RISK, RICE, and RISING SEAS – IMPACTS OF CLIMATE CHANGE ON MARITIME TRANSPORT

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ABSTRACT

Most research on shipping and climate change is focussed on shipping as a source of greenhouse gas emissions and, consequently, on mitigation options. However, the interaction goes both ways – as climate change, in turn, affects the shipping sector. Many of the consequences of climate change are uncertain and predictions on the scale, timing, and regional variation of impact are often vague. In order to develop a deeper understanding of the risks and opportunities for the shipping sector, a simple framework is used to categorise potential climate change impacts in terms of their implications for the shipping sector. An oft-quoted example of a climate change impact on shipping is the potential opening of Arctic shipping routes, which can be categorised as a direct climate change impact on the shipping system. An example of an indirect impact is offered by the radical changes to current trade patterns and volume of energy commodities, as implied by many climate change mitigation scenarios. Agricultural bulk commodities, represent another significant component of global seaborne trade, not merely in terms of traded tonnage but also in fulfilling the vital service of providing food. However, both production and consumption of agricultural commodities are likely to be sensitive to climate change, particularly under a scenario with high temperature increases or reduced water availability. This paper applies a more in-depth analysis to agricultural bulk trade and how it may be affected by climate change impacts on agricultural production and presents preliminary results.

Keywords: Climate change impacts, climate change adaptation, agricultural bulk commodities

1. INTRODUCTION

Most research on shipping and climate change is focussed on shipping as a source of greenhouse gas emissions – that is on the impact of shipping on the climate – and, consequently, on mitigation options. Here we consider the reverse effect, investigating the impact of climate change on shipping. There are many, and complex ways in which future climate change might affect shipping (see Figure 1), Some of them, such as changing sea storms are more direct than others; and, as shipping is not an isolated entity but sits within a wider and more complex socio-technical system, some arise from the interaction between this wider shipping system and climate change

Answering the question of how climate change impacts on the shipping system is not just complex but also subject to uncertainties due to the inherently chaotic nature of the climate system. Considering, for example, the impact of climate change on food production: Figure 1 illustrates how increased atmospheric greenhouse gas concentrations change global patterns of temperature (with an increase of the global mean) and of precipitation (Wheeler and von Braun, 2013). Both temperature and precipitation patterns are major elements of the conditions determining growing conditions and potential yield, which is also affected by atmospheric CO_2 concentration (see Figure 1). Predicting the combined impact of these effects is particularly difficult when impacts occur at local and regional scales.

The picture is further complicated by the potential for adaptation to climate change impacts; agriculture may adapt to different growing conditions by growing different crop species or increasing agricultural inputs, redesigned ports will enable them to continue to function despite any changes. At the same time, social drivers influence the production of commodities, shaping trade patterns. The recent liberalisation of trade policies, for example, and government subsidies, has resulted in many developing regions investing (and specializing) in cash crops production for the export market (such as coffee) as opposed to the production of staple food for the domestic market (Mittal, 2008). Adaptation to climate change cannot therefore be entirely disentangled from the response to other drivers such as population growth, economic development and changing societies.

However, while highly uncertain, climate change will bring opportunities (as well as risks) to participants in the shipping sector through changing trade patterns, with a knock-on effect on port and logistical infrastructure, the need for new technologies and new market developments. At the same time as contending with the more immediate impacts of climate change, the shipping sector will support climate change adaptation strategies through the provision of shipping services, and linking consumers and producers.

1.1 AIM AND OBJECTIVES

The aim of this paper is therefore to explore the potential interaction between climate change and the shipping sector in order to identify plausible and relevant impacts and risks. Section 2 begins this task by giving an overview of the elements of climate change, and how they interact with the shipping system. Section 3 categorises the causal chains that may constitute an impact from climate change on shipping. Section 4 focuses on the trade in agri-bulk and presents short case studies of climate related impacts upon the shipping aspect of supply chains, and uses projections of climate change to identify possible future vulnerabilities. Section 5 concludes.

2. ELEMENTS OF CLIMATE CHANGE AND HOW THEY MIGHT AFFECT SHIPPING: GENERAL FRAMEWORK

The focus of this research is the shipping sector and its interaction with a defined set of climate change impacts: temperature rise, changes to precipitation, population, sea level rise, extreme weather and land use. Each element can be linked to other elements as presented in Figure 1. As shown, climate change and related policy can potentially influence decisions on ship choice or design, suitable routes and essential coastal infrastructure. For example, climate change policy can target shipping via changes in fuel prices or demand for sea transport lead to technological and operational change while changes in sea state, storms, and ice cover may lead to technological and operational changes.

In this section, we have therefore laid out some aspects of climate change as well as some other elements that may interact with climate change, all of which may ultimately affect shipping in some way. We have grouped these elements as changes in the atmosphere, ocean and land and socio-economic systems. The list of *elements of climate change* is neither complete (health impacts or extreme events are not even mentioned) nor is the grouping unique (e.g. the bio-sphere has been neglected in the schematic of Figure 1). The purpose of a schematic representation, as given in Figure 1, is to investigate causal links and chains between the different elements, in order to identify the potential impacts on and risks to the shipping sector in a structured way.

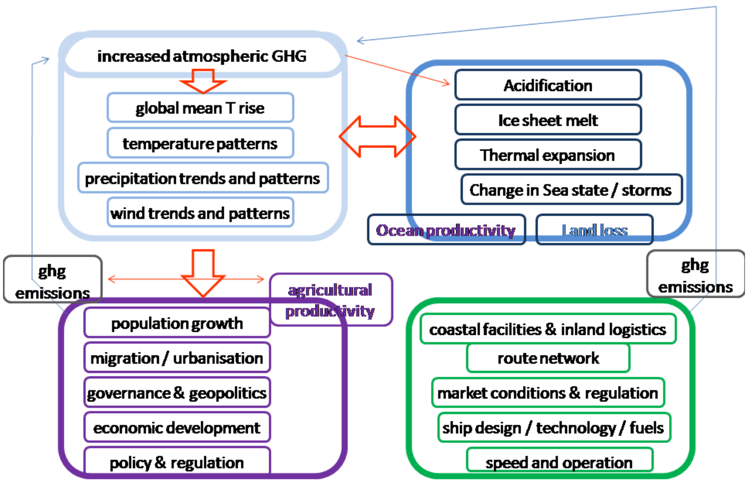

Figure 1: Impacts of climate change upon the shipping system

The basic mechanisms of anthropogenic climate change are generally well understood (IPCC 2013). However, as they manifest within a complex system, the more immediate climate change effects have far-reaching ramifications and may lead to complex interactions and feedbacks.

2.1 ATMOSPHERIC CHANGES

The retention of long lived anthropogenic greenhouse gases in the atmosphere are the main driver of climate change. Increased atmospheric greenhouse gas levels cause radiative forcing, increasing Earth's average surface temperature, and changing patterns of temperature, precipitation, and of winds and storms (as highlighted in the top left of Figure 1).

2.2 OCEAN AND LAND

The atmosphere is in contact with the Earth's oceans and land surfaces. For the purpose of this brief overview, we focus on the oceans (top right in Figure 1). Increased atmospheric concentration of carbon dioxide, the most important manmade greenhouse gas, leads to acidification of the oceans that take up some of the additional carbon in the atmosphere. Exchanging heat with the atmosphere, the oceans also warm, albeit slower than land due to the large heat storage capacity of the deep oceans, resulting in thermal expansion and melting of the large ice sheets(as in the Arctic). Ice melt and thermal expansion together lead to sea-level rise and changes in storm frequency (e.g. Nicholls et al., 2014). These, in turn, may lead to modification of ocean, coastal and atmospheric processes.

2.3 SOCIO-ECONOMIC SYSTEMS

Potentially the most significant impact of climate change for the shipping system will result from the myriad of interactions with wider socio-economic systems. For example, changing climates will affect agricultural productivity in location-specific ways .External landscape effects, such as population growth, urbanisation, and migration are likely to interact with consequences from climate change. Migration (which may be caused by climate change as low-lying, coastal regions become uninhabitable, for example) can be a severe geopolitical issue. Economic development, historically linked with consumption of fossil fuels and resultant carbon dioxide emissions interacts with climate change, as does policy and regulation that may seek to deal with causes and effects of climate change.

3. CAUSAL CHAINS AND CATEGORISATION OF EFFECTS

In this Section, we develop further a framework for identifying potential climate change impacts on shipping and categorising them, with respect to three specific dimensions: direct/indirect climate impacts on shipping, effects on shipping supply/shipping demand, and timeframe. Whilst this framework is useful for our purposes, there are other ways in which impacts on shipping could be classified.

3.1 DIRECT AND INDIRECT IMPACTS

We can categorise climate change impacts on shipping as direct where the causal chain linking changes in climate to an impact on shipping is short, with one or few causal links; and as indirect where more links occur. Consequently, direct impacts tend to be those which can be addressed by the various sectors of the shipping system themselves. At the coast, port infrastructure can be adapted or designed to cope with any anticipated change in storm surge heights or wind speeds; at sea, ships can be chosen or designed with regard to any change in sea state, wind speed or ice cover. Such responses would be considered as part of normal operation. However, changes in production of, and demand for, commodities as a consequence of climate change are outside the control of the shipping sector and are, therefore, considered indirect. Table 1 provides some examples of potential direct and indirect impacts.

Table 1: Potential direct and indirect climate impacts on shipping

	Direct Impact	Indirect Impact
Ship Level	• Weather routing due to increased storm frequency • Increased refrigeration requirements when transporting perishable goods	• Disruption to ship scheduling in response to sudden/unforeseen harvest failure (e.g. following an extreme weather event)
Port Level	• Enhanced sea wall due to storm frequency. • Changes to loading and unloading practices to reflect changing water levels (e.g. quay cranes with more flexible reach). • Movement of storage or staging zones in low level port areas.	• Port congestion if timing of harvest cycle is disrupted. • Additional storage requirements in response to changing trade patters or weather events. • Reduced throughput following export ban due to harvest failure.

As the sequence of events between initial impact and the shipping sector lengthens, this reduces the capacity to predict how the shipping sector will be affected and how it may respond. This is particularly true when socio-economic or (geo-) political decision making is involved[1]. Clearly, climate impacts can be the starting point of any number of causal chains, and an appreciation of the wider indirect consequences is essential.

3.2 AFFECTING SHIPPING SUPPLY VS. AFFECTING SHIPPING DEMAND

Shipping supply is considered to encompass all aspects of the shipping system that are there to satisfy demand for shipping services. To illustrate this: if global warming leads to the melting of Arctic ice, freeing up Arctic shipping route will affect shipping supply; without adaptation, the ultimate impact from sea-level rise is that the Maldives disappear in the water, a fairly direct impact on their need for imports and therefore demand for shipping. Figure 2 schematically represents this link.

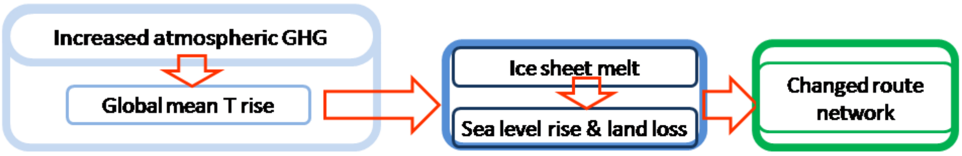

Figure 2: Schematic diagrams of specific climate change impacts on shipping

Similarly, climate change impacts can lead to decreasing agricultural yields in sub-Saharan Africa, increasing demand for food imports; the former is an impact on supply, the latter on shipping demand.

3.3 TIMEFRAMES

Impacts can also be categorised in terms of the time horizons involved, with respect to both onset of an effect and how long it lasts for. For example, an extreme weather event linked to climate change, such as a drought or a heat wave may be seen as a short term event while a trend of increasing likelihood of extremes may be considered as a medium or long term effect. While the latter are generally seen as incremental in nature, associated impacts may be characterised by sudden onset and longevity – described as tipping points - the depletion of fish stocks, for example. Table 2 summarises some of the more incremental changes that could occur.

[1] As an aside: air conditioning has been called an enabler of Singapore's success (Singapore's first prime minister Lee Kuan Yew in an interview, via http://www.huffingtonpost.com/nathan-gardels/lee-kuan-yew-remembered_b_6920292.html, accessed 15 October 2015) – substantial warming in a carbon-constrained world might pose a severe challenge.

Table 2. Examples of time-classified impacts of climate change

Climate change timeframe	Impacts due to increased temperature and reduced rainfall
Short Term	• High temperatures impact negatively on working conditions in ports and cause spoiling of stored crops • Increased temperature and reduced rainfall leads to crop failure • Reduction of annual production may result in temporary export bans
Medium Term	• Ports become important for storage of potable water. • Sustained increased temperatures may result in port closures • Warmer and more humid conditions may increase risk of spoilage of fresh food • Increased temperature anticipated to result in prevalent yield reductions due to shorter growing period
Longer Term	• Significant increase in temperatures at port will increase demand for demand for more refrigerated storage and additional power requirements at port would increase vulnerability to port-wide power failure. • Regions in lower latitudes likely to experience greater import dependency. Movement of optimal agricultural productive zones in key exporters (such as into the more northerly latitudes in Canada for example) may increase transport time to port hubs.

Any of the examples on Table 2 may have unexpected and sudden consequences. For example, weather extremes and harvest failure in Sumatra, Singapore, and peninsular Malaysia. Harvest failure could lead to a food crisis and governance breakdown in the region; governance breakdown and resulting instability render the Strait of Malacca impassable due to an increase in piracy (Figure 3). In turn this could lead to a long-term change in shipping routes. In terms of timescales, the onset may unfold over the order of a year, while the effect, piracy and (near-impassability) of the Strait of Malacca might persist of many years, of the order of a decade, therefore this is a short term onset impact with a medium term lifetime.

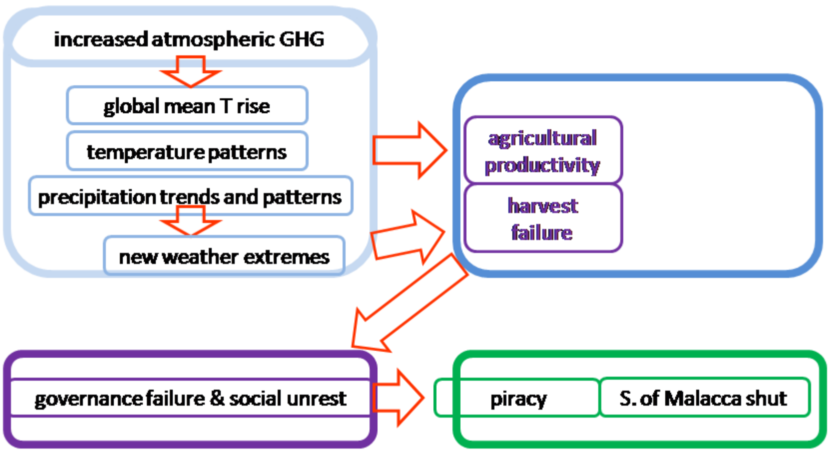

Figure 3: Schematic representation of a potential climate impact

Appreciating the more far-reaching nature of such climate changes impacts requires seeking to understand how the climate change impact (which is direct at the point at which it is initially manifested) is transposed into an impact on shipping. Identifying the means by which such impacts move along the linkages will assist in developing measures to're-arrange' the causal chain, identifying both risks and possible intervention (and prevention) points.

4. AGRIBULK CASE STUDY

Having set up a framework to guide investigations climate change impacts on shipping, the remainder of the paper focuses in more details on the impacts of climate change in relation to agri-bulk commodities. Shipping is a key enabler of food security through the movement of agricultural commodities, and as we show, agriculture will be impacted by climate change.

4.1 BRIEF OVERVIEW OF CLIMATE CHANGE IMPACTS ON AGRICULTURE

Different food commodities will have optimal growing conditions which will determine not just seasonal but also geographic distribution of production. For example, the production of rice requires either intermittently or continually flooded conditions. For grain commodities, increasing temperatures in general accelerate kernal development, which reduces the growing period and hence decreased yields. This may mean that bulk transport of grain becomes more difficult (due to spoilage risks) or will necessitate additional storage capacity at port. Crops such as wheat are considered especially vulnerable to increased temperatures (Wheeler and von Braun, 2013). Increased or more intensive patterns of rainfall can damage crops (particularly if under irrigated conditions) as well as disrupting the timing and agricultural run-off in rain fed conditions. The impact of CO_2 fertilisation (impact of increased carbon concentration in the atmosphere) is less certain with many studies such as integrated assessment models including results which include or omit its impact.

4.2 CURRENT TRADE PATTERNS AND ISSUES OF DEPENDENCY

In terms of volume and importance the trade of grain commodities (also referred to as agricultural bulk) is one of the most significant and individually distinguishable categories of trade commodities which are susceptible to climate change impacts. At president, the trade of grain commodities, including wheat, barely, rice, oil crops etc. is dominated by a relatively small number of exporters supplying a larger number of importing regions as shown in Figures 4 and 5.

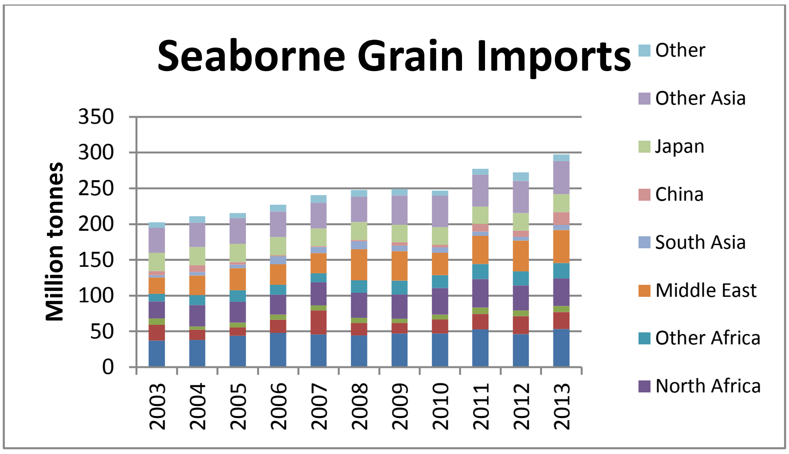

Figure 4: Seaborne Grain Imports by region

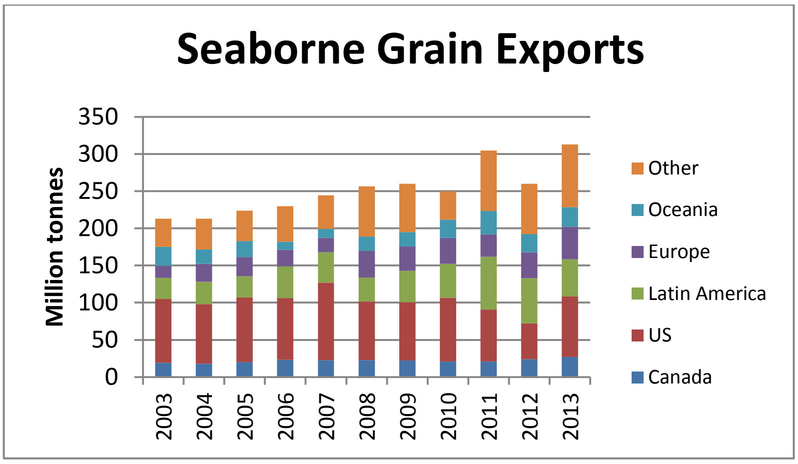

Figure 5: Seaborne Grain exports by region

A comparison of exporting and importing regions highlights how developing regions are dependent on the functioning of export markets in the developed world. This is further illustrated by Figure 6 showing the import dependency (ratio between imports and domestic supply) of different markets.

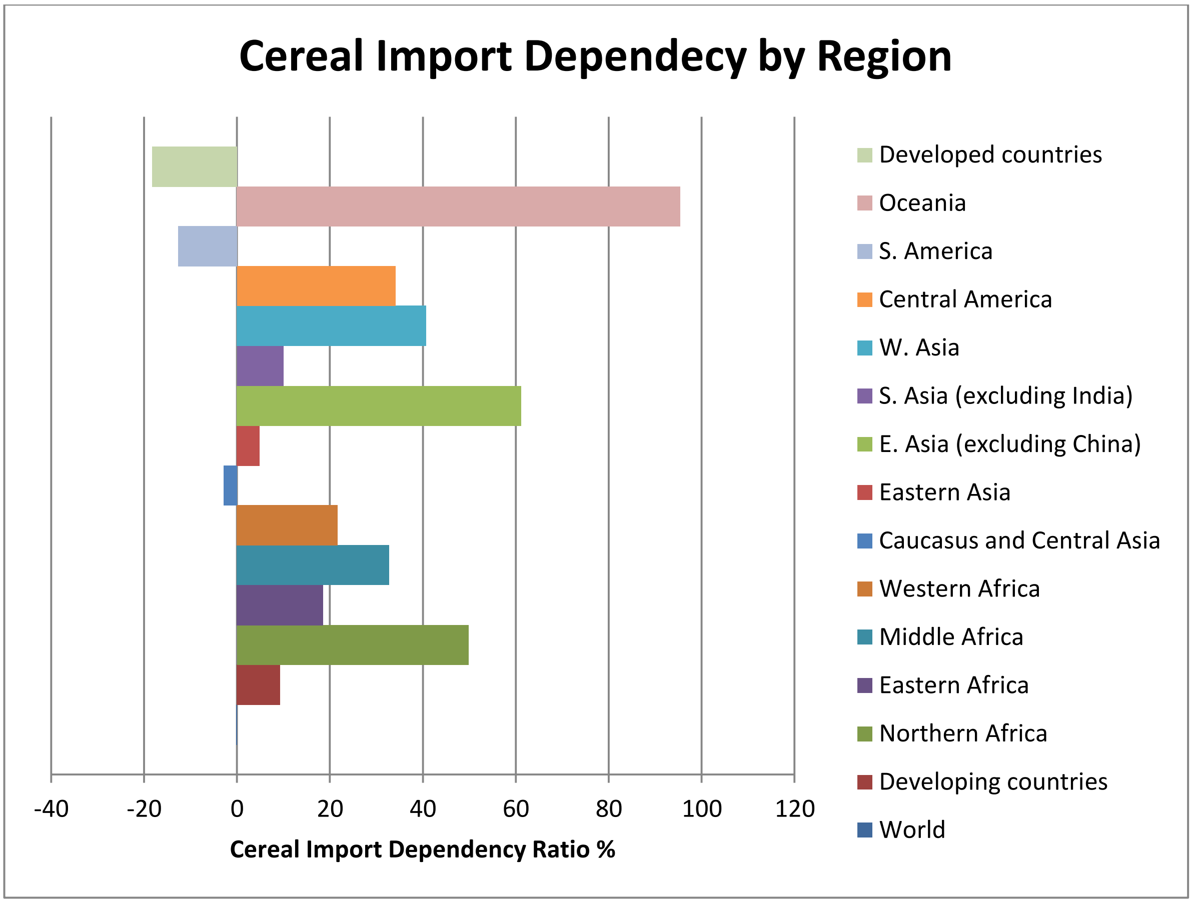

Figure 6: Cereal import dependency ratio (cereal imports - cereal exports)/(cereal production + cereal imports - cereal exports) x 100 Negative values indicate that the country is a net exporter of cereals. (FAO, 2013)

The reliance of so many countries on a small number of exporters makes querying the potential impact of climate change on trade in agricultural commodities a timely subject of research, in light of vulnerability to climate change impacts, and also as increasing populations and changing dietary patterns (such as increased meat consumption) are likely to result in increasing demand for grain commodities.

Having demonstrated both the importance of international trade in agricultural commodities, and the vulnerability of production to climate change impacts, we now identify some exemplar case studies which have demonstrated recent, i.e. short term impacts on the shipping sector as well as identifying potential future analogues which may be more relevant in the longer term.

4.3 REGION SPECIFIC CLIMATE RISKS TO AGRICULTURE

As suggested in figures 4 and 5, the trade of agricultural goods is heavily independent by the dynamics of supply and demand in key regions, which will experience distinct impacts or adaptation challenges. Some regional specific challenges are summarised below.

North America is an important exporter of wheat and maize and is likely to remain so by 2030 if not (Alexandratos, and Bruinsma 2012) while optimum temperatures have been reached for dominant crops. In the United States (US) Maize demonstrates a decrease in yields, a consequence of dry spells of longer duration. Increases in the number of hotter days, and higher maximum temperatures all result in lower yields for spring wheat (Troy et al., 2015). In Canada much of the central prairies wheat production is dependent on the supply and timing of glacial run-off which would be reduced under increasing temperatures. In general it is anticipated that precipitation increases will partially offset but not entirely compensate for temperature-related declines in productivity Under differing A1 scenarios (scenarios which project economic growth and a peaking population mid-century, differentiated in terms of whether they reflect a fossil dependent, renewable focused or balanced pathway) projected temperature increases would reduce corn, soy, and cotton yields by 2020, with declines ranging from 30 to 82% by 2099. (Romero-Lankao et al., 2014).

For much of Latin America adaptive capacity is projected to be exceeded in regions closest to the equator if temperatures increase by 3°C or more. Soya beans are an important export crop in Latin American markets. The soybean crop needs to absorb at least 50% of its weight in water to ensure proper germination and is sensitive to reductions in water availability. Projections for yield reductions are difficult to resolve, as scenarios which project increased rainfall could result in reductions in yields due to drier periods associated with increased inter-decadal variability (Margin et al. 2014). Similarly for maize it is estimated that a minimum of 200 mm of rainfall during the summer months is necessary to maintain yields without irrigation (Marego et al. 2014).

Drier conditions and increasing temperatures in the parts of Eastern Europe/Former Soviet Union may result in lower yields and the adoption of new varieties and cultivation methods. Such yield reductions have been estimated for Eastern Europe, and the yield variability may increase, especially in the steppe regions (Sirotenko et al., 1997). The impacts of climate change on winter wheat are thought to be negative across most of the agricultural productive regions. Warmer and drier conditions by 2050 (Trnka et al., 2010, 2011) would cause moderate declines in crop yields in Central Europe regions. However under a water limited scenario without adaptation different models project a 10-20% reduction in winter wheat yields by 2030 under a A1B scenario (Kovats, 2014)

4.4 IMPACTS ON SHIPPING OVER TIME

Examples of how climate has directly and indirectly affected the shipping sector are summarised below. These examples are accompanied by future analogues.

4.4a Short term

In 2013 increased temperatures, resulted in a bumper soya harvest in Brazil, and shifted the harvest period to Brazil to coincide with the sugar harvest; this impacted agricultural production directly which indirectly resulted in increased demand for shipping services (BBC, 2013). Due to limited storage and road transport capacity the movement of crops from field to port was disorganised with competition between different crop suppliers for use of infrastructure. This placed significant pressure on the few ports which were linked to the agricultural production regions. As these ports, did not invest in additional loading capacity this resulted in significant congestion at both the road and the ships waiting at port. Furthermore heavy rain forced the loading of ships to be suspended for up to 25 days; a direct impact upon shipping supply. This resulted in significant ship capacity remaining idle at ports and some importers choosing to purchase soya from alternative markets. In response to these supply chain stresses, additional loading capacity and road linkages to the port were established.

Following a significant drought in Russia in 2010, approximately 17% of the agricultural area was affected, resulting in a significant increase in crop prices and an export ban designed to ensure food security; an indirect impact on shipping demand by reducing exports at Russian ports (Welton, 2011). At the time Egypt was the main export market for Russian grain, due to domestic production constraints, with 50% of its imports originating from Russia. The ban on Russian exports prompted the Egyptian importers to panic buy grain from multiple exporters, with changing patterns of trade a further indirect impact on shipping demand.

4.4b Long term

Increased precipitation and more frequent instances of storms are identified as a risk for regions such as the Gulf coast in the US. This is relevant to ports such as New Orleans and the Port of South Louisiana which are vital export ports for grain and link productive regions such as New Mexico (for maize) to Latin American markets (Frittelli, 2005). Through provision of river and inland waterways, most grain transported to these port by river barge prior to loading on international ships. The US is projected to remain a key exporter of grain commodities, particularly maize to satisfy animal feed requirements in import region such as Mexico. This process is interrupted during periods of extreme weather such as Hurricane Katrina, as well periods of drought (inland) where river levels are reduced; direct impacts on shipping. Increased storm frequency or conversely reduced river levels will disrupt the waterway linkage between the field and the port. This can suspend the supply and loading of grain, requiring ships to wait at port or for ports or alternatively shift exports to alternative ports which are less dependent on the inland waterways.

Whilst Egypt remains the largest wheat producer in North Africa, given Egypt's large consumption, the country can only meet approximately half of its demand with domestic production. For general cereal consumption Egypt demonstrated an import dependency ratio (ratio of imports and domestic demand) of approximately 47%, and studies such as Alexandratos and Bruinsma, (2012) project that due to population North Africa will exhibit one of the sharpest increases in grain demand due to population growth. Whilst production will also increase into the future, this is due to increased yields as regions such as Egypt will have limited capacity to expand their productive area, although increased yields may not be feasible, due to potential climate change impacts on yields. Data from the AR4 (referred to in the AR5) that combine all agricultural regions south of the Sahara project consistently *negative effects of climate change on major cereal crops in Africa, suggest wheat yields decrease by 40% by* mid-century under a A2 (in which emissions rise and economic development is primarily regionally oriented) scenario with an approximate 3^{o}C temp increase (Nelson et al., 2009). If a reduction in cereal yields of 20% is assumed, (without an increase in productive area) and domestic demand grows in line with projected population and per capita cereal demands, this would suggest that by 2050, the absolute quantity of Egypt's imports would double, as suggested in Weigand (2011), but arguably more importantly, import dependency increases to approximately 70%. This would increase the demand for shipping but may also require diversifying of trading partners to ensure disruptions in supply (as seen in 2010) are mitigated. Given the increased import dependency this is likely to become a priority. Additionally this may require additional grain storage capacity at ports, currently Egypt maintains stocks of 4 month's supply, which may need to be increased as a necessary mitigation measure.

5. CONCLUSIONS

In this paper we have presented a method of classifying climate change impacts on shipping which encourages a wider appreciation of potential consequences and have highlighted the research and analysis necessary to better understand and predict such impacts; and the possible actions that can be taken in order to prepare for and manage the risks associated them. However, the categorisation of climate change impacts on shipping presented above is neither unique nor complete, and there may be other ways in which it could be carried out.

The issue of timeframe is a crucial aspect in how the shipping sector can respond to the challenges of climate change. A sudden stress or shock will, by definition, be difficult to prepare for, whereas more gradual changes can arguably be prepared for. Similarly the distinction between direct and indirect impacts will also determine how the shipping sector can respond. Direct climate change impacts (such as changes to weather patterns) are already defined, albeit with high degrees of uncertainty. Some components of the shipping sector (such as ports) have already produced risk assessments due to climate change (FDRC, 2011).Similarly, the anticipated impacts due to climate change may reasonably be incorporated into decisions on ship design etc. A crucial issue is the extent to which both broad impact types can be planned for or indeed managed. Shipping remains a derived service and therefore must respond to the dynamics of both commodity supply and demand which will be inherently more difficult to manage, reflecting changes to populations, trade policy etc. as well as the climate impact on productive regions.

REFERENCES

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. Food and Agriculture Organisation of the United Nations.

BBC (2013) Brazil congestion delays export of record soybean crop [online], available: http://www.bbc.co.uk/news/world-latin-america-22188250.stm [accessed 21 September2015].

Kokic, P., Heaney, A., Pechey, L., Crimp, S., & Fisher, B. S. (2005). Climate change: predicting the impacts on agriculture: a case study. Australian Commodities: Forecasts and Issues, 12(1), 161.

Felixstowe Dock and Railway Company (2011) Climate Change Adaptation Report.

Frittelli, J. (2005). Hurricane Katrina: Shipping Disruptions. Washington, DC: Congressional Research Service, Library of Congress, RS22257.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.MMidgley (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA doi:10.1017/CBO9781107415324

Kovats, R.S., R. Valentini, L.M. Bouwer, E. Georgopoulou, D. Jacob, E. Martin, M. Rounsevell, and J.-F. Soussana, (2014) Europe. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267-1326.

Magrin, G.O., J.A. Marengo, J.-P. Boulanger, M.S. Buckeridge, E. Castellanos, G. Poveda, F.R. Scarano, and S. Vicuña (2014) Central and South America. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1499-1566.

Marengo, JA., Chou, SC., Torres, RR., Giarolla, A., Alves, LM., Lyra, A. (2014) Climate Change in Central and South America: Recent Trends, Future Projections, and Impacts on Regional Agriculture. CCAFS Working Paper no. 73. CGIAR Research Program on Climate Change, Agriculture and Food Security

Mittal, A. (2009). The 2008 food price crisis: rethinking food security policies. United Nations.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, (2009) Climate Change: Impact on Agriculture and Costs of Adaptation. Food Policy Report No. 19, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 30

Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, (2014) Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholls, R. J., Hanson, S. E., Lowe, J. A., Warrick, R. A., Lu, X. & Long, A. J. (2014) Sea-level scenarios for evaluating coastal impacts. Wiley Interdisciplinary Reviews-Climate Change, 5, 1 pp129-150 http://dx.doi.org/10.1002/wcc.253

Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz, 2014: North America. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.

Sirotenko, O.D. & E.V. Abashina,E.V. (2008) Modern climate changes of biosphere productivity in Russia and adjacent countries. Russian Meteorology and Hydrology, 33(4), 267-271.

Troy, T. J., Kipgen, C., & Pal, I. (2015). The impact of climate extremes and irrigation on US crop yields. Environmental Research Letters, 10(5), 054013.

Trnka, M., E. Kocmánková, J. Baleka, J. Eitzinger, F. Ruget, H. Formayer, P. Hlavinka, M. Schaumberger, V. Horáková, M. Možný, and Z. Žaluda, (2010) Simple snow cover model for agrometeorological applications. Agricultural and Forest Meteorology, 150, 1115-1127.

Trnka, M., J.E. Olesen, K.C. Kersebaum, A.O. Skjelvåg, J. Eitzinger, B. Seguin, P. Peltonen-Sainio, R. Rötter, A. Iglesias, S. Orlandini, M. Dubrovský, P. Hlavinka, J. Balek, H. Eckersten, E. Cloppet, P. Calanca, A. Gobin, V. Vučetić, P. Nejedlik, S. Kumar, B. Lalic, A. Mestre, F. Rossi, J. Kozyra, V. Alexandrov, D. Semerádová, and Z. Žalud, (2011) Agroclimatic conditions in Europe under climate change. Global Change Biology, 17(7), 2298-2318.

Wheeler, T. & von Braun, J. (2013). Climate change impacts on global food security. Science, 341(6145), 508-513.
Welton, G. (2011). The impact of Russia's 2010 grain export ban. Oxfam Policy and Practice: Agriculture, Food and Land, 11(5), 76-107.

Weigand, C. (2011) Wheat Import Projections Towards 2050. Wheat Associates.