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)

Tobias Bauer (TROPOS), Olaf Hellmuth (TROPOS)
✉ tobias.bauer@tropos.de
July 11, 2018
Contents

1 Coastal upwelling in Western Baltic Sea

2 Air-sea interactions: ICON & GETM

3 Idealised atmosphere-ocean model

4 Conclusions & Outlook
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
Motivation: coastal upwelling
Air-sea interactions: ICON & GETM
Idealised model
Conclusions & Outlook

What happens at the water surface?

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
How are atmosphere and ocean models online coupled?

- Atmosphere
- Ocean

- Surface fluxes of momentum, heat and radiation, precipitation, etc.
- Sea surface temperature, evaporation, etc.

• 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?
How are atmosphere and ocean models online coupled?

- Atmosphere
- Ocean
- Coupler

- 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?
How are atmosphere and ocean models online coupled?

- 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?
How are atmosphere and ocean models online coupled?

- 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?
Motivation: coastal upwelling

Air-sea interactions: ICON & GETM

Idealised model

Conclusions & Outlook

Coupling scheme for ICON and GETM

- **ICON**
  - ESMF
  - 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
- **GETM**
  - Hydrostatic set of equations with Boussinesq approximation and eddy viscosity assumption (Burchard et al., 2004)
Coupling scheme for ICON and GETM

- Local mass conservation by flux-form for continuity equation
- Compressible non-hydrostatic set of equations on global domains

**ICON**

- Local mass conservation by flux-form for continuity equation

**ESMF**

**GETM**

- 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

Zängl et al., 2015
Burchard et al., 2004
Coupling scheme for ICON and GETM

- Local mass conservation by flux-form for continuity equation
  - Zängl et al., 2015
- Compressible non-hydrostatic set of equations on global domains
- Drying and flooding processes for coastal and estuarine domains
- Hydrostatic set of equations with Boussinesq approximation and eddy viscosity assumption
  - Burchard et al., 2004
Coupling scheme for ICON and 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]
Air-sea interactions: ICON & GETM – uncoupled

\[ \theta \]
\[ |v| \]

ICON

\[ \theta \] potential temperature

\[ |v| \] wind

GETM

\[ \theta \] potential temperature

\[ |v| \] wind

Tobias Bauer (tobias.bauer@tropos.de)
Air-sea interactions: ICON & GETM – uncoupled

\[ P: \text{precipitation} \]
\[ T_{\text{air}} : \text{air temperature} \]
\[ SST : \text{sea surface temperature} \]
\[ \theta : \text{potential temperature} \]
\[ u_{10}/v_{10} : \text{u/v-wind at 10 m} \]
\[ |v| : \text{wind} \]
\[ p_{\text{air}} : \text{air pressure} \]

\[ \theta \]
\[ v \]
\[ \text{ICON} \]
\[ u_{10}, v_{10} \]
\[ P \]
\[ T_{\text{air}}, p_{\text{air}} \]
\[ \text{SST} \]
\[ \text{GETM} \]

Tobias Bauer (tobias.bauer@tropos.de)
Realisation of air-sea interactions in ICON & GETM

ICON:

Momentum:
\[
\tau_s^x = -\rho \cdot C_m^d \cdot |v| \cdot u \\
\tau_s^y = -\rho \cdot C_m^d \cdot |v| \cdot v
\]

Heat:
\[
Q = Q_s + Q_l + Q_b + Q_{SW}
\]

GETM:

Momentum:
\[
\tau_s^x = \rho \cdot C_m^d \cdot |v| \cdot u \\
\tau_s^y = \rho \cdot C_m^d \cdot |v| \cdot v
\]

Heat:
\[
Q = Q_s + Q_l + Q_b
\]
Realisation of air-sea interactions in ICON & GETM

ICON:

Momentum: \( \tau^x_s = -\rho \cdot C_m^d \cdot |v| \cdot u \)
\( \tau^y_s = -\rho \cdot C_m^d \cdot |v| \cdot v \)

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: \( \tau^x_s = \rho \cdot C_m^d \cdot |v| \cdot u \)
\( \tau^y_s = \rho \cdot C_m^d \cdot |v| \cdot v \)

Heat: \( Q = Q_s + Q_l + Q_b \)

Considering of precipitation and evaporation for salinity flux.
Air-sea interactions: ICON & GETM – uncoupled

\[ \theta, \text{SST} \]

ICON

\[ u_{10}, v_{10}, P, T_{\text{air}}, p_{\text{air}} \]

GETM

- \( P \): precipitation
- \( T_{\text{air}} \): air temperature
- \( \text{SST} \): sea surface temperature
- \( \theta \): potential temperature
- \( u_{10}/v_{10} \): \( u/v \)-wind at 10 m
- \( |v| \): wind
- \( p_{\text{air}} \): air pressure
Air-sea interactions: ICON & GETM – coupled

\[ \begin{align*}
\theta & : \text{potential temperature} \\
|v| & : \text{wind} \\
u_{10}, v_{10} & : \text{u/v-wind at 10 m} \\
P & : \text{precipitation} \\
p_{\text{air}} & : \text{air pressure} \\
T_{\text{air}} & : \text{air temperature} \\
SST & : \text{sea surface temperature} \\
\tau & : \text{shear stress} \\
E & : \text{evaporation} \\
Q_{\text{SW}} & : \text{solar short wave radiative flux} \\
Q_{\text{LW}} & : \text{terrestrial long wave radiative flux} \\
Q_{b} & : \text{long wave net radiative flux} \\
\tau & : \text{shear stress} \\
E & : \text{evaporation} \\
P & : \text{precipitation} \\
T_{\text{air}} & : \text{air temperature} \\
SST & : \text{sea surface temperature} \\
\theta & : \text{potential temperature} \\
u_{10}, v_{10} & : \text{u/v-wind at 10 m} \\
|v| & : \text{wind} \\
p_{\text{air}} & : \text{air pressure}
\end{align*}\]
Air-sea interactions: ICON & GETM – coupled

Motivation: coastal upwelling

Air-sea interactions: ICON & GETM

Idealised model

Conclusions & Outlook

Air-sea interactions Western Baltic Sea

Tobias Bauer (tobias.bauer@tropos.de)
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)
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
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
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
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
**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
Idealised atmosphere-ocean model: source and sink connections

**Atmosphere**
- d
- v
- l
- i
- r
- sn

**Ocean**
- sa
- f
Motivation: coastal upwelling

Air-sea interactions: ICON & GETM

Idealised model

Conclusions & Outlook

Idealised atmosphere-ocean model: source and sink connections

Air-sea interactions Western Baltic Sea

July 11, 2018

13 / 27

Water vapour (v):

\[ l_v = -l_{v,l} - l_{v,i} - l_{v,r} \]

\[ S_v = S_{f,v} \]
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 ($l$):
\[ I_l = I_{v,l} - I_{l,i} - I_{l,r} \]
Motivation: coastal upwelling

Air-sea interactions: ICON & GETM

Idealised model

Conclusions & Outlook

Idealised atmosphere-ocean model: source and sink connections

**Atmosphere**

<table>
<thead>
<tr>
<th>Water vapour ($v$):</th>
<th>$I_v = -I_{v,l} - I_{v,i} - I_{v,r}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid water ($l$):</td>
<td>$I_l = I_{v,l} - I_{l,i} - I_{l,r}$</td>
</tr>
<tr>
<td>Ice ($i$):</td>
<td>$I_i = I_{v,i} + I_{l,i} - I_{i,sn}$</td>
</tr>
</tbody>
</table>

**Ocean**

<table>
<thead>
<tr>
<th>Water vapour ($v$):</th>
<th>$S_v = S_{f,v}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid water ($l$):</td>
<td>$S_l = S_{f,l}$</td>
</tr>
<tr>
<td>Ice ($i$):</td>
<td>$S_i = S_{f,i}$</td>
</tr>
</tbody>
</table>
Motivation: coastal upwelling

Air-sea interactions: ICON & GETM

Idealised model

Conclusions & Outlook

---

**Idealised atmosphere-ocean model: source and sink connections**

**Atmosphere**

- **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):**
  - \[ I_r = I_{v,r} + I_{l,r} - I_{r,sn} \]
  - \[ S_r = -S_{r,f} \]

**Ocean**

- **Fresh water (f):**
  - \[ S_f = S_{r,f} + S_{sn,f} - S_{f,v} \]
Motivation: coastal upwelling

Air-sea interactions: ICON & GETM

Idealised model

Conclusions & Outlook

Tobias Bauer (tobias.bauer@tropos.de)

Air-sea interactions Western Baltic Sea

July 11, 2018

13 / 27

Idealised atmosphere-ocean model: source and sink connections

Atmosphere

Ocean

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

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): \[ I_r = I_{v,r} + I_{l,r} - I_{r,sn} \]

Snow (sn): \[ I_{sn} = I_{r,sn} + I_{i,sn} \]

Fresh water (f): \[ S_f = S_{f,v} \]

Rain drops (sn): \[ S_{sn,f} = -S_{sn,f} \]
Idealised atmosphere-ocean model: source and sink connections

**Atmosphere**

- 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 ($f$):
  \[ S_f = S_{r,f} + S_{sn,f} - S_{f,v} \]

**Ocean**

Tobias Bauer (tobias.bauer@tropos.de)
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
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

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

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

4. No internal source and sink term for fresh water
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

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:

\[ \Rightarrow \text{exchange of mass at air-sea interface} \]

\[ \Rightarrow \text{atmosphere and ocean, each on its own not mass conserving} \]

\[ \Rightarrow \text{compressible and non-hydrostatic set of equation} \]
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**: 
  \[
  \frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \cdot \mathbf{v}_k) = I_k + S_k
  \]
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:
  \[
  \frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \cdot \mathbf{v}_k) = I_k + S_k
  \]

\[
\frac{\partial \rho^A}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A) = \sum [I_k + S_k] = S
\]
**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:**
  \[ \frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \cdot \mathbf{v}_k) = I_k + S_k \]

- **Mass conserving:**
  \[ \frac{\partial (\rho_A + \rho_O)}{\partial t} + \nabla \cdot (\rho_A \cdot \mathbf{v}_A + \rho_O \cdot \mathbf{v}_O) = S + S_f = 0 \]

  \[ \Rightarrow S = -S_f \]

**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 ($d$):
  \[
  \frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \mathbf{v}_d) = 0
  \]

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

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

Ocean:

- Fresh water ($f$):
  \[
  \frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \mathbf{v}_f) = S_f
  \]

- Salinity ($sa$):
  \[
  \frac{\partial \rho_{sa}}{\partial t} + \nabla \cdot (\rho_{sa} \mathbf{v}_{sa}) = 0
  \]

\[ \frac{\partial \rho^O}{\partial t} + \nabla \cdot (\rho^O \mathbf{v}^O) = S_f \]
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:**
  \[
  \frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \cdot \mathbf{v}_k) = I_k + S_k
  \]

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

**Ocean:**

- **Fresh water** ($f$):
  \[
  \frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \cdot \mathbf{v}_f) = S_f
  \]

- **Salinity** ($sa$):
  \[
  \frac{\partial \rho_{sa}}{\partial t} + \nabla \cdot (\rho_{sa} \cdot \mathbf{v}_{sa}) = 0
  \]

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

**Mass conserving:**

\[
\frac{\partial (\rho^A + \rho^O)}{\partial t} + \nabla \cdot (\rho^A \cdot \mathbf{v}^A + \rho^O \cdot \mathbf{v}^O) = S + S_f = 0
\]

\[
\Rightarrow S = -S_f
\]
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: $\rho^O = \rho_0^O \cdot (1 + \alpha \cdot (\theta - \theta_I) + \beta \cdot (sa - sa_I))$
Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

\[
\frac{\partial (\rho^A v^A)}{\partial t} + \nabla \cdot \left( \rho^A v^A \cdot v^{AT} \right) = -\nabla p^A - \rho^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho^A v^A + \nabla \cdot \tau^A + v^A \cdot S \\
+ \sum \left[ (v_k - v^A) \cdot (I_k + S_k) \right] - \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right]
\]
Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

\[
\frac{\partial (\rho^A v^A)}{\partial t} + \nabla \cdot \left( \rho^A v^A v^A_T \right) = -\nabla p^A - \rho^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho^A v^A + \nabla \cdot \tau^A + v^A \cdot S
\]

\[
+ \Sigma \left[ (v_k - v^A) \cdot (I_k + S_k) \right] - \Sigma \left[ \nabla \cdot \left( \rho_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right]
\]

Differences to ICON:

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

\[
\frac{\partial (\rho^A v^A)}{\partial t} + \nabla \cdot \left( \rho^A v^A v^A \right) = - \nabla p^A - \rho^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho^A v^A + \nabla \cdot \tau^A + v^A \cdot S \\
+ \sum \left[ (v_k - v^A) \cdot (I_k + S_k) \right] - \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right]
\]

Differences to ICON:
- Mass conservation: \( S = 0 \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

\[ \frac{\partial (\rho^A v^A)}{\partial t} + \nabla \cdot \left( \rho^A v^A \cdot v^{AT} \right) = - \nabla p^A - \rho^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho^A v^A + \nabla \cdot \tau^A \]

\[ + \sum \left[ (v_k - v^A) \cdot (I^k + S_k) \right] - \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right] \]

Differences to ICON:

- Mass conservation: \( S = 0 \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

\[
\begin{align*}
\frac{\partial (\rho^A v^A)}{\partial t} + \nabla \cdot \left( \rho^A v^A \cdot v^A T \right) &= - \nabla p^A - \rho^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho^A v^A + \nabla \cdot \tau^A \\
&\quad + \sum [ (v_k - v^A) \cdot (I_k + S_k)] - \sum [ \nabla \cdot (\rho_k (v_k - v^A) \cdot (v_k - v^A)^T) ]
\end{align*}
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)
- a) \( \sum [ (v_k - v^A) \cdot (I_k + S_k)] = 0 \) (conservation of momentum due to chemical reactions)

Lange, 2002, Gassmann et al., 2008
Motivation: coastal upwelling
Air-sea interactions: ICON & GETM
Idealised model
Conclusions & Outlook

**Idealised atmosphere-ocean model: momentum equation of atmosphere**

Momentum equation (atmosphere):

\[
\frac{\partial (\rho A v^A)}{\partial t} + \nabla \cdot (\rho A v^A \cdot v^A T) = - \nabla p^A - \rho A v^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho A v^A + \nabla \cdot \tau^A - \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right]
\]

Differences to ICON:

- **Mass conservation:** \( S = 0 \)
- a) \( \sum \left[ (v_k - v^A) \cdot (I_k + S_k) \right] = 0 \) (conservation of momentum due to chemical reactions)
- b) \( v_k \approx v^A \Rightarrow \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right] \ll \nabla \cdot \left( \rho A v^A \cdot v^A T \right) \Rightarrow \text{negligible} \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: momentum equation of atmosphere

Momentum equation (atmosphere):

\[
\frac{\partial (\rho^A v^A)}{\partial t} + \nabla \cdot \left( \rho^A v^A \cdot v^A_T \right) = -\nabla p^A - \rho^A \cdot \nabla \phi - 2 \cdot \Omega \times \rho^A v^A + \nabla \cdot \tau^A
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)
- a) \( \sum \left[ (v_k - v^A) \cdot (I_k + S_k) \right] = 0 \) (conservation of momentum due to chemical reactions)
- b) \( v_k \approx v^A \Rightarrow \sum \left[ \nabla \cdot \left( \rho^A_k (v_k - v^A) \cdot (v_k - v^A)^T \right) \right] \ll \nabla \cdot \left( \rho^A v^A \cdot v^A_T \right) \Rightarrow \text{negligible} \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: momentum equation of ocean

Momentum equation (ocean):

\[
\frac{\partial (\rho^O v^O)}{\partial t} + \nabla \cdot \left( \rho^O v^O \cdot v^O \right) = -\nabla p^O - \rho^O \cdot \nabla \phi - 2 \cdot \Omega \times \rho^O v^O + \nabla \cdot \tau^O + v_f \cdot S_f
- \sum \nabla \cdot \left( \rho_k (v_k - v^O) \cdot (v_k - v^O)^T \right)
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \(S_f = 0\)
- \(v_k = v^O\) ⇒ \(\sum \nabla \cdot \left( \rho_k (v_k - v^O) \cdot (v_k - v^O)^T \right) = 0\)
Idealised atmosphere-ocean model: momentum equation of ocean

Momentum equation (ocean):

\[
\frac{\partial (\rho^Ov^O)}{\partial t} + \nabla \cdot \left( \rho^Ov^O \cdot v^O_T \right) = -\nabla p^O - \rho^O \cdot \nabla \phi - 2 \cdot \Omega \times \rho^Ov^O + \nabla \cdot \tau^O + v_f \cdot S_f \\
- \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^O) \cdot (v_k - v^O)^T \right) \right]
\]

Differences to GETM:

Burchard et al., 2004
Idealised atmosphere-ocean model: momentum equation of ocean

Momentum equation (ocean):

\[
\frac{\partial (\rho^O v^O)}{\partial t} + \nabla \cdot \left( \rho^O v^O \cdot v^{OT} \right) = -\nabla p^O - \rho^O \cdot \nabla \phi - 2 \cdot \Omega \times \rho^O v^O + \nabla \cdot \tau^O + \mathbf{v}_f \cdot S_f \\
- \sum \left[ \nabla \cdot \left( \rho_k (v_k - v^O) \cdot (v_k - v^O)^T \right) \right]
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)

Burchard et al., 2004
Momentum equation (ocean):

\[
\frac{\partial (\rho^O v^O)}{\partial t} + \nabla \cdot \left( \rho^O v^O \cdot v^O \right) = -\nabla p^O - \rho^O \cdot \nabla \phi - 2 \Omega \times \rho^O v^O + \nabla \cdot \tau^O \\
- \Sigma \left[ \nabla \cdot \left( \rho_k (v_k - v^O) \cdot (v_k - v^O)^T \right) \right]
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)
- \( v_k = v^O \Rightarrow \Sigma \left[ \nabla \cdot \left( \rho_k (v_k - v) \cdot (v_k - v)^T \right) \right] = 0 \)
Momentum equation (ocean):

\[
\frac{\partial (\rho^O v^O)}{\partial t} + \nabla \cdot \left( \rho^O v^O \cdot v^O T \right) = -\nabla p^O - \rho^O \cdot \nabla \phi - 2 \cdot \Omega \times \rho^O v^O + \nabla \cdot \tau^O
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)
- \( v_k = v^O \Rightarrow \sum \left[ \nabla \cdot \left( \rho_k (v_k - v) \cdot (v_k - v)^T \right) \right] = 0 \)
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\sum \left[ \frac{\partial (\rho_{k} K_{k})}{\partial t} + \nabla \cdot (\rho_{k} K_{k} \cdot \mathbf{v}_{k}) \right] + \frac{\partial \rho A \phi}{\partial t} + \nabla \cdot (\rho A \phi \cdot \mathbf{v} A) + \frac{\partial \rho A e A}{\partial t} + \nabla \cdot (\rho A e A \cdot \mathbf{v} A) \\
= \sum \left[ - (\mathbf{v} - \mathbf{v} A) \cdot \nabla p + (\mathbf{v}_{k} - \mathbf{v} A) \cdot (\nabla \cdot \tau_{k}) + (K_{k} - K A) \cdot (l_{k} + S_{k}) \right] \\
- \nabla \cdot (\rho A \cdot \mathbf{v} A) + \nabla \cdot (\tau A \cdot \mathbf{v} A) - \nabla \cdot Q A + (K A + \phi + h A) \cdot S
\]
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\sum \left[ \frac{\partial (\rho K_k)}{\partial t} + \nabla \cdot (\rho_k K_k \cdot v_k) \right] + \frac{\partial (\rho A \phi)}{\partial t} + \nabla \cdot (\rho A \phi \cdot v^A) + \frac{\partial (\rho A e^A)}{\partial t} + \nabla \cdot (\rho A e^A \cdot v^A) = \sum \left[ -(v_k - v^A) \cdot \nabla p_k + (v_k - v^A) \cdot (\nabla \cdot \tau_k) + (K_k - K^A) \cdot (I_k + S_k) \right] - \nabla \cdot (\rho A \cdot v^A) + \nabla \cdot (\tau^A \cdot v^A) - \nabla \cdot Q^A + (K^A + \phi + h^A) \cdot S
\]

Differences to ICON:

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\sum \left[ \frac{\partial (\rho_k K_k)}{\partial t} + \nabla \cdot (\rho_k K_k \cdot v_k) \right] + \frac{\partial (\rho^A \phi)}{\partial t} + \nabla \cdot (\rho^A \phi \cdot v^A) + \frac{\partial (\rho^A e^A)}{\partial t} + \nabla \cdot (\rho^A e^A \cdot v^A) = \sum \left[ - (v_k - v^A) \cdot \nabla p_k + (v_k - v^A) \cdot (\nabla \cdot \tau_k) + (K_k - K^A) \cdot (I_k + S_k) \right] \\
- \nabla \cdot (\rho^A \cdot v^A) + \nabla \cdot (\tau^A \cdot v^A) - \nabla \cdot Q^A + (K^A + \phi + h^A) \cdot S
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\sum \left[ \frac{\partial (\rho K_k)}{\partial t} + \nabla \cdot (\rho K_k \cdot v_k) \right] + \frac{\partial (\rho A \phi)}{\partial t} + \nabla \cdot (\rho A \phi \cdot v^A) + \frac{\partial (\rho A e^A)}{\partial t} + \nabla \cdot (\rho A e^A \cdot v^A) \\
= \sum \left[ -(v_k - v^A) \cdot \nabla p_k + (v_k - v^A) \cdot (\nabla \cdot \tau_k) + (K_k - K^A) \cdot (l_k + S_k) \right] \\
- \nabla \cdot (\rho A \cdot v^A) + \nabla \cdot (\tau^A \cdot v^A) - \nabla \cdot Q^A
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)
- \( v_k \approx v^A \Rightarrow K_k \approx K^A \Rightarrow \text{negligible} \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\sum \left[ \frac{\partial (\rho_k K_k)}{\partial t} + \nabla \cdot (\rho_k K_k \cdot v_k) \right] + \frac{\partial (\rho^A \phi)}{\partial t} + \nabla \cdot (\rho^A \phi \cdot v^A) + \frac{\partial (\rho^A e^A)}{\partial t} + \nabla \cdot (\rho^A e^A \cdot v^A)
\]

\[
= \sum \left[ -(v_k - v^A) \cdot \nabla p_k + (v_k - v^A) \cdot (\nabla \cdot \tau_k) + (K_k - K^A) \cdot (I_k + S_k) \right]
- \nabla \cdot (\rho^A \cdot v^A) + \nabla \cdot (\tau^A \cdot v^A) - \nabla \cdot Q^A
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)
- \( v_k \approx v^A \Rightarrow K_k \approx K^A \Rightarrow \text{negligible} \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\sum \left[ \frac{\partial (\rho_k K^A)}{\partial t} + \nabla \cdot (\rho_k K^A \cdot \mathbf{v}_k) \right] + \frac{\partial (\rho^A \phi)}{\partial t} + \nabla \cdot (\rho^A \phi \cdot \mathbf{v}^A) + \frac{\partial (\rho^A e^A)}{\partial t} + \nabla \cdot (\rho^A e^A \cdot \mathbf{v}^A)
\]

\[
= - \nabla \cdot (p^A \cdot \mathbf{v}^A) + \nabla \cdot (\tau^A \cdot \mathbf{v}^A) - \nabla \cdot Q^A
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)
- \( \mathbf{v}_k \approx \mathbf{v}^A \Rightarrow K_k \approx K^A \Rightarrow \) negligible

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: energy equation of atmosphere

Energy equation (atmosphere):

\[
\frac{\partial}{\partial t} \left( \rho^A (K^A + \phi + e^A) \right) + \nabla \cdot \left( \rho^A (K^A + \phi + e^A) \cdot v^A \right) = - \nabla \cdot (p^A \cdot v^A) + \nabla \cdot (\tau^A \cdot v^A) - \nabla \cdot Q^A
\]

Differences to ICON:

- Mass conservation: \( S = 0 \)
- \( v_k \approx v^A \Rightarrow K_k \approx K^A \Rightarrow \text{negligible} \)

Lange, 2002, Gassmann et al., 2008
Idealised atmosphere-ocean model: energy equation of ocean

Energy equation (ocean):

\[
\sum \left[ \frac{\partial (\rho_k K_k)}{\partial t} + \nabla \cdot (\rho_k K_k \cdot \mathbf{v}_k) \right] + \frac{\partial (\rho^O \phi)}{\partial t} + \nabla \cdot (\rho^O \phi \cdot \mathbf{v}^O) + \frac{\partial (\rho^O e^O)}{\partial t} + \nabla \cdot (\rho^O e^O \cdot \mathbf{v}^O) \\
= \sum [- (\mathbf{v}_k - \mathbf{v}^O) \cdot \nabla p_k + (\mathbf{v}_k - \mathbf{v}^O) \cdot (\nabla \cdot \tau_k)] \\
- \nabla \cdot (\rho^O \cdot \mathbf{v}^O) + \nabla \cdot (\tau^O \cdot \mathbf{v}^O) - \nabla \cdot Q^O + (K_f + \phi + h^O) \cdot S_f
\]
Idealised atmosphere-ocean model: energy equation of ocean

Energy equation (ocean):

\[
\begin{align*}
\sum \left[ \frac{\partial (\rho_k K_k)}{\partial t} + \nabla \cdot (\rho_k K_k \cdot \mathbf{v}_k) \right] + \frac{\partial (\rho^O \phi)}{\partial t} + \nabla \cdot (\rho^O \phi \cdot \mathbf{v}^O) + \frac{\partial (\rho^O e^O)}{\partial t} + \nabla \cdot (\rho^O e^O \cdot \mathbf{v}^O) \\
= \sum \left[ - (\mathbf{v}_k - \mathbf{v}^O) \cdot \nabla p_k + (\mathbf{v}_k - \mathbf{v}^O) \cdot (\nabla \cdot \tau_k) \right] \\
- \nabla \cdot (p^O \cdot \mathbf{v}^O) + \nabla \cdot (\tau^O \cdot \mathbf{v}^O) - \nabla \cdot Q^O + (K_f + \phi + h^O) \cdot S_f
\end{align*}
\]

Differences to GETM:

Burchard et al., 2004
Idealised atmosphere-ocean model: energy equation of ocean

Energy equation (ocean):

\[
\begin{align*}
\sum \left[ \frac{\partial}{\partial t} \left( \rho_k K_k \right) + \nabla \cdot \left( \rho_k K_k \cdot v_k \right) \right] + \frac{\partial}{\partial t} \left( \rho^O \phi \right) + \nabla \cdot \left( \rho^O \phi \cdot v^O \right) + \frac{\partial}{\partial t} \left( \rho^O e^O \right) + \nabla \cdot \left( \rho^O e^O \cdot v^O \right) \\
= \sum \left[ - (v_k - v^O) \cdot \nabla p_k + (v_k - v^O) \cdot (\nabla \cdot \tau_k) \right] \\
- \nabla \cdot (p^O \cdot v^O) + \nabla \cdot (\tau^O \cdot v^O) - \nabla \cdot Q^O + (K_f + \phi + h^O) \cdot S_f
\end{align*}
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)
Idealised atmosphere-ocean model: energy equation of ocean

Energy equation (ocean):

\[
\begin{align*}
\sum \left[ \frac{\partial (\rho_k K_k)}{\partial t} + \nabla \cdot (\rho_k K_k \cdot \mathbf{v}_k) \right] + \frac{\partial (\rho^O \phi)}{\partial t} + \nabla \cdot (\rho^O \phi \cdot \mathbf{v}^O) + \frac{\partial (\rho^O e^O)}{\partial t} + \nabla \cdot (\rho^O e^O \cdot \mathbf{v}^O) \\
= \sum \left[ - (\mathbf{v}_k - \mathbf{v}^O) \cdot \nabla p_k + (\mathbf{v}_k - \mathbf{v}^O) \cdot (\nabla \cdot \tau_k) \right] \\
- \nabla \cdot (p^O \cdot \mathbf{v}^O) + \nabla \cdot (\tau^O \cdot \mathbf{v}^O) - \nabla \cdot Q^O
\end{align*}
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)
- \( \mathbf{v}_k = \mathbf{v}^O \Rightarrow K_k = K^O \)
Idealised atmosphere-ocean model: energy equation of ocean

Energy equation (ocean):

\[ \sum \left[ \frac{\partial (\rho_k K^O)}{\partial t} + \nabla \cdot (\rho_k K^O \cdot v_k) \right] + \frac{\partial (\rho^O \phi)}{\partial t} + \nabla \cdot (\rho^O \phi \cdot v^O) + \frac{\partial (\rho^O e^O)}{\partial t} + \nabla \cdot (\rho^O e^O \cdot v^O) \]

\[ = - \nabla \cdot (p^O \cdot v^O) + \nabla \cdot (\tau^O \cdot v^O) - \nabla \cdot Q^O \]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)
- \( v_k = v^O \Rightarrow K_k = K^O \)
**Idealised atmosphere-ocean model: energy equation of ocean**

Energy equation (ocean):

\[
\frac{\partial}{\partial t} \left( \rho^O (K^O + \phi + e^O) \right) + \nabla \cdot \left( \rho^O (K^O + \phi + e^O) \cdot \mathbf{v}^O \right) = - \nabla \cdot (p^O \cdot \mathbf{v}^O) + \nabla \cdot (\tau^O \cdot \mathbf{v}^O) - \nabla \cdot Q^O
\]

Differences to GETM:

- Boussinesq approximation leads to mass conservation, i.e. \( S_f = 0 \)
- \( v_k = v^O \Rightarrow K_k = K^O \)
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
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
Idealised atmosphere-ocean model: air-sea interactions

- Mass exchange due to
  a) Precipitation: $S_{r,f} + S_{sn,f}$
  b) Evaporation: $S_{r,v}$
Idealised atmosphere-ocean model: source and sink connections

Atmosphere

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): \[ S_f = S_{r,f} + S_{sn,f} - S_{f,v} \]

Ocean
Motivation: coastal upwelling
Air-sea interactions: ICON & GETM
Ideational model
Conclusions & Outlook

Tobias Bauer (tobias.bauer@tropos.de)  Air-sea interactions Western Baltic Sea  July 11, 2018  23 / 27
Idealised atmosphere-ocean model: source and sink connections

**Atmosphere**

- d (dust)
- v (water vapour)
- l (liquid water)
- i (ice)

**Ocean**

- sa (salinity)
- f (fresh water)
- sn (snow)

**Water vapour (v):**

\[ S_v = S_{f,v} \]

**Liquid water (l):**

\[ S_l = S_{l,i} \]

**Ice (i):**

\[ S_i = S_{i,r} \]

**Rain drops (r):**

\[ S_r = -S_{r,f} \]

**Snow (sn):**

\[ S_{sn} = -S_{sn,f} \]

**Fresh water (f):**

\[ S_f = S_{r,f} + S_{sn,f} - S_{f,v} \]
Idealised atmosphere-ocean model: air-sea interactions

- Mass exchange due to
  a) Precipitation: $S_{r,f} + S_{sn,f}$
  b) Evaporation: $S_{f,v}$
Idealised atmosphere-ocean model: air-sea interactions

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

**Note:** Mass conservation is assumed, i.e. precipitation leaves the atmosphere and enters the ocean, for evaporation vice versa.
Idealised atmosphere-ocean model: air-sea interactions

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

**Note:** Mass conservation is assumed, i.e. precipitation leaves the atmosphere and enters the ocean, for evaporation vice versa.

- Heat exchange and radiative energy intake: formulation of $\nabla \cdot Q^A$ and $\nabla \cdot Q^O$
Mass exchange due to
a) Precipitation: $S_{rf} + S_{sn, f}$
b) Evaporation: $S_{f, v}$

Note: Mass conservation is assumed, i.e. precipitation leaves the atmosphere and enters the ocean, for evaporation vice versa.

Heat exchange and radiative energy intake: formulation of $\nabla \cdot Q^A$ and $\nabla \cdot Q^O$

Treatment as external forcing of internal energy for individual atmosphere and ocean models:

$Q^A = Q_s + Q_l + Q_{bA} + Q_{LWA} + Q_{SWA}$ and $Q^O = -Q_s - Q_l + Q_{bO} + Q_{LWO} + Q_{SWO}$
Idealised atmosphere-ocean model: air-sea interactions

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

  **Note:** Mass conservation is assumed, i.e. precipitation leaves the atmosphere and enters the ocean, for evaporation vice versa.

- Heat exchange and radiative energy intake: formulation of $\nabla \cdot Q^A$ and $\nabla \cdot Q^O$

  1. 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 $Q^O = -Q_s - Q_l + Q_b^O + Q_{LW}^O + Q_{SW}^O$

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

Tobias Bauer (tobias.bauer@tropos.de)
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
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


Air-sea interactions
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

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

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

(geopotential, relative topography and surface pressure)
Coupling techniques

Models
- Atmosphere
- Ocean
- Land
- Sea/Land-Ice...

Coupling techniques
- Offline
- Semi-offline
- 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

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

- Similar to offline
- Exchange after short time period

Tobias Bauer (tobias.bauer@tropos.de)
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
### Coupled models for the Baltic Sea or coastal upwelling

<table>
<thead>
<tr>
<th>Model</th>
<th>Atmosphere</th>
<th>Ocean</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIRLAM/BOBA-PROBE</td>
<td>HIRLAM</td>
<td>BOBA-PROBE</td>
<td>Gustafsson et al., 1998</td>
</tr>
<tr>
<td>REMO/BSMO</td>
<td>REMO</td>
<td>BSMO</td>
<td>Hagedorn et al., 2000</td>
</tr>
<tr>
<td>RCAO</td>
<td>RCA2</td>
<td>RCO</td>
<td>Döscher et al., 2002</td>
</tr>
<tr>
<td>BALTIMOS</td>
<td>REMO</td>
<td>BSIOM</td>
<td>Lehmann et al., 2004</td>
</tr>
<tr>
<td>COAMPS/ROMS</td>
<td>COAMPS</td>
<td>ROMS</td>
<td>Perlin et al., 2007</td>
</tr>
<tr>
<td>COSTRICE</td>
<td>COSMO-CLM</td>
<td>TRIMNP</td>
<td>Ho et al., 2012</td>
</tr>
<tr>
<td>COSMO-CLM/NEMO</td>
<td>COSMO-CLM</td>
<td>NEMO</td>
<td>Van Pham et al., 2014</td>
</tr>
<tr>
<td>RCA4_NEMO</td>
<td>RCA4</td>
<td>NEMO</td>
<td>Wang et al., 2015</td>
</tr>
</tbody>
</table>
Coupled models for the Baltic Sea or coastal upwelling

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

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