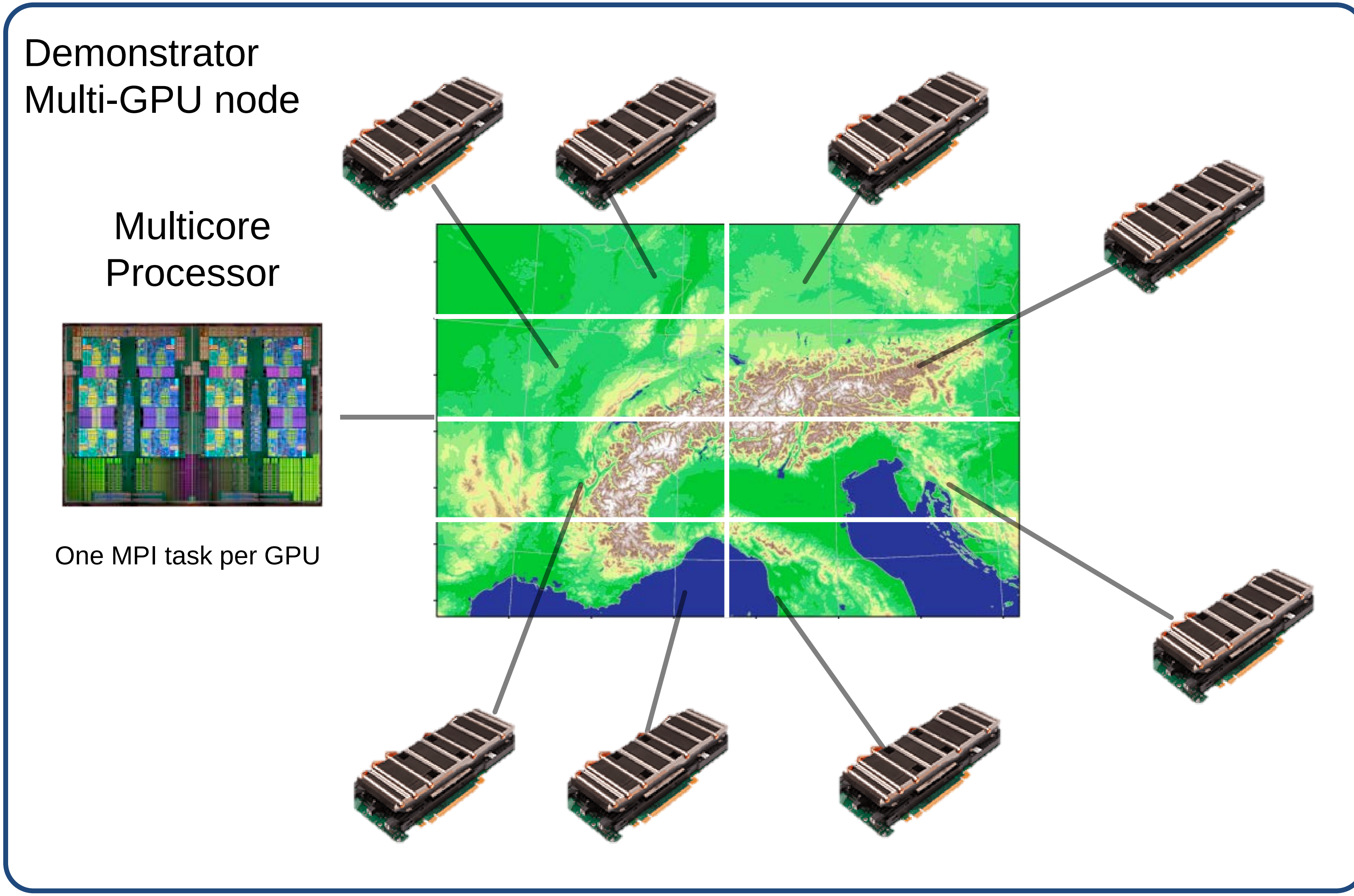
IFS @ ECMWF:
lateral boundaries
4x /day
16km, 91 levels



COSMO-2: 33h 8x/day
2.2km, 60 levels

520 x 350 x 60 grid points

COSMO on the demonstrator system



Dynamical core refactoring

Dynamics

- Small group of developers
- Memory bandwidth bound
- Complex stencils (IJK-dependencies)
- 60% of runtime
- 40 000 lines (18%)

→ Complete rewrite in C++

→ Development of a stencil library

→ Target architectures CPU (x86) and GPU

→ Could be extended to other architectures

→ Long term adaptation of the model

Communication library

- Requirement for multi-node communications that can be called from the new dynamical core.

→ New communication library (GCL)

→ Can be called from C++ and Fortran code

→ Can handle CPU-CPU and GPU-GPU communication

→ Allows overlap of communication and computation

Note : only single node results will be presented

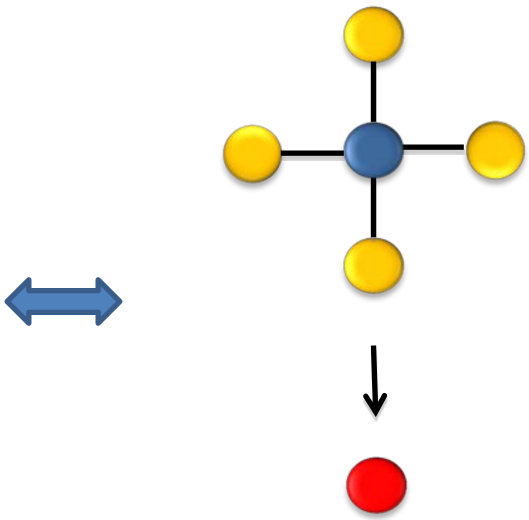
Stencil computations

- COSMO is using finite differences on a structured grid
- Stencil computation is the dominating algorithmic motif within the dycore

- Stencil Definition
- Kernel updating array elements according to a fixed access pattern

- Example 2D Laplacian

```
lap(i,j,k) = -4.0 * data(i,j,k) +
    data(i+1,j,k) + data(i-1,j,k) +
    data(i,j+1,k) + data(i,j-1,k);
```



Stencil library development

Motivation

- Provide a way to implement stencils in a platform independent way
- Hide complex/hardware dependent optimizations from the user

→ Single source code which is performance portable

Solution retained

- DSEL : Domain Specific Embedded Language
- C++ library using template meta programming
- Optimized back-ends for GPU and CPU

	CPU	**GPU**
Storage Order (Fortran)	KIJ	IJK
Parallelization	OpenMP	CUDA

Stencil code concepts

loop-logic

update-function / stencil

```
DO k = 1, ke
  DO j = jstart, jend
    DO i = istart, iend
      lap(i,j,k) =
          -4.0 * data(i,j,k) +
          data(i+1,j,k) + data(i-1,j,k) +
          data(i,j+1,k) + data(i,j-1,k)
    ENDDO
  ENDDO
ENDDO
```

A stencil definition consists of 2 parts

- Loop-logic: Defines stencil application domain and execution order ➡ DSEL
- Update-function: Expression evaluated at every location ➡ USER

While the loop-logic is platform dependent the update-function is not
→ treat the two separately

Programming the new dycore

```
enum { data, lap };

template<typename TEnv>
struct Lap
{
  STENCIL_STAGE(TEnv)

  STAGE_PARAMETER(FullDomain, data)
  STAGE_PARAMETER(FullDomain, lap)

  static void Do(Context ctx, FullDomain)
  {
    ctx[lap::Center()] =
      -4.0 * ctx[data::Center()] +
      ctx[data::At(iplus1)] +
      ctx[data::At(iminus1)] +
      ctx[data::At(jplus1)] +
      ctx[data::At(jminus1)];
  }
};
```

Update-function

```
IJKRealField lapfield, datafield;
Stencil stencil;

StencilCompiler::Build(
  stencil,
  "Example",
  calculationDomainSize,
  StencilConfiguration<Real, BlockSize<32,4> >(),
  …
  define_sweep<KLoopFullDomain>(
    define_stages(
      StencilStage<Lap, IJRange<cComplete,0,0,0,0> >()
    )
  )
  …
);

for(int step = 0
{
  stencil.Apply(
}
```

Stencil Setup

```
DO k = 1, ke
  DO j = jstart, jend
    DO i = istart, iend
      lap(i,j,k) = data(i+1,j,k) + …
    ENDDO
  ENDDO
ENDDO
```

Dynamics, single-node performance

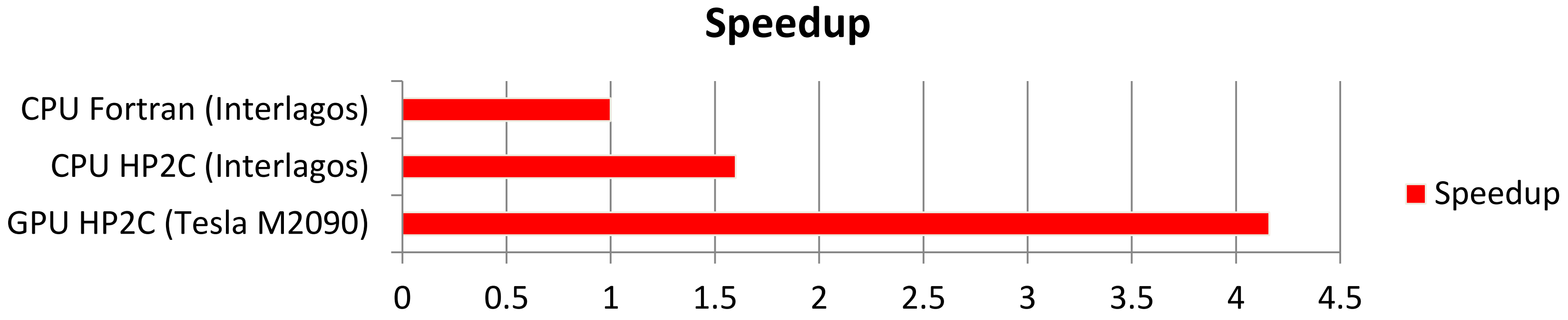
- **Test domain 128x128x60. CPU: 16 cores Interlagos CPU; GPU : X2090**

CPU / OpenMP Backend

- Factor 1.6x - 1.7x faster than the COSMO dycore
- No explicit use of vector instructions (10% up to 30% improvement)

GPU / CUDA backend

- Tesla M2090 (GPU with 150 GB/s memory bandwidth) is roughly a factor 2.6x faster than Interlagos (CPU with 52 GB/s memory bandwidth)
- Ongoing performance optimizations



Pros and Cons of the rewrite approach

Pros

•Performance and portability

•Better separation of implementation strategy and algorithm

•Single source code

•The library suggest / forces certain coding conventions and styles

•Flexibility to extend to other architecture

Cons/difficulties

•This is a big step with respect to the original Fortran code

- Can this be taken over by main developers of the dycore ? (workshop, knowledge transfer …)

•Adding support for new hardware platforms requires a deep understanding of the library implementation

Physics and data assimilation port to GPU

Physics
- Large group of developers
- Some code maybe shared with other model
- Less memory bandwidth bound
- Simpler stencils (K-dependencies)
- 20% of runtime
- 43 000 lines (19%)

→ GPU port with OpenACC directives
→ Optimization of the code to get optimal performance on GPU
→ Most routines have for the moment a GPU and CPU version

Data assimilation
- Very large code
- 83 000 lines (37%)
- 1 % of runtime

→ GPU port with OpenACC directives only for parts accessing multiple grid data field
→ No code optimization
→ Single source code
→ Some parts still computed on CPU

Directives / Compiler choices for OPCODE

```
!$acc parallel
 !$acc loop gang vector
do i=1,N
 a(i)=b(i)+c(i)
end do
!$acc end parallel
```

OpenAcc: Open standard, supported by 3 compiler vendors PGI, Cray, Caps

- Solution retained for OPCODE (for physics and assimilation)
- PGI : some remaining issues with the compiler
- Cray: The code can be compiled and run. Gives correct results
- CAPS: not investigated yet

- PGI proprietary:
  - First implementation of the physics
  - Translation to OpenAcc is not an issue

➡ Being able to test code with different compilers is essential

Implementation strategy with directives

- Parallelization: horizontal direction, 1 thread per vertical column
- Most loop structures unchanged, one only adds directives
- In some parts, loop restructuring to reduce kernel call overheads, and profit from cache reuse.

```
!$acc data present(a,c1,c2)
!vertical loop
do k=2,Nz
 !work 1
 !$acc parallel loop vector_length(N)
 do ip=1,nproma
  c2(ip)=c1(ip,k)*a(ip,k-1)
 end do
 !$acc end parallel loop
!work 2
!$acc parallel loop vector_length(N)
do ip=1,nproma
    a(ip,k)=c2(ip)*a(ip,k-1)
end do
!$acc end parallel loop
end do
!$acc end data
```

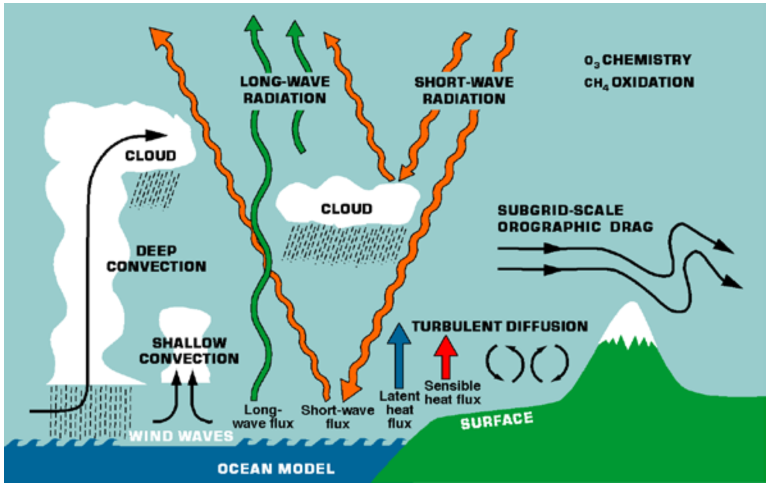
→

```
!$acc data present(a,c1)
!$acc parallel loop vector_length(N)
do ip=1,nproma
 !vertical loop
 do k=2,Nz
  !work 1
  c2=c1(ip,k)*a(ip,k-1)
  !work 2
   a(ip,k)=c2*a(ip,k-1)
 end do
end do
!$acc end parallel loop
!$acc end data
```

- Remove Fortran automatic arrays in subroutines which are often called (to avoid call to cudamalloc)
- Data regions to avoid CPU-GPU transfer
- Use profiler to target specific parts which need further optimization: reduce memory usage, replace intermediate arrays with scalars …

Lapillonne and Fuhrer submitted to Parallel Processing Letters

Ported Parametrizations

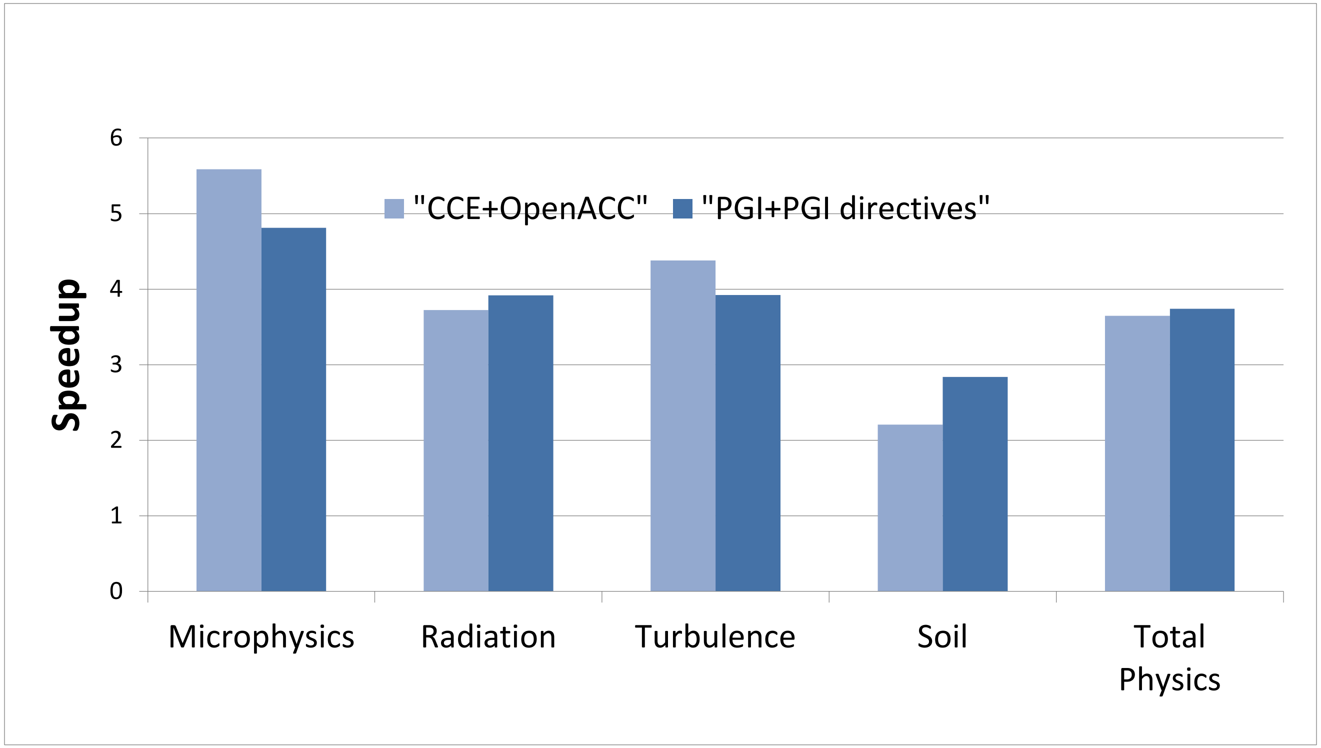


- Currently implemented and tested physics:
  - Microphysics (ice-scheme)
  - Radiation (Ritter-Geleyn)
  - Turbulence (Raschendorfer)
  - Soil (Terra)

- These 4 parametrizations account for 90-95% of the physics time of a typical COSMO-2 run. First meaningful real case simulations are possible with this reduced set.

Performance results for the physics

- Test domain 128x128x60 – 16 cores Interlagos CPU vs X2090 GPU



- Overall speed up x3.6
- Similar performance with Cray CCE and PGI
- Running the GPU-Optimized code on CPU is about 25% slower
  ➔ separate source for time critical routines

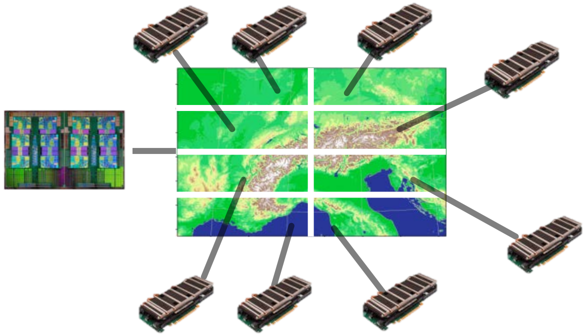
Our experience using directives

- Relatively easy to get the code running
- Useful to port large part of the code
- Requires some work to get performance: data placement, restructuring, additional optimization …
  - Ex: GPU part of assimilation is 20% to 50% slower on GPU than on CPU
- Having a single source code that run efficiently on GPU and CPU (x86) is still an issue

Putting all together: can we run this ?

- The dynamical core is compiled as a library:
  - gcc + nvcc
- Linked with the Fortran part + OpenACC
  - So far only working with Cray CCE
- GPU pointers are passed from fortran to C++ library using the host_data directive:
  - No data transfer required !

Conclusions



- Our strategy : full GPU port
- Dynamics : complete rewrite
- Physics and data assimilation : OpenACC directives
- Could achieve same time to solution than current operational with a Multi-GPU node having o(10) GPUs : demonstrator system for end 2012

Acknowledgments

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