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Transportation and climate change

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In its fourth assessment report published in spring 2007, leading scientists on the Intergovernmental Panel for Climate Change (IPCC) reached consensus that human activity is responsible for many observed climate changes, particularly the warming temperatures of the last several decades, and concluded that there is a need for far more extensive adaptation than is currently occurring to reduce vulnerability to future climate changes.

However, while human activities cause significant climate changes on the one hand, these changes affect humans and their activities in return on the other. Therefore, it is natural to talk about two-directional link between human activities and climate change, and transportation is a good example of this approach.

Numerous studies have examined the link between climate change and the transportation sector. These studies have been conducted primarily from the perspective of transportation's contribution to global warming through the burning of fossil fuels, which releases carbon dioxide (CO2) and other greenhouse gases (GHGs) into the atmosphere. Far less attention has been paid to the consequences of potential climate changes for transportation infrastructure and operations. For example, projected rising sea levels, flooding, and storm surges could swamp marine terminal facilities, airport runways near coastlines, subway and railroad tunnel entrances, and roads and bridges in low-lying coastal areas.

There are also likely to be many indirect effects of climate changes on transportation. Potential climate-caused shifts in demographics as well as redistribution of production and consumption in agricultural sector, manufacturing sector, forestry, fisheries and others can affect the existing transportation patterns. Transportation patterns can also shift as the tourism industry responds to changes in ecologically or recreationally interesting destinations. Eventually it may lead to significant redistribution of transportation flows since all of the above from an economic standpoint are consumers of transportation. Therefore, it appears to be that while direct impacts of climate change affect supply of transportation, indirect impacts affect demand for transportation, and both types of impacts should be taken into account.

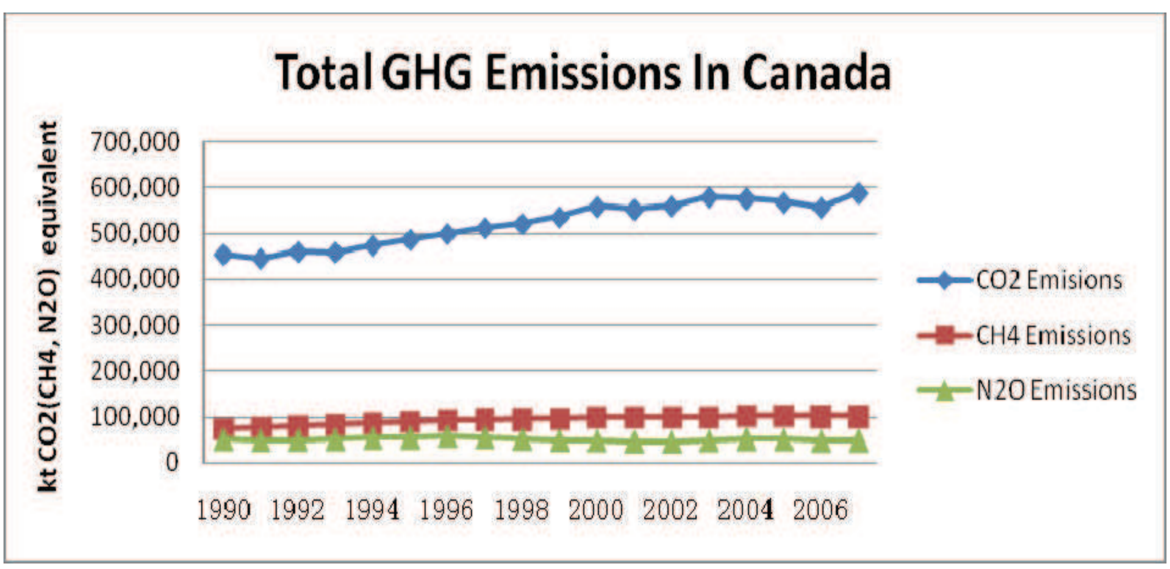
Here we analyze the link between transportation and climate in both directions - contribution of transportation to climate change as well as impacts of climate change on transportation.

1. Contribution of Transportation to Climate Change

Transportation sector is the primary consumer of petroleum products. It accounts for a growing fraction of global carbon dioxide (CO2) emissions – one of the main greenhouse gases (GHG). Transportation currently accounts for approximately 21% of global CO2 emissions. Even with projected improvements in efficiency, emissions from transportation are going to increase to 23% of total CO2 by 2030 (IEA WEO 2009). In some studies dedicated to the future of the GHG emissions, transportation emissions are estimated to account for an even larger fraction of future emissions, with greater reductions in emissions coming from other sectors. This result is not surprising if one considers the continuing growth of transportation all over the world.
Carbon dioxide is not the only GHG emitted by transportation. Methane (CH4) and nitrous oxide (N2O) are the other two. As an example of transportation GHG emissions, let us take a closer look at Canadian transportation sector.

1.1 Transportation sector in Canada as an example of greenhouse emissions

Canada has the world's 13th largest economy and is the world's 8th largest emitter of GHG. The latest 2009 GHG inventory from Environment Canada shows that after a slight decrease in 2004-2006, Canada's total GHG emissions increased again. According to this report, it is transportation and energy production that has driven emissions up. Between 1990 and 2007, emissions from energy industries such as the oil sands and transportation increased by about 143 million tons, or most of the overall increase of 155 million tones, the report says.
In general, transportation is responsible for more than 26% of Canada's total GHG emissions which means that in Canada transportation is the largest single contributor to GHG. 63% of these GHG emissions come from passenger travel and 37% from freight transportation. 50% of all personal GHG emissions in Canada are from transportation. The following graph shows dynamics of the GHG emissions by transportation in Canada over period of 1990-2007.



The above described situation is typical for developed economies, and it points to a significant contribution of transportation emissions to the climate change via the so-called greenhouse effect. The greenhouse effect is the process by which absorption and emission of infrared radiation by gases in the atmosphere warm a planet's lower atmosphere and surface. It was discovered by Joseph Fourier in 1824 and was first investigated quantitatively by Svante Arrhenius in 1896 (Weart, 2008).

The question is: Why should we care about climate changes at all? There are many reasons for that. However, we are going to emphasize only economic ones. From an economic standpoint, changes in climate directly affect our infrastructure and shift our consumption and production patterns. Moreover, these changes are associated with a lot of uncertainty which increases risk of future economic development. Investors in many fields are continually making decisions in the face of uncertain information about risks and outcomes. Wrong decisions can lead to some negative macroeconomic and microeconomic consequences. That is why addressing climate change in terms of quantitative assessments, such as, for example, the development of probabilistic climate change scenarios, may reduce this risk and the costs associated with wrong decisions. In terms of transportation, the results of such quantitative studies can be directly incorporated into planning forecasts and engineering design guidelines and standards. And since transportation professionals typically plan 20 to 30 years into the future, many decisions taken today, particularly about the location of infrastructure, will help shape economic development patterns and markets that endure far beyond these planning horizons

1.2 Analysing the link: climate-transportation emissions-climate change

There are two general views on the relationship between economic development on the one hand and the state of our environment on the other. The first one is associated with the so-called neo-Malthusian approach started with the study "The Limits to Growth" (Meadows et al, 1972). This study produced two basic conclusions: (i) under existing consumption rates the world would run out of resources in the next 100 years; and (ii) to prevent this from happening it is necessary to reduce economic growth, population growth and the level of pollution. According to Daly and Cobb (1989), "further growth beyond the present scale is overwhelmingly likely to increase costs more rapidly than it increases benefits thus ushering in a new era of "uneconomic growth" that impoverishes rather than enriches"

In contrary, the second view states that economic growth and development would eventually lead to a decrease in pollution and cleaner environment. In this regard, numerous studies have been conducted to prove the existence of a positive link between economic growth and environmental quality.

In 1990, this debate between two views led to the appearance of the so-called Environmental Kuznets Curve – an inverted U-shape relationship between the level of pollution and per capital income: With an increase in per capital income, the level of pollution increases initially but decreases eventually. In order to explain this phenomenon economists proposed 3 models: (i) overlapping generations' models; (ii) production/consumption models, and (iii) political economy models.

Grossman and Krueger (1991) conducted the first empirical study of the EKC relationship as part of a wider study to assess the environmental impacts of the North American Free Trade Agreement (NAFTA). Their analysis confirmed that ambient concentrations of SO2 and dust exhibit the EKC relationship with turning points between $4,000 and $5,000 in 1985 US dollars. After that numerous studies in various countries have been conducted to detect and estimate the EKC relationship.

Since then there have been enormous number of studies dedicated to the existence of the EKC. These studies tested the EKC hypothesis for various pollutants for different countries, for regions within a country and for different economic sectors of a country. Unfortunately, transportation sector has not been a primary target of these studies. That is why we decided to test the relationship between GHG emissions by transportation and Canadian standard of living statistically. In particular, a more specific question was addressed: Do GHG emissions by transportation in Canada and per capita income follow the inverse U-shape relationship known in the literature as Environmental Kuznets Curve (EKC) and how climate enters this relationship?

The relationship between environment and economy, expressed by the EKC, is affected by the climate in two ways:

1. Climate-pollution link. Many factors govern the severity and timing of pollution. Meteorological factors are among them. Various studies have been conducted by researchers in this area. For example, Aw and Kleeman (2003) modeled the link between temperature and pollution, Mickley et al.(2004) tested the effect of changing wind patterns on pollutant concentrations, Hogrefe et al. (2004) focused on the effect of climate change on surface ozone. Overall these studied proved the existence of the link between climate and the level of pollution. Moreover, it is a fact that environmental adaptive capacity - the capacity of a environment to adapt to pollution over time – depends on climate, and if the latter changes so does the adaptive capacity which means a change in the relationship between the environment and the level of pollution.
2. Climate-economy link. From an economic viewpoint, climate change leads to a change in consumption and production patterns that eventually affect the standard of living expressed in the EKC by per capita income.

Therefore, climate affects the EKC relationship on both sides – on pollution side and on income side – and therefore, it should be explicitly included into this relationship if a study period is long enough. In our study a period of 18 years was chosen with annual temperature as the most important indicator of the climate change.

There is a broad variety of the EKC specifications in the literature. In some studies it is expressed in levels while in others in logarithms. In some studies concentrations of pollutants are used while in others emissions. In some studies quadratic relationship is estimated while in others cubic. In this study we decided to combine all of these approaches. Of course, since transportation is associated with mobile sources of pollution, only GHG emissions make sense to detect the EKC. That is why three transportation GHG emissions were used as dependent variables. However, we estimated the EKC relationship with annual temperature in both levels and logarithms as well as for quadratic and cubic functional forms.

The data set used in that study included three blocks: (i) the income block; (ii) the pollution block, and (iii) the climate block Sample period was from 1990 to 2007.

The income block included GDP data at provincial level - 10 Canadian provinces and 2 territories – and population data. *The pollution block* consisted of three GHG emissions by transportation namely CO_2, CH_4 and N_2O. Annual emission data on 10 Canadian provinces and 2 territories was taken from the database of Environment Canada. *The climate block*

consisted of annual average temperatures from 1990 to 2007 taken from Environment Canada. One major city data from each province/territory was chosen.
Estimation of the EKC relationship between transportation GHG emissions and per capita GDP in Canada has been performed at two levels: (i) federal level, and (ii) provincial level.
At federal level, in general, evidence in favour of the EKC relationship was found in 55% of all our statistical experiments. The strongest evidence for this relationship was found for methane CH4. This relationship was found to hold in levels as well as in logarithms for all provinces and territories. The value of turning point varied in range from $297 to $16,623 in regressions in levels and from $19,930 to $24,338 in regressions in logs which is consistent with findings by other researchers. Temperature appeared to be significant at 10% level in regressions in logarithms only.
For CO2, turning point was defined in the range from $86,000 to $98,000 in the EKC in levels. The EKC relationship in logarithms was found in all regressions. However, the value of the turning point ranged from $189,874 to $719,795. It is somewhat high value. One reason for that is sensitivity of the logarithmic transformation to both types of errors - measurement and estimation. However, more importantly CO2 appears to be the most sensitive transportation emission to climate change. Annual temperature is significant at 5% in logs in all regressions and at 10% significance level in regression in levels.
Finally, N2O does not seem to exhibit the EKC relationship in levels. Only weak cubic relationship between N2O emissions and per capita GDP was found. However, the EKC relationship was supported by regressions in logs with turning points in the range from $23,181 to $44,112 which is also consistent with the existing literature including Canadian study by Day and Grafton (2001). Annual temperature plays no role in regressions in levels but it is significant at 10% level in almost all regressions in logs.
Overall, results for the EKC relationship in logs exhibit higher degree of consistency compared to the results in levels. With respect to annual temperature, it seems to be insignificant in levels but significant in logs.
What conclusions can be drawn from these results? Since we are interested in climate change impacts it appears to be that mostly warmer climate leads to a higher level of pollution by transportation. On the other hand, higher level of pollution contributes to a warmer climate. In particular it is true with respect to CO2 emissions by transportation – the largest contributor to climate change. When we estimated this relationship at provincial level, we ended up with slightly better results. It looks like the link climate-pollution-climate change in the case of transportation is even stronger at this level.

2. Climate change impacts on transportation

Climate change will affect transportation primarily through increases in several types of weather and climate extremes, such as very hot days; intense precipitation events; intense hurricanes; drought; and rising sea levels, coupled with storm surges and land subsidence. The impacts will vary by mode of transportation and region, but they will be widespread and costly in both human and economic terms and will require significant changes in the planning, design, construction, operation, and maintenance of transportation systems. In 2008 report of U.S. Transportation Research Board the following statement was made:

"Potentially, the greatest impact of climate change for North America's transportation systems will be flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence… The Atlantic and Gulf Coasts are particularly vulnerable because they have already experienced high levels of erosion, land subsidence, and loss of wetlands…"

That is why we decided to study transportation in Atlantic Canada as an example of climate change impacts on transportation.

2.1 Atlantic Canada transportation sector as an example of regional approach

Transportation sector in Canada accounts for about 4% of Canada's gross domestic product in terms of value added, employs more than 800,000 people, and is associated with about 13% of total expenditures by Canadians. It has been estimated that the road system alone has an asset value approaching $100 billion (Richardson, 1996). As a matter of fact, in 2001 Canadian transportation system was rated as one of the best in the world (World Economic Forum, 2001).

However, it appears to be that transportation in Canada remains sensitive to a number of weather-related hazards. The first general assessment of climate change impacts on transportation in Canada was undertaken in the late 1980s (BI Group, 1990), and focused mainly on sensitivities and expert opinion. In the late 1990s, Andrey and Snow (1998) conducted a more comprehensive analysis. They concluded that it is difficult to generalize about the effects of climate change on Canada's transportation system since impacts are certain to vary by region and mode.

Why these impacts are so important? Climate and weather affect the planning, design, construction, maintenance and performance of transportation fixed facilities such as roads, railways, airport runways, shipping terminals, canals and bridges throughout their service life. Major concern is that future weather conditions may reach or exceed the limits of tolerance for some parts of the transportation system with all negative consequences.

Of course, climate change impacts on transportation infrastructure will vary regionally, reflecting differences both in the magnitude of climate changes, and in environmental conditions. As well, climate changes will have secondary impacts on demand for transportation since many sectors of modern economies are consumers of various transportation services. Climate change impacts in these sectors will affect their demand for transportation causing redistribution of transportation flows. It implies that detailed studies are needed to evaluate the consequences of the climate change impacts at regional level. And as an example of such regional approach, we decided to analyze climate change impacts on ground freight transportation in Atlantic Canada.

There are approximately 67,000 kilometers of highways in the Atlantic Canada of which 2,880 kilometers have been designated as part of the National Highway System (Transport Canada, 2008). Freight rail transportation in Atlantic Canada accounts for over 11 percent of all Canadian national railways' total traffic (Transport Canada, 2008). In terms of infrastructure, there are approximately 2,400 kilometers of main railway tracks in the Atlantic Region, of which 925 kilometers are operated by Canadian National (CN), while the rest is owned and operated by five provincial short-line railways. In addition, there are approximately 950 kilometers of spur and yard track age (Transport Canada, 2008). Sea ports and harbors in Atlantic Canada play an important role in economic activities that enable more and more commodities to be transported to inland markets. Intra-, inter-

regional and international trades are active since there is a linkage between shipping and trucking/rail.
The above facts show the importance of freight transportation in Atlantic Canada for regional economy. In our opinion, Atlantic Canada is a nice representative for regional studies on climate change impacts on transportation. Moreover, assessing the vulnerability of transportation system in Atlantic Canada to climate changes is an important step toward ensuring a safe, efficient and resilient transportation system in general.

2.2 Climate change in Atlantic Canada

As the first step in our analysis, we addressed the following questions: Is there a climate change in Atlantic Canada? In general, the existing literature suggests that Atlantic Canada may not experience as much warming as central, western, and northern Canada, however, the region may be particularly hard hit by secondary effects such as

- rising sea level
- extreme weather events
- coastal erosion
- wetter winters
- drier summers
- reduced freshwater resources
- drought on farms
- exotic pests bringing new diseases and threats to farms and forests with infestation
- increased forest fires
- plant and animal communities may not be able to adapt fast enough

Based on the existing literature and expert opinion, it was hypothesized in our study that climate change in Atlantic Canada came about sometime in the period between 1940 and 2006. In this regard, time series data was collected on climate related variables over this period to primarily test the following stylized facts:

(i) An increase in mean annual temperature
(ii) An increase in sea level rise
(iii) Wetter winters
(iv) Drier summers

The data was obtained from the National Climate Archive of the Environment Canada. The main idea of our statistical experiments was to detect potential regime changes in the following time series:

- Annual mean temperature;
- Sea level;
- Annual total precipitations;
- Annual snowfall;
- Annual rainfall.

According to our statistical analysis, in the 1990s on average mean annual temperature in Atlantic Canada has been 0.8°C higher. As well during that period there has been a 3.2 cm increase in the overall trend in the sea level with an average rise of 0.2 cm per year. In addition, snowfall has decreased by 94 cm per year during the 1990s while rainfall has increased by 30 mm/year over the same period. This dynamics allows us to make the following conclusion: Due to an increase in average temperature in the 1990s by 0.8°C, some snowfall was converted into rainfall; however, the decrease in snowfall exceeded the increase in rainfall, and that is why total precipitations decreased

Based on comprehensive time series analysis eventually we came to the following conclusions:

- There was a definite climate change in the 1990s in Atlantic Canada. Two series – mean temperature and sea level rise – unambiguously point to a regime change in the mid 1990s.
- Regime change with respect to precipitation is not so obvious. Break points associated with the 1990s are not dominant but statistically significant.
- There was a regime change in the 1950-1960s with respect to precipitations
- Statistical evidence supports "the drier summers" stylized fact while rejecting "the wetter winters" fact.

More importantly, our analysis produced marginal impacts of the climate change on regional economy. These impacts can be summarized as follows:

- a one-degree increase in annual temperature increases regional GDP by $142.2 million;
- a one-centimetre increase in the sea level decreases regional GDP by $155.8 million;
- an increase in total precipitation by 100 millimetres increases regional GDP by $79.1 million;
- a decrease in total precipitation by 100 millimetres decreases regional GDP by $79.1 million.

2.3 Estimating consequences of climate change impacts

According to the existing literature, resource based economies are likely to be harder hit by climate change than industrial economies. Therefore, Atlantic Canada may suffer proportionately more economic hardship than, for example, central Canada. If the warming trend continues in Atlantic Canada, ice break-up and flooding on the rivers will become more severe and less predictable. This can cause increasing damage to public and private property, including transportation infrastructure such as highways and bridges.

According to the Government of Canada (2004), the Atlantic Canada can also anticipate an increased risk of trees blowing down as storms become more frequent and intense as a result of climate change. For example, a massive blow-down in 1994 caused 30 million trees to be felled which cost $100 million in damages.

Agricultural sector of the regional economy, which is one of the largest consumers of freight transportation, will be the primary beneficiary of climate change. Due to warming, the growing season for such crops as corn and other cereals will be prolonged producing larger yields. However, the probability of droughts is going to increase, thus raising the issue of supplementary irrigation. In addition, warmer winters will boost insect reproduction, forcing local farmers to apply bigger amounts of pesticides. Some other natural phenomena such as floods and hail can substantially damage crops as well as livestock.

Forestry is another large consumer of freight transportation. Climate change may increase the risk to forests in Atlantic Canada as well. According to the Government of Canada report *"warmer winter temperatures may allow invasive insects, such as the gypsy moth, to become more pervasive, while warmer, drier summers would increase the threat of forest fires in the Atlantic Provinces"* (Government of Canada, 2004).

Analysis of the cost structure of the major industrial producers in Atlantic Canada shows that adjustment to the global climate change will result in the following (Government of Canada, 2004):

- The price of pulp and paper will rise by 0.06 percent or by about 59 cents per ton;
- The price of electricity (coal) will rise by 1.94 percent or by 0.14 cents per KWH;
- The price of electricity (gas) will rise by 0.60 percent or by 0.04 cents per KWH;
- The price of steel (conventional) will rise by 0.29 percent or by $2.10 per ton;
- The price of aluminum will rise by 0.23 percent or by $4.73 per ton.
- The price of natural gas will rise by 0.14 percent or by 0.5 cents/million cubic feet.

All these changes will inevitably affect the allocation of production, consumption and trade flows in the regional economy which, in turn, will affect allocation of freight transportation flows.

In order to address this issue at aggregate level, the following three scenarios were assumed in order to trace consequences of the climate change impacts on regional economy and its transportation system:

	Expected	**Best**	**Worst**
Sea level rise	0.5 cm/year	0.2 cm/year	1.0cm/year
Temperature	0.03/year	0.01/year	0.05/year
Precipitations	0	0	-50 mm/year

Table 1. Scenarios of climate changes in Atlantic Canada

These scenarios were formed on the basis of the forecasts made by the Government of Canada for Atlantic Canada. Using these assumptions, computer simulation was performed. The results of the computer simulation are summarized in the following tables:

Year	Best Case Scenario	Expected Scenario	Worst Case Scenario
2010	-0.06%	-0.14%	-0.36%
2050	-1.05%	-2.60%	- 6.66%

Table 2. Change in the volume of ground freight transportation in Atlantic Canada

Year	Best Case Scenario	Expected Scenario	Worst Case Scenario
2010	-0.17%	-0.41%	-1.05%
2050	-1.04%	-2.58%	- 6.57%

Table 3. Change in Atlantic Canada GDP

In general, the results are consistent with the Government of Canada forecasts with respect to regional GDP. Government of Canada (2004) predicted a 0.3% decrease in Atlantic Canada GDP by the year of 2010. According to our simulation, except for the worst case scenario, a decrease in Atlantic Canada GDP is expected to be in the range of 0.17-0.41%.

Therefore, it is possible to argue that a longer forecast until 2050 is also valid as a first approximation as well as long-term impacts on transportation.

A distinguishing future of our result is: While in the short-term climate change has a stronger impact on economy as a whole compared to freight transportation, in the longer term the consequences of the climate change for the regional economy and freight transportation converge. It is not surprising since in the short-run economy is unable to quickly adjust to the climate change impacts while in the long-run it will adjust through redistribution of production, consumption, trade and transportation flows.

3. Conclusion

As stated at the beginning of this chapter, the relationship between transportation and climate is two-directional. Based on our statistical analysis performed for Canada, we can make some general conclusions about this relationship. On the one hand, transportation is one of the largest contributors to GHG emissions which, in turn, cause various changes in climate. On the other hand, these climate changes negatively affect transportation in terms of its infrastructure and operations. Therefore, this study sends a clear signal to policy makers: "Do-nothing" alternative with respect to climate changes and transportation is no longer viable, and the interaction between the two should be explicitly taken into account by transportation professionals.

In terms of contribution of transportation to climate change, any global warming that will be experienced during the next several decades will largely be the result of GHG emissions. As already noted, transportation sector in general is a significant source of GHG emissions. In order to limit future warming, GHG concentrations in the atmosphere must be stabilized. This will require reducing GHG emissions by transportation not merely to below what they might otherwise be if present trends were to continue but to well below current levels. Some decisive steps must be taken now to begin to implement different approaches. For example, U.S. Transportation Research Board proposes the following approaches:

- Utilization of carbon neutral fuels;
- Improved traffic flow and other changes in transport activity resulting from better integration of transport systems, enabled by information technology;
- Use of power trains that are highly energy efficient;
- Change in the historical mix-shifting trend to larger vehicle categories;

And some others.

In terms of climate change impacts on transportation, first of all, transportation agencies and service providers should inventory critical infrastructures according to the existing climate change projections. As well, transportation agencies and service providers should incorporate potential climate changes into their long-term capital improvement plans, facility designs, maintenance practices, operations, and emergency response plans. It means that from now on climate change should become a mandatory factor in any design of transportation facilities and operations.

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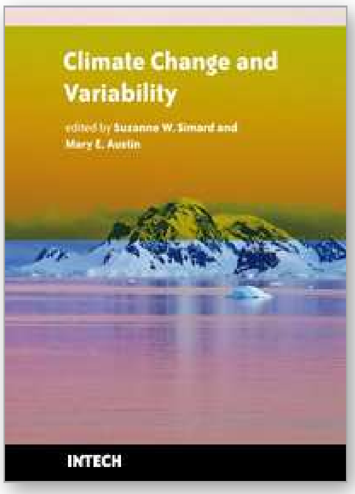

Climate Change and Variability
Edited by Suzanne Simard

ISBN 978-953-307-144-2
Hard cover, 486 pages
Publisher Sciyo
Published online 17, August, 2010
Published in print edition August, 2010

Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Yuri Yevdokimov (2010). Climate Change and Transportation, Climate Change and Variability, Suzanne Simard (Ed.), ISBN: 978-953-307-144-2, InTech, Available from: http://www.intechopen.com/books/climate-change-and-variability/climate-change-and-transportation

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