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Making coastal research useful — cases from practice

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Summary Coastal research deals with that part of the sea, which is significantly affected by the land, and the part of the land, which is significantly affected by the sea. Coasts are in most cases densely populated, and the activities of people are shaping and changing the land/seascape of the coast. Thus, coast encompasses the coastal sea, the coastal land, coastal flora and fauna, and people. Since peoples' economic and political preferences change and compete, the human impact on the coast changes is contested and subject to societal decision making processes.

While some coastal research can help informing and constraining such decisions, many legitimate scientific efforts have little bearing on society. All decision making processes are political, so that scientific knowledge is not the dominant driver in such processes. Using cases from the Institute of Coastal Research of Helmholtz Zentrum Geesthacht, we describe some of these potentially useful parts of science, and discuss under which circumstances the potential usefulness transform into real utility. These cases do not span the full range of coastal science.

Important issues are the recognition of alternative knowledge claims, the inevitableness of uncertainties and incompleteness of scientific analysis, the acceptance of the political nature of decisions and the ubiquitous presence of social values. Modesty, self-reflexivity and skepticism are needed on the side of science and an organized exchange with stakeholders and public through designated "border" services.

1. Societal utility — bugaboo or reality?

It is nowadays a common requirement when preparing scientific proposals that the project is generating societally useful knowledge or skills. Thus, almost all proposals feature a section or at least a paragraph which describes "outreach", "knowledge transfer" or "stakeholder-interaction". In many cases, the proposers and reviewers have only lay-concepts for doing so, and the activity goes rarely beyond giving a few

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talks on public events and a press release, while others generate advanced web-pages ("tool boxes" and "roadmaps") for the public and policy makers.

Thus, the reference to stakeholders and decision making is often merely rhetorical and is not backed by thought-through concepts and approaches, but are based on naïve "linear" models operating with superior knowledge, which needs to be filled in stakeholders, who ask for enlightenment (e.g., van der Sluijs, 2010).

Many scientifically legitimate and valid questions or answers have no direct bearing for any stakeholder. Therefore it is not surprising that the stakeholder-interaction is often not taken seriously. Indeed, most scientific achievements will have no significant direct applications, but contribute "merely" to the overall understanding of a complex and multi-faceted natural and social milieu. Indeed, it is one of the narratives of the logic of funding science, which some relate to the US thinker Vannevar Bush (1945), that a few supported efforts of many will result in very useful offsprings, such as the famous Teflon pan. In this logic, the cost—benefit balance of funding science is positive because of some practical hits, while most efforts result in scientifically exciting insights with little relevance for anything except for a better understanding of often remote niches of reality. Since nobody knows, which of the many efforts will prove useful, it is best to fund all of them, as long as they are "scientifically good". Whether this strategy is realistic is another question, and other thinkers contend that science, which is based on the desire for being able to explain our natural and social environment, is just a fundamental need of western civilization and culture.

Admittedly, some of these scientific insights provide clues for a better understanding or better modeling of the system at hand. In the spirit of Vannevar Bush, some of these improvements turn out being useful in decision processes at a later time. However, it is not so that science would solve societal conflicts and would lead to sustainable "solutions", such as how to use certain areas, or how to decide about conflicting usages of coastal seas, such as off-shore wind energy, fishing and natural conversation.

In the end, all decisions about solutions are political. They are related to and associated with socially constructed values, preferences and interests. But science can help to determine which probable or possible consequences the different options may have ("recursive model", cf. Weingart, 1999). By answering "if—then" questions and dealing with options of decision making, science can contribute valuably to quality of life, both in terms of "making sense" of a complex environment and practical management. This is particularly so with respect to coastal sea systems.

The body of potentially useful knowledge about the state, the development of the coast, about options for managing the coast, needs a sustainably managed infrastructure. This infrastructure comprises coastal observatories, process and simulation models, tools for dynamical and statistical analysis of change, interdisciplinary exchange between the involved disciplines from physics to geology, from engineering to ecology, and socio-economic assessment methods for the integration of relevant data and expert judgments. Useful coastal science must be based on a solid scientific basis.

But such a basis is not enough for making coastal science "useful". The attribute "scientific" is not sufficient for an analysis to gain acceptance in the public and among stakeholders. This is clearly demonstrated by the public debate about the reality of man-made climate change. Instead, scientifically legitimized knowledge is just one form of knowledge, which has to compete with other forms of knowledge in the public domain (von Storch, 2009).

Stakeholders, including the public and media, are often confronted with developments and events in coastal environments that appear hazardous, alarming or promising. Some events are noticed only by a few decision makers, who ask for intensity, spatial and temporal extension, for options, systematic changes and perspectives. In other cases, the general public is getting involved, and the issue becomes a legal or political one. In both cases, coastal science is asked for answers, orientation and, when societal interests are involved, provision of a broader context. However, stakeholders have already knowledge what is going on; sometimes this understanding is consistent with scientific insights, but often it is partially or even completely inconsistent. For placing consolidated scientific knowledge in such a "knowledge-environment", scientific actors need to understand these "other" knowledge about the dynamics, statistics and conditioning of the coastal sea environment. We come back to this issue in the concluding section.

For this purpose, we not only need "border organizations", which identify the utility of scientific achievements for societal needs, but also apprehend societally relevant questions. These border organizations nowadays go often with the concept of "services". A successful service needs a rooting in scientific concepts, in understanding social dynamics, and in an exchange with stakeholder perceptions (von Storch and Stehr, 2014).

Under the headline of servicing, political manipulation in favor of specific "solutions" may take place. The issue of blending the roles of activists and scientists, for instance in the form of stealth activist scientists (Pielke, 2007) is a significant challenge, also for coastal science. Some political and economic actors appreciate favorable support by such stealth advocate scientists for pushing their views and interests. It seems that many in the scientific community have little reservation with such activities.

In this situation it makes sense to think about and discuss, in which way coastal science can become useful. What are the typical types of knowledge, which provides utility in real-world problems, tasks and decisions? For doing so, we first sketch five categories. These categories are not independent of each other. Also, they may be considered of different epistemological levels; they address different stakeholder groups.

1. "**Making sense**" refers to the scientific understanding of complex phenomena, and its use for supporting societal framing and decision making. Examples are consequences of eutrophication or the manifestation of natural system variations vis-a-vis anthropogenic climate change. Novel or recurrent but threatening events in complex coastal environments can attract considerable attention in stakeholder groups and the public. Meaning-providing frames, which allow for causal interpretation and understanding, satisfy not only curiosity, but allow for engineering preparedness and options for specific stakeholders. A significant constraint is that science is

not the sole supplier of such understanding, but other knowledge brokers are active as well (cf. Section 2).

2. "**Marine Spatial Planning** (MSP)" describes the "public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process".[1] MSP is an approach for deciding about competitive concepts of usage of coastal space. This process needs mostly quantitative information from natural sciences for project-specific technical planning exercises, but in addition (social) science needs to provide (mainly qualitative) information concerning societal and political context and structures to inform decision makers in strategic planning (cf. Section 3).
3. "**Monitoring**" aims at the assessment of the current status of the coastal environment and short term trends, and their (deterministic) short-term forecasts. Such assessments are based on observations and related (model-guided) data analysis. The process of making data, assessments and forecasts available for users is also a challenge (cf. Section 4).
4. Assessments of (statistical) "**hazards, risks and opportunities**" are needed for almost any kind of onshore and offshore operation. An important component of this activity is the determination of ongoing long-term changes. For the assessment of negative outlooks and positive perspectives comprehensive and homogeneous data are needed. The situation is particularly challenging, when too short, too fragmented or only inhomogeneous observed data are available. Then, sometimes, model-derived estimates can be used (cf. Section 5).
5. "**Scenarios**", differently to forecasts, address questions of the type "What may happen, if ... and nothing else". Such projections provide a useful outlook for assessing consequences of possible future developments and uncertainties. Therefore scenarios have become increasingly popular in various scientific and decision making contexts (Schwartz, 1991; cf. Section 6).

The first "making sense" addresses the general public, scientists, media, but to a lesser extent planning exercises. This is so, because this category provides first of all qualitative "knowledge" about mechanisms. This is different with the other categories, where numbers are produced, which may guide short term decisions, as in case of monitoring, or economic planning, as in case of assessing risks and their changes.

In the center part of the paper, we illustrate these categories with the help of examples selected from the practice of the HZG Institute of Coastal Research In Geesthacht, Germany. In the concluding Section 7, the issue of building science-stakeholder interaction is addressed.

2. Making sense

"Making sense" refers to the scientific understanding of complex phenomena, and its use for supporting societal framing and decision making. Conceptual frames, which allow for causal interpretation and understanding, serve not only curiosity but allow for rising awareness, engineering preparedness and options for specific stakeholders.

2.1. The case of Baltic Sea eutrophication

Eutrophication is the term used for environmental degradation by increased production of organic matter and subsequent oxygen depletion in deeper waters of freshwater, estuarine, or marine water bodies. Although it is a natural phenomenon associated with organic matter transformation and oxygen depletion in aging water bodies isolated from atmospheric oxygen, it is accelerated by nutrient enrichment from human sources that enhance organic matter flux.

One difficulty in dealing with eutrophication is that there is no accepted metric for eutrophication thresholds, but those marine systems are considered eutrophic where organic carbon fluxes are in excess of 300 g m^{-2} a^{-1} (Nixon, 1995). More frequently, eutrophication is qualitatively identified by changes in oxygenation status, in winter water nutrient concentrations, in water transparency, or in biological assemblages as compared to a reference condition in the past.

Productivity estimates for the entire Baltic Sea are around 150 gC m^{-2} a^{-1} (Wasmund et al., 2001), but it is considered to be one of the most glaring examples of eutrophication in Europe (HELCOM, 2010). Large areas of its seafloor are intermittently anoxic, blooms of nitrogen-fixing bacteria are a recurring nuisance during summer months, and the coincidence of deteriorating environmental conditions observed with increasing river nutrient loads in the 1970s and 1980s implicated nutrient effluxes from rivers (and reactive N inputs from the atmosphere) as the causal reason (Rosenberg et al., 1990).

The Baltic Sea is a silled basin with an excess of precipitation and river runoff over evaporation, and thus is an archetypical estuarine nutrient trap prone to oxygen depletion in dense deep water that is isolated (Seibold, 1970). Investigations of sediment cores suggest that its largest deposition area of fine-grained and organic-rich sediments in the Gotland Basin has been intermittently anoxic for much of its history since 8000 years ago (Sohlenius et al., 2001). Biogeochemical proxies in sediment dated cores imply that cyanobacterial nitrogen fixation has been a characteristic feature of the pre-industrial Baltic Sea since that time (Bianchi et al., 2000; Struck et al., 2000).

Even though countries bordering the Baltic Sea reduced phosphate and nitrate loads of rivers to the Baltic Sea by 68% and 60% in the period from 1990 to 2000 (HELCOM, 2010), direct positive responses of winter nitrate and phosphate concentrations in surface water of the central Baltic Sea were not observed. Nutrient concentrations remained high and phosphate concentrations showed no reaction.

This is a plausible consequence of **phosphate** release from anoxic sea floor sediments (Conley et al., 2002, 2009; Emeis et al., 2000). These anoxic sediments release 2/3 back into the water column (Hille et al., 2005) of the phosphate arriving in sedimented organic matter. The added phosphate in turn promotes blooms of N_2-fixing cyanobacteria in the sea surface (Vahtera et al., 2007). Recent model experiments suggest that the residence time of river-borne phosphorus in the Baltic Sea exceeds 35 years.

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[1] www.unesco-ioc-marinesp.be.

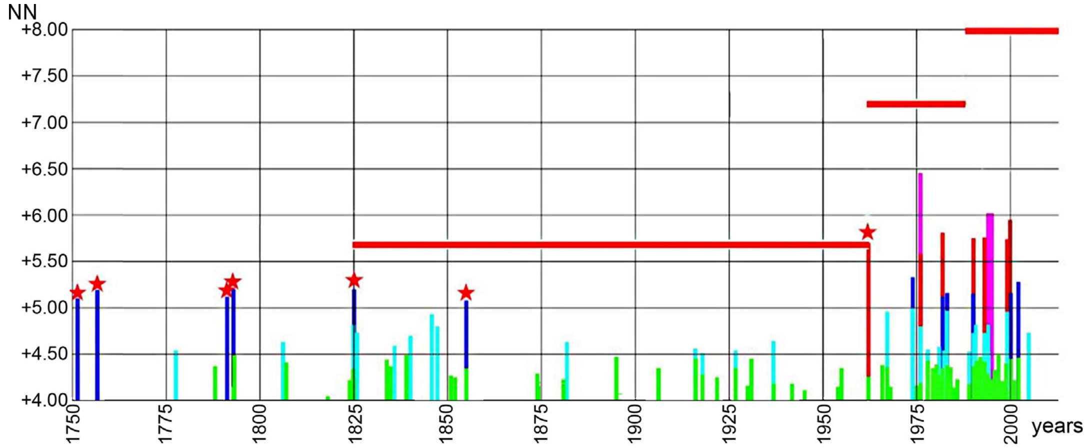

Figure 1 Storm surges as recorded at the tide gauge St Pauli in Hamburg. The horizontal bars indicate stipulated dike heights. Dike failures are marked by red stars. The color codes mark surge heights. Data provided by Gabriele Gönnert; diagram prepared by Ingeborg Nöhren.

A biogeochemical proxy for eutrophication fueled by riverborne **nitrate** is the N-isotope composition of particulate nitrogen ($\delta^{15}N$) in surface sediments and sediment cores. Elevated values of $\delta^{15}N$ were only found in deposits of coastal lagoons and of the Arkona Basin close to major river discharge areas (Struck et al., 2000). The large depocenters of sediments in the central Baltic Sea showed no eutrophication signal. Detailed analyses of the fate or riverborne reactive nitrogen from the Odra River mouth to the Arkona Basin indicated that the isotopic signal of eutrophication vanishes in close distance from the river discharge areas (Emeis et al., 2002).

The balance of evidence (Voss et al., 2005) suggests that the **nitrate** discharged by rivers is effectively denitrified in sandy sediments of the coastal rim of the Baltic Sea, and that the central Baltic Sea is supplied dominantly with nitrate from atmospheric N_2 fixation. On the other hand, **phosphate** regulation will have to run up against the legacy of sedimentary phosphate, which is difficult to control (Emeis et al., 2000): "even dramatic reductions in phosphorus loads will only show improvements of the eutrophication status on a multidecadal time scale" (Radtke et al., 2012).

2.2. The case of storm surges in Hamburg

The City of Hamburg is threatened by storm surges, as is displayed by Fig. 1 (von Storch et al., 2008). Until about 1850, the city was regularly hit, often with dike failures. A new dike height was mandated beginning with 1825. Then not only failures ceased to take place, but water level maxima were much lower than previously. However, a massive coastal defense failure took place in 1962 (cf., von Storch et al., 2014). After this event, significant fortifications of coastal defense were stipulated. Also, after 1962 many very strong storm surges took place, some with water levels well beyond the 1962 mark. However, damages were limited, because of the improved coastal defense. The clustering of these strong storm surges created significant concern in the city, and some scientists and activists related this clustering to a change in storm activity — which was said to have intensified because of ongoing climate change.

Analysis of storm statistics using homogeneous data[2] indicates that the storms have undergone intensification from about 1970—1995, with a recent return to more normal times. Also, there was a trend toward higher annual mean high tides, whereas the variability of high tides relative to the annual mean high tide was mostly stationary. This observation falsifies the hypothesis that the increase in storm surge levels would be mostly associated with a change in storminess; it could, however reflect a change in sea level or other causes.

Sea level in the North Sea did increase by about 20 cm in the 20th century (Albrecht et al., 2011), but such an increase is too small for explaining the increase in storm surge height in Hamburg of the order of 1 m. Finally, a comparison of storm surge heights in Hamburg and in Cuxhaven, at the mouth of the Elbe, revealed that in the period between 1962 until 1980, the relative storm surge heights in Hamburg compared to those in Cuxhaven rose from 30 cm to about 1 m. Since about 1980 the differences are stationary at about 1 m (von Storch, 2009). This difference is best explained by two factors, namely the dredging of the shipping channel and measures for improving storm surge defense (by shortening dike lines and blocking tributaries).

Thus, the increasing storm surge hazard in Hamburg is hardly related to man-made climate change, but mostly to modifications of the topography of the river Elbe and of the tidal regime in this river. The tidal wave — and thus also any storm surge — travels upstream much faster and peaks more efficiently in Hamburg. The change in hazard is man-made, but not by emitting greenhouse gases, but by modifying the river.

This explains the past changes in a plausible manner; however, this explanation does not imply that future minor

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[2] Data are said to be homogeneous, when changes in the numbers are due to changes of the variable observed (say wind speed), and not to changes in the observational process or in the observational environment (cf., Lindenberg et al., 2012). Very often data are not homogeneous, even though quality controlled. Long homogeneous time series for wind hardly exist.

modifications of the river will lead to further significant increase of hazards. Also, even if presently climate change is a minor factor, this may change, when an accelerated sea level rise takes place in the North Sea.

This analysis is a typical "**detection and attribution**" case (Hasselmann, 1979): In this format, it is first asked if we observe a change, which is beyond the range of "normal" variations — and the increase of storm surge heights after 1962 is clearly beyond that range. In that case we conclude that we have "detected" a change, which needs an explanation beyond "natural variations". In the "attribution"-step, different possible causes are examined, which of them is most successful in explaining the change. In our case it is the modification of the estuary.

Unfortunately, all too often, complex phenomena are prematurely related to some causes, often those which fit certain political or economic interests best. Also, some scientific institutions seem to have bound themselves to certain explanatory frameworks, and find it difficult to think beyond a once chosen paradigm (Fleck, 1980).

3. Marine spatial planning

The use of coastal zones are changing, reflecting changing political, economic and societal human activities and preferences. "Marine Spatial Planning" (MSP) describes the "public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process" (UNESCO, 2014). This process needs contributions not only from natural sciences and engineering, but also from social science for understanding structures, perceptions, interests and power balances of the involved actors and affected population.

Marine Spatial Planning is in itself not a scientific task; science contributes to this task by providing background knowledge and information, and by analyzing and suggesting methods of how to implement this type of planning.

When planning for future use, various different uses and interests have to be considered as determining factors (Gee et al., 2006). Relevant factors are: **shipping**, due to globalization and increasing global exchange of goods, and associated expansions of ports and hinterland connections; **energy generations**, for example using large-scale offshore wind farms, and associated cable connections to the land; **environmental regulations**, such as designation of marine protected areas and the obligations for achieving good ecological status in coastal seas. Other constraints relate to **coastal defense**, sand and gravel extraction, military, and all forms of cables and pipelines. Factors of direct economic significance relate marine aquaculture, fishing, mussel fishing, and **tourism**. An overarching issue in all planning exercises is anthropogenic climate change.

Marine planning is confronted not only with ecological, hydrodynamic and morphological dynamics but also with significant social dynamics (cf., Kannen, 2012) — such as: Conflicting options for using coastal space and resources; cumulative impacts from the existing or developing usages; competition of partially antagonistic perceptions and attitudes of stakeholders and public; complexities arising from transnational levels and transboundary scales.

These challenges request particular processes and pose specific information demands for planners and managers in order to attain a holistic understanding of the coastal sea as a system with a multitude of social and ecological interactions. However, these challenges are not independent of each other and interfere in many ways.

Spatial planning takes place on two different levels, namely on the **management** level and on the **strategic** level. Management relates to the process by which human and material resources are harnessed to achieve a known goal within a known institutional structure. Strategic planning is related to governance — understood as the regulating and moderating processes between parties beyond fixed decision structures.

For management planning, goals and administrative mechanisms are usually well established and widely accepted (Olsen, 2003). Typical examples are the design of a specific wind farm, port extension measures, the installation of marine protected areas or specific environmental compensation measures.

This type of planning is mostly a technical approach, which asks for specific data and information to support economic or political decisions. Scientific support for such planning includes the provision of specific data, such as consistent meteo-ocean data. An example is "CoastDat" (Geyer, 2013; Weisse and Günther, 2007), which describes wind, currents and waves derived at high space-time detail in the North Sea (see also below in Section 5). This data set was used in ship-building design and offshore operation profiles and design, in offshore wind industries planning, or in setting-up oil-release fighting strategies (Weisse et al., 2009), or long-term strategic co-operation of offshore wind energy and coal-fired power plants (Wiese, 2008).

Strategic planning, on the other hand, is often subject to the **values, policies, laws** and **institutions** by which a set of issues are addressed. Governance in this context relates interests, stakeholder driven objectives as well as institutional processes and structures which are the basis for planning and decision-making. Governance therefore sets the stage within which management occurs (Olsen, 2003).

While management focuses on "tame" problems, strategic planning is often related to so-called "wicked" problems. "Wicked" problems are described as complex, tricky, unstructured, and difficult to define. They delineate from other and bigger problems and involve normative judgments (Jentoft and Chuengpagdee, 2009). Therefore, in addition to technical information from natural sciences and economics, information and scientific advice referring to the political, societal and cultural context of decision making is needed.

Solutions of such wicked problems require the recognition of conflicting values, beliefs and perceptions. Such planning produces winners and losers. Also the scientific support needs to be understood as a social process comprising interactions among actors, mediating between different stakeholders' interest and respecting lobbying and existing power structures (Kannen, 2012). For a scientist to be a successful knowledge broker, the scientist needs to understand actors' perceptions of particular problems and issues and how this is related to their attitudes and values (von Storch, 2009; von Storch and Stehr, 2014).

A tool for doing so is surveying stakeholders and regional and local residents. In one case, local residents from the

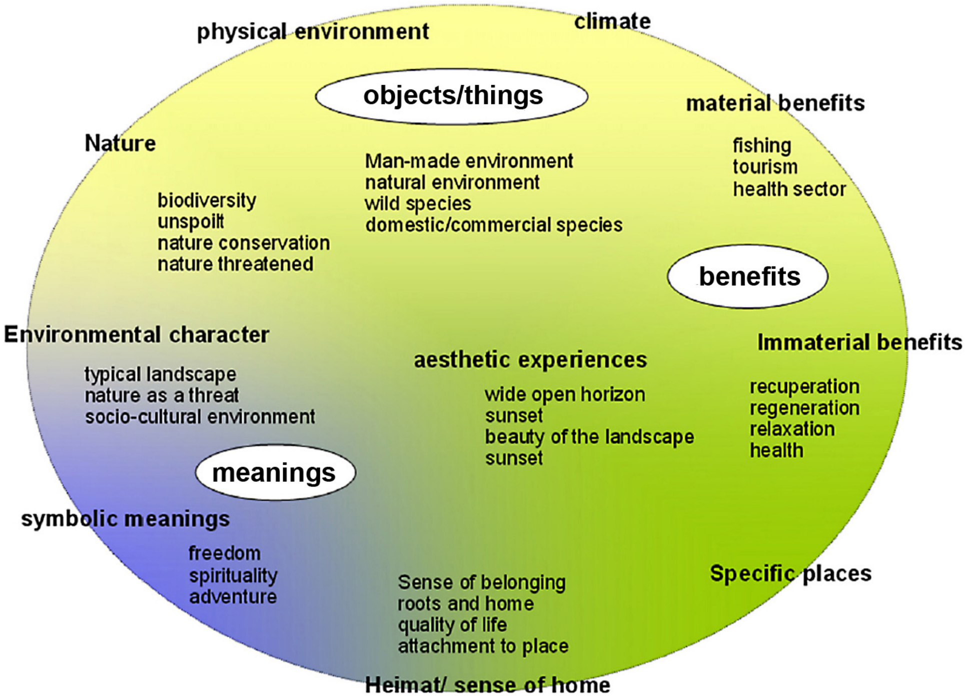

Figure 2 A landscape of values at the west coast of Schleswig-Holstein, Germany (categories mentioned in answers to the question "What springs to your mind when you hear `west coast of Schleswig-Holstein'", Ratter and Gee, 2012).

North Sea coast of Schleswig-Holstein shared antagonistic views about wind farms emerged (Gee, 2010; Ratter and Gee, 2012, see Fig. 2). One group saw wind farms as incompatible with their understanding of the sea as an open and wild natural area, mainly due to their esthetic impacts. Others argue that wind farms as a renewable source for electricity production are favorable and visual aspects are less relevant. This information may guide communication strategies of project developers and planners and help them to properly address particular groups of society.

In general, social science analysis may support planning processes and (re-)shaping governance processes and actor interactions (e.g., Cormier et al., 2013; Kannen et al., 2013). An example is the long-term vision for MSP in the Baltic Sea developed in the framework of the BalticSeaPlan project. Gee et al. (2011a) first identified a set of key transnational issues: a healthy marine environment, a coherent Pan-Baltic energy policy, safe, clean and efficient maritime transport and sustainable fisheries and aquaculture. Together with three key principles, namely Pan-Baltic thinking, spatial efficiency and spatial connectivity, these provide the core of a vision for transnational MSP (Gee et al., 2011b; Kannen, 2012). How this vision or elements of this vision can be implemented is currently under discussion in relevant policy networks including HELCOM and VASAB (Vision and Strategies around the Baltic Sea).

4. Monitoring

"Monitoring" aims at the assessment of the current status of the coastal environment and short term trends, and their (deterministic) short-term forecasts. Such routine analyses and short-term forecasts are required for dealing with all sorts of practical problems such as coastal risk management (coastal flooding and extreme wave conditions), combating ocean pollution (Soomere et al., 2014; Xi et al., 2012), search and rescue operations.

Similar as with marine spatial planning, monitoring is not a scientific task itself; but, again, the task of monitoring is supported by coastal science in providing methods — in this case, of observations, analysis and prediction. Also, science is a stakeholder in monitoring efforts as well: Chances to disentangle complex oceanic processes and phenomena are considerably increased if a good state description in space and time is available.

For spatial domains and time intervals of practical interest the space—time detailed state of the coastal sea can hardly be determined from observations alone, because a sustainable data acquisition is too expensive. However, amalgamating observations and output of dynamical models enables efficient, consistent and realistic estimations and forecasting of the ocean state (Robinson et al., 1998). The challenge of such an amalgamation, also named **data assimilation,** is the extraction of the most important information from relatively sparse observations, and the propagation of this information in an optimal way into predictive models accounting for errors in the models and observations.

There exist still a number of challenges in coastal ocean data assimilation. Diagnostics and metrics for assessing performance of the coastal assimilation models need further improvements. Coupling between coastal and open-ocean assimilation systems is still an open problem. Forecasting biogeochemistry state in the coastal ocean, although much asked for, is still in infancy. Treatment of river flows, mixing, bottom roughness and small-scale topography is still an issue. Non-homogeneity in space and time of model error statistics needs further consideration. Of particular importance is the

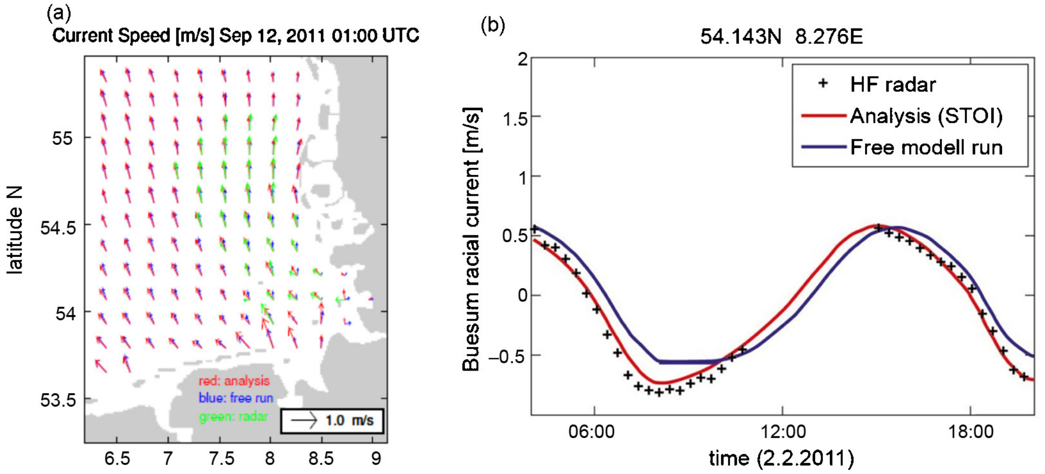

Figure 3 Comparison of HF radar determined surface currents with an analysis using STOI, and a simulation with the same dynamical model, which is used in STOI, but without constraint with HF data. (a) A snapshot in time of the 2-current field. (b) A time series of radial velocities at a grid-point.

optimal use of non-homogeneous data from different origin and platforms.

Another application, which is still under development, is the design of observational networks. In numerical "Observation System Simulation Experiments" (OSSEs) possible monitoring networks can be tested, how accurate and efficient field estimates may become, given a certain number or quality of observing stations (Schulz-Stellenfleth and Stanev, 2010). Such OSSEs prepare the ground for designing sustained coastal ocean observing systems, advance the planning and design targeted scientific coastal observations.

In the following we present the example of a system designed to construct operationally analyses of **surface currents in the German Bight**. The example is challenging, because of the high space-time variability of currents caused by the dominance of tidal currents. We first describe the system, and then illustrate the performance. Then, we describe an application of such a "product" in the context of "search and rescue".

The system was developed in the framework of Coastal Observing SYstem for Northern and Arctic Seas (COSYNA) in recent years (Stanev et al., 2011). It uses radial current velocities from three high frequency (HF) radars. The employed assimilation method STOI (spatio-temporal optimal interpolation; Stanev et al., 2014) uses elements of assimilation filters and smoother. The STOI method does not only interpolate, but also `extends' in space the radar data, which makes possible to generate homogeneous mapped data series over areas larger than the observational array (Stanev et al., 2014). Surface currents are analyzed simultaneously using an analysis window of 13 or 24 h, thus continuous surface current trajectories over one or two M2 tidal cycles are obtained.

In Fig. 3a, a snapshot of three different descriptions of a surface current field are displayed, namely HF radar observations (green), the result of the data assimilation using STOI (red) and a simulation with the same model, which is employed in STOI, but which is not constrained by the HF radar observations (free run; blue). The data assimilation changes the description of the current in particular at near coastal grid points, e.g., in the Elbe estuary. Also, the region covered by the analysis is larger than the area covered by HF radar observations.

Fig. 3b shows radial velocities during a M2 tidal cycle for a point, as recorded from a HF radar station (black crosses), the analysis using STOI (green) and the free run mentioned above (blue). Note that the HF data are not available for the entire time — for a period of 4 h, no data have been recorded. Obviously, the data assimilated describe the observations very well, and are capable to "fill" the data gap consistently.

An operational product based on this analysis system may find an application in search and rescue operations. The utility is demonstrated by the large differences for the estimated transport trajectories, when unconstrained current simulations are used, compared to the trajectories derived from analyzed currents.

In a transport model, many particles have been released in the center of every grid cell and were then moved with the surface currents derived from the STOI product. The mean travelled distances vary mostly between 2 and 4 km, but in some cases the distance amounts to 5 and more km.

Fig. 4 shows 3-day trajectories emanating from six exemplary locations. The black one is run with unconstrained

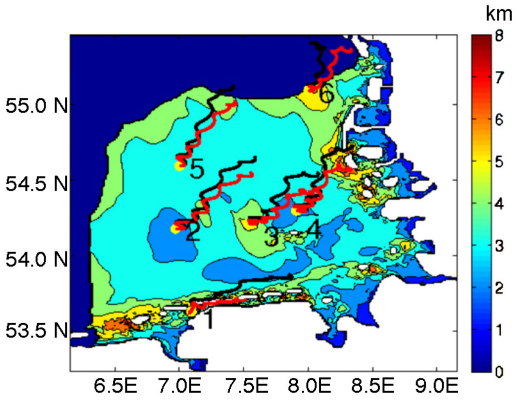

Figure 4 Pairs of 3-day trajectories emanating from six locations. In black: unconstrained currents; in red: constrained STOI currents.

currents, the red one with constrained STOI currents. The wiggles in the trajectories represent the effect of tides. The dominant direction is the same in both cases, but the details become significant after a day, or so. For a search-and-rescue operation differences like those between the black and red curves become unacceptable. This advocates for the need of using intra-tidal information from measurements into the surface current product, to correct model trajectories.

The development of monitoring systems receives increasing attention. The project **MyOcean** is a project devoted for developing an operational Earth observation capacity. It is the marine component of the joint Copernicus-project run by the European Commission and the European Space Agency. Five years after its start this activity reached an operational status with currently more than 3000 users. This center aims at providing information for designing policies, assessing state and change, and implementing regulations of maritime safety, managing marine resources and marine environment and responding to ongoing and possible future climate change. Also seasonal and weather forecasting is an important task.

The available Copernicus marine service and products cover global ocean and European regional seas. However, coastal-sea products are considered as separate, "downstream" products, so that they are mostly supported by national programs. In Germany, the COSYNA-program is an example is focusing on such issues. Apart of this example, further development of new coastal sea products in Germany is framed under the German Copernicus initiative **Demarine**.

5. Hazards, risks and opportunities

Assessments of (statistical) **"hazards, risks and opportunities"** are needed for almost any kind of onshore and offshore operation. Knowledge about statistics of marine weather including ocean parameters such as sea level, storm surges, wind waves, temperature, salinity etc. are important to coastal societies. This comprises knowledge about mean and extreme conditions together with their variability and long-term changes. Such information is needed in making appropriate decisions, for example, in planning and designing of coastal and offshore structures or evaluating and assessing past and potential future policy regulations or adaptations (see also Section 3).

For such evaluations and assessments, long and homogeneous data records are needed from which the (changing) statistics, and thus hazards, risks and opportunities can be derived. For marine and coastal areas, such data are rarely available. In most cases observations are simply missing, cover too short periods, or are lacking homogeneity (e.g., Lindenberg et al., 2012); that is, long-term changes in the time series are not entirely related to corresponding geophysical changes, but are partly due to changes in instrumentation, measurement technique, or other factors unrelated to the parameter monitored. In particular when long-term changes are assessed, such in-homogeneities may lead to wrong inferences when not adequately considered (e.g., Weisse and von Storch, 2009).

There are principally two approaches to address this issue. **Proxy data** are physically linked with the variable of interest and are available for longer periods and sometimes more homogeneously than the variable itself. An example is seasonal percentiles of geostrophic wind speeds derived from air pressure readings to assess long-term changes in storm climate (Krueger and von Storch, 2011; Schmidt and von Storch, 1993). Proxy-data are helpful in describing trends, and in discriminating between signals with a cause and natural variability (cf. Section 2).

However proxy data are less useful for providing numbers with a practically significant level of accuracy. There is an alternative approach that utilizes numerical models to "**hindcast**" or "re-analyze" the coastal sea and coastal atmosphere state during the past decades of years. Such hindcasts are partly constrained (in the spirit of Section 4) by some observations or by large-scale states, known to be adequately described by global re-analyses of the atmospheric states.

Such a data set, named coastDat, is describing atmospheric and oceanic variables since 1948 (Geyer, 2013; Weisse et al., 2009). In particular storm surges, currents and wind waves have been constructed for the North Sea and, to some extent, the Baltic Sea (Weisse et al., 2009). Thermodynamic variables were added more recently (Meyer et al., 2011). Similar efforts for describing space-time details of meteo-marine weather are underway in East Asia and other parts of the world.

We have touched upon the application of such a "product" already in Section 3. Here we sketch two more applications, for demonstrating the width of applications possible.

The building and operation of large **offshore wind farms** is expected to grow substantially in the coming decades. The North Sea is an area in Europe where heavy development is presently going on. Even if the North Sea represents a continental shelf sea with a relatively dense observational network, even here the observations are insufficient to provide the database needed by companies to develop designs, maintenance schemes, or prepare construction planning.

Meteo-marine hindcasts as CoastDat allow the construction of otherwise unavailable consistent and complete statistics covering decades of years (Weisse et al., 2009). Such statistics have been used during planning and design of nearly every offshore wind farm planned or built in the German Exclusive Economic Zone. Applications cover estimating long-term statistics such as mean or extreme significant wave heights (e.g., 50 year return values) which are needed e.g., for detailed design of foundations and turbines, or for estimating joint frequency distributions, for example of wave height and direction or of wave height and period. Another relevant statistics describes so called (fair) weather windows, which are a relevant constraint in operating of vessels, cranes or transport systems needed for installing or accessing of-shore wind farms.

Chronic oil pollution of coastal seas is an ongoing process that is, however, difficult to monitor. Small accidental discharges or illegal oil dumping often go undetected. The number of oil-contaminated sea birds beached along the German coast, available since 1984, may serve as a proxy for the frequency and intensity if oil releases — the question is how representative such data are as an indicator for changes in oil releases, or if they reflect drift conditions subject to meteo-marine weather variability. Using the meteo-marine re-analysis allowed for clarifying this question

(Chrastansky and Callies, 2009; Chrastansky et al., 2009) — the seasonal drift conditions are not stationary but show substantial inter-annual variations and even decadal trends. Thus, the survey data of beached sea birds may be used as proxies for oil-releases only to limited extent.

An early application of such a long-term reconstruction of the weather stream was an effort to estimate the amount **of lead which was deposited into the Baltic Sea** in the post-war industrialization period (von Storch et al., 2003). The main mechanism for emission of lead into the atmosphere, and later deposition on land and sea surfaces was automobile traffic, which grew exponentially in the 1950s and 1960s in Europe. Beginning 1972, gradually legislation was adopted, which limited the amount of lead in gasoline, until only traces of lead or no lead at all was emitted when burning gasoline. For estimating the airborne transport and the eventual deposition, first the daily weather was reconstructed for the time period 1958—2002 in space—time detail. Emissions of lead were estimated using mainly the sale of gasoline in the different countries; then these emissions were transported in the atmosphere and deposited. The data available for validating the exercise were rather limited, but the simulation seemed mostly consistent with these data. Finally, emitter-deposition matrices were calculated. The total deposition into the Baltic Sea is shown in Fig. 5.

Until the mid-1970s, the deposition steadily increased, but then the trend was reversed. Estimates of depositions, derived from observations, are added in the diagram — the model generated curve is consistent with these estimates. However, the “observed” depositions cover only the later development, when the regulations have been in place for a few years. From the “observed” data, it is not possible to derive an estimate of the total depositions across time; the model generated data allow such an estimate.

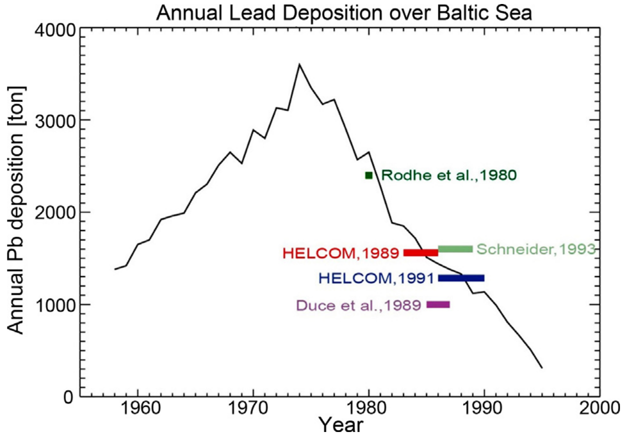

Figure 5 Estimated annual depositions of lead into the Baltic Sea (black curve) plus estimated depositions derived from a number of limited observations (von Storch et al., 2003).

The final example refers to emissions related to shippng. More than 90% of the global trade volume is transported on the world seas, thereby causing high emissions of pollutants into the atmosphere. In Europe, the biggest harbors are at the North Sea. Consequently, North Sea coastal areas can be highly affected by **emission from shipping**. Although sulphur emissions from shipping have been reduced significantly in the last years in the North and Baltic Seas (see e.g., Matthias et al., 2010), nitrogen oxide emissions still pose a problem in large parts of Europe, including NW Europe, where EU limit values for NO_2 are frequently exceeded and eutrophication of the seas is significant (OSPAR, 2010).

To investigate the effects of shipping emissions on air quality and deposition of pollutants in the North Sea, accurate emission maps have been derived from ship movement data and detailed information about the ship's technical specifications (Aulinger et al., 2014). The emissions were fed into the chemistry transport model CMAQ (Byun and Schere, 2006) that calculates transport, chemical transformation and deposition of all major gaseous pollutants and aerosol particles.

Fig. 6 shows the average NO_2 concentrations close to ground and the contribution of ship emissions to the modeled concentrations in the North Sea area as average of three winter months (December, January, and February). The

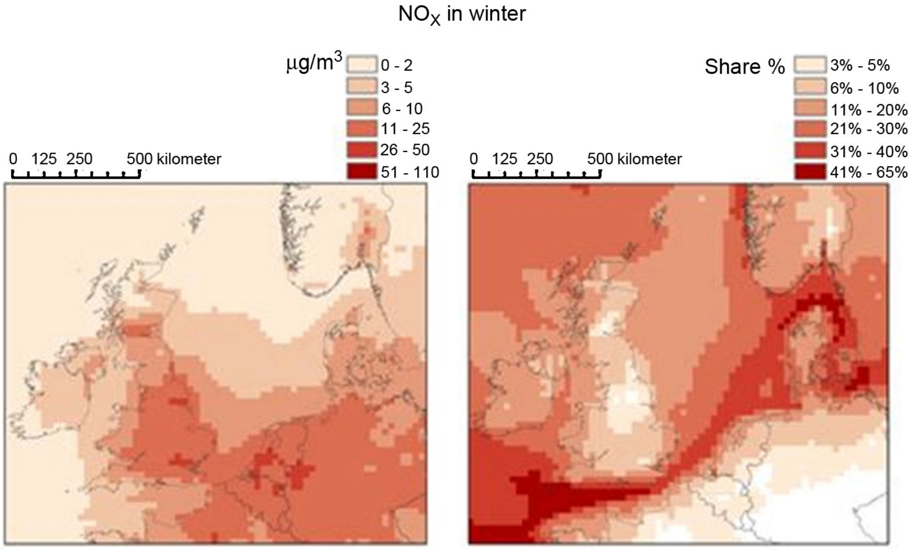

Figure 6 Average NO_x concentration in the North Sea area in winter (left) and the contribution of shipping emissions to the total concentrations (right).

model results show that ships contribute 30—40% to the NO_2 concentration in the Southern North Sea. At land, the contribution from ships decreases rapidly with distance from the coast; however, in Denmark for example, ships contribute 10—30% to the NO_2 concentrations in the entire country.

6. Scenarios

"Scenarios" or projections provide useful outlooks for assessing consequences of possible future developments and uncertainties. Therefore, scenarios have become increasingly popular in various scientific and decision making contexts (e.g., Schwartz, 1991; von Storch, 2007).

Predictions are descriptions of future conditions, which are framed as "most probable". Thus, when many independent predictions are made, it is expected that the distribution of predictions is close to the distribution of the real developments, which were supposedly predicted. Scenarios, on the other hand are possible, plausible, internally consistent but not necessarily probable descriptions of future conditions.

The IPCC[3] defines "A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual or long-term time scales" and explains "Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized."

The difference between predictions, or forecasts, and scenarios, is often difficult to understand, not only for lay people but also for environmental scientists. Bray and von Storch (2009) found that about one quarter of surveyed climate scientists mix up the two terms. Among lay people this rate likely will be considerably higher.

Even though scenarios of socio-economic (e.g., Bray et al., 2003) and other developments, as described in Section 3, are also constructed and are in use, climate change and impact scenarios have been most prominent in recent years.

In the scope of the "German adaptation strategy" there was an increased request regarding regional climate change scenarios. Regional climate scenarios are available from a number of research groups (e.g., Déqué et al., 2005). Running such scenarios is no longer a challenge, and is done routinely.

For many stakeholders and for the public, adequate interpretation of scenarios is crucial. To develop tools, which meet these stakeholder needs, the North German Climate Office[4] has been set up. The office has developed a number of information products: A fact sheet on the use of regional climate scenarios documents the most frequent misunderstandings by using scenarios (Meinke et al., 2011). Emphasis has been placed on the significance of ranges due to different emission scenarios and different models used. Consistent with this fact sheet an interactive climate web atlas has been developed where twelve atmospheric regional scenarios were analyzed for Northern Germany and sub-regions (Meinke and Gerstner, 2009). For different time horizons, ranges of possible future climate changes in Northern Germany are visualized by maps together with short interpretations. Another product, developed together with the German Weather Service, illuminates to what extent recent atmospheric changes in Northern Germany are consistent with the perspectives envisaged by the scenarios (Meinke et al., 2014).

For coastal regions, obviously the possibly changing impact of rising storm water levels is of great concern. A future change in the **storm surge risk** demands adaptation in terms of coastal defense, spatial planning and logistics. Two major factors in such scenarios are the rise in mean sea level and the change in storm related short term accumulation of coastal water.

The first factor is a contested issue, because there is much uncertainty in the question, how much less, or more, water is stored on the big ice sheets Antarctica and Greenland (cf., Katsman et al., 2011). New satellite-born measurements of the ice sheets, as well as continued monitoring of the mean sea level will help to reduce the uncertainty in the coming years and decades, but for the time being, it may be best to simply accept a large uncertainty about the perspectives. An analysis determined that largest possible values of sea level rise at the end of the 21st century could be 1.2 m, or so.

The second factor, related to storms, can be much better described, at least with respect to extra-tropical storms, which are well described in atmospheric climate change scenarios. The usual approach employed nowadays is to dynamically downscale atmospheric scenarios of possible climate change, and then feed the changing winds and air pressures into a hydrodynamic model of, for instance, the North Sea (e.g., Gaslikova et al., 2012; Woth, 2005). Local features such as estuaries or barrier islands are not routinely resolved, and some statistical "location" methods may be used (Grossmann et al., 2007). For the German Bight and Hamburg, possible storm related changes were derived up to 20 cm until 2030, and 60 cm until 2085, with significant uncertainties. In case of Hamburg, climatically induced changes have to be combined with other changes, which may result from further modifications of the Elbe estuary (see Section 2).

An important facet of these scenarios is the perspective of different time horizons, which will be associated with different geophysical changes. While not quantifiable, it is clear that also the uncertainty of future projections will be diminishing. A scenario for a certain time window constructed with the knowledge of 2030 will be less uncertain than a scenario for the same time window constructed with the knowledge available in 2010.

7. The science-stakeholder exchange

7.1. Knowledge

Natural science is generating knowledge about the sensitivity of coastal processes to natural and human influences and about possible pathways of future developments. However, transforming these insights into Francis Bacon's knowledge,

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[3] Intergovernmental Panel on Climate Change: http://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf.

[4] http://www.norddeutsches-klimabuero.de/.

scientia est potentia = capacity to set something in motion (Stehr, 2012), needs more than just "good science". When it comes to **decisions**, the role of science diminishes, and the responsibility is with stakeholders representing political, economic or social interests. Decisions are not scientific, but follow power structures, political and economic priorities and societal developments. Scientifically produced decision support systems can support decisions by providing specific sets of information and supply evidence-based decision support. Decisions themselves are in most cases normative and interest driven.

When scientific actors try to interact with stakeholders, including media and public at large, they often follow simplistic worldviews — in particular the "linear model" according to which scientifically constructed knowledge is superior und "true" (van der Sluijs, 2010). Therefore, in this naïve view, science is legitimized in determining what is a "right" or a "wrong" decision. The other model is that of the "empty vessel", according to which stakeholders and public are simply uneducated and do not understand (like small children). Thus, they need to be taught by scientists. As soon as these so far uneducated people understand the considered system, they will opt for the "right" decision.

Philosophy of science informs us that science is not providing "truth" but "best explanations" for the time being, consistent with empirical evidence and with generally accepted theories (e.g., Fleck, 1980). Attempting falsification is important, because it represents a permanent testing if an explanation is still the "best" for the time being.

According to social science models like the linear one or the empty vessel are not realistically describing social reality. Stakeholders hold their own knowledge, which often enough is not really science-based but rooted in cultural constructions or economic or political interests (von Storch and Stehr, 2014). Social science informs that the scientific actors themselves are part of society, thus conditioned in their scientific analysis by their preferences. This conditioning takes place, in particular, when scientists select research topics, and when they assess certain evidence as sufficient for accepting a hypothesis.

There are two major challenges for science, namely, first to limit the significance of worldviews in the scientific process itself, and second, to convince stakeholders to accept the result of scientific analysis as valid constraints for societal decision making.

When stakes are high, decisions are urgent, societal values involved and the knowledge uncertain, the situation becomes what is called "post-normal" (Funtowicz and Ravetz, 1985; van der Sluijs, 2010) — and knowledge provided by scientists, or people perceived as scientists, is valued by political and scientific actors in terms of its utility in favoring certain policies and less so according to the scientific methodology (von Storch, 2009).

Thus, **science-stakeholder interaction** entails not only **information provision** and **contextualization** of research findings, but also a self-reflection of the scientific actors. Science-stakeholder interaction becomes multifaceted and complicated. Social and cultural science knowledge is urgently needed for a successful participation of science in the process of advising decision making.

The field of science-stakeholder interaction is still under development, even if the tradition of "science, technology and society" (STS) is pursued for several decades (Weingart, 1999). A better understanding of conditions, constraints, misconceptions and options tailored for environmental sciences and in particular coastal science is needed.

But even if the coastal science—coastal stakeholder link needs more analysis, systematic efforts within coastal science are needed. One is to understand which results may indeed be "useful", and what is mere rhetoric. The purpose of this paper was to identify a first catalog of categories, and to illustrate this catalog with examples. Another is to build border organizations, which facilitate dialog between coastal science institutions and coastal stakeholders.

7.2. Dialog platforms

The Institute of Coastal Research of HZG is regularly confronted with specific request by stakeholders, including the public and media — like all other such institutes. The cases presented in the main part of this article illustrate the type and range of such demands.

For dealing with requests concerning regional climate, climate change and climate impact, in particular with respect to coastal seas in the North Sea and the Baltic Sea, a **regional climate office** (Norddeutsches Klimabüro) has been set up in 2006 (see also Section 5; von Storch and Meinke, 2008). The main tasks are compilation of assessments about the scientifically legitimate knowledge, the provision of data sets on past development and scenarios of future developments (such as CoastDat mentioned above) and building dialogs with different stakeholders. The task of the office is to not only reaching out for public and stakeholders, but also for allowing them to integrate the state of science in their understanding and decisions. As a border activity, the office monitors not only the feed-back into science, assumed and actual demands and needs for decision processes but also of competing knowledge claims, misunderstanding and other hindrances for communication. For doing so, direct interaction is needed, which may help overcoming mutual misunderstanding and divergent language but may lead to sustainable communication. Setting up anonymous data-portals, even with suitable Q&A sections, is insufficient.

About once a week the regional climate office is contributing to a public dialog event. Many individual requests are answered and interviews are given to the media. From these activities information demands of different stakeholder groups are localized to develop decision relevant information products which may serve a broader group with similar information needs. Crucial aspects of this transformation are besides using an understandable language, reducing the knowledge of complex phenomena to substantial aspects. At the same time the whole range of plausible conclusions derived from the scientific insights has to be communicated. Following the concept of the honest broker (Pielke, 2007) societal processes are in this way supported in arriving at societally preferred decisions.

One challenge of this stakeholder dialog is the dynamic of scientific knowledge, its limitation and uncertainty resulting from the methods and instruments used as well as the role and interest of the individual researcher. This diverse scientific knowledge is widely scattered, and scientific agreement is hardly documented especially on regional and local scales. Hence, important instruments are assessments of the scientifically legitimate knowledge about the regional coastal state, its change, its risks and societal role. The results are regional knowledge assessment reports, mimicking to some extent the IPCC documents. Two such regional assessment reports have been published so far, one for the Baltic Sea Region (BACC, 2008) and one for the metropolitan region of Hamburg (von Storch et al., 2010). Another one on the North Sea Region as well as a second version of the Baltic report is presently in the concluding phase. For the Baltic Sea report, a "stakeholder" summary (Reckermann et al., 2008) has been assembled. The Hamburg assessment has been updated after three years on a web-platform.[5] All regional assessments procedures are repeated after a couple of years.

Scientists need interaction with critical and independent social and cultural science competence encouraging self-reflexivity, such as to whether "stealth advocating" (Pielke, 2007) is going on, if fallacious models like the linear communication model or the empty vessel model are in use, or if the reference to societal needs is just rhetorical camouflage.

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