THE FUTURE OF ATMOSPHERIC RIVERS

And Actions to Reduce Impacts on British Columbians

Pinna Sustainability

The Future of Atmospheric Rivers and Actions to Reduce Impacts on British Columbians
2014

This project was made possible with the support from
Natural Resources Canada through the Adaptation Platform.

Natural Resources Canada
Ressources naturelles Canada
Canada

This project was delivered in partnership with the BC Ministry of Environment,
Pacific Institute for Climate Solutions and the Pacific Climate Impacts Consortium.

British Columbia

Pacific Institute for Climate Solutions
Knowledge. Insight. Action.

Pacific Climate Impacts Consortium

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Extreme precipitation and flooding impact communities across British Columbia (BC). Some impacts along the coast are the result of 'Atmospheric River' (AR) events. An atmospheric river is an intense and relatively narrow flow of moisture-laden air.

In British Columbia, atmospheric rivers most frequently occur in the fall and winter. Their impacts are greatest on British Columbia's coast where moist air is forced to rise over the Coast Mountains, resulting in intense precipitation. Atmospheric rivers have triggered a number of flood events over the past decade in BC that required intensive emergency response efforts.

To improve local understanding and manage the impacts of atmospheric river events, the BC Ministry of Environment and Natural Resources Canada commissioned work to summarize the current state of knowledge pertaining to BC on this topic and conduct a multi-agency qualitative risk assessment.

In April 2013, scientists and researchers gathered in Victoria, BC to review and summarize the current state of knowledge on atmospheric rivers. As a result of their efforts, the Pacific Climate Impacts Consortium (PCIC) and Pinna Sustainability produced an 'Atmospheric River State of Knowledge Report' which:

- Summarized the current understanding of AR events,
- Explored ways to enhance understanding through scientific research,
- Identified ways stakeholders can work together to enhance our collective response, and
- Outlined key stakeholders to be engaged in this process.

Based on recommendations in this initial report, the Ministry of the Environment commissioned further work to explore future predictions of AR events and map potential indicators of vulnerability to impacts across the province.

On February 27th, 2014, the BC Ministry of the Environment, the PCIC and Pacific Institute for Climate Solutions (PICS) co-hosted a workshop to discuss the risks associated with extreme precipitation events in British Columbia in a changing climate.

Participants included:

- Climate scientists, to share research on projecting extreme precipitation
- Weather forecasters, to discuss challenges in forecasting extreme precipitation and communicating potentially dangerous events to vulnerable communities
- Responders from the BC Government and local communities, to share their knowledge and experience of 'on the ground' responses.

This second report summarizes the activities which took place during the workshop, provides a high level summary of future predictions in extreme weather, offers insights from attempts to map vulnerability, and summarizes efforts to identify high impact consequences and priority areas of action to reduce those impacts.

CURRENT SCIENTIFIC UNDERSTANDING

Observed Trends in Extreme Precipitation

Due to the highly variable nature of precipitation, trends in extremes are often difficult to detect. However, it is likely that the number of heavy precipitation days has increased in many land regions globally, consistent with a warming climate and observed increases in atmospheric water vapour (Seneviratne *et al.*, IPCC 2012).

The Clausius-Clapeyron relationship is a thermodynamics equation that is used to describe the water vapour content of the atmosphere as a function of temperature. For each degree Celsius that the temperature increases, we can expect a 7% increase in water vapour held in the atmosphere. A statistical analysis of global annual maximum one-day amounts over the last 100 years shows an increase in precipitation between 6% and 8% per degree of warming, matching the principles of the Clausius-Claperyron relationship (Westra *et al*., 2013).

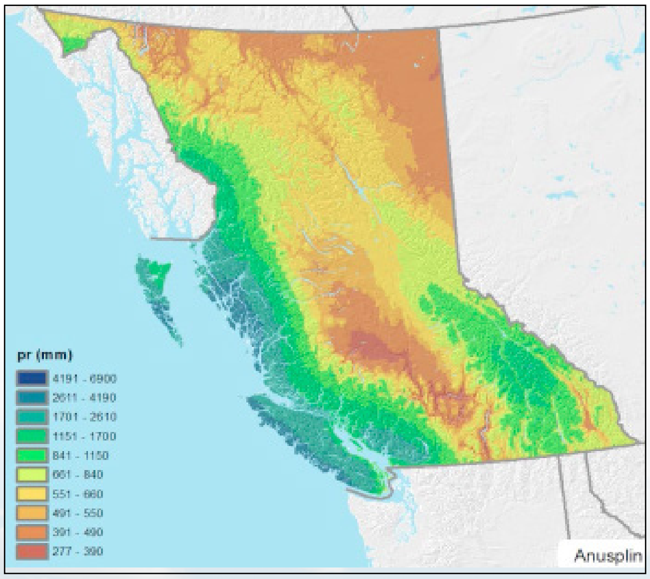
The largest annual and extreme precipitation totals for British Columbia are found on the coast. (Figure 1). Extreme precipitation in British Columbia has increased over the period 1966–2005, particularly in the summer season and for events of short duration (Burn *et al.,* 2013).

Future Projections of Extreme

Global

On a global scale, it is very likely that precipitation will increase in future, while the increase will vary from region to region. Studies using an ensemble of global climate models (GCMs) from the recent international CMIP5 experiment (Taylor, et al., 2012) project an increase in the global average 20-year return

Total Annual Precipitation pTOT (1971-2000)



20-Year Return Period, One-Day Extreme Event (1971 - 2000)

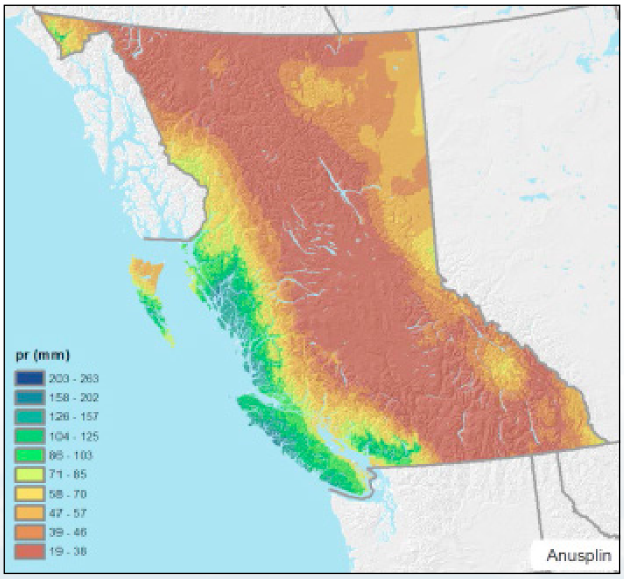


Figure 1: Observed annual average total (***left***) and 20-year return period one-day (***right***) precipitation in British Columbia over 1971-2000, on a 10km grid (McKenney, *et al.* 2011). These figures illustrate amounts averaged over large areas, and do not reflect the intensity experienced at specific sites.

values of annual extremes of daily precipitation amounts (the 20-year return value is the intensity of the extreme event with a 1 in 20 likelihood of occurring in a given year). The change in global precipitation depends upon the future Greenhouse Gas emissions scenarios, with projections of 6%, 10% and 20% increases for the low, medium and high emissions scenarios (RCP 2.6, 4.5 and 8.5)[1] respectively. Increases in the frequency of extreme events are also projected, as expected waiting times for 20-year extreme events characteristic of the late 20th century in the climate models decrease over land to 14, 11, or 6 years for the low, medium, and high emissions scenarios, respectively. In addition, the intensity of extreme precipitation events increases 2 to 3 times more than the increase in annual mean precipitation (Kharin et al., 2013).

British Columbia

Larger increases in precipitation are projected for BC than for the global average, in particular for the coastal regions. The frequency of extreme events (by today's classification) is also expected to increase. Under the medium emissions scenario, a suite of GCMs indicate a modest increase in annual precipitation for British Columbia by 2046-2065 that is slightly greater than the global average of about 3% (Kharin *et al.,* 2013). As was found for global precipitation, the frequency of extreme precipitation events is projected to increase across British Columbia. Under the medium emissions scenario (4.5), events that historically occurred once in 20 years in the province are projected to occur once in 10 to 15 years over much of the province, with larger changes indicated for the coast, by 2046-2065 (Kharin *et al.,* 2013).

Analysis with a suite of higher-resolution regional climate models in the Canadian Columbia river basin indicates a 1% to 9% increase in annual total precipitation by 2041– 2070 under a high emissions scenario (Murdock *et al.,* 2013).[2] The amount of precipitation on very wet days is projected to increase. The 25-year return period one-day event (by today's classification) is projected to occur twice as often in the future period on average, with a wide range of spatial variability throughout the basin (Murdock *et al.,* 2013). This is consistent with results reported by Kharin et al (2013) described above.

Global climate projections were statistically adjusted (downscaled) to provide detailed climate projections on a 10 km grid for British Columbia.[3] This provides estimates of how projected changes in mean and extreme precipitation vary across British Columbia (Figures 2 and 3). The results show slightly larger precipitation increases than indicated by coarse scale global climate model projections directly for the region. It should be noted, though, that many locations showing a large percentage increase, such as the interior and Northeast, have historically low precipitation (Figure 2). As such, dry areas with a large projected percentage increase may experience smaller absolute increases (in mm) compared to wetter locations such as the coast, where the percentage increase is smaller, but the amount (in mm) is larger. Increases in the total amount of extreme rainfall (in mm) are largest on the coast, followed by the Kootenays and the Northeast. These maps show the average of 12 individual projections, the majority of which indicate an increase in annual precipitation throughout the province, except in the Southern Interior. Furthermore, all simulations project an intensification of extreme precipitation.

1 The acronym "RCP" refers to "Representative Concentration Pathway" (Van Vuurren *et al.,* 2011). The IPCC 5th Assessment Report considers 4 RCPs (RCP2.6, 4.5, 6.0 and 8.5) that are labeled according to the strength of forcing, or warming effect, that is produced in year 2100, in units of watts per square meter. RCPs 2.6, 4.5 and 6.0 consider different levels of mitigation, while RCP8.5 represents essentially an unmitigated "business-as-usual" emissions scenario.

2 The "SRES" emissions scenarios used in this analysis (Nakicenovic, N., *et al.* Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change (Cambridge Univ. Press, 2000) were used in previous IPCC assessment reports in which the "A2" scenario represents an unmitigated emissions scenario that results in forcing in year 2100 that is very similar to that under the RCP8.5 scenario (IPCC WG1 Assessment Report 5. Chapter 1, Fig 1.15).

3 Downscaling was conducted using the BCCAQ method (Cannon, A.J. et al. 2014, in prep)

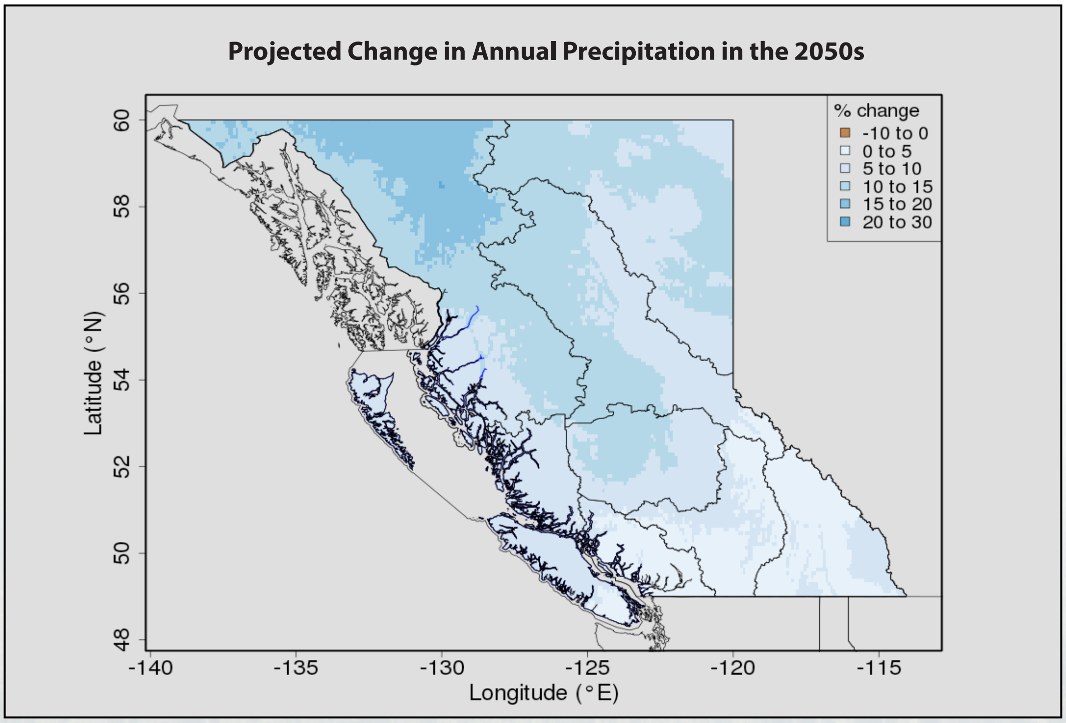


Figure 2: High-resolution (10km) maps of projected (2041-2070) changes as percent of historical baseline (1971-2000) in annual precipitation for British Columbia. Source: preliminary findings by PCIC based of an ensemble of 12 CMIP5 GCMs following RCP4.5 statistically downscaled using BCCAQ (Cannon *et al.,* in prep).

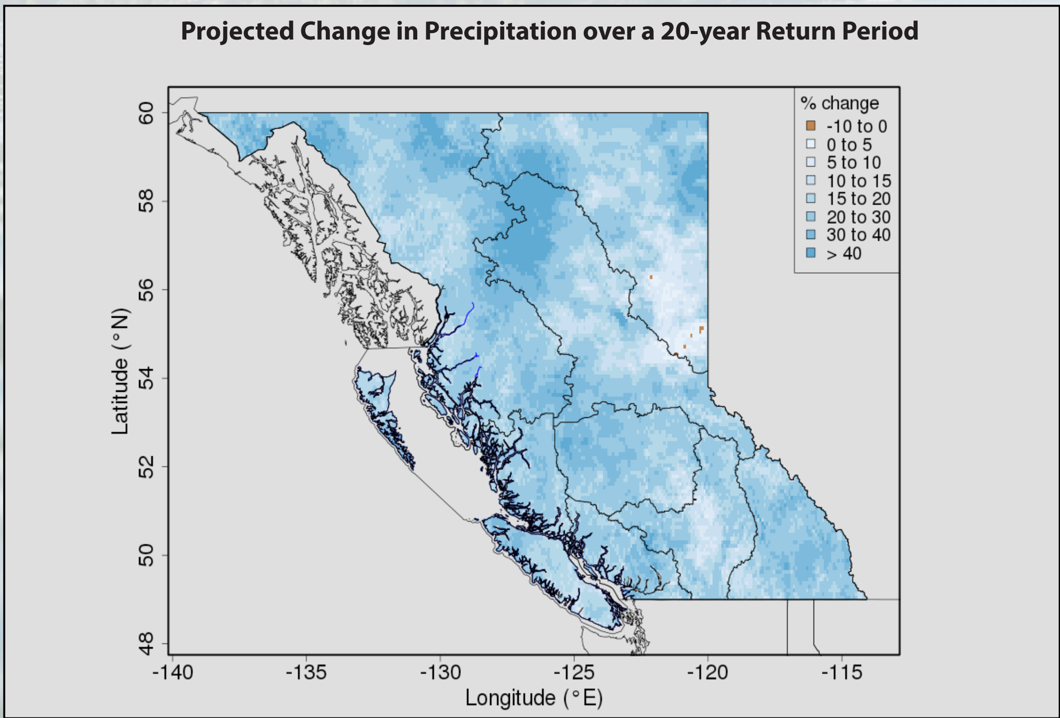


Figure 3: High-resolution (10km) maps of projected (2041-2070) changes as percent of historical baseline (1971-2000) in 20-year return period 1-day precipitation event intensity for British Columbia. Source: preliminary findings by PCIC based of an ensemble of 12 CMIP5 GCMs following RCP4.5 statistically downscaled using BCCAQ (Cannon et al., in prep).

Atmospheric Rivers in BC

Atmospheric rivers affecting BC originate in the tropical and subtropical Pacific, and for this reason are sometimes referred to by the popular term "Pineapple Express." They can transport as much water as a river. A typical criterion for detecting an atmospheric river (individual rivers have relatively short lifetimes, measured in hours to days) involves a water transport metric (*e.g.* a volume of water in liters or kilograms travelling past the given stretch of coastline each second, on average per meter of that coastline) and a length criterion (in km). Past trends in atmospheric rivers were explored in BC using such a definition in conjunction with data from the ERA-Interim

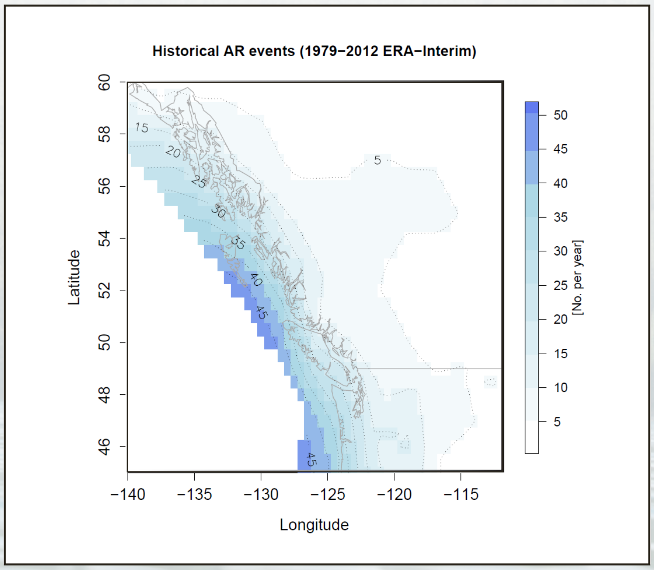


Figure 4: The number of AR events (based on integrated vapour transport) per year that influence British Columbia for 1979-2012 from ERA-Interim reanalysis (Dee *et al.*, 2011)

reanalysis (Dee *et al.,* 2011).[4] Between1979–2012, the frequency of atmospheric rivers was largest on the coast, with more than 20 events per year influencing coastal regions and less than 10 elsewhere (Figure 4). Furthermore, in the wet season (November–April), around 10% of days meet atmospheric river conditions on the coast, compared to 3% elsewhere. The British Columbian coast receives between 20% to 25% of its total annual precipitation from atmospheric river events, while other regions receive less than 6% of annual rainfall from ARs.[5]

[4] Atmospheric rivers were defined as events in which a plume of moisture transporting over 250 kg /s/m of water vapour extended for at least 2000 km.

[5] Reanalysis techniques combine model simulations with observations to produce a best estimate of the atmospheric conditions of recent decades. The dominant influence of AR events on the coast is also reflected in indicators of extremes, such as days with greater than 20 mm of rainfall and days with precipitation above the historical 95th percentile of precipitation on wet days.

Global Projections

Future projections are largely based on coarse resolution global climate models. This makes it difficult to identify future patterns in atmospheric river events; however, as extreme precipitation increases, similar increases in atmospheric rivers are also expected.

A multi-model analysis for California indicates a 30% increase in the number of 'atmospheric river days' (AR days) by 2100. All Global Climate Models examined in that study project that California will experience an increase in the number of AR days (Dettinger *et al.,* 2011).

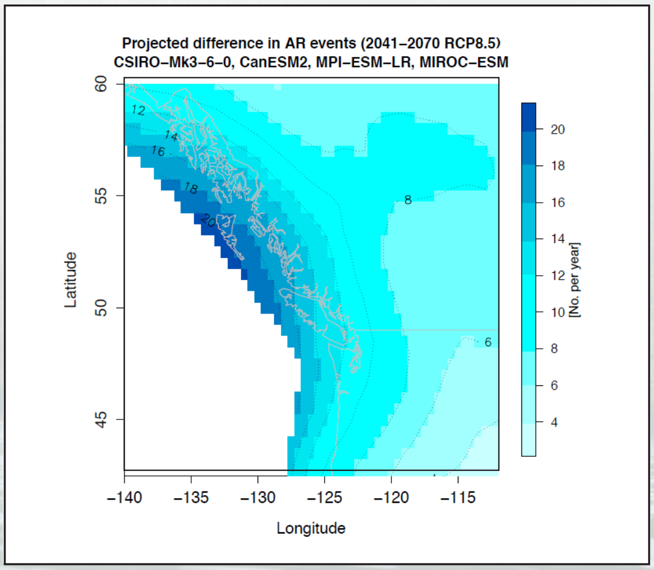


Figure 5: The projected difference between the historical (1979-2012) and future (2041-2070) mean in an ensemble of global climate models under RCP 8.5 (right). Source: preliminary findings by PCIC based on analysis of four GCM runs (CSIRO-Mk3-6.0, CanESM2, MPI-ESM-LR, and MIROC-ESM) and ERA-Interim reanalysis.

Another study of Global Climate Model projections also suggests that atmospheric rivers in the North Atlantic will become more intense (Lavers *et al.,* 2013) and indicates an approximate doubling of atmospheric river frequency under a high emissions scenario by 2074–2099 in that region.

BC Projections

Preliminary findings by the Pacific Climate Impacts Consortium using an ensemble of Global Climate Models suggest that the frequency of atmospheric rivers in British Columbia will increase by 2041-2070 under a high emissions scenario (Figure 3). The largest increases are projected to occur on the coast but the average number of atmospheric river days per year is projected to approximately double at most locations including the interior.

MULTI-AGENCY RISK EXPLORATION

This report reflects the outcome of activities with experts and stakeholders designed to:

1. Identify high-consequence impacts of atmospheric river events in BC
2. Explore how risks might be identified or measured
3. Use a scenario-based exercise to identify and prioritize potential actions to reduce risks.

The International Panel on Climate Change (IPCC) defines risk as the "potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values", noting that risk is often represented as the combination of the probability of an event and its consequences. Extreme precipitation events may trigger landslides, floods, and other damage in the province; however, many of these hazards occur in unpopulated regions and therefore are considered to be of low consequence. When a hazard has a significant impact on a community, either directly on populations, or indirectly to infrastructure or the economy, the consequences may be high and the events are considered 'natural disasters.' Considering the projected increase in frequency and intensity of atmospheric river events in a changing climate, workshop organizers asked participants to engage in a session identifying potential risks: the "risk exploration." The objective was to:

Identify and prioritize impacts, explore vulnerability and risk and identify measures and tools to reduce future risk.

For the purposes of this exercise, the term 'high consequence impact' was used to focus the conversation on the impacts of extreme precipitation events that have significant social, physical, or monetary consequences.

High Consequence Impacts

The following impacts were identified as being of greatest concern:

1. Mortality
2. Isolation (e.g. community cut-off from transportation and communications)
3. Loss of critical infrastructure.

These were determined using a combination of a democratic process (voting with dots) and consensus based group discussions. They reflect the refinement of the following list developed though a brainstorming session by experts and stakeholders:

- Loss of critical infrastructure
- Dike failure
- Dam failure
- Access (roads/ airports, etc.) cut-off
- Loss of life
- Economic losses
- Psycho-social impacts
- Destruction of homes and businesses
- Displaced people
- Water shut-off
- Loss of communication
- Surface water flooding
- Water borne illness
- Liability claims
- Contamination
- Pipeline ruptures
- Drinking Water
- Environmental
- Sewer and Septic failures
- Livestock death and crop failure
- Electricity & energy failure

Exploring Vulnerability and Risk

The impact of an atmospheric river event depends largely on the vulnerability of the system hit by the event. Vulnerability is commonly defined as "the degree to which a system is susceptible to, and unable to cope with, adverse impacts." Systems may have socio-economic vulnerabilities (e.g. low income, old age, low levels of mobility) or geophysical vulnerabilities (e.g. steep terrain, location in floodplain).

In advance of the workshop, a project advisory group selected several potential vulnerability indicators based on their expert judgment and available data. Maps were produced in an experimental attempt to illustrate how these vulnerabilities could be overlaid on maps of extreme future precipitation to identify regional variation in risk.

To explore socio-economic vulnerability, the socio-economic index produced by BC Statistics (BC Stats, 2013) was divided into four levels of severity, ranging from 0 (low socio-economic vulnerability) to 1 (high socio-economic vulnerability). This map was overlaid with statistically adjusted (downscaled), high-resolution maps of the intensity of the future 1-in-20 year daily rainfall events.

To explore geophysical vulnerability, regions identified as high slope (Danielson, 2011) and low stability (Danielson, 2011), in designated floodplains (Data BC, 1999) and/or in regions of high shoreline sensitivity (Biffard et al., 2009) were identified as highly vulnerable and assigned a value of 1 (as opposed to a value of 0). When added together, these resulted in an index of geophysical vulnerability ranging from 0–4. This vulnerability map was then overlaid with regions of future extreme daily rainfall events.

These overlays were developed with the intent of encouraging an informed discussion about vulnerability and risk. Many more combinations of social and geophysical index with present extreme precipitation climatology and projected precipitation extremes were created for the workshop. A sample of two of these maps are given in Figures 7 and 8.

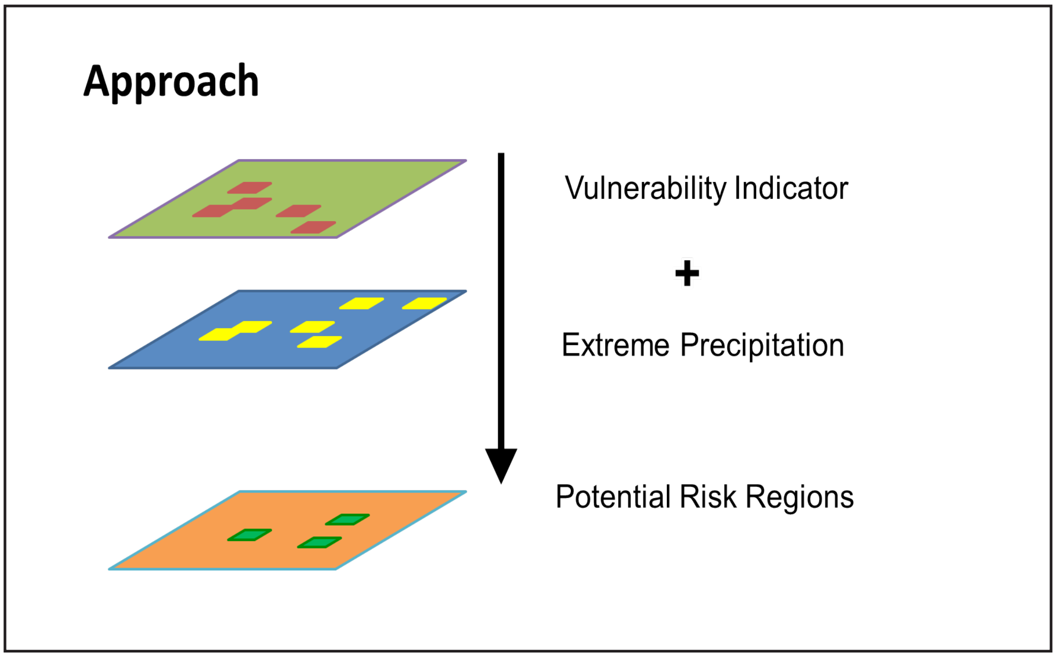


Figure 6: Methodology for creation of risk maps

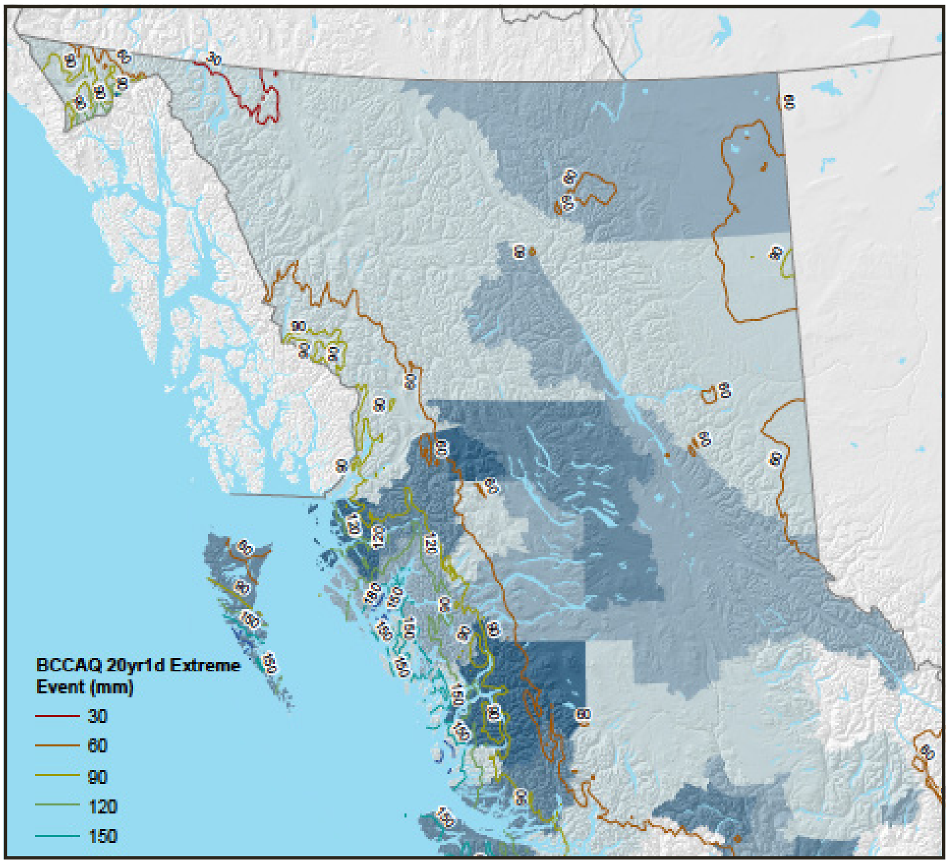


Figure 7: Sample social risk assessment map composed of (1) the Regional Socio-Economic Index, which factors a number of metrics of how "well off" a region is on average with higher number indicate poorer regions, and (2) projected 20-Year one-day extreme events (2050s). A 20-year, one-day event is the total precipitation over one day that is expected in a storm with a 5% chance of occurrence in any given year. These maps were developed by PCIC and the B.C. Ministry of the Environment for use at the workshop, and are not intended for wider distribution.

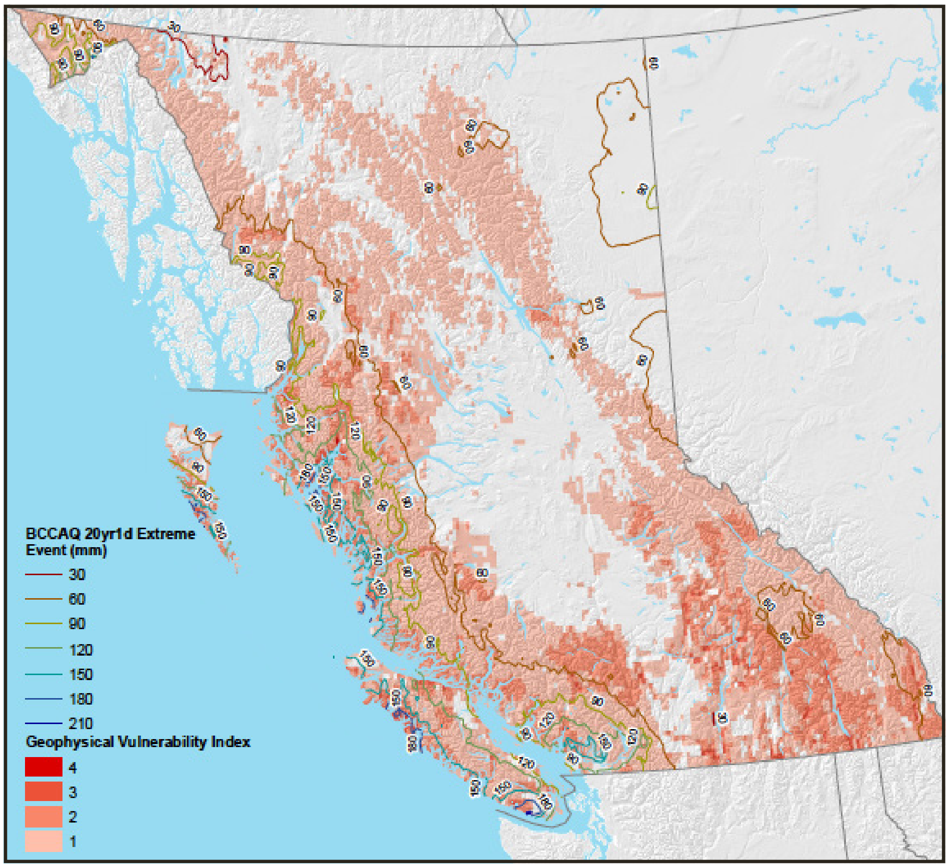


Figure 8: Geophysical Vulnerability Index, which combines coastal vulnerability, slope stability, regions with slope greater than 60%, and mapped floodplains in the province, overlaid with 20-year 1-day extreme event (2050s) as presented in Figure 7. These maps were developed by PCIC and the B.C. Ministry of the Environment for use at the workshop, and are not intended for wider distribution.

These exploratory images suggest there are several areas of the province that may be particularly at risk based on the co-occurrence of potential heavy precipitation and one of the vulnerability indexes. These locations include:

1. Southern Queen Charlotte Islands
2. the Kitimat coast
3. the Central coast
4. Mount Waddington
5. Capital region.

Participants from the provincial and federal weather offices, emergency managers, local governments, and responders all agreed that a response management tool based on these or similar maps would provide an improved spatial understanding of physical and social vulnerabilities could enable a better response. A map-based tool could be used to:

- Support governments in land-use planning decisions to ensure critical infrastructure and response centers are appropriately sited
- Allow pre-allocation of resources to known risk areas – *e.g.* sand bags available to the right areas
- Support risk-based funding and response decisions.

Future Vulnerability and Risk Maps

Experts and stakeholders suggested several key information layers for future vulnerability and risk maps, including:

- Population centres, including towns, villages, unincorporated areas and First Nations communities
- Socio-economic indicators
- Soil stability indicators
- Location of floodplains and critical infrastructure
- Location of economic infrastructure (mines, pipelines, tourism, construction sites etc.)
- Location and extent of damage from past events
- Level of community preparedness weather forecasts
- Snow pack and freshet flow information

Experts and stakeholders also recognized the importance of developing complementary grassroots community maps which would reflect community-specific priorities and capture unique socio-economic and geophysical features.

Measures and Tools to Reduce Risk

Multi-agency working groups were formed to identify priority risk-reduction measures and tools using scenarios involving two fictional communities on BC's coast. Half of these working groups explored the impacts of an atmospheric river event on a mid-size community (pop 30,000). The other half explored impacts on a small community of 450 people. The groups were asked to consider the following questions:

1. Of the top consequences identified earlier, which are most likely to affect your community?
2. What role could your agency play in reducing the consequences of atmospheric river events in the future?
3. What constraints do you foresee impeding your ability to respond to these expected high-consequence impacts?
4. What appropriate measures could be taken to reduce the consequences of atmospheric river events in the future?
5. What information or tools would help to reduce the consequences of atmospheric river events in the future?
6. How is this response unique from what would be needed in a different coastal community (if at all)?

Each group presented their findings back to the larger audience.

OUTCOMES

Priority Actions

A total of 15 priority actions were identified to reduce future risk.

Geographic Information: Our ability to act effectively is closely connected to our understanding of the complex geography of our province.

1. Develop a repository of gridded digital elevation data to provide a more detailed understanding of our complex provincial geography.
2. Update floodplain maps.
3. Pilot the use of vulnerability maps which include information on vulnerable populations and physical hazards.

Knowledge and Communication: Before and during an event, communication between experts, local governments, and emergency responders is critical to saving lives and reducing damage.

4. Improve forecasting and early warning of events with enhanced meteorological data, hydrometric monitoring and models.
5. Provide conference calls, webinars, and other social media communications tools in advance and during events to transmit technical details to the emergency management community as well as the public.
6. Develop a decision making matrix with pre-determined timelines for alerting vulnerable populations to extreme weather.
7. Develop a record of past events including information on impacts, response measures and recovery costs and invest in modelling potential damage from these events.

Common Constraints

Several common constraints were identified, regardless of the impact or community being assessed.

Limited financial resources: Communities often lack the financial resources to invest meaningfully in improved infrastructure or preparedness planning. Budget restrictions result in competition for resources during response and recovery.

Scientific information: Current lead times for forecasting extreme precipitation events (2 to 3 days) do not provide much time to alert vulnerable populations and allocate emergency resources in advance of an event.

Land availability: Many communities vulnerable to extreme precipitation events are located adjacent to mountains and rivers, which limits their ability to manage risk by relocating homes and critical infrastructure away from hazardous landscapes.

Political authority: Authority for siting and maintaining critical infrastructure (e.g. hospitals, roads) as well as for responding to events is divided across multiple agencies and levels of government, adding complexity to planning for extreme events.

Public response: Competing priorities lead many to dismiss messages about preparing for extreme weather. Fear of declining real estate values, higher insurance, relocation or evacuation often prevents action to reduce risk.

Policy and Planning: Measures can be taken well in advance of an event to ensure communities are protected from extreme weather.

8. Introduce bylaws to restrict new building in floodplains and hazardous areas.
9. Provide financial assistance and incentives that encourage redevelopment and relocation outside of hazardous areas.
10. Complement community-level planning activities with provincial risk assessments and scenarios to ensure a coordinated response and prioritization of resources.

Infrastructure: Reliable, functioning infrastructure is at the core of a community's ability to be resilient to extreme events. In order to ensure our infrastructure is able to provide people and communities with needed services and supplies, participants suggested the following measures be taken:

11. Develop maps of critical infrastructure.
12. Assess the vulnerability of critical infrastructure.
13. Relocate critical infrastructure where needed.

Preparedness: Preventative measures taken before an event can significantly reduce the risk of injury, death, and destruction of infrastructure.

14. Ensure communities have:
    - Safe stores of critical items (e.g. medical supplies, emergency food, clean water, energy *etc.*).
    - Back-up options for critical infrastructure (*e.g.* emergency transportation, satellite phones, evacuation routes).
15. Conduct community-wide emergency drills involving businesses, schools, and families.

Conclusions & Next Steps

Scientific findings suggest it is reasonable to expect atmospheric rivers to increase in severity and intensity over the coming century. The workshop outcomes reflect an expert and stakeholder informed process to identify future projections in extreme precipitation events, identify high-consequence impacts of these events and propose risk reduction measures. Workshop participants identified near-term opportunities to improve preparedness and response, such as vulnerability mapping and community based preparedness planning. They also identified longer-term considerations to reduce risk, such as moving critical infrastructure out of harms way. Together with the 'State of Knowledge' report, this report provides a foundation for future discussions and collaborative action by all levels of governments, corporations, scientists and emergency managers to reduce the future impact of atmospheric river events across BC.

Appendix A: Workshop Participants

The following individuals participated in the workshop:

Faron Anslow Pacific Climate Impacts Consortium
Marten Geertsema BC Ministry of Forests, Lands and Natural Resource Operations
Jesal Shah BC Ministry of Forests, Lands and Natural Resource Operations
Bill Elsner Sunshine Coast Regional District
Jim Barnes BC Ministry of Transportation and Infrastructure
David Campbell BC Ministry of Forests, Lands and Natural Resource Operations
Wenda Mason BC Ministry of Forests, Lands and Natural Resource Operations
Alex Cannon Pacific Climate Impacts Consortium
Cam Filmer Emergency Management BC
David Jones Pacific Storm Prediction Centre, Environment Canada
Doug McCollor BC Hydro
Trevor Murdock Pacific Climate Impacts Consortium
Dirk Nyland BC Ministry of Transportation and Infrastructure
Sarah O'Keefe Climate Action Secretariat, BC Ministry of Environment
Brad Snyder Pacific Storm Prediction Centre, Environment Canada
Basil Veerman Pacific Climate Impacts Consortium
Ted Weick Water and Air Monitoring and Reporting Section, BC MOE
Cheryl Waugh Central Coast Regional District, Bella Coola
Tamsin Mills City of Vancouver
Jeri Grant Juan De Fuca Emergency Program
Clare Fletcher Emergency Management British Columbia
Cathy LeBlanc BC Ministry of Community, Sport and Cultural Development
Luanne Chew Water Information, BC Ministry of Environment
Chris Jensen BC Ministry of Community, Sport and Cultural Development
Tobi Gardner BC Minister of Forests, Lands and Natural Resource Operation
Tim Preece Emergency Management BC, BC Ministry of Justice
Thomas White Climate Action Secretariat, BC Ministry of Environment
Cassbreea Dewis Pacific Climate Impacts Consortium
James Hiebert Pacific Climate Impacts Consortium
Camille Fouchier Pacific Climate Impacts Consortium
Gillian Aubie Vine Pinna Sustainability
Cariad Garratt Pinna Sustainability
Jenny Fraser Climate Action Secretariat, BC Ministry of Environment
Avril Nagel Emergency Management BC, BC Ministry of Justice

References

Burn, D.H., Mansour, R., Zhang, K., Whitfield, P.H., 2011. Trends and Variability in Extreme Rainfall Events in British Columbia. Canadian Water Resources Journal 36, 67–82. doi:10.4296/cwrj3601067

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., Vitart, F., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137, 553–597. doi:10.1002/qj.828

Dettinger, M., 2011. Climate Change, Atmospheric Rivers, and Floods in California – A Multimodel Analysis of Storm Frequency and Magnitude Changes. JAWRA Journal of the American Water Resources Association 47, 514–523. doi:10.1111/j.1752-1688.2011.00546.x

IPCC WGII AR5 Summary for Policymakers, Climate Change 2014: Impacts, Adaptation, and Vulnerability, copyedit pending, http://ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf

Kharin, V.V., Zwiers, F.W., Zhang, X., Wehner, M., 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change 119, 345–357. doi:10.1007/s10584-013-0705-8 McKenney, Daniel W., and Coauthors, 2011: Customized Spatial Climate Models for North America. Bull. Amer. Meteor. Soc., 92, 1611–1622. doi: http://dx.doi.org/10.1175/2011BAMS3132.1

Lavers, D.A., Allan, R.P., Villarini, G., Lloyd-Hughes, B., Brayshaw, D.J., Wade, A.J., 2013. Future changes in atmospheric rivers and their implications for winter flooding in Britain. Environ. Res. Lett. 8, 034010. doi:10.1088/1748-9326/8/3/034010

Murdock, T.Q., Sobie, S.R., Zwiers, F.W., Eckstrand, H.D., 2013. Climate Change and Extremes in the Canadian Columbia Basin. Atmosphere-Ocean 51, 456–469. doi:10.1080/07055900.2013.816932

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 779-810. <https://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch19s19-es.html Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, J., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., 2012. Change in climate extremes and their impacts on the natural physical environment, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, UK and New York, NY, USA, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Westra, S., L.V. Alexander, and F.W. Zwiers. 2013. Global Increasing Trends in Annual Maximum Daily Precipitation. *Journal of Climate*, 26, 3904-3918. doi: 10.1175/JCLI-D-12-00502.1