Opportunities and limitations to detect climate-related regime shifts in inland Arctic ecosystems through eco-hydrological monitoring

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Abstract
This study has identified and mapped the occurrences of three different types of climate-driven and hydrologically mediated regime shifts in inland Arctic ecosystems: (i) from tundra to shrubland or forest, (ii) from terrestrial ecosystems to thermokarst lakes and wetlands, and (iii) from thermokarst lakes and wetlands to terrestrial ecosystems. The area coverage of these shifts is compared to that of hydrological and hydrochemical monitoring relevant to their possible detection. Hotspot areas are identified within the Yukon, Mackenzie, Barents/Norwegian Sea and Ob river basins, where systematic water monitoring overlaps with ecological monitoring and observed ecosystem regime shift occurrences, providing opportunities for linked eco-hydrological investigations that can improve our regime shift understanding, and detection and prediction capabilities. Overall, most of the total areal extent of shifts from tundra to shrubland and from terrestrial to aquatic regimes is in hydrologically and hydrochemically unmonitored areas. For shifts from aquatic to terrestrial regimes, related water and waterborne nitrogen and phosphorus fluxes are relatively well monitored, while waterborne carbon fluxes are unmonitored. There is a further large spatial mismatch between the coverage of hydrological and that of ecological monitoring, implying a need for more coordinated monitoring efforts to detect the waterborne mediation and propagation of changes and impacts associated with Arctic ecological regime shifts.

Keywords: Arctic, climate change, regime shifts, eco-hydrology, hydrology, biogeochemical cycling, permafrost, ecosystem dynamics, feedbacks, monitoring

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1. Introduction

Detecting, monitoring, and anticipating the ecological consequences of climate change is a particular challenge in the Arctic. The consequences of Arctic change are complicated by a dynamic cryosphere, shifting hydrological connections, and ecological dynamics that can cause surprising reorganizations of ecological structure and function.

Climate change is rapidly transforming the Arctic (White et al 2007, Francis et al 2009). In the past century, the
Arctic has warmed much faster than the planet as a whole. Temperatures in the north (40–70°N) have increased up to 2–3°C over the past 50 years (ACIA 2005), much more than the 0.65°C increase in global mean surface air temperature during the same period (IPCC 2007). Current temperatures are the highest experienced in the Arctic in the past 400 years (Overpeck et al 1997), and these highs are forecast to be exceeded by a further 2.5°C by the mid-21st century, and up to 5–7°C by the end of the 21st century (ACIA 2005).

Arctic warming has triggered substantial changes in the cryosphere. Annual snow cover has declined by 10% since 1972 (Serreze et al 2000, Hinzman et al 2005, White et al 2007, Francis et al 2009). The September sea ice extent has declined about 30% (~0.7 million km²/decade, linear trend) during the period 1979–2008 (Holland et al 2010). Retreat or melting of glaciers and ice caps has increased melt water flows to the Arctic Ocean, with the glacier contribution increasing by up to 42% between 1961–1992 and 1993–2006 (Dyurgerov et al 2010).

Warming of the air has warmed the permafrost, ground that has been frozen for two or more consecutive years, which underlies and extends over 20–25% of the exposed land surface in the Arctic (Osterkamp and Romanovsky 1999, Serreze et al 2000). For instance, in northern Alaska, deep boreholes have measured a temperature increase of between 2 and 4°C during the last 50–100 years, with an additional warming of 3°C since the late 1980s (Lachenbruch and Marshall 1986, Nelson et al 2001, Yoshikawa and Hinzman 2003, Hinzman et al 2005). Similar patterns have been observed in the Nordic area with increasing active layer depths and rising permafrost temperatures during the past 10 years (Christiansen et al 2010), and in Russia, measurements in boreholes show substantial warming of permafrost during the past 20–30 years (Romanovsky et al 2010). Continued warming is expected to deepen the active layer (seasonally frozen ground) and cause a northward movement of the permafrost boundaries between areas of continuous, discontinuous, and sporadic permafrost (ACIA 2005).

Ecosystem responses to Arctic warming are largely determined by changes in the cryosphere, which are in turn also reflected in observable hydrological changes (Rowland et al 2010). The latter have been demonstrated in terms of changes in the characteristic behavior of hydrological discharge dynamics (Lyon et al 2009, Lyon and Destouni 2010), as well as in soil moisture, drainage patterns and surface runoff (Prowse et al 2006) in permafrost regions. Frey and McClelland (2009) and Rowland et al (2010) have shown that permafrost degradation may have significant consequences on the Arctic freshwater system by causing a transition from a surface water-dominated system to a groundwater-dominated system. Furthermore, Bense et al (2009) have presented a process-based model clarification of the essential links between groundwater hydrology and permafrost change, while Lyon et al (2010) have done so for the links between groundwater hydrology and the waterborne carbon cycle in permafrost regions, and a series of other studies for the groundwater hydrology links to nitrogen and phosphorus flux dynamics (Baresel and Destouni 2005, 2006, Lindgren et al 2007, Darraaq et al 2008, Destouni and Darraaq 2009, Destouni et al 2010, Basu et al 2010). These studies all support earlier assessments of Hodkinson et al (1999) and Chapin et al (2006) that changes in hydrological conditions both reflect and contribute to essential transformations of the functioning of inland Arctic ecosystems, because water in its various forms couples the biotic and the abiotic components of the Arctic environment.

The combination of gradual climate change and multiple ecological feedback processes, many of which include and are propagated by water, can cause Arctic ecosystems to shift, from one set of mutually reinforcing feedbacks to another (Holling 1973, Scheffer and Carpenter 2003) (see also supplementary information S1 and figure S1 available at stacks.iop.org/ERL/6/014015/mmedia). Such ecological regime shifts have been described for a diverse set of ecosystems worldwide, including tropical coral reefs, savannas, temperate lakes, and coastal zones (Folke et al 2004, Drever et al 2006, Gordon et al 2008). In the inland Arctic, a number of ecological regime shifts have been observed but not yet been systematically analyzed. Understanding if and which ecological changes represent rapid regime shifts is important because these shifts can in turn quite rapidly reduce important ecosystem services. Analyzing regime shifts that have already occurred and their spatio-temporal occurrence patterns is also important for identification of the key variables, characteristics and types of related changes that can trigger and be used to detect or monitor Arctic ecological change.

Detecting early warning signs of ecological regime shifts requires substantial monitoring data from both biotic and abiotic ecosystem components (Scheffer et al 2009). Rowland et al (2010) have outlined how and why ecosystem responses to Arctic warming are largely determined by cryosphere changes, but these changes are difficult to observe directly. However, as discussed above, changes in the cryosphere can be observed in changes in hydrological fluxes. Hydrological flux changes thus reflect cryosphere changes that are in turn related to Arctic ecological change (Hodkinson et al 1999, Chapin et al 2006). Changes in both water fluxes and waterborne mass fluxes should therefore be expected to reflect climate, cryosphere and ecological condition changes in the catchment areas that feed into the flux observation points. Support for this expectation has, for instance, been demonstrated by quantification of the links between groundwater hydrology and waterborne carbon cycling (Lyon et al 2010), and changes in essential characteristics of hydrological discharge dynamics (Lyon et al 2009, Lyon and Destouni 2010) in permafrost regions. However, the use of hydrological monitoring to detect ecological changes may be limited by gaps and decline in available Arctic hydrological monitoring data, in particular with regard to the largely unmonitored waterborne nutrient transport (Bring and Destouni 2009) and the fact that, across the Pan-Arctic, river basins with the largest expected climatic changes have the least dense and most declining hydrological monitoring (Bring and Destouni 2010).

This study aims to identify key opportunities and limitations in the Arctic eco-hydrological monitoring windows, i.e., in the systematic hydrological monitoring records
combined with relevant ecological surveys, which might enable improved detection, interpretation and projection of inland ecosystem regime shifts by reflecting associated changes in water discharge and waterborne mass transport dynamics. To achieve this aim, the study (a) reviews observed changes in inland Arctic ecosystems to identify potential climate-driven and hydrologically mediated regime shifts, (b) systematizes the identified regime shifts, and (c) analyzes if current eco-hydrological monitoring can help detect or help predict such shifts.

The study defines and includes three types of regime shifts in inland Arctic ecosystems: (i) shift from tundra to shrubland or forest, (ii) shift from terrestrial ecosystems to thermokarst lakes and wetlands, and (iii) shift from thermokarst lakes and wetlands to terrestrial ecosystems. To determine the eco-hydrological monitoring window with regard to these types of regime shifts, the identified occurrence area of such shifts is quantified and mapped against the spatial coverage and temporal extent of relevant hydrological monitoring, and the distribution of ecological research stations within the 24 million km² Pan-Arctic drainage basin (PADB).

2. Materials and methods

To identify and potentially classify reported ecological changes in the Arctic as ecosystem regime shifts, we reviewed the scientific literature for clear reports of changes in the inland parts of the Arctic that can be considered as regime shifts on the basis of reported: (1) change in ecosystem structure and function; (2) change in feedbacks; and (3) shift into new reinforcing set of feedbacks (see also a more detailed general description and discussion of ecological regime shifts in supplementary information S1 available at stacks.iop.org/ERL/6/014015/mmedia). Along with references cited in the Arctic Climate Impact Assessment report (ACIA 2005), we searched for relevant literature in the ISI Web of Science using key words related to climate change and responses to it in the structure and dynamics of inland ecosystems, disturbance regimes, and landscape processes (e.g. hydrology and permafrost). In this search process, we looked for reported patterns of abrupt change between different types of ecosystems at a landscape scale and in key variables and feedbacks, and their relation to climate change as a possible driver of the ecosystem shifts (Bennett et al. 2005).

The identified and systematized three major types of inland ecosystem regime shifts in the Arctic ((i) from tundra to shrubland or forest; (ii) from terrestrial to aquatic ecosystem; and (iii) from aquatic to terrestrial ecosystem) all represent substantial ecological changes and involve not just gradual transitions but clear shifts between different types of terrestrial and aquatic ecosystems. Almost 200 scientific articles were reviewed in the process of identifying these regime shifts. Among the articles that included change reports that could be classified as regime shifts, the majority referred to the tundra–shrub/forest shift (i), while the shift from terrestrial to aquatic ecosystem (ii) was the least frequently represented one among the reported changes. To clearly identify and connect the key mechanisms involved in the three considered types of regime shifts and the interactions between them, we constructed a joint system diagram (Meadows 2008) for all three shift types, outlining the involved alternative regimes, key variables and drivers.

Furthermore, we mapped the identified regime shift occurrences and their area coverage against the spatial and temporal extent of hydrological monitoring of water discharges, and waterborne carbon, nitrogen and phosphorus fluxes (from measured concentrations in the water discharges) within the PADB. These variables were chosen because they are relevant for possible improved understanding, detection and projection of linked cryosphere (permafrost), hydrological–hydrochemical and ecosystem changes (Hodkinson et al. 1999, Chapin et al. 2006, Lyon et al. 2009, 2010, Lyon and Destouni 2010).

The Arctic monitoring data used for the comparison between reported regime shift occurrences and hydrological–hydrochemical monitoring were acquired from Bring and Destouni (2009). They performed a comprehensive quantitative study of the current status of accessible monitoring data for water discharge and waterborne mass fluxes from the PADB to the Arctic Ocean, where the starting year, length and end year of the observation time series were summarized for each hydrological station. For the present assessment, we only considered time series longer than ten years and with the end year in the recent decade, as landscape-scale ecosystem changes typically occur in a time range of decades.

The regime shift mapping and hydrological monitoring comparison was carried out using ArcGIS. In the regime shift mapping, the area coverage of each observation report that was identified as a regime shift case was assigned to the observation center point, based on location and area given from the reports. For regime shifts with no area coverage reported in the literature, a minimum area resolution value was assigned from the 30' x 30' grid net used in the study by Bring and Destouni (2009), with cell area ranging from approximately 950 km² (72°N) to 1800 km² (55°N). Overlapping area coverage for different regime shifts was only accounted for once. Finally, to also compare how the identified ecosystem regime shifts and the hydrological monitoring relate to ecological surveys and their spatial distribution within the PADB, we added the locations of available ecological research stations, as acquired from SCANNET (2010) and UNEP/GRID-Arendal (2008), to the regime shift and hydrological monitoring maps.

3. Results

The internal controlling variables, processes and feedbacks, and the external system drivers and disturbances of the different considered types of regime shifts are shown in figure 1. All components in figure 1 are described and discussed further and in more detail in supplementary information S2 (available at stacks.iop.org/ERL/6/014015/mmedia), including individual system diagrams for each regime shift type (figures S2–S4 available at stacks.iop.org/ERL/6/014015/mmedia). In general, the joint diagram in figure 1 reveals that the hydrological and biogeochemical
Joint system diagram for the three investigated regime shifts: (i) from tundra to shrubland or forest, (ii) from terrestrial to aquatic ecosystems, and (iii) from aquatic to terrestrial ecosystems. The plus and minus signs show positive and negative relationships, respectively. Red text represents the different ecosystem regimes and blue text indicates hydrological variables. Shaded text indicates external forcings (at least partly for soil moisture, which is also part of the internal ecosystem dynamics). Regime shift processes, feedbacks and impact implications are described and discussed further and in more detail in supplementary information S2 (available at stacks.iop.org/ERL/6/014015/mmedia), including also individual system diagrams for each regime shift type (figures S2–S4 available at stacks.iop.org/ERL/6/014015/mmedia).

cycling effects of permafrost thawing connect the three types of regime shifts, their internal feedbacks, and impacts.

The three identified regime shifts all occur at the landscape scale, however their consequences go beyond that scale and beyond the direct ecosystem changes, through their reshaping of regional hydrology (changes in water balance and surface water connection/fragmentation) and alteration of regional supplies of ecosystem services (figure 2; see more detailed discussions on ecosystem change implications in supplementary information S2 available at stacks.iop.org/ERL/6/014015/mmedia). In a wider context, these regime shifts also have implications for the Earth system as a whole, through their feedbacks to global climate change by changes in albedo, and energy and carbon fluxes (Hinzman et al 2005, McGuire et al 2006).

The majority of the identified regime shifts are found in Alaska (67%), but some are also reported in Canada, northern Scandinavia and northwest Russia. No identified regime shifts or reports of ecosystem changes are found for large parts of Canada and eastern Russia. The individual area coverage of the identified regime shifts ranges from approximately 950 to 450,000 km², with a mean of 14,500 km² (for comparison, the total PADB area is 24 million km²). Figure 3 shows an overview of the mapped regime shifts and their area coverage, along with the temporal and spatial extent of the monitoring of relevant hydrological and hydrochemical observation parameters, and the locations of 25 ecological research stations identified within the PADB.

The different types of regime shifts vary in their timing, location and area coverage. Regime shift type (i), from tundra to shrubland or forest (the manifestations, processes and implications of which are explained in more detail in supplementary information S2a and figure S2 available at stacks.iop.org/ERL/6/014015/mmedia), has occurred throughout the Arctic during the past 50 years (Sturm et al 2001a, Kharuk et al 2008, Kammer et al 2009, Tombok et al 2009). Chapin et al (2005) estimated that about 2% (11,600 km²) of the treeless area in Alaska has changed from tundra to forest over this 50 year period. Evidence of transition from tundra to shrubland/forest has been reported for Alaska (over 320 km² from 1948–50 to 1999–2000, mainly alder; Sturm et al (2001b), Tape et al (2006)) and Siberia (forest expansion by 20–60 m in altitude during the last century; Devi et al 2008).

Regime shift (ii), from terrestrial ecosystems to thermokarst lakes and wetlands (see supplementary information S2b and figure S3 available at stacks.iop.org/ERL/6/014015/mmedia for a more detailed explanation and discussion of this shift), has been observed in Alaska (Osterkamp et al 2000, Hinzman et al 2005, Grosse et al 2010) and Siberia (Smith et al 2005). In Tanana Flats, Alaska, 2600 km² of permafrost-supporting birch forests are changing into minerotrophic floating mat fens (Osterkamp et al 2000, Jorgenson et al 2001, Hinzman et al 2005), and in Mentasta Pass, thermokarst features such as lakes, bogs and sedge meadows are replacing white and black spruce forests (Osterkamp et al 2000). In Siberia, total lake area increased by 12% (133 km²) between 1973 and 1997–8 in a region with ice-rich continuous permafrost (Smith et al 2005).

Regime shift (iii), from thermokarst lakes and wetlands to terrestrial ecosystems (see supplementary information S2c and figure S4 available at stacks.iop.org/ERL/6/014015/mmedia for a more detailed explanation and discussion of this shift), has been observed in Siberia, Alaska, and in the western Canadian Arctic during recent decades (Smith et al 2005,
Figure 2. Drivers of and feedbacks from the three investigated types of regime shifts in inland Arctic ecosystems. Global climate change drives changes in regional temperature and precipitation, and these changes interact with regional topography and landscape patterns of permafrost and plant communities, and are mediated and propagated by hydrology (with blue text indicating hydrological variables) in pushing Arctic ecosystem regimes towards directional regime shifts (black arrows). When these regime shifts occur they can feed back to regional and global scales (gray arrows). Tundra to shrub/forest shifts can alter water balance, wind pattern, and regional climate; tundra to thermokarst lake shifts can increase the hydrological surface water connections in the landscape, while the drainage of thermokarst lakes triggers hydrological surface water fragmentation. Regime shifts feed back to regional climate by altering albedo, and carbon, energy, water, and waterborne mass fluxes, and if these changes accumulate across large areas they can also affect the global climate.

Figure 3. Reported regime shift observations: tundra–shrub/forest, thermokarst lake development, and thermokarst lake drainage, where graduated symbols represent different area coverage for the reported regime shifts. The regime shift observations are for comparison shown along with the spatial coverage (and temporal extent) of the hydrological monitoring of water (a), carbon (b), nitrogen (c), and phosphorus (d) fluxes, and the locations of major ecological research stations in the PADB.
Figure 4. Fraction of the total occurrence area of each regime shift type that lies within the hydrologically unmonitored area part of the Pan-Arctic drainage basin (PADB) for each hydrological observation parameter. These parameters are water discharge, and waterborne carbon, nitrogen and phosphorus transport, which could be subject to alterations by the three regime shift types (figure 1, and supplementary figures S2–S4 available at stacks.iop.org/ERL/6/014015/mmedia).

Riordan et al 2006, Hinkel et al 2007, Kirpotin et al 2008, Marsh et al 2009). For example, a study area of 515 000 km² in Siberia had an about 6% decline (930 km²) in total regional lake surface area between 1973 and 1998 (Smith et al 2005). Thermokarst ponds near Council, Alaska, have experienced a decrease in surface area between 1950 and 2000. Yoshikawa and Hinzman (2003) suggest that some of these ponds should be completely drained by now (1.5 years after the study) if they do not receive any additional inputs of water. On the Arctic Coastal Plain, northern Alaska, where thousands of lakes are found (covering 46% of the landscape), Hinkel et al (2007) report that 50 lakes have been completely or partially drained between the mid-1970s and 2000. In the Tuktoyaktuk Coastlands and Anderson Plain regions, western Canadian Arctic, 41 thermokarst lakes drained between 1950 and 2000 (Marsh et al 2009). In NW Alaska, total lake area of 86 km² (22%) was lost between 1950 and 2008 in a region with ice-rich continuous permafrost, where 8.2% of the lakes were drained completely (Grosse et al 2010).

Comparisons of the location and coverage of the identified regime shifts against hydrological and hydrochemical monitoring within the PADB shows substantial hydrological monitoring gaps, revealing limitations of detecting and improving our understanding and prediction capability for the considered types of regime shifts through observations in the Arctic eco-hydrological monitoring window. While most of the identified regime shifts are located in near range of an ecological research station, most of the ecological research stations are located in hydrologically unmonitored areas of the PADB. Consequently, the majority of the identified regime shifts (75–100% of the total occurrence extent) occur in the hydrologically and hydrochemically unmonitored areas (figure 4). The only exception is for the shift from thermokarst lakes and wetlands to terrestrial ecosystems (iii), with 83, 85 and 53% of its occurrence being in areas that are monitored with regard to water discharge and waterborne nitrogen and phosphorus fluxes, respectively, but not to waterborne carbon fluxes. In general, the area covered by water discharge monitoring is substantially different from that of water chemistry monitoring (figure 3). The water discharge monitoring covers more than 73% of the non-glaciated PADB, while the nitrogen monitoring covers 57%, the phosphorus monitoring covers 39%, and the carbon monitoring covers less than 1%.

Despite these gaps in monitoring there are some areas where the eco-hydrological window presents opportunities for observing ecological regime shifts. Figure 5 shows locations where there is substantial overlap between hydrologically and hydrochemically monitored areas and regime shift locations. River basins with such hotspots include for discharge (insets (A) and (B)): Yukon, Mackenzie, Barents/Norwegian Sea and Ob, and in addition for waterborne carbon (inset (C)): Barents/Norwegian Sea, and waterborne nitrogen (inset (D) and (E)) and phosphorus (inset (F) and (G)): Yukon, Barents/Norwegian and Ob. Some of these hotspot opportunities have started to be investigated, yielding identification and quantification of significant hydrological alteration signals from permafrost thawing (hotspot areas for discharge A: Lyon and Destouni (2010), and C: Lyon et al (2009)), and catchment-scale dissolution rate estimates for dissolved organic and inorganic carbon from observations of their waterborne mass fluxes (hotspot area for carbon C: (Lyon et al 2010)). Forthcoming work will investigate similar and additional detection opportunities and aspects in other hotspot areas identified in this figure.

4. Discussion

While there are large areas of the PADB in which there are substantial mismatches between ecological and hydrological monitoring, the identified monitoring hotspots represent areas in which there are opportunities to identify and detect characteristic hydrological and hydrochemical signatures of the different types of regime shifts.

The identified shift occurrences and their key drivers, variables, feedbacks and impacts are reasonably well known, but the total occurrence area of the shifts may be underestimated. The regime shift locations identified here are all in regions of considerable ecological observation effort (figure 3), but do not necessarily represent the areas of greatest
shift occurrence. Possible regime shift occurrences in both hydrologically and ecologically unmonitored areas imply that the actual distribution and total area affected by regime shifts can be larger than indicated by the ecological changes so far reported in the literature.

The regime shifts identified in this paper are likely to continue to occur. Further climate warming is expected in the Arctic, despite potential future reductions in greenhouse gas emissions. Consequently, management of inland ecosystem regime shifts in the Arctic has to focus on adaptation, and forecasting of regime shifts and their impacts.

Enhanced forecasting requires improved understanding of how local topography, permafrost and vegetation interact with changes in water, mass and energy fluxes, and how these fluxes propagate changes and their impacts through and from the Arctic ecosystems. A main aim of forecasting is to determine the effects of and vulnerability to regime shifts, and the likelihood that local regime shift consequences will influence other areas. Better understanding of the distribution of hydrological and other factors that regulate the regime shifts of inland Arctic ecosystems could enhance our capacity to forecast when and where shifts may occur. With increased understanding and forecasting of the regime shifts and their effects, we can reduce the uncertainty, and better plan to minimize the negative impacts and enhance the positive impacts of these shifts on the people and ecosystems of the Arctic.

5. Conclusion

The regime shifts discussed in this study involve substantial ecological changes occurring at the landscape scale over the Pan-Arctic land region, over time frames that range from days to decades. The impacts and feedbacks of these shifts may also affect larger spatial scales, through changes in energy, carbon, water and other fluxes and feedbacks to regional and global change. In order to fully understand these shifts, changes and feedbacks, a multidisciplinary approach is needed to move from individual component analysis to a system-wide approach. Such an approach must also involve improved understanding and quantification of water flow and waterborne mass transport processes, and their role in mediating regime shifts, and linking and propagating various
shift impacts through different system components. We have here identified and mapped a number of hotspot areas, where systematic hydrological—hydrochemical monitoring overlaps with ecological monitoring and observed ecosystem regime shift occurrences, providing opportunities for improved regime shift understanding, detection and prediction through linked eco-hydrological investigations.

Apart from the hotspot areas, however, there is large hydrological monitoring blindness to the water flow and waterborne mass transport effects of the considered climate-driven regime shifts in the inland Arctic ecosystems. Furthermore, there is large incompatibility between the spatial coverage of hydrological and ecological change monitoring in the PADB, limiting the possibilities for systematic, multidisciplinary observation of different waterborne change aspects, manifestations and linkages of inland ecological regime shifts. To improve our understanding of where regime shifts have occurred, as well as which regions may be most vulnerable to such regime shifts in the future, coordinated hydrological and ecological monitoring efforts are needed to systematically observe the ecosystem shifts in conjunction with associated hydrological and biogeochemical cycling changes, and their interactions with changes in climate across the Pan-Arctic.

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