

Package **AquaEnv**: an Aquatic modelling Environment in R

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Abstract

AquaEnv is an integrated development toolbox for aquatic chemical model generation focused on (ocean) acidification and CO₂ air-water exchange.

- It contains all elements necessary to model the pH, the related CO₂ air-water exchange, as well as aquatic acid-base chemistry in general for an arbitrary marine, estuarine or freshwater system. Also chemical batches can be modelled.
- Next to the routines necessary to calculate desired information, **AquaEnv** also contains a suite of tools to visualize this information.
- Furthermore, **AquaEnv** can not only be used to build dynamic models of aquatic systems, but it can also serve as a simple desktop tool for the experimental aquatic chemist to generate and visualize all possible derived information from a set of measurements with one single easy to use R function.
- Additionally, the sensitivity of the system to variations in the input variables can be visualized.
- **AquaEnv** also contains a number of example “applications” that make use of the aquatic modelling toolbox that **AquaEnv** provides:
 - a theoretical titration simulator
 - and a routine to determine total alkalinity ([TA]), the total dissolved inorganic carbon concentration ($[\sum \text{CO}_2]$), as well as additionally the electrode standard potential (E_0) and the first dissociation constant of the carbonate system ($K_{\text{CO}_2}^*$)

Keywords: aquatic modelling, pH, pH scales, dissolved inorganic carbon, total alkalinity, total alkalinity curve fitting, theoretical titration, revelle factor, omega, solubility products, CO₂, ocean acidification, estuaries, carbonate system, seawater, R.

Contents

1	Introduction	3
2	The elements of an object of class <i>aquaenv</i>	5
3	Using AquaEnv	9
3.1	Basic features	9
3.1.1	calling the “K” functions directly	9
3.1.2	Minimal <i>aquaenv</i> definition	9
3.1.3	Defining the complete <i>aquaenv</i> system in different ways	10
3.1.4	Calculating $[\sum \text{CO}_2]$	14
3.1.5	Cloning an object of class <i>aquaenv</i>	15
3.1.6	Preparing input variables	16
3.1.7	Vectors as input variables	16
3.1.8	Calculating $[\sum \text{CO}_2]$ from input vectors	19
3.1.9	Conversion from and to a dataframe	20
3.1.10	Converting elements in an object of class <i>aquaenv</i>	20
3.1.11	Quantities needed for explicit pH modelling	20
3.2	The <code>plot.aquaenv</code> function	21
3.3	Using objects of class <i>aquaenv</i> in dynamic models	23
3.3.1	Ordinary dynamic models	23
3.3.2	Models using the explicit pH modelling approach	26
3.3.2.1	In one single model	26
A	References for the elements of an object of class <i>aquaenv</i>	31

1 Introduction

AquaEnv is a toolbox for aquatic modelling that serves several purposes

- It provides functions to calculate the stoichiometric equilibrium constants (K^*) for key acid base systems in natural seawater, the Henry's constants (K_0), as well as the solubility products (K_{sp}) for calcite and aragonite. This functionality is provided via the functions `K_CO2`, `K_HCO3`, `K_BOH3`, `K_W`, `K_HSO4`, `K_HF`, `K_NH4`, `K_H2S`, `K_H3PO4`, `K_H2PO4`, `K_HPO4`, `K_SiOH4`, `K_SiOOH3`, `KO_CO2`, `KO_O2`, `Ksp_aragonite`, and `Ksp_calcite`.
- It is designed to make its use as easy as possible: all the information that can be calculated from the set of parameters known of a system or sample can be obtained by one single function: `aquaenv`. This function returns a list of class `aquaenv` that contains next to the input parameters
 - the chlorinity, the ionic strength, $[\sum B(OH)_3]$, $[\sum H_2SO_4]$, $[\sum HF]$, $[Cl^-]$, $[Cl^-]$, $[\sum Br]$, $[Na^+]$, $[Mg^{2+}]$, $[Ca^{2+}]$, $[K^+]$, $[Sr^{2+}]$ calculated from salinity as given in [DOE \(1994\)](#) (Please note that if values for $[\sum B(OH)_3]$, $[\sum H_2SO_4]$, $[\sum HF]$ are given as input parameters, these parameters are used and not the ones calculated from salinity.)
 - the hydrostatic pressure calculated from the given depth and the seawater density calculated from temperature and salinity as given by [Millero and Poisson \(1981\)](#)
 - a set of conversion factors to convert between different pH scales ([Dickson 1984](#); [Zeebe and Wolf-Gladrow 2001](#)) and between mol/kg-H₂O and mol/kg-solution (inferred from [Roy, Roy, Vogel, PorterMoore, Pearson, Good, Millero, and Campbell \(1993b\)](#) and [DOE \(1994\)](#))
 - the Henry's constants for CO₂ ([Weiss 1974](#)) and for O₂ (inferred from [Weiss 1970](#)) calculated from temperature and salinity as well as the associated saturation concentrations of CO₂ and O₂.
 - the ion product of water ([Millero 1995](#)), the stoichiometric equilibrium constants of HSO₄⁻ ([Dickson 1990a](#)), HF ([Dickson and Riley 1979a](#)), CO₂ ([Roy et al. 1993b](#)), HCO₃⁻ ([Roy et al. 1993b](#)), B(OH)₃ ([Dickson 1990a](#)), NH₄⁺ ([Millero, Yao, and Aicher 1995](#)), H₂S ([Millero 1995](#)), H₃PO₄ ([Millero 1995](#)), H₂PO₄⁻ ([Millero 1995](#)), HPO₄²⁻ ([Millero 1995](#)), SiOH₄ ([Millero, Plese, and Fernandez 1988](#)), SiOOH₃⁻ ([Wischmeyer, Del Amo, Brzezinski, and Wolf-Gladrow 2003](#)), HNO₂ ([Riordan, Minogue, Healy, O'Driscoll, and Sodeau 2005](#)), HNO₃, H₂SO₄ ([Atkins 1996](#)), HS ([Atkins 1996](#)) mostly calculated as functions of temperature and salinity and pressure corrected according to [Millero \(1995\)](#).
 - the solubility products of calcite and aragonite ([Mucci 1983](#)) as well as the associated Ω 's if a full speciation is calculated (see below)
 - the partial pressure of CO₂ - if a full speciation is calculated (see below)
 - if $[\sum CO_2]$ and pH are given $[TA]$ is calculated, if $[\sum CO_2]$ and $[TA]$ are given pH is calculated, if $[\sum CO_2]$ and $[CO_2]$ or pCO₂ are given, pH and $[TA]$ are calculated.
 - if either one of the pairs pH and $[CO_2]$ or pCO₂, pH and $[TA]$, or $[TA]$ and $[CO_2]$ or pCO₂ is given, $[\sum CO_2]$ is calculated

- if sufficient information is given and the flag `speciation=TRUE` is set, a full speciation of $[\sum \text{CO}_2]$, $[\sum \text{NH}_4]$, $[\sum \text{H}_2\text{S}]$, $[\sum \text{HNO}_3]$, $[\sum \text{HNO}_2]$, $[\sum \text{H}_3\text{PO}_4]$, $[\sum \text{Si}(\text{OH})_4]$, $[\sum \text{B}(\text{OH})_3]$, $[\sum \text{H}_2\text{SO}_4]$, $[\sum \text{HF}]$, as well as water itself is calculated
- if the flag `revelle=TRUE` is set, the Revelle factor (Zeebe and Wolf-Gladrow 2001) is calculated. If the flag `revelle=TRUE` is set, all necessary quantities for the explicit “direct substitution approach” (DSA) to pH modelling as given in Hofmann, Meysman, Soetaert, and Middelburg (2008b) are calculated. These are the buffer factor (the partial derivative of $[\text{TA}]$ with respect to $[\text{H}^+]$) and the partial derivatives of $[\text{TA}]$ with respect to the other total quantities. Furthermore, the partial derivatives of $[\text{TA}]$ with respect to changes in the equilibrium constants (K^*), multiplied with the partial derivatives of the equilibrium constants with respect to their variables needed for the DSA with time variable equilibrium constants as described in Hofmann, Meysman, Soetaert, and Middelburg (2008a) are calculated. Finally, the ionization fractions as defined by Stumm and Morgan (1996) and used in Hofmann, Middelburg, Soetaert, Wolf-Gladrow, and Meysman (2008c) are calculated for the full speciation.
- Input for **aquaenv** has to be supplied in standard SI units, the free proton pH scale and in molality¹ (mol/kg-solution). Conversion of input parameters to these necessary units and pH scale can be done with the generic function `convert`.
- The information created with **aquaenv** is also supplied in standard SI units and in molality. All elements of an object of class *aquaenv* of a certain unit or pH scale can be converted into other units or pH scales with the function `convert` as well.
- One can use input vectors of temperature *T*, salinity *S* or depth *d* for **aquaenv** to obtain vectors of all calculated information as function of the input vector. This can be visualized in a large variety of ways using the `plot` function specially defined for objects of type *aquaenv*.
- Objects of class *aquaenv* can be used in dynamic models to define the state of the system in each timestep of the numerical integration (done e.g. with **deSolve**). With the function **aquaenv** and the flag `from.data.frame=TRUE` it is possible to convert output of those dynamic models into objects of type *aquaenv* which allows the user to use the whole suite of visualisation tools that is provided by the function `plot` in **AquaEnv**.
- As mentioned above Hofmann *et al.* (2008b), Hofmann *et al.* (2008a), and Hofmann *et al.* (2008c) describe methods for an “explicit” pH modelling which allows for the quantification of the influences of kinetically modelled processes on the pH. Objects of type *aquaenv* provide all needed quantities (partial derivatives of $[\text{TA}]$, ionization fractions, etc.) to employ both of those methods in dynamic models. Furthermore, **AquaEnv** provides the functionality to cumulatively plot the obtained influences on the pH.
- As an example of how to use the toolbox that is **AquaEnv**, two applications are provided

¹Note that it is not sufficient to give a gravimetric concentration in mol/kg since there is a substantial difference between mol/kg-H₂O (molality) and mol/kg-solution (molinity).

- The function **titration**: creates theoretical titrations which can be used e.g. to create bjerrum plots, something that can also be done with the function **plot** in **AquaEnv**.
- The function **TAfit**: a routine based on a method in DOE (1994) that makes use of that theoretical titration function and allows for determining total alkalinity ([TA]), the total dissolved inorganic carbon concentration ($[\sum \text{CO}_2]$), as well as additionally the electrode standard potential (E_0) and the first dissociation constant of the carbonate system ($K_{\text{CO}_2}^*$) using the Levenberg-Marquart algorithm (least squares optimization procedure) as provided in **minpack.lm**.

2 The elements of an object of class *aquaenv*

The function **aquaenv**, the central function of **AquaEnv**, returns an object of class *aquaenv*. This object is a list of different elements which can be accessed with the **\$** character or with the **[[]]** operator

```
> test <- aquaenv(10, 35)
> test$Tc
```

```
[1] 10
attr(,"unit")
[1] "deg C"
```

```
> test[["Tc"]]
```

```
[1] 10
attr(,"unit")
[1] "deg C"
```

Maximally, i.e., if the enough input data is supplied to define the pH of the system and the flags **speciation**, **dsa**, and **revelle** are **TRUE** while the flag **skeleton** is **FALSE**, an object of class *aquaenv* contains the following elements

element	unit	explanation
Tc	°C	temperature
Tk	K	absolute temperature
S	“psu” (no unit)	salinity
Cl	‰	chlorinity
I	mol/kg-H ₂ O	ionic strength
d	m	depth
hydroP	bar	hydrostatic pressure
density	kg/m ³	(seawater) density
SumCO2	mol/kg-soln	$[\sum \text{CO}_2]$, total dissolved inorganic carbon concentration
SumNH4	mol/kg-soln	$[\sum \text{NH}_4^+]$, total ammonium concentration
SumH2S	mol/kg-soln	$[\sum \text{H}_2\text{S}]$, total sulfide concentration

SumHNO3	mol/kg-soln	$[\sum \text{HNO}_3]$, total nitrate concentration
SumHNO2	mol/kg-soln	$[\sum \text{HNO}_2]$, total nitrite concentration
SumH3PO4	mol/kg-soln	$[\sum \text{H}_3\text{PO}_4]$, total phosphate concentration
SumSiOH4	mol/kg-soln	$[\sum \text{Si}(\text{OH})_4]$, total silicate concentration
SumBOH3	mol/kg-soln	$[\sum \text{B}(\text{OH})_3]$, total borates concentration
SumH2SO4	mol/kg-soln	$[\sum \text{H}_2\text{SO}_4]$, total sulfate concentration
SumHF	mol/kg-soln	$[\sum \text{HF}]$, total fluoride concentration
SumBr	mol/kg-soln	$[\sum \text{HBr}]$, total bromide concentration
ClConc	mol/kg-soln	$[\text{Cl}^-]$, chloride concentration
Na	mol/kg-soln	$[\text{Na}^+]$, sodium concentration
Mg	mol/kg-soln	$[\text{Mg}^{2+}]$, magnesium concentration
Ca	mol/kg-soln	$[\text{Ca}^{2+}]$, calcium concentration
K	mol/kg-soln	$[\text{K}^+]$, potassium concentration
Sr	mol/kg-soln	$[\text{Sr}^{2+}]$, strontium concentration
molal2molin	(mol/kg-soln)/(mol/kg-H2O)	concentration conversion factor: from molality to molinity
free2tot	-	pH conversion factor: free scale to total scale
free2sws	-	pH conversion factor: free scale to seawater scale
tot2free	-	pH conversion factor: total scale to free scale
tot2sws	-	pH conversion factor: total scale to seawater scale
sws2free	-	pH conversion factor: seawater scale to free scale
sws2tot	-	pH conversion factor: seawater scale to total scale
K0_CO2	mol/(kg-soln*atm)	Henry's constant for CO ₂
K0_O2	mol/(kg-soln*atm)	Henry's constant for O ₂
CO2_sat	mol/kg-soln	CO ₂ saturation concentration at an atmospheric partial pressure/fugacity of Fugacity\$CO2
O2_sat	mol/kg-soln	O ₂ saturation concentration at an atmospheric partial pressure/fugacity of Fugacity\$O2
K_W	(mol/kg-soln) ² , free pH scale	stoichiometric equilibrium ion product of H ₂ O: $K_W^* = [\text{H}^+][\text{OH}^-]$
K_HSO4	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{HSO}_4}^* = [\text{H}^+][\text{SO}_4^{2-}]/[\text{HSO}_4^-]$
K_HF	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{HF}}^* = [\text{H}^+][\text{F}^-]/[\text{HF}]$
K_CO2	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{CO}_2}^* = [\text{H}^+][\text{HCO}_3^-]/[\text{CO}_2]$
K_HCO3	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{HCO}_3}^* = [\text{H}^+][\text{CO}_3^{2-}]/[\text{HCO}_3^-]$
K_BOH3	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{B}(\text{OH})_3}^* = [\text{H}^+][\text{B}(\text{OH})_4^-]/[\text{B}(\text{OH})_3]$
K_NH4	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{NH}_4}^* = [\text{H}^+][\text{NH}_3]/[\text{NH}_4^+]$
K_H2S	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{H}_2\text{S}}^* = [\text{H}^+][\text{HS}^-]/[\text{H}_2\text{S}]$
K_H3PO4	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{H}_3\text{PO}_4}^* = [\text{H}^+][\text{H}_2\text{PO}_4^-]/[\text{H}_3\text{PO}_4]$

K_H2PO4	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{H}_2\text{PO}_4^-}^* = [\text{H}^+][\text{HPO}_4^{2-}]/[\text{H}_2\text{PO}_4^-]$
K_HPO4	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{HPO}_4^{2-}}^* = [\text{H}^+][\text{PO}_4^{3-}]/[\text{HPO}_4^{2-}]$
K_SiOH4	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{Si(OH)}_4}^* = [\text{H}^+][\text{SiO(OH)}_3^-]/[\text{Si(OH)}_4]$
K_SiOOH3	mol/kg-soln, free pH scale	stoichiometric equilibrium constant $K_{\text{SiO(OH)}_3^-}^* = [\text{H}^+][\text{SiO}_2(\text{OH})_2^{2-}]/[\text{SiO(OH)}_3^-]$
K_HNO2	mol/kg-soln; mol/kg-H2O; mol/l	approximate value for equilibrium constant $K_{\text{HNO}_2}^* = [\text{H}^+][\text{NO}_2^-]/[\text{HNO}_2]$
K_HNO3	mol/kg-soln; mol/kg-H2O; mol/l	approximate value for equilibrium constant $K_{\text{HNO}_3}^* = [\text{H}^+][\text{NO}_3^-]/[\text{HNO}_3]$
K_H2SO4	mol/kg-soln; mol/kg-H2O; mol/l	approximate value for equilibrium constant $K_{\text{H}_2\text{SO}_4}^* = [\text{H}^+][\text{HSO}_4^-]/[\text{H}_2\text{SO}_4]$
K_HS	mol/kg-soln; mol/kg-H2O; mol/l	approximate value for equilibrium constant $K_{\text{HS}^-}^* = [\text{H}^+][\text{S}^{2-}]/[\text{HS}^-]$
Ksp_calcite	(mol/kg-soln) ²	stoichiometric equilibrium solubility product of calcite $K_{\text{sp,cal}}^* = [\text{Ca}^{2+}][\text{CO}_3^{2-}]$
Ksp_aragonite	(mol/kg-soln) ²	stoichiometric equilibrium solubility product of aragonite $K_{\text{sp,ara}}^* = [\text{Ca}^{2+}][\text{CO}_3^{2-}]$
TA	mol/kg-soln	[TA], total alkalinity
pH	-, free scale	pH
pCO2	atm,	partial pressure (fugacity) of CO ₂ in the water
CO2	mol/kg-soln	[CO ₂]
HCO3	mol/kg-soln	[HCO ₃ ⁻]
CO3	mol/kg-soln	[CO ₃ ²⁻]
BOH3	mol/kg-soln	[B(OH) ₃]
BOH4	mol/kg-soln	[B(OH) ₄ ⁻]
OH	mol/kg-soln	[OH ⁻]
H3PO4	mol/kg-soln	[H ₃ PO ₄]
H2PO4	mol/kg-soln	[H ₂ PO ₄ ⁻]
HPO4	mol/kg-soln	[HPO ₄ ²⁻]
PO4	mol/kg-soln	[PO ₄ ³⁻]
SiOH4	mol/kg-soln	[Si(OH) ₄]
SiOOH3	mol/kg-soln	[SiO(OH) ₃ ⁻]
SiO2OH2	mol/kg-soln	[SiO ₂ (OH) ₂ ²⁻]
H2S	mol/kg-soln	[H ₂ S]
HS	mol/kg-soln	[HS ⁻]
S2min	mol/kg-soln	[S ²⁻]
NH4	mol/kg-soln	[NH ₄ ⁺]
NH3	mol/kg-soln	[NH ₃]
H2SO4	mol/kg-soln	[H ₂ SO ₄]
HSO4	mol/kg-soln	[HSO ₄ ⁻]

SO4	mol/kg-soln	$[\text{SO}_4^{2-}]$
HF	mol/kg-soln	$[\text{HF}]$
F	mol/kg-soln	$[\text{F}^-]$
HNO3	mol/kg-soln	$[\text{HNO}_3]$
NO3	mol/kg-soln	$[\text{NO}_3^-]$
HNO2	mol/kg-soln	$[\text{HNO}_2]$
NO2	mol/kg-soln	$[\text{NO}_2^-]$
omega_calcite	-	saturation state Ω with respect to calcite
omega_aragonite	-	saturation state Ω with respect to aragonite
revelle	-	Revelle factor
c1	-	ionization fraction $c_1 = [\text{CO}_2]/[\sum \text{CO}_2]$
c2	-	ionization fraction $c_2 = [\text{HCO}_3^-]/[\sum \text{CO}_2]$
c3	-	ionization fraction $c_3 = [\text{CO}_3^{2-}]/[\sum \text{CO}_2]$
dTAdSumCO2	-	$\frac{\partial[\text{TA}]}{\partial \sum \text{CO}_2}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots)$
b1	-	ionization fraction $b_1 = [\text{B}(\text{OH})_3]/[\sum \text{B}(\text{OH})_3]$
b2	-	ionization fraction $b_2 = [\text{B}(\text{OH})_4^-]/[\sum \text{B}(\text{OH})_3]$
dTAdSumBOH3	-	$\frac{\partial[\text{TA}]}{\partial \sum \text{B}(\text{OH})_3}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots)$
so1	-	ionization fraction $so_1 = [\text{H}_2\text{SO}_4]/[\sum \text{H}_2\text{SO}_4]$
so2	-	ionization fraction $so_2 = [\text{HSO}_4^-]/[\sum \text{H}_2\text{SO}_4]$
so3	-	ionization fraction $so_3 = [\text{SO}_4^{2-}]/[\sum \text{H}_2\text{SO}_4]$
dTAdSumH2SO4	-	$\frac{\partial[\text{TA}]}{\partial \sum \text{H}_2\text{SO}_4}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots)$
f1	-	ionization fraction $f_1 = [\text{HF}]/[\sum \text{HF}]$
f2	-	ionization fraction $f_1 = [\text{F}^-]/[\sum \text{HF}]$
dTAdSumHF	-	$\frac{\partial[\text{TA}]}{\partial \sum \text{HF}}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots)$
dTAdH	-	$\frac{\partial[\text{TA}]}{\partial [\text{H}^+]}$: buffer factor with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots)$
dTAdKdKdS	-	$\sum_i \frac{\partial[\text{TA}]}{\partial K_i^*} \frac{\partial K_i^*}{\partial S}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots, K_i^*)$
dTAdKdKdT	-	$\sum_i \frac{\partial[\text{TA}]}{\partial K_i^*} \frac{\partial K_i^*}{\partial T}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots, K_i^*)$
dTAdKdKdd	-	$\sum_i \frac{\partial[\text{TA}]}{\partial K_i^*} \frac{\partial K_i^*}{\partial d}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots, K_i^*)$
dTAdKdKdSumH2SO4	-	$\sum_i \frac{\partial[\text{TA}]}{\partial K_i^*} \frac{\partial K_i^*}{\partial [\sum \text{H}_2\text{SO}_4]}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots, K_i^*)$
dTAdKdKdSumHF	-	$\sum_i \frac{\partial[\text{TA}]}{\partial K_i^*} \frac{\partial K_i^*}{\partial [\sum \text{HF}]}$ with $[\text{TA}] = f([\text{H}^+], [\sum \text{CO}_2], \dots, K_i^*)$

For elements that are calculated according to certain literature references, those references are given in appendix [A](#).

3 Using AquaEnv

3.1 Basic features

3.1.1 calling the “K” functions directly

The elements `K_CO2`, `K_HCO3`, `K_BOH3`, `K_W`, `K_HSO4`, `K_HF`, `K_NH4`, `K_H2S`, `K_H3PO4`, `K_H2PO4`, `K_HP04`, `K_SiOH4`, `K_SiOOH3`, `KO_CO2`, `KO_O2`, `Ksp_aragonite`, and `Ksp_calcite` can be calculated directly, without creating an object of class *aquaenv*. This is done via functions that bear the same as those elements

```
> K_CO2(15, 30)

[1] 9.089117e-07
attr(,"unit")
[1] "mol/kg-soln"
attr(,"pH scale")
[1] "free"

> KO_CO2(15, 30)

[1] 0.03852158
attr(,"unit")
[1] "mol/(kg-soln*atm)"

> Ksp_calcite(15, 30, 100)

[1] 3.644549e-07
attr(,"unit")
[1] "(mol/kg-soln)^2"
```

3.1.2 Minimal *aquaenv* definition

Minimally, an object of class *aquaenv* can be defined with just a temperature and salinity value

```
> ae <- aquaenv(Tc = 15, S = 30)
> ae$K_CO2

[1] 9.089117e-07
attr(,"unit")
[1] "mol/kg-soln"
attr(,"pH scale")
[1] "free"
```

Optionally, a mean depth can be given. As in the above case, the returned object of class *aquaenv* then contains a standard set of elements as shown by the `names` command.

```

> ae <- aquaenv(Tc = 15, S = 30, d = 10)
> ae$Ksp_calcite

[1] 3.588429e-07
attr(,"unit")
[1] "(mol/kg-soln)^2"

> names(ae)

[1] "Tc"          "Tk"          "S"           "Cl"
[5] "I"           "d"           "hydroP"      "density"
[9] "SumCO2"      "SumNH4"      "SumH2S"      "SumHNO3"
[13] "SumHNO2"     "SumH3PO4"    "SumSiOH4"    "SumBOH3"
[17] "SumH2SO4"    "SumHF"       "SumBr"       "ClConc"
[21] "Na"          "Mg"          "Ca"          "K"
[25] "Sr"          "molal2molin" "free2tot"    "free2sws"
[29] "tot2free"    "tot2sws"     "sws2free"    "sws2tot"
[33] "K0_CO2"      "K0_O2"       "CO2_sat"     "O2_sat"
[37] "K_W"         "K_HSO4"      "K_HF"        "K_CO2"
[41] "K_HCO3"      "K_BOH3"      "K_NH4"       "K_H2S"
[45] "K_H3PO4"     "K_H2PO4"     "K_HPO4"      "K_SiOH4"
[49] "K_SiOOH3"    "K_HNO2"      "K_HNO3"      "K_H2SO4"
[53] "K_HS"        "Ksp_calcite" "Ksp_aragonite"

```

A minimal set of elements in an object of class *aquaenv* can be obtained by setting the flag `skeleton` to `TRUE`

```

> ae <- aquaenv(Tc = 15, S = 30, d = 10, skeleton = TRUE)
> names(ae)

[1] "Tc"          "Tk"          "S"           "Cl"          "I"           "d"
[7] "hydroP"      "density"     "SumCO2"      "SumNH4"      "SumH2S"      "SumHNO3"
[13] "SumHNO2"     "SumH3PO4"    "SumSiOH4"    "SumBOH3"     "SumH2SO4"    "SumHF"
[19] "K_W"         "K_HSO4"      "K_HF"        "K_CO2"       "K_HCO3"      "K_BOH3"
[25] "K_NH4"       "K_H2S"       "K_H3PO4"     "K_H2PO4"     "K_HPO4"      "K_SiOH4"
[31] "K_SiOOH3"    "K_HNO2"      "K_HNO3"      "K_H2SO4"     "K_HS"

```

3.1.3 Defining the complete *aquaenv* system in different ways

If enough information is given to define a complete speciation, i.e. either one of the pairs SumCO2 and pH, SumCO2 and TA, SumCO2 and CO2, or SumCO2 and pCO2, a full *aquaenv* system can be defined.

```

> Tc <- 15
> S <- 30
> d <- 10

```

```

> SumCO2 <- 0.002
> pH <- 8
> TA <- 0.002140323
> pCO2 <- 0.000533576
> CO2 <- 2.055419e-05
> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH)
> ae$TA

[1] 0.002140800
attr(,"unit")
[1] "mol/kg-soln"

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, TA = TA)
> ae$pH

[1] 7.998791
attr(,"pH scale")
[1] "free"

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, CO2 = CO2)
> ae$pH

[1] 7.999293
attr(,"pH scale")
[1] "free"

> names(ae)

[1] "Tc"           "Tk"           "S"
[4] "Cl"           "I"            "d"
[7] "hydroP"       "density"      "SumCO2"
[10] "SumNH4"       "SumH2S"       "SumHNO3"
[13] "SumHNO2"      "SumH3PO4"     "SumSiOH4"
[16] "SumBOH3"      "SumH2SO4"     "SumHF"
[19] "SumBr"        "ClConc"       "Na"
[22] "Mg"           "Ca"           "K"
[25] "Sr"           "molal2molin"  "free2tot"
[28] "free2sws"     "tot2free"     "tot2sws"
[31] "sws2free"     "sws2tot"      "K0_CO2"
[34] "K0_O2"        "CO2_sat"      "O2_sat"
[37] "K_W"          "K_HSO4"       "K_HF"
[40] "K_CO2"        "K_HCO3"       "K_BOH3"
[43] "K_NH4"        "K_H2S"        "K_H3PO4"
[46] "K_H2PO4"      "K_HPO4"       "K_SiOH4"
[49] "K_SiOOH3"     "K_HNO2"       "K_HNO3"
[52] "K_H2SO4"      "K_HS"         "Ksp_calcite"

```

[55]	"Ksp_aragonite"	"TA"	"pH"
[58]	"pCO2"	"CO2"	"HCO3"
[61]	"CO3"	"BOH3"	"BOH4"
[64]	"OH"	"H3PO4"	"H2PO4"
[67]	"HPO4"	"PO4"	"SiOH4"
[70]	"SiOOH3"	"SiO2OH2"	"H2S"
[73]	"HS"	"S2min"	"NH4"
[76]	"NH3"	"H2SO4"	"HSO4"
[79]	"SO4"	"HF"	"F"
[82]	"HNO3"	"NO3"	"HNO2"
[85]	"NO2"	"omega_calcite"	"omega_aragonite"

As seen above, a full speciation is calculated along with the pH or total alkalinity respectively. If only pH or total alkalinity is needed, the calculation of the full speciation can be toggled off. Furthermore the flag `skeleton` also works for a full system.

```
> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH, speciation = FALSE)
> names(ae)
```

[1]	"Tc"	"Tk"	"S"	"Cl"
[5]	"I"	"d"	"hydroP"	"density"
[9]	"SumCO2"	"SumNH4"	"SumH2S"	"SumHNO3"
[13]	"SumHNO2"	"SumH3PO4"	"SumSiOH4"	"SumBOH3"
[17]	"SumH2SO4"	"SumHF"	"SumBr"	"ClConc"
[21]	"Na"	"Mg"	"Ca"	"K"
[25]	"Sr"	"molal2molin"	"free2tot"	"free2sws"
[29]	"tot2free"	"tot2sws"	"sws2free"	"sws2tot"
[33]	"K0_CO2"	"K0_O2"	"CO2_sat"	"O2_sat"
[37]	"K_W"	"K_HSO4"	"K_HF"	"K_CO2"
[41]	"K_HCO3"	"K_BOH3"	"K_NH4"	"K_H2S"
[45]	"K_H3PO4"	"K_H2PO4"	"K_HPO4"	"K_SiOH4"
[49]	"K_SiOOH3"	"K_HNO2"	"K_HNO3"	"K_H2SO4"
[53]	"K_HS"	"Ksp_calcite"	"Ksp_aragonite"	"TA"
[57]	"pH"	"pCO2"	"CO2"	

```
> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH, speciation = FALSE,
+   skeleton = TRUE)
> names(ae)
```

[1]	"Tc"	"Tk"	"S"	"Cl"	"I"	"d"
[7]	"hydroP"	"density"	"SumCO2"	"SumNH4"	"SumH2S"	"SumHNO3"
[13]	"SumHNO2"	"SumH3PO4"	"SumSiOH4"	"SumBOH3"	"SumH2SO4"	"SumHF"
[19]	"K_W"	"K_HSO4"	"K_HF"	"K_CO2"	"K_HCO3"	"K_BOH3"
[25]	"K_NH4"	"K_H2S"	"K_H3PO4"	"K_H2PO4"	"K_HPO4"	"K_SiOH4"
[31]	"K_SiOOH3"	"K_HNO2"	"K_HNO3"	"K_H2SO4"	"K_HS"	"TA"
[37]	"pH"	"pCO2"	"CO2"			

Furthermore all the quantities needed for the explicit pH modelling approaches as given in Hofmann *et al.* (2008b) and Hofmann *et al.* (2008c) can be calculated by setting the flag `dsa` to `TRUE`. The Revelle factor can be calculated using the flag `revelle`.

```
> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pCO2 = pCO2,
+             dsa = TRUE, reveille = TRUE)
> ae$dTAdH
```

```
[1] -17096.98
attr(,"unit")
[1] "(mol-TA/kg-soln)/(mol-H/kg-soln)"
attr(,"pH scale")
[1] "free"
```

```
> ae$revelle
```

```
[1] 13.77498
```

If an ambivalent situation is created because the user enters too much information, an error message is displayed

```
> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, CO2 = CO2, pCO2 = pCO2)

[1] "Error! Overdetermined system: entered pCO2: 0.000533576 , calculated pCO2: 0.000533575978437754"
[1] "Please enter only one of: pH, TA, CO2, or pCO2."

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH, TA = TA)

[1] "Error! Overdetermined system: entered TA: 0.002140323 , calculated TA: 0.00214079972077581"
[1] "Please enter only one of: pH, TA, CO2, or pCO2."

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH, CO2 = CO2)

[1] "Error! Overdetermined system: entered pH: 8 , calculated pH: 7.99929303203143"
[1] "Please enter only one of: pH, TA, CO2, or pCO2."

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH, pCO2 = pCO2)

[1] "Error! Overdetermined system: entered pH: 8 , calculated pH: 7.99929301525035"
[1] "Please enter only one of: pH, TA, CO2, or pCO2."

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, TA = TA, CO2 = CO2)

[1] "Error! Overdetermined system: entered TA: 0.002140323 , calculated TA: 0.002140520813372"
[1] "Please enter only one of: pH, TA, CO2, or pCO2."

> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, TA = TA, pCO2 = pCO2)

[1] "Error! Overdetermined system: entered TA: 0.002140323 , calculated TA: 0.00214052080675498"
[1] "Please enter only one of: pH, TA, CO2, or pCO2."
```

3.1.4 Calculating $[\sum \text{CO}_2]$

$[\sum \text{CO}_2]$ can be calculated by giving a constant pair of either pH and CO₂, pH and pCO₂, pH and TA, TA and CO₂, or TA and pCO₂

```
> pCO2 <- 0.0006952296
> CO2 <- 2.678134e-05
> pH <- 7.888569
> TA <- 0.0021
> Tc <- 15
> S <- 30
> d <- 10
> ae <- aquaenv(Tc, S, d, SumCO2 = NULL, pH = pH, CO2 = CO2)
> ae$SumCO2

[1] 0.001999999
attr("unit")
[1] "mol/kg-soln"

> ae <- aquaenv(Tc, S, d, SumCO2 = NULL, pH = pH, pCO2 = pCO2)
> ae$SumCO2

[1] 0.001999999
attr("unit")
[1] "mol/kg-soln"

> ae <- aquaenv(Tc, S, d, SumCO2 = NULL, pH = pH, TA = TA)
> ae$SumCO2

[1] 0.002
attr("unit")
[1] "mol/kg-soln"

> ae <- aquaenv(Tc, S, d, SumCO2 = NULL, TA = TA, CO2 = CO2)
> ae$SumCO2

[1] 0.002
attr("unit")
[1] "mol/kg-soln"

> ae <- aquaenv(Tc, S, d, SumCO2 = NULL, TA = TA, pCO2 = pCO2)
> ae$SumCO2

[1] 0.002
attr("unit")
[1] "mol/kg-soln"
```

3.1.5 Cloning an object of class *aquaenv*

It is possible to clone an object of class *aquaenv*, either 1 to 1 or with different pH, TA, or K_{CO2}

```
> Tc <- 15
> S <- 30
> SumCO2 <- 0.002
> TA <- 0.00214
> ae <- aquaenv(Tc, S, SumCO2 = SumCO2, TA = TA)
> ae$pH
```

```
[1] 7.99838
attr("pH scale")
[1] "free"
```

```
> ae1 <- aquaenv(ae = ae)
> ae1$pH
```

```
[1] 7.99838
attr("pH scale")
[1] "free"
```

```
> pH <- 9
> ae2 <- aquaenv(ae = ae, pH = pH)
> ae2$TA
```

```
[1] 0.002982758
attr("unit")
[1] "mol/kg-soln"
```

```
> TA <- 0.002
> ae3 <- aquaenv(ae = ae, TA = TA)
> ae3$pH
```

```
[1] 7.548174
attr("pH scale")
[1] "free"
```

```
> K_CO2 <- 1e-06
> ae4 <- aquaenv(ae = ae, k_co2 = K_CO2)
> ae4$pH
```

```
[1] 7.99838
attr("pH scale")
[1] "free"
```

Note that K_{CO2} as an input variable is in lower cases!

3.1.6 Preparing input variables

Input variables for the function `aquaenv` need to be in mol/kg-solution and on the free pH scale. Data in other concentration units or pH scales can be converted using the function `convert`.

```
> Tc <- 15
> S <- 10
> pH_NBS <- 8.142777
> SumCO2molar <- 0.002016803
> pH_free <- convert(pH_NBS, "pHscale", "nbs2free", Tc = Tc,
+   S = S)
> SumCO2molin <- convert(SumCO2molar, "conc", "molar2molin",
+   Tc = Tc, S = S)
> ae <- aquaenv(Tc, S, SumCO2 = SumCO2molin, pH = pH_free)
> ae$pH

[1] 8
attr(,"pH scale")
[1] "free"

> ae$SumCO2

[1] 0.002000000
attr(,"unit")
[1] "mol/kg-soln"
```

3.1.7 Vectors as input variables

One of the input variables for the function `aquaenv` may be a vector. All the other input variables are then assumed to be constant. The elements of the resulting two dimensional object of class `aquaenv` are then vectors containing the elements as a function of the input variable for which a vector is given.

```
> SumCO2 <- 0.002
> pH <- 8
> Tc <- 1:15
> S <- 30
> d <- 10
> ae <- aquaenv(Tc, S, d, SumCO2 = SumCO2, pH = pH, revelle = TRUE)
> ae$revelle

[1] 17.60495 17.30006 16.99846 16.70066 16.40710 16.11818 15.83422
[8] 15.55549 15.28222 15.01459 14.75275 14.49679 14.24679 14.00280
[15] 13.76482
```

A two dimensional object of class `aquaenv` can be visualized using the `plot` function. For convenience of the user, the default setting for the `plot` function for an object of class `aquaenv` results in a new plotting device being opened. Setting the flag `newdevice` to `FALSE` prevents that.


```

> ae <- aquaenv(Tc = 15, S = 30, d = seq(1, 1000, 100),
+   SumCO2 = SumCO2, pH = pH, revelle = TRUE)
> plot(ae, xval = seq(1, 1000, 100), xlab = "depth/m")

> ae <- aquaenv(Tc = 1:15, S = 30, d = 10, SumCO2 = SumCO2,
+   TA = 0.0023)
> plot(ae, xval = 1:15, xlab = "T/(deg C)")

> ae <- aquaenv(Tc = 15, S = 20:30, d = 10, SumCO2 = SumCO2,
+   TA = TA)
> plot(ae, xval = 20:30, xlab = "S")

> ae <- aquaenv(Tc = 15, S = 30, d = seq(1, 1000, 200),
+   SumCO2 = SumCO2, TA = TA, revelle = TRUE, dsa = TRUE)
> plot(ae, xval = seq(1, 1000, 200), xlab = "depth/m")

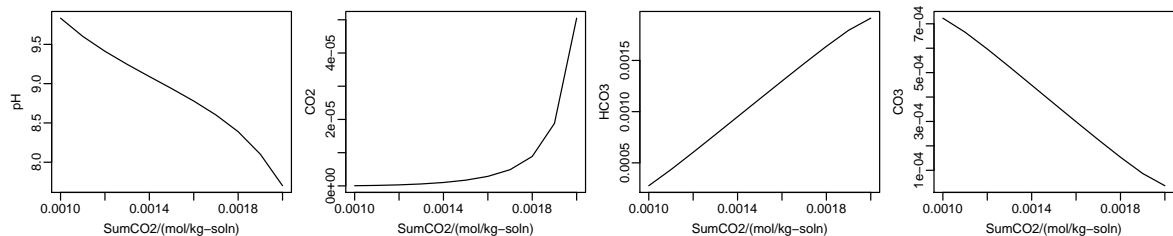
```

Interesting to note is that also, e.g., SumCO2, TA, pH and SumNH4 can be vectors

```

> ae <- aquaenv(10, 20, SumCO2 = seq(0.001, 0.002, 1e-04),
+   TA = 0.002)
> plot(ae, xval = ae$SumCO2, xlab = "SumCO2/(mol/kg-soln)",
+   what = c("pH", "CO2", "HCO3", "CO3"), newdevice = FALSE,
+   mfrow = c(1, 4))

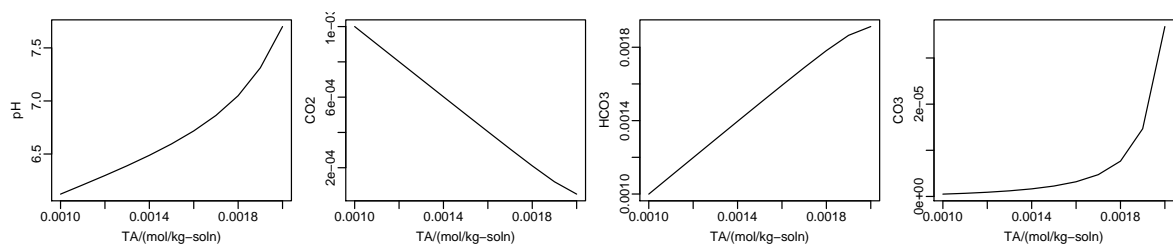
```



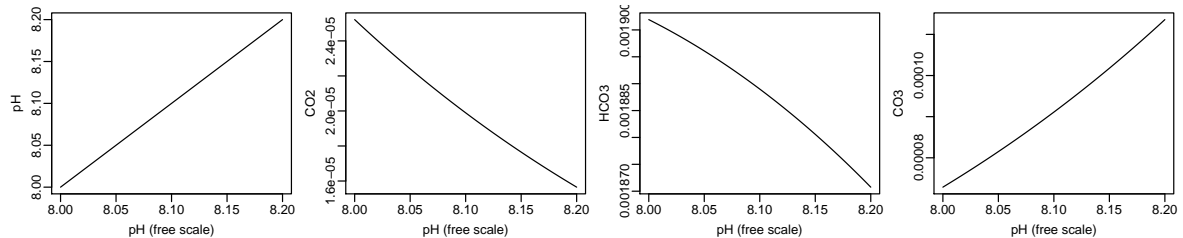
```

> ae <- aquaenv(10, 20, SumCO2 = 0.002, TA = seq(0.001,
+   0.002, 1e-04))
> plot(ae, xval = ae$TA, xlab = "TA/(mol/kg-soln)", what = c("pH",
+   "CO2", "HCO3", "CO3"), newdevice = FALSE, mfrow = c(1,
+   4))

```



```
> ae <- aquaenv(10, 20, SumCO2 = 0.002, pH = seq(8, 8.2,
+ 0.001))
> plot(ae, xval = ae$pH, xlab = "pH (free scale)", what = c("pH",
+ "CO2", "HCO3", "CO3"), newdevice = FALSE, mfrow = c(1,
+ 4))
```



```
> ae <- aquaenv(10, 20, SumCO2 = 0.002, SumNH4 = seq(1e-04,
+ 2e-04, 1e-05), pH = 8)
> ae$NH3
```

```
[1] 1.534562e-06 1.688018e-06 1.841474e-06 1.994930e-06 2.148386e-06
[6] 2.301842e-06 2.455299e-06 2.608755e-06 2.762211e-06 2.915667e-06
[11] 3.069123e-06
attr("unit")
[1] "mol/kg-soln"
```

3.1.8 Calculating $[\sum \text{CO}_2]$ from input vectors

The functionality of calculating SumCO2 can also be used together with vectors as input variables.

```
> ae <- aquaenv(Tc = 11:15, S = 30, SumCO2 = NULL, pH = pH,
+ CO2 = CO2, revelle = TRUE, dsa = TRUE)
> ae$SumCO2
```

```
[1] 0.002415982 0.002463453 0.002511189 0.002559171 0.002607383
attr("unit")
[1] "mol/kg-soln"
```

Two further examples

```
> ae <- aquaenv(Tc = 15, S = 20:30, SumCO2 = NULL, pH = pH,
+ pCO2 = pCO2)
> plot(ae, xval = 20:30, xlab = "S")

> ae <- aquaenv(Tc = 15, S = 30, d = seq(1, 1000, 100),
+ SumCO2 = NULL, pH = pH, TA = TA)
> plot(ae, xval = seq(1, 1000, 100), xlab = "depth/m")
```

3.1.9 Conversion from and to a dataframe

Objects of class *aquaenv* can be converted to an R *data.frame* to further post-process them with standard R means. Similarly, R *data.frames* can be converted to objects of class *aquaenv* to use the plotting facilities that exist for objects of class *aquaenv*. This can be helpful for plotting output of a dynamic model run, e.g. from R package **deSolve**, and will be shown later in this document.

```
> aedataframe <- as.data.frame(ae)
> aetest <- aquaenv(ae = aedataframe, from.data.frame = TRUE)
```

3.1.10 Converting elements in an object of class *aquaenv*

Elements of an object of class *aquaenv* are calculated in, e.g., the concentration unit mol/kg-solution (molality). The function **convert** can be used to convert all elements in an object of class *aquaenv* that share a common attribute, e.g. the unit.

```
> ae <- aquaenv(10, 30)
> ae$SumBOH3

[1] 0.0003563636
attr(,"unit")
[1] "mol/kg-soln"

> ae <- convert(ae, "mol/kg-soln", "umolkg-H2O", 1e+06/ae$molal2molin,
+             "unit")
> ae$SumBOH3

[1] 367.442
attr(,"unit")
[1] "umolkg-H2O"
```

3.1.11 Quantities needed for explicit pH modelling

As already mentioned above, the quantities needed for the explicit pH modelling approach (direct substitution approach - DSA) as presented by [Hofmann *et al.* \(2008b\)](#) can be calculated with the function **aquaenv** by setting the flag **dsa**.

```
> ae <- aquaenv(Tc = 15, S = 30, d = 10, SumCO2 = 0.002,
+             pH = 8, dsa = TRUE, reveille = TRUE)
```

This command calculated the buffer factor and the partial derivatives of [TA] with respect to other summed quantities referred to in [Hofmann *et al.* \(2008b\)](#)

```
> ae$dTAdH
```

```
[1] -17142.05
attr("unit")
[1] "(mol-TA/kg-soln)/(mol-H/kg-soln)"
attr("pH scale")
[1] "free"

> ae$dTAdSumCO2

[1] 1.045937
attr("unit")
[1] "(mol-TA/kg-soln)/(mol-SumCO2/kg-soln)"
```

as well the sums partial derivatives of [TA] with respect to the equilibrium constants (K^* 's) multiplied with the partial derivatives of the respective equilibrium constant with one of their variables (i.e., S, T, d, SumH2SO4, od SumHF) as introduced in [Hofmann *et al.* \(2008a\)](#).

```
> ae$dTAdKdKdS

[1] 3.9865e-06
attr("unit")
[1] "(mol-TA/kg-soln)/\"psu\""

> ae$dTAdKdKdSumH2SO4

[1] -0.001086853
attr("unit")
[1] "(mol-TA/kg-soln)/(mol-SumH2SO4/kg-soln)"
```

Furthermore the ionization fractions used for the pH dependent fractional stoichiometric pH modelling approach described in [Hofmann *et al.* \(2008c\)](#) are calculated as well

```
> ae$c1

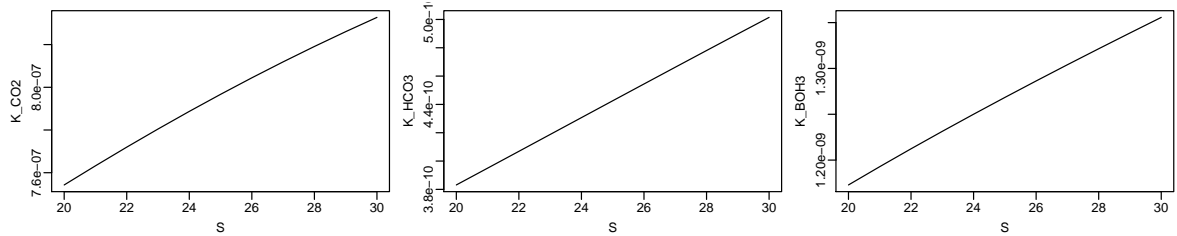
[1] 0.01025961
```

3.2 The `plot.aquaenv` function

In the previous sections, the `plot` function has been introduced. What actually is called if the first element of the arguments list of `plot` is an object of type *aquaenv* is the function `plot.aquaenv`. This is a multifunctional tool to visualize information contained in an object of class *aquaenv*. For the convenience of the users, `plot.aquaenv` combines the call of standard R plotting functions and the previous call of the function `par` to set parameters like `mfrow`, `mar`, etc. as well as the opening of a plotting device with a certain size. As already shown above, setting the flag `newdevice` to `FALSE` suppresses the opening of a new plotting device (this feature is needed here to create a plot that will be woven into the \LaTeX document by Sweave).

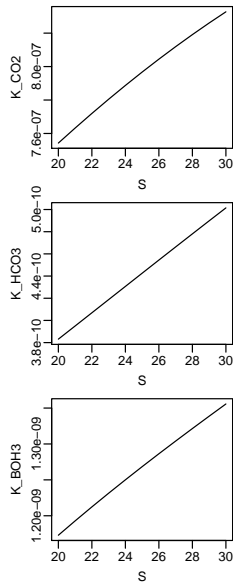
For example

```
> ae <- aquaenv(10, 20:30)
> plot(ae, xval = 20:30, xlab = "S", what = c("K_CO2",
+       "K_HCO3", "K_BOH3"), size = c(10, 2), mfrow = c(1,
+       3), newdevice = FALSE)
```



and

```
> plot(ae, xval = 20:30, xlab = "S", what = c("K_CO2",
+       "K_HCO3", "K_BOH3"), size = c(2, 10), mfrow = c(3,
+       1), newdevice = FALSE)
```



Furthermore the parameter `device` can be specified which allows the user to write the plots to .eps and .pdf files. The parameter `filename` can be used to specify a filename other than the default filename "aquaenv".

```
> ae <- aquaenv(10, 20:30)
> plot(ae, xval = 20:30, xlab = "S", what = c("K_CO2",
+       "K_HCO3", "K_BOH3"), size = c(10, 2), mfrow = c(1,
+       3), device = "pdf")
```

X11

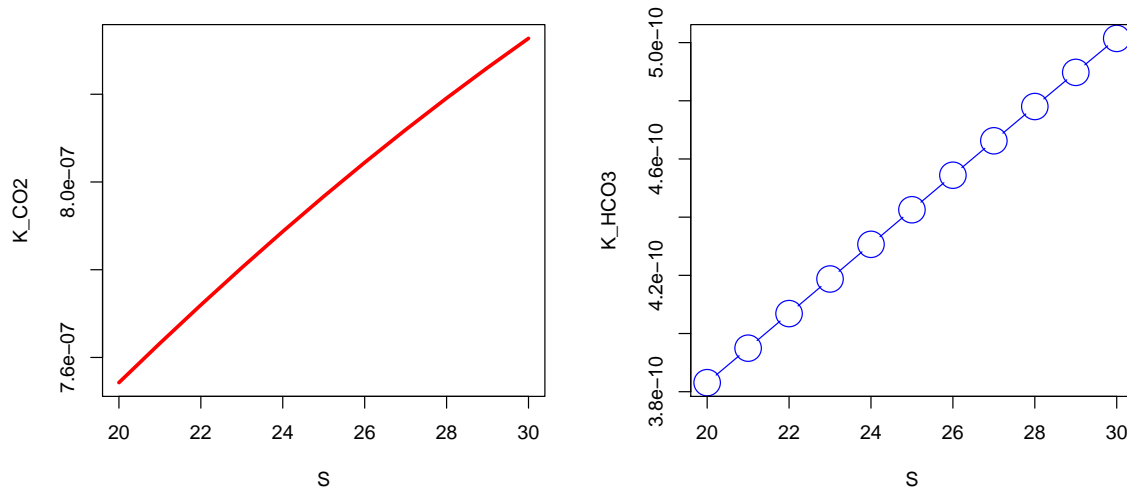
2

```
> plot(ae, xval = 20:30, xlab = "S", what = c("K_CO2",
+       "K_HCO3", "K_BOH3"), size = c(2, 10), mfrow = c(3,
+       1), device = "eps", filename = "test")
```

X11
2

These features make the function `plot.aquaenv` different from standard R plotting functions. However, if the flags `newdevice` and `setpar` are set to `FALSE`, `plot.aquaenv` behaves like a “normal” R plotting function

```
> par(mfrow = c(1, 2))
> plot(ae, xval = 20:30, xlab = "S", what = "K_CO2", lwd = 3,
+      col = "red", newdevice = FALSE, setpar = FALSE)
> plot(ae, xval = 20:30, xlab = "S", what = "K_HCO3", cex = 3,
+      type = "b", col = "blue", newdevice = FALSE, setpar = FALSE)
```



Furthermore, the function `plot.aquaenv` can be used to create “cumulative” plots and “Bjerrum” plots. This will be explained in some of the following sections.

3.3 Using objects of class *aquaenv* in dynamic models

3.3.1 Ordinary dynamic models

It is convenient to use objects of class *aquaenv* in a dynamic model, e.g. solved using the R package **deSolve**. This can be illustrated with an example. (For information about how to set up a dynamic model with **deSolve**, consult the documentation of **deSolve**).

```
> require(deSolve)
```

```
[1] TRUE
```

A list of parameters is specified

```
> parameters <- list(S = 25, Tc_min = 5, Tc_max = 25, d = 10,
+   k = 0.4, rOx = 3e-07, rNitri = 2e-07, rPP = 6e-06,
+   ksDINPP = 1e-06, ksNH4PP = 1e-06, D = 0.1, O2_io = 0.000296,
+   NO3_io = 3.5e-05, SumNH4_io = 8e-06, SumCO2_io = 0.00232,
+   TA_io = 0.002435, C_Nratio = 8, a = 30, b = 50, modeltime = 100)
```

A model function is defined which will be executed every timestep of the numerical integration. An object of class *aquaenv* is created in each timestep, some of its elements are used to calculate kinetic rate expressions and the whole object is returned as output.

```
> Waddenzeebox <- function(timestep, currentstate, parameters) {
+   with(as.list(c(currentstate, parameters)), {
+     Tc <- c(seq(Tc_min, Tc_max, (Tc_max - Tc_min)/(modeltime/2)),
+       seq(Tc_max, Tc_min, -(Tc_max - Tc_min)/(modeltime/2)))[round(timestep) +
+       1]]
+     ae <- aquaenv(Tc = Tc, S = S, SumCO2 = SumCO2,
+       SumNH4 = SumNH4, TA = TA)
+     ECO2 <- k * (ae$CO2_sat - ae$CO2)
+     EO2 <- k * (ae$O2_sat - O2)
+     TO2 <- D * (O2_io - O2)
+     TNO3 <- D * (NO3_io - NO3)
+     TSumNH4 <- D * (SumNH4_io - SumNH4)
+     TTA <- D * (TA_io - TA)
+     TSumCO2 <- D * (SumCO2_io - SumCO2)
+     RNit <- rNitri
+     ROx <- rOx
+     ROxCarbon <- ROx * C_Nratio
+     pNH4PP <- 0
+     RPP <- 0
+     if ((timestep > a) && (timestep < b)) {
+       RPP <- rPP * ((SumNH4 + NO3)/(ksDINPP + (SumNH4 +
+         NO3)))
+       pNH4PP <- 1 - (ksNH4PP/(ksNH4PP + SumNH4))
+     }
+     else {
+       RPP <- 0
+     }
+     RPPCarbon <- RPP * C_Nratio
+     dO2 <- TO2 + EO2 - ROxCarbon - 2 * RNit + (2 -
+       2 * pNH4PP) * RPP + RPPCarbon
+     dNO3 <- TNO3 + RNit - (1 - pNH4PP) * RPP
+     dSumCO2 <- TSumCO2 + ECO2 + ROxCarbon - RPPCarbon
+     dSumNH4 <- TSumNH4 + ROx - RNit - pNH4PP * RPP
+     dTA <- TTA + ROx - 2 * RNit - (2 * pNH4PP - 1) *
+       RPP
+     ratesofchanges <- c(dO2, dNO3, dSumNH4, dSumCO2,
+       dTA)
```



```

+         transport <- c(TO2 = T02, TNO3 = TNO3, TSumNH4 = TSumNH4,
+           TTA = TTA, TSumCO2 = TSumCO2)
+         airseaexchange <- c(ECO2 = ECO2, EO2 = EO2)
+         return(list(ratesofchanges, list(transport, airseaexchange,
+           ae)))
+       })
+ }

```

The model is solved

```

> with(as.list(parameters), {
+   initialstate <- c(O2 = O2_io, NO3 = NO3_io, SumNH4 = SumNH4_io,
+     SumCO2 = SumCO2_io, TA = TA_io)
+   times <- c(0:modeltime)
+   output <- as.data.frame(vode(initialstate, times,
+     Waddenzeebox, parameters, hmax = 1))[-1, ]
+ })

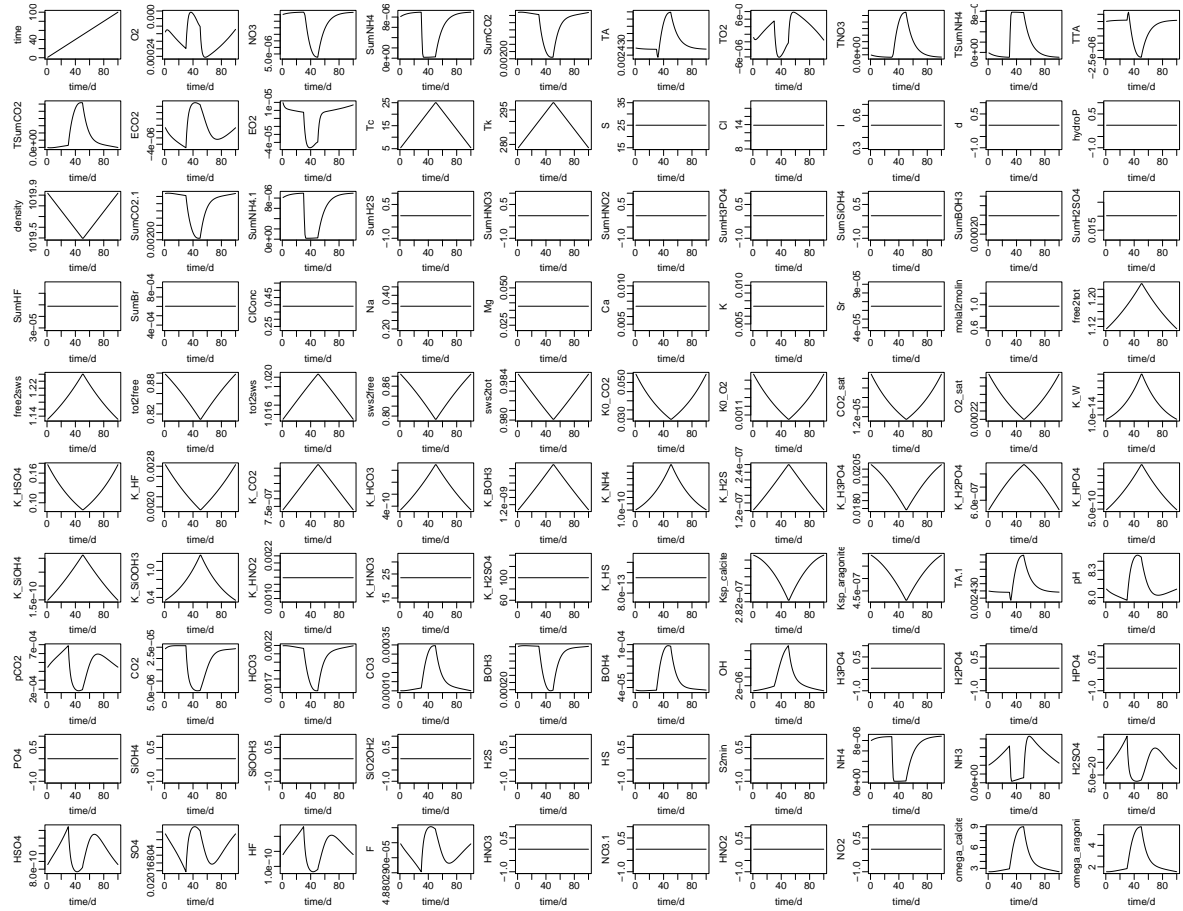
```

and the output can be plotted in the same way as a two dimensional object of class *aquaenv* by converting it to an object of class *aquaenv* using the `from.data.frame` flag of the function `aquaenv`

```

> plot(aquaenv(ae = output, from.data.frame = TRUE), xval = output$time,
+   xlab = "time/d", mfrow = c(10, 10), newdevice = FALSE)

```



3.3.2 Models using the explicit pH modelling approach

3.3.2.1 In one single model Since an object of class *aquaenv* can contain all quantities necessary to employ the explicit pH modelling approaches as introduced by Hofmann *et al.* (2008b,a,c), they can be readily used in an explicit pH model.

As an example, we give a model that calculates the pH in the “classical” way in every timestep using *aquaenv*, also employs the explicit pH modelling approach (direct substitution approach - DSA) given in Hofmann *et al.* (2008b) and additionally employs fractional stoichiometry as given in Hofmann *et al.* (2008c). The pH evolution is thus calculated in three different ways which allows comparing the three values for consistency.

Again, a list of parameters is defined

```
> parameters <- list(S = 25, Tc = 15, d = 10, k = 0.4,
+   rOx = 3e-07, rNitri = 2e-07, rPP = 6e-07, ksSumNH4 = 1e-06,
+   D = 0.1, O2_io = 0.000296, NO3_io = 3.5e-05, SumNH4_io = 8e-06,
+   SumCO2_io = 0.00232, TA_io = 0.002435, C_Nratio = 8,
+   a = 30, b = 50, modeltime = 100)
```

And a model function is defined. Again, an object of class *aquaenv* is created in each timestep and respective elements are used.

```
> boxmodel <- function(timestep, currentstate, parameters) {
+   with(as.list(c(currentstate, parameters)), {
+     ae <- aquaenv(Tc = Tc, S = S, SumCO2 = SumCO2,
+       SumNH4 = SumNH4, TA = TA, dsa = TRUE)
+     ECO2 <- k * (ae$CO2_sat - ae$CO2)
+     EO2 <- k * (ae$O2_sat - O2)
+     RNit <- rNitri
+     ROx <- rOx
+     if ((timestep > a) && (timestep < b)) {
+       RPP <- rPP * (SumNH4/(ksSumNH4 + SumNH4))
+     }
+     else {
+       RPP <- 0
+     }
+     dO2 <- EO2 - C_Nratio * ROx - 2 * RNit + C_Nratio *
+       RPP
+     dNO3 <- RNit
+     dSumCO2 <- ECO2 + C_Nratio * ROx - C_Nratio *
+       RPP
+     dSumNH4 <- ROx - RNit - RPP
+     dTA <- ROx - 2 * RNit - RPP
+     dH <- (dTA - (dSumCO2 * ae$dTAdSumCO2 + dSumNH4 *
+       ae$dTAdSumNH4))/ae$dTAdH
+     DSApH <- -log10(H)
+     rhoHECO2 <- ae$c2 + 2 * ae$c3
+     rhoHRNit <- 1 + ae$n1
+     rhoHROx <- C_Nratio * (ae$c2 + 2 * ae$c3) - ae$n1
+     rhoHRPP <- -(C_Nratio * (ae$c2 + 2 * ae$c3)) +
+       ae$n1
+     dH_ECO2 <- rhoHECO2 * ECO2/(-ae$dTAdH)
+     dH_RNit <- rhoHRNit * RNit/(-ae$dTAdH)
+     dH_ROx <- rhoHROx * ROx/(-ae$dTAdH)
+     dH_RPP <- rhoHRPP * RPP/(-ae$dTAdH)
+     dH_stoich <- dH_ECO2 + dH_RNit + dH_ROx + dH_RPP
+     DSAstoichpH <- -log10(H_stoich)
+     ratesofchanges <- c(dO2, dNO3, dSumNH4, dSumCO2,
+       dTA, dH, dH_stoich)
+     processrates <- c(ECO2 = ECO2, EO2 = EO2, RNit = RNit,
+       ROx = ROx, RPP = RPP)
+     DSA <- c(DSApH = DSApH, rhoHECO2 = rhoHECO2,
+       rhoHRNit = rhoHRNit, rhoHROx = rhoHROx, rhoHRPP = rhoHRPP,
+       dH_ECO2 = dH_ECO2, dH_RNit = dH_RNit, dH_ROx = dH_ROx,
+       dH_RPP = dH_RPP, DSAstoichpH = DSAstoichpH)
+     return(list(ratesofchanges, list(processrates,
```

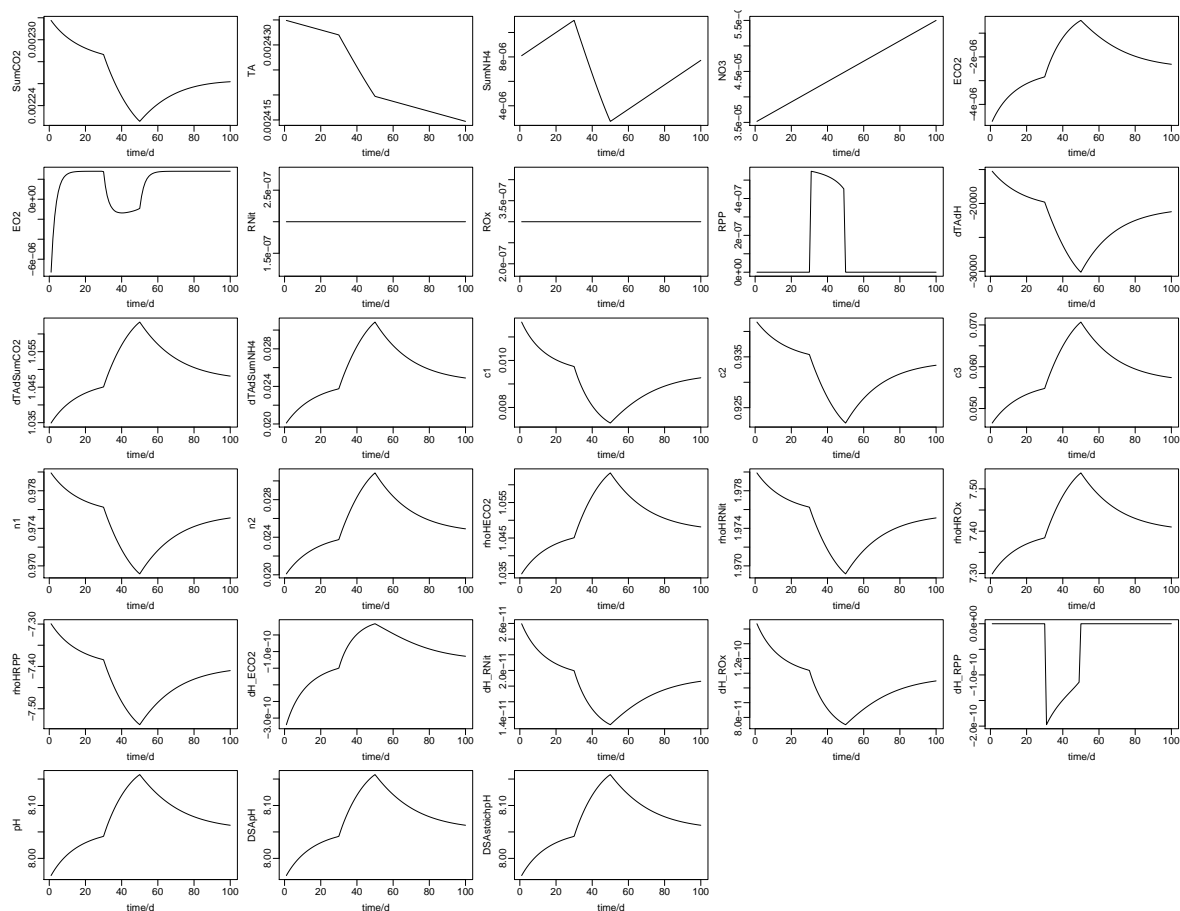
```
+           DSA, ae)))
+   })
+ }
```

The model is solved

```
> with(as.list(parameters), {
+   H_init <- 10^(-(aquaenv(Tc = Tc, S = S, SumCO2 = SumCO2_io,
+     SumNH4 = SumNH4_io, TA = TA_io, speciation = FALSE)$pH))
+   initialstate <- c(O2 = O2_io, NO3 = NO3_io, SumNH4 = SumNH4_io,
+     SumCO2 = SumCO2_io, TA = TA_io, H = H_init, H_stoich = H_init)
+   times <- c(0:modeltime)
+   output <- as.data.frame(vode(initialstate, times,
+     boxmodel, parameters, hmax = 1))[-1, ]
+ })
```

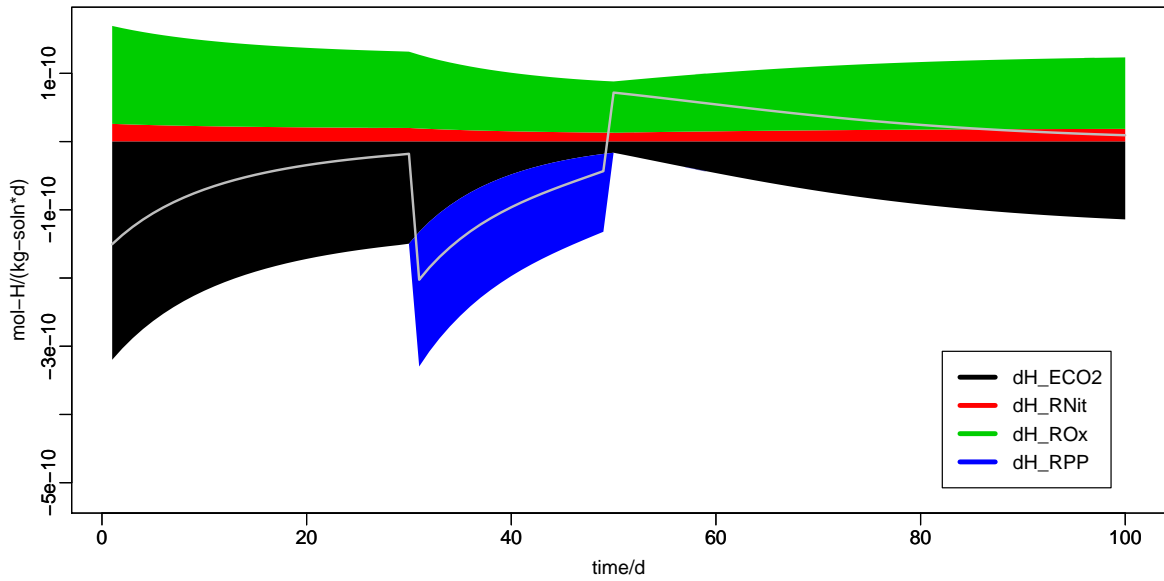
and output can be plotted. Again using `plot.aquaenv`. Note that here the parameter `what` is used.

```
> what <- c("SumCO2", "TA", "SumNH4", "NO3", "ECO2", "EO2",
+   "RNOx", "ROx", "RPP", "dTAdH", "dTAdSumCO2", "dTAdSumNH4",
+   "c1", "c2", "c3", "n1", "n2", "rhoHECO2", "rhoHRNOx",
+   "rhoHROx", "rhoHRPP", "dH_ECO2", "dH_RNOx", "dH_ROx",
+   "dH_RPP", "pH", "DSApH", "DSAstoichpH")
> plot(aquaenv(ae = output, from.data.frame = TRUE), xval = output$time,
+   what = what, xlab = "time/d", mfrow = c(6, 5), size = c(20,
+   13), newdevice = FALSE)
```



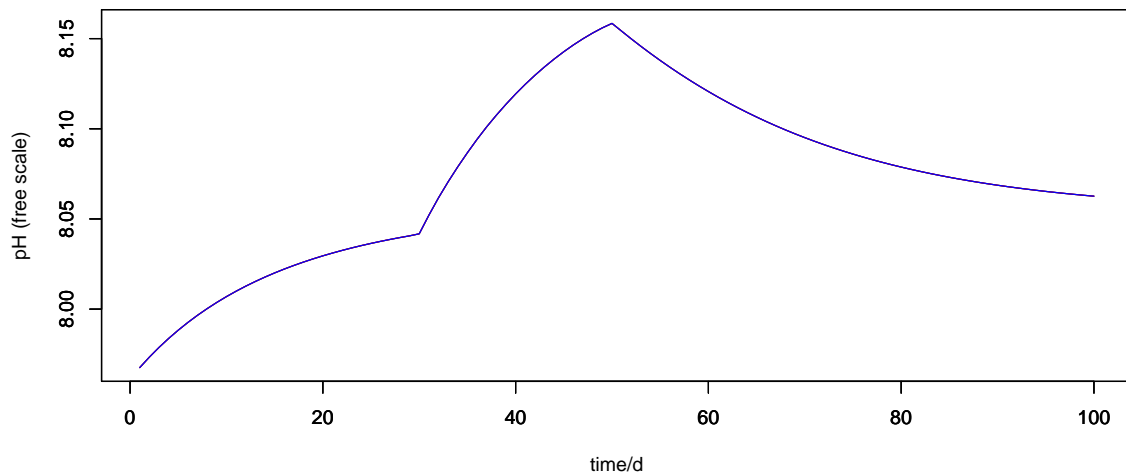
Here, the cumulative plotting functionality of `plot.aquaenv` can be employed as well to visualize the influences of the different kinetically modelled processes on $[H^+]$.

```
> what <- c("dH_ECO2", "dH_RNIt", "dH_ROx", "dH_RPP")
> plot(aquaenv(ae = output, from.data.frame = TRUE), xval = output$time,
+      what = what, xlab = "time/d", size = c(7, 5), ylab = "mol-H/(kg-soln*d)",
+      legendposition = "bottomright", cumulative = TRUE,
+      newdevice = FALSE)
```



Finally, the pH values calculated with the three different methods can be plotted in one single graph to see if they are identical, i.e. the three methods of pH calculation are consistent with each other

```
> ylim <- range(output$DSApH, output$DSAstoichpH, output$pH)
> plot(output$DSApH, ylim = ylim, type = "l", xlab = "time/d",
+       ylab = "pH (free scale)")
> par(new = TRUE)
> plot(output$DSApH, ylim = ylim, type = "l", col = "red",
+       xlab = "", ylab = "")
> par(new = TRUE)
> plot(output$DSAstoichpH, ylim = ylim, type = "l", col = "blue",
+       xlab = "", ylab = "")
```



A References for the elements of an object of class *aquaenv*

element	references
Cl	(DOE 1994, chapter 5, p. 11), and (Zeebe and Wolf-Gladrow 2001, p. 100, footnote 3)
I	(DOE 1994, chapter 5, p. 13, 15), (Zeebe and Wolf-Gladrow 2001, p.12), and (Roy <i>et al.</i> 1993b, p.257). Note that the approximation $I/(\text{mol/kg-solution}) \approx 0.0199201$ S is given in (Millero 1982, p. 428.). This relationship converted into mol/kg-H ₂ O and the last digits adjusted (from 0.0199201 to 0.019924) results in the formula used here.
density	Millero and Poisson (1981) and (DOE 1994, chapter 5, p. 6f).
SumBr, ClConc, Na, Mg, Ca, K, Sr	(DOE 1994, chapter 5, p.11)
molal2molin	(Roy <i>et al.</i> 1993b, p.257), and (DOE 1994, chapter 5, p. 15)
free2tot, tot2free	(Dickson 1984, p.2302), (DOE 1994, chapter 4, p.16), (Zeebe and Wolf-Gladrow 2001, p.57, 261)
free2sws, tot2sws, sws2free, sws2tot	(Dickson 1984, p.2303), (Zeebe and Wolf-Gladrow 2001, p.57)
K0_CO2	Weiss (1974), (DOE 1994, chapter 5, p. 13) (here it is stated that the unit is mol/(kg-solution*atm)), (Millero 1995, p.663), (Zeebe and Wolf-Gladrow 2001, p.257)
K0_O2	derived from a formula for the oxygen saturation concentration in ml-O ₂ /kg-solution by Weiss (1970) using the first virial coefficient of oxygen (Atkins 1996, p. 41, 1029) and the atmospheric oxygen fugacity (Williams 2004)
K_W	(Millero 1995, p.670) (original reference , but slightly different formula for seawater pH), (DOE 1994, chapter 5, p. 18) (NOT the original reference! DOE (1994) cites in an update from 1997 Millero (1995)! However the version of the formula used here is the one converted to total pH scale given in DOE (1994)), and (Zeebe and Wolf-Gladrow 2001, p. 258). Constant type (stoichiometric), pH scale (total, converted to free here) , and concentration unit (mol/kg-solution squared): (DOE 1994, chapter 5, p. 12,18), pH scale also in (Zeebe and Wolf-Gladrow 2001, p. 258).
K_HSO4	(DOE 1994, chapter 5 page 13), (Zeebe and Wolf-Gladrow 2001, p. 260), Dickson (1990b) (original reference). Constant type (stoichiometric), pH scale (free) , and concentration unit (mol/kg-H ₂ O converted to mol/kg-solution here): (DOE 1994, chapter 5, p. 13).
K_HF	(Dickson and Riley 1979b, p. 91) (original reference), (DOE 1994, c. 5, p. 15), (Roy <i>et al.</i> 1993b, p. 257), (Dickson and Millero 1987, p. 1783), (Millero 1995, p. 664), (Zeebe and Wolf-Gladrow 2001, p. 260) (converted to molinty and total scale). Constant type (stoichiometric), pH scale (free) , and concentration unit (mol/kg-H ₂ O converted to mol/kg-solution here): (DOE 1994, chapter 5, p. 15, 16).
K_CO2, K_HCO3	(Roy <i>et al.</i> 1993b, p. 254) (original reference), (DOE 1994, chapter 5, p.14) (in a version converted to mol/kg-H ₂ O), (Millero 1995, p. 664), (Zeebe and Wolf-Gladrow 2001, p. 255). Constant type (stoichiometric) and concentration unit (mol/kg-H ₂ O converted to mol/kg-solution here): (DOE 1994, chapter 5, p. 14, 15), pH scale (total, converted to free here): In (DOE 1994, chapter 5, p. 12) the total scale is stated for the formula for high salinities and thus can be inferred for the formula for low salinities. The scale is also indirectly stated for both formulations in the original reference Roy <i>et al.</i> (1993b). Note that in Roy <i>et al.</i> (1993b) a function for pure water (Millero 1979) is cited and a function for seawater is derived. In Millero (1995) it is stated that for S<5 the fresh water formula of (Millero 1979) should be used and for S>=5 the seawater formula derived in Roy <i>et al.</i> (1993b). However, both formulations do not always intersect at S=5. The true intersection with respect to salinity S is a function of temperature Tk. Here, we first calculate this intersection by numerical root finding and then decide which formulation to use. This practise results in a continuous function with respect to S. (Note that Millero (1979) is restated wrongly in Roy <i>et al.</i> (1993b): one of the numerical values for the function for K _{CO2} [*] is given as 310.48919, but correct is 2310.48919. However, in Millero (1995) this value is stated correctly.)

K_BOH3	(Dickson 1990a, p. 763) (original, but mol/kg-H ₂ O version), (DOE 1994, ch. 5, p. 14), (Zeebe and Wolf-Gladrow 2001, p. 262), (Millero 1995, p.669) (mol/kg-H ₂ O version) , agrees with data in Roy, Roy, Lawson, Vogel, Moore, Davis, and Millero (1993a). Constant type (stoichiometric) and concentration unit (mol/kg-solution): (DOE 1994, chapter 5, p. 14), pH scale (total): (DOE 1994, chapter 5, p. 12) and (Zeebe and Wolf-Gladrow 2001, p.263).
K_NH4	Millero <i>et al.</i> (1995) (original reference), (Millero 1995, p.671). Constant type (stoichiometric) and concentration unit (mol/kg-solution): (Millero 1995, p.671), pH scale (seawater, converted to free here): Lewis and Wallace (1998) (in corrections of Millero (1995)).
K_H2S	Millero <i>et al.</i> (1988) (original reference), (Millero 1995, p.671). Constant type (stoichiometric) and concentration unit (mol/kg-solution): (Millero 1995, p.671), pH scale (seawater, converted to free here): Lewis and Wallace (1998) (in corrections of Millero (1995)).
K_H3PO4, K_H2PO4, K_HPO4	(Millero 1995, p.670) (original reference, but formula for seawater scale pH), (DOE 1994, ch. 5, p 16,17), agrees with data in Dickson and Riley (1979a). Constant type (stoichiometric), concentration unit (mol/kg-solution), and pH scale (total, converted to free here): (DOE 1994, chapter 5, p. 12, 16, 17).
K_SiOH4	Millero <i>et al.</i> (1988) (original reference), (DOE 1994, chapter 5, p 17), (Millero 1995, p.671) (formula for seawater scale pH) Constant type (stoichiometric), concentration unit (mol/kg-H ₂ O converted to mol/kg-solution here by omitting the conversion summand $\ln(1-0.001005\text{ S})$), and pH scale (total, converted to free here): (DOE 1994, chapter 5, p. 12, 17).
K_SiOOH3	Wischmeyer <i>et al.</i> (2003) (original reference), corrected due to personal communication with Dieter Wolf-Gladrow (one of the authors). The corrected version can be obtained from either Dieter Wolf-Gladrow or Andreas F Hofmann (a.hofmann@nioo.knaw.nl). Constant type (stoichiometric), concentration unit (mol/kg-solution), and pH scale (total, converted to free here): Wischmeyer <i>et al.</i> (2003).
K_HNO2	Constant value, not a function of temperature and salinity! Obtained as a hybrid pk value (featuring the activity of the proton but the concentration of other species (see Zeebe and Wolf-Gladrow (2001) for a treatment of different types of equilibrium constants) in molar concentration (mol/l) on the NBS pH scale (Durst 1975) from Riordan <i>et al.</i> (2005). Used as an approximation for the stoichiometric $K_{\text{HNO}_2}^*$ in mol/kg-solution on the free proton pH scale here.
K_H2SO4	Constant value, not a function of temperature and salinity! Obtained as a standard pK value from (Atkins 1996, p. 1045). Used as an approximation for the stoichiometric $K_{\text{H}_2\text{SO}_4}^*$ in mol/kg-solution on the free proton pH scale here.
K_HS	Constant value, not a function of temperature and salinity! Obtained as a standard pK value from (Atkins 1996, p. 1045). Used as an approximation for the stoichiometric $K_{\text{HS}^-}^*$ in mol/kg-solution on the free proton pH scale here.
Ksp_calcite, Ksp_aragonite	Mucci (1983) (original reference), Boudreau (1996). Note that in there are errors in Boudreau (1996): b_0 for calcite is not 0.7712 but 0.77712 and b_1 for aragonite is not 0.001727 but 0.0017276.
pH	As given in Dickson (1984), p. 2303 (use of "m") and Dickson and Riley (1979a), p. 91f all concentrations appearing in the definition of the total and the seawater pH scale are molal (mol/kg-H ₂ O) concentrations. But in Roy <i>et al.</i> (1993b), p. 257 and in DOE (1994), chapter 4, SOP 6, p. 1 it is stated, that concentrations for the seawater and total pH scale are in mol/kg-solution. To be consistent with DOE (1994) molal concentrations (mol/kg-solution) are chosen for calculating the pH.
revelle	(Zeebe and Wolf-Gladrow 2001, p.73)
dTAdKdKdS, dTAdKdKdT, dTAdKdKdd, dTAdKdKd- SumH2SO4, dTAdKdKd- SumHF	Hofmann <i>et al.</i> (2008a)

The values for K_W, K_HSO4, K_HF, K_CO2, K_HCO3, K_BOH3, K_NH4, K_H2S, K_H3PO4, K_H2PO4, K_HPO4, K_SiOH4, K_SiOOH3, Ksp_calcite, Ksp_aragonite obtained as functions

of salinity S and temperature T_c from the above references are pressure corrected using the given depth d and the calculated hydrostatic pressure $hydroP$ according to [Millero \(1995\)](#) with corrections by [Lewis and Wallace \(1998\)](#).

In general it is to be said that all corrections from [Lewis and Wallace \(1998\)](#) have been applied.

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