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Does globalization of water reduce societal resilience to drought?

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[1] Most food production depends, directly or indirectly, on freshwater resources. In the absence of importation of food commodities, population growth is constrained by the availability of local resources—including water—as well as by cultural and health-related factors. The global trade of massive amounts of food makes societies less reliant on locally available water resources, thereby allowing some populations to exceed the limits posed by their local water budget. Thus, international trade implies a virtual transfer of water resources from areas of food production to importing regions. While it is recognized that in the short term this globalization of (virtual) water resources may prevent malnourishment, famine, and conflicts, its long-term effects on the coupled human-natural system remain poorly investigated. Here we develop a minimalist modeling framework to investigate the effect of the uncontrolled trade of food products on the resilience of human societies with respect to drought and famine. Our results suggest that in the long run the globalization of water resources reduces the societal resilience with respect to water limitations in that it leaves fewer options available to cope with exceptional droughts and crop failure. **Citation:** D'Odorico, P., F. Laio, and L. Ridolfi (2010), Does globalization of water reduce societal resilience to drought?, *Geophys. Res. Lett.*, *37*, L13403, doi:10.1029/2010GL043167.

1. Introduction

[2] Human societies rely on water resources for drinking, household usage, industrial and agricultural production [e.g., *Gleick*, 1993; *Rosegrant et al.*, 2009]. Water requirements for food production exceed by far all the other water needs [*Hoekstra and Chapagain*, 2008]. Thus, food security strongly depends on water availability, and major anthropogenic disturbances of the water cycle are often associated with the intensive use of water resources imposed by the need for food production [*Baron et al.*, 2002]. These water-driven interactions between societies and the environment are typically investigated comparing for different regions of the world the water demand to the water resources locally available. Societal water deficit emerges in regions where the anthropic demand exceeds the supply, while excess of water resources occurs in the opposite case. Thus, different regions can sustain populations of different sizes (i.e., with different carrying capacities), depending on climate, amount of land and water resources allocated to agro-ecosystems, and the type of diet [*Hoekstra and Chapagain*, 2008; *Falkenmark et al.*, 2004].

[3] Population growth has historically adjusted to the local ecohydrological, social, and economical constraints (Figure 1a) with the population carrying capacity being controlled by the available resources (including water), and severe droughts leading to famine, starvation and malnourishment. Cities have always relied on the supply of food from the surrounding countryside and some local trade of food commodities has existed since the antiquity [e.g., *Lopez*, 1976; *Braudel*, 1982]. However, until recently most of the food was used either locally or traded over relatively short distances. The current global trade of food commodities has completely changed this scenario, causing an unprecedented disconnection between consumer and natural resources. If we estimate the water demand (including water required for food production) in many arid regions around the world (e.g., the Middle East), we find that some societies often exceed their ecohydrologically-controlled carrying capacity [*Allan*, 1998]. How can these situations be sustained? Mainly through the import of food from other regions (e.g., grain from North America), which bear the water cost of its production. Thus, by importing food a region virtually imports water [*Allan*, 1998]. This virtual water is conceptually embedded - though not physically present - in the goods that are transported. It is the trade of virtual water that allows some societies, mainly in dryland regions, to persist in a water deficit state. Thus, the exchange of virtual water has often been acclaimed as one of the achievements of the modern world, which prevents water crises from breaking into water wars [*Allan*, 1998; *Barnaby*, 2009].

[4] What is the downside of the "story"? Here we suggest that there are some negative and undesired effects of the globalization of water resources, due to the relation existing between virtual water imports and population growth [*Rosegrant and Ringler*, 1999; *Liu et al.*, 2007]. In recent times the international trade of food commodities has allowed for a disproportionate growth in some dryland populations, which can rely on a regular basis on food produced in other regions [*Allan*, 1998]. The increase in the interconnectedness of the network of virtual water trade and in the degree of utilization of the world's freshwater resources may reduce the resilience of human societies to drought-induced crop failure. When a drought strikes the system, there are less unutilized water resources that can be allocated to cope with the emergency. As a result, higher rates of famine-induced mortality can occur.

[5] We support this point through a simplistic model of population dynamics, accounting for exchanges of virtual water. For the purposes of this study the world's population is divided into two sets of metapopulations, namely water poor meta-populations (D_i, i = 1,…, n), whose growth is limited by water availability (e.g., societies living in dry regions), and water rich meta-populations (R_j, j = 1,…, m)

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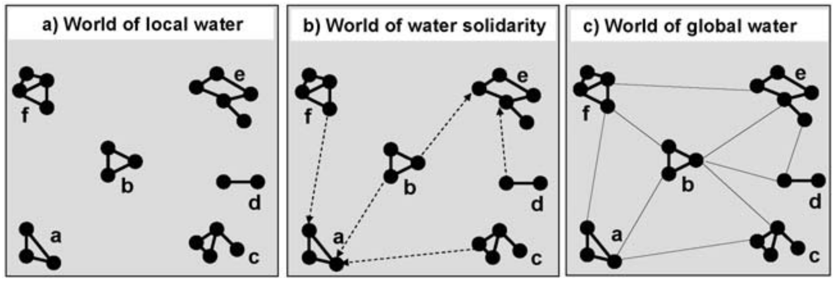

Figure 1. Possible patterns of virtual water redistribution around the world. (a) In a "local water world" (virtual) water is redistributed only by local trade (thick solid lines within each region, a, b,…). No major interregional transport occurs, not even in case of regional drought. (b) The situation can be improved if the trade of virtual water remains local but in case of regional crop failure (e.g., in regions "a" and "e") solidarity programs activate international transport of virtual water (dashed) for the duration of the emergency. (c) In a "global water world" an intense global trade (solid thin lines) of virtual water increases the levels of food locally available to communities in water-limited regions.

that are not limited by water resources but by other environmental, cultural, or health-related factors. This dependence on other factors is here only acknowledged but not investigated in detail. Its effect on water consumption patterns is that some societies do not need to use all their water resources to produce the food they require. This leaves some water resources available for the production of food commodities that can be exported to foreign markets, particularly in water limited regions. To simplify the analysis of the impact of virtual water fluxes associated with these transfers of food products, we concentrate on the effect of virtual water trade between water rich and water poor meta-populations (i.e., $R_j \rightarrow D_i$) without considering exchanges among the water rich societies. Such exchanges are likely to exist but in this simplified representation of global water trade they do not affect population dynamics in that water rich meta-populations are by definition not limited by water resources. The existence of the $R_j \rightarrow D_i$ exchanges depends on a parameter, P_1 (with $0 \leq P_1 \leq 1$), expressing the connectivity between water poor and water rich meta-populations (see Methods). We use the model to compare average mortality rates from drought-induced famine under three scenarios (Figure 1): (i) a "local water world", whereby water resources are used only locally and are not exchanged in the form of virtual water (i.e., $P_1 = 0$); (ii) a "global water world", with a highly connected network of virtual water trade (i.e., $P_1 \rightarrow 1$); and a world of "water solidarity", in which water resources are generally used locally except in case of drought-induced famine. When these conditions occur, virtual water (embedded in food resources) is transferred from water rich regions to the area of crisis. Water solidarity allows for a transfer of these resources only throughout the duration of the emergency.

2. Results

[6] In the absence of crop failure occurrences the dynamics tend to an equilibrium state whereby the total population increases with the connectivity, P_1 (Figure 2a, dashed line). Thus, the exchange of virtual water allows the system to sustain a larger population and to make an apparently more efficient use of the existing resources, with less water resources in water-rich regions remaining unutilized. The existence in these regions of water resources exceeding the requirements of the local populations favors the export of food commodities to water limited areas, thereby providing virtual water to support a larger population therein. A similar result is found when the system is affected by crop failure induced by random drought occurrences: the total population increases as the connections in the global network of virtual water increase (i.e., $P_1 \rightarrow 1$). Thus, even in a world affected by drought, crop failure and famine, the globalization of water resources leaves less unutilized water resources and allows the total population to exceed the levels reached in the absence of virtual water exchange (i.e., $P_1 \rightarrow 0$), as shown in Figure 2a (thin solid line). However, as P_1 increases, the mortality rates (i.e., average annual decrease in total population due to crop failure) also slightly increase (Figure 2b), indicating that the globalization of water does not improve (in fact it worsens) the ability of societies to cope with drought occurrences, in that malnourishment and famine can still claim numerous human lives.

[7] The situation drastically changes in the case of exchanges of virtual water driven by a principle of water solidarity, which allows for transfers of virtual water to drought-affected regions only for the duration of the drought and providing these regions with resources only up to the value of the local (unstressed) carrying capacity. In this case P_1 represents the degree of solidarity. The total population, p, does not increase with increasing values of P_1, whereas the total mortality rate rapidly tends to zero (Figure 2, thick lines).

3. Discussion

[8] The results presented in Figure 2 suggest that through the long-range transport and globalization of virtual water, international trade is modifying the dependence of human societies on their regional water balance [*Falkenmark et al.*, 2004; *Hoekstra and Chapagain*, 2008]. The globalization of water resources allows for the persistence of a higher global population than in the case of exclusively local water use (i.e., $P_1 = 0$). Rather than activating a long-range transport of virtual water only during exceptional droughts (Figure 1b), global scale international trade virtually increases the carrying capacity of water-limited regions, thereby allowing their (human) populations to grow relying - on a regular basis - on additional food resources from abroad [*Hoekstra and Chapagain*, 2008]. This situation (Figure 1c) has profound implications on the resilience of these complex ecohy-

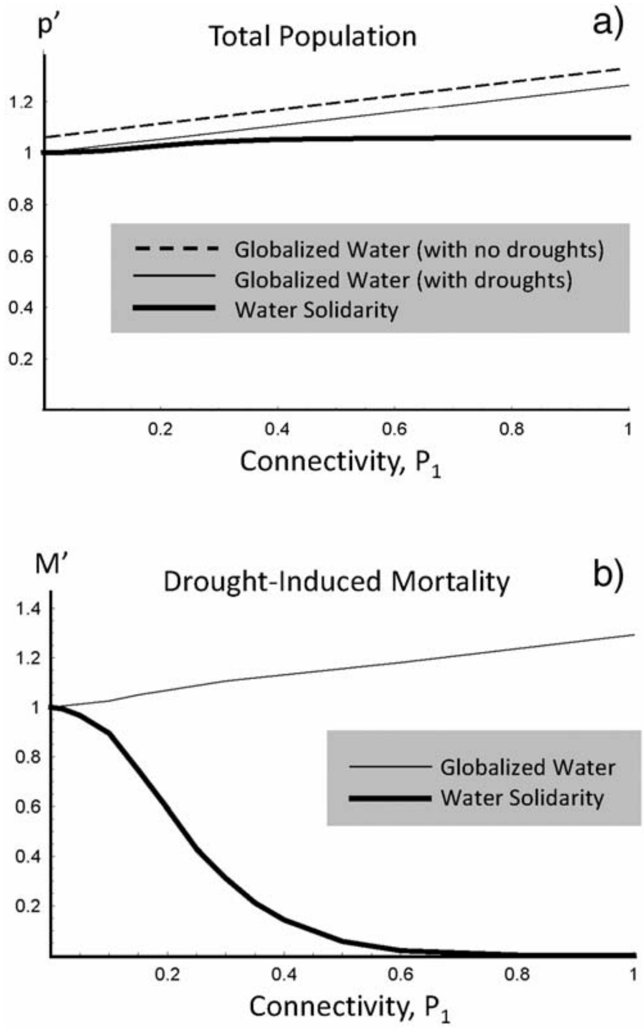

Figure 2. (a) dependence of the normalized total population, p', on the connectivity (P_1) of the virtual water trade network. Values of $p' = p/p_0$ are normalized with respect to the population, p_0, in the case with no virtual water exchange (i.e., $P_1 = 0$). The dashed line corresponds to dynamics with no drought-induced famine (equation (4)), while the solid lines correspond to a system accounting for the effects of random drought occurrences in the case of global (virtual) water trade (thin line) and water solidarity (thick line); (b) average annual mortality rates calculated in the case of global water trade (thin line) and water solidarity (thick line). Mortality rates, are normalized with respect to the case with no exchange of virtual water (i.e., $M' = M/M_0$ with M_0 given by equation (7) with $P_1 = 0$). Calculated with $m = 10$; $n = 40$; $\lambda_D = 0.1$; $\lambda_R = 0.001$; $\varepsilon = 0.1$; $\alpha = 1\ \mathrm{yr}^{-1}$; $\beta = 0.6$; $D_{c0} = 1$; $R_{c0} = 4\ D_{c0}$.

drological-social systems. In fact, while it may optimize the use of food resources worldwide by reducing the redundancy of unused water resources, this optimization occurs at the expenses of the ability of the system to respond to disturbances [*Walker and Salt*, 2006]. As new links in the global network of food trade are activated, fewer options remain available as "safety margins" when the system needs to respond through food solidarity to the shock generated by exceptionally severe droughts. This situation is consistent with the idea that the loss of redundancy associated with an optimized use of resources in ecological systems implies a loss of resilience [*Walker and Salt*, 2006].

[9] Higher mortality rates associated with drought and famine occur in the scenario with globalized water resources, while mechanisms of water solidarity are able to dramatically limit mortality episodes in metapopulations affected by exceptional droughts. The main difference with respect to the case of global water trade is that in the water solidarity scenario virtual water fluxes are invoked only as a short term remedy to droughts without making the populations in water limited areas reliant (on a regular basis) on these additional inputs of virtual water. Thus, except for instances of drought and crop failure, most food is produced and consumed locally, without causing a disconnection between societies and their natural resources. This means that water rich regions have a bigger amount of available water resources that remains regularly unused, thereby leaving a larger margin of safety to face periods of crisis when they occur around the world. This fact explains why in the case of severe droughts societies are expected to be affected by lower mortality rates in the water solidarity scenario than in the case of globalized water resources (Figure 2b). However, it should be noticed that the results shown in Figure 2b do not account for the delay that is likely to exist in the response of water solidarity initiatives to drought and crop failure. This delay would be particularly strong in the case a system of global water trade was not already in place to readily activate an effective transfer of virtual water and food resources to the area of crisis.

[10] This study concentrates on the effect of virtual water trade on societal resilience. It has been argued before [e.g., *Rosegrant and Ringler*, 1999] that there are other possible negative effects of the globalization of water resources. In fact, in some regions of the world the increase in human population has stimulated an intensification of virtual water imports [e.g., *Liu et al.*, 2007], thereby increasing societal reliance on international markets. If in these regions population growth and the increase in amounts of imported food are not paralleled by an adequate economical development, at some point the importing societies would be unable to pay for the imported goods they need. Thus, they would have to rely on international food aid programs to avoid (or limit) food shortage and malnourishment [*Rosegrant and Ringler*, 1999]. Therefore, globalization of water resources does not necessarily offer a long-term solution to water limitations. Although these analyses of the long-term economical implications of water imports are not included in the modeling framework presented here, they seem to offer additional support to the water solidarity model discussed in this section.

4. Conclusions

[11] The trade and transport of virtual water appears to be a great remedy to short term local water deficit. Indeed, it may prevent severe stress, famine, and even water wars. However, the globalization of water may allow for a disproportionate demographic growth in water-poor geographic areas, which would heavily depend on "flows" of virtual water from other regions of the world. Besides being energy costly, the long-distance transport of food weakens the resilience of the coupled natural-human system and

reduces its ability to cope with changes in environmental conditions and available resources. It also disconnects societies from the natural resources they use, and causes a spatial separation between production and consumption of food commodities. We advocate for a model of virtual water trade based on the notion of water solidarity, whereby (1) long distance transport of food occurs mainly in times of crop failure and food shortage, and (2) it does not let the available resources exceed the carrying capacity that the region would have in periods with no drought. Water solidarity (Figure 1b) appears to be a good alternative to the global trade of virtual water: it activates long-distance transport of food commodities only to mitigate the effect of resource shortage during exceptional crop failures, thereby reducing the rates of drought induced mortality. Thus, although this study supports a more local pattern of water use, it recognizes the importance of water solidarity and the need for the development of effective and prompt solidarity mechanisms that can be activated in conditions of crisis.

5. Methods

[12] To investigate the possible societal impacts of the globalization of water resources, we develop a simplified model of population growth coupled with different scenarios of virtual water trade. To this end, we model population dynamics dividing the world's population into two sets of meta-populations: m water rich (R_j, $j = 1,\ldots, m$) and n water poor (D_i, $i = 1,\ldots, n$) meta-populations.

[13] Interactions among these groups occur only as net virtual water transfers from R_j to D_i, and are expressed by a connectivity matrix, $K_{i,j}$ (i = 1,…, n; j = 1,…, m). $K_{i,j}$ is equal to 1 if R_j provides virtual water resources to D_i, and $K_{i,j}$ is zero otherwise. For the purposes of this study the connectivity matrix is expressed using an Erdos-Renyi random graph model [*Erdos and Renyi*, 1959], whereby the connectivity between any pair of water rich and water poor metapopulations (say, R_j and D_i) is randomly generated,

$$K_{i,j} = \begin{cases} 1 \text{ with probability } P_1 \\ 0 \text{ with probability } (1 - P_1) \end{cases} \tag{1}$$

with P_1 expressing the connectivity of the system.

[14] Because - by definition - the dynamics of water-rich meta-populations are not limited by water availability, they do not depend on water resources from water poor meta-populations. Thus, we model these dynamics as

$$\frac{dR_j}{dt} = aR_j(\beta R_{cj} - R_j) \quad (j = 1,\ldots,m) \tag{2}$$

with α being a parameter determining the growth rate in the logistic equation (2), R_{cj} the maximum population density for R_j allowed by the available water resources (i.e., R_{cj} is the carrying capacity of R_j), and β ($0 < \beta \leq 1$) a parameter accounting for the degree of utilization of these resources. Because water rich meta-populations are limited by other factors than water, they do not use all of their available water resources (i.e., $\beta < 1$). The unutilized fraction of these resources (i.e., $(1 - \beta)R_{cj}$) is distributed to water poor meta-populations through networks of virtual water trade or of water solidarity (see Figure 1). In a "global water world" the meta-populations D_i can rely on a regular basis on these water imports, and their carrying capacity is augmented by inputs from connected water-rich meta-populations. Thus, the logistic growth of D_i is expressed as

$$\frac{dD_j}{dt} = \alpha D_i\left(D_{ci} + \sum\nolimits_{j=1}^{m} K_{i,j}F_j - D_i\right) \quad (i = 1,\ldots,n) \tag{3}$$

with $F_j \leq R_{cj}$ $(1 - \beta)/(\Sigma_i\ K_{i,j})$ expressing the fraction of resource excess in R_j used by D_i. Notice that in equation (3) each addendum in the sum term is multiplied by the corresponding element of the connectivity matrix to account for the fact that only the water-rich metapopulations connected - through virtual water trade - to D_i contribute to increase the carrying capacity of D_i. We assume that all the resources not used by R_{cj} are equally distributed among the connected D_i groups and express F_j as $F_j = P_1\ R_{cj}\ (1 - \beta)/(\Sigma_i\ K_{i,j})$. In this expression the coefficient P_1 accounts for the fact that the amount of unutilized resources distributed to water poor metapopulations increases with the connectivity of the water trade network.

[15] In the absence of hydroclimatic fluctuations the carrying capacities, R_{cj} and D_{ci}, are constant and the dynamics tend to the equilibrium state, with $R_j \rightarrow R_{cj}$ and $D_i \rightarrow D_{ci} + \Sigma_{j=1}^{m}\ K_{i,j}\ F_j$. In other words, water rich metapopulations converge towards their carrying capacities, while the water poor metapopulations converge to their augmented carrying capacities, in that they can rely on imported food resources. If the carrying capacities are the same for all the water poor and all the water rich meta-populations (i.e., $R_{cj} = R_{c0}$ and $D_{ci} = D_{c0}$), with sufficiently large values of n and m the total world's population, $p = \Sigma_i\ D_{i,} + \Sigma_j\ R_j$, is

$$p = nD_{c0} + m\beta R_{c0} + (1 - \beta)mR_{c0}P_1 \tag{4}$$

Equation (4) shows that the total population, p, is an increasing function of the connectivity, P_1. Thus, a larger total population can be supported in more interconnected networks of food trade.

[16] To account for the effect of drought-induced crop failures, we model the carrying capacities as independent random variables: in each growing season crop failure happens with probability λ_D in each meta-population D_i, and with probability λ_R in each meta-population R_j

$$D_{ci} = \begin{cases} D_{c0} \text{ with prob. } (1 - \lambda_D) \\ \varepsilon D_{c0} \text{ with prob. } \lambda_D \end{cases}; \quad R_{cj} = \begin{cases} R_{c0} \text{ with prob. } (1 - \lambda_R) \\ \varepsilon R_{c0} \text{ with prob. } \lambda_R \end{cases} \tag{5}$$

with $\varepsilon < 1$ being a reduction factor accounting for the decrease in available local resources during the drought, while D_{c0} and R_{c0} are the values of the two carrying capacities in the absence of drought conditions. Equation (5) expresses the effect of random climate fluctuations and their impact on the occurrence of drought conditions. If $R_{cj} = R_{c0}$ the dynamics of R_j are not affected by water stress and are expressed by equation (2). Under water stress conditions (i.e., $R_{cj} < R_{c0}$) the water-rich meta-population R_j does not share resources with any of the water poor meta-populations (i.e., $K_{i,j} = 0$ for all values of i). In these conditions, R_j uses some or all of its resources depending on how the level of resources available during the drought (i.e., $\varepsilon\ R_{c0}$) compare with the needs, βR_{c0}, of the metapopulation, R_j (i.e., on the relative importance of β and ε). Thus, the dynamics of R_j are expressed by the logistic growth

$$\frac{dR_j}{dt} = aR_j\left(R'_{cj} - R_j\right) \tag{6}$$

with $R'_{cj} = \mathrm{Min}(\beta, \varepsilon)R_{c0}$ (i.e., the minimum between β and ε multiplied by the unstressed carrying capacity, R_{c0}). Similarly, the dynamics of D_i are expressed by equation (3) with temporally fluctuating random carrying capacity modeled as in equation (5).

[17] Population dynamics in the case of meta-population interactions driven by water solidarity are expressed modeling the carrying capacity as in equation (5). If $R_{cj} = R_{c0}$ the dynamics of R_j are expressed by equation (2), otherwise (i.e., if $R_{cj} < R_{c0}$) they are modeled by equation (6). Similarly, if $D_{ci} = D_{c0}$ the dynamics of D_i are expressed by equation (3) but with no connections (i.e., $K_{i,j} = 0$ for all values of j). Conversely, if the metapopulation, D_i, is under water stress, its dynamics are modeled by equation (3) with $D_{ci} = \varepsilon D_{c0}$ and with active connections to water rich meta-populations. These connections provide resources through a mechanism of water solidarity, which lasts only throughout the duration of the drought and provides resources for an amount that does not exceed the local carrying capacity D_{c0}. In this case $K_{i,j} = 1$ with probability P_1, with P_1 expressing the "degree of solidarity" from water rich countries.

[18] At the end of each year we calculate the total annual mortality from drought-induced famine as the absolute value of the total annual decrease in population

$$M(t) = \sum\nolimits_{j=1}^{n} M_{D,i}(t) + \sum\nolimits_{j=1}^{m} M_{R,j}(t) \tag{7}$$

where $M_{D,i}(t) = \mathrm{Max}\ \{0, [D_i(t) - D_i(t + \Delta t)]\}$ and $M_{R,j}(t) = \mathrm{Max}\ \{0, [R_j(t) - R_j(t + \Delta t)]\}$ represent the annual mortalities in meta-populations D_i and R_j, respectively, while Δt = 1 year. Plots of $m(t)$ and of the total population, $p = \Sigma_i D_{i,} + \Sigma_j R_j$, are shown in Figure 2.

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