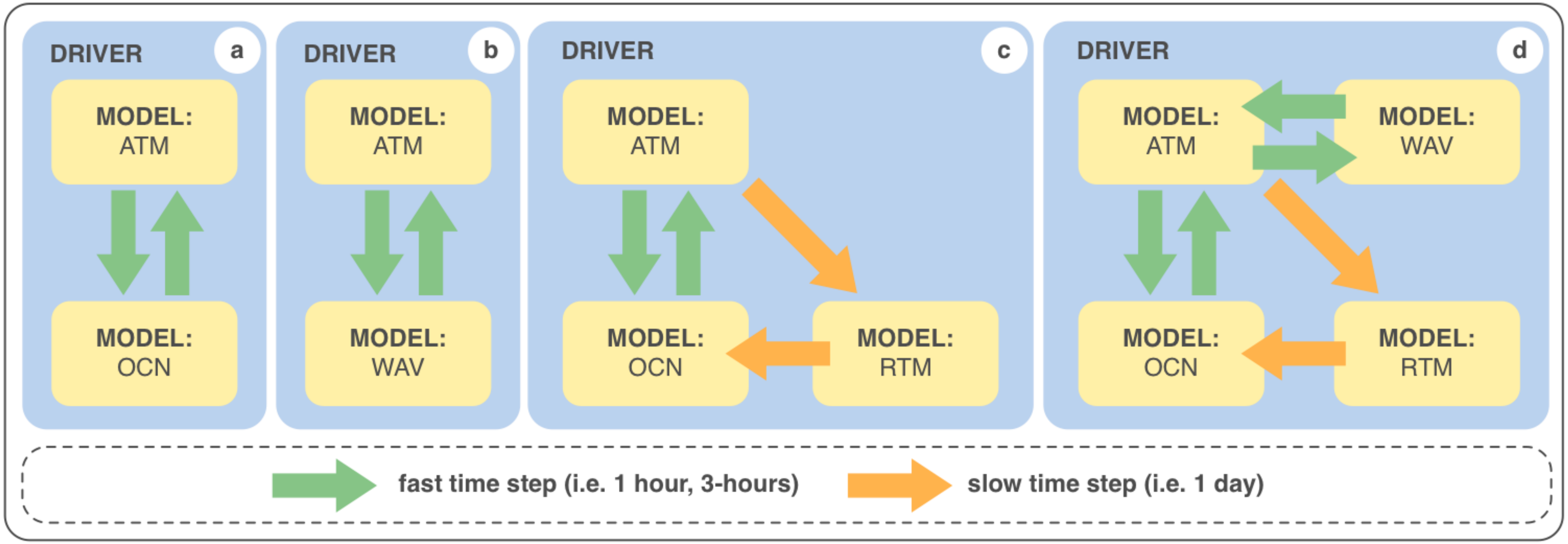


Introduction to Model Coupling in Earth System Science and Recent Developments

Ufuk Utku Turuncoglu

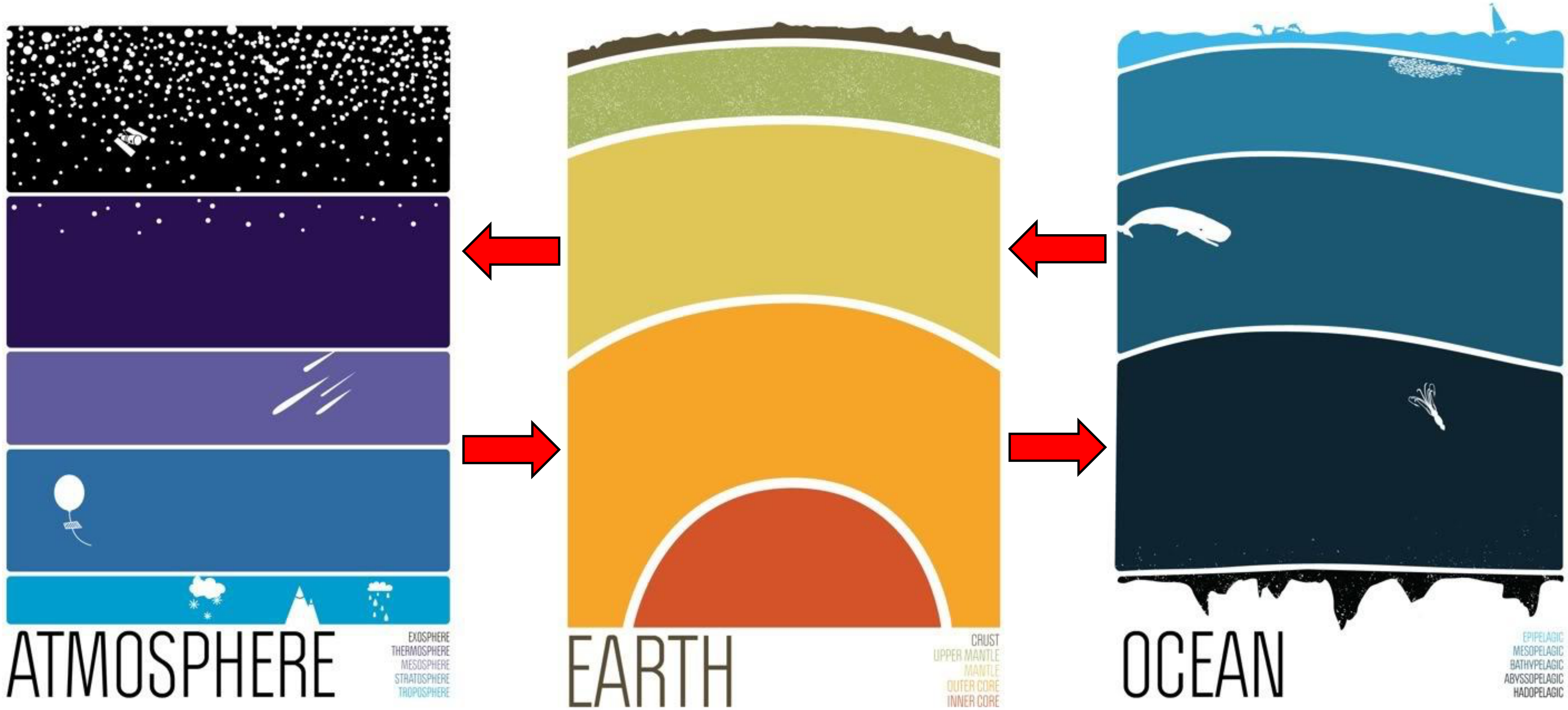
ITU, Informatics Institute

ICTP, ESP Section

1st Regional Earth System Modeling Summer School, 5-7 September 2016, ITU, Turkey

Earth System

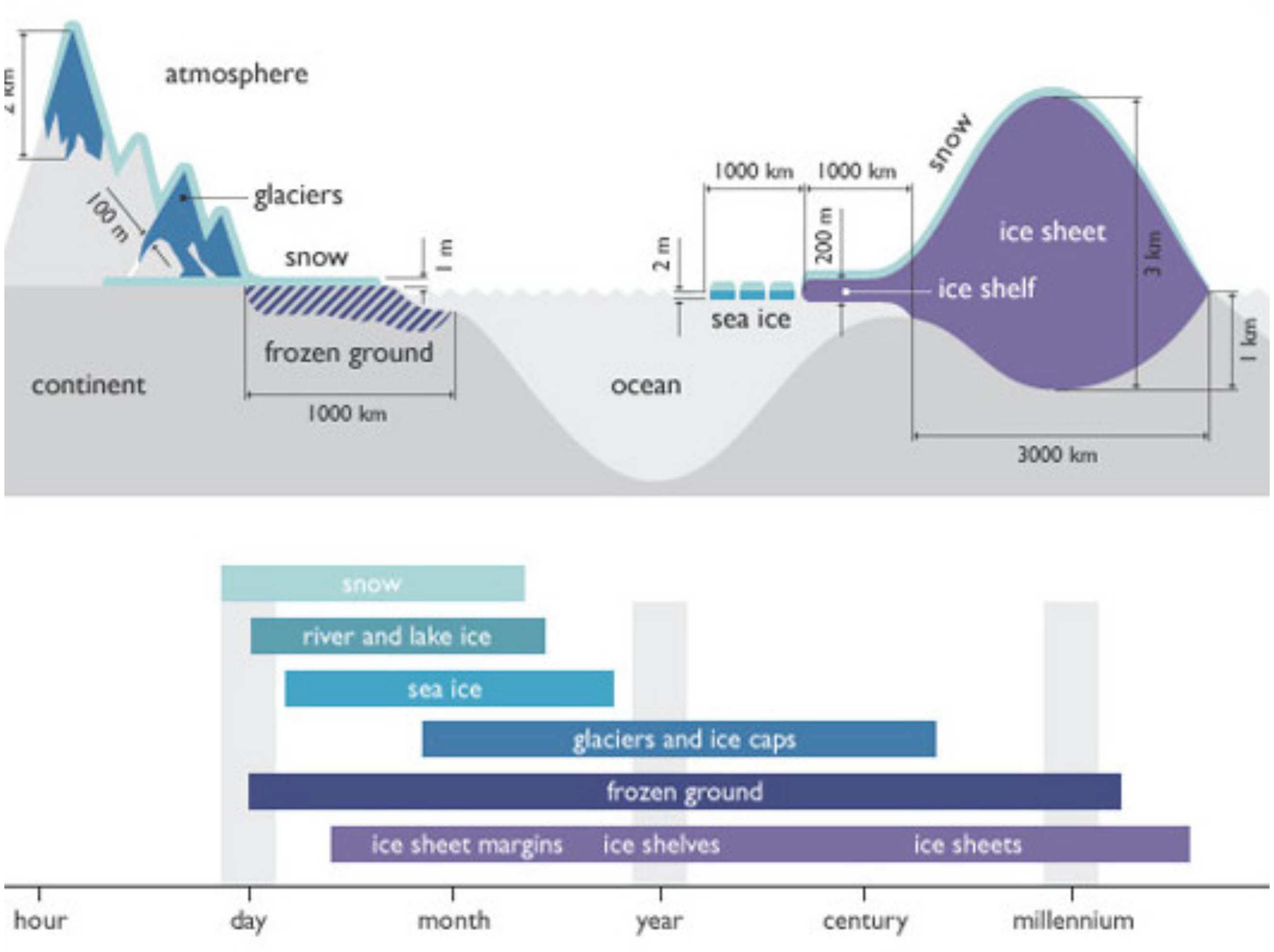
- It is represented by complex and non-linear interaction between different elements (atmosphere, hydrosphere, geosphere and biosphere).
- All the processes have different spatial and temporal scales



http://wearebrainstorm.com/products/earth-science-set-of-4-prints

Earth System …

- All the processes have different spatial and temporal scales
- Response time under forcing also differs

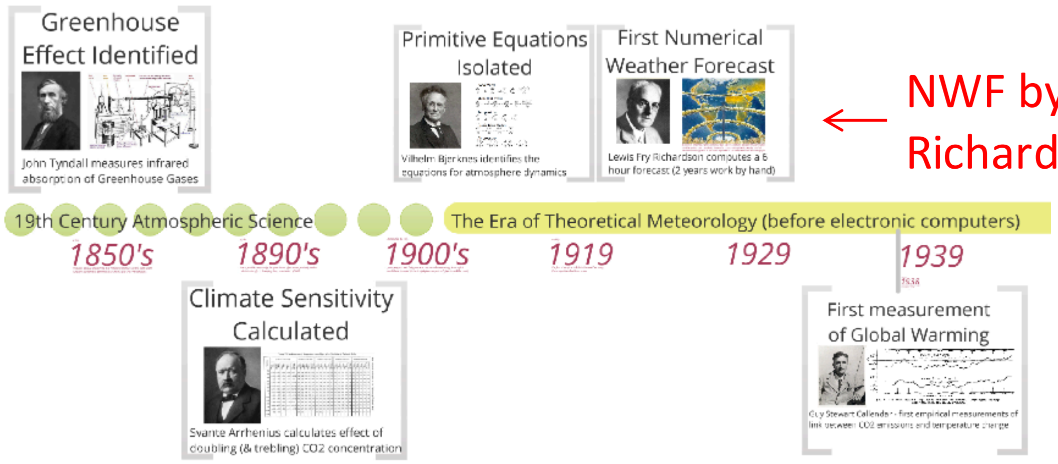


IPCC Report

Climate Modeling

• Evolution:

NWF by Richardson

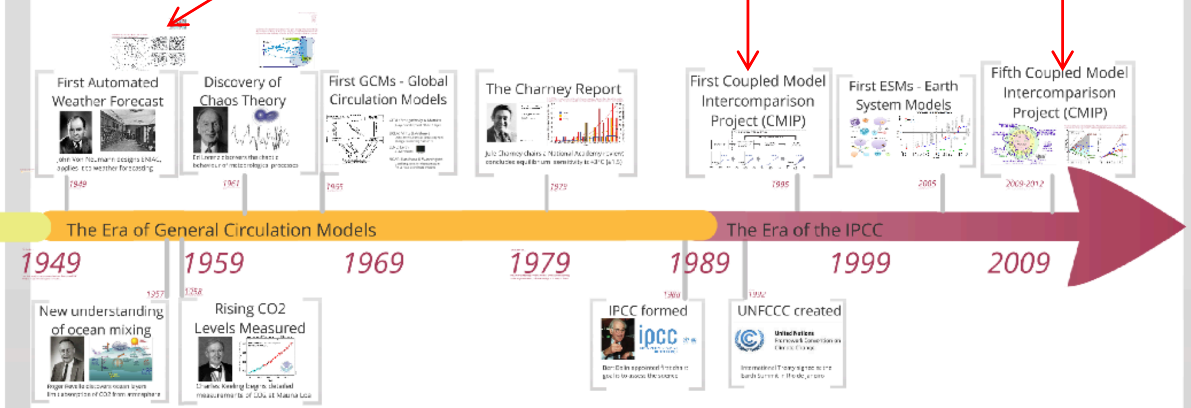


1850 - 1900: How does the "Green-house Effect" work?

1900 - 1949 Can we calculate the weather?

Coordinated Experiments CMIPs

Automatized NWF by Von Neumann



1959-1979: How much warmer will it get?

1980s onwards Where will the impacts occur? What are our policy choices?

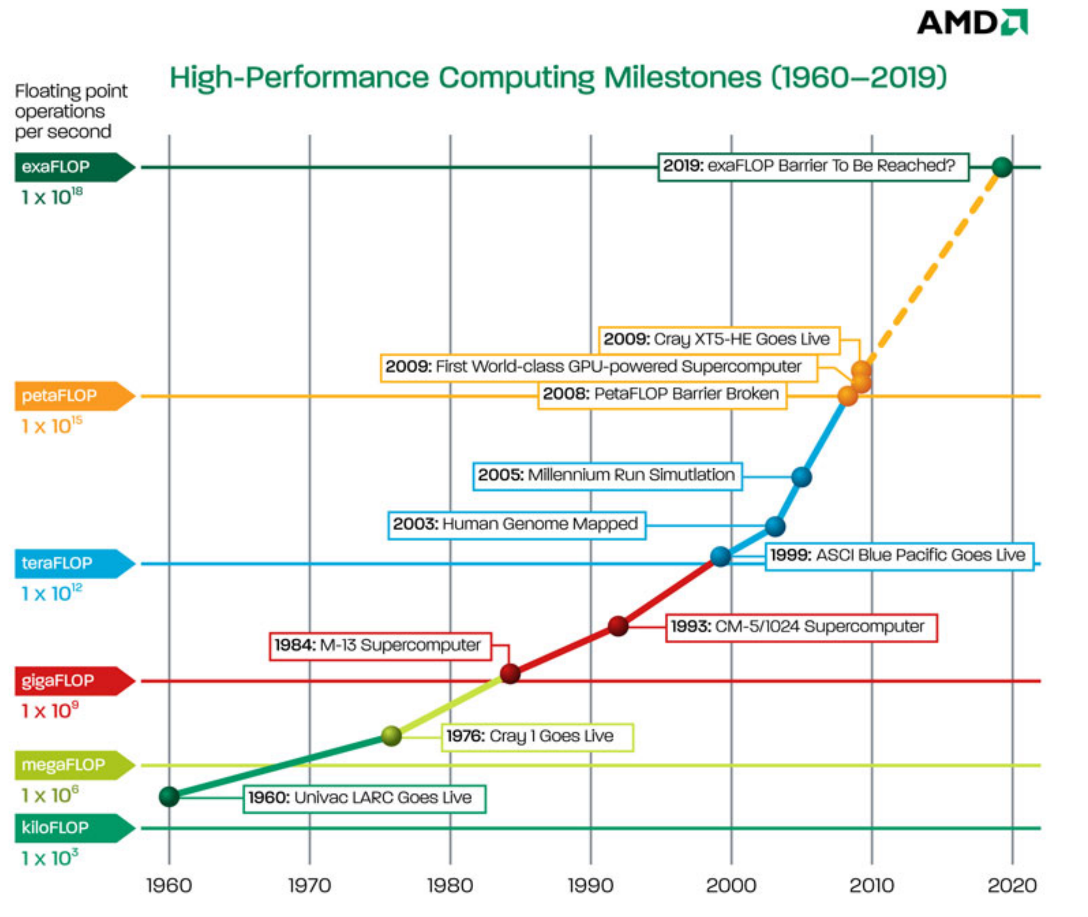
http://prezi.com/pakaaiek3nol/timeline-of-climate-modeling/

High Performance Computing

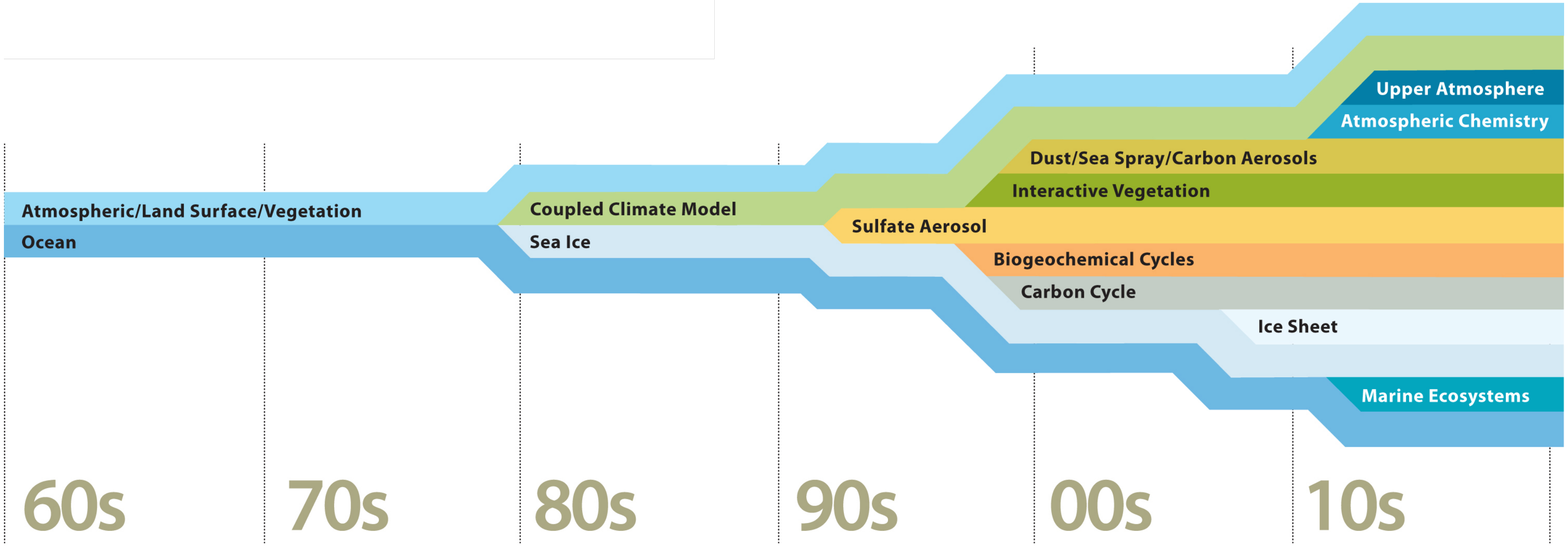
- Evolution:

  Close relationship between development in HPC and climate modelling

  The development curve (or slope) is more steep after 80s!

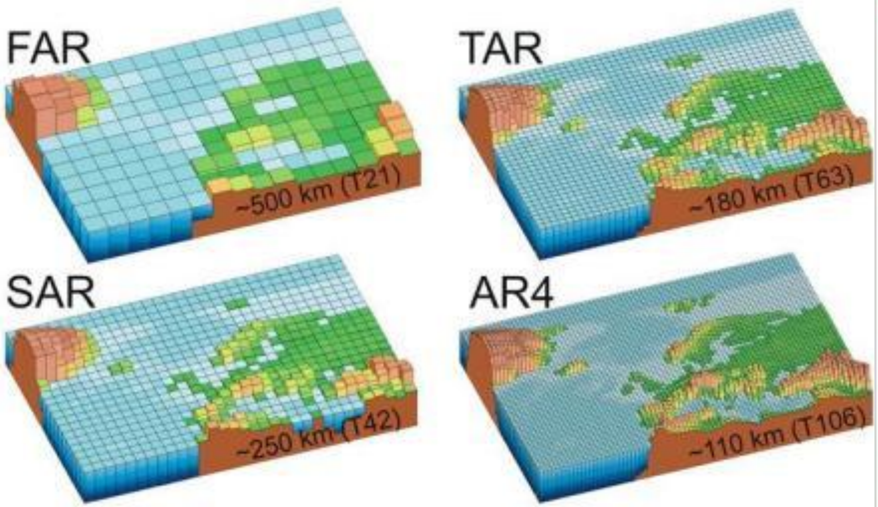


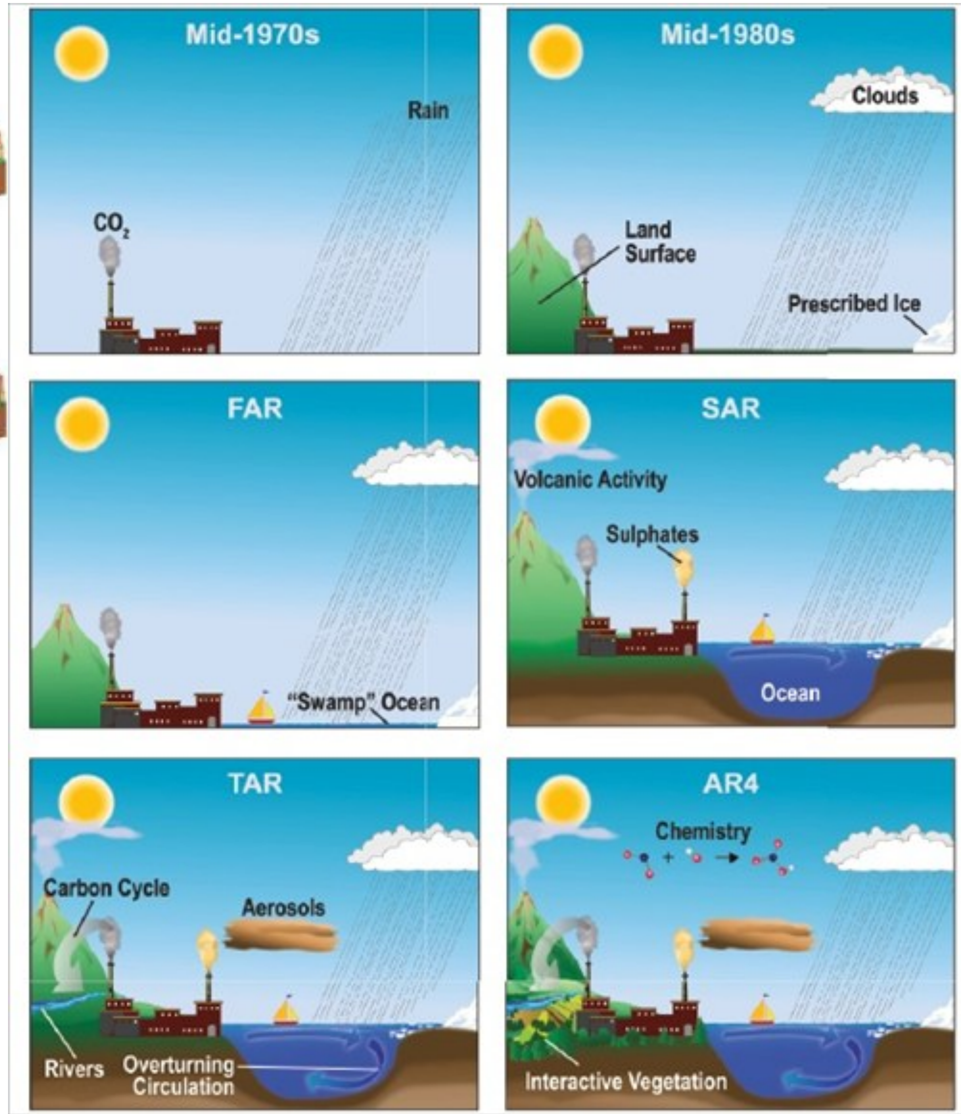
Complexity of Climate Models



- Model complexity is increasing in terms of physics and model components
- Along with the development in HPC, the horizontal and vertical resolutions of models are increasing

Evolution of Models

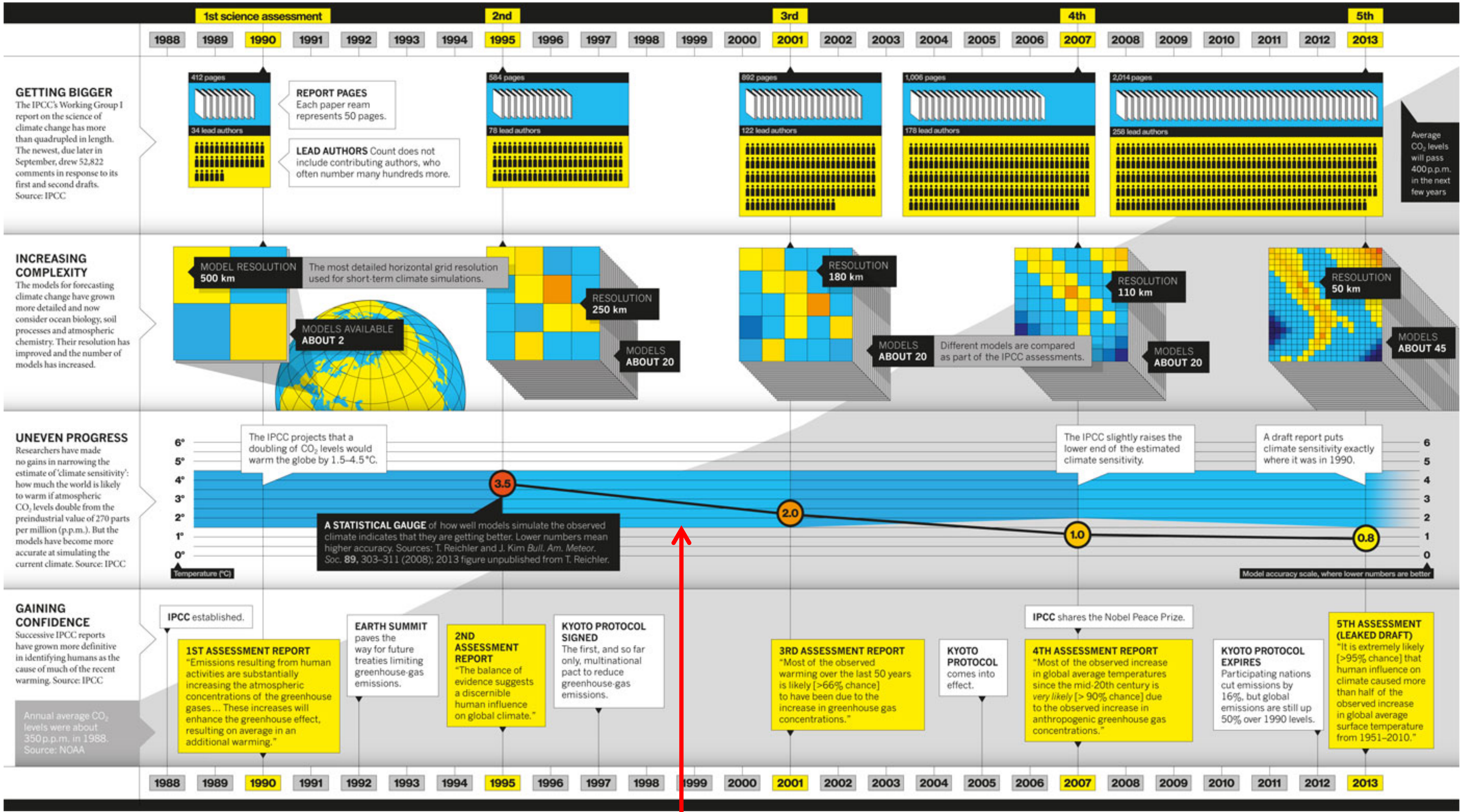




- More processes are represented (i.e. chemistry, sea-ice, glaciers, dynamic vegetation)
- Higher temporal and spatial scales

Climate Assessments

- Evolution of IPCC Reports



No decrease in uncertainty!

but models are more accurate in 20C

http://www.scientificamerican.com/article/climate-assessments-25-years-of-the-ipcc/

What is Model Coupling?

- It is a sophisticated way of simulate climate system and complex interactions between its components.
- The individual components are not perfect !
- Our theoretical understanding of climate is still incomplete, and certain simplifying assumptions are unavoidable when building these models (Reichler and Kim, 2008) !
- Coupled model does not always gives best results but help to understand interactions and processes between components !

How Well Do Coupled Models Simulate Today's Climate?

BY THOMAS REICHLER AND JUNSU KIM

OVERVIEW OF THE COUPLED MODEL INTERCOMPARISON PROJECT

BY GERALD A. MEEHL, CURT COVEY, BRYANT MCAVANEY, MOJIB LATIF, AND RONALD J. STOUFFER

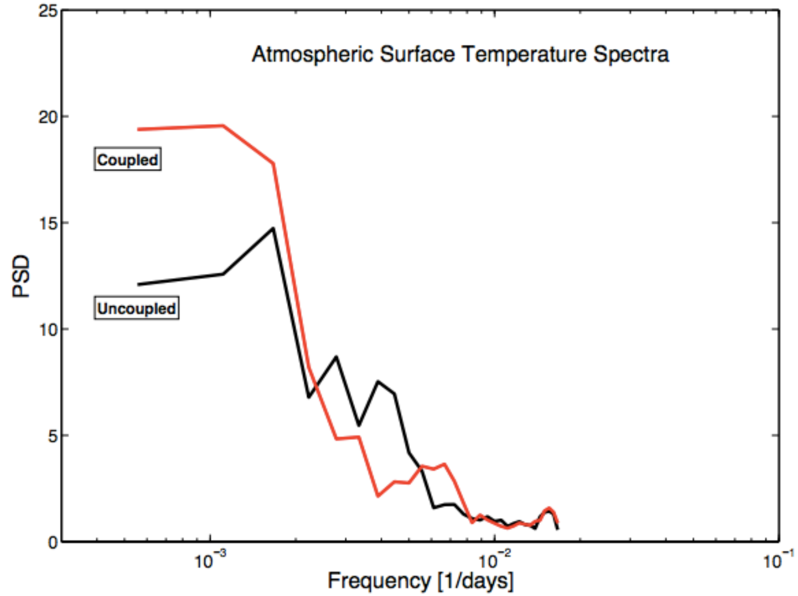
An Appraisal of Coupled Climate Model Simulations

K. AchutaRao, C. Covey, C. Doutriaux, M. Fiorino, P. Gleckler, T. Phillips, K. Sperber, K. Taylor

Edited by D. Bader

Basic effects of ocean-atmosphere coupling

- Increases variance of both media
- Decrease energy fluxes between them
- Prescribing mid-latitude SSTs does not lead to a correct simulation of low-frequency thermal variance in the atmosphere.



- We need coupled atmosphere-ocean model !!!
- How does it work?
  - Strong wind speed -> lower SST via mixing and turbulent flux. Negative correlation = atmosphere drives ocean
  - Enhanced (reduced) wind speed over warm (cold) SSTs. Positive correlation = ocean drives atmosphere

Difficulties in Model Coupling?

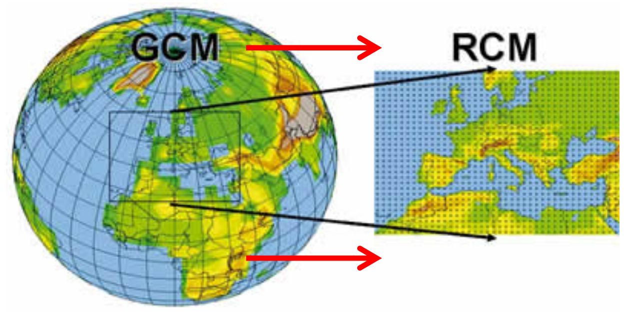
- Example from Atmosphere + Ocean Coupling

1. Initial state of the ocean is not precisely known
   Lack of continuous and high resolution observations.
   Remote sensing might help but covers only ocean surface and recent decades. The quality also depends on many issues (atmospheric correction and used algorithm, coastal regions etc.)
2. An imbalance in the surface flux (heat, momentum and freshwater) much smaller than the observational accuracy is enough to cause a drifting of coupled GCM simulations into unrealistic states

- It is not easy tightly couple models that are written by different groups
- Monolithic model development approach does not work anymore!
- High accuracy of conservation (heat and mass) is needed!

http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch1s1-5-3.html

Types of Model Coupling



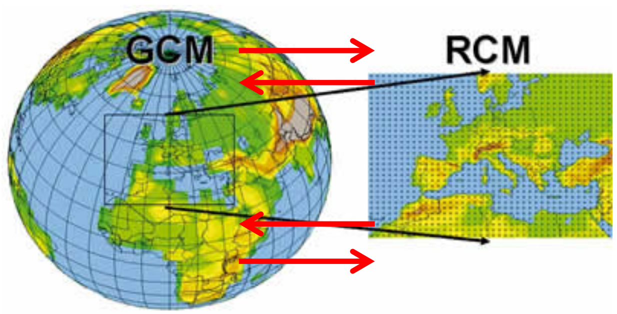
<u>There are two types of model coupling:</u>

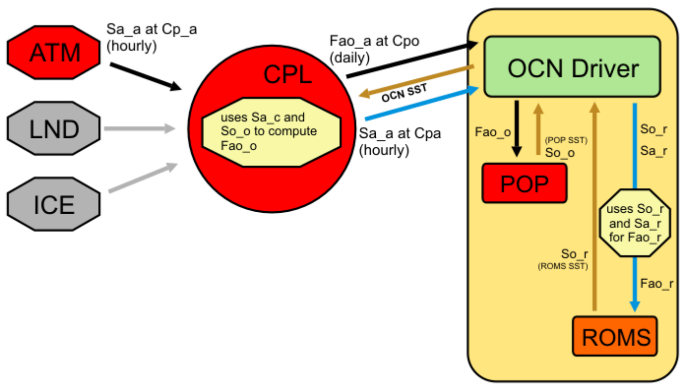
1. Offline

Models run sequentially and the interaction between them is in only one way. The simplest example is dynamical downscaling (GCM to RCM) or one-way nesting (RCM to RCM)

2. Online

In this case, models interact in both way and feedback mechanisms among components represented (two way nesting, fully coupled atmosphere-ocean models or ESMs.)





Techniques for Model Coupling

The ESM components might be coupled using different programming approaches

1. Merge individual model codes

☺ **easy to code, portable**

☹ **not flexible and generic**

host / parent

```
program atm                                   ATM
...
! read initial and boundary data
call read()
! run model
call run()
! write results to file
...
end program atm
```

```
program ocn                                   OCN
...
! read initial and boundary data
call read()
! run model
call run()
! write results to file
...
end program ocn
```

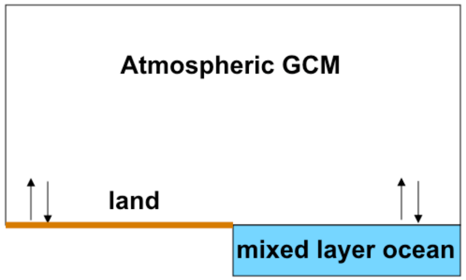
```
program atm
...
! read initial and boundary data
call read()
! run model
call run()
! run ocn model
call ocn(exchange vars)
! write results to file
...
end program atm
```

\+

```
subroutine ocn (exchange vars)
...
! read initial and boundary data
call read()
! run model
call run()
! write results to file
...
end subroutine ocn
```

=

single executable!



more information in Valcke, 2009 EGU

Techniques for Model Coupling

<u>The ESM components might be coupled using different programming approaches</u>

2. Use existing communication protocols: MPI, InterComm …

host / parent

ATM

```
program atm
…
! read initial and boundary data
call read()
! run model
call run()
! write results to file
…
end program atm
```

OCN

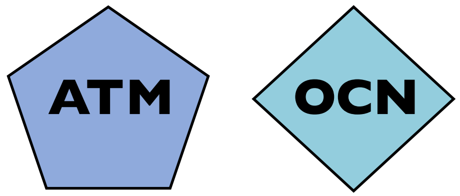
```
program ocn
…
! read initial and boundary data
call read()
! run model
call run()
! write results to file
…
end program ocn
```

```
program atm
…
! receive exchange field
call recv()
! run model
call run()
! send exchange field
call send()
! write results to file
…
end program atm
```

\+

```
program ocn
…
! receive exchange field
call recv()
! run model
call run()
! send exchange field
call send()
! write results to file
…
end program ocn
```

=



☺ **existing code and concurrent components**

☹ **not easy to implement, not flexible and generic**

multiple executable!

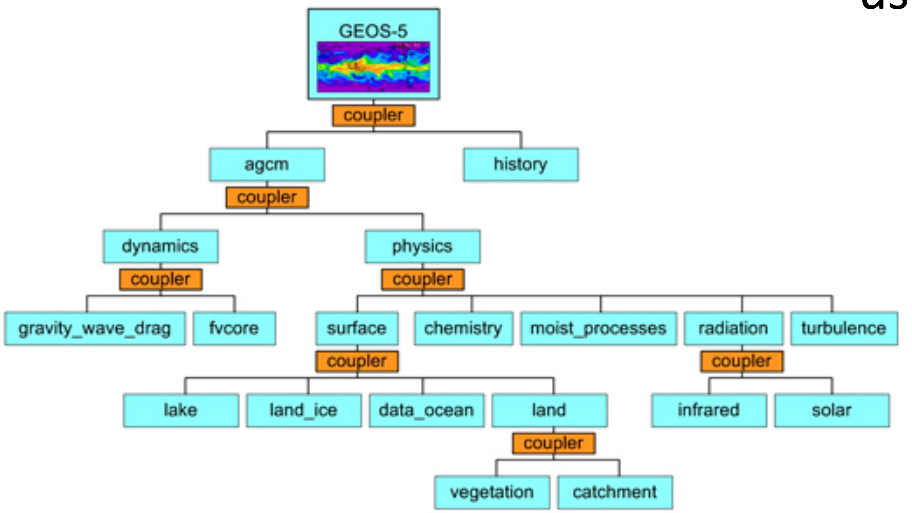
more information in Valcke, 2009 EGU

Techniques for Model Coupling

<u>The ESM components might be coupled using different programming approaches</u>

3. Use coupling framework & libraries: FMS, ESMF, MCT …

- Code divided into units and calling interface redesigned (i.e. initialization, run and finalize)
- Hierarchical model structures are supported



☺ flexible, efficient, portable, support to use generic utilities for interpolation, time management and unit conversions), support both sequential and concurrent components

☹ **Existing codes must be restructured**

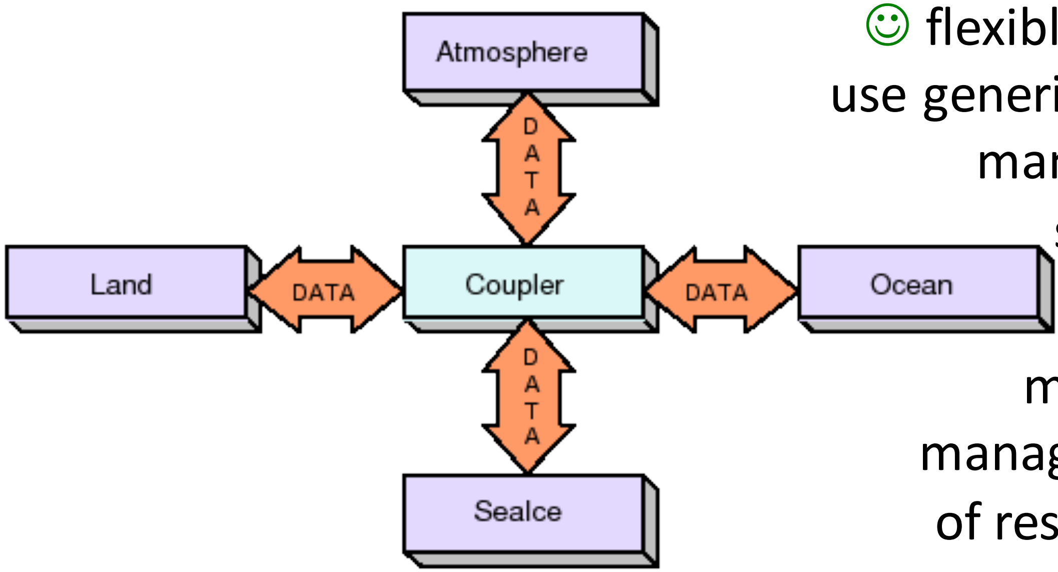
more information in Valcke, 2009 EGU

Techniques for Model Coupling

The ESM components might be coupled using different programming approaches

4. Use a coupler: OASIS, OASIS-MCT, MPCCI, PALM …

- Coupler link the model components and handle coupling processes such as interpolation, synchronization etc.
    - Components models might be separate or single executable



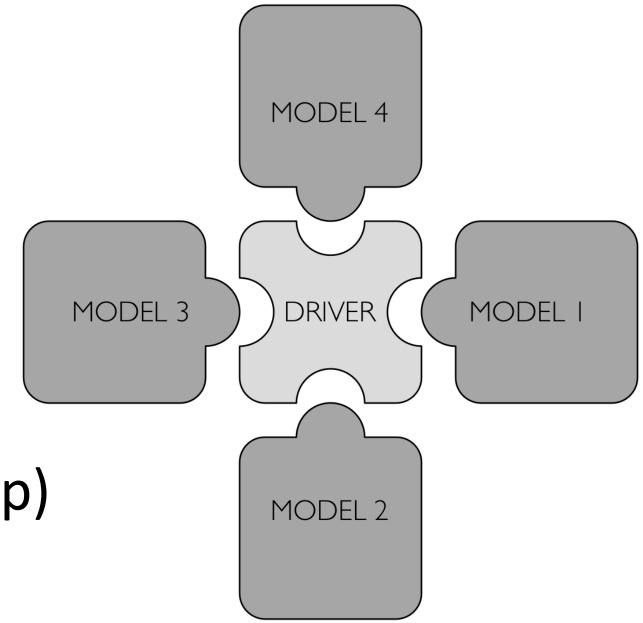
☺ flexible, efficient, portable, support to use generic utilities for interpolation, time management and unit conversions), support concurrent components

☹ multi-executable: more difficult to debug; harder to manage for the OS and possible waste of resource if seq. execution enforced

more information in Valcke, 2009 EGU

What is driver / coupler ?

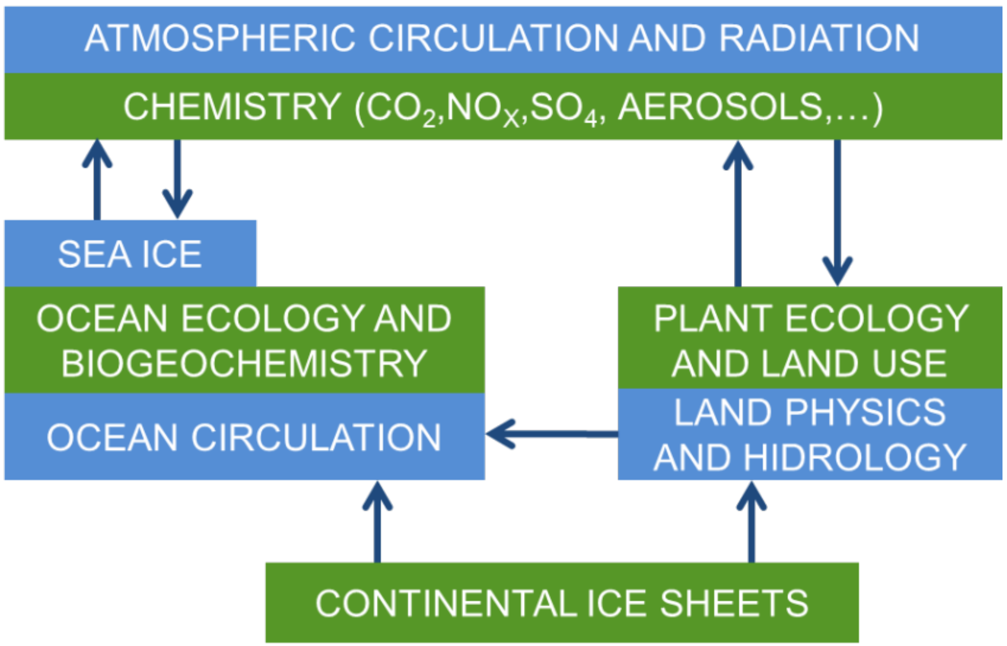
- The driver can be defined as a "glue"
- It merges the different components of the modeling system
- In general, the modeling system might be designed to have
  - Single executable
  - Multiple executable (each component has an executable)
- In the multiple executable case, the usage of the modeling system might be difficult
- The driver is generally responsible for
  - Interaction among the components: exchange boundary data between the components, regridding etc.
  - Synchronization: to coordinate the time evolution of the physical models (coupling time step)



http://www.climateurope.eu/earth-system-modeling-a-definition/

Earth System Models

- Defines interaction between components to simulate the state of the climate system in regional and global scale
- ESMs include processes, impacts, and complete feedback cycles; for example, they can simulate droughts as well as the resulting change in plant cover due to the drought, which may lead to more or less drought (Heavens et al, 2013).
- Climate Model vs. Earth System Model

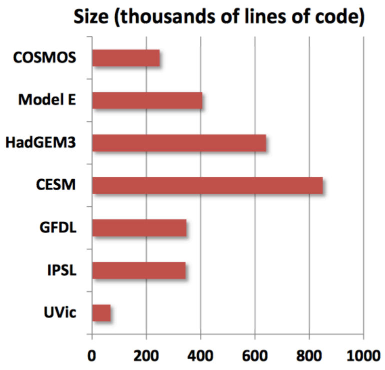


blue boxes represent the processes included in a **climate model**;

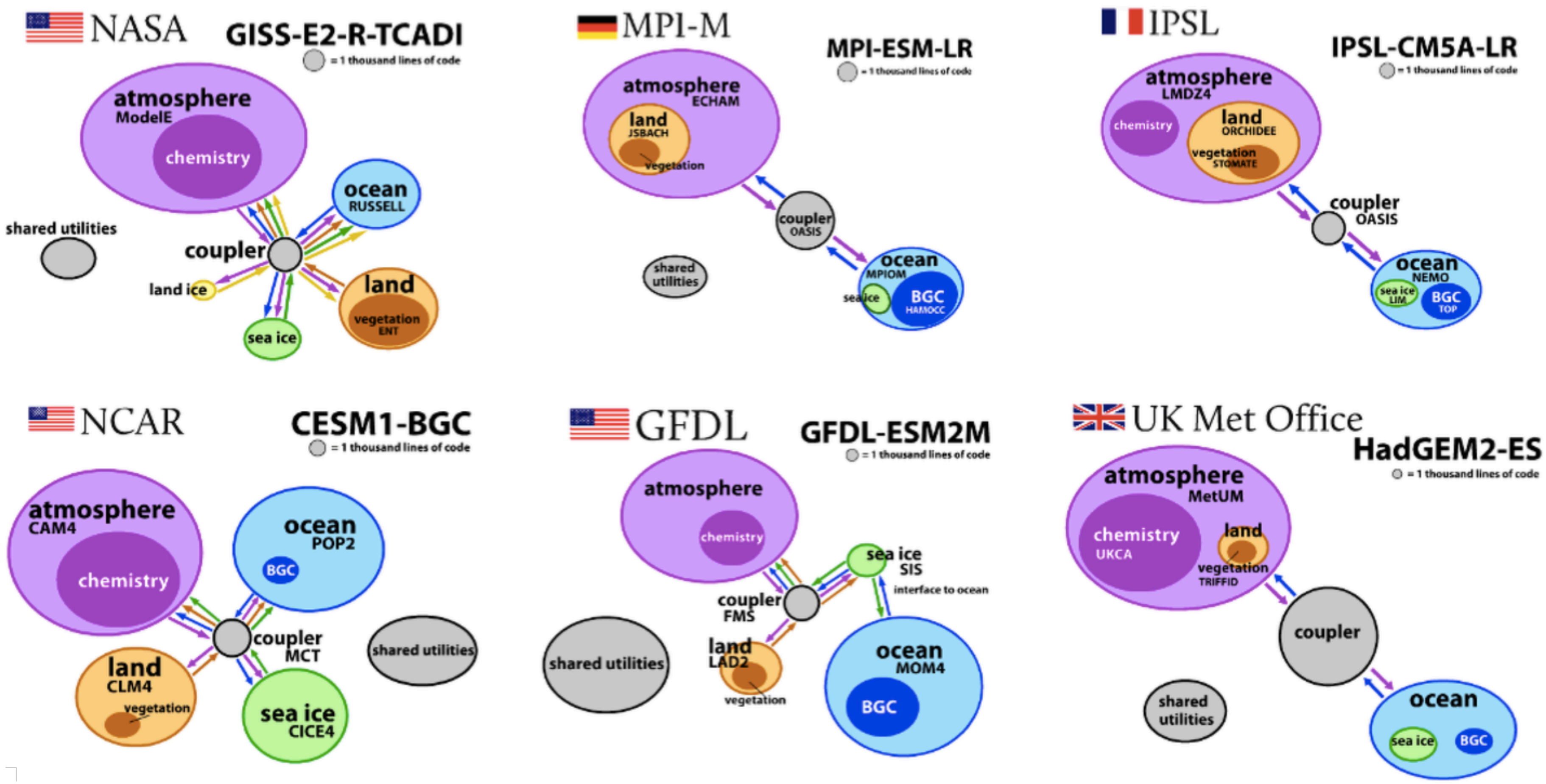
green boxes represent the additional components that may be included in an **Earth System Model**

Coupled Model Design

- Global Models (GCMs and ESMs)
- There is no single design and ultimate solution!



Generated using David A. Wheeler's "SLOCCount".

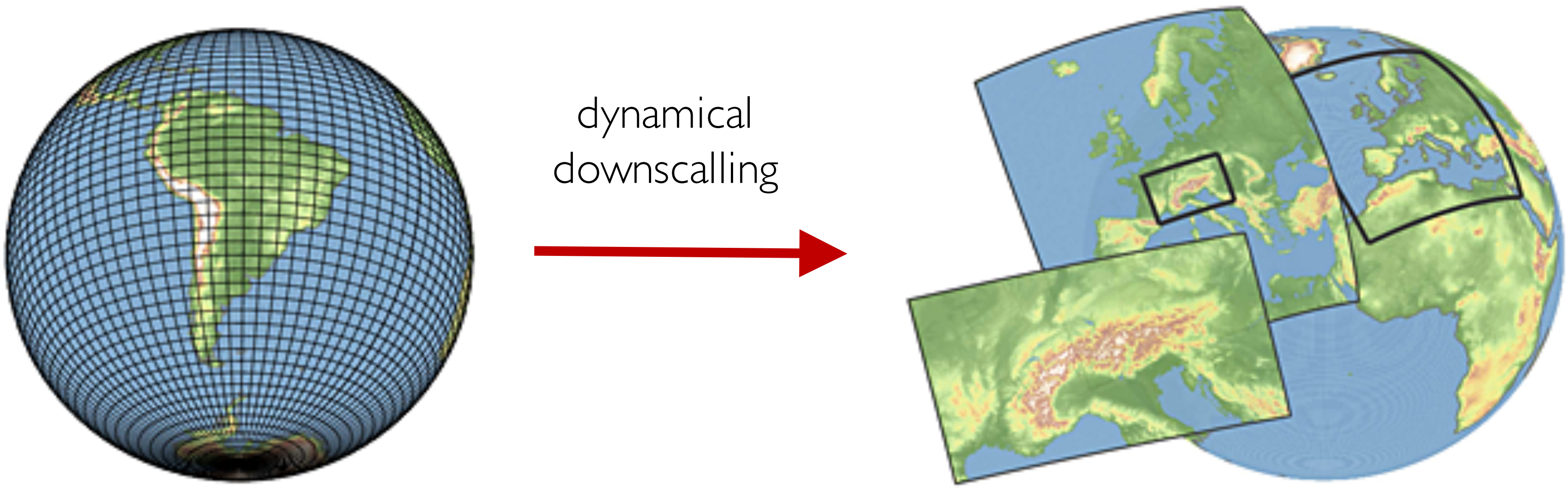


Kaitlin Alexander and Steve Easterbrook

http://climatesight.files.wordpress.com/2011/08/poster.pdf

Regional Earth System Modeling (RESM)

- Higher resolution representation of physical processes
- Includes more sophisticated physical parameterizations and additional processes along with their non-linear interactions
- It might also include human behavior (pollution, irrigation etc.)
- Apart from the global ESMs, they require boundary condition (global ESMs, reanalysis datasets etc.), which adds extra complexity to the system

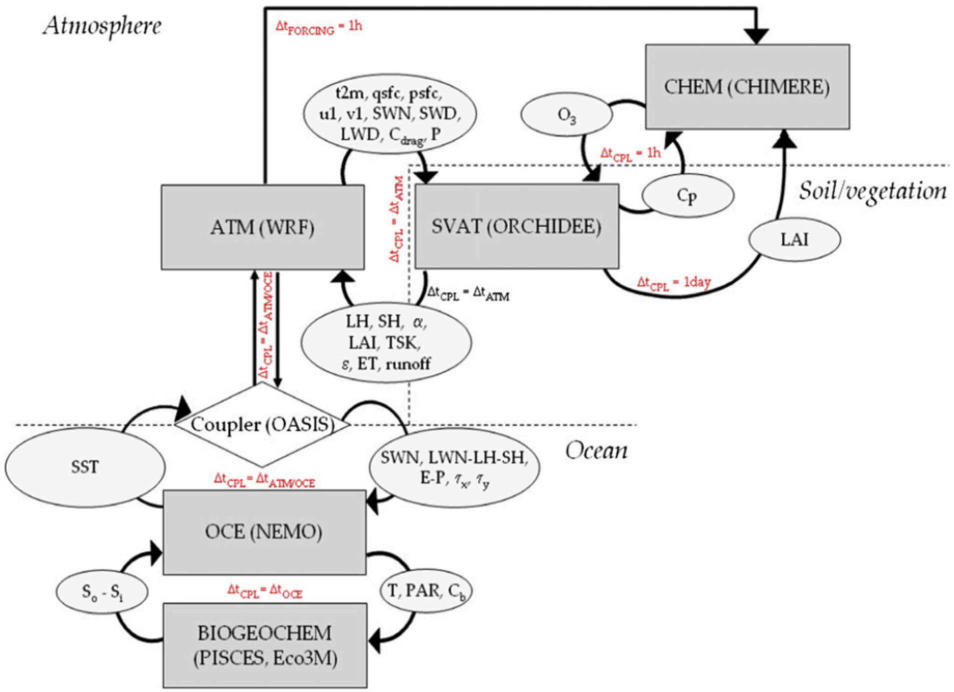


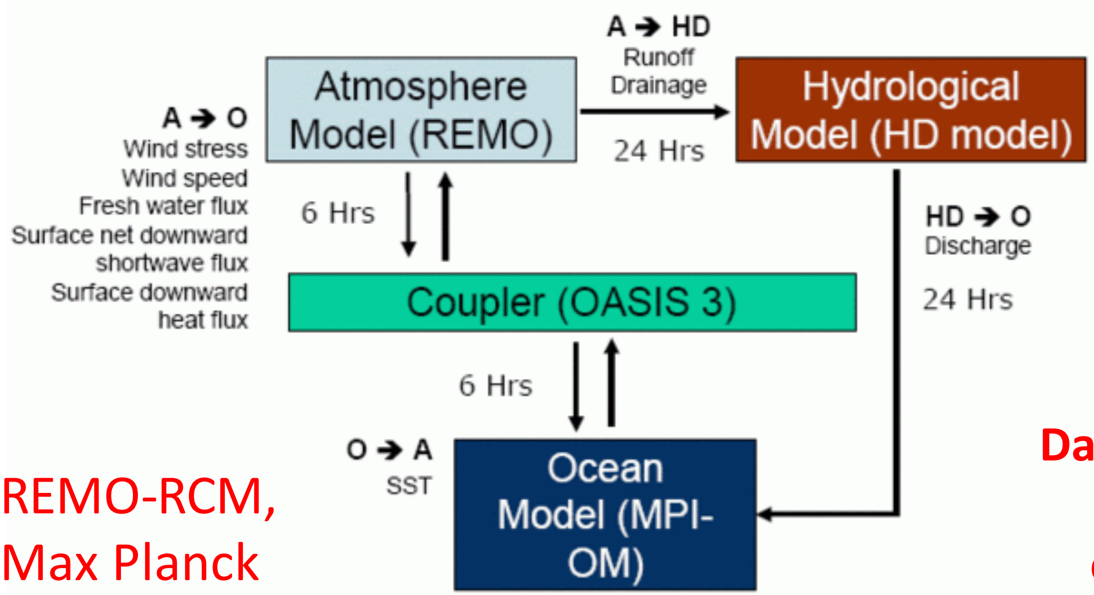
Prein et al., 2015 @ Reviews of Geophysics

Coupled Model Design

- Examples for Regional Models

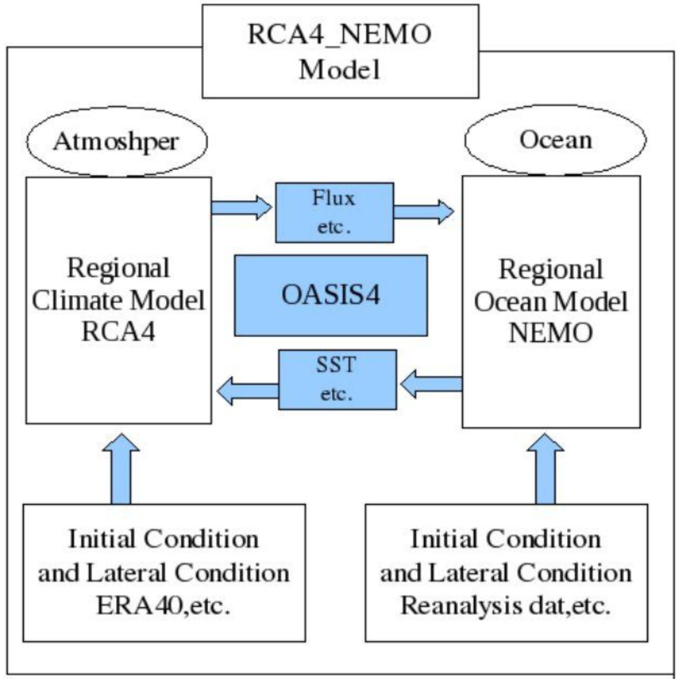
MORCE, IPSL





REMO-RCM, Max Planck

http://www.remo-rcm.de/Atmosphere-Ocean-coupled.1269.0.html



RCA4-NEMO, SMHI

http://www.smhi.se/polopoly_fs/1.28917!/RO_47.pdf

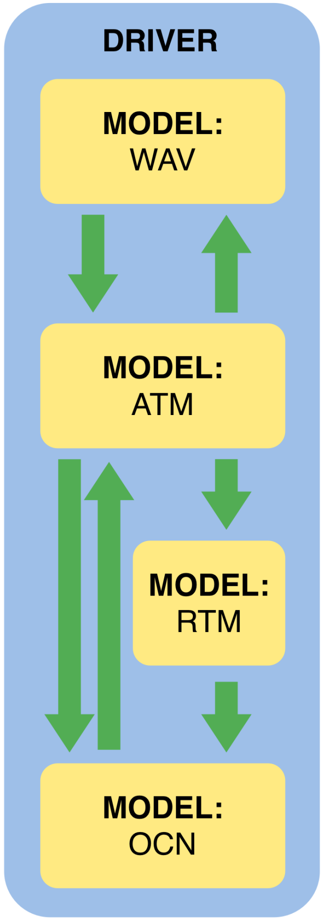
Data exchange and interpolation is one of the most important component of the model design!

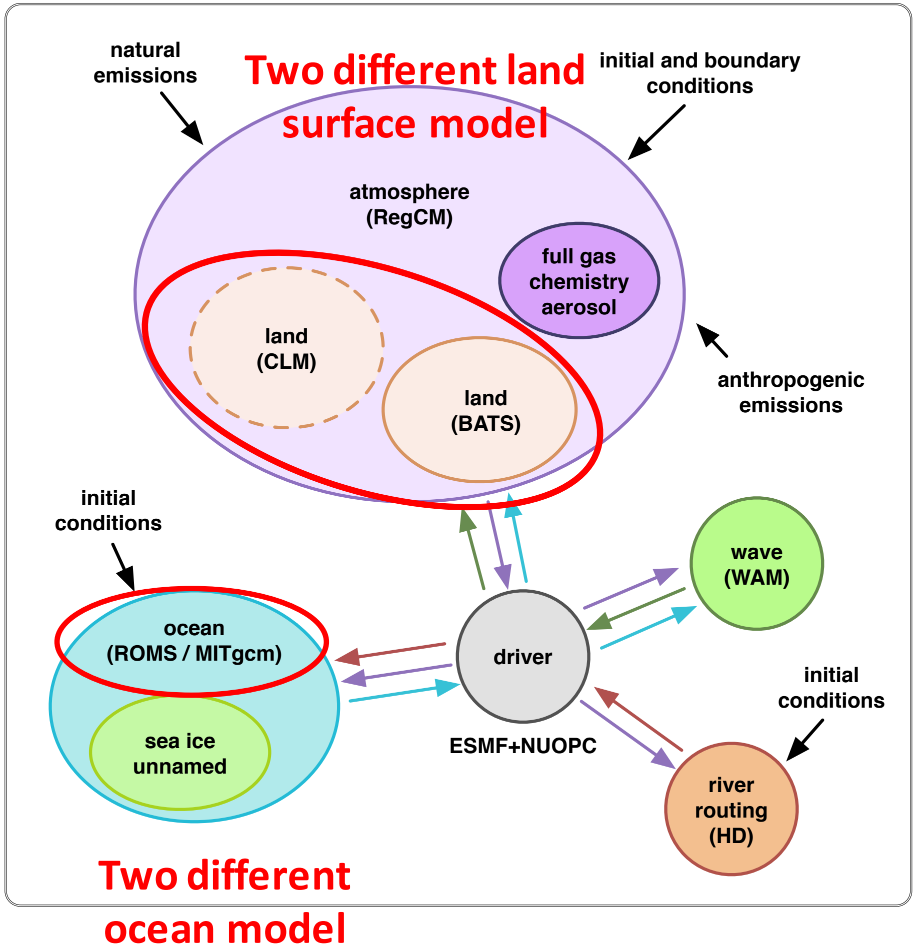
Regional Earth System Modeling / ITU

Year	Description	Domains
2012	• No driver RegCM is hosting also ocean component • Single ocean model is supported (ROMS) • Poor mass and energy conservation for exchange fields • No automatized extrapolation (unaligned land-sea masks !!!) • Hard to include additional components such as river, wave etc.	Caspian Sea (Turuncoglu et al., 2013; Geophysical Model Dev.)
2013	• Centralized driver using ESMF's NUOPC layer (via connectors) • All components are plugged into the driver • Added support for two different ocean model component (ROMS and MITgcm) • Mass and energy conservation is improved via customized bilinear interpolation along with global conservation support • Support for extrapolation (unaligned land-sea masks) • River Routing (Max Planck's HD) component is included	Med. Sea
2014 **2015**	• The wave component (ECMWF's WAM) is included (Surenkok & Turuncoglu, 2015; EGU) • Extensive benchmarking (PRACE – 2010PA2442)	Med. Sea Black Sea
2016	• ESMF library is updated to 7.0.0 • Validation for Mediterranean domain (Turuncoglu & Sannino, 2016; Climate Dynamics) • Extensive validation with different configuration (2/3/4 component, different coupling intervals etc.) – paper is on-the-way	Med. Sea Caribbean Indian Ocean South Atlantic

RegESM Design

- Model components merged with ESMF/NUOPC





ATM:
ICTP's RegCM 4.4 / 4.5

OCN:
Rutgers Univ.
ROMS (r737)
MITgcm (63s / 64s)

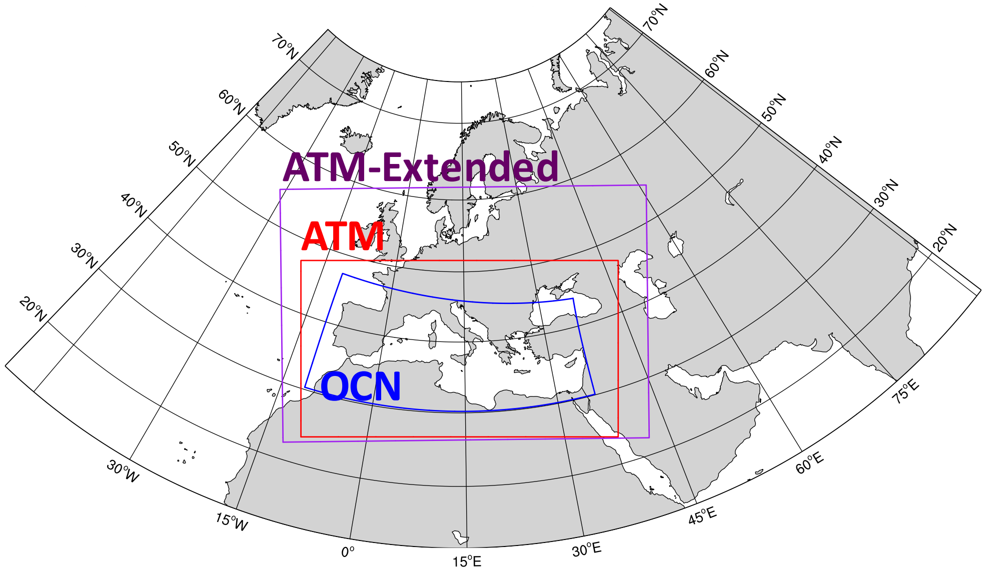
WAV:
ECMWF's WAM
4.5.3 MPI

RTM:
Max Planck's HD
(1.0.2 modified)
Special thanks to
Prof. Stefan Hagemann

 # Following combination of model components can be used: 2 component: ATM-OCN, ATM-WAV, 3 component: ATM-OCN-RTM, 4 component: ATM-OCN-WAV-RTM

Performance Benchmark @ PRACE

- Test with Mediterranean domain (Standard + Extended)



ATM: 12 km - 24 layer

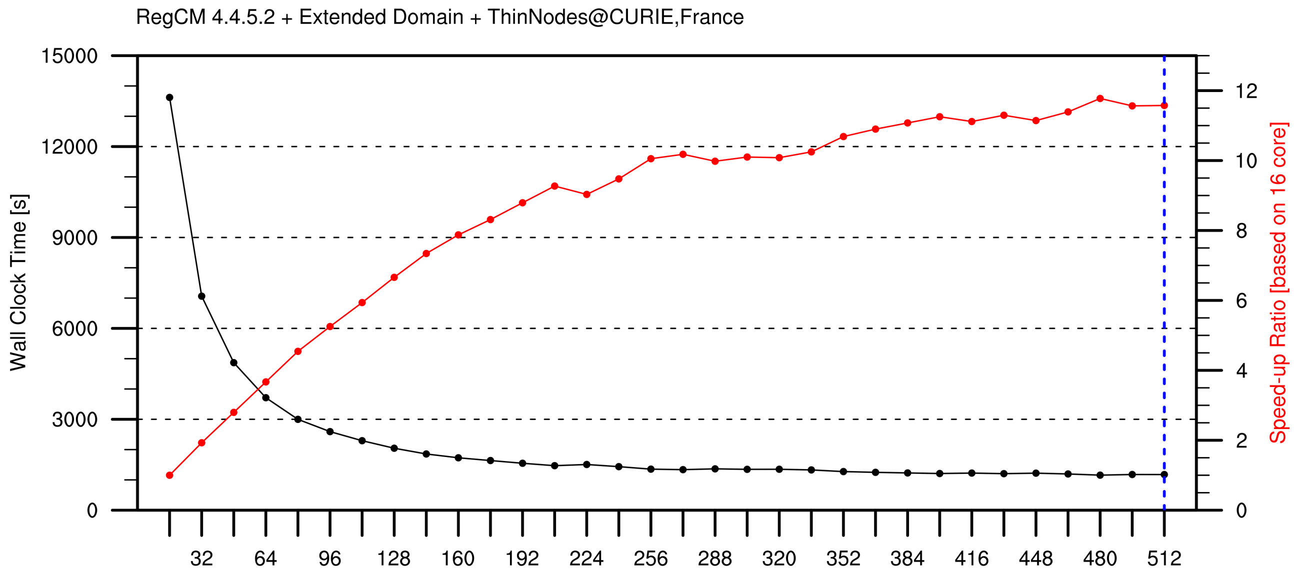
OCN: 1/12 deg. - 32 layer (ROMS)

extended domain is configured to feed the computational resources

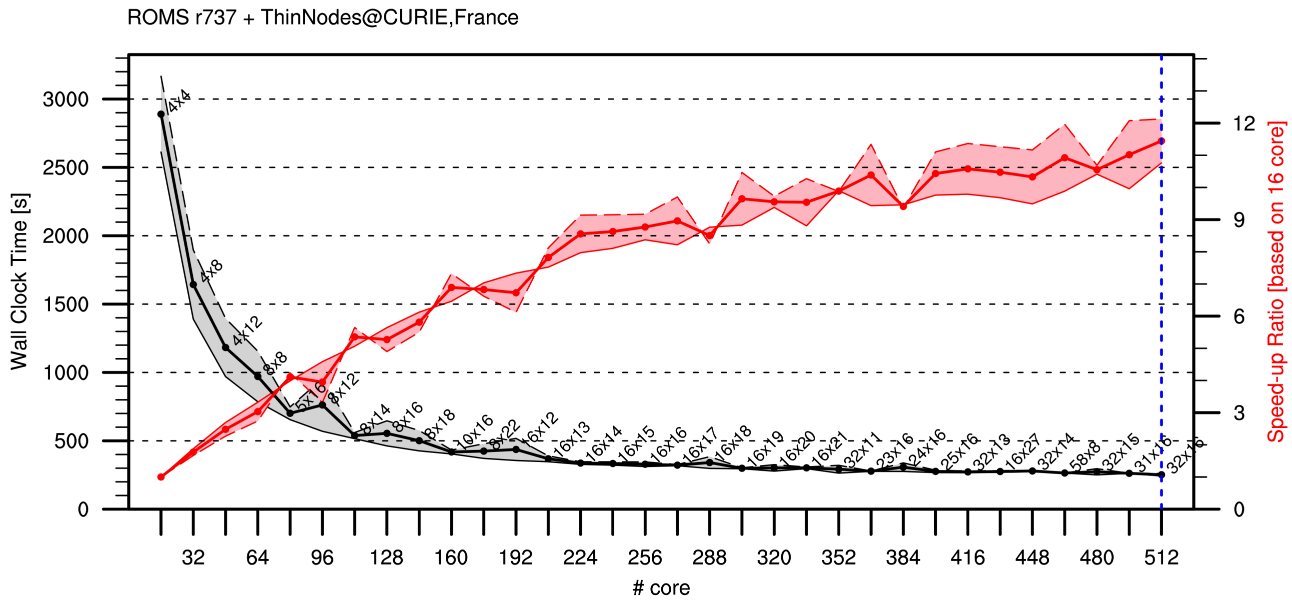
- Tests:
  - Different coupling interval (30 min., 1 hour, 3 hours)
  - Different execution type (sequential vs. concurrent)
  - Different number of component (ATM-OCN, ATM-OCN-RTM)
- Test Environment:
  - CURIE @ France (PRACE – 2010PA2442)

Performance Benchmark …

- Individual model components



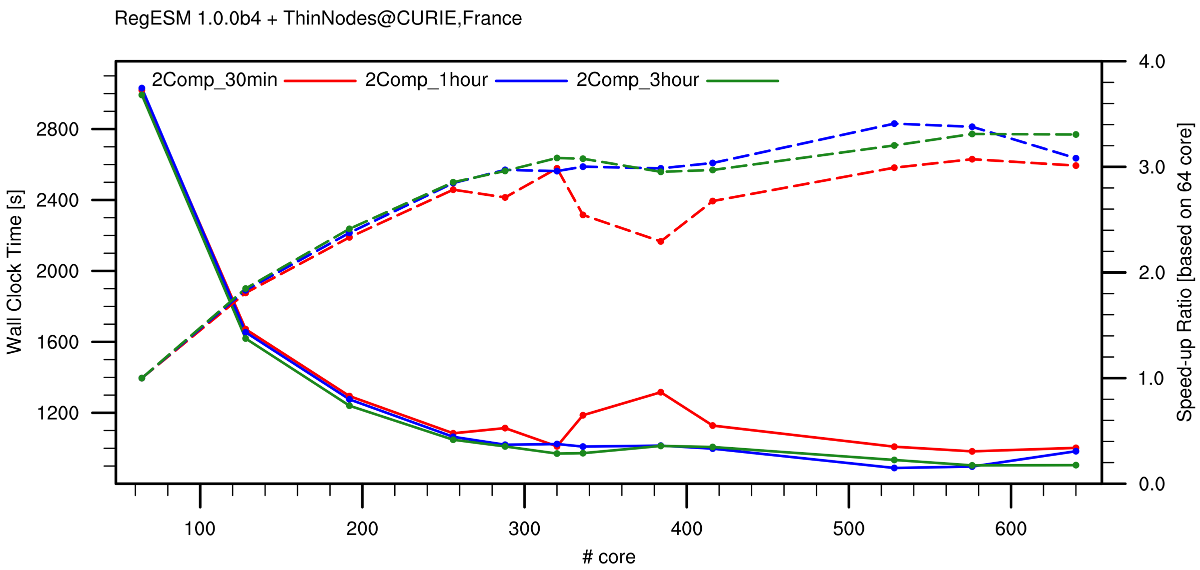
Better scaling results for extended domain



To find best 2d decomposition parameters for ROMS

Performance Benchmark …

- Coupling interval (only two component)

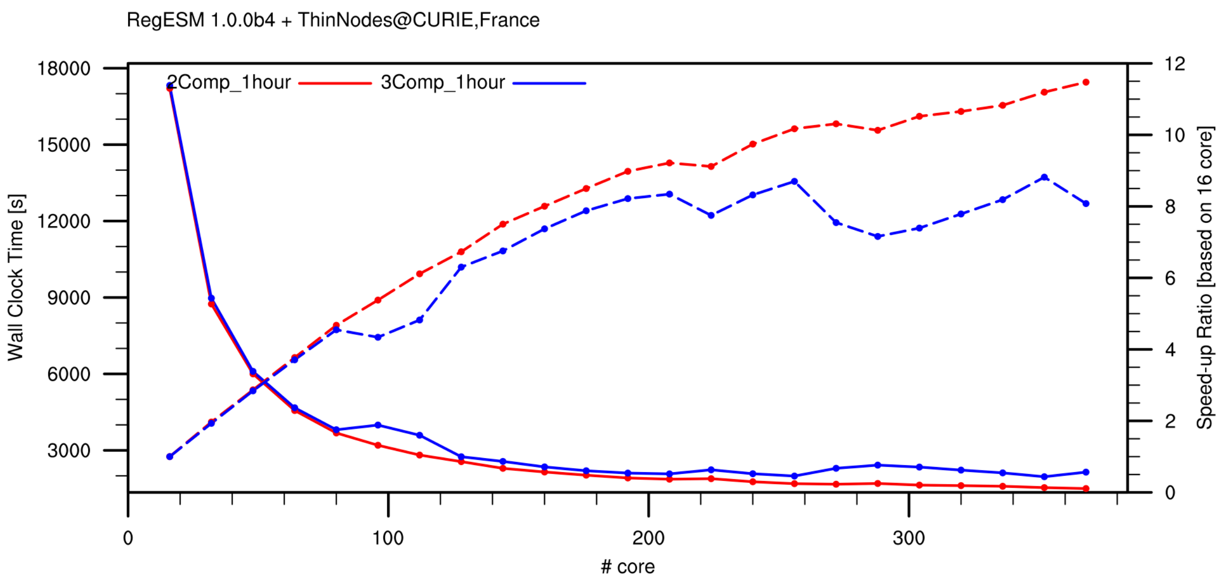


# core	% diff 30m/1hr	% diff 3hr/1hr
64	-0.38	1.29
128	1.06	2.15
192	1.45	2.89
256	1.86	1.58
288	9.20	0.95
320	-1.27	5.55
336	17.50	3.84
384	29.66	0.18
416	13.04	-0.92
528	13.50	-4.83
576	9.57	-0.75
640	1.93	8.68
AVG	**8.09**	**1.72**

- The effect of coupling interval is very limited ☺
- 30 min case has more fluctuations (it might be related with the overload of the cluster)
- It is better to repeat tests couple of time to take more reliable measurements ☹

Performance Benchmark …

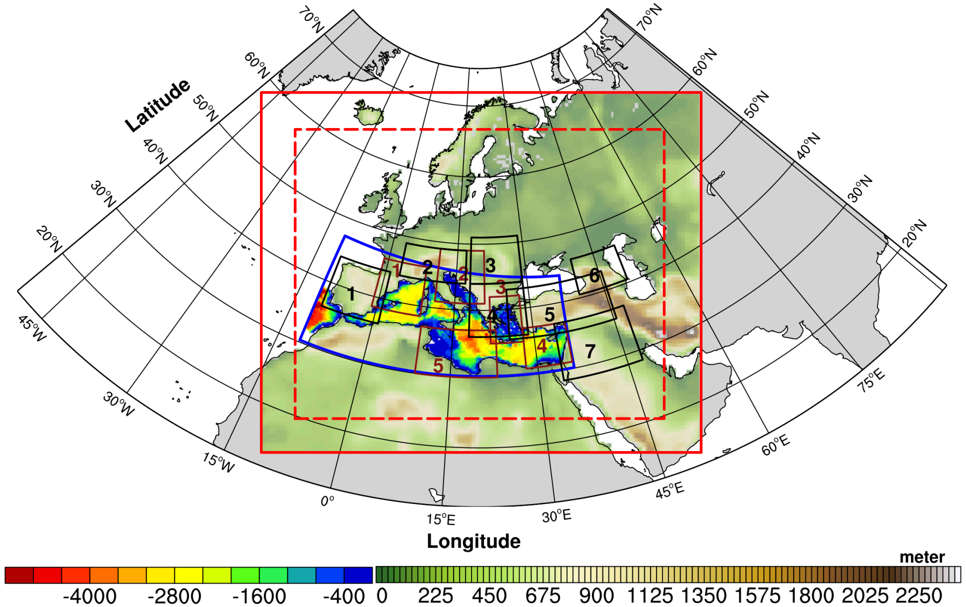
- Number of model components (const. coupling time step)



Sequential coupling

- Last processor is shared between OCN and RTM
- RTM component reduces the performance ~ 30% in higher processor counts ☹
- Solutions:
  - Integrated RTM component (with RegCM4, i.e. Chym)
  - Using higher resolution and parallelized (MPI) RTM component such as RAPID etc. It could also help to improve river rep.

Model for Mediterranean Basin



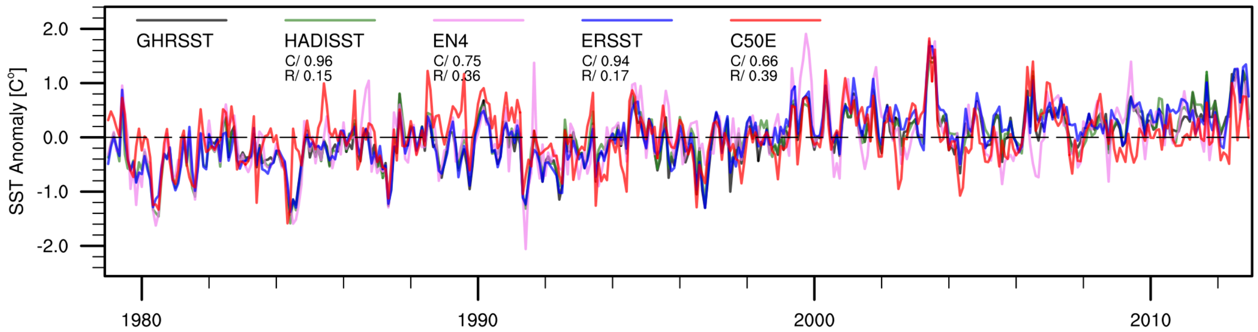
The Scientific and Technological Research Council of Turkey (TUBITAK) founded 2 year project (under grant 113Y108), ended in Dec. 2015

- Atmosphere: RegCM4 revision 4283 (~50 km)
- Ocean: ROMS revision783 (1/12 deg. ~ 9 km)
    - Closed boundary in Atlantic – used as a buffer zone
    - The coupling time step is 3 hour
    - ATM-OCN: wind stress, net heat and freshwater flux (E-P), shortwave rad., surface pressure and OCN-ATM: sea surface temperature
    - Prescribed river discharge (generated by Max Planck HD model)

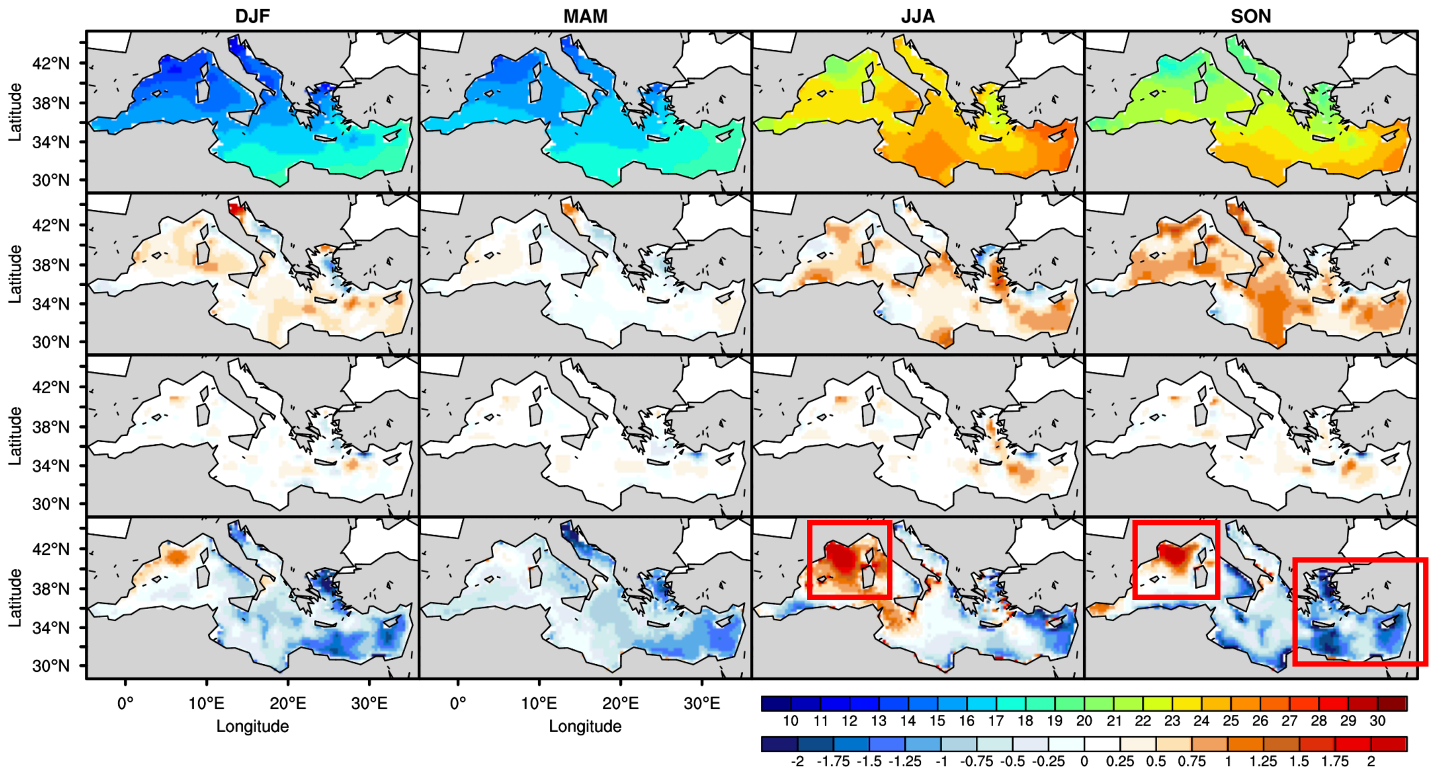
 # It is the first attempt for the validation of ROMS (Regional Ocean Modeling System) ocean model for Med.

Validation

- Sea Surface Temperature



SST anomaly over Med. Sea



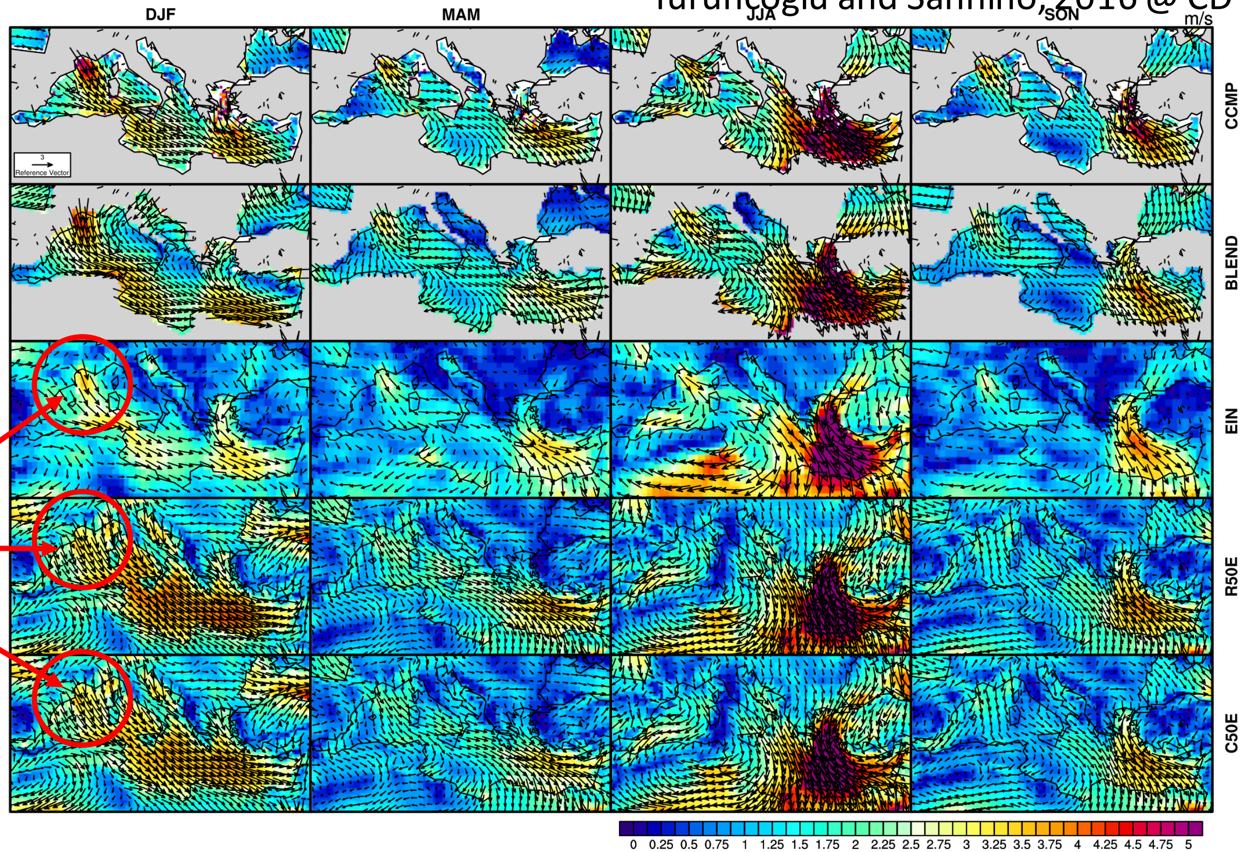
Seasonal SST Climatology

ERSST used in standalone simulation

Turuncoglu and Sannino, 2016 @ CD

Validation …

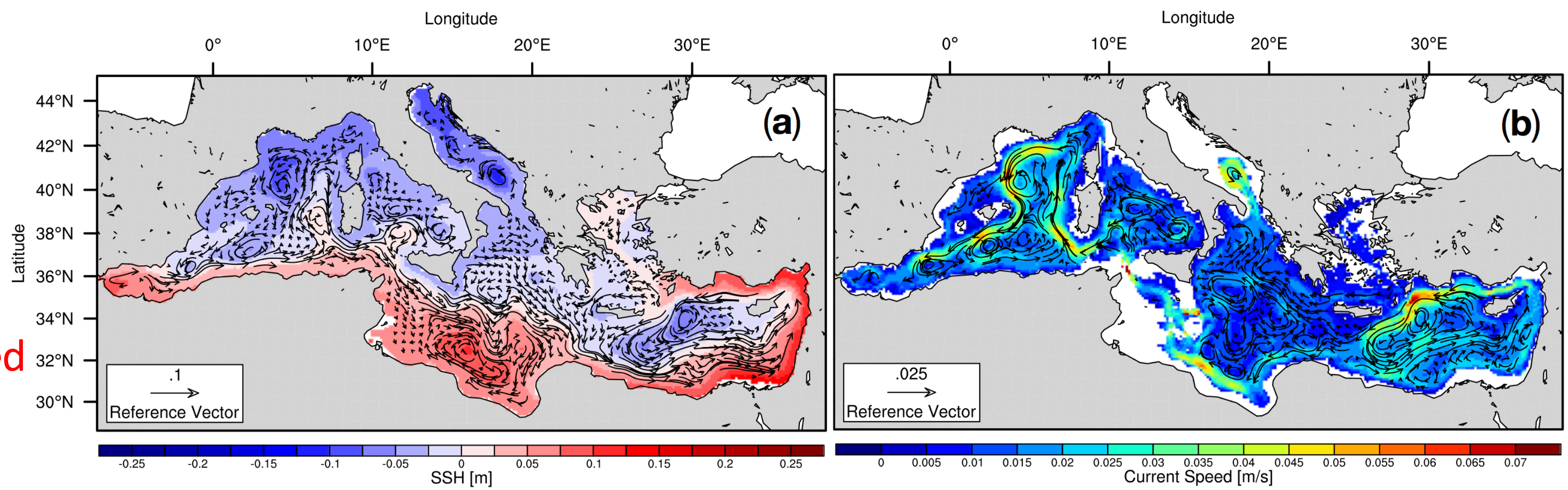
- Surface Wind and Circulation



Wind speed underestimated over Gulf of Lion

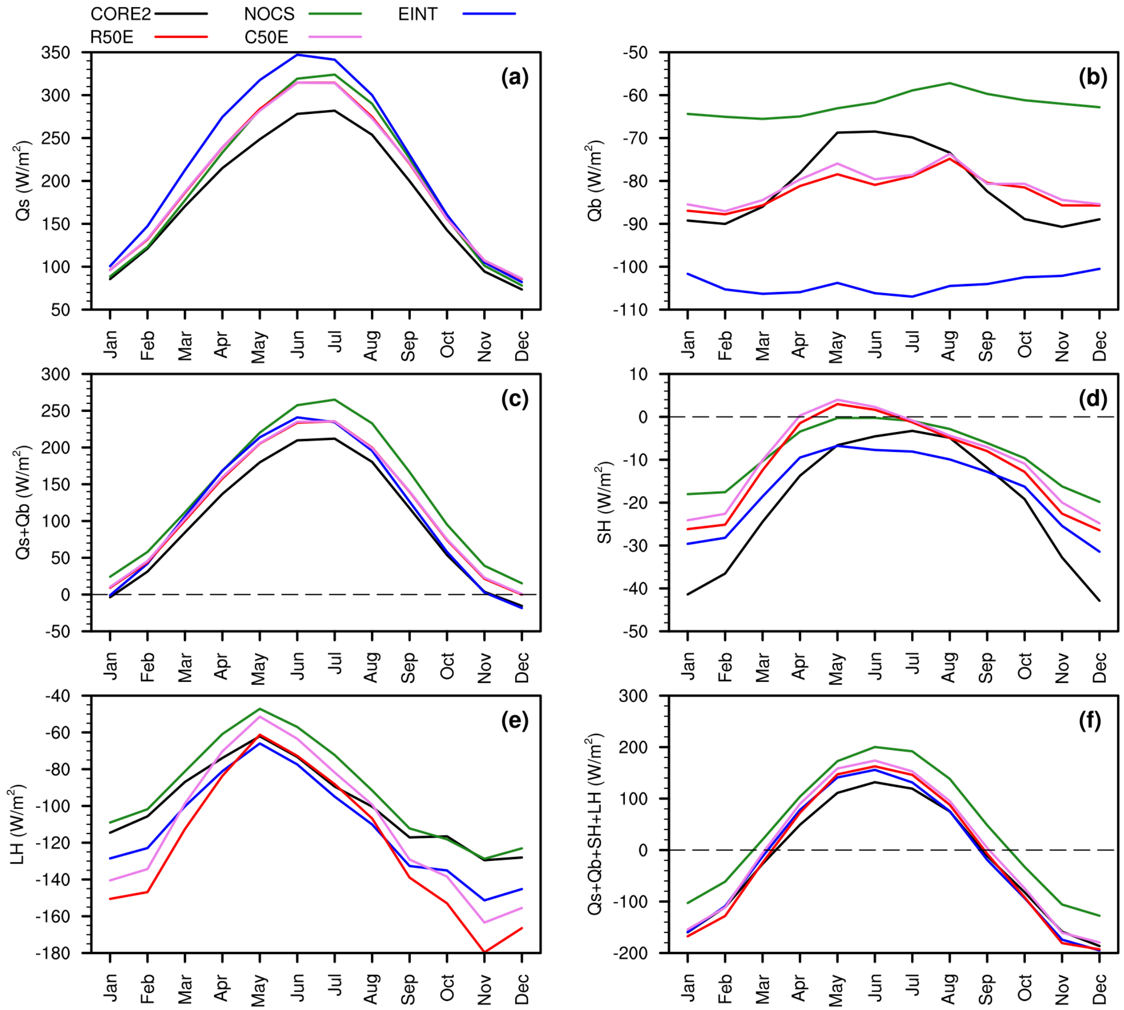
 # coupled model tends to decrease wind speed over the sea when it is compared with standalone simulation

Surface and 300 m circulation is well represented



Validation …

- Heat flux components over Med.
- Coupled and Standalone model simulations are very similar except LHF
- The net heat flux is in the range for both CPL and STD runs



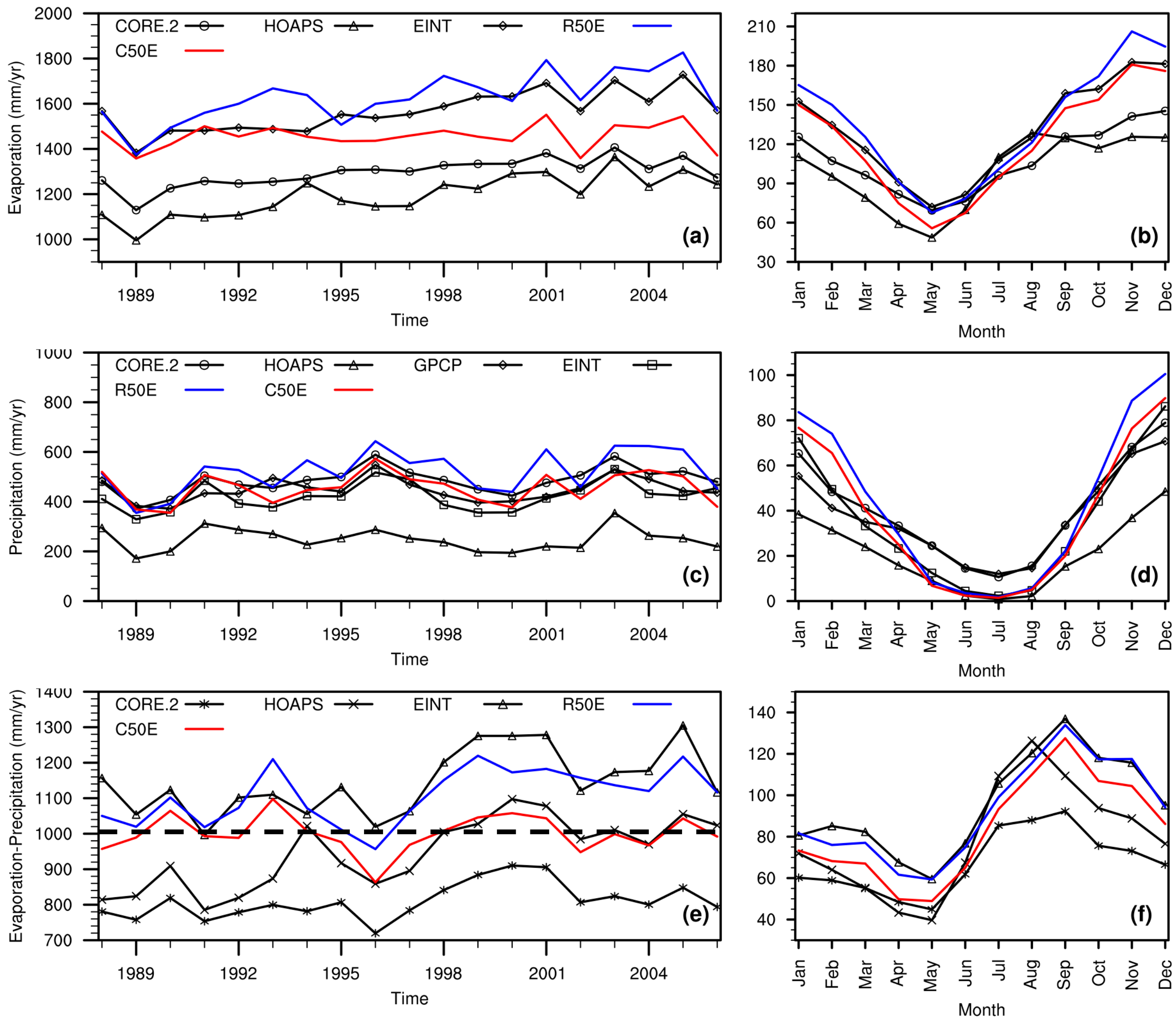
	SWF	LWF	SWF+LWF	SH	LH	NET
CORE.2	180.41	-81.24	99.17	-20.18	-99.80	-20.81
NOCS	200.02	-62.21	137.81	-8.79	-91.93	37.10
EINT	218.26	-100.14	114.12	-17.03	-112.12	-15.03
R50E	200.75	-82.34	118.41	-11.38	-121.72	-14.70
C50E	200.70	-81.31	119.39	-9.85	-110.52	-0.99

The coupled model reduces LH over Mediterranean Sea

Turuncoglu and Sannino, 2016 @ CD

Validation …

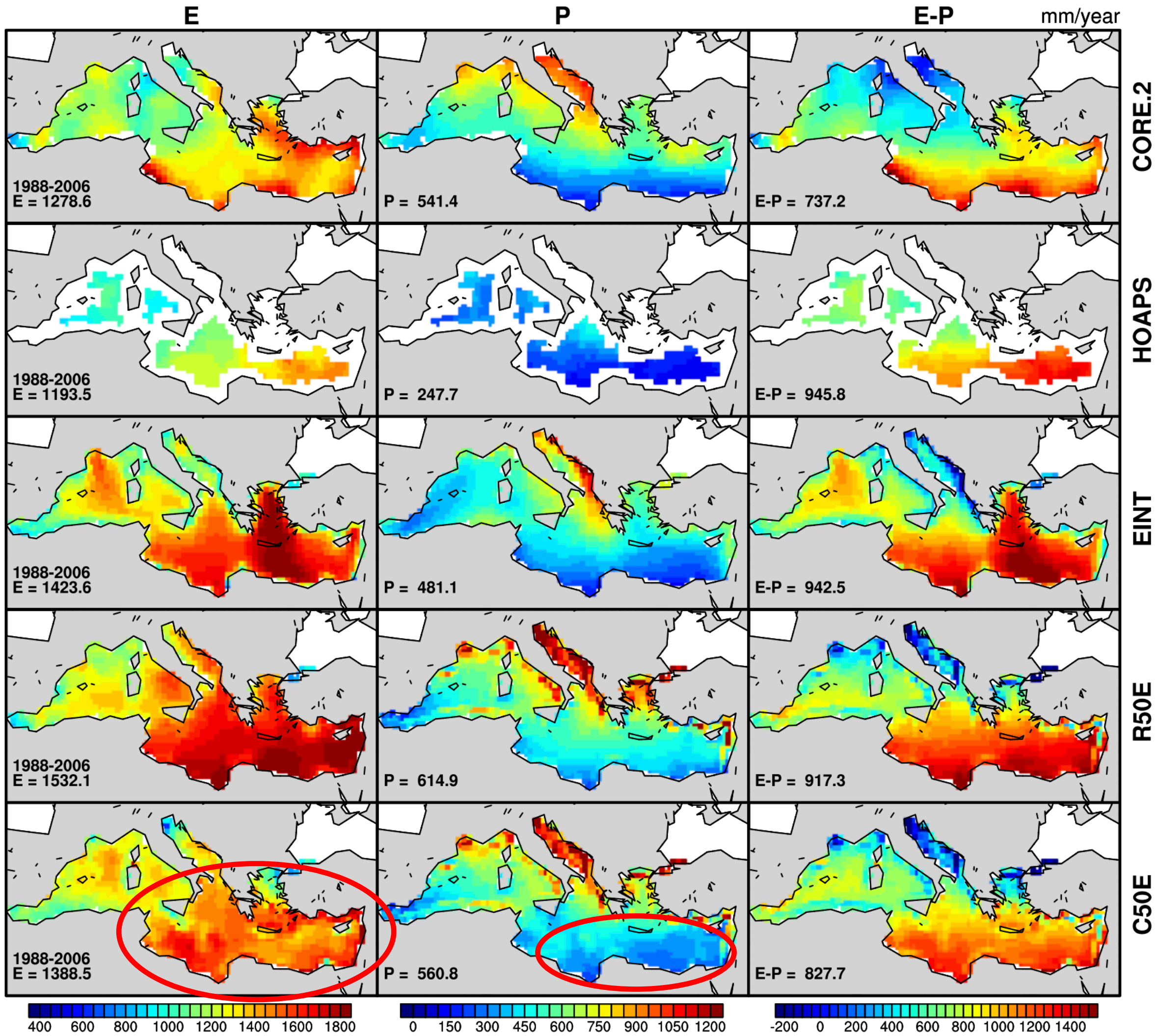
- E, P and E-P over Med.
- Coupled model tends to reduce evaporation
- The monthly distribution of E, P and E-P are very similar for STD and CPL
- The accepted E-P is 1000 mm/yr



Turuncoglu and Sannino, 2016 @ CD

Validation …

- Spatial distribution of E, P and E-P
- The effect of coupled model is more apparent in EMED
- The CPL model has more P in south of EMED
- The E-P estimates are consistent with available obs. for CPL model

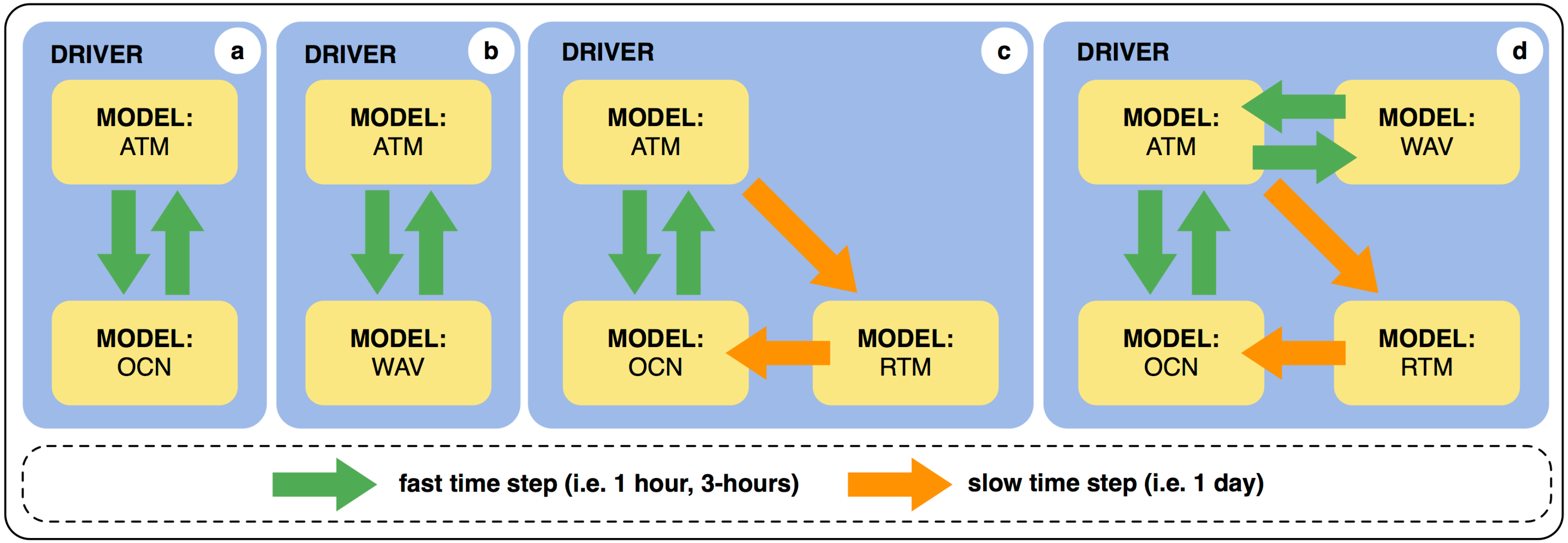


Turuncoglu and Sannino, 2016 @ CD

Data Access

- Currently, ITU is a data provider for MedCORDEX project
- Both coupled (RegCM4+ROMS) and standalone model simulations (RegCM4) are uploaded
  - Spatial resolution is MED44
  - Daily and monthly averages of surface variables
  - Monthly average of atmospheric variables (ua, va, ta, z) at 850 and 500 mb
- Documentation of simulations
  - ITU-RegCM4 - http://mistrals.sedoo.fr/?editDatsId=1434
  - ITU-RegESM1 - http://mistrals.sedoo.fr/?editDatsId=1433
  - Turuncoglu and Sannino, 2016 @ Climate Dynamics
- Data Access
  - It is distributed via MedCORDEX database
  - https://www.medcordex.eu/medcordex_help_get.php

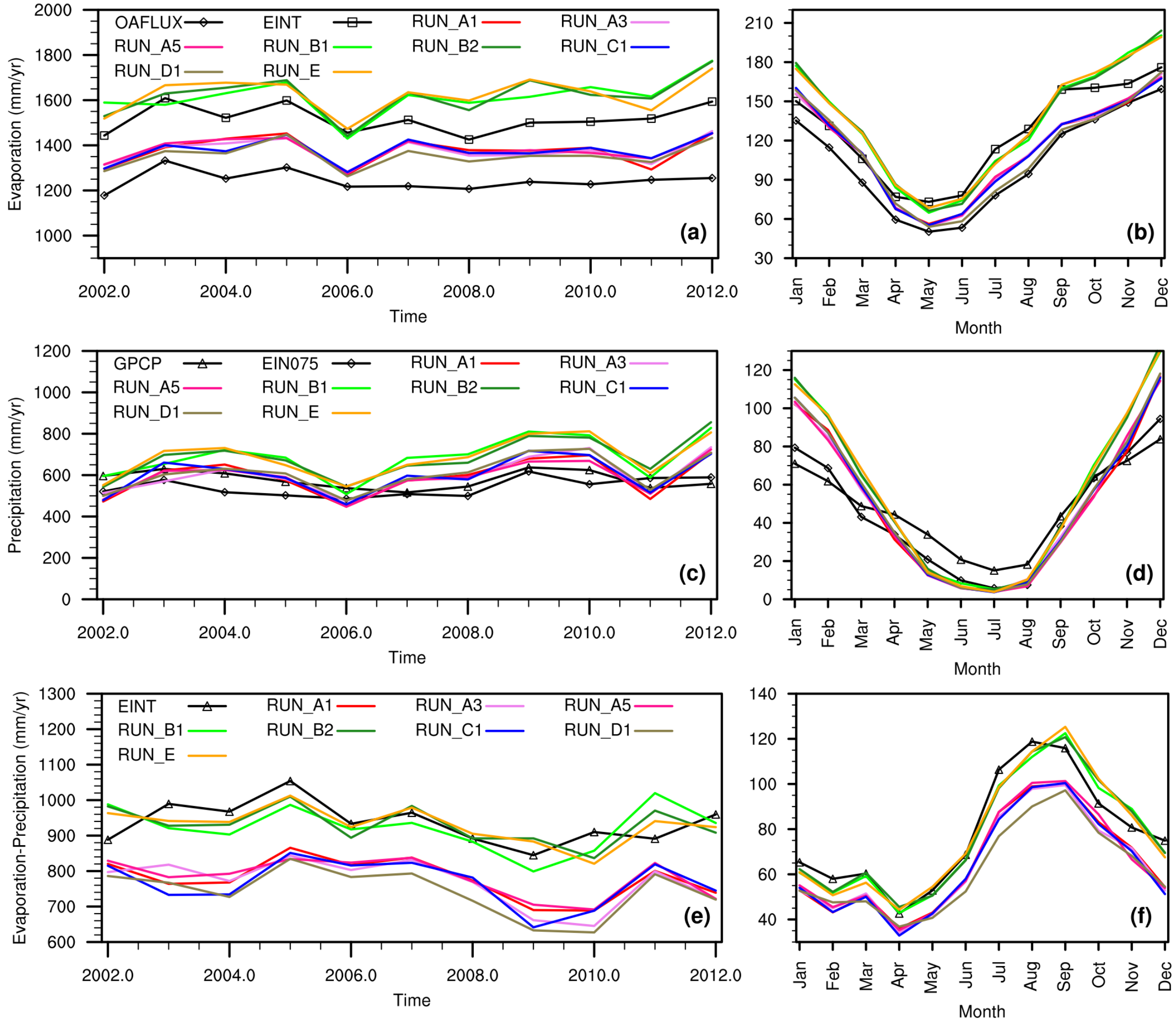
Extensive Testing of Modeling System



Run Short Name	Run Id	Coupling Type	Coupling Time Step	Active Models	Description
AO1	A1	Explicit	30 mins	ATM+OCN	
AO2	A2	Explicit	1 hour	ATM+OCN	
AO3	A3	Explicit	3 hours	ATM+OCN	base run
AO4	A5	Semi-implicit	3 hours	ATM+OCN	
AW1	B1	Explicit	3 hours	ATM+WAV	u and v <-> rough.
AW2	B2	Explicit	3 hours	ATM+WAV	wdir, friction vel.<-> rough.
AOR	C1	Explicit	3 hours	ATM+OCN+RTM	river discharge as SBC
AORW	D1	Explicit	3 hours	ATM+OCN+RTM+WAV	
Standalone	E, F, G, H	-	-	ATM/OCN/RTM/WAV	

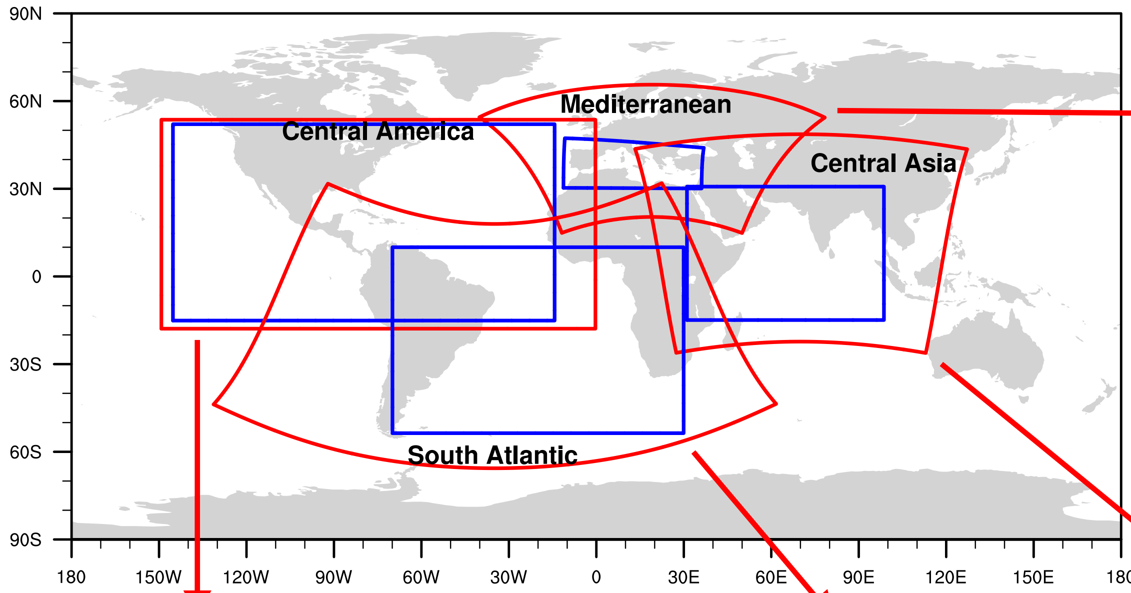
Comparison based on # used models

- Inter-annual variability and monthly climatology of E, P and E-P
- The effect of WAV component is minimal in E, P and E-P
- The OCN mainly affects the E-P balance by reducing E and P
- The monthly climatology is also modified



A – ATM-OCN / B – ATM-WAV / C – ATM-OCN-RTM / D – ATM-OCN-RTM-WAV

Applications



Mediterranean

	ATM	OCN	RTM
Models	RegCM 4.4.5.7	MITgcm c64s	HD
Res.	20 km, 23L 353x253	1/12º, 75L 276x408	0.5º global
ICBC	ERA-Int ERSST	12 km ALADIN	online ATM
Details	BATS Grell+MIT	GGL90	17 major rivers

- Coupled with RegESM driver
- 3 hours coupling interval between ATM and OCN and 1 day in interaction with RTM
- 1979-2013 (35 years)

Central America

	ATM	OCN	RTM
Models	RegCM 4.4.5.9	MITgcm c63s	HD
Res.	50 km, 23L 308x170	1/8º, 40L 1050x540	0.5º global
ICBC	ERA-Int ERSST	0.25º MOM	online ATM
Details	CLM, Grell, KF	KPP	10 major rivers

- Coupled with RegESM driver
- 3 hours coupling interval between ATM and OCN and 1 day in interaction with RTM
- ?

South Atlantic

	ATM	OCN	RTM
Models	RegCM 4.4.5.9	MITgcm c63s	HD
Res.	50 km, 23L 330x206	1/8º, 40L 800x510	0.5º global
ICBC	ERA-Int ERSST	0.25º MOM	online ATM
Details	CLM, UW-PBL, MIT	KPP	7 major rivers

- Coupled with RegESM driver
- 3 hours coupling interval between ATM and OCN and 1 day in interaction with RTM
- ?

Central Asia

	ATM	OCN	RTM
Models	RegCM 4.4.5.9	MITgcm c63s	HD
Res.	50 km, 18L 170x216	1/6º, 45L 276x408	0.5º global
ICBC	ERA-Int ERSST	0.25º MOM	online ATM
Details	CLM, UW-PBL, MIT	KPP	30 major rivers

- Coupled with RegESM driver
- 3 hours coupling interval between ATM and OCN and 1 day in interaction with RTM
- 1979-2007 (25 years)

RegESM Modeling System

THE GOOD

1/ easy to use and extend flexible modeling system
2/ model components can be upgraded easily
3/ state-of-art driver design that follows common conventions / standards
4/ ready to use with new non-hydrostatic core
5/ supports both CLM and BATS

THE BAD

1/ only global conservation is supported and might have a problem for large domains
2/ the bottleneck due to sequential RTM component
3/ WAM uses 1d decomposition and limits higher number of processor for seq. type coupling

AND THE UGLY

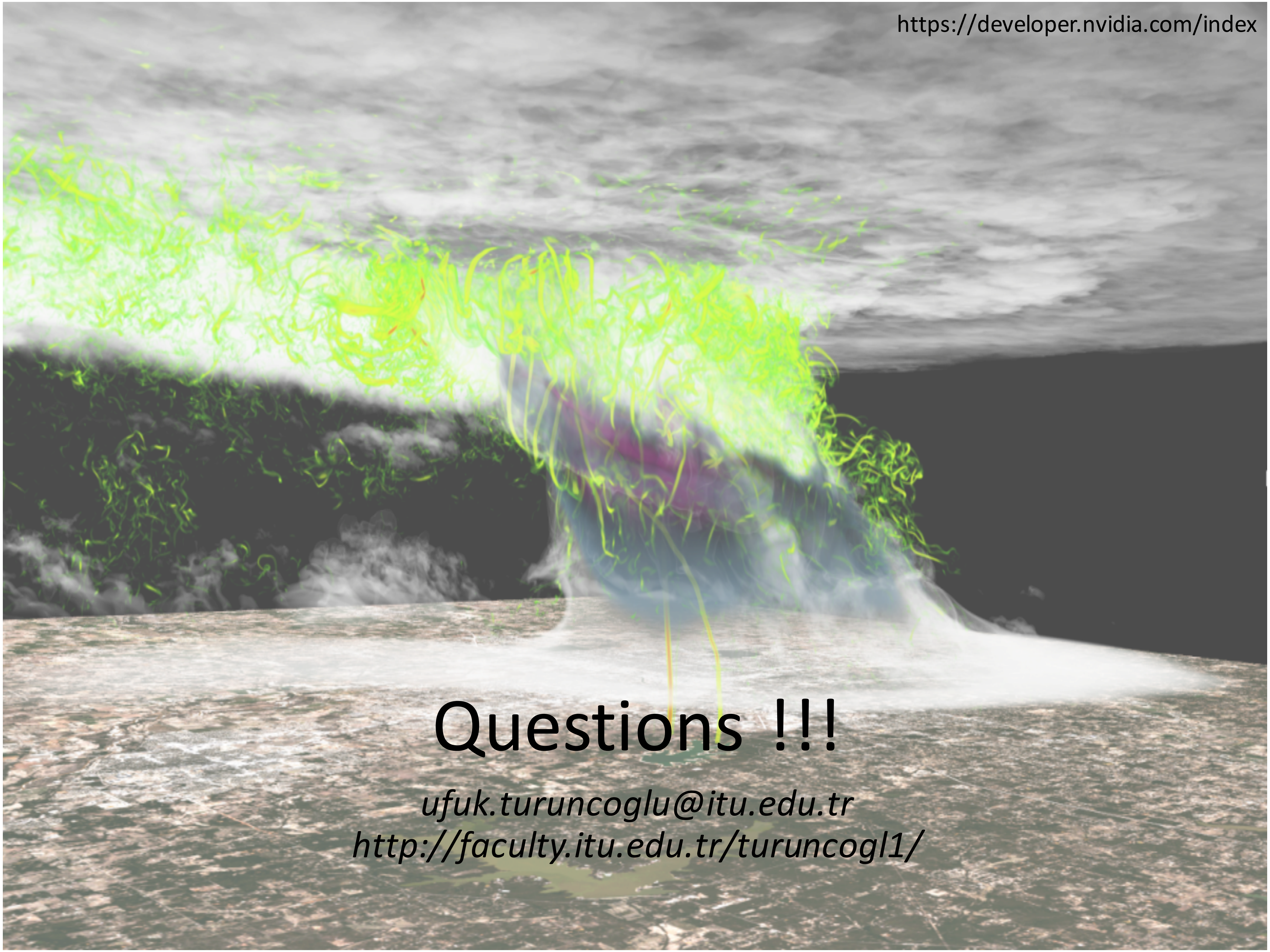
1/ sharp gradient between interactive and prescribed SST (issue #12)
2/ no wind rotation algorithm for Polar Stereographic (POLSTR) projection (issue #14)

Plans: Short - Mid - Long

#	Description	Domains
1	• Using modeling system for different applications and domains • Future climate scenarios using CMIP5 models	Med. Sea. Black Sea Caspian Sea
2	• New applications using hydrostatic core at higher spatial (3-12 km) and temporal resolution for Med-CORDEX-2, extreme events and fast-moving processes	Med. Sea.
3	• Wave effect on current (WEC): 1) gradient of radiation stress tensor or 2) vortex force (VF) • Additional wave component such as WW3 to support curvilinear grids in the wave component. It will allow to cover whole atmospheric model domain • Higher resolution river routing component for better representation of rivers (i.e. Chym, CaMa-Flood etc.)	

4	• Continuous Integration (CI)
	    • Standardization of model installation (integrate with **Travis-ci** to test the build)
	    • Usage of virtualization technologies such as Docker containers to run and test modeling system in the cloud (Google, Azure, Amazon etc.)	

5	• New approaches to analyze fast-moving processes in high res.	



https://developer.nvidia.com/index

Questions !!!

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