The dry sky: future scenarios for humanity's modification of the atmospheric water cycle

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Abstract

Non-Technical Summary. Human societies are changing where and how water flows through the atmosphere. However, these changes in the atmospheric water cycle are not being managed, nor is there any real sense of where these changes might be headed in the future. Thus, we develop a new economic theory of atmospheric water management, and explore this theory using creative story-based scenarios. These scenarios reveal surprising possibilities for the future of atmospheric water management, ranging from a stock market for transpiration to on-demand weather. We discuss these story-based futures in the context of research and policy priorities in the present day.

Technical Summary. Humanity is modifying the atmospheric water cycle, via land use, climate change, air pollution, and weather modification. Historically, atmospheric water was implicitly considered a 'public good' since it was neither actively consumed nor controlled. However, given anthropogenic changes, atmospheric water can become a 'common-pool' good (consumable) or a 'club' good (controllable). Moreover, advancements in weather modification presage water becoming a 'private' good, meaning both consumable and controllable. Given the implications, we designed a theoretical framing of atmospheric water as an economic good and used a combination of methods in order to explore possible future scenarios based on human modifications of the atmospheric water cycle. First, a systematic literature search of scholarly abstracts was used in a computational text analysis. Second, the output of the text analysis was matched to different parts of an existing economic goods framework. Then, a group of global water experts were trained and developed story-based scenarios. The resultant scenarios serve as creative investigations of the future of human modification of the atmospheric water cycle. We discuss how the scenarios can enhance anticipatory capacity in the context of both future research frontiers and potential policy pathways including transboundary governance, finance, and resource management.

Social Media Summary. Story-based scenarios reveal novel future pathways for the management of the atmospheric water cycle.

1. Introduction

Human societies are changing the atmospheric water cycle – evaporation, moisture transport, precipitation – via land-use change, climate change, air pollution, and more recently also via weather modification. Land-use changes directly affect evaporation from land and include everything from replacing tropical forests with rangelands, to irrigating deserts, and converting grasslands to monocultures (Gasparri et al., 2016; Lambin et al., 2001; Lambin & Meyfroidt, 2011). Climate change influences precipitation patterns profoundly, and increasing air pollution, aerosols in particular, affects atmospheric physics including cloud formation and precipitation (Allan et al., 2020; Ramanathan et al., 2001; Rosenfeld et al., 2008). These modifications can have significant consequences for the timing, magnitude, and duration of evaporation delivery to the atmosphere, and the fate of precipitation elsewhere (Bagley et al., 2012; Keys et al., 2016; Mahmood et al., 2014; Staal et al., 2018; Swann et al., 2015; Tuinenburg et al., 2014; Wang-Erlandsson et al., 2018, 2022; Wei et al., 2012; Zemp et al., 2017). Given the actual, and potential, changes globally, we conceptualize these flows of atmospheric water – including the delivery of evaporation, the flow of water vapor, and eventual precipitation – as economic goods.

Historically, flows of atmospheric water could implicitly be considered 'public goods' since evaporation flows and atmospheric water vapor were generally neither consumed (rival) nor controlled (exclusive) (Farley & Costanza, 2010). However, given that people can change this relationship via land-use change, atmospheric water may transition into a 'common-pool' good (rival and non-excludable; Rockström et al., 2023), and possibly to a controlled 'club' good (non-rival and excludable). Now, with the advent of scientifically verifiable cloud seeding, specifically via recent work on wintertime orographic cloud seeding (French et al., 2018; Tessendorf et al., 2015, 2019), deliberate atmospheric water manipulation may accelerate in its deployment, in the near future. Along with scientific advancements in the understanding of fog harvesting (Qadir et al., 2018; Tu et al., 2018), it is now conceivable for atmospheric moisture to enter the domain of 'private good' (i.e. excludable and rival). Yet, there has been no documented effort to seriously consider the implications or future pathways of anthropogenic modification of the atmospheric water cycle, despite the far reaching implications for society (Keys et al., 2017; te Wierik et al., 2020). Therefore, we explore the possible implications that could arise if atmospheric water transitions away from a public good, to become a common-pool, club, or private good. In doing so, we aim to identify new pathways forward that could better anticipate and support research and policy needs.

Scenarios are a commonly used tool for exploring future trajectories of science, policy, and culture (Carpenter et al., 2006), yet scenarios can vary widely in terms of approach, style, and depth of detail (Kishita et al., 2016). Scenario narratives are commonly used to provide both qualitative interpretations of observed or model-based findings, and to facilitate stakeholder engagement (Carpenter et al., 2006; O'Neill et al., 2017; Raskin, 2005). Importantly though, scenario narratives are often only descriptions – not stories – of possible future worlds. While such descriptions can be creative, they often fail to foster student curiosity, engage the public, or interest policymakers (Milkoreit, 2017). Story-based scenarios have emerged as successful vehicles for impactful scenarios (Calvert, 2019; Johnson & Winkelman, 2017; Merrie et al., 2018; Nature, 2018) given the ways that stories and storytelling can allow for sense- and meaning-making, reveal assumptions or hidden biases, and create alternate worlds (Bentz et al., 2022; Riedy, 2020). Story-based scenarios represent a deeper exploration of future worlds (Carbonell et al., 2017), and allow participants to explore how their daily lives, values, and habits can be mapped onto different projections of the future.

Despite ongoing recognition of the various ways in which anthropogenic changes actively modify the atmospheric water cycle (Gordon et al., 2005; Keys et al., 2016; Kleidon, 2006; Schumacher et al., 2022; Wang-Erlandsson et al., 2018), there remain gaps in mainstream water policy, nationally and internationally, for managing changes to the atmospheric water cycle via land-use change (Keys & Wang-Erlandsson, 2018; te Wierik et al., 2020). The main international policies that do exist guide the use of precipitation enhancement (e.g. to avoid hostile actions) and have existed for decades. The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, popularly known as ENMOD, was intended to ban weather modification for warfare (Bonnheim, 2010; Wunsch, 1980). However, weather modification, specifically precipitation enhancement that is not for hostile use, is typically managed on a national basis. For example, in the United States any activities seeking to modify weather must submit a report of their activities to the National Oceanographic and Atmospheric Administration (Charak & DiGiulian, 1974; Simon, 2021) and China passed its first national law on weather modification in 2002 (Chien et al., 2017). Nevertheless, there is no global policy for guiding human actions specifically regarding changes in atmospheric moisture and the effects on the overall global hydrological cycle. Chen (2016) explored the opportunity for updated property rights framings to be incorporated for atmospheric moisture in the United States, and that legal interpretations of atmospheric moisture have led to communal, that is, governmental, rights to management rather than individual or private rights. However, this discussion does not include anthropogenic modification of evaporation, and the associated delivery of moisture to the atmosphere. Thus, there is a gap in the scientific understanding of the potentially diverse sources of weather modification, and the associated policy discourse. This gap between scientific understanding and policy is, in part, due to the lack of framing terrestrial moisture recycling and atmospheric water manipulation in terms that are salient to policy (Keys et al., 2017). Our study responds to this gap by framing this topic in policy terms that are directly related to ownership and control.

2. Conceptual development

2.1 Rivalry and excludability for atmospheric water

In economics, the concept of 'goods' (e.g. timber, theater tickets, parking spaces) can be categorized into four quadrants based on how use and control of goods affects their status. First, if the use of a good reduces its available supply for others, it is called rival, while if use does not reduce availability it is considered non-rival (Kaul et al., 1999). Second, if a good can be intentionally or unintentionally controlled such that others can be prevented from access, it can be considered excludable, while if such control is not possible it is considered non-excludable (Kaul et al., 1999). This classification produces a four quadrant space, including: 'public' goods (non-rival, non-excludable), 'common-pool' goods (rival, non-excludable), 'club' goods (non-rival, excludable), and 'private' goods (rival, excludable) (Figure 1). Many natural resources are considered 'public' goods, especially spatially extensive phenomena such as clouds, air, timber, or even ice caps. This classification is appropriate, human intervention being absent. However, there are now few if any actual 'public' goods remaining, given the pervasive and widespread anthropogenic impacts on temperature, ocean heat budgets, and other planetary changes (Steffen et al., 2015) that drive and perpetuate unequal access to ecosystem services within societies and across generations (Hamann et al., 2018; Thiery et al., 2021).

We classify atmospheric water into the four quadrants, based on how humans modify rivalry and excludability (Figure 1). For atmospheric water to be categorized as a 'public' good, anthropogenic activities that could modify atmospheric water would need to steward atmospheric water availability elsewhere in an undirected way. If anthropogenic activities change the quantity of moisture that is available elsewhere, then atmospheric water moves toward becoming a 'common-pool' resource. If anthropogenic activities exert control over the distribution of moisture but do not change the availability of moisture, then atmospheric water moves toward a 'club' good. Finally, if anthropogenic activities modify both the quantity and exert control over atmospheric water, then it moves toward a 'private' good.

Figure 1. Conceptual overview of atmospheric water as an economic good. The horizontal axis indicates excludability of a resource. The vertical axis indicates whether the resource is rivalrous. Within each, there is a brief detail of the key requirement for atmospheric water to exist in that domain.

The core objective of this study is to introduce the conceptual exploration of atmospheric water as an economic good, with story-based scenarios of how such human modifications of the atmospheric water cycle may unfold in the future. To do this we blended multiple methods, incorporating computational text analysis, expert participation, and creative science fiction storytelling. Our paper is organized as follows. First, we will explain our methods, which blend a structured literature search, with computational text analysis, with expert training and collaboration, and storytelling. We then interpret these story-based scenarios in the context of improving our understanding of the future of human modification of the atmospheric water cycle. Further, we discuss both policy and research frontiers that need to be explored given the findings of this scenario exercise.

3. Methods

There were five key steps in this research, which we highlight here and explain in detail below. First, a structured literature search was performed, and we collected a large set, or corpus, of scholarly abstracts on the topic of human modification of the atmospheric water cycle. Second, we employed a machine learning-based computational text analysis (called latent Dirichlet allocation, LDA), which is a method for revealing the latent topics and keywords that exist across a corpus of documents. Third, the topics and keywords were mapped to the economic goods framework, based on a subjective interpretation of each topic's keywords. Fourth, we used the results of the LDA to inform a structured futuring exercise among a group of global water experts. This collaborative process involved guiding the experts through a set of creative exercises to develop imaginative visions of future worlds, where humans are (or are not) modifying the atmospheric water cycle. Fifth, a subset of the expert collaborators took these imaginative worlds, and were guided through a creative story-telling process. The results of this study are ten

story-based scenarios. We provide a detailed explanation of each step below.

3.1 Structured literature search

The first task was to create a structured literature query to collect scholarly abstracts related to human modification of the atmospheric water cycle (Table 1). After a preliminary exploration of various search terms, phrases, and exclusions, we used the search query below, which was intended to maximize the literature collected, while avoiding false returns. We exclusively used the Web of Science search function, which permits a sophisticated search query and automated download process for collecting

Table 1. Words and phrases that comprised the structured literature query in Web of Science

Must include a *word* (or *phrase*, enclosed by quotes) from the following		Must include a *word* from the following
land atmosphere precipitation	AND	human*
OR		OR
'moisture recycling'		anthropo*
OR		OR
'precipitation recycling'		soci*
OR		OR
'cloud seeding'		people
OR		OR
'precipitation enhance*'		agricult*
OR		
'glaciogenic seed*'		
OR		
'weather modification'		
OR		
'climate manage*'		
OR		
'atmospheric water harvest*'		

scholarly abstracts. Throughout the query, we used asterisks (*), which allowed a word to be completed by numerous suffixes, for example, 'human*' indicates that it would include 'human', 'humanity', 'humans', or 'humanities'. Similarly, metadata about the abstracts was downloaded in a tabular format permitting easy cross referencing. The query is represented in Table 1, indicating that these words and phrases would need to be present in any of the searchable fields within Web of Science, including the article title, keywords, abstract, or other searchable text.

Using the table of metadata, we performed a manual quality control to ensure that the abstracts included the necessary relevant information, specifically the full text of the abstract, and were, for example, not erroneously blank. Additionally, the quality control checks involved identifying whether a given document was associated with an abstract, searching for duplicate abstracts, and manually searching for abstracts that were not automatically retrieved with the Web of Science search. These abstracts (i.e. documents) were then used in our computational text analysis forming the corpus of analyzed literature.

The abstracts collected in the structured literature search above were prepared for the computational text analysis by batch converting them into plain text format, so that they would be machine readable. Similarly, additional information, such as author or other watermarks, were removed from the text so that only the abstract content was included in each document.

3.2 Latent Dirichlet allocation

The computational text analysis was performed using Python-based software including the natural language toolkit, the GENSIM package, and other common computational packages. The specific Python software versions used for the analysis were Python v3.7.7, Natural Language Toolkit (i.e. NLTK), v3.4.4, and Gensim Python package v3.8.0. Following the methods of Keys and Meyer (2022), the LDA was performed sequentially including: pre-processing the documents (including tokenization, stopword removal, and lemmatization), sensitivity testing to identify the most suitable number of topics for the LDA, and visualization of the final text analysis. First, during tokenization each word across all documents in the corpus was converted into an individual unit (i.e. token) of analysis (e.g. 'all of these words' becomes four tokens 'all', 'of', 'these', 'words'). Second, stopwords, which are words that appear in texts but convey little to no information (e.g. 'I', 'we', 'and', 'as', 'the', etc.), were removed. Third, words were lemmatized, which means similar words were collapsed into a common form (e.g. 'connections' becomes 'connection'). This process allowed a greater number of unique tokens to be represented in the analysis.

LDA was a process of iteratively identifying the underlying topic structure across the entire corpus of documents. First, a target number of topics was assigned for the analysis (e.g. 15 topics). Then, the LDA was performed aiming to find the most representative set of 15 topics (with the corresponding keywords). Thus, by varying the number of topics, a different set of topics and keywords could have been revealed. Several methods exist to find the most statistically robust set of topics, such as 'coherence'. The idea of 'coherence' refers to a statistical representation of how each topic makes interpretable sense for a machine, such that the keywords included within each topic have some common meaning or connection. The

coherence metric c_v (Röder et al., 2015) was used in a sensitivity analysis to identify the most statistically robust number of topics, by iteratively varying the number of topics in the LDA from 5 to 35. Then, we identified the top three topics with the highest coherence scores, to determine whether the resultant topics and keywords were interpretable. To do this, the keywords corresponding to each topic for each LDA analysis were manually examined for interpretable coherence by the lead author. This primarily involved identifying whether keywords within a cluster exhibited some common characteristics, and that the clusters themselves were distinct from one another.

Finally, if the keywords for a topic represented <1% of total terms across the entire corpus, then that topic was removed from the analysis. Topics with low term representation were not coherent enough for the story-based scenario process (Keys & Meyer, 2022).

3.3 Map themes onto economic goods framework

The topics produced from the text analysis were interpreted based on the semantic content of the keywords. This interpretation was then mapped onto the economic goods quadrants, as a way to connect the text analysis explicitly to the economic goods classification. This process was subjective and led by the lead author of this study. Multiple interpretations of this mapping are possible, and we discuss the implications of this in Section 5.4.

3.4 Expert participatory science fiction prototyping

The next step was to work with a set of global water experts to collaboratively interpret the thematic output of the computational text analysis and systematically develop science fiction prototypes. Water experts were recruited from a group of scientists, scholars, and practitioners with broad expertise on global water topics who attended a virtual water resilience symposium hosted by the Stockholm Resilience Centre. A series of two, virtual workshops (February 22, 2022 and March 3, 2022) were convened to train the water experts in story-based scenario development, specifically a workshop on worldbuilding using futures methods (e.g. science fiction prototyping), and a workshop on storytelling. The lead author of this article prepared the materials and conducted the workshops for the participants.

3.5 Workshop no. 1: worldbuilding

Worldbuilding is defined as 'the creation of imaginary worlds with coherent geographic, social, cultural, and other features' (von Stackelberg & McDowell, 2015). The expert participants were led in individual, guided exercises that began with each participant reviewing a specific topic and its associated keywords. Participants were assigned an economic good quadrant, which provided some constraints to the worldbuilding while also ensuring each of the quadrants was examined by at least some participants. Participants were then prompted to visualize a future beyond 2050 that was inspired by the keywords and topic. After taking notes on these visualizations each participant was led in a structured Futures Wheels exercise (Pereira et al., 2018). Futures Wheels permit an exploration of direct interactions and consequences, flowing from a focal event or item in the future (Hamann et al., 2020).

After the individual exercises, groups were formed for each economic good quadrant, with two participants each representing public good and private good and three participants each representing club good and common pool. Each group was then guided through three exercises: (1) three horizons framework; (2) probe reality; and (3) make-it-weird. The three horizons framework is a structured exercise to systematically describe historical transitions from the present status quo, through a transition period toward a futuristic transformed third horizon (Sharpe et al., 2016). The first, second, and third horizons are often characterized as paradigms that shift in dominance over time. The three horizons exercise involves putting the visualized futures (e.g. from the Futures Wheels exercise) at the end of the third horizon and describing the first and second horizons. After the three horizons exercise, participants were encouraged to 'Probe reality' and discuss what broader cultural forces might shape the broader future world. To do this, we employed the heuristic of the 'cultural iceberg' (Hall, 1989), which is used to reflect on deeper, less visible aspects of culture. Lastly, groups were encouraged to make it weird by pushing their ideas to ridiculous domains (Dator, 1993). This included probing social norms, technological surprises, and more.

3.6 Workshop no. 2: storytelling

This second virtual workshop focused on guiding participants through the storytelling process, namely designing a character for a story and then systematically drafting a plot. For the character design section, participants were encouraged to imagine a character that would inhabit their world from the first workshop. Then, progressive activities focused on defining internal and external characteristics, motivations of what make the character act, obstacles that are relevant to their character, and thinking about the wants of a character versus what they might need for a satisfying story arc. In the second part of the workshop, participants designed a plot set in their world that their characters would navigate (Keys & Meyer, 2022). The exercises here were built around identifying 'Story beats', specifically:

- Act I
  - Once upon a time…
  - Every day…
  - Until one day…
- Act II
  - Because of this…
  - Because of that…
- Act III
  - Until finally…
  - Ever since then…

The story beats were nominally split into three acts, as a way to distribute action across a given story. This structure provided a basic scaffold on which a story could be built that would allow a character to navigate the created world, and work through obstacles to ultimately reveal something about the particular economic goods quadrant. Following the two workshops, participants were invited to contribute scenarios based on their workshop output. These scenarios were collaboratively edited by different members of the author team, with all stories edited by the lead author. We note that there was an explicit emphasis on creativity and strangeness in the development of the story-based scenarios. An implication of this is limited control of bias or subjectivity. In the particular context of creative and generative scenario development, this is viewed as both necessary and an advantage for exploring novel possibilities.

4. Results

4.1 Literature query

The structured web query returned 2573 abstracts. Following quality control checks, 2274 articles remained.

4.2 Latent Dirichlet allocation

Based on the coherence metric c_v, we identified LDA models with topics numbering 11, 15, and 17 as good candidates for our analysis (Supplementary Figure 1). Ultimately, while 11 topics yielded the highest coherence value, we selected 17 topics as the most suitable LDA model given it had the highest (subjective) interpretability for its words and topics. We also adjusted the pyLDAvis 'relevance metric' slider to 0.6, which corresponds to the recommended value for maximum novelty and coherence in a given topic analysis (Sievert & Shirley, 2014).

The overall topic visualization is shown in Figure 2, and shows the distribution of the 17 topics, the terms (i.e. keywords) corresponding to the overall corpus, and the representativeness of these terms across the corpus. We ended up excluding topics 13–17 because they each represented less than 1% of terms in the corpus, and had quite low interpretability. While this removal could have led to missing some weakly represented ideas in the dataset, we considered this appropriate given that the remaining topics covered a substantial range of disciplines and ideas. A full set of visualizations for topics 1–12 are available in the Supplementary pyLDAvis figures.

A filtering of topics 1–12 was performed by the lead author, to ensure the keywords formed interpretable clusters. Several topics were obviously focused on issues that were only tangentially connected to the topics we aimed to better understand in the scenario and storytelling work. Ultimately, of the 12 topics, topic 2 was removed (focused on carbon uptake, and nutrient loss, but not on atmospheric water) and topic 10 was removed (focused on organic sediment and river discharge, but not atmospheric water). Thus, we were left with ten total topics to be explored in the workshops and structured futuring (Table 2; the full table of all topics and keywords is available in the Supplementary material).

4.3 Map themes onto economic goods framework

Next, we took the remaining topics and mapped them directly onto the economic goods framing (Figure 3). This step allowed for a direct connection of certain topics and keywords to be explicitly explored in the context of particular economic goods framings. For each topic, the keywords were considered how and where they might exist in the spectrum of excludability and rivalry. For example, topic 11 included keywords that refer to cloud microphysics, aircraft, cloud condensation nuclei (CCN), mountains, and ice. All of these would be relevant for glaciogenic cloud seeding, that is, the deliberate enhancement of wintertime precipitation. Thus, this topic and keywords were assigned to the 'private good' quadrant. We note here that our classification is but one of many potential classifications. An opportunity exists to classify the topics into different quadrants, which would
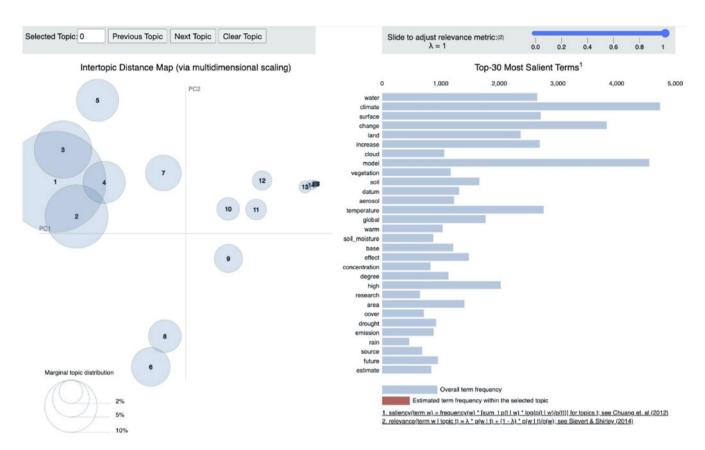
Figure 2. Visualization of topic distribution (left), and full list of keywords for the overall topic analysis (right). This visualization was created using the pyLDAvis Python package. Note that visualizations for each individual topic are included in the Supplementary material.

eventually lead to different types of story-based scenarios, which we explore in Section 5 (Table 3).

4.4 Expert workshops overview

The first workshop included ten participants, with specific activities for each workshop participant to complete individually, and then as a group. The disciplinary backgrounds included hydrometeorology, land-use change, urban water infrastructure, comparative governance, water resources management, and ecology. Both the first and second workshops were conducted virtually, which enabled broad geographic collaboration. The second workshop included five participants, and was explicitly focused on story-based development informed by the results from the first workshop.

During the first workshop, the participants first worked individually using exercises including a guided visualization and a Futures Wheels exercise (an example of a Futures Wheels diagram for the 'private good' category is shown in Supplementary Figure S2). Second, participants were then grouped together based on each of the four economic goods quadrants, and collaboratively participated in exercises using the three horizons framework (Supplementary Figure S3), the cultural iceberg (Supplementary Figure S4), and the 'make-it-weird' framework (Supplementary Figure S5). During the second workshop, five of the original ten participants were led through a set of guided exercises, and produced outlines of characters and plots for their scenario worlds that they designed in the first workshop.

4.5 Collaborative scenario writing

Ten story-based scenarios were generated that are representative of the original ten topics identified in the computational text analysis. The full set of stories is available in the Supplementary material. The lead author provided editing and guidance for all of the scenarios. The final scenarios are short, written stories ranging in length from approximately 1000 to 2000 words and include a range of forms including oratory, journal entries, internal reflections, third-person narrative, conversations and dialogues, and a podcast transcript. Similarly, the scenarios are set on all populated continents, in Myanmar, India, Australia, United States, Brazil, Nigeria, Germany, and China.
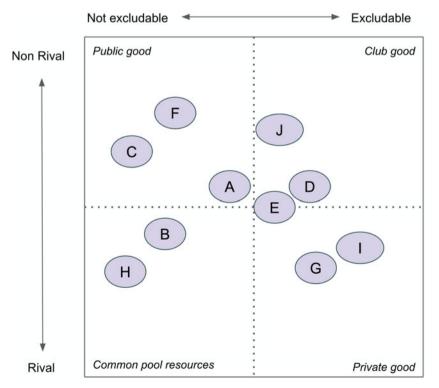
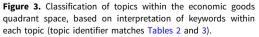### 4.6 Scenarios illustrate strange possibilities

Based on the final story output, we analyze the patterns and the possibilities that illustrate important aspects of the future of human modification of the atmospheric water. First, geophysical realities, such as proximity to coastlines, may confer some resistance of atmospheric moisture becoming anything other than a public good, given both the constant replenishment (i.e. non-rival) and limited potential for control (i.e. non-excludable) of oceanic sources of moisture. Second, technology change could lead to surprising social and legal problems related to transboundary decision making and liability related to manipulation of weather. Third, climate changes will modulate every aspect of human society, and thus lead to an ever-broadening incentive to control and manage precipitation. Fourth, social norms that are radically

Table 2. LDA topic number and keywords used in the scenario development

LDA topic number	LDA topic keywords	Topic identifier
1	precipitation, model, region, rainfall, study, observation, result, variability, observe, time, simulation, simulate, seasonal, scale, atmospheric, pattern, compare, air, high, associate, low, large, spatial, analysis, season, show, summer, difference, occur, event	A
2	climate, change, global, future, model, impact, management, scenario, land, project, regional, include, uncertainty, human, earth, country, current, strategy, landscape, projection, natural, terrestrial, expect, date, predict, tool, challenge, problem, population, assess	B
3	drought, temperature, increase, forest, area, trend, extreme, record, crop, annual, growth, yield, index, high, condition, degree, average, factor, agricultural, production, urban, year, significant, decrease, china, plant, stress, map, climatic	C
5	aerosol, warm, increase, response, effect, warming, decrease, induce, cool, ocean, reduction, anthropogenic, direct, temperature, surface, instrument, forcing, reduce, radiative, bc, force, degree, ozone, enhance, lead, east asia, heating, modus, ghg, maize	D
6	datum, method, base, approach, information, satellite, estimate, product, quality, performance, application, technique, provide, improve, pressure, measurement, develop, delta, propose, parameter, group, signal, objective, indicator, space, test, monitoring, new, obtain, achieve	E
7	vegetation, surface, soil moisture, land, cover, soil, energy, heat, exchange, water vapor, canopy, stage, flux, green, evaporation, australia, layer, leaf, atmosphere, content, moisture, cropland, subsurface, age, grass, condensation, dynamic, desert, heterogeneous, slight	F
8	research, design, technology, effort, scientific, community, policy, weather, science, program, system, development, paper, economic, knowledge, control, plan, use, gap, cost, review, address, benefit, solution, conclusion, weather modification, risk, issue, biotic, resource	G
9	water, irrigation, supply, series, demand, relevant, sector, requirement, availability, hydrologic, theory, deforestation, flow, efficiency, standard, platform, wetland, chamber, stream, amazon basin, operate, cycle, hold, amazon, capacity, energy, learn, connect, sky, evaporation	H
11	cloud, rain, ice, radar, snow, droplet, melt, aircraft, liquid, microphysical, snowpack, cell, altitude, artificial, suppress, storm, channel, mountain, boundary, reflectivity, hour, sequence, stratiform, pass, orographic, westward, scientist, radar reflectivity, formation, kilometer	I
12	match, island, april, middle, validate, drop, band, damage, image, bring, wrf, protection, wind, ccn, easterly, mm, bay, composite, air mass, size distribution, dry land, daytime, suppression, mature, salinity, ion, adequate, peninsula, night time, bulk	J

An alphabetic 'Topic identifier' is provided to link Tables 2 and 3.

Figure 3. Classification of topics within the economic goods quadrant space, based on interpretation of keywords within each topic (topic identifier matches Tables 2 and 3).

Table 3. Summary of scenario story names, economic good quadrant, and corresponding descriptions of worlds and story plots

Topic identifier	Scenario name	Economic good	Scenario description
A	We are as Gods	Public good	*World*: Scientific advancements in the manipulation of seasonal precipitation for agricultural production. *Story*: Speech by Dr. Kay Rasmusdottir, recipient of the Inaugural AGU Tessendorf Lectureship on Weather Modification, speaks about the history of weather modification, and the dangers it may pose.
B	Pride of Burma	Common pool	*World*: International treaties exist to manage international moisture flows, to ensure that no adverse consequences arise from uncoordinated land-use change. *Story*: An activist and scientist in Myanmar discovers that moisture flows are being manipulated in southeast Asia, and investigates the origin of this scheme.
C	The Palash	Public good	*World:* Profound 21st century weather modification led to global rejection because of problems, with transformation of precipitation toward a public good. *Story*: Journal of 21st century farmer discovered by distant descendent, who is herself journaling about the contrasting worlds.
D	Helping Heaven	Club good	*World*: Weather control is normal and is conducted on a community basis, but finding a balance is often challenging among competing demands. *Story*: Three water managers reflect on past management of droughts in their community, using integrated water management approaches.
E	Igor's Diary	Club good	*World:* Weather can be manipulated from satellite-based platforms, and the prohibitions on weather modification for hostile intent are ignored by some groups. *Story:* A leader struggling to cling to power aims to use weather control in an effort to lift his claim to historical legitimacy.
F	The Fertilizer Incident	Common pool	*World*: Transpiration is curated as a public good, and collaboratively stewarded to help mitigate downwind drought and precipitation deficits. *Story*: A grandmother tells story to her grandkids of how her daughter and son-in-law met in the transpiration fields of Australia's outback.
G	AnyWeather	Private good	*World:* Weather is privatized to the extent that rainfall and cloud cover can be requested, if a customer can pay the price. *Story*: A farming household in Germany must see if they can outbid a neighbor to secure the precipitation that they need for their harvest.
H	T-Trading	Common pool	*World:* Weather modification has been banned, but transpiration is managed to maximize downwind moisture, leading to the surprising outcome of forest conservation. *Story:* An employee of SkyConnect LLC, a Transpiration Futures trading firm, reflects on her life and career.
I	Queen Bee	Private good	*World:* Weather is modified for private customers in mountainous areas, so tourists can holiday at expensive ski resorts. *Story:* A group of ski resort cloud seeding employees try and one-up each other with stories about horrible customer experiences.
J	Too Much Rain in Paradise	Club good	*World:* Manipulation of cloud condensation nuclei (CCN) is regularly deployed to suppress destructive rainfall and flooding events. *Story:* A history podcast shares a story of how a CCN suppression effort in a future Lagos Bay led to a catastrophic outcome.

different from the present day may emerge from transformations caused by increasingly frequent Anthropocene crises. We summarized key characteristics of these scenarios in Table 4.

The scenarios allowed us to explore relationships among water-related sectors, as well as draw connections among disciplines and topics that are unconnected to water science. Table 5 includes excerpts from four of the ten scenarios that were developed in this study. The public good quadrant is represented by an excerpt from 'The Palash'. The excerpt references how historical weather modification led to Earth system consequences (e.g. transformation of South Asian monsoon dynamics) and was later globally banned as a result. The story explicitly mentions human rights consequences that could arise resulting from human modification of the atmospheric water cycle. This 'assault' led to atmospheric water being recognized and protected as a public good.

The common-pool quadrant includes an excerpt from the scenario 'T-Trading'. The excerpt mentions how a comprehensive

conservation and preservation effort for the Amazon led to a different perspective on how to profit from the intact forest cover. This story explores unexpected implications of successful conservation efforts, such as the financialization of the Amazonian atmospheric water cycle. While financialization is already discussed in the contexts of deforestation and commodities in the Amazon (Galaz et al., 2018), financialization of the atmospheric water cycle is a new topic.

The club good quadrant is represented by 'Too much rain in paradise', and the excerpt highlights the role of weather modification in community-scale efforts to avoid flooding or unwanted rain. This story could be viewed as a technologically advanced descendent of existing weather modification efforts that seek clear skies, particularly efforts throughout China (Bluemling et al., 2020). The story also draws connections among new topics, including advances in drone-based, three-dimensional monitoring of atmospheric conditions as well as the manipulation of

Table 4. Comparison of scenario characteristics among economic goods quadrants

Public good	Club good
● Collaborative stewardship of moisture recycling processes ● Misuse of weather modification technology instigates treaty-based protections ● Transnational governance ● Civil society is in the lead	● Community or group management of atmospheric moisture in the absence of national and international coordination ● Technologies related to suppression of unwanted rainfall, as well as for generating more rainfall, are common ● Access to weather management technologies is in the hands of a low number of operators.
Common pool	**Private good**
● Democratically coordinated management ● Large-scale land-use changes (such as deforestation) are tightly regulated ● Moisture recycling monitoring is comprehensive, open access, and technologically advanced	● Private management of atmospheric moisture privileges those with the most power or money ● Economies are built around the manipulation of weather, including tourism and agriculture ● Technology companies exist to exploit the desire for 'on-demand' weather ● Trade-offs between recipients of increased rainfall and those that receive less

conditions with the continuous management (and curation) of desired atmospheric aerosol conditions.

The private good quadrant is represented by 'AnyWeather', and the excerpt highlights how weather services are now 'on demand', similar to other delivery services. While this requires non-existent technological advancements in microscale weather modification, the story is especially about the implications of pay-to-play services in the context of competing user interests. In this case, the story explores how a for-profit company might create different types of solutions for managing competing requests, including letting those with more money have greater levels of priority for their desired weather.

5. Discussion

5.1 Improved anticipatory capacity

The scenarios depict a range of social, technological, and physical changes – many of which seem implausible or even impossible in the present. Yet, climate change, together with technological progress, is rapidly rendering the impossible, possible; and the unimaginable, a current event (Pettit et al., 2021; Samenow & Patel, 2022). Thus, prudence dictates that we take seriously the highly consequential ideas depicted in these scenarios. In this vein, we recommend several relevant anticipatory practices that also apply to water policy governance:

(1) Anticipate changes in regulatory regimes that may be needed at multiple levels for atmospheric water modification.

(2) Anticipate substantial improvements in the diagnostic and monitoring capability of atmospheric moisture, precipitation, and cloud microphysics and the risks of unequal access.

(3) Anticipate overlapping crises, that relate to atmospheric water flows in surprising ways, and that will motivate unexpected social, economic, and geopolitical surprises.

(4) Anticipate technological surprises that are disruptive, transformative, and seemingly impossible in the present, which will change what is plausible regarding modification of atmospheric water flows.

(5) Anticipate changes in power dynamics (e.g. geopolitical, social, cultural), that could lead to new configurations of who is able to exert disproportionate control over atmospheric water flows.

Intentionally adopting these and perhaps other anticipatory approaches, will improve the responsiveness of both science and policy toward addressing a rapidly changing human relationship with the atmospheric water cycle.

5.2 Implications for the governance of atmospheric water

Another important dimension of thinking about this study is how existing governance and management of atmospheric water fit into this futures-oriented discussion. Existing research has discussed the broad outlines of atmospheric water governance (Keys et al., 2017; te Wierik et al., 2020) and others have discussed manipulation of the weather more broadly (Bonnheim, 2010;

Table 5. Brief excerpts from the story scenarios that discuss aspects relevant to the economic goods framing

Public good – Excerpt from 'The Palash'	Club good – Excerpt from 'Too Much Rain in Paradise'
'Weather modification, particularly cloud-seeding came to be viewed as an assault on a basic human right. While the collapse of the AMOC ensured that the southwest monsoon winds never quite returned to their normal state, eastern monsoon winds, now freed from the cloud seeding efforts of several eastern nations, became the dominant harbinger of rain in drought-stricken areas such as Palashpaari'.	'The suppression of precipitation relies on careful and complete monitoring of air quality via the EkoCloud, a 3D network of sensors that continuously monitor and balance the right distribution of particles in the atmosphere. Many people who visit Lagos apparently comment on the strange haze over the bay. This haze is not by accident, but by design'.
Common pool – Excerpt from 'T-Trading'	**Private good – Excerpt from 'AnyWeather'**
'At the NGO they were tireless proponents of additional ecological protections for the entire Amazon basin. With the tailwind of the Manaus Protocol, decades of mismanagement were being re-written. But the advent of T-trading saw Defenda being subsumed by an EcoFinance startup, SkyConnect LLC. Her job flipped inside out from advancing ecologically-based financial safeguards for her home, to working as a cog to maximize transpiration flows'.	'AnyWeather regrets to inform you that your request for our 'Spring Rains service' conflicts with an earlier request by *Mueller, Tom* that supersedes your own. We apologize for any inconvenience. Note that your account has been credited a full refund. For any further questions, please click here for more information'.

Chien et al., 2017). Depending on the types of technologies that are deployed and the spatial scales over which atmospheric water changes operate, the administrative responsibility could shift. For small-scale situations, as depicted in the scenarios 'AnyWeather' and 'Helping Heaven' (where weather conditions are manipulated on a local basis), it could be that regulations remain a national issue, and governance need not interact with transboundary discussions. Indeed, there are some contemporary organizations which seek to directly modify regional evapotranspiration to moisture recycling patterns, despite the absence of transboundary governance mechanisms (Rose, 2021). However, scenarios that involve large-scale transpiration modification, such as 'T-Trading' and 'The Fertilizer Incident' (which depict very large-scale modifications of land-use and corresponding large changes to evaporation and transpiration) would necessarily involve transboundary negotiations. The scenario 'T-Trading' specifically lists several international treaties and agreements which create the operational guardrails for financial instruments to emerge that manage transpiration. While fictional, this is analogous to other traded commodities that are regulated (to varying extents) at national and international levels (e.g. staple food crops, housing) (Clapp & Helleiner, 2012; Smith, 2010). Future research could advance the understanding of both practical examples of analogous governance structures that would be relevant for different quadrants of the economic goods framing, as well as to describe theoretical governance structures that could meet an as-yet non-existent activity (e.g. what types of regulatory schemes would be necessary to govern Transpiration Futures trading?).

5.3 Limitations

This is an initial exploration of atmospheric water as an economic good, specifically focusing on how humans are modifying this water globally. Given that we have aimed to be brief in the introduction regarding the conceptual framing, there is a substantial discussion that should yet be had regarding the economic goods classification. This discourse, however, is likely to be most fruitful when examined from multiple disciplinary perspectives, as well as inter- and trans-disciplinary perspectives. In this study, we have aimed to introduce the concept, and highlight how a specific approach (i.e. hybrid futures methods blending computational text analysis and expert creativity) can advance our perception of key issues. In this way, our study should be viewed as a horizon scanning exercise that can begin to enumerate the ideas, pitfalls, and potential challenges associated with thinking about human modification of the atmospheric water cycle.

The mapping of topics and keywords from the LDA onto the economic goods quadrants was conducted prior to the expert workshops by the lead author, and we emphasize that different subjective interpretations of this mapping could lead to different creative outcomes. Future efforts could explore the implications of different subjective mappings, which could lead to entirely different types of story scenarios being developed. Similarly, future research could aim to develop an objective procedure for interpretation of the LDA results into an economic goods framework. Yet, given that the entire research effort aims to embrace creativity, it may be more worthwhile to lean into the opportunity for numerous creative interpretations of the empirical LDA results to inform options for more flexible and responsive policy and governance environments.

Also, while the group of experts collaborating in this study is highly interdisciplinary (with expertise spanning resource economics, engineering, urban water systems, environmental humanities, biodiversity conservation, ecohydrology, and more), there are yet more disciplines that could be engaged. In particular, it could be worthwhile to engage weather modification personnel and practitioners to think about the future of their industry to better understand the perspective of 'insiders' for this topic.

5.4 Research frontiers

Given that this is among the first efforts to discuss human modification of atmospheric water using an economic goods framing (Keys, 2021), there is much yet to do to understand its dimensions, critique the framing, and deploy empirical tools to test hypotheses. First, there is already considerable scholarship surrounding water as an economic good more broadly (Rogers et al., 2002; Savenije, 2001; Savenije & van der Zaag, 2002), and these ideas could be brought to bear more fully to think about atmospheric water specifically. This could include reflection from similar types of 'source–sink' relationships such as watersheds that incorporate upstream and downstream ideas into their study (Jansson et al., 1999), as well as the payment for ecosystem services literature (Jack et al., 2008). Second, the notion of water as an economic good presupposes that concepts such as 'valuation' and other ideas that enable management and control are tenable in the discourse of atmospheric water (Jenerette et al., 2006; Schaubroeck et al., 2016). Future research ought to more deeply engage other topics that have managed to examine valuation of diffuse economic goods, such as air quality (Levinson, 2012), or more broadly through cultural ecosystem services (Sukhdev, 2009).

Third, a tremendous amount of opportunity exists to use these scenarios as springboards for empirical analysis. This could take many forms and span numerous disciplines, such as mechanical engineering, ecohydrological modeling, theoretical economics, and weather modeling. We provide a snapshot of questions that emerged from discussion among the group, which could guide future research and policy into aspects of human modification of the atmospheric water cycle:

- *What are the theoretical limits of land-based weather modification?* What is the theoretical maximum evaporative contribution of the terrestrial biosphere? How does this vary around the planet? Are there biological restrictions to evapotranspiration that could be lifted with genetic modification? What are the barriers to this type of change?
- *What are the technological limits of drone technology and its use in weather modification?* How small could drones theoretically be constructed, while carrying a payload? What types of payloads could drones carry that are relevant to the weather modification conversation, including aerosols, CCN, etc.?
- *What are the smallest scales of weather modification?* What are the smallest spatial- and time-scales at which weather could be modified? What prevailing regional and large-scale weather conditions would be more or less permissible for this type of micro-manipulation?
- *What types of financial instruments could emerge to manage the flow of atmospheric water flows?* Are there existing financial mechanisms (e.g. trade rules, stock exchange listing agreements) which indirectly manage atmospheric moisture? Could there ever be a 'futures' or 'options' market to modify atmospheric water flows?

6. Conclusions

Humanity is transforming the atmospheric water cycle not least through climate change and large-scale land-use change. The advent of scientifically verifiable cloud seeding may accelerate the uptake of atmospheric water manipulation in the near future to an even larger extent. Moreover, scientific policies, legal frameworks, and governance strategies will need to anticipate this expanded manipulation and its effects on further altering the global hydrological cycle. Thus, in this study we have introduced an economic goods framework for classifying the types of human modification of the atmospheric water cycle including atmospheric water as a public good, a club good, a common-pool resource, and a private good. Moreover, we combined computational text analysis and collaborative expert visioning, to create ten story-based scenarios of the future. Specifically, this blending of objective and subjective approaches provided a rapid method for efficiently summarizing a large amount of information for a creative scenario workshop.

Our scenarios depict both familiar and strange futures. These include detailed worlds with characters that explore issues such as an Amazon basin dominated not by deforestation, but by Transpiration Futures trading; privatized on demand weather that can be called up via an app; transformed drylands to provide continental moisture bridges; and, international efforts coordinating the management of the atmospheric water commons. Our approach effectively blended a broad literature survey into a rapid, expert-driven scenario development process that resulted in ten creative visions of the future. To be very clear, these scenarios are not meant to be prognostic. They are, instead, intended to provide a clearer perspective on present-day scientific and social changes that require outside-the-box thinking. As the world changes around us, these scenarios can help ignite new policy questions and lead to novel scientific inquiry to better understand the future of humanity's modification of the atmospheric water cycle.

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