Partnership
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Infrastructures
in earth
System
Modelling
prism

A revised ocean-atmosphere physical coupling interface

and about technical coupling software

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with numerous contributions from the community

Outline

Part I – On an revised ocean-atmosphere physical coupling interface

- Context and guidelines for the design of a new physical interface
- The physical exchanges
- Time sequence of exchanges

Part II - About technical coupling software

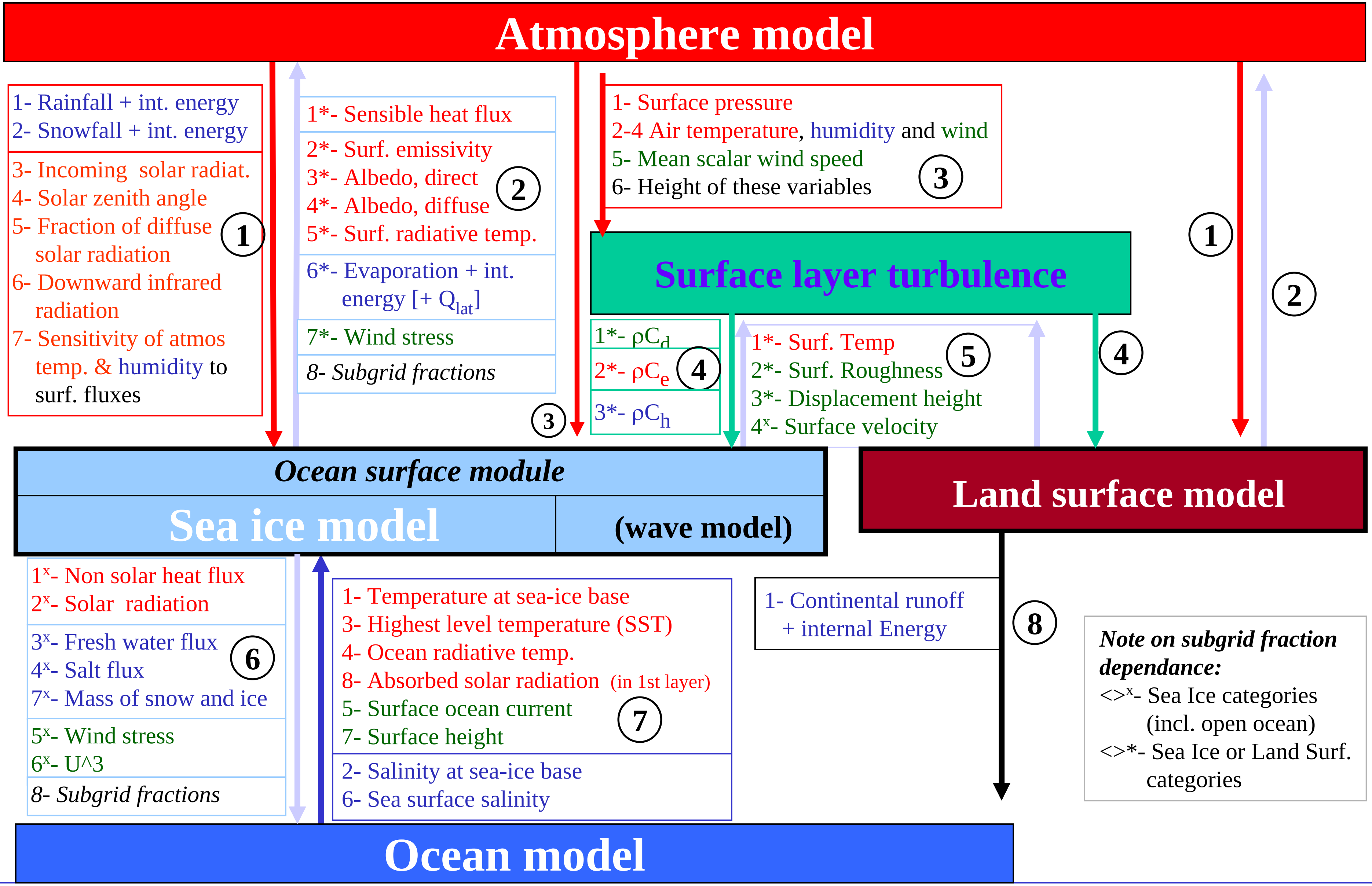
- Different technical solutions to assemble model codes
- The OASIS coupler (historic, community, …)
- Regridding algorithms in OASIS
- 1st order conservative remapping (2nd order, SUBGRID)
- Non-matching sea-land mask
- Vector interpolation

I.1 Context and guidelines for the design of a revised interface

- Proposition discussed during the EU PRISM project (definition of "standard" physical interfaces), following the PILPS experience (Polcher et al 1998)
- J.Polcher (LMD), T. Fichefet (UCL), G. Madec (LOCEAN), O. Marti (LSCE), S. Planton (Meteo-France), E. Guilyardi (LOCEAN)
- Guidelines:
  - physically based interfaces across which conservation of mass, momentum and energy can be ensured
  - which process should be computed by which component/module
  - numerical constraints (stability, regridding, subgrid issues, local conservation,…)
  - historical and practical constraints

Part I - On a revised ocean-atmosphere physical coupling interface

I.2 The physical exchanges



Atmosphere model

1- Rainfall + int. energy
2- Snowfall + int. energy

3- Incoming solar radiat.
4- Solar zenith angle
5- Fraction of diffuse solar radiation
6- Downward infrared radiation
7- Sensitivity of atmos temp. & humidity to surf. fluxes

①

1*- Sensible heat flux

2*- Surf. emissivity
3*- Albedo, direct
4*- Albedo, diffuse
5*- Surf. radiative temp.

②

6*- Evaporation + int. energy [+ Q_{lat}]

7*- Wind stress

8- Subgrid fractions

1- Surface pressure
2-4 Air temperature, humidity and wind
5- Mean scalar wind speed
6- Height of these variables

③

Surface layer turbulence

1*- ρC_d
2*- ρC_e
3*- ρC_h

④

1*- Surf. Temp
2*- Surf. Roughness
3*- Displacement height
4^x- Surface velocity

⑤

④

①

②

③

Ocean surface module

Sea ice model

(wave model)

Land surface model

1^x- Non solar heat flux
2^x- Solar radiation

3^x- Fresh water flux
4^x- Salt flux
7^x- Mass of snow and ice

5^x- Wind stress
6^x- U^3

8- Subgrid fractions

⑥

1- Temperature at sea-ice base
3- Highest level temperature (SST)
4- Ocean radiative temp.
8- Absorbed solar radiation (in 1st layer)
5- Surface ocean current
7- Surface height

2- Salinity at sea-ice base
6- Sea surface salinity

⑦

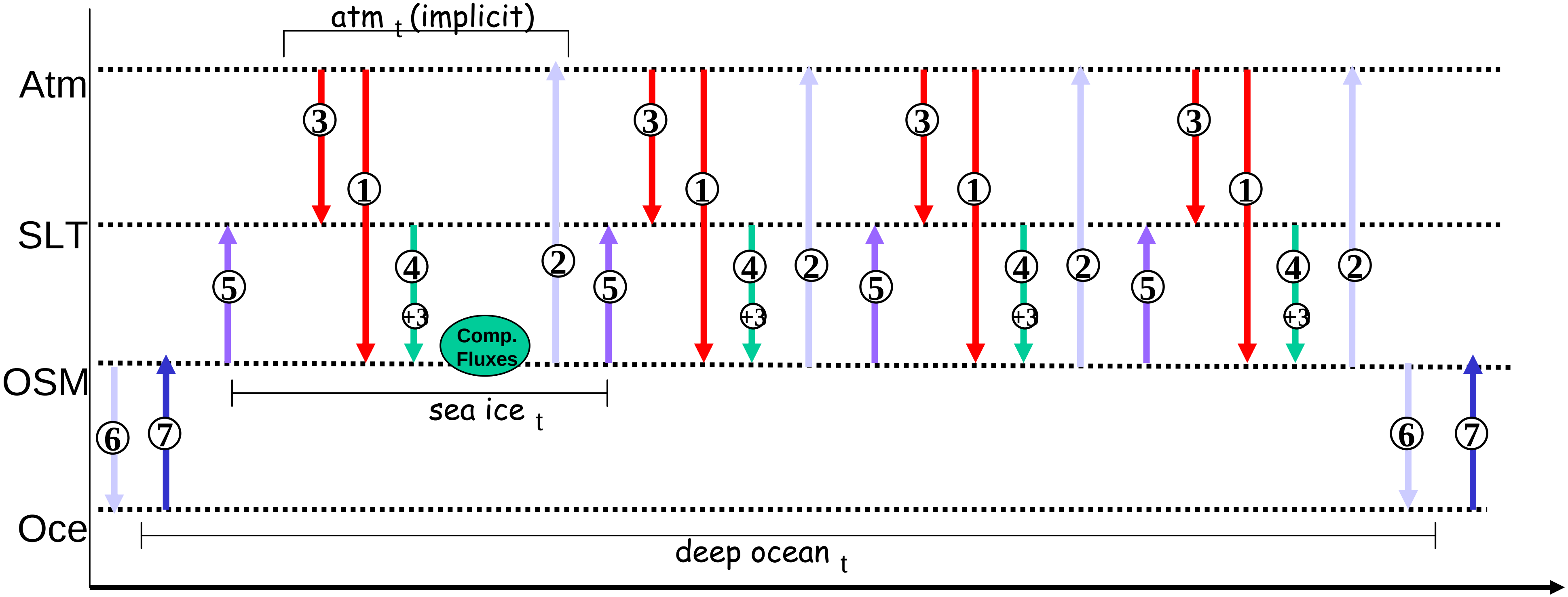
1- Continental runoff + internal Energy

⑧

Note on subgrid fraction dependance:
<>^{x}- Sea Ice categories (incl. open ocean)
<>*- Sea Ice or Land Surf. categories

Ocean model

I.3 Time sequence of exchanges



Frequency of coupling exchanges:

$$\underbrace{F_7 = F_6}_{\text{slow}} < \underbrace{F_5 = F_3 = F_1 = F_4 = F_2}_{\text{fast}}$$

Comments and conclusions

- Increased modularity with SLT and OS modules.
- SLT runs on finer grid and computes surface turbulent coefficient.
- OS computes radiation and turbulent fluxes.

✓ Separation of fast ocean + sea ice surface processes involving heat, water and momentum exchanges with the atmosphere from slower deeper ocean processes.

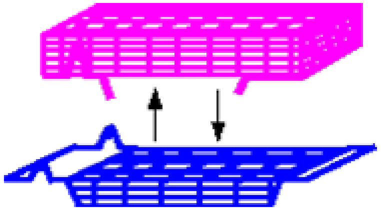
✓ Calculation of fluxes at the resolution of the surface (would be non-physical to regrid the turbulent exchange coefficients C_d, C_e, C_h).

✓ Implicit calculation of energy fluxes from the base of the sea-ice to the top of the atmosphere.

Part II - About technical coupling software

Why couple ocean and atmosphere (and sea-ice and land and …) models?

- ➢ Of course, to treat the Earth System globally



What does "coupling of codes" imply?

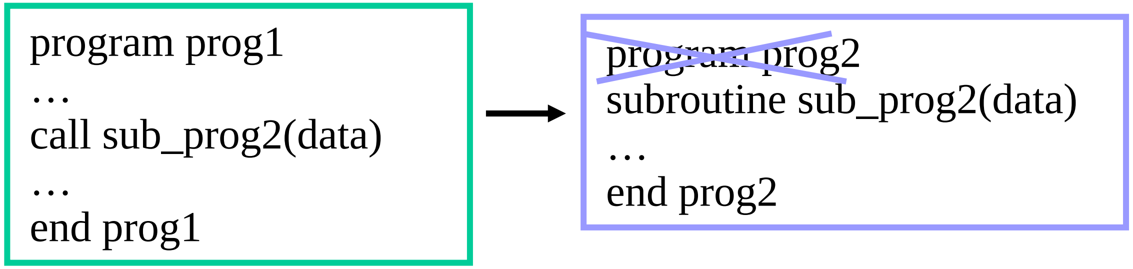
- ➢ Exchange and transform information at the code interface
- ➢ Manage the execution of the codes

What are the constraints?

- ✓ The coupling should be easy to implement
- ✓ The coupling should be flexible
- ✓ The coupling should be efficient
- ✓ The coupling should be portable
- ✓ We start from independently developed existing codes

II.1 Different technical solutions to assemble model codes:

1. merge the codes:



```
program prog1
…
call sub_prog2(data)
…
end prog1
```

```
~~program prog2~~
subroutine sub_prog2(data)
…
end prog2
```

- ☹ ~~easy~~
- ☹ ~~flexible~~
- ☺ efficient
- ☺ portable
- ☹ ~~existing codes~~

2. use existing communication protocole (MPI, CORBA, UNIX pipe, files, …)

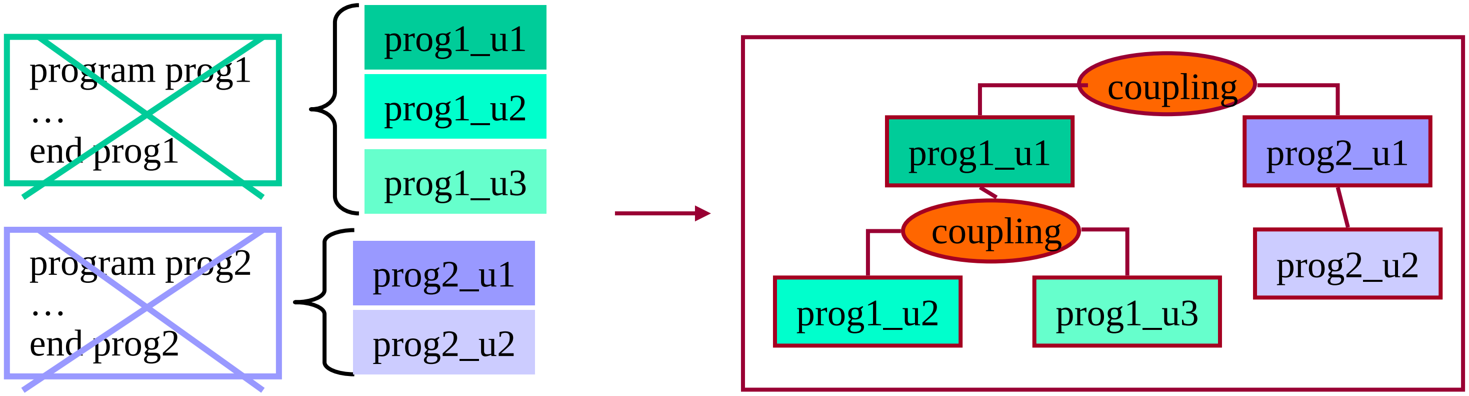
```
program prog1
…
call xxx_send (prog2, data, …)
end
```

```
program prog2
…
call xxx_recv (prog1, data)
end
```

- ☹ ~~easy~~
- ☹ ~~flexible~~
- 😐 (efficient)
- 😐 (portable)
- ☺ existing codes

3. use coupling framework (ESMF, FMS, …)

- Split code into elemental units
- Write or use coupling units
- Use the framework to build and control a hierarchical merged code
- Adapt code data structures



~~program prog1~~
~~…~~
~~end prog1~~

prog1_u1
prog1_u2
prog1_u3

~~program prog2~~
~~…~~
~~end prog2~~

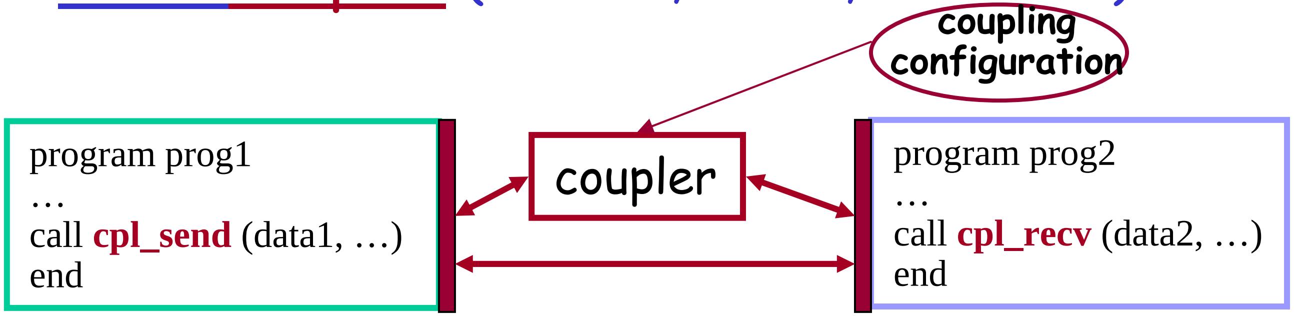
prog2_u1
prog2_u2

coupling
prog1_u1
prog2_u1
coupling
prog2_u2
prog1_u2
prog1_u3

😐 (easy)
☺ flexible
☺ efficient
☺ portable
😐 (existing codes)

→ probably best solution in a controlled development environment

4. use a coupler (OASIS, PALM, MPCCI …)



coupling configuration

```
program prog1
…
call cpl_send (data1, …)
end
```

coupler

```
program prog2
…
call cpl_recv (data2, …)
end
```

😐 (easy)
☺ flexible
😐 (efficient)
☺ portable
☺ existing codes

→ probably best solution to couple independently developed codes

II.2 The OASIS coupler

- ❖ developed by CERFACS since 1991 to couple existing GCMs
- ❖ currently an active collaboration between NLE-IT, CNRS and CERFACS

1991 **2001**
|--→ |--- PRISM →
OASIS 1 → OASIS 2 → OASIS3→
→ OASIS4 →

OASIS1, OASIS2, OASIS3:

- low resolution, low number of 2D fields, low coupling frequency:
  - ➔flexibility very important, efficiency not so much!
    - ❖ New OASIS3_3 release in the next few weeks!

OASIS4:

- high resolution parallel models, massively parallel platforms, 3D fields
  - ➔need to optimise and parallelise the coupler
    - ❖ OASIS4 beta version available

Part II - About technical coupling software

II.2.1 OASIS community today

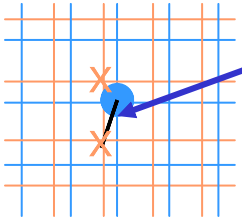
•CERFACS (France)	ARPEGE3-ORCA2/LIM, ARPEGE4-NEMO/LIM-TRIP
•METEO-FRANCE (France)	ARPEGE4-ORCA2, ARPEGE3-OPAmed ARPEGE3-OPA8.1/GELATO
•IPSL- LODYC, LMD, LSCE (France)	LMDz-ORCA2/LIM LMDz-ORCA4 ORCA4
•MPI-M&D (Germany)	ECHAM5-MPI-OM, ECHAM5-C-HOPE, PUMA-C-HOPE, EMAD-E-HOPE
•ECMWF	IFS - CTM (GEMS), IFS - ORCA2 (MERSEA)
•MET Office (UK)	MetOffice ATM - NEMO
•IFM-GEOMAR (Germany)	ECHAM5 - NEMO (OPA9-LIM)
•NCAS / U. Reading (UK)	ECHAM4 - ORCA2 HADAM3-ORCA2
•SMHI (Sweden)	RCA(region.) – RCO(region.)
•NERSC (Norway)	ARPEGE - MICOM, CAM - MICOM
•KNMI (Netherlands)	ECHAM5 - TM5/MPI-OM
•INGV (Italy)	ECHAM5 - MPI-OM
•ENEA (Italy)	MITgcm - REGgcm
•JAMSTEC (Japan)	ECHAM5(T106) - ORCA ½ deg
•IAP-CAS (China)	AGCM - LSM
•KMA (Korea)	CAM3 – MOM4
•BMRC (Australia)	BAM3–MOM2, BAM5–MOM2, TCLAPS-MOM
•CSIRO (Australia)	Sea Ice code - MOM4
•RPN-Environment Canada (Canada)	MEC - GOM
•UQAM (Canada)	GEM - RCO
•U. Mississippi (USA)	MM5 - HYCOM
•IRI (USA)	ECHAM5 - MOM3
•JPL (USA)	UCLA-QTCM - Trident-Ind4-Atlantic

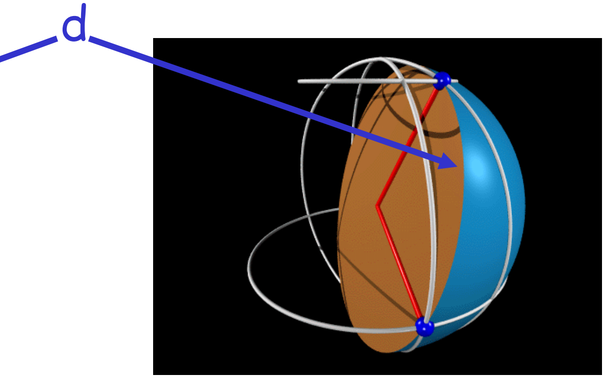
II.3 Regridding algorithms available in OASIS

(Los Alamos SCRIP library, Jones 1999)

x: source grid point
● target grid point

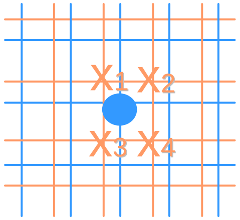
- n-nearest-neighbours: weight(x) α $1/d$
  d: great circle distance on the sphere:
  d = arccos[sin(lat1)*sin(lat2) + cos(lat1)*cos(lat2) * cos(lon1-lon2)]



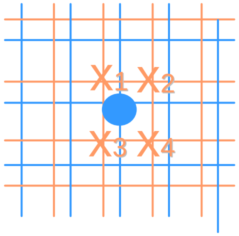


- gaussian weighted n-neighbours: weigth(x) α $\exp(-{}^{1}/_{2}\, d^2/\sigma^2)$

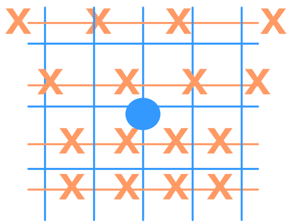
- bilinear interpolation
  - general bilinear iteration in a continuous local coordinate system using $f(x)$ at x_1, x_2, x_3, x_4



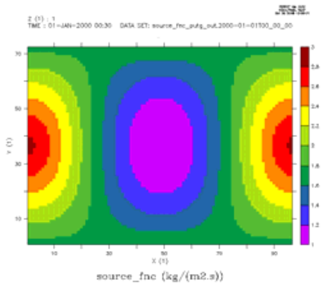
- bicubic interpolation: conserves 2nd order properties such as wind curl
  - general bicubic iteration continuous local coordinate system: $f(x)$, $\delta f(x)/\delta i$, $\delta f(x)/\delta j$, $\delta^2 f/\delta i \delta j$ in x_1, x_2, x_3, x_4 for logically-rectangular grids (i,j)



  - standard bicubic algorithm: 16 neighbour points for Gaussian Reduced grids

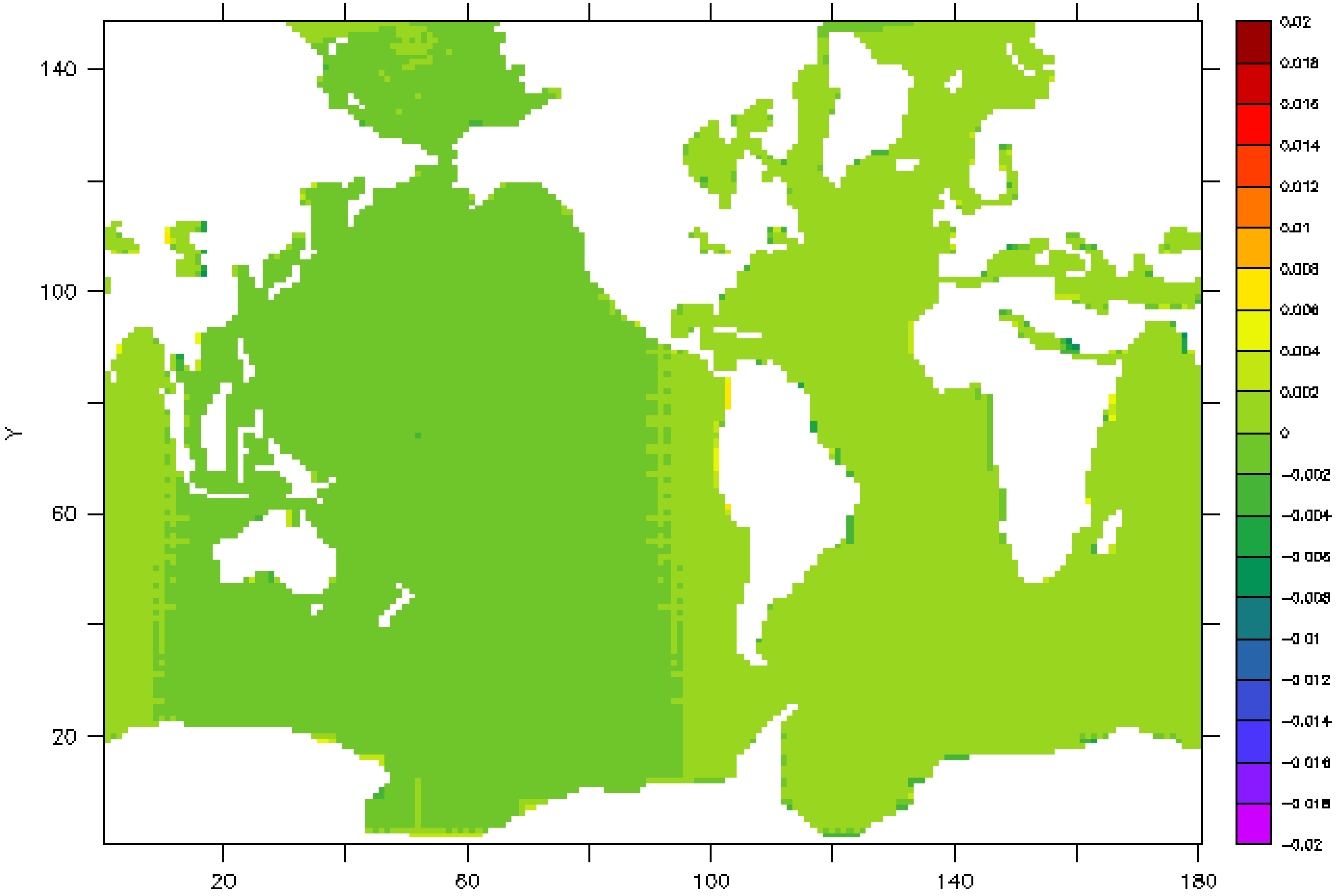


Part II - About technical coupling software



One example of bilinear interpolation error

F = 2 + cos[π * acos(cos(lon)cos(lat))]   LMDz grid (96 x 72) -> ORCA2

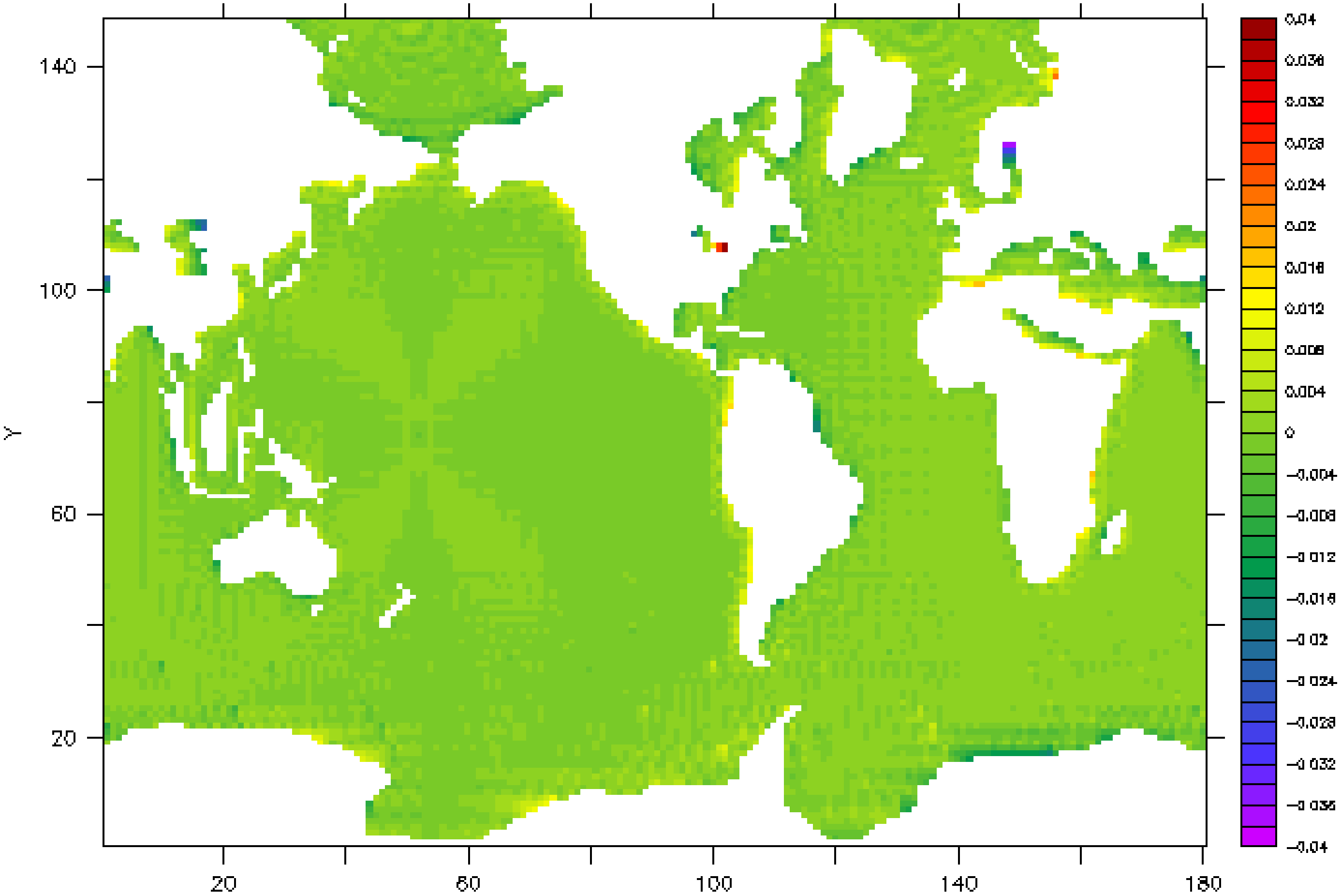


- < 0.2% whole domain; ~1% near the coastline

Part II - About technical coupling software

- One example of bicubic interpolation error

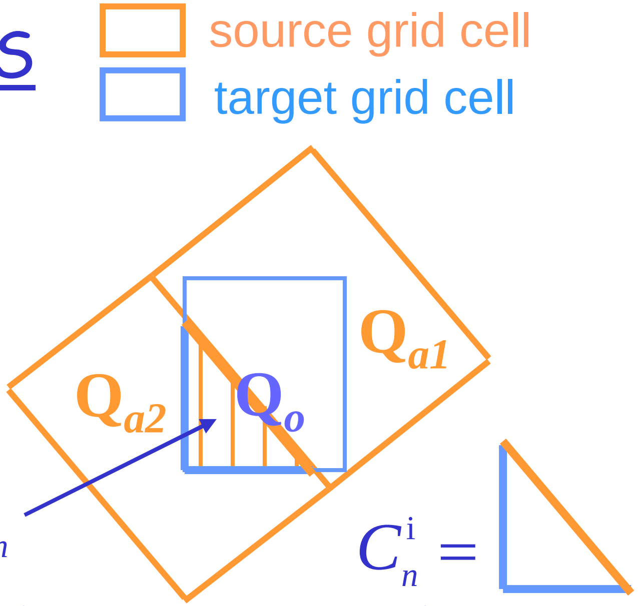
F = 2 – cos[π * acos(cos(lon)cos(lat)]
BT42 Gaussian red. -> ORCA2



➢ < 0.2% in equatorial and tropical regions,
< 0.4% at higher or lower latitudes (where the Gaussian grid is effectively reduced),
up to 4% near the coastline

II.3 Regridding algorithms available in OASIS

(Los Alamos SCRIP library, Jones 1999)



- 1st order conservative remapping:
  - ➢ conserves integral of extensive properties
  - ➢ weight of a source cell α to intersected area

$$Q_o^i = \frac{1}{A_o} \sum_{n=1}^{N} Q_{a\,n} w_n^i \quad \text{with} \quad w_n^i = \oint_{C_n^i} -\sin(\text{lat})\,d\text{lon}$$

- ❖ assumes borders are linear in (lat,lon)
  - ➢ Lambert equivalent azimuthal projection near the pole for intersec. calc.

Actual limitations:

- assumes sin(lat) linear function of lon (for line integral calculation)
  - ➢ need to use a projection near the pole (as done for intersect. calc.)
- exact calculation is not possible as "real shape" of the borders are not known
  - ➢ could use of border middle point
  - ➢ to ensure conservation, need to normalize by true area of the cells

Other methods e.g.:

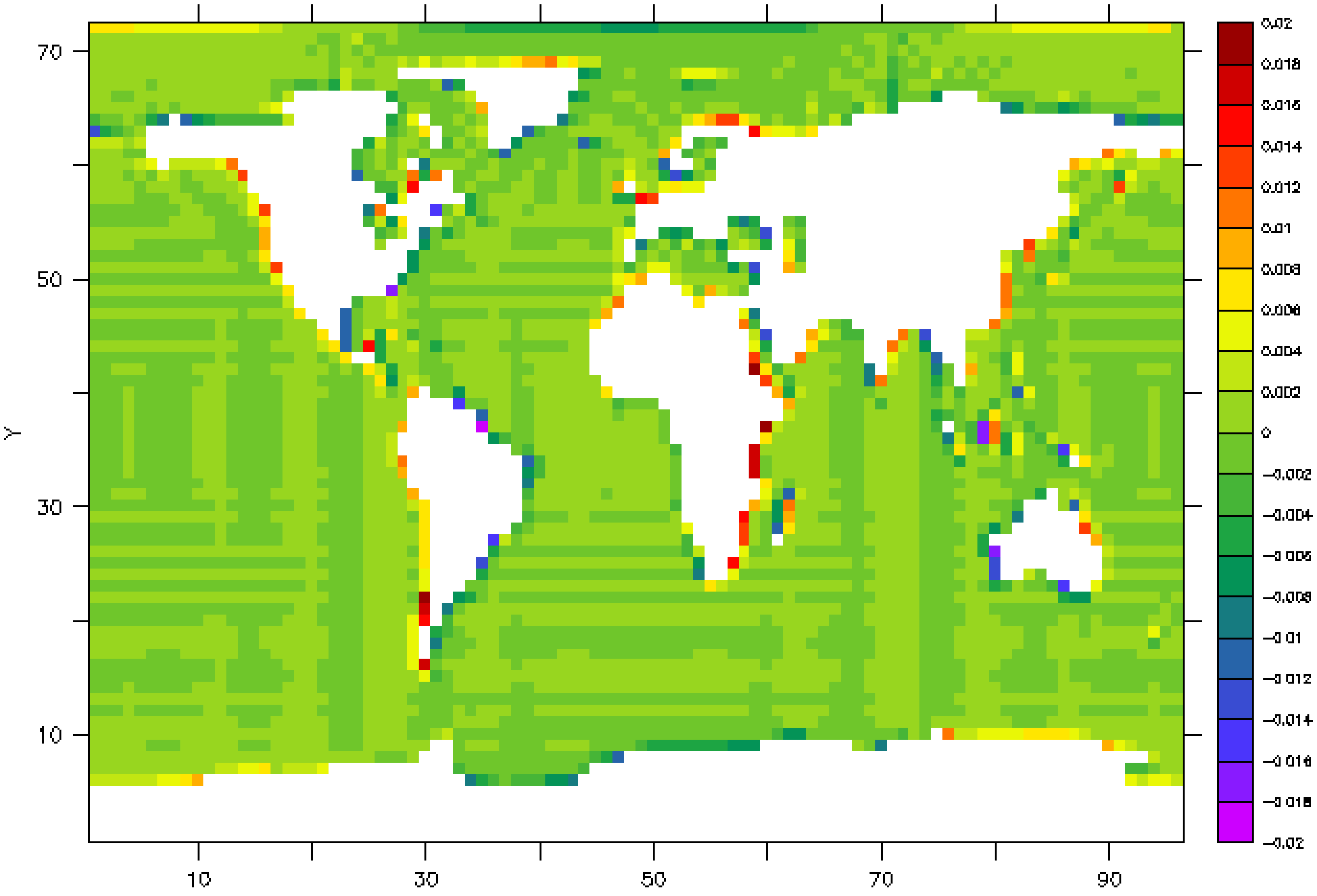
- Monte Carlo random walk
- Projection of the source and target polygons on a plane (IPSL)

Part II - About technical coupling software

- One example of conservative remapping error

$F = 2 - \cos[\pi * \mathrm{acos}(\cos(lon)\cos(lat))]$

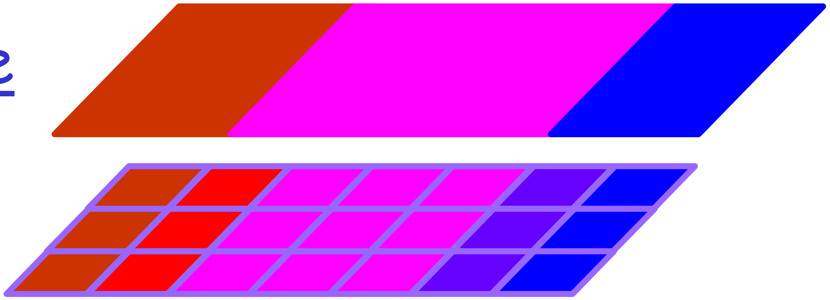
ORCA2 -> LMDz (96x72)



- < 0.2% everywhere except
  ~ 0.8% for LMDz last row close to the North pole
  ~ 2% near the coastline

II.4 Problem with 1st order conservative remapping

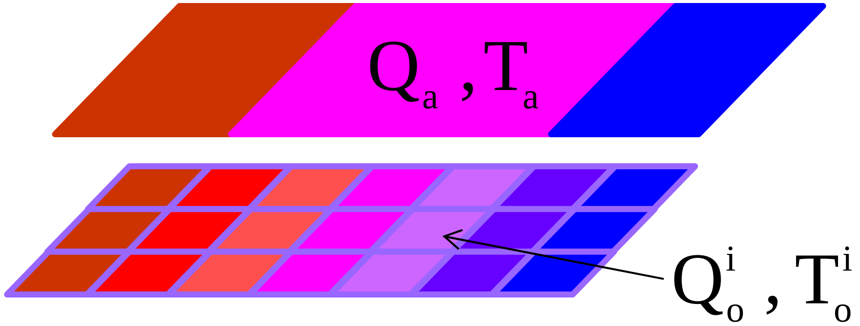
(low to high resolution) :



- Solution 1: use 2nd order conservative remapping:

$$Q_o^i = Q_a w_1^i + \frac{\partial Q_a}{\partial lat} w_2^i + \frac{1}{\cos(lat)} \frac{\partial Q_a}{\partial lon} w_3^i$$

- Solution 2: use SUBGRID transformation:



Solar type: $Q_o^i = \frac{(1-\alpha_o^i)}{(1-\alpha_a)} Q_a$

Non-solar type: $Q_o^i = Q_a + \left.\frac{\partial Q_a}{\partial T}\right|_{T=T_a} (T_o^i - T_a)$

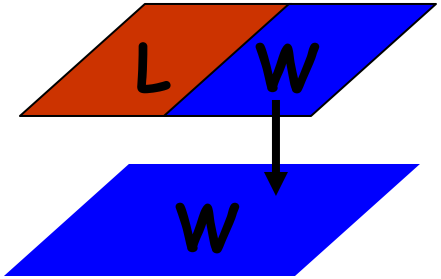
*conservative if α_a / T_a correspond to conservative remapping of α_o^i / T_o^i

II.5 Problem with non-matching sea-land masks

$$Q_o^i = \frac{1}{A_o} \sum_{n=1}^{N} Q_{a\,n} w_n^i$$

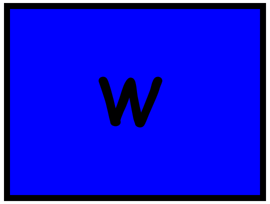
1- Ideally: Support subsurfaces in the atmosphere

and use the ocean land-sea mask in the atmosphere to determine the fractional area of each type of surface



2-"DESTAREA" option

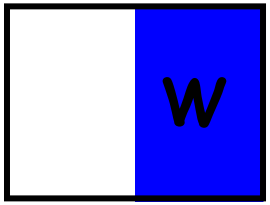
$A_o =$



- ➢ local flux conservation
- ➢ possibly unrealistic flux values

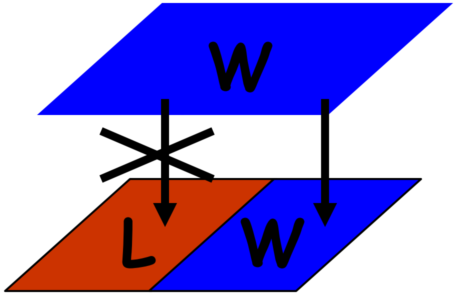
3-"FRACAREA" option

$A_o =$



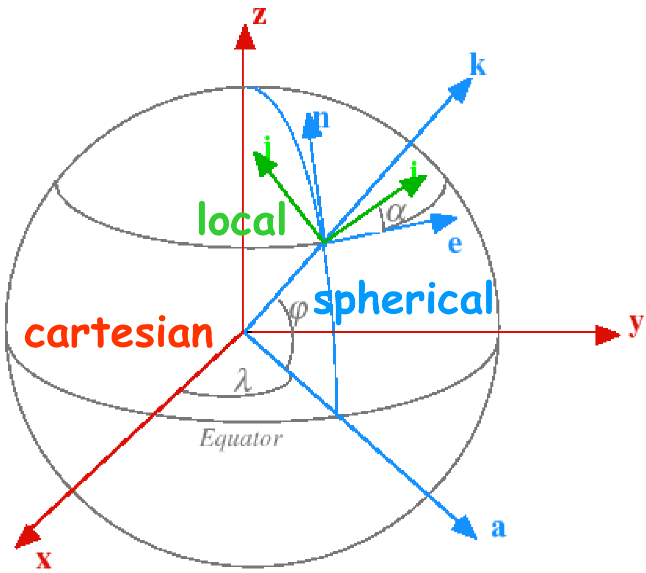
- ➢ no local conservation of flux
- ➢ realistic flux values

+ nearest non-masked value for ocean cells covered only with masked atmospheric cells



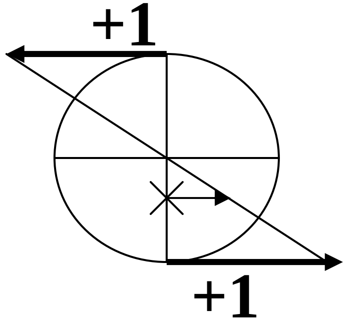
- ➢ no local conservation of flux
- ➢ global conservation can be artificially imposed

II.6 Vector interpolation (winds, currents, …)



- ❖ interpolation of vectors component per component is not accurate, especially where the referential changes rapidly

Example interpolation of a zonal wind in the spherical referential near the pole



- ➢At x, one would expect a zonal wind between 0 and 1.
- ➢Interpolation comp. per comp. -> zonal wind of 1.

Solution (proposed by O. Marti, LSCE, implemented in OASIS):

- • "turn" the vector in the spherical referential and project the resulting vector in a cartesian referential
- • interpolate the 3 components in the cartesian referential
- • project back in the spherical referential; check that k component is zero
- • possibly "turn" the resulting vector in the target local referential

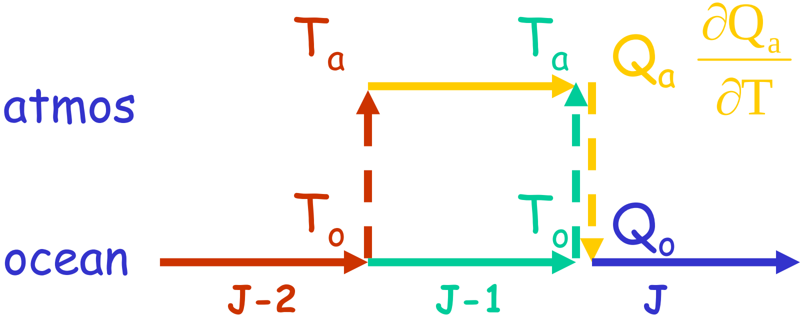
Conclusions

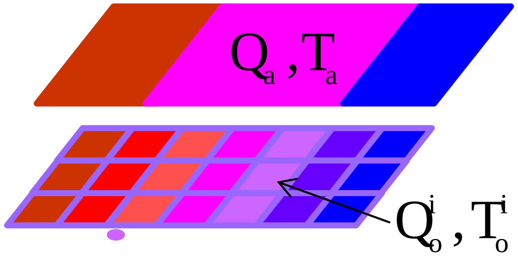
- Different technical solutions to assemble model codes:
  - Coupling framework (e.g. ESMF):
    - ➢ best solution in a controlled development environment
  - Coupler (e.g. OASIS):
    - ➢ best solution to couple independently developed codes

- The OASIS coupler :
  - Coarse to fine grid remapping: subgrid variability with 2nd order remapping or SUBGRID (1st order Taylor expansion)
  - Non-matching sea-land masks:
    - DESTAREA: local flux conservation but unrealistic flux values
    - FRACAREA: no local flux conservation but realistic flux values
    - Global conservation can be artificially imposed
  - Vector interpolation: need to project components in a cartesian referential before interpolation.

The end

Use of SUBGRID transformation in practice:





Method 1:

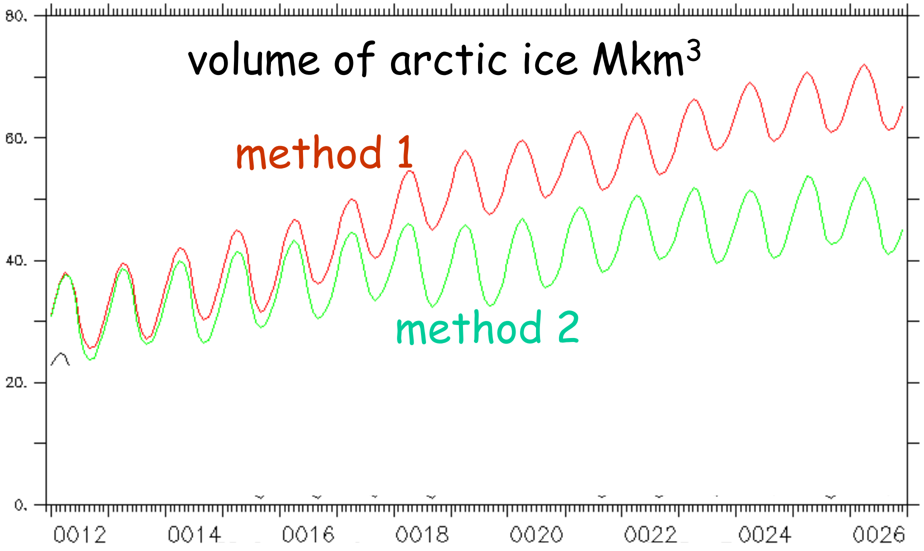
keep and use $T_o^i - T_a$ from J-2

$$Q_o^i = Q_a(T_a) + \delta Q_a/\delta T|_{T_a} \times (T_o^i - T_a)$$

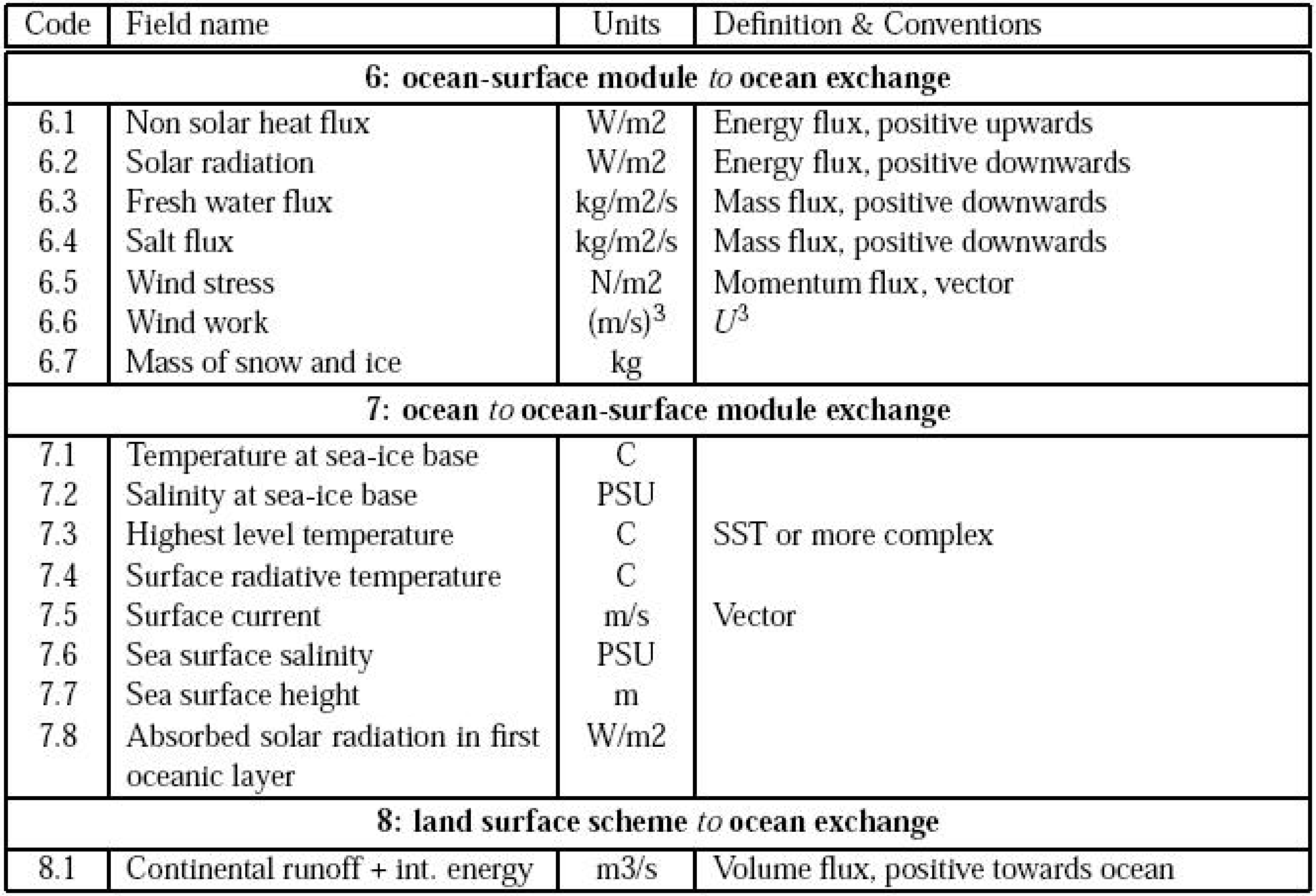
Method 2:

send back Ta and use $T_o^i - T_a$ from J-1

$$Q_o^i = Q_a(T_a) + \delta Q_a/\delta T|_{T_a} \times (T_o^i - T_a)$$



Code	Field name	Units	Definition & Conventions
1: atmosphere *to* Ocean-surface module exchange			
1.1	Rainfall + int. energy	kg/m2/s + W/m2	Mass flux and associated internal energy, positive downwards, includes all liquid precip.
1.2	Snowfall + int. energy	kg/m2/s + W/m2	Mass flux and associated internal energy, positive downwards, includes all solid precip.
1.3	Incoming solar radiation	W/m2	Energy flux, positive downwards
1.4	Solar zenith angle	radians	
1.5	Diffuse solar radiation	W/m2	Energy flux, positive downwards
1.6	Downward infrared radiation	W/m2	Positive downward
1.7	Sensitivity of atmos. T and q to surface fluxes		$\partial T/\partial Q_s$ and $\partial q/\partial Q_s$
2: ocean-surface module *to* atmosphere exchange			
2.1	Sensible heat flux	W/m2	Energy flux, positive upwards
2.2	Surface emissivity		
2.3	Albedo, direct	-	
2.4	Albedo, diffuse	-	
2.5	Surface radiative temperature	K	
2.6	Evaporation + int. energy	kg/m2/s	Mass flux, positive upwards
2.7	Wind stress	N/m2	Momentum flux, vector
2.8	Subgrid fractions	array of [0-1]	If multiple surfaces and tiling scheme
3: atmosphere *to* surface layer turbulence exchange			
3.1	Mean sea level surface pressure	hPa	
3.2	Air temperature at lowest level	K	
3.3	Air humidity at lowest level	g/g	
3.4	Wind at lowest level	m/s	Vector
3.5	Wind module at lowest level	m/s	Possibly including gustiness effects
3.6	Lowest level height	m	
4: surface layer turbulence *to* ocean-surface module exchange			
4.1	ρC_d drag coefficient	kg/m2/s	Surface layer exchange coeff. for momentum
4.2	ρC_e exch. coeff.	kg/m2/s	Surface layer exchange coeff. for sensible heat
4.3	ρC_h exch. coeff.	kg/m2/s	Surface layer exchange coeff. for moisture
5: ocean-surface module *to* surface layer turbulence exchange			
5.1	Surface temperature	K	
5.2	Surface roughness		
5.3	Displacement height		
5.4	Surface velocity	m/s	

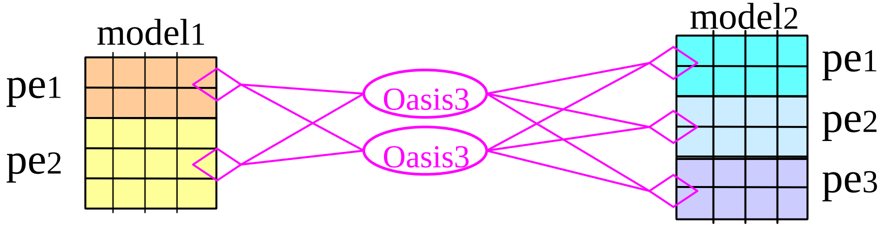


Code	Field name	Units	Definition & Conventions
	6: ocean-surface module *to* ocean exchange		
6.1	Non solar heat flux	W/m2	Energy flux, positive upwards
6.2	Solar radiation	W/m2	Energy flux, positive downwards
6.3	Fresh water flux	kg/m2/s	Mass flux, positive downwards
6.4	Salt flux	kg/m2/s	Mass flux, positive downwards
6.5	Wind stress	N/m2	Momentum flux, vector
6.6	Wind work	$(m/s)^3$	U^3
6.7	Mass of snow and ice	kg	
	7: ocean *to* ocean-surface module exchange		
7.1	Temperature at sea-ice base	C	
7.2	Salinity at sea-ice base	PSU	
7.3	Highest level temperature	C	SST or more complex
7.4	Surface radiative temperature	C	
7.5	Surface current	m/s	Vector
7.6	Sea surface salinity	PSU	
7.7	Sea surface height	m	
7.8	Absorbed solar radiation in first oceanic layer	W/m2	
	8: land surface scheme *to* ocean exchange		
8.1	Continental runoff + int. energy	m3/s	Volume flux, positive towards ocean

II.2.2 The OASIS coupler: data exchange

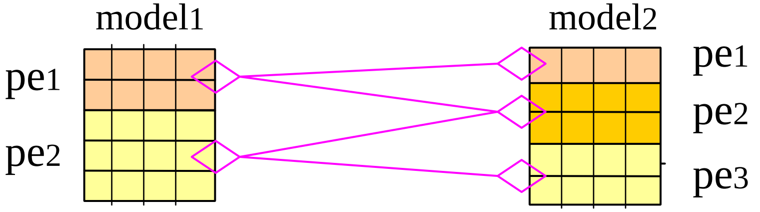
- communication library (MPI message passing) linked to the models

OASIS3: Parallel communication between parallel models and mono-process interpolation instance(s)

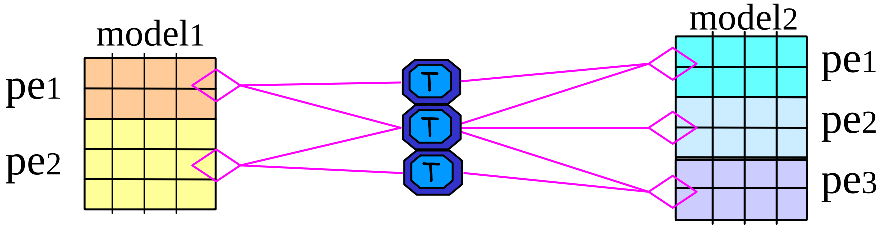


OASIS4: Parallel communication including

repartitioning and **parallel interpolation**

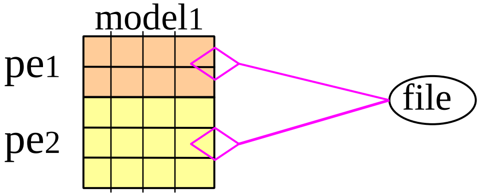


same grids, different decompositions

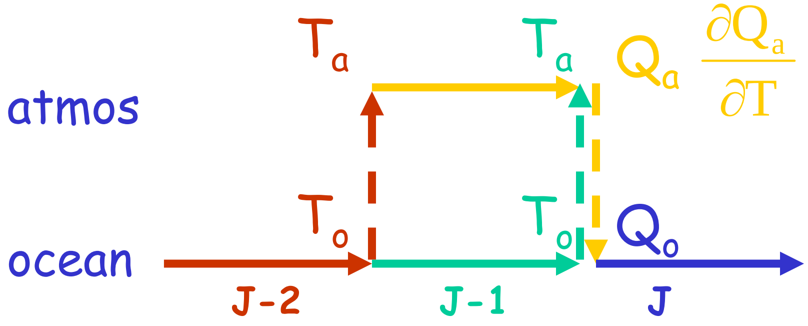


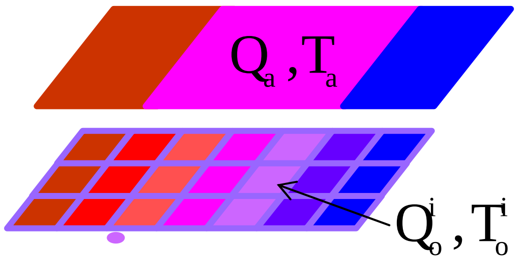
different grids, different decompositions

+ I/O functionality (GFDL mpp_io library)
  - switch between coupled and forced mode



Use of SUBGRID transformation in practice:





Method 1:

send back Ta and use T_o^i from J-1 , T_a from J-2

$$Q_o^i = Q_a(T_a) + \delta Q_a/\delta T|_{T_a} \times (T_o^i - T_a)$$

Method 2:

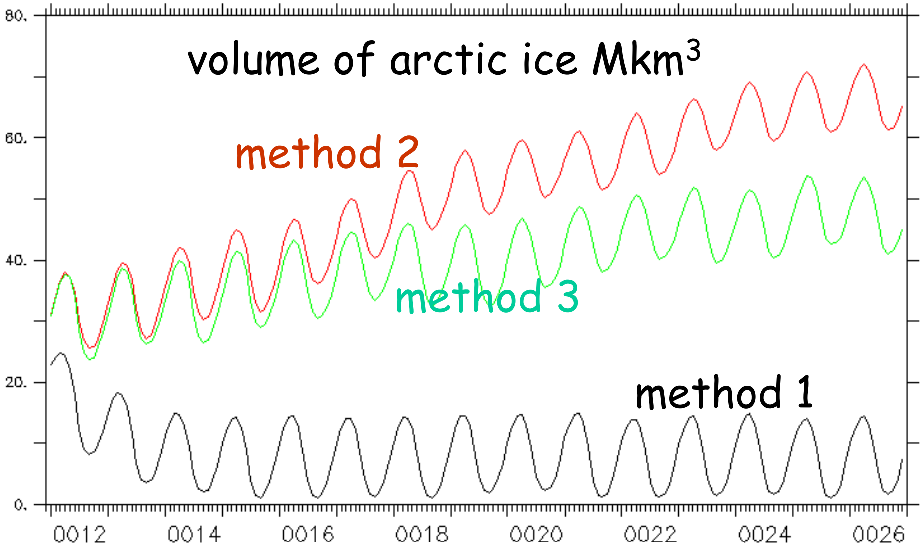
keep and use $T_o^i - T_a$ from J-2

$$Q_o^i = Q_a(T_a) + \delta Q_a/\delta T|_{T_a} \times (T_o^i - T_a)$$

Method 3:

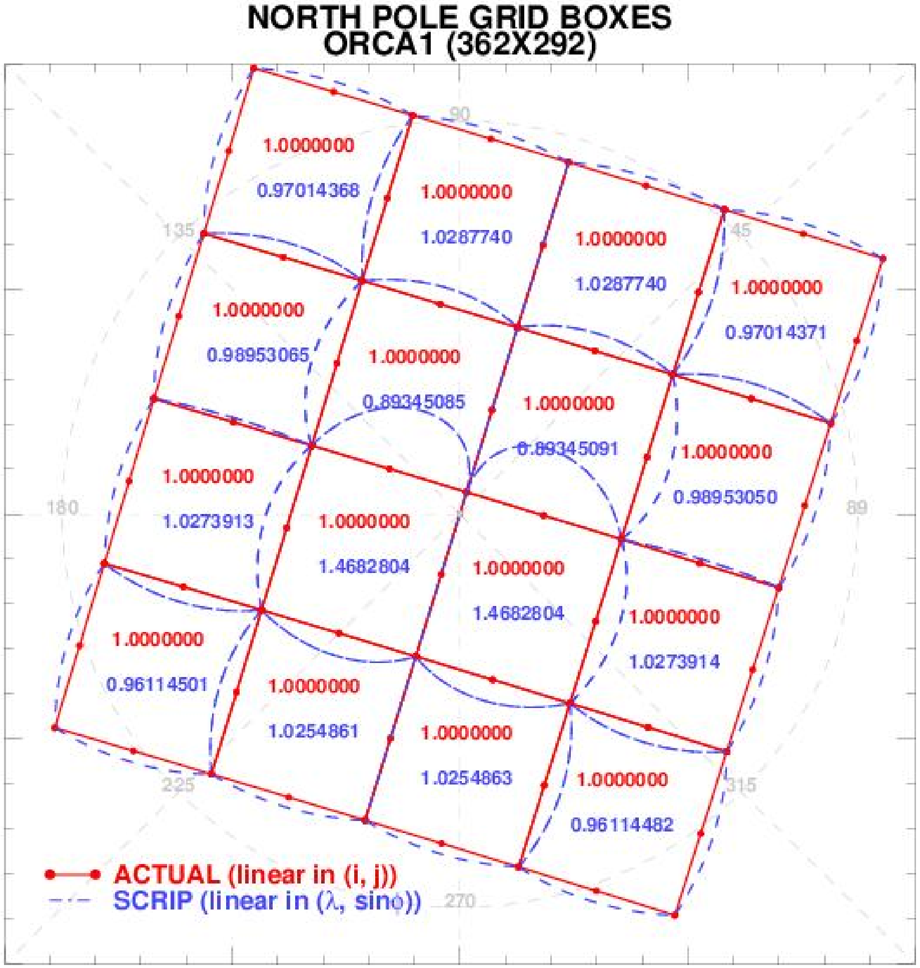
send back Ta and use $T_o^i - T_a$ from J-1

$$Q_o^i = Q_a(T_a) + \delta Q_a/\delta T|_{T_a} \times (T_o^i - T_a)$$



Remapping algorithms available in OASIS

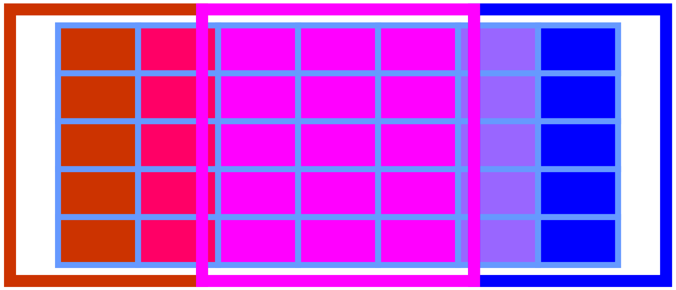
(Los Alamos SCRIP library)


NORTH POLE GRID BOXES
ORCA1 (362X292)

Actual limitations:

- borders are linear in (lat,lon) between corne (for intersection calculation)
  - ➢ uses Lambert equivalent azimuthal projection near the pole
- sin(lat) linear function of in lon (for line inte calculation); fractional error is < .001 further than 10 deg from the pole, and only ~0.1 with about 1 deg of it, for the ORCA1 example (fo most gridcells the two measures of gridcell a agree to < 5%, but for two gridcells they're by 10%, and for another two they're out by 5
  - ➢ need to use a projection for line integ calculation too
- exact calculation is not possible as "real sho of the borders are not known
  - ➢ to ensure conservation, need to normal by true area of the cells (i.e. as consider by the models themselves)

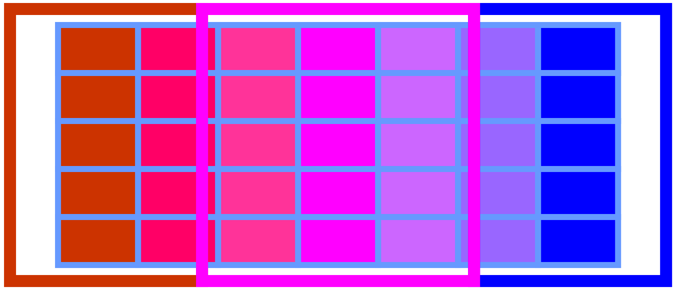
Part B - about ocean-atmosphere technical coupling software



- Problem with 1st order conservative remapping (low to high resolution)

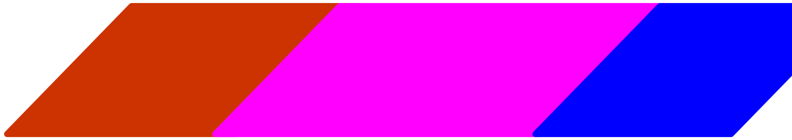
- Solution 1: use 2nd order conservative remapping:

$$F_k = \sum_{n=1}^{N} [f_k w_{1nk} + \left(\frac{\partial f}{\partial lat}\right)_n w_{2nk} + \left(\frac{1}{\cos(lat)}\frac{\partial f}{\partial lon}\right)_n w_{3nk}]$$

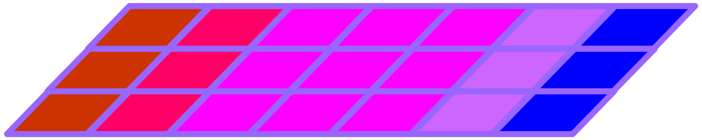


- Solution 2: use SUBGRID transformation:

Solar type

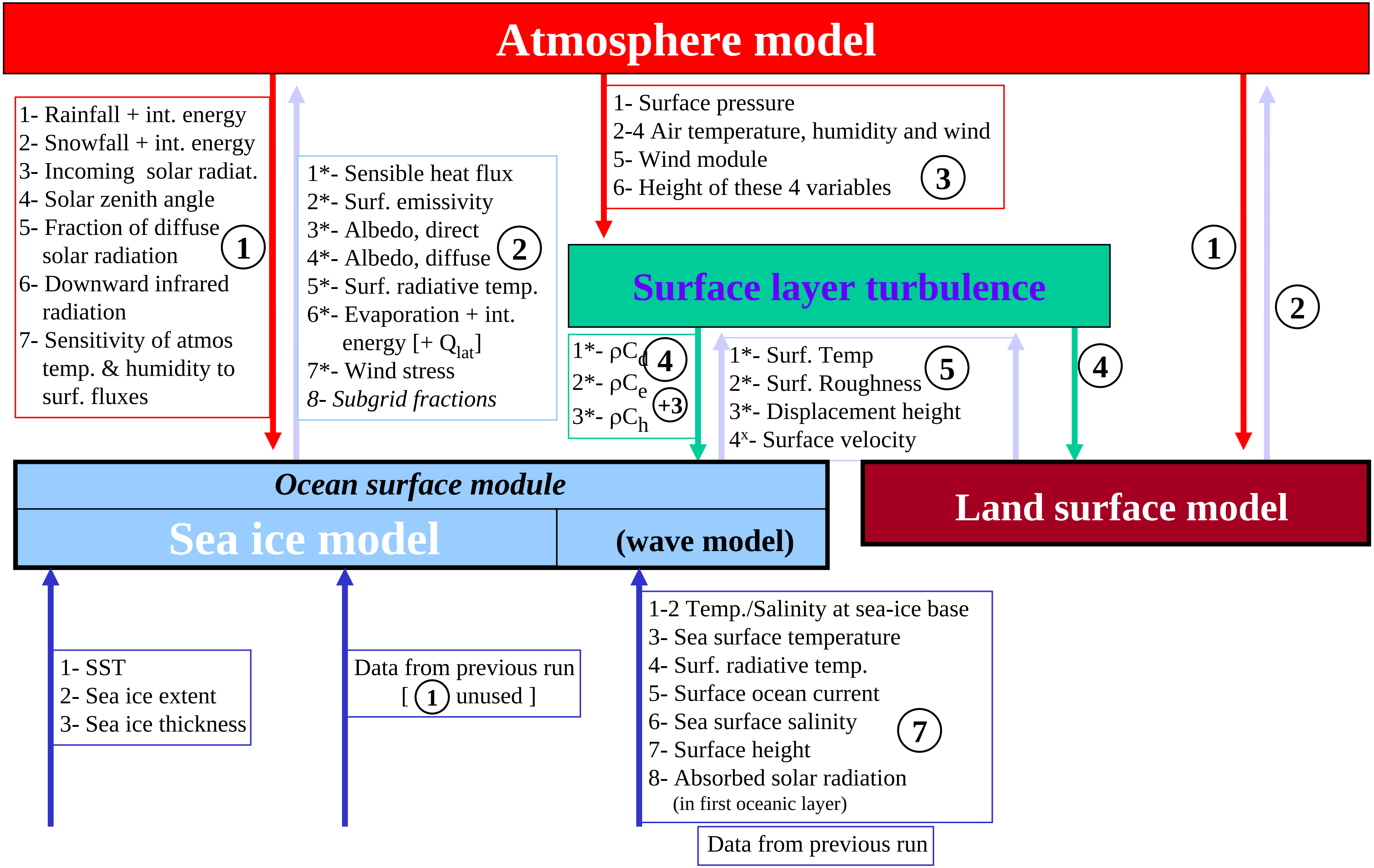


Non-solar type



Part I - On a revised ocean-atmosphere physical coupling interface

Stand alone (forced AGCM)



Atmosphere model

1- Rainfall + int. energy
2- Snowfall + int. energy
3- Incoming solar radiat.
4- Solar zenith angle
5- Fraction of diffuse solar radiation
6- Downward infrared radiation
7- Sensitivity of atmos temp. & humidity to surf. fluxes
①

1*- Sensible heat flux
2*- Surf. emissivity
3*- Albedo, direct
4*- Albedo, diffuse
5*- Surf. radiative temp.
6*- Evaporation + int. energy [+ Q_{lat}]
7*- Wind stress
8- Subgrid fractions
②

1- Surface pressure
2-4 Air temperature, humidity and wind
5- Wind module
6- Height of these 4 variables
③

Surface layer turbulence

1*- ρC_d
2*- ρC_e
3*- ρC_h
④ (+3)

1*- Surf. Temp
2*- Surf. Roughness
3*- Displacement height
4^x- Surface velocity
⑤

④

①

②

Ocean surface module

Sea ice model

(wave model)

Land surface model

1- SST
2- Sea ice extent
3- Sea ice thickness

Data from previous run
[① unused]

1-2 Temp./Salinity at sea-ice base
3- Sea surface temperature
4- Surf. radiative temp.
5- Surface ocean current
6- Sea surface salinity
7- Surface height
8- Absorbed solar radiation (in first oceanic layer)
⑦

Data from previous run