Interactions and feedbacks in CRAICC ESMs

As their name suggests, Earth System Models (ESMs) try to integrate all components and processes to describe the state of the Earth System. In ESMs, the Earth System is divided into three main components: land, ocean and atmosphere. These main components can be further broken into models of dynamics, biogeochemistry, chemistry, aerosol microphysics, cryosphere, etc. The level of complexity of these submodels varies between different models which, together with the limited interactions between model compartments, affects the possible response of a certain model component to changing model state. The motivation behind this document is not to list details of the components inside ESMs, but to introduce the available ESMs in CRAICC regarding their potential to simulate the necessary interactions and climate feedbacks.

Optimally, there would be several options for including an component in an ESM: disabled/omitted, prescribed, parameterized, and as a fully interactive submodel. A component is disabled when no direct information is included in the model, however, the component can still be implicitly included into properties of another model component. If enough information is available, a component can be prescribed in the model. The component can be described in various dimensions, usually as global/latitudinal/grid cell and annual/monthly/daily average. Prescribed components are independent on the model state, and hence lack two-way interaction with other model components. Here, interactive components are derived into two categories: parameterized and fully interactive components. The distinction is done based on the level of complexity (and added computations) of the included component. A parameterized component applies a predefined function on a set of required parameters to compute a desired quantity but does not include additional prognostic variables. A full submodel on the other hand, can include any number of new prognostic quantities and computations, and even exceed the original model in complexity.

What are the reasons to choose from the above options for a given model component in an ESM? Intentionally omitting a certain component can result from the assumption that the component has no significant effect on the Earth System or vice versa. Naturally, there are likely important processes that are not yet included in any ESM, purely due to lack of knowledge. The reasoning between prescribing or actively simulating certain components can be due to several factors: insufficient knowledge, computational performance, or the need to artificially limit the model response. Fig. 1 presents an example between three submodels and their interactions. Property A is parameterized as a function of B, while the calculation of B and D is connected between two separate submodels. Also, the calculation of D requires additional prognostic variable C to be simulated in submodel 2.

An example of level of complexity and implemented interactions for a ESM submodel can be presented for the ocean. An atmosphere-only simulation generally applies prescribed monthly-average sea-surface temperatures (SST) and sea-ice fraction for each model grid cell. This model setup is required when the ocean response is unwanted, e.g. when calculating the fixed-SST (quasi-)forcing of aerosols. The ocean can be driven by an observed ocean state of a given year or a climatology. The ocean response can be included with two levels of complexity: as mixed layer ocean (MLO) model or as a ocean general circulation model (OGCM). As opposed to the full ocean model, the mixed layer ocean can be used to achieve equilibrium in a short time scale, but the model can not simulate changes in deep ocean heat content and ocean currents, and the simulated transient climate response could be unrealistic.

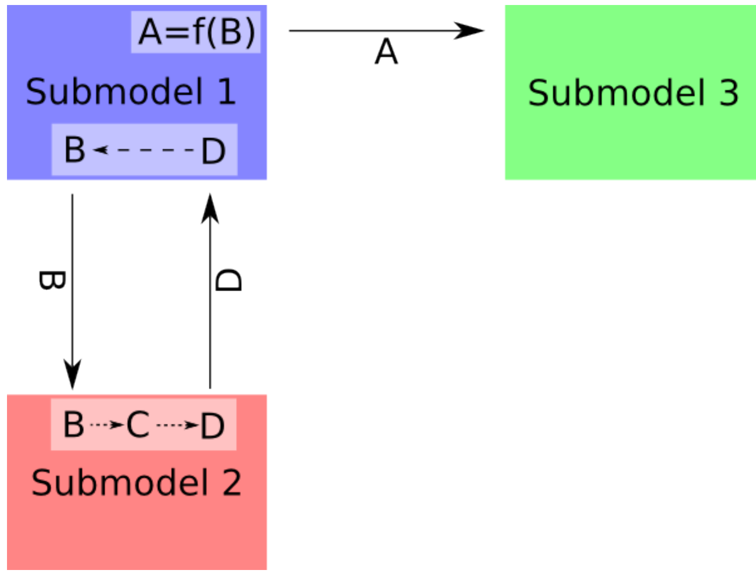

Figure 1: Example of interactions of 3 submodels.

While for some components it is rather straightforward to choose between an interactive (online) and prescribed (offline) model version, it is technically difficult to limit the interactivity of certain dynamic processes. For example, aerosol particles affect cloud properties by acting as cloud condensation nuclei (CCN). The aerosol concentration can modify not only cloud albedo, but also cloud lifetime and other cloud micro-physical properties. To quantify only the effect of aerosols on cloud albedo, the models radiation code can be called twice, with perturbed and unperturbed CCN concentrations. When aerosols are interactively included in the cloud micro-physics, the cloud fields in two simulations can be radically different resulting in a large change in climate. To artificially limit the response of the atmosphere to perturbations, some models can nudge the atmospheric state (temperature, vorticity, divergence) to some prescribed state.

CRAICC ESMs

The CRAICC community includes three ESMs: the Norwegian Earth System Model (NorESM), the Max Planck Institute for Meteorology Earth System Model (MPI-ESM) and EC-Earth. All three models are included in the recent coupled model intercomparison (CMIP5). Although the number of ESMs in CMIP studies has increased since CMIP2 and CMIP3, all models in CMIP5 are definitely not unique but instead share a vast amount of code and whole submodels (Knutti et al., 2013). Both EC-Earth and MPI-ESM are based on the same atmospheric model, derived from different versions of the ECMWF weather forecast model. The “genes” of NorESM are further away from the two other models, since NorESM is largely based on the NCAR CESM. However, NorESM shares the same ocean biogeochemistry model (HAMOCC) with MPI-ESM, and the chemistry model in both ESMs is based on the MOZART chemistry scheme. The model similarities/differences can be seen in Fig.3 of Knutti et al. (2013), where EC-Earth and MPI-ESM are almost identical while NorESM is somewhat separated in terms of simulated temperature and precipitation.

Even with some similarities in codes and results between the three models, the models include a significant amount of different submodels and components that interact and respond in various ways. The main features of the three ESMs are presented in Fig. 2.

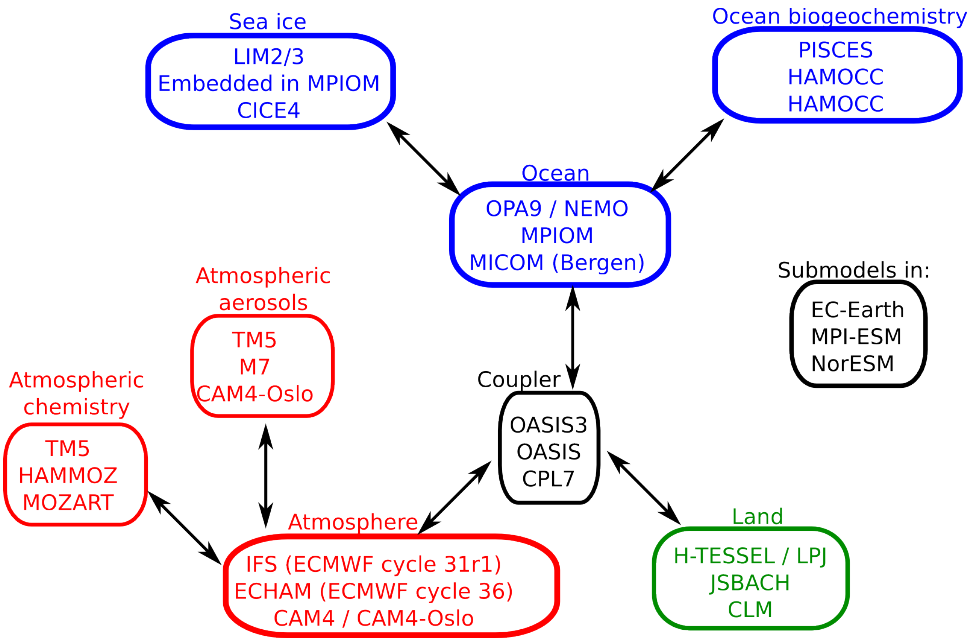

Figure 2: CRAICC ESMs and their submodels.

Some of the proposed interlinks and loops in CRAICC (Fig. 3) include components and interactions that have been included in ESMs since their birth. Naturally, all three models can be used to simulate climate change and Arctic warming (B in Fig. 3). The three models provide a distinct behavior for example with respect to Arctic sea-ice extent (Fig. 4), hence the strength of the potential feedbacks might also vary between models. Changes in cryosphere (C in Fig. 3) are included in the models to some extent. While atmospheric snow formation is described already in the basic atmosphere-only models, the formation processes can be refined by cloud micro-physical models coupled to the atmosphere models. In all models snow is deposited on ground where it affects the surface albedo, however the effect of aerosol deposition on snow varies between models. While sea-ice has been a predicted component in ESMs since 1990s, the coupling of interactive land-ice components has been lagging in development.

Table 1 lists selected model properties from each ESM. The Table 1 indicates if a component is modeled interactively in the ESM (component depends on model state), in contrast to being prescribed or completely omitted. The interactive properties are classified as “not available”, “in CMIP5” and “available for CRAICC”. The model versions for CMIP5 were to be frozen for a certain date and might not include the newest model developments. The components available for CRAICC listed in Table 1 are at least available in the corresponding submodel, but it is not guaranteed that they have been fully implemented and tested for the ESM.

In general, ESMs prescribe all human activities (D in Fig. 3) in the model. For example, emissions from anthropogenic sources are either monthly or yearly averages. There are some examples of human interactions that could be parameterized based on model state, such as residential heating as a function of simulated atmospheric temperature. More detailed couplings could be achieved by connecting ESMs with Integrated Assessment Models (IAMs). The current approach of decoupling IAMs from ESMs to model the societal changes, human impact and mitigation separately from the climate system is required to force several models with similar scenarios, but the simulations will always be inconsistent in terms of simulated climate state and the corresponding anthropogenic activities.

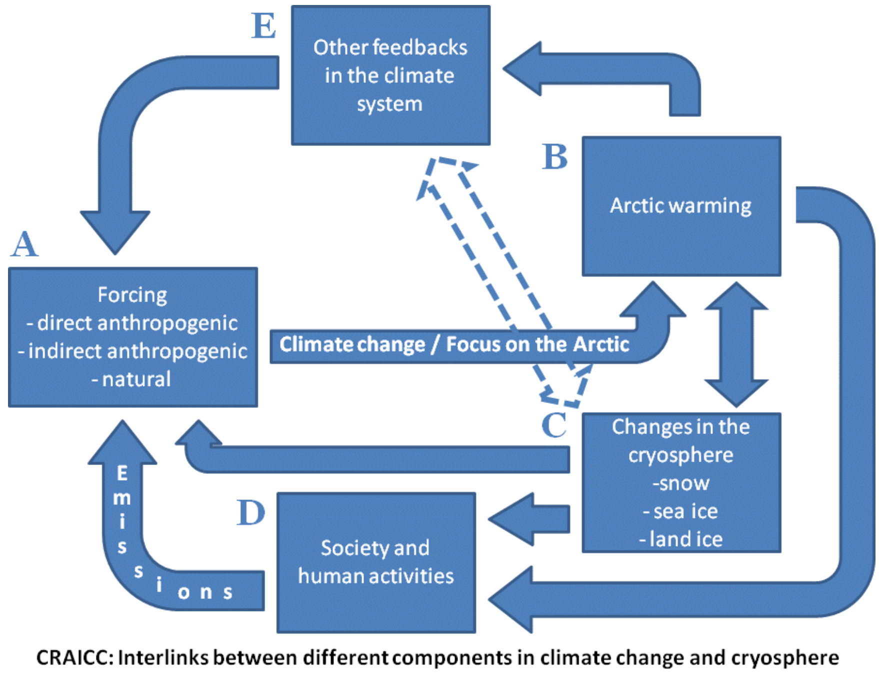

Figure 3: Interlinks between different components in CRAICC.

Can we quantify the proposed loops in Fig. 3 with the ESMs? For loop 1 (albedo feedback, A-->B-->C-->A), most processes are included in the model to some extent and the strength of the feedback can be quantified by perturbing the model by an external forcing. The second loop (C-->D-->A-->B-->D) is related to increased Arctic activity due to changes in Arctic conditions. Since the models are lacking the interactivity in the anthropogenic component, the loop is not closed and can not be driven by changes in cryosphere (C-->D). Instead, the change in anthropogenic activities due to Arctic changes must be estimated separately and prescribed into the model system as changes in emission, land use etc (D). Similarly, in loop 3 (geoengineering, D-->A-->B-->(C)-->D) the changes in anthropogenic emissions are used to drive the feedback loop. Although it is technically possible to quantify the strength of most of the proposed interlinks, it should be kept in mind that even the simulated present-day response of the Arctic system can still differ significantly from the observations (e.g. Fig. 4).

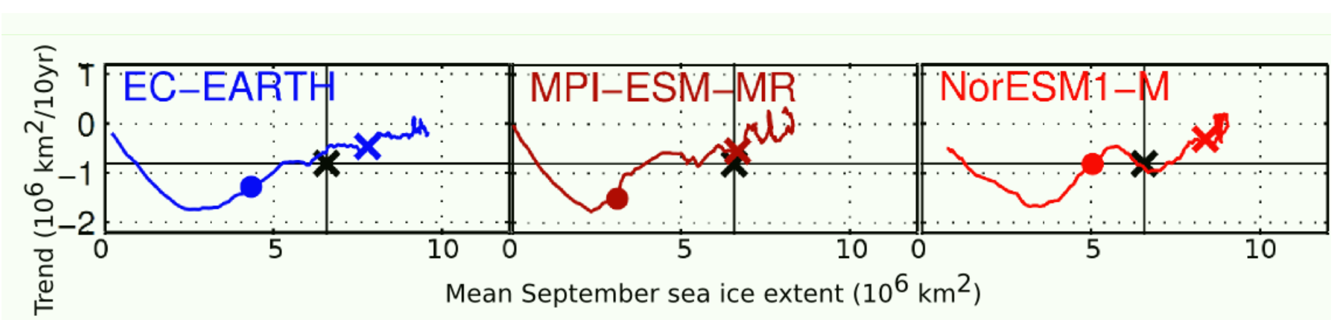

Figure 4: The simulated evolution of the Arctic September sea-ice extent and trend from year 1850 to 2100 with three CRAICC ESMs. The black cross is the observed and the colored crosses are simulated current sea ice extent. Figure adapted from Massonnet et al. (2012).

A significant part of the total Arctic feedback loops could lie in the "other feedbacks in the climate system" (E in Fig.3): some of these other feedbacks are likely to be unknown and some may be inadequately included in the model. Individual missing feedback loops are not simply added to the ESM, but rather the required interlinks are improved and developed. Naturally, CRAICC provides new data that will improve existing interactions and even establish new feedback loops. For example, interactive oceanic DMS emissions have been implemented in NorESM in CRAICC. This will allow the DMS emission to respond to changes in e.g. Arctic temperatures, wind speed and sea ice cover, creating a new feedback mechanism in the model. Also, the BVOC-aerosol-climate feedback loop (Kulmala et al., 2004) is now established in NorESM within CRAICC, with the introduction of interactive BVOC emissions and new organic aerosol formation mechanisms.

What potential feedbacks are the current models lacking, especially in Arctic point-of-view?

One of the most crucial feedback related to Arctic warming is the increase in methane and CO_2 emissions from the thawing Arctic soils. An immense positive climate feedback could lay in the sub-sea permafrost, which could release a significant amount of methane with warmer Arctic Ocean temperatures. Although the advanced chemistry submodels in ESMs do include methane, there are no mechanism included to simulate the permafrost methane hydrates and their release interactively. Hence, feedback studies regarding abrupt increases in methane emission from permafrost will need to rely on prescribed emission scenarios.

Arctic climate change could open the door for new pest and invasive species to high latitudes. Depending on the response of the e.g. native vegetation, this could lead to changes in emissions, distribution of vegetation and related human activities. Pearson et al. (2013) found significant changes in Arctic vegetation until year 2050, with more than 50% of vegetation cover switching to different physiognomic class. Together with an 52% increase in forest coverage would lead to a strong positive feedback if albedo and evapo-transpiration are considered. The ESMs are not yet able to consider large-scale changes in vegetation patterns or the introduction of invasive pest species. The land/vegetation models in ESMs need to be developed in terms of responses of vegetation to environmental conditions (Arneth et al., 2012).

Climate change can have a large impact on river flows: while some rivers might experience drying, the occurrence and severity of floods is increasing. This would likely directly influence the anthropogenic activities in nearby areas, but increased or decreased river flow and the occurrence of floods affects also several natural aspects which are either poorly included or omitted in the ESMs. Due to increased evapo-transpiration in warmer climate, a smaller fraction of the collected runoff water will reach the ocean. Models assuming instant runoff collection to ocean model (no river delay) will overestimate output to oceans. Also, the nutrient and DOC river input to oceans is currently not included in the ESMs. Floods will temporarily increase the amount of transported material, but also disturb the vegetation and soil along its path. Neither of these effects are considered in current models. River input is especially important for the Arctic Ocean properties due to its small size (Holmes et al., 2012). The possible feedbacks relating e.g. climate warming, river input to Arctic, and biogeochemistry in the Arctic ocean are currently missing in the ESMs.

Warming climate, earlier spring and changes in precipitation and hydrology will affect the occurrence of wildfires (e.g. Westerling et al., 2006). While wildfires induce a direct local impact by changing the vegetation distribution and albedo of the area, they also emit large amounts of CO_2, organic matter, black carbon and nutrients. Current ESMs usually prescribe wildfire emissions as monthly averages for each grid point, usually based on Global Fire Emissions Database (GFED, http://www.globalfiredata.org). Hence, the modeled wildfire emissions can not respond to the simulated climate change. Also, the occurrence of wildfire in the model does not influence e.g. the emissions BVOCs by the vegetation. There are several possible wildfire-related feedbacks that are currently not included in the ESMs (Carslaw et al., 2010).

Ocean is a source of biogenic VOC emissions, such as monoterpene and isoprene (e.g. Shaw et al., 2010). Partly due to scarcity of observations, the global estimates of the oceanic BVOC emissions are highly uncertain, with isoprene fluxes ranging from <1 to >10 Tg(C) yr^{-1} (Shaw et al., 2010). Also, insufficient knowledge of the dependence of the emission on environmental conditions, chlorophyll concentration and plankton species prevents the inclusion of emission models in ESMs. Currently, most ESMs completely exclude oceanic VOC emissions. However, natural oceanic emissions of aerosols and aerosol precursors are important in determining both the pre-industrial reference state of the aerosol climate effect and the relative effect of anthropogenic aerosols above the oceans. The ESMs are unable to respond to the possible changes in marine BVOC emissions in a changing climate.

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0=not available, 1=in CMIP5-version, 2=not in CMIP5, but available for CRAICC

				NorESM	MPI-ESM	EC-Earth	More information: NorESM	ECHAM-ESM	EC-Earth
Ocean									
	Ocean dynamics								
		General circulation model		1	1	1	MICOM	MPIOM	OPA
		Option to use mixed-layer ocean		2	1	1			
	Biogeochemistry			1	1	2	HAMOCC	HAMOCC	PISCES
		Ocean carbon cycle		1	1	2			
		P, N, Si, Fe		1	1	2			
		DOC, dissolved oxygen		1	1	2			
		Formation of calcium carbonate		1	1	2			
	Sea-ice	Dynamic sea-ice model		1	1	1	CICE4	In MPIOM	LIM2/3
		Melt ponds		1	1	1	Holland et al. (2012).	Roeckner et al. (2012)	Koltzov et al. 2007
Ocean-Atmosphere									
	Interactive emissions								
		Sea salt (wind driven)		1	1	0	Mårtensson et al. (2003)	Monahan et al. (1986)	
		DMS (wind-driven, prescribed sea-water conc.)		2	1	0		Prescribed DMS sea-water concentration:	
		DMS (effect from nutrient deposition etc.)		2	1	0	HAMOCC	HAMOCC	
		Biogenic vapours		0	0	0			
		Primary organic aerosol (wind driven)		2	0	0	Spracklen et al. (2008)		
		O2, N2,N2O		1	1	2	HAMOCC	HAMOCC	PISCES
		Methane		0	0	0			
	Deposition								
		Black carbon on sea-ice		1	1	2	Holland et al. (2012)		
		Iron (dust), nutrients		1	1	2	(Prescribed: Mahowald et al. (2005))	HAMOCC	
Atmosphere									
	Water vapour concentration			1	1	1			
	Clouds	Stratiform		1	1	1	Rasch and Kristjansson (1998)		
		Deep convective		1	1	1	Zhang and McFarlane (1995)		
	Interactive aerosol components		Sulfate	1	1	2			Prescribed monthy average 3D fields; for CMIP: only sulfate
			Black carbon	1	1	2			
			Organic carbon	1	1	2			
			Dust	1	1	2			
			Sea salt	1	1	2			
			Number conc.	0	1	2			
	Aerosol-cloud interactions	Prognostic CDNC		1	1	2	Abdul-Razzak and Ghan (2000)	Lohmann et al. (2007)	Aerosol-CDNC connection: Jones et al. (2001) & Lohmann (1995)
		Prognostic ICNC		0	1	0		Lohmann et al. (2007)	
	Interactive chemistry	Basic DMS/sulfate chemistry with prescribed oxidants		1	1	2			
		Chemistry model		2	2	0	MOZART	HAMMOZ	
	Aerosol-radiation interactions (direct effect)			1	1	1			
	Semi-direct effect			1	1	1			

Land-Atmosphere

Interactive emissions	Biogenic	VOC	2	2	2	CMIP5: prescribed monthly	CMIP5: prescribed monthly	
		Nox	2	2	2			
		PBAP	0	0	0	Primary Biological Aerosol Particles		
	Dust (wind speed, hydrological parameters)		0	1	0	Daily AeroCom emission	Cheng et al., (2008)	
	Wildfire (occurrence, intensity, temperature, hydrology)		0	0	0			
	Volcanoes		0	0	0	Annual averages, divided into erupting/continuous		
Deposition								
	Black carbon on snow/ice		1	1	2	Flanner and Zender, 2006		
	Dust on snow/ice		1	1	2			
	Nutrient deposition on vegetation		1	1	2			
	Acid deposition on vegetation		0	0	0			
	Aerosol deposition on leaves		0	0	0	Effect on leaf-surface wetness, risk of pathogen attack (Cape, 2008)		

Land

Vegetation model						CLM4	JSBACH	CMIP5:HTESSEL (LPJ available)
	Fully dynamic vegetation		0	0	0			
	Prognostic carbon		1	1	2			
	Prognostic nitrogen		1	1	2			
	River runoff to oceans: nutrients, DOC		2	0	0			
	Potential dust sources (vegetation change, erodicity)		0	0	0			
Wildfire	Frequency, occurrence		0	0	0	Monthly average emissions based on GFED		
	Impact of fire on vegetation (albedo, BVOC emission etc.)		0	0	0			
Land ice			0	0	0	Prescribed		
Land snow	cover		1	1	1			
	aging		1	1	1			
	albedo		1	1	1			
Rivers	Water flow		1	1	1	Runoff without river delay		
	Location, river path		0	0	0	Prescribed		
Lakes	Temperature		1	1	1		Only lakes > 50% grid size, mixed-layer model	
	Ice cover		1	1	1		Ice-covered/ice-free	

Anthroposphere

Interactive emissions	Fossil fuel		0	0	0			
	Biomass burning		0	0	0			
	Residential heating		0	0	0			
Land-use change			0	0	0			
Shifts in human activities due to climate change	(e.g. shipping routes)		0	0	0			

Animalia

	Effect of pests on vegetation		0	0	0			
	Effect of climate and pollution on animals		0	0	0			

Geosphere

Volcanism			0	0	0	Volcanic emissions are averaged over the year and emitted at each time step		
Earthquakes			0	0	0			
Tectonics			0	0	0			