Representation of air-sea interactions on an idealised coupled atmosphere-ocean model with focus on the Western Baltic Sea

3rd Workshop on Physics Dynamics Coupling – PDC18

ECMWF, Reading (UK)

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July 11, 2018

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❹ Conclusions & Outlook

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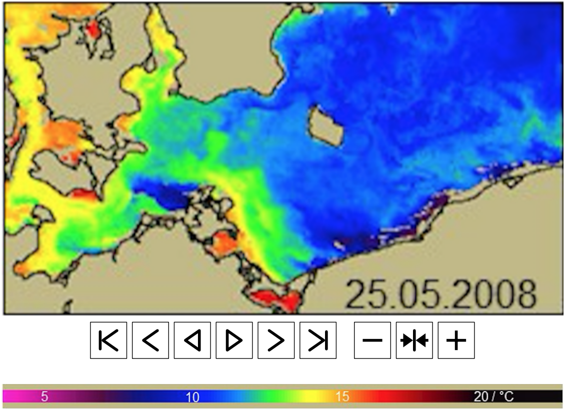
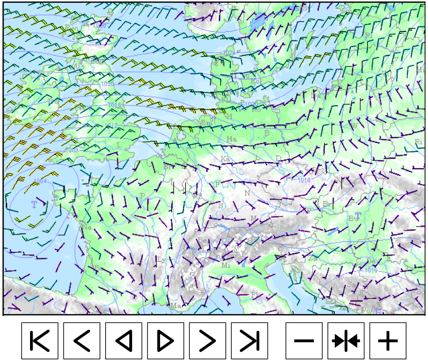
Coastal upwelling – coast of Poland: May 25 – Jun 08, 2008



Sea surface temperature western Baltic Sea – May/June 2008



Wind map of central Europe at 6am UTC

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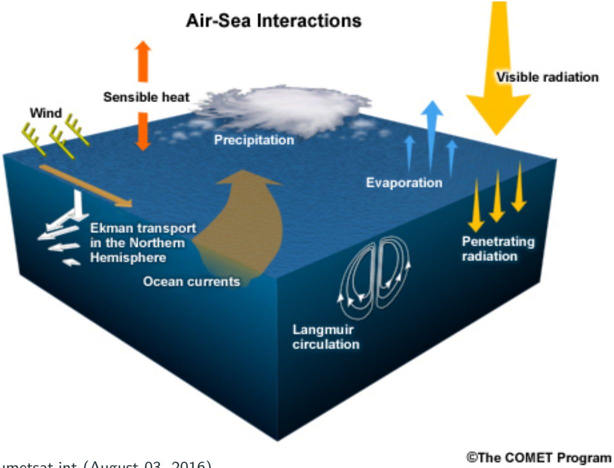
What happens at the water surface?



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www.eumetsat.int (August 03, 2016)

Linking of atmosphere and ocean via transfer of heat and momentum and gas exchange, i.e.

- Waves and currents in the ocean caused by wind
- Dissolution of greenhouse gases like carbon dioxide into the ocean
- Heat absorption (due to radiation) and emission by the ocean

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How are atmosphere and ocean models online coupled?

Atmosphere

Ocean

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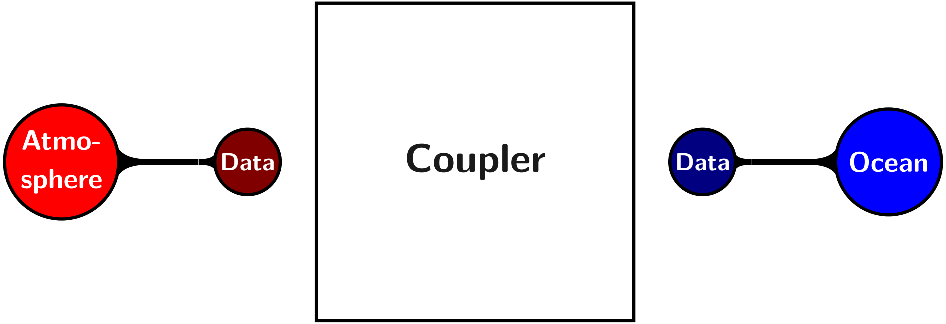
How are atmosphere and ocean models online coupled?



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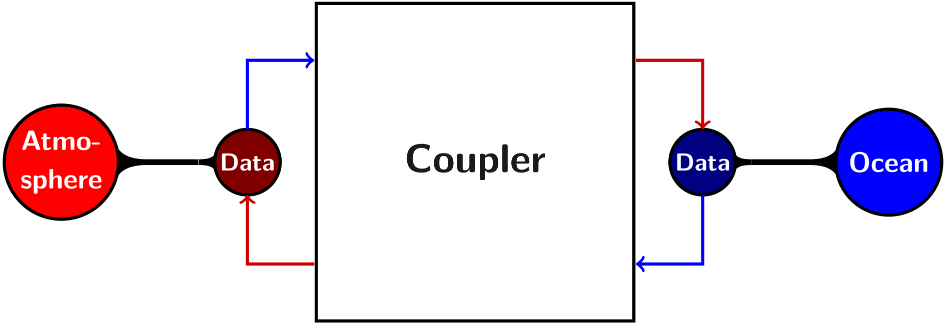

- Which variables will be exchanged?
- Which time intervals will be suitable for a data exchange?
- Which interpolation method will best fit for a data exchange?

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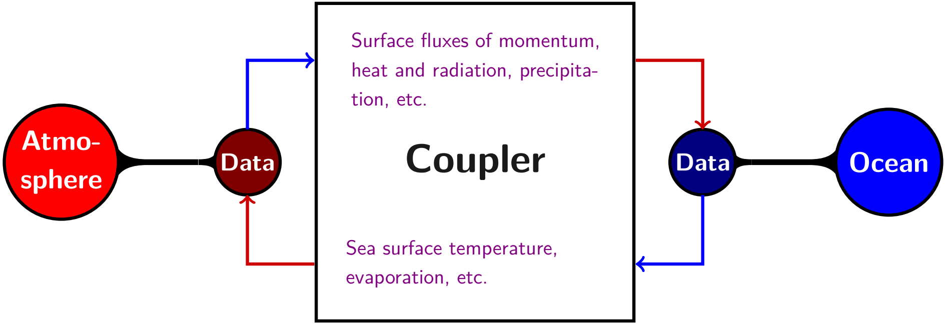
How are atmosphere and ocean models online coupled?



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Coupling scheme for ICON and GETM

ICON

ESMF

GETM

Coupling scheme for ICON and GETM

ICON

- Local mass conservation by flux-form for continuity equation Zängl et al., 2015
- Compressible non-hydrostatic set of equations on global domains

ESMF

GETM

Coupling scheme for ICON and GETM

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ESMF

GETM

- Drying and flooding processes for coastal and estuarine domains
- Hydrostatic set of equations with Boussinesq approximation and eddy viscosity assumption Burchard et al., 2004

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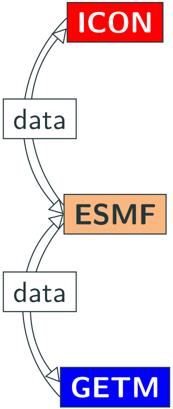
Coupling scheme for ICON and GETM


ICON
data
ESMF
data
GETM

- Local mass conservation by flux-form for continuity equation Zängl et al., 2015
- Compressible non-hydrostatic set of equations on global domains

- Data exchange: momentum and surface heat flux, evaporation, etc.
- Horizontal interpolation of data at air-sea interface

- Drying and flooding processes for coastal and estuarine domains
- Hydrostatic set of equations with Boussinesq approximation and eddy viscosity assumption Burchard et al., 2004

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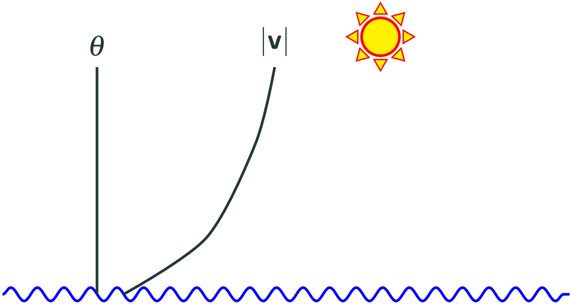
Air-sea interactions: ICON & GETM – uncoupled



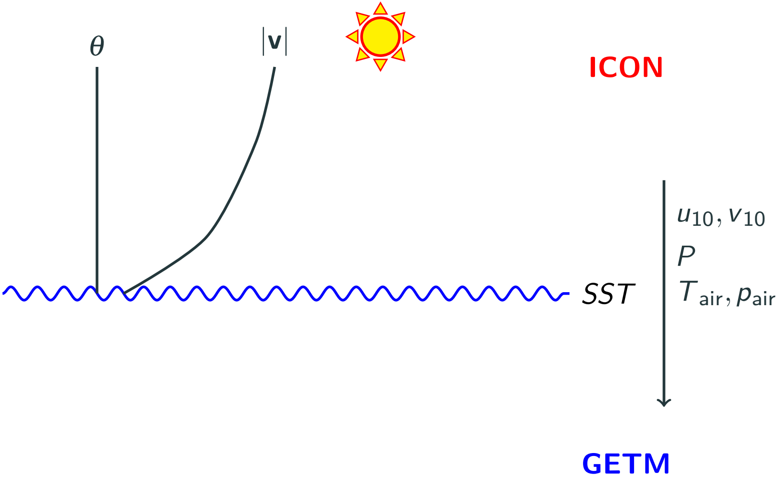
ICON

GETM

θ potential temperature

$|\mathbf{v}|$: wind

Air-sea interactions: ICON & GETM – uncoupled



P:	precipitation
T_{air} :	air temperature
SST :	sea surface temperature
θ	potential temperature
u_{10}/v_{10} :	u/v-wind at 10 m
$\|\mathbf{v}\|$:	wind
p_{air} :	air pressure

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Realisation of air-sea interactions in ICON & GETM

ICON:

Momentum:

$$\begin{aligned}\tau_s^x &= -\rho \cdot C_m^d \cdot |\mathbf{v}| \cdot u \\ \tau_s^y &= -\rho \cdot C_m^d \cdot |\mathbf{v}| \cdot v\end{aligned}$$

Heat:

$$Q = Q_s + Q_l + Q_b + Q_{SW}$$

GETM:

Momentum:

$$\begin{aligned}\tau_s^x &= \rho \cdot C_m^d \cdot |\mathbf{v}| \cdot u \\ \tau_s^y &= \rho \cdot C_m^d \cdot |\mathbf{v}| \cdot v\end{aligned}$$

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Realisation of air-sea interactions in ICON & GETM

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Heat:

$$Q = Q_s + Q_l + Q_b + Q_{SW}$$

No mass exchange with ocean via precipitation and evaporation due to exact local mass conservation.

GETM:

Momentum:

$$\begin{aligned}\tau_s^x &= \rho \cdot C_m^d \cdot |\mathbf{v}| \cdot u \\ \tau_s^y &= \rho \cdot C_m^d \cdot |\mathbf{v}| \cdot v\end{aligned}$$

Heat:

$$Q = Q_s + Q_l + Q_b$$

Considering of precipitation and evaporation for salinity flux.

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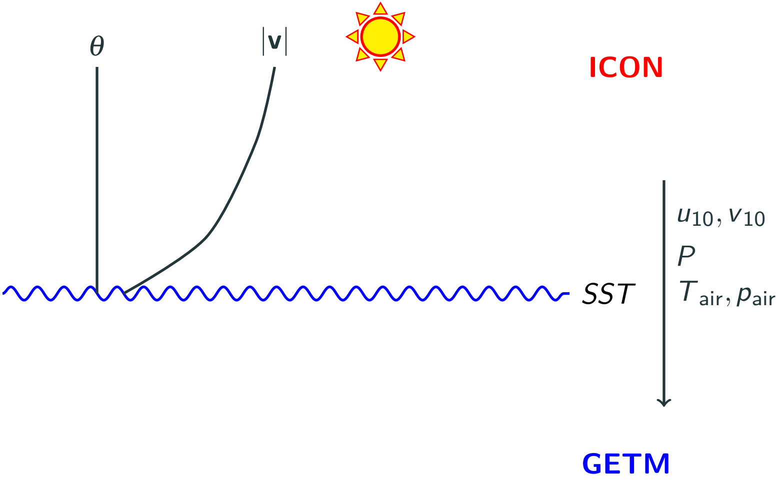
Air-sea interactions: ICON & GETM – uncoupled



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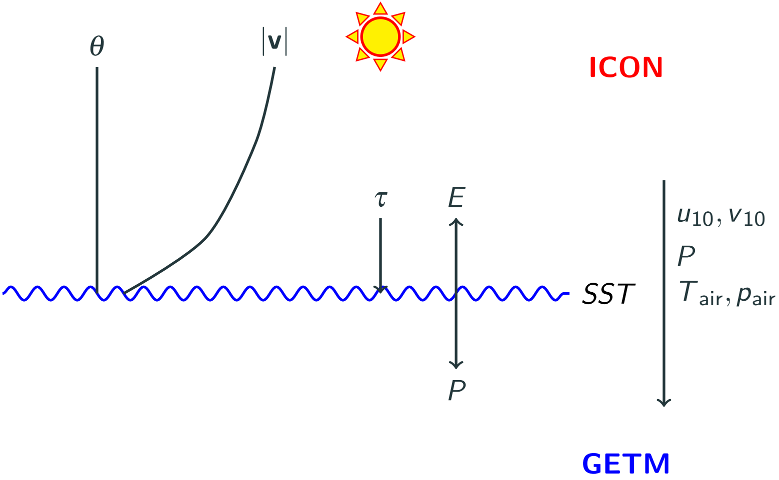
Air-sea interactions: ICON & GETM – coupled



τ:	shear stress
E:	evaporation
P:	precipitation
T_{air} :	air temperature
SST :	sea surface temperature
θ	potential temperature
u_{10}/v_{10} :	u/v-wind at 10 m
$\lvert\mathbf{v}\rvert$:	wind
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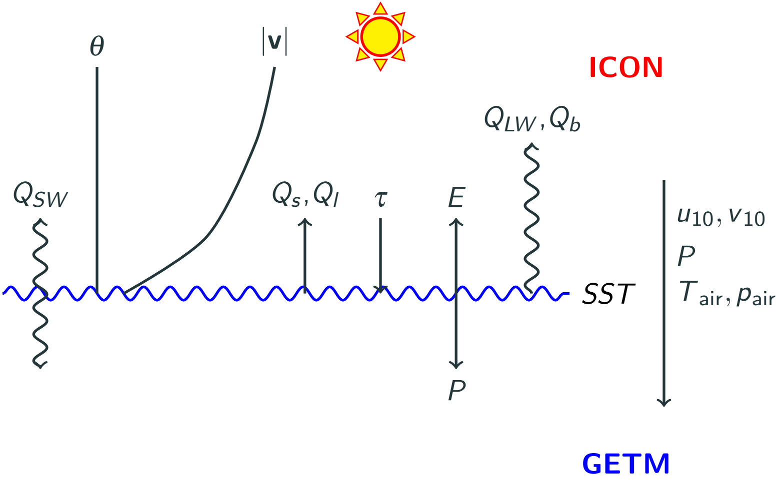
Air-sea interactions: ICON & GETM – coupled



Q_s, Q_l:	sensible/latent heat flux
Q_{SW}:	solar short wave radiative flux
Q_{LW}:	terrestrial long wave radiative flux
Q_b:	long wave net radiative flux
τ:	shear stress
E:	evaporation
P:	precipitation
T_{air} :	air temperature
SST :	sea surface temperature
θ	potential temperature
u_{10}/v_{10} :	u/v-wind at 10 m
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Idealised atmosphere-ocean model: objectives

- Development of idealised model for

  1D: Studying mass, momentum and energy coupling between atmosphere and ocean with a water/air column model system

  2D: Constructing an idealised coupled model system with straight coast and upwelling favourable winds

  3D: Fully coupled idealised atmosphere-ocean experiment (Baltic Sea)

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Idealised atmosphere-ocean model: objectives

- Development of idealised model for
  - 1D: Studying mass, momentum and energy coupling between atmosphere and ocean with a water/air column model system
  - 2D: Constructing an idealised coupled model system with straight coast and upwelling favourable winds
  - 3D: Fully coupled idealised atmosphere-ocean experiment (Baltic Sea)
- Utilising different coupling strategies
  - a) Online coupling with coupler (e.g. ESMF)
  - b) Derivation and application of numerical methods with multirate approaches for atmosphere-ocean models

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Idealised atmosphere-ocean model: properties

- Mass and momentum conservation and energy consistency
- Unified parameterisation of air-sea interactions
- Applying parameterisation for radiative energy intake in ocean
- Utilising turbulence closure scheme for atmosphere and ocean
- Possible different discretisation for atmosphere and ocean, i.e. horizontal interpolation at air-sea interface as part of discretisation

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Idealised atmosphere-ocean model: continuity equation

❶ Atmosphere components: dry air (d), water vapour (v), liquid water (l), ice (i), rain drops (r) and snow (sn)

Wacker et al., 2006, Bott, 2008

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Idealised atmosphere-ocean model: continuity equation

1. Atmosphere components: dry air (d), water vapour (v), liquid water (l), ice (i), rain drops (r) and snow (sn) Wacker et al., 2006, Bott, 2008
2. Ocean components: fresh water (f) and salinity (sa) Burchard et al., 2004

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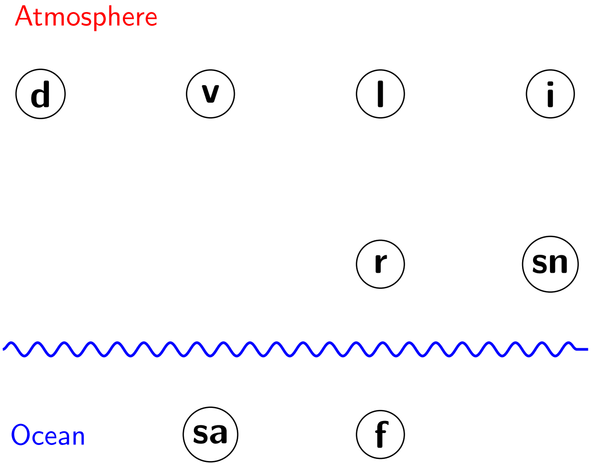
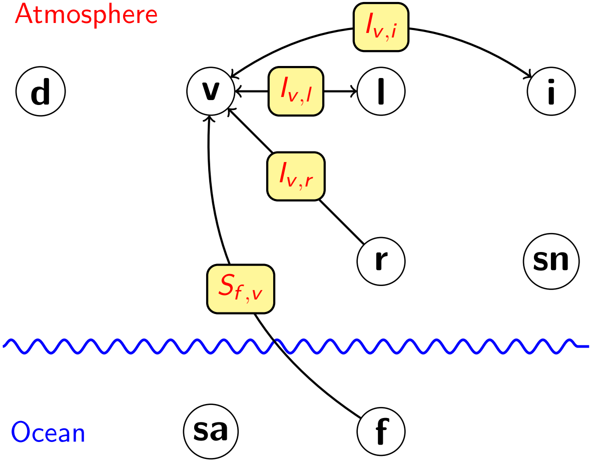
Idealised atmosphere-ocean model: source and sink connections



Idealised atmosphere-ocean model: source and sink connections



Water vapour (v):

$$I_v = -I_{v,l} - I_{v,i} - I_{v,r}$$
$$S_v = S_{f,v}$$

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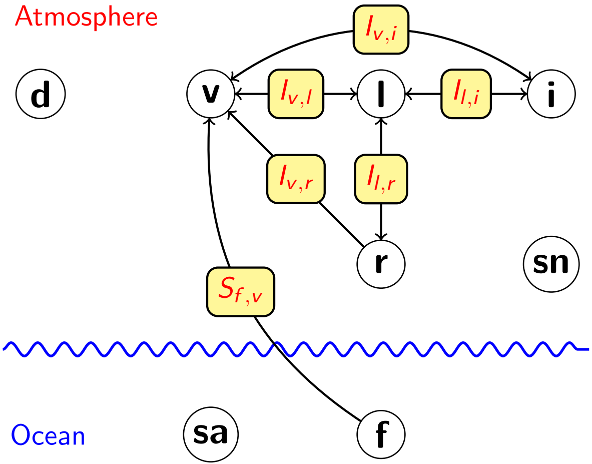
Idealised atmosphere-ocean model: source and sink connections



Water vapour (v):
$$I_v = -I_{v,l} - I_{v,i} - I_{v,r}$$
$$S_v = S_{f,v}$$

Liquid water (l):
$$I_l = I_{v,l} - I_{l,i} - I_{l,r}$$

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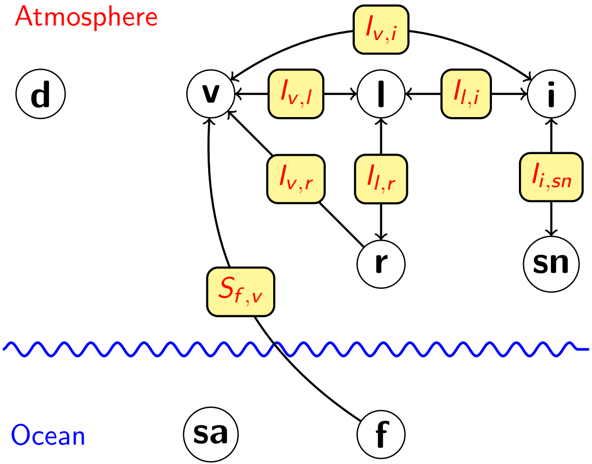
Idealised atmosphere-ocean model: source and sink connections



Water vapour (v):
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Liquid water (l):
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Ice (i):
$$I_i = I_{v,i} + I_{l,i} - I_{i,sn}$$

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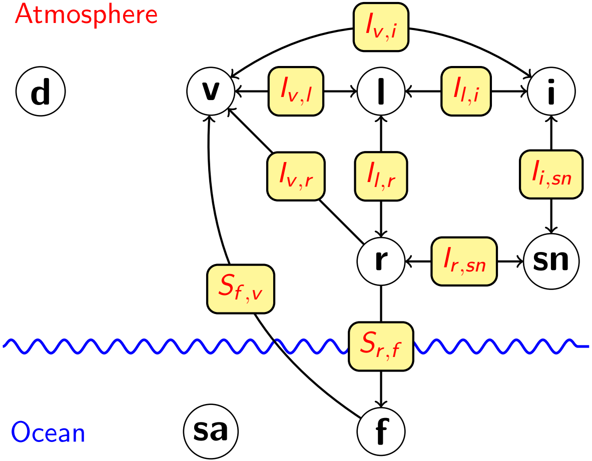
Idealised atmosphere-ocean model: source and sink connections



Water vapour (v):
$$I_v = -I_{v,l} - I_{v,i} - I_{v,r}$$
$$S_v = S_{f,v}$$

Liquid water (l):
$$I_l = I_{v,l} - I_{l,i} - I_{l,r}$$

Ice (i):
$$I_i = I_{v,i} + I_{l,i} - I_{i,sn}$$

Rain drops (r):
$$I_r = I_{v,r} + I_{l,r} - I_{r,sn}$$
$$S_r = -S_{r,f}$$

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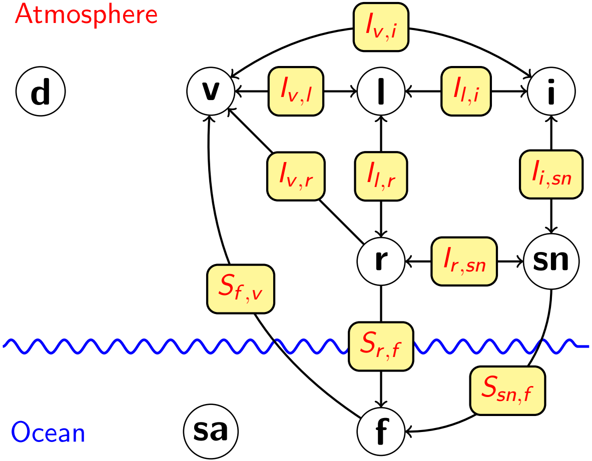
Idealised atmosphere-ocean model: source and sink connections



Water vapour (v): $I_v = -I_{v,l} - I_{v,i} - I_{v,r}$

$S_v = S_{f,v}$

Liquid water (l): $I_l = I_{v,l} - I_{l,i} - I_{l,r}$

Ice (i): $I_i = I_{v,i} + I_{l,i} - I_{i,sn}$

Rain drops (r): $I_r = I_{v,r} + I_{l,r} - I_{r,sn}$

$S_r = -S_{r,f}$

Snow (sn): $I_{sn} = I_{r,sn} + I_{i,sn}$

$S_{sn} = -S_{sn,f}$

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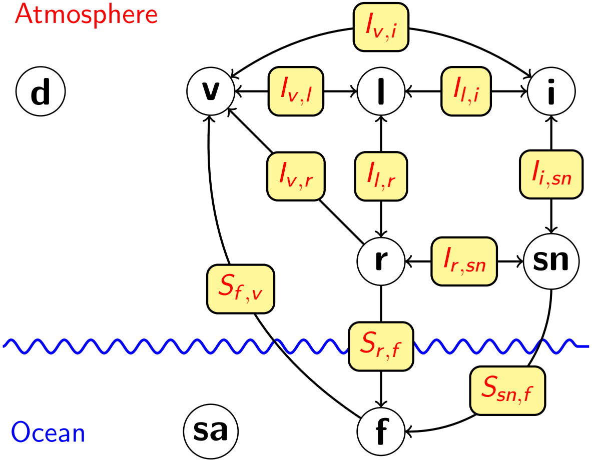

Water vapour (v): $I_v = -I_{v,l} - I_{v,i} - I_{v,r}$

$S_v = S_{f,v}$

Liquid water (l): $I_l = I_{v,l} - I_{l,i} - I_{l,r}$

Ice (i): $I_i = I_{v,i} + I_{l,i} - I_{i,sn}$

Rain drops (r): $I_r = I_{v,r} + I_{l,r} - I_{r,sn}$

$S_r = -S_{r,f}$

Snow (sn): $I_{sn} = I_{r,sn} + I_{i,sn}$

$S_{sn} = -S_{sn,f}$

Fresh water (f): $S_f = S_{r,f} + S_{sn,f} - S_{f,v}$

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Idealised atmosphere-ocean model: continuity equation

1. Atmosphere components: dry air (d), water vapour (v), liquid water (l), ice (i), rain drops (r) and snow (sn) Wacker et al., 2006, Bott, 2008
2. Ocean components: fresh water (f) and salinity (sa) Burchard et al., 2004

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3. No internal and external source and sink terms for dry air and salinity

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4. No internal source and sink term for fresh water

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3. No internal and external source and sink terms for dry air and salinity
4. No internal source and sink term for fresh water

Mass conservation of atmosphere-ocean system:

$\Rightarrow$ exchange of mass at air-sea interface

$\Rightarrow$ atmosphere and ocean, each on its own not mass conserving

$\Rightarrow$ compressible and non-hydrostatic set of equation

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Idealised atmosphere-ocean model: continuity equation

Atmosphere:

- Dry air (d):
  $\frac{\partial \rho_d}{\partial t} + \nabla \bullet (\rho_d \cdot \mathbf{v}_d) = 0$
- All other components:
  $\frac{\partial \rho_k}{\partial t} + \nabla \bullet (\rho_k \cdot \mathbf{v}_k) = I_k + S_k$

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Idealised atmosphere-ocean model: continuity equation

Atmosphere:

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- All other components:
  $$\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \cdot \mathbf{v}_k) = I_k + S_k$$

$$\boxed{\frac{\partial \rho^A}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A) = \sum [I_k + S_k] = S}$$

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Idealised atmosphere-ocean model: continuity equation

Atmosphere:

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- All other components:
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$$\boxed{\frac{\partial \rho^A}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A) = \sum [I_k + S_k] = S}$$

Ocean:

- Fresh water (f):
  $\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \cdot \mathbf{v}_f) = S_f$
- Salinity (sa):
  $\frac{\partial \rho_{sa}}{\partial t} + \nabla \cdot (\rho_{sa} \cdot \mathbf{v}_{sa}) = 0$

Idealised atmosphere-ocean model: continuity equation

Atmosphere:

- Dry air (d):
  $\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \cdot \mathbf{v}_d) = 0$
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$$\boxed{\frac{\partial \rho^A}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A) = \sum [I_k + S_k] = S}$$

Ocean:

- Fresh water (f):
  $\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \cdot \mathbf{v}_f) = S_f$
- Salinity (sa):
  $\frac{\partial \rho_{sa}}{\partial t} + \nabla \cdot (\rho_{sa} \cdot \mathbf{v}_{sa}) = 0$

$$\boxed{\frac{\partial \rho^O}{\partial t} + \nabla \cdot (\rho^O \cdot \mathbf{v}^O) = S_f}$$

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Idealised atmosphere-ocean model: continuity equation

Atmosphere:

- Dry air (d):
  $$\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \cdot \mathbf{v}_d) = 0$$
- All other components:
  $$\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \cdot \mathbf{v}_k) = I_k + S_k$$

$$\boxed{\frac{\partial \rho^A}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A) = \sum [I_k + S_k] = S}$$

Ocean:

- Fresh water (f):
  $$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \cdot \mathbf{v}_f) = S_f$$
- Salinity (sa):
  $$\frac{\partial \rho_{sa}}{\partial t} + \nabla \cdot (\rho_{sa} \cdot \mathbf{v}_{sa}) = 0$$

$$\boxed{\frac{\partial \rho^O}{\partial t} + \nabla \cdot (\rho^O \cdot \mathbf{v}^O) = S_f}$$

Mass conserving: $\frac{\partial (\rho^A + \rho^O)}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A + \rho^O \cdot \mathbf{v}^O) = S + S_f = 0$

$$\Rightarrow \boxed{S = -S_f}$$

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Idealised atmosphere-ocean model: further assumptions

Atmosphere:

- Treatment as ideal gas
- No pressure forces on hydrometers, i.e. only on dry air and water vapour
- Equation of state: $p = \rho^A \cdot R \cdot T = \rho^A \cdot R_d \cdot T_v$

Ocean:

- Handling of salinity as tracer
- Linearised equation of state: $\rho^O = \rho_0^O \cdot (1 + \alpha \cdot (\theta - \theta_l) + \beta \cdot (sa - sa_l))$

Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

$$\boxed{\begin{aligned}\frac{\partial\left(\rho^A\mathbf{v}^A\right)}{\partial t}+\nabla\bullet\left(\rho^A\mathbf{v}^A\cdot\mathbf{v}^{A^T}\right)=&-\nabla p^A-\rho^A\cdot\nabla\phi-2\cdot\Omega\times\rho^A\mathbf{v}^A+\nabla\bullet\tau^A+\mathbf{v}^A\cdot S\\&+\sum\left[\left(\mathbf{v}_k-\mathbf{v}^A\right)\cdot\left(I_k+S_k\right)\right]-\sum\left[\nabla\bullet\left(\rho_k\left(\mathbf{v}_k-\mathbf{v}^A\right)\cdot\left(\mathbf{v}_k-\mathbf{v}^A\right)^T\right)\right]\end{aligned}}$$

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Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

$$\boxed{\begin{aligned}\frac{\partial(\rho^A \mathbf{v}^A)}{\partial t} + \nabla \bullet \left(\rho^A \mathbf{v}^A \cdot {\mathbf{v}^A}^T\right) &= -\nabla p^A - \rho^A \cdot \nabla\phi - 2\cdot\Omega\times\rho^A\mathbf{v}^A + \nabla\bullet\tau^A + \mathbf{v}^A\cdot S \\ &+ \sum\left[\left(\mathbf{v}_k - \mathbf{v}^A\right)\cdot\left(I_k + S_k\right)\right] - \sum\left[\nabla\bullet\left(\rho_k\left(\mathbf{v}_k-\mathbf{v}^A\right)\cdot\left(\mathbf{v}_k-\mathbf{v}^A\right)^T\right)\right]\end{aligned}}$$

Differences to ICON:

Lange, 2002, Gassmann et al., 2008

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Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

$$\boxed{\begin{aligned}\frac{\partial(\rho^A \mathbf{v}^A)}{\partial t} + \nabla\bullet\left(\rho^A\mathbf{v}^A\cdot{\mathbf{v}^A}^T\right) = &-\nabla p^A - \rho^A\cdot\nabla\phi - 2\cdot\Omega\times\rho^A\mathbf{v}^A + \nabla\bullet\tau^A + \mathbf{v}^A\cdot S\\ &+\sum\left[\left(\mathbf{v}_k-\mathbf{v}^A\right)\cdot(I_k+S_k)\right] - \sum\left[\nabla\bullet\left(\rho_k\left(\mathbf{v}_k-\mathbf{v}^A\right)\cdot\left(\mathbf{v}_k-\mathbf{v}^A\right)^T\right)\right]\end{aligned}}$$

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Idealised atmosphere-ocean model: air-sea interactions

- Mass and momentum conservation and energy consistency
- Unified parameterisation of air-sea interactions
- Applying parameterisation for radiative energy intake in ocean
- Utilising turbulence closure scheme for atmosphere and ocean
- Possible different discretisation for atmosphere and ocean, i.e. horizontal interpolation at air-sea interface as part of discretisation

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Idealised atmosphere-ocean model: air-sea interactions

- Mass exchange due to
  a) Precipitation: $S_{r,f} + S_{sn,f}$
  b) Evaporation: $S_{f,v}$

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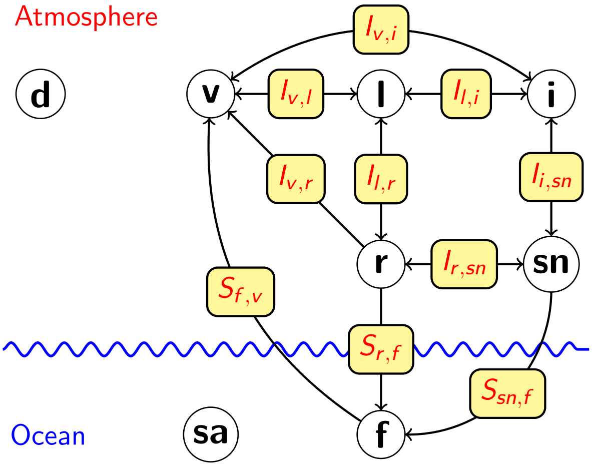
Idealised atmosphere-ocean model: source and sink connections



Water vapour (v):
$$\begin{aligned} I_v &= -I_{v,l} - I_{v,i} - I_{v,r} \\ S_v &= S_{f,v} \end{aligned}$$

Liquid water (l):
$$I_l = I_{v,l} - I_{l,i} - I_{l,r}$$

Ice (i):
$$I_i = I_{v,i} + I_{l,i} - I_{i,sn}$$

Rain drops (r):
$$\begin{aligned} I_r &= I_{v,r} + I_{l,r} - I_{r,sn} \\ S_r &= -S_{r,f} \end{aligned}$$

Snow (sn):
$$\begin{aligned} I_{sn} &= I_{r,sn} + I_{i,sn} \\ S_{sn} &= -S_{sn,f} \end{aligned}$$

Fresh water (f):
$$S_f = S_{r,f} + S_{sn,f} - S_{f,v}$$

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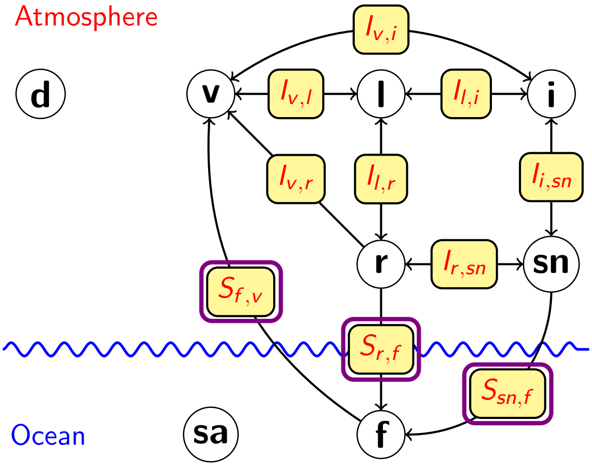

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Rain drops (r): $I_r = I_{v,r} + I_{l,r} - I_{r,sn}$

$S_r = -S_{r,f}$

Snow (sn): $I_{sn} = I_{r,sn} + I_{i,sn}$

$S_{sn} = -S_{sn,f}$

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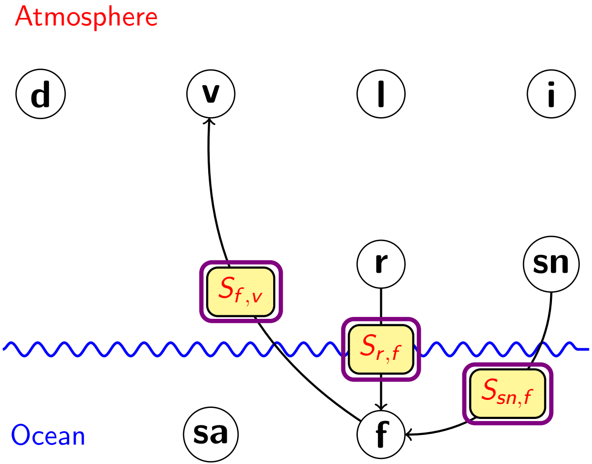

Water vapour (v):

$$S_v = S_{f,v}$$

Liquid water (l):

Ice (i):

Rain drops (r):

$$S_r = -S_{r,f}$$

Snow (sn):

$$S_{sn} = -S_{sn,f}$$

Fresh water (f): $S_f = S_{r,f} + S_{sn,f} - S_{f,v}$

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Idealised atmosphere-ocean model: air-sea interactions

- Mass exchange due to
  a) Precipitation: $S_{r,f} + S_{sn,f}$
  b) Evaporation: $S_{f,v}$

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  ❶ Treatment as external forcing of internal energy for individual atmosphere and ocean models:
  $Q^A = Q_s + Q_l + {Q_b}^A + {Q_{LW}}^A + {Q_{SW}}^A$ and $Q^O = -Q_s - Q_l + {Q_b}^O + {Q_{LW}}^O + {Q_{SW}}^O$

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  ❷ Atmosphere-ocean model: *radiative energy intake as external forcing of internal energy*:
  $Q = {Q_b}^A + {Q_b}^O + {Q_{LW}}^A + {Q_{LW}}^O + {Q_{SW}}^O + {Q_{SW}}^O$

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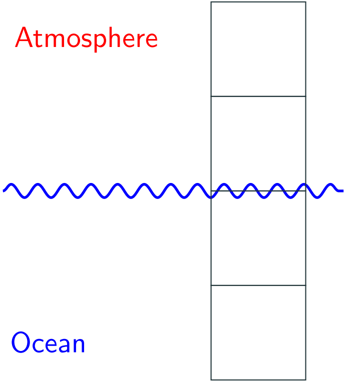
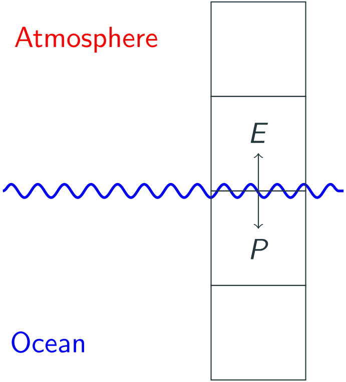
Idealised atmosphere-ocean model: vertical discretisation

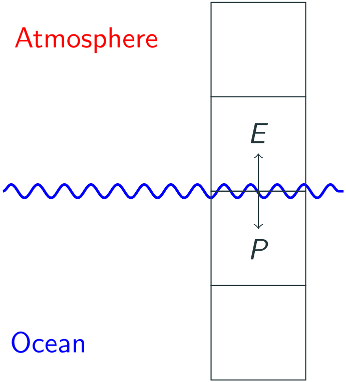


Idealised atmosphere-ocean model: vertical discretisation



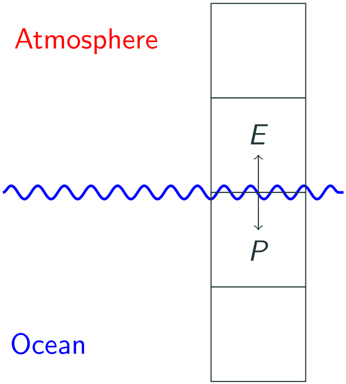
- Rise and sink of sea level with precipitation (P) and evaporation (E)

Idealised atmosphere-ocean model: vertical discretisation



- Rise and sink of sea level with precipitation (P) and evaporation (E)
- Fixed vertical layer at $z = 0$ either in atmosphere or ocean

Idealised atmosphere-ocean model: vertical discretisation



- Rise and sink of sea level with precipitation (P) and evaporation (E)
- Fixed vertical layer at $z = 0$ either in atmosphere or ocean
- Adaptive vertical discretisation necessary

Conclusions

- Coupling of atmosphere-ocean systems only recommended with unified parameterisation of air-sea interactions
- Mass conservation only for atmosphere-ocean systems and **not** for individual subsystems
- Idealised atmosphere-ocean model with further assumptions reformable to coupled ICON-GETM model
- Heat fluxes as external source for internal energy in atmosphere and ocean models, but not for whole atmosphere-ocean models
- Radiative energy intake always as external source for internal energy

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Outlook

- Applying turbulence closure scheme for idealised model
- Formulation of heat fluxes for idealised model with use of a coupler
- Investigation of different discretisation approaches for needs of idealised model
- Validation of idealised model against benchmark tests for atmosphere and ocean parts

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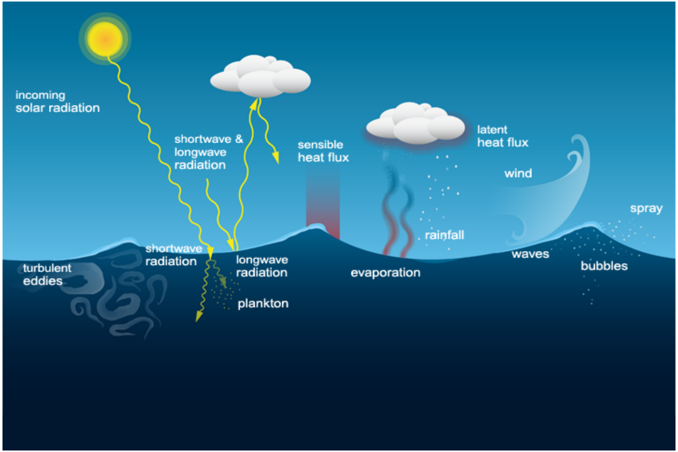
Air-sea interactions



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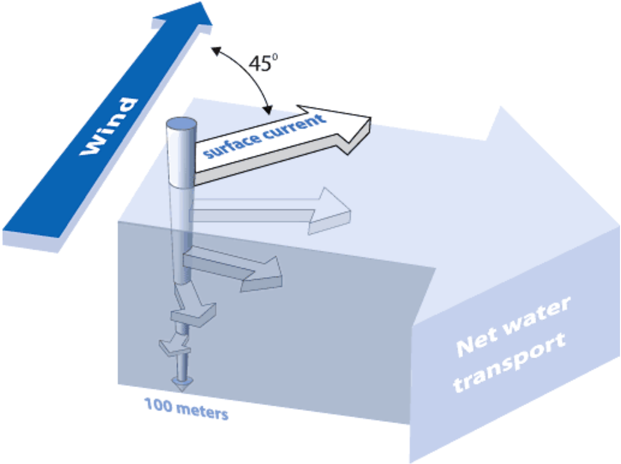
Ekman transport in water



- Rotation of 45° of surface current due to Coriolis force (Coriolis effect)
- Continuing of rotation into ocean till wind looses influence (Ekman spiral)
- Transporting of water in 90° angle of the wind (Ekman transport)
- Northern/southern hemisphere in right/left direction

www.oceanservice.noaa.gov (21.09.2016)

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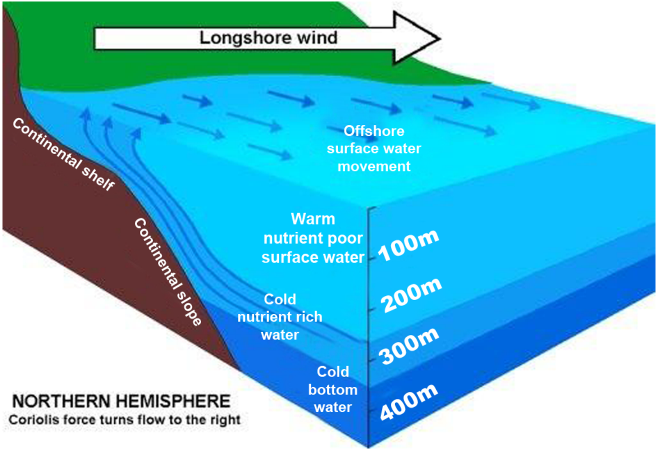
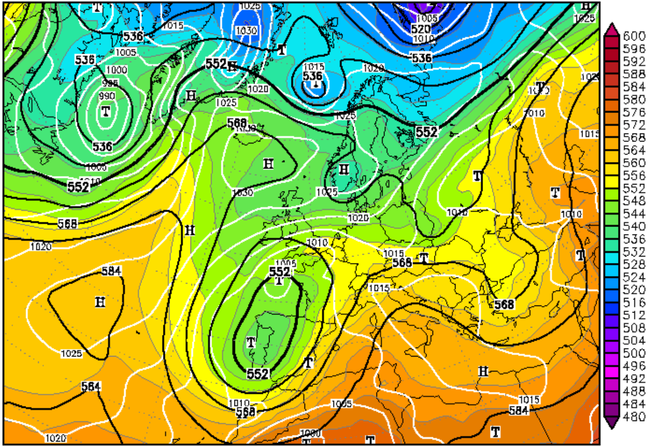
What is coastal upwelling?



- Oceanographic phenomenon
- Main drivers: wind, Coriolis effect and Ekman transport
- Brings dense, cooler and usually nutrient-rich water towards the ocean surface
- Higher marine productivity due to an increase in plankton
- Cooling of lower atmosphere

www.seos-project.eu (15.07.2016)

Coastal upwelling – coast of Poland: May 25 – Jun 08, 2008



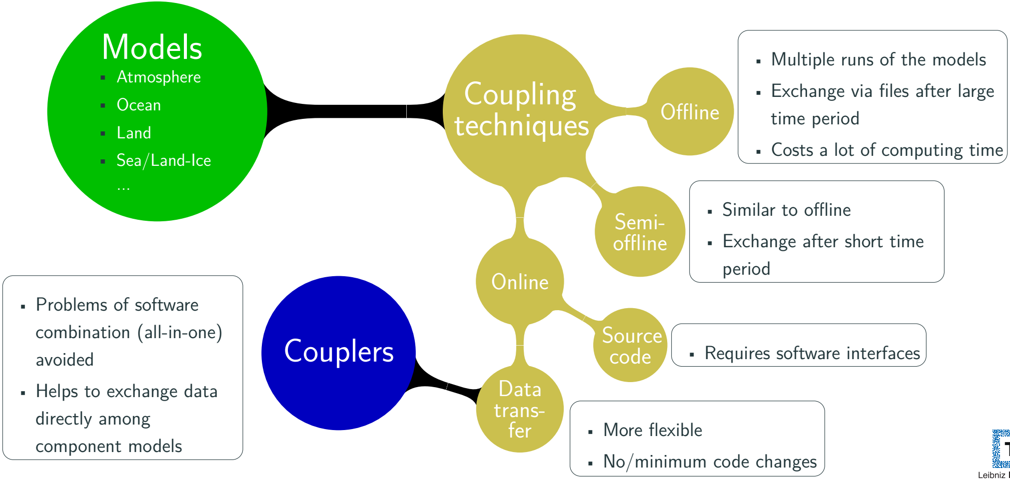
(geopotential, relative topography and surface pressure)

Weather map of Europe on 25th of May 2008 at 6am UTC

- Occasionally weather situation
- High pressure system over southern Scandinavia
- Wind direction mainly northeast

www.wetter3.de (21.09.2016)

Coupling techniques



Models

- Atmosphere
- Ocean
- Land
- Sea/Land-Ice

…

Coupling techniques

Offline

- Multiple runs of the models
- Exchange via files after large time period
- Costs a lot of computing time

Semi-offline

- Similar to offline
- Exchange after short time period

Online

Source code

- Requires software interfaces

Data transfer

- More flexible
- No/minimum code changes

Couplers

- Problems of software combination (all-in-one) avoided
- Helps to exchange data directly among component models

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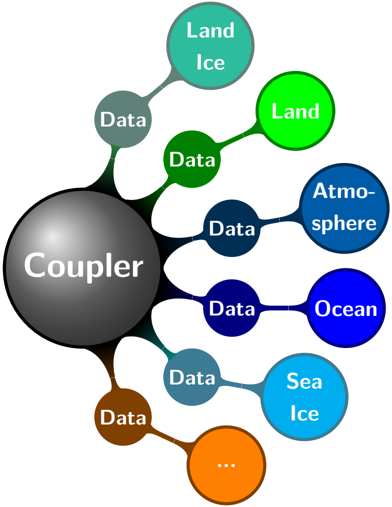
Online coupling – What are the benefits of a coupler?



- Coupling of additional components to existent models, e.g. atmospheric chemistry, marine biology, carbon cycle etc.
- Developing of components independently from models
- Changing of existing code in the components minimized
- Performing of necessary interpolations
- Supporting of multiple core applications

Couplers: ESMF, MCT, OASIS, YAC

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Coupled models for the Baltic Sea or coastal upwelling

Model	Atmosphere	Ocean	Reference
HIRLAM/BOBA-PROBE	HIRLAM	BOBA-PROBE	Gustafsson et al., 1998
REMO/BSMO	REMO	BSMO	Hagedorn et al., 2000
RCAO	RCA2	RCO	Döscher et al., 2002
BALTIMOS	REMO	BSIOM	Lehmann et al., 2004
COAMPS/ROMS	COAMPS	ROMS	Perlin et al., 2007
COSTRICE	COSMO-CLM	TRIMNP	Ho et al., 2012
COSMO-CLM/NEMO	COSMO-CLM	NEMO	Van Pham et al., 2014
RCA4_NEMO	RCA4	NEMO	Wang et al., 2015

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COAMPS/ROMS	COAMPS	ROMS	Perlin et al., 2007
COSTRICE	COSMO-CLM	TRIMNP	Ho et al., 2012
COSMO-CLM/NEMO	COSMO-CLM	NEMO	Van Pham et al., 2014
RCA4_NEMO	RCA4	NEMO	Wang et al., 2015

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COAMPS/ROMS vs. COSMO-CLM/NEMO

	COAMPS/ROMS (Perlin et al., 2007)		COSMO-CLM/NEMO (Van Pham et al., 2014)	
	COAMPS	ROMS	COSMO-CLM	NEMO
Coupler	MCT		OASIS3	
Equation	Non-hydrostatic, compressible	Hydrostatic, free-surface	Non-hydrostatic, compressible	Hydrostatic, free-surface
Horizontal resolution	50x20 1-km by 1-km grid boxes		50 km	3 km
Vertical layers	47	40	40	56
Main achievement	Modelling of wind-driven upwelling system along the coast of Oregon		Investigation of 2 m temperature biases between observed data and (un-)coupled results	

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Coupler: ESMF – Earth System Modeling Framework

- Suite of software tools for developing high-performance, multicomponent Earth science modeling applications
- Components: atmosphere, ocean, terrestrial or other physical domains and constituent processes (dynamical, chemical, biological etc.)
- Set of simple, consistent component interfaces – applicable even to couplers themselves
- Variety of data structures for transferring data between components, libraries for regridding/interpolation, time advancement and other common modeling functions

Hill et al., 2004

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