HB

173

<TARGET><BILL>HB 173</BILL><SUBJECT>HB 173</SUBJECT><COMM>HSTA30</COMM></TARGET>

ALASKA STATE LEGISLATURE

REPRESENTATIVE ANDY JOSEPHSON

Sponsor Statement

HB 173 – Climate Change Response Commission

The purpose of HB 173 is to create a commission within the Governor's office to improve the state's response to the impacts of climate change. It is widely agreed that Alaska, and the Arctic generally, is experiencing the effects of climate change at a rate and degree greater than other parts of the world and it may be the most impacted of all of the U.S. states.

The Climate Change Response Commission has several features. First, it will be made up of five state agency commissioners and the community and regional affairs director and nine elected municipal officials from around the state. The involvement of the latter group will help ensure that the needs of all regions of the state are considered.

Second, one of the primary duties of the Commission is to seek out grants, aid, and other forms of financing and to assist rural communities and non-governmental organizations (NGOs) in securing funding. The federal government has spent about $38 billion on climate change, directly and through aid, since 2003. Globally, public and private entities spend about $392 billion per year on climate change financing. Alaska is missing out on these opportunities due to a lack of a dedicated office, an assistance program, or governmental spending on the upfront costs of securing climate change aid.

Beyond grant writing, the Commission will monitor climate change, consult with experts, publish reports, coordinate with the University of Alaska, advance green technology, reach out to non-profits and rural communities, and seek out ways to reduce greenhouse gas emissions in the public and private sectors. It will develop a program to distribute money from a climate change response fund, discussed below, based on these duties.

The Commission will be funded by a mechanism paralleling that of the Spill Prevention and Response Fund: a one cent surcharge on every barrel of oil. The SPAR Fund has received on average about $2 million per year in the past four years from the surcharge and the Commission will be funded with an identical one cent per barrel. Similar to the SPAR Fund, the Climate Change Response Fund will have a limit of $50 million after which the surcharge will not be collected.

I invite you to discuss this bill and urge your support. Please contact my staff, Megan Rowe at 465-4939, with any questions.

State Capitol – Juneau, Alaska 99801 – (907) 465-4939
Rep.Andy.Josephson@akleg.gov – Facebook.com/RepAndyJosephson – Twitter.com/RepAndyJ

Fiscal Note

State of Alaska
2017 Legislative Session

Bill Version: HB 173
Fiscal Note Number:
() Publish Date:

Identifier: HB173-DOR-TAX-04-07-17
Title: CLIMATE CHANGE COMMISSION
Sponsor: JOSEPHSON
Requester: House State Affairs

Department: Department of Revenue
Appropriation: Taxation and Treasury
Allocation: Tax Division
OMB Component Number: 2476

Expenditures/Revenues

Note: Amounts do not include inflation unless otherwise noted below. (Thousands of Dollars)

	FY2018 Appropriation Requested	Included in Governor's FY2018 Request	Out-Year Cost Estimates				
OPERATING EXPENDITURES	**FY 2018**	**FY 2018**	**FY 2019**	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**
Personal Services							
Travel							
Services							
Commodities							
Capital Outlay							
Grants & Benefits							
Miscellaneous							
Total Operating	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Fund Source (Operating Only)

None							
Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Positions

Full-time							
Part-time							
Temporary							

Change in Revenues

1250 UGF Rev (UGF)	1,512.0		1,475.0	1,432.0	1,373.0	1,321.0	1,259.0
Total	**1,512.0**	**0.0**	**1,475.0**	**1,432.0**	**1,373.0**	**1,321.0**	**1,259.0**

Estimated SUPPLEMENTAL (FY2017) cost: 0.0 *(separate supplemental appropriation required)*
(discuss reasons and fund source(s) in analysis section)

Estimated CAPITAL (FY2018) cost: 50.0 *(separate capital appropriation required)*
(discuss reasons and fund source(s) in analysis section)

ASSOCIATED REGULATIONS

Does the bill direct, or will the bill result in, regulation changes adopted by your agency? No
If yes, by what date are the regulations to be adopted, amended or repealed?

Why this fiscal note differs from previous version:

Initial version.

Prepared By:	Dan Stickel, Chief Economist	Phone:	(907)465-3279
Division:	Tax Division	Date:	04/07/2017 04:30 PM
Approved By:	Jerry Burnett, Deputy Commissioner	Date:	04/07/17
Agency:	Department of Revenue		

FISCAL NOTE ANALYSIS

STATE OF ALASKA
2017 LEGISLATIVE SESSION

BILL NO. HB173

Analysis

Bill Overview
This bill would create the Alaska Climate Change Response Commission, which would administer the Climate Change Response Fund, a new subfund of the general fund.

Under this bill, the legislature may appropriate 50 percent of revenue from the conservation surcharge levied under AS 43.55.211 and collected by the Tax Division along with the oil and gas production tax. Currently, 100% of conservation surcharge revenue may be appropriated to the oil and hazardous substance release prevention and response fund; under this bill that fund would receive 50 percent of revenue. This bill increases the amount of the conservation surcharge from $0.01 to $0.02 per taxable barrel of oil produced in the state. Thus, the amount of revenue available for the oil and hazardous substance release prevention and response fund would not change under this bill.

Currently, the conservation surcharge is collected only when the balance of the oil and hazardous substance release prevention and response fund is less than $50 million; this bill increases that threshold balance to $100 million.

Revenues
Based on the fall 2016 revenue and production forecast, an additional $1.3 to $1.5 million annually would be generated by the conservation surcharge increase in this bill. This revenue is shown as General Fund, and may be appropriated each year for the desired purpose by the legislature. The estimated revenue is tied to the oil production forecast and under the fall 2016 forecast, production is expected to decline over time.

Expenditures
The Tax Division would incur one-time costs of approximately $50,000 for contractual costs for reprogramming of the Tax Revenue Management System.

Fiscal Note

State of Alaska
2017 Legislative Session

Bill Version: HB 173
Fiscal Note Number:
() Publish Date:

Identifier: HB173-GOV-CCC-04-10-17
Title: CLIMATE CHANGE COMMISSION
Sponsor: JOSEPHSON
Requester: House State Affairs

Department: Office of the Governor
Appropriation: Commissions/Special Offices
Allocation: Alaska Climate Change Response Commission
OMB Component Number:

Expenditures/Revenues

Note: Amounts do not include inflation unless otherwise noted below. (Thousands of Dollars)

	FY2018 Appropriation Requested	Included in Governor's FY2018 Request	Out-Year Cost Estimates				
OPERATING EXPENDITURES	**FY 2018**	**FY 2018**	**FY 2019**	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**
Personal Services							
Travel							
Services							
Commodities							
Capital Outlay							
Grants & Benefits							
Miscellaneous	1,512.0		1,475.0	1,432.0	1,373.0	1,321.0	1,259.0
Total Operating	**1,512.0**	**0.0**	**1,475.0**	**1,432.0**	**1,373.0**	**1,321.0**	**1,259.0**

Fund Source (Operating Only)

1178 temp code (UGF)	1,512.0		1,475.0	1,432.0	1,373.0	1,321.0	1,259.0
Total	**1,512.0**	**0.0**	**1,475.0**	**1,432.0**	**1,373.0**	**1,321.0**	**1,259.0**

Positions

Full-time							
Part-time							
Temporary							

Change in Revenues

None							
Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Estimated SUPPLEMENTAL (FY2017) cost: 0.0 *(separate supplemental appropriation required)*
(discuss reasons and fund source(s) in analysis section)

Estimated CAPITAL (FY2018) cost: 0.0 *(separate capital appropriation required)*
(discuss reasons and fund source(s) in analysis section)

ASSOCIATED REGULATIONS

Does the bill direct, or will the bill result in, regulation changes adopted by your agency? No
If yes, by what date are the regulations to be adopted, amended or repealed? N/A

Why this fiscal note differs from previous version:

Initial version.

Prepared By: Guy Bell, Director of Administrative Services — Phone: (907)465-3876
Division: Office of the Governor — Date: 04/10/2017 08:00 AM
Approved By: Guy Bell, Director of Administrative Services — Date: 04/10/17
Agency: Office of the Governor

FISCAL NOTE ANALYSIS

STATE OF ALASKA **BILL NO.** HB 173
2017 LEGISLATIVE SESSION

Analysis

This bill would create the Alaska Climate Change Commission in the Office of the Governor.

Under Section 1 of the bill, a $0.01 per barrel of oil surchage is added. Under new Sec. 44.19.666 on page 7 of the bill, a climate change reponse fund would be established in the general fund. The new fund would consist of money appropriated to the fund by the legislature from the new surcharge established in Section 1 . Once appropriated, the money would be administered by the commission for the purposes of the commission without further appropriation and appropriations do not lapse.

The fiscal note assumes the full amount of the anticipated annual appropriation is allocated to the miscellaneous line item with detailed expenditures to be determined at the discretion the commission.

Fiscal Note

State of Alaska
2017 Legislative Session

Bill Version: HB 173
Fiscal Note Number:
() Publish Date:

Identifier: HB173-DEC-SPAR-04-06-17
Title: CLIMATE CHANGE COMMISSION
Sponsor: JOSEPHSON
Requester: House State Affairs

Department: Department of Environmental Conservation
Appropriation: Spill Prevention and Response
Allocation: Spill Prevention and Response
OMB Component Number: 3094

Expenditures/Revenues

Note: Amounts do not include inflation unless otherwise noted below. (Thousands of Dollars)

	FY2018 Appropriation Requested	Included in Governor's FY2018 Request	Out-Year Cost Estimates				
OPERATING EXPENDITURES	**FY 2018**	**FY 2018**	**FY 2019**	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**
Personal Services							
Travel							
Services							
Commodities							
Capital Outlay							
Grants & Benefits							
Miscellaneous							
Total Operating	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Fund Source (Operating Only)

None							
Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Positions

Full-time							
Part-time							
Temporary							

Change in Revenues

None							
Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Estimated SUPPLEMENTAL (FY2017) cost: 0.0 *(separate supplemental appropriation required)*
(discuss reasons and fund source(s) in analysis section)

Estimated CAPITAL (FY2018) cost: 0.0 *(separate capital appropriation required)*
(discuss reasons and fund source(s) in analysis section)

ASSOCIATED REGULATIONS

Does the bill direct, or will the bill result in, regulation changes adopted by your agency? No
If yes, by what date are the regulations to be adopted, amended or repealed?

Why this fiscal note differs from previous version:

Not applicable, initial version.

Prepared By: Kristin Ryan, Director Phone: (907)269-7604
Division: Spill Prevention and Response Date: 04/06/2017 04:00 PM
Approved By: Alice Edwards, Deputy Commissioner Date: 04/07/17
Agency: Department of Environmental Conservation

FISCAL NOTE ANALYSIS

STATE OF ALASKA
2017 LEGISLATIVE SESSION

BILL NO. HB173

Analysis

This bill will establish a Climate Change Response Commission, funded by a one-cent increase to the existing per barrel conservation surcharge (AS 43.55) that funds the Response Account of the Oil and Hazardous Substance Release Prevention and Response Fund. The two-cent surcharge would be split with one cent continuing to go into the Response Account, and one cent going into the Climate Change Fund. This should have no impact to the amount of revenue available to appropriate into the Response Account.

The bill would also increase the cap on the Response Account at which point the one-cent surcharge is turned off, from $50 million to $100 million. This would have no impact on the Department's authority to access the Response Account in the event of a release that poses an immiment and substantial threat to public health or welfare, or to the environment as defined in AS 46.08.040(a)(1).

Climate change damages to Alaska public infrastructure and the economics of proactive adaptation

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved November 9, 2016 (received for review July 7, 2016)

Climate change in the circumpolar region is causing dramatic environmental change that is increasing the vulnerability of infrastructure. We quantified the economic impacts of climate change on Alaska public infrastructure under relatively high and low climate forcing scenarios [representative concentration pathway 8.5 (RCP8.5) and RCP4.5] using an infrastructure model modified to account for unique climate impacts at northern latitudes, including near-surface permafrost thaw. Additionally, we evaluated how proactive adaptation influenced economic impacts on select infrastructure types and developed first-order estimates of potential land losses associated with coastal erosion and lengthening of the coastal ice-free season for 12 communities. Cumulative estimated expenses from climate-related damage to infrastructure without adaptation measures (hereafter damages) from 2015 to 2099 totaled $5.5 billion (2015 dollars, 3% discount) for RCP8.5 and $4.2 billion for RCP4.5, suggesting that reducing greenhouse gas emissions could lessen damages by $1.3 billion this century. The distribution of damages varied across the state, with the largest damages projected for the interior and southcentral Alaska. The largest source of damages was road flooding caused by increased precipitation followed by damages to buildings associated with near-surface permafrost thaw. Smaller damages were observed for airports, railroads, and pipelines. Proactive adaptation reduced total projected cumulative expenditures to $2.9 billion for RCP8.5 and $2.3 billion for RCP4.5. For road flooding, adaptation provided an annual savings of 80–100% across four study eras. For nearly all infrastructure types and time periods evaluated, damages and adaptation costs were larger for RCP8.5 than RCP4.5. Estimated coastal erosion losses were also larger for RCP8.5.

Alaska | climate change | damages | adaptation | infrastructure

Climate change at high latitudes is causing rapid and unprecedented environmental change. The rate of temperature rise across the Arctic has been twice the global average in recent decades (1–3). Sea and land ice has diminished (4, 5), and increased coastal erosion (6, 7), permafrost thaw (8–10), and wildfire activity (11–14) have been observed. Models project that these changes will continue (15–17) and that the corresponding societal impacts will be greater (18) without substantial near-term global reductions in greenhouse gas (GHG) emissions. In the state of Alaska and across the broader circumpolar north, these changes are exacerbating existing challenges and introducing new risks for communities, including increased damage to critical infrastructure (19–21).

Climate change increases the vulnerability of infrastructure by enhancing environmental stressors, thereby creating additional strains on structures beyond what is expected from normal conditions and use. Risks to infrastructure associated with climate change in the Arctic have been studied previously for some environmental stressors. Increased near-surface permafrost thaw associated with climate warming has been widely recognized as a cause of increased infrastructure damage (22–25). This climate-driven thaw can occur concurrent with thaw induced by natural disturbances, such as wildfire (26, 27), and human activities (20, 23, 27, 28), including the construction of infrastructure. Permafrost thaw and subsequent ground subsidence, particularly where permafrost is ice-rich, negatively impact buildings, roads, railroads, pipelines, and oil and gas infrastructure (19, 20, 24, 29). In Alaska, Hong et al. (25) found the greatest near-term risks of thaw settlement in relatively warm permafrost found in the discontinuous permafrost zone in the interior and longer-term risks in the continuous permafrost zone in the northern part of the state (Fig. 1 shows a map of permafrost distribution). Warmer temperatures can also alter the frequency of freeze–thaw cycles (FTCs), impacting foundation and underground infrastructure stability and vulnerability (30, 31). Extensive erosion influenced by sea ice loss, permafrost thaw, and inland flooding (7, 32) threatens numerous coastal and riverine communities in Alaska and affects most infrastructure types (33). As climate change continues, the extent of infrastructure damage as well as the costs

Significance

Climate change in Alaska is causing widespread environmental change that is damaging critical infrastructure. As climate change continues, infrastructure may become more vulnerable to damage, increasing risks to residents and resulting in large economic impacts. We quantified the potential economic damages to Alaska public infrastructure resulting from climate-driven changes in flooding, precipitation, near-surface permafrost thaw, and freeze–thaw cycles using high and low future climate scenarios. Additionally, we estimated coastal erosion losses for villages known to be at risk. Our findings suggest that the largest climate damages will result from flooding of roads followed by substantial near-surface permafrost thaw-related damage to buildings. Proactive adaptation efforts as well as global action to reduce greenhouse gas emissions could considerably reduce these damages.

Author contributions: A.M.M., B.B., and J.M. developed and coordinated the study; P.L. contributed to study development and provided expert guidance; B.B., J.E.N., P.C., X.E., M.S.B., L.R., A.B., D.J.N., and S.S.M. compiled data and performed the technical analyses; and A.M.M. wrote the paper, with input on technical methods from all authors.

The authors declare no conflict of interest.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1611056113/-/DCSupplemental.

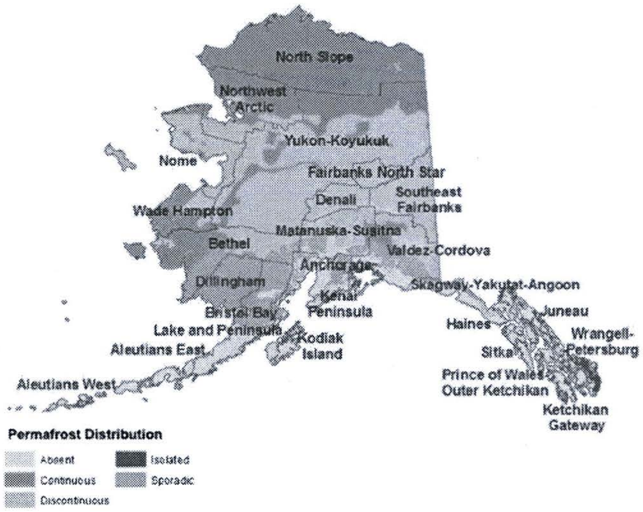

Fig. 1. Alaska's boroughs overlaid on a map of permafrost distribution across the state. The area defined as continuous permafrost has >90% of land underlain by permafrost, discontinuous represents 50–90% areal permafrost extent, sporadic indicates 10–50% areal permafrost extent, and isolated indicates >0–10% areal permafrost extent.

to maintain, replace, and adapt the built environment are expected to increase.

Few studies have moved beyond observation and risk evaluation to quantify the potential economic impacts of climate change on Alaska public infrastructure. Climate change-related increases in costs have been estimated at about $50 million (original values converted to 2015 dollars using the Consumer Price Index) annually (34) for a subset of stressors affecting roads and the electricity sector, whereas Larsen et al. (35) estimated approximately $7.3–14.5 billion (from 2006 to 2080; values converted to 2015 dollars using the Consumer Price Index) above "normal" operations and maintenance resulting from permafrost thaw, flooding, and coastal erosion impacts on a wide range of infrastructure types. In recent years, the analysis by Larsen et al. (35) has served as a guide for considering damage to infrastructure in Alaska and the broader Arctic under different climate futures. Although this study has provided valuable insights, the authors noted that estimates could be improved considerably with a more comprehensive inventory of public infrastructure and the use of nonlinear damage functions that better capture relationships among environmental stressors, infrastructure lifespan, and the associated incremental change in capital and operation and maintenance costs (35, 36).

We addressed the recommendations made by Larsen et al. (35) and developed new estimates of potential economic impacts of climate change to Alaska's public road, building, airport, rail, and pipeline infrastructure. Using high and low climate forcing scenarios [representative concentration pathway 8.5 (RCP8.5) and RCP4.5, respectively, from the Coupled Model Intercomparison Project Phase 5 (CMIP5)] (37) for five general circulation models (GCMs), we evaluated the climate-related change in incurred costs (hereafter damages) required to maintain infrastructure. We estimated the benefits (or avoided damages) to infrastructure of global reductions in GHG emissions and identified where proactive adaptation measures may reduce climate change-related expenses. Climate model projections were incorporated into a reconfigured version of the Infrastructure Planning Support System (IPSS) software tool (38–40) that accounts for climate change impacts unique to northern latitudes, including near-surface permafrost thaw and extreme freeze–thaw dynamics. This model also considers damages from precipitation and precipitation-caused flooding. Independently, we developed an approach to generate first-order estimates of projected coastal erosion rates and evaluated how GHG mitigation may influence erosion in 12 coastal communities where immediate actions to manage erosion or relocate have been recommended (33). This study is one component of a broader multisector modeling framework developed for the Environmental Protection Agency Climate Change Impacts and Risk Analysis Project (41, 42), which seeks to quantify the avoided or reduced impacts of climate change resulting from GHG mitigation and adaptation.

Results

Damages. The analysis presented here was designed to isolate the incremental change in damages and expenditures resulting from climate change. Costs incurred as a result of operation and maintenance or infrastructure replacement required irrespective of climate change are not included in the damage values. For precipitation, flooding, and freeze–thaw stressors, damages represent the expenditures required to maintain current levels of service, enabling the infrastructure to remain functional through the intended design lifespan. In the case of near-surface permafrost thaw, where repair approaches are limited, damages represent the cost of infrastructure replacement. Damage estimates reflect expenditures incurred when no adaptation measures are taken. Adaptation costs are quantified separately and explained in *Adaptation*. Reported damages (and adaptation costs) reflect the difference between projected values and a historic baseline period (1986–2005) (detailed in *Methods* and *SI Text*) to isolate climate change impacts from weather variability not attributed to climate change. When the IPSS determines that infrastructure is in need of replacement, the model tabulates expenditures based on historical building standards and construction costs. Therefore, the damage estimates do not estimate the effect that more climate-resilient construction could provide or additional design and engineering costs associated with such efforts. Although this estimation approach may not seem intuitive, in practice, it is generally the construction approach taken, because design and construction practices follow established codes and guidelines. The specific types of damages modeled in the IPSS are summarized in Table 1 and detailed in *Methods*.

We used two approaches to present damages (and adaptation costs) in this study: cumulative estimates for the 2015–2099 time period reported in 2015 dollars and discounted at 3% and annual undiscounted estimates that represent expenditures across four 20-y eras. The discounted cumulative values reflect the net value in the present day, thereby providing an equal basis to sum and compare the values for different time periods. A 3% discount rate is commonly used in climate impacts literature and consistent with the central rate used in the US Government's Social Cost of Carbon estimates (43). For reference, we have provided cumulative undiscounted values in Table S1 but do not discuss them here. We present undiscounted mean annual damages and adaptation costs across study eras to illustrate the trajectory of impacts between the two RCPs over time, which can be masked when discounting is applied (i.e., late century differences between RCPs can be minimized after discounting).

Statewide Damages to Infrastructure. Total cumulative (discounted) damages to infrastructure (without adaptation) resulting from projected climate change this century were estimated to be approximately $5.5 billion for RCP8.5 and $4.2 billion for RCP4.5 (Table 2). For both RCPs, flooding associated with changes in precipitation accounted for about 45% of damages, and near-surface permafrost thaw was responsible for 38% (although high variability was observed among GCMs) (Table 2 shows minimum and maximum values). Changes in precipitation accounted for about 17% of cumulative damages. The largest total damages were observed for roads ($3.1 and $2.4 billion for

Table 1. Causes of damage and proactive adaptation approaches modeled in the IPSS for each infrastructure type–climate stressor evaluated in this analysis

Infrastructure type and environmental stressor	Damage sources	Adaptation approaches
Roads and runways		
Flooding	Culvert and road washout	Increased diameter culverts and drainage systems
Permafrost thaw	Cracking, subsidence	Base-layer modification, thermosyphon installation
Precipitation	Erosion, base-layer damage	Modified binder/sealant application, base-layer strengthening
Freeze–thaw	Base-layer damage, cracking, rutting	Not evaluated
Buildings		
Precipitation	Pooled water on roof	Increased diameter roof drainage systems
Permafrost thaw	Cracking, subsidence	Not evaluated
Railroads		
Permafrost thaw	Cracking, subsidence	Base-layer modification, thermosyphon installation
Pipelines		
Permafrost thaw	Cracking, subsidence	Not evaluated

RCP8.5 and RCP4.5, respectively) and buildings ($1.7 and $1.4 billion, respectively); however, the environmental stressors responsible for the damages differed, with ~75% of road damages caused by flooding and 90% of building damages caused by near-surface permafrost thaw under both RCPs. Airports, railroads, and pipelines made up a smaller fraction of the overall public infrastructure inventory, which contributed to considerably lower projected damages, collectively accounting for just over 10% of total damages (Table 2).

Total damages for RCP8.5 were $1.3 billion more than those observed for RCP4.5 (Table 2), suggesting that global reductions in GHG emissions provide monetary benefits for Alaska public infrastructure. This pattern was observed across nearly all infrastructure types and environmental stressors considered in this analysis. The one exception was the negative values observed for freeze–thaw damages, which indicate that warming associated with unmitigated climate change may reduce future damages from this environmental stressor, especially to roads, to levels below those reported historically. However, this benefit provided little offset against total projected damages caused by other stressors.

Mean annual projected damages (undiscounted; summed for all evaluated environmental stressors) varied by infrastructure type and RCP across study eras (Fig. 2). Roads exhibited increased annual damages over time that were consistently higher for RCP8.5, with the largest differences observed in the 2090 era ($212 million y^{-1} vs. $109 million y^{-1} for RCP8.5 and RCP4.5, respectively) (Fig. 2*A*). This pattern was driven primarily by increased flood-related damages, which totaled about $58 million y^{-1} in the 2030 era and reached $165 million y^{-1} in 2090 for RCP8.5. In contrast, annual building damages were projected to be largest in the 2030 era ($84 million for RCP8.5) (Fig. 2*B*) and decrease over time, with smaller relative differences between RCPs than observed for roads. For buildings, annual changes over time were driven primarily by near-surface permafrost thaw. Some of the GCMs projected complete loss of near-surface permafrost from much of interior Alaska by the end of the century (Fig. S1), suggesting that no additional damages from this environmental stressor would occur in some areas and therefore, total statewide damages in later eras would decrease. It is possible that deeper, ice-rich permafrost could cause subsidence at the local scale and result in future damages, even if near-surface permafrost is lost; however, these impacts were not evaluated in this analysis. Additionally, our model included the assumption that, if a building was damaged to the point that replacement was required, the new building would (when possible) not be built on permafrost or that additional measures would be taken to reduce the likelihood of future damages from this stressor. For airports, the 2090 era incurred the largest annual damages for RCP8.5 ($22 million y^{-1}) and the smallest damages for RCP4.5 (11 million y^{-1}) (Fig. 2*C*). Airport runway damages from flooding and precipitation as well as near-surface permafrost thaw impacts on airport buildings contributed to the observed pattern in damages across eras for this infrastructure type. For railroads and pipelines, near-surface permafrost thaw was the only environmental stressor modeled. Both these infrastructure types showed the largest damages in the 2070 era for RCP8.5 (Fig. 2 *D* and *E*), which is likely because of a large change in near-surface permafrost during this timeframe. However, railroads tended toward larger damages in earlier eras, whereas pipeline damages increased over time, especially for RCP8.5. Damage estimates for these infrastructure types were highly variable, resulting from the range of projected near-surface permafrost thaw among GCMs.

Distribution of Damages Across Alaska. The distribution of cumulative (discounted) damages this century varied across the state, with the largest damages projected for RCP8.5 in interior and southcentral boroughs, including Fairbanks North Star, Valdez-Cordova, and Yukon-Koyukuk (Figs. 1, borough locations and 3*A*). The smallest projected damages were observed in the southwest boroughs of Bristol Bay, Lake and Peninsula, and Kodiak Island. In the Aleutians East borough, no discernable damages were observed, which was likely driven by less relative climate change in this portion of the state and a small infrastructure inventory. Cumulative damages were smaller for RCP4.5 than RCP8.5 for every borough (Fig. 3 *A* and *B*), indicating that global reductions in GHG emissions could provide benefits across the state. The largest benefits were observed for Fairbanks North Star and Yukon-Koyukuk boroughs, where cumulative damages were estimated to be approximately $286 and $191 million less, respectively, for RCP4.5. Cumulative per capita damages were larger for RCP8.5 than RCP4.5 for all boroughs (Fig. 3 *C* and *D*). The largest reductions in per capita damages between RCPs were observed for Yukon-Koyukuk, Southeast Fairbanks, and Denali boroughs.

Adaptation. The costs of proactive adaptation were quantified for infrastructure type–climate stressor combinations where effective adaptation methods exist and costs are quantifiable (listed in Table 1). As such, these adaptation costs were modeled for a subset of the infrastructure type–climate stressor combinations reported for damages. These adaptation costs include upfront investment and modification of infrastructure before the occurrence of climate-related damages. For precipitation and flooding, adaptation measures are only applied in the IPSS when infrastructure is determined to be vulnerable to climate change

Table 2. Cumulative climate change damages (without adaptation) and total costs when proactive adaptation measures are included for 2015–2099 presented by infrastructure type and environmental stressor (in 2015 millions of dollar, 3% discount)

RCP	Flooding	Permafrost thaw	Precipitation	Freeze–thaw	Total
Damages (without adaptation)					
Roads					
8.5	2,300 (1,700, 3,100)	180 (9, 380)	640 (480, 820)	−20 (−27, −9)	3,100 (2,200, 4,300)
4.5	1,800 (1,500, 2,200)	65 (−18, 280)	520 (450, 630)	−16 (−20, −11)	2,400 (1,900, 3,100)
Buildings					
8.5	Not included	1,500 (1,200, 1,900)	120 (110, 140)	Not included	1,700 (1,300, 2,100)
4.5		1,300 (910, 1,900)	120 (110, 120)		1,400 (1,000, 2,000)
Airports*,†					
8.5	180 (130, 250)	170 (110, 240)	120 (99, 180)	−5 (−6, −3)	470 (330, 670)
4.5	150 (120, 200)	120 (60, 220)	100 (84, 150)	−4 (−5, −3)	370 (250, 570)
Railroads					
8.5	Not included	200 (44, 340)	No impact	No impact	200 (44, 340)
4.5		97 (−7, 320)			97 (−7, 320)
Pipelines					
8.5	Not included	33 (−4, 83)	Not included	Not included	33 (−4, 83)
4.5		4 (−5, 33)			4 (−5, 33)
Total					
8.5	2,500 (1,800, 3,300)	2,100 (1,300, 3,000)	890 (690, 1,100)	−25 (−33, −12)	5,500 (3,800, 7,400)
4.5	1,900 (1,600, 2,400)	1,600 (950, 2,700)	750 (650, 900)	−20 (−24, −14)	4,200 (3,200, 6,000)
Costs when proactive adaptation is modeled					
Roads					
8.5	340 (310, 430)	Damages only‡	370 (320, 470)	Damages only	870 (610, 1,300)
4.5	320 (240, 400)		330 (260, 380)		700 (460, 1,000)
Buildings					
8.5	Not included	Damages only	7 (5, 12)	Not included	1,500 (1,200, 2,000)
4.5			6 (5, 8)		1,300 (920, 1,900)
Airports*					
8.5	46 (41, 58)	Damages only‡	87 (71, 120)	Damages only	300 (210, 420)
4.5	46 (36, 58)		73 (53, 100)		240 (140, 380)
Railroads					
8.5	Not included	Damages only‡	No impact	No impact	200 (44, 340)
4.5					97 (−7, 320)
Pipelines					
8.5	Not included	Damages only	Not included	Not included	33 (−4, 83)
4.5					4 (−5, 33)
Total					
8.5	380 (350, 490)	2,100 (1,300, 3,000)	470 (400, 600)	−25 (−33, −12)	2,900 (2,100, 4,100)
4.5	370 (280, 450)	1,600 (950, 2,700)	410 (320, 490)	−20 (−24, −14)	2,300 (1,500, 3,700)

Adaptation includes the sum of the costs for adapting those infrastructure units where damages are projected to occur plus any damages incurred to infrastructure units where adaptation was not applied. For infrastructure type–climate stressor combinations where adaptation was not modeled, the damage estimates were used in the calculations for costs when proactive adaptation is modeled. Reported values are mean (minimum, maximum) for five GCMs. Summed means may not equal the total because of rounding. Not included indicates where impacts are unexpected or minimal or inclusion in the IPSS would require extensive model revision that was outside the scope of this analysis. No impact indicates instances where the environmental stressor is not expected to affect the given infrastructure type.

*Airports values include the sum of expenditures for airport buildings and runways.

†Damage values for airports include runway flooding, permafrost thaw, precipitation, and freeze–thaw stressors as well as permafrost thaw and precipitation damages to airport buildings.

‡Near-surface permafrost thaw adaptation costs were quantified for these infrastructure types; however, adaptation was found to be more expensive than incurred damages, and therefore, damages were used when calculating total costs.

based on the design change threshold. No adaptation measures for permafrost thaw were identified that were less expensive than complete infrastructure replacement. Therefore, we only report estimated damages from this stressor here. When adaptation measures are applied in the IPSS, the costs associated with that adaptation are quantified. After a unit of infrastructure is adapted, it is assumed that the future vulnerability of that infrastructure to future climate damages is inconsequential and that no climate-related damages are incurred from the time of adaptation through the remainder of the intended design lifespan. For the cumulative costs presented in this analysis, we sum the adaptation costs with the incurred damages to units of infrastructure where adaptation measures are not taken (and damages from near-surface permafrost thaw, because adaptation was found to be more expensive) to provide total estimated expenditures this century when adaptation is applied.

Benefits of Adaptation. Cumulative projected incurred costs (discounted) when proactive adaptation is modeled totaled $2.9 billion for RCP8.5 and $2.3 billion for RCP4.5 (costs when proactive adaptation is modeled) (Table 2). These values suggest a reduction in expenditures of $2.6 billion for RCP8.5 and $1.9 billion for RCP4.5 compared with damages without adaptation. Adaptation to flooding (modeled for roads and runways) and

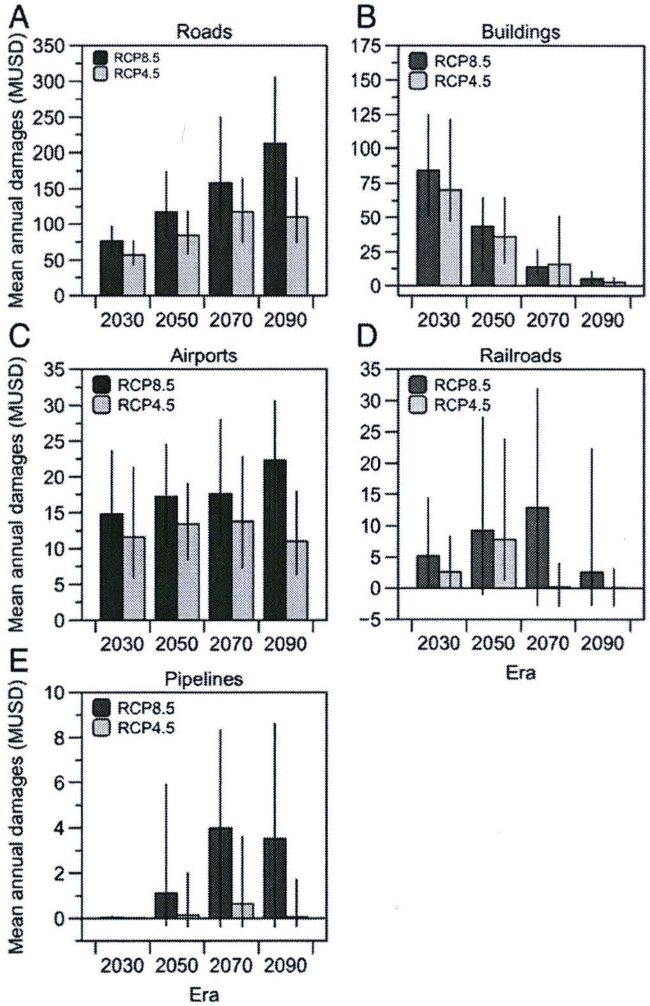

Fig. 2. Annual damages [undiscounted and without adaptation in million US dollars (MUSD)] to each infrastructure type [(*A*) roads, (*B*) buildings, (*C*) airports, (*D*) railroads, and (*E*) pipelines] for four study eras. Values are the mean ± minimum, maximum for five GCMs and represent the mean annual damages (sum of all evaluated environmental stressors for each infrastructure type) for the 20 y included in each era. Note the difference in scales among panels.

precipitation (modeled for roads, runways, buildings, and airport buildings) reduced the expected cumulative (discounted) costs of climate change this century for both RCPs; however, adaptation benefits were consistently larger for RCP8.5 (Table 2). The benefits of adaptation were largest for road flooding under RCP8.5, where adaptation reduced the total economic impact from the projected \$2.3 billion in cumulative damages to \$340 million in adaptation costs. Adaptation to precipitation nearly halved the total expenses to roads and provided a large reduction in building expenses, although the damages to buildings were relatively small. In contrast, there are limited cost-effective options for adapting infrastructure to near-surface permafrost thaw. Our analysis considered permafrost thaw-related adaptation costs for roads, runways, and railroads and determined that adapting was more expensive then the cumulative projected damage estimates.

Across study eras, mean annual (undiscounted) costs to adapt roads and runways to flooding and buildings and airport buildings to precipitation were highest in the 2030 era and generally declined over time for both RCPs. This cost estimate assumes that well-designed adaptation measures were taken early in the century and continued to provide economic benefits into later eras. Declines in adaptation costs were concurrent with increased projected damages from these stressors (Fig. 4), resulting in an increased relative benefit of adaptation over time (expressed as percentage savings in Fig. 4). For roads and runways, the benefits of adaptation (and the projected damages where adaptation was not considered) were consistently larger for flooding than precipitation (Fig. 4 *A* and *C*). For both buildings and airport buildings, total annual damages from precipitation were much smaller than for roads and runways (note the difference in scales in Fig. 4 *B* and *D*); however, the benefits of adaptation were large, with a percentage savings in expenditures (i.e., difference between damages and adaptation costs) ranging from 95 to 105% for all study eras (where values exceeding 100% indicate adaptation costs lower than historical maintenance costs).

Change in Coastal Erosion Rates for Select Communities. The coastal ice-free season was projected to lengthen by about 11, 17, and 15 d decade^{-1} in the south (56°N to 60°N), central (60°N to 65°N), and north (>65°N) regions, respectively, for RCP8.5 and 8, 13, and 10 d decade^{-1} in the south, central, and north regions, respectively, for RCP4.5. This finding represents an ~80–90% increase in coastal ice-free days by 2095 for the central and north regions under RCP8.5 and just over a 60% increase for RCP4.5 (Table S2). In the south, 39% and 31% increases were projected for RCP8.5 and RCP4.5, respectively. The difference in length of the ice-free season between RCPs increased with time for all regions (Fig. 5*A*), with the largest difference between scenarios being 36 d observed for the north region in 2095 (Fig. 5*A* and Table S2). Projected cumulative land losses from erosion in 2095 varied across communities (Fig. 5 *B*–*D* and Table S3) and were strongly influenced by the current erosion rates used in calculating future change. The largest losses were projected for Newtok (Fig. 5*C*). Land losses were consistently higher for RCP8.5 than RCP4.5, and projections generally suggested that communities located in the central and south regions could experience larger erosion-driven land losses resulting from a longer

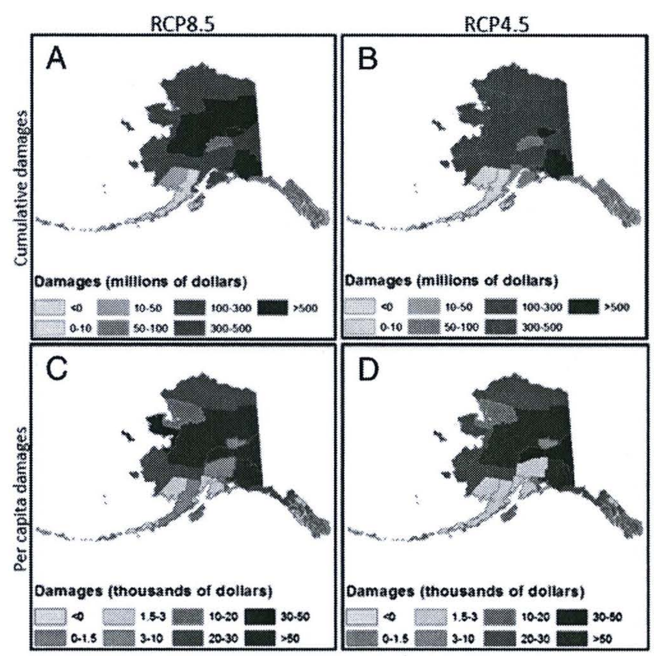

Fig. 3. (*A* and *B*) Cumulative damages (2015–2099; 3% discount) to infrastructure and (*C* and *D*) per capita damage estimates for each borough across Alaska for (*A* and *C*) RCP8.5 and (*B* and *D*) RCP4.5. Values for each borough represent the mean of five GCMs included in this analysis.

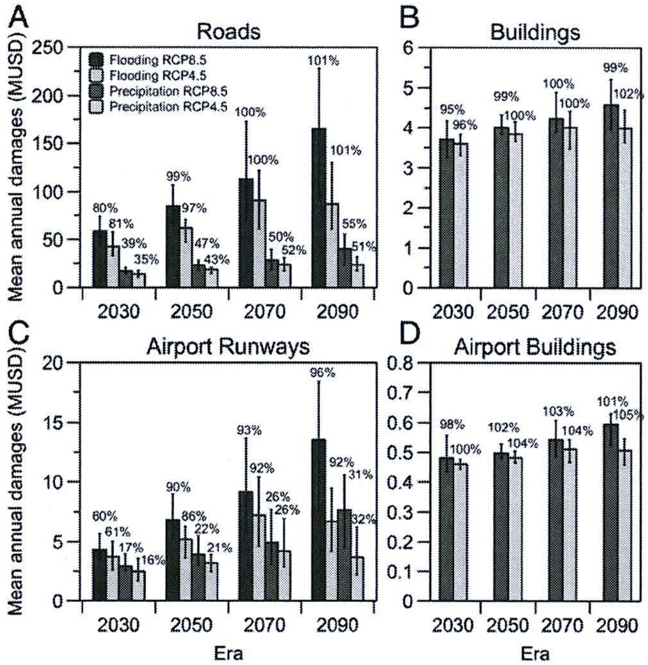

Fig. 4. Bars illustrate the annual damages [undiscounted, in million US dollars (MUSD)] to (*A*) roads, (*B*) buildings, (*C*) airport runways, and (*D*) airport buildings specifically from flooding (blue) and precipitation (purple) for the two RCPs. Percentages represent the percentage savings in total expenditures for the given stressor and RCP resulting from proactive adaptation compared with mean estimated damages (where damages assume no adaptation). Adaptation costs were lower than estimated climate damages for all environmental stressors and infrastructure types shown here. Percentages greater than 100 indicate instances where estimated adaptation costs fell below the historical baseline maintenance costs. Values represent the mean (± minimum, maximum) for five GCMs. Note the difference in scales among panels.

ice-free season than those in the north. For example, for sites in the south, erosion rates were ~22% higher for RCP8.5 compared with current baseline erosion rates and about 18% higher for RCP4.5. Comparable values in the central region were about 44% and 34%, respectively, and for the north region sites, erosion rates were 51% and 35%, respectively, higher than current rates.

Discussion

Damages to Alaska public infrastructure from climate change are projected to be large and widespread. Many previous studies have recognized the risks of permafrost thaw (20, 24, 25), and our findings indicate extensive damages from this stressor. However, the largest estimated damages in this analysis resulted from flooding caused by increased precipitation. This finding suggests that climate damages to infrastructure will extend well beyond areas underlain by permafrost and that greater attention to future flooding risks is warranted. Although damages are projected to be large, the total financial impacts of climate change could be reduced considerably by proactive investment in adaptation. The largest monetary benefits of adaptation could be achieved by modifying road drainage systems to reduce flooding impacts. Additional benefits could result from changes to road and runway surfaces and base-layer modifications and by improving building roof drainage systems and installing materials that better withstand projected precipitation increases (Fig. S2*B*). For flooding and precipitation damages to roads, runways, and buildings, our model initiated adaptation measures at the time point when projected damages began, which typically occurred early in the century. Generally, this initiation of adaptation resulted in larger annual adaptation costs (and smaller relative adaptation benefits compared with damages) during the 2030 era. These early actions are projected to reduce the vulnerability of infrastructure in subsequent time periods, resulting in late century eras having proactive adaptation costs comparable with and sometimes even lower than historic maintenance costs.

Total economic impacts of climate change on Alaska public infrastructure could also be lessened through global action that reduces GHG emissions to meet RCP4.5. The $1.3 billion difference in cumulative damages between RCP8.5 and RCP4.5 reflects greater infrastructure damages associated with a larger projected increase in temperature, precipitation, and near-surface permafrost thaw under the RCP8.5 scenario (Figs. S1 and S2). With the exception of buildings in the 2070 era, which may experience delayed damages from near-surface permafrost thaw because of the lower temperature increase under RCP4.5, mean annual projected damages to all infrastructure types were lower under RCP4.5. These findings are consistent with other studies that have found reduced economic impacts under lower GHG emissions scenarios (35, 44).

Our reported cumulative damages ($5.5 and $4.2 billion for RCP8.5 and RCP4.5, respectively) are similar in magnitude to those in the work by Larsen et al. (35), which estimated $7.3–14.5 billion (converted to 2015 dollars using the Consumer Price Index) in damages to 2080 without adaptation using different methodologies and climate scenarios. Larsen et al. (35) also included reactive, "event-based" adaptation, where adaptive actions were taken when damages reduced the lifespan of structures. Using this approach, they projected a 10–45% reduction in economic impacts from 2006 to 2080 under a moderate GHG emissions scenario. Our analysis suggests a much larger benefit of adaptation, indicating a 45–47% reduction in expenditures compared with damages when no adaptation measures are taken. We attribute this difference to our proactive adaptation method, where action is taken before deterioration of structures, to maintain the full lifespan. This approach can result in upfront investments that are lower than replacement costs and reduced future vulnerability, which led to the observed increase in benefits over

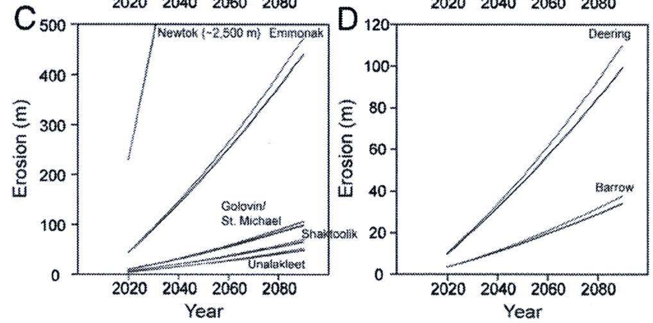

Fig. 5. (*A*) Length of coastal ice-free season and estimates of cumulative coastal land loss from erosion this century for select coastal communities in the (*B*) south (56°N to 60°N), (*C*) central (60°N to 65°N), and (*D*) north (>65°N) regions designated for this analysis.

time for many of the infrastructure type–climate stressor relationships that we modeled.

Estimated annual damages to infrastructure stemming from the added environmental stresses (above normal "wear and tear") caused by climate change could have large financial implications if our projections translate to realized damages and adaptation costs. For the 2030 era, mean annual damages were approximately \$181 and \$142 million for RCP8.5 and RCP4.5, respectively (sum of all infrastructure types is in Fig. 1) and are projected to increase over time. These values represent 14–18% of the fiscal year 2017 capital budget request for the Alaska Department of Transportation and Public Facilities (45). In this budget, \$8 million was requested specifically for "Deferred Maintenance, Renewal, Repair and Equipment," which is a decrease from recent years, where enacted appropriations totaled \$25–27 million to address this need (https://www.omb.alaska.gov/html/budget-report/fy-2016-budget.html). Collectively, this information suggests that climate-related damages could place an additional strain on state finances. We are aware of only one other study that has estimated annual climate change damages for Alaska's public infrastructure. Relying on a limited number of examples, Cole et al. (34) suggested that climate damages could reach about \$50 million y^{-1} (converted to 2015 dollars using the Consumer Price Index) in the near term. The large difference between these findings and our results is likely driven by our more comprehensive inventory, which includes more than just state-owned public infrastructure, and thorough evaluation of dominant climate stressors, especially inclusion of projected flooding damages.

Multiple factors contributed to our estimated extent, timing, and distribution of damages. For each infrastructure type, the quantity of infrastructure included in our inventory, the unique engineering-based stressor–response functions developed for that infrastructure, and the price of maintenance and repair of that type of structure affected projected damages. The timing of damages was impacted by the rate of change of each environmental stressor and the sensitivity of each type of infrastructure to the change. Distribution of damages across the state and individual boroughs was affected by the quantity and location of infrastructure and the impact of the environmental stressors at any given location. For instance, the southcentral borough of Valdez-Cordova includes among the highest total road area in our inventory and is in a region projected to have a relatively large increase in precipitation for many of the GCMs (Fig. S2*B*), which strongly influenced the projected cumulative flooding damages for that borough.

We did not estimate climate damages associated with coastal erosion in the IPSS analysis; however, our infrastructure inventory included assets in coastal communities, and therefore, damages from modeled environmental stressors are reflected in the reported damages and adaptation costs. We excluded coastal erosion from the economic analysis because our approach represents a first-order approximation of rates that relied heavily on the assumption that the projected lengthening of the coastal ice-free season is proportional to changes in coastal erosion. Although this relationship has been noted (46), we determined that improved understanding of this linkage is needed to appropriately project climate-related erosion damages. Also, many of the coastal communities experiencing erosion problems are affected by both river and ocean processes (33), making climate and source attribution more challenging. Despite these limitations, the underlying literature indicates a strong likelihood of a lengthening of the coastal ice-free season throughout this century, and our projections show that, for many communities, global GHG emissions reduction could reduce erosion, thereby lessening impacts.

This study describes an improved approach to quantifying climate damages to public infrastructure, but these estimates could be further strengthened. Additional modeling capabilities that build on the stressor–response relationships developed here along with creation of new functions that capture damages to ports, telecommunications, and other infrastructure types would provide a more comprehensive evaluation of potential vulnerabilities and associated damages. Improved knowledge of the influence of a lengthening coastal ice-free season on coastal infrastructure would further refine our ability to estimate potential damages from climate change. Continued updates and expansion of our infrastructure inventory, which includes counts and more detailed location information of infrastructure, would also better inform damage estimates and adaptation costs. Additionally, analysis at a finer resolution would allow for community-level evaluation and reduce assumptions about infrastructure distribution, which could be especially important for accurately projecting damages from near-surface permafrost thaw. Projections of deep, ice-rich permafrost thaw could also improve estimates of damages from this stressor. Quantification of loss of use impacts would also inform potential damages and could be particularly meaningful in Alaska, where there is a lack of infrastructure redundancy across much of the state. Within the climate modeling framework, inclusion of additional GCMs, climate scenarios, and climate sensitivities could provide a more robust evaluation of the range and variability of projected damages and adaptation costs. Finally, new economic opportunities will be made possible by climate change, including longer ice-free seasons for ports. Future research combining our analytical approach with projections of future socioeconomics, demand, technology, and new infrastructure siting could provide a more comprehensive estimate of future impacts.

This study provides new estimates of the potential damages from climate change to Alaska public infrastructure and suggests that taking proactive action to adapt infrastructure in the near term could dramatically reduce damages across the state throughout this century. Variation and general trends in the timing of damages and relative adaptation benefits to different infrastructure types may help to inform decisions about prioritizing investments. Together with global reductions in GHG emissions, these efforts may reduce damages to infrastructure and the impacts of climate change on Alaskan communities.

Methods

Estimated damages to public infrastructure from climate change and costs when adaptation measures are used were evaluated using downscaled climate model projections and the IPSS software tool (38, 39). The IPSS model was modified to include unique impacts of climate change at high latitudes. Damages and adaptation costs were estimated for four 20-y eras, with the mean annual era value presented with the central year: 2030 (2020–2039), 2050 (2040–2059), 2070 (2060–2079), and 2090 (2080–2099). The analysis relied on a public infrastructure inventory compiled for this study. We also developed first-order estimates of projected coastal erosion rates for 12 vulnerable coastal communities and evaluated how global GHG mitigation influenced these rates.

Climate and Near-Surface Permafrost Thaw Projections. We used downscaled climate data developed by the Scenarios Network for Alaska + Arctic Planning at the University of Alaska, Fairbanks (47). This dataset included climate projections for RCP8.5 and RCP4.5 for five GCMs from the CMIP5 archive that have the most skill for Alaska and the Arctic (48) (https://www.snap.uaf.edu/methods/models). Change in active-layer thickness (ALT), which indicates near-surface permafrost thaw, was projected for each study era, GCM, and RCP using reduced form equations developed for this study (detailed in *SI Text*) and based on the Geophysical Institute Permafrost Lab model (49, 50). Projected minimum and maximum annual temperatures, precipitation, change in mean annual ground temperature (MAGT), ground ice content (GIC), and ALT as well as baseline permafrost and GIC maps (51) were input to the IPSS model to determine impacts on infrastructure (details of climate model selection, spatial and temporal downscaling, and projections are in *SI Text*).

Inventory Compilation. Counts and units of measure for publicly owned roads, airports, buildings, railroads, and pipelines were compiled from numerous sources, including State of Alaska and national geospatial datasets (all sources are listed in *SI Text*). Much of the inventory database contained exact locations of infrastructure. When exact locations were not provided, assumptions regarding locations within villages and boroughs were made (*SI Text*). This analysis assumes no change in inventory size during the study period, which could lead to an underestimate of potential damages if additional infrastructure is added this century in response to population growth or other factors.

IPSS. The IPSS tool incorporates engineering knowledge, stressor–response algorithms, and climate projections to quantify potential vulnerabilities resulting from climate change for numerous infrastructure types.

Modeling damages. The IPSS has been previously configured to estimate damages (and adaptation costs) caused by precipitation and precipitation-caused flooding, and we used the same approach in this analysis (described below). Stressor–response relationships are specific to each environmental stressor and infrastructure combination. Damages are quantified using engineering- and material science-based relationships between each environmental stressor and the extent of damages associated with the projected amount of change in the stressor after an empirically determined threshold is crossed. For precipitation, flooding, and freeze–thaw stressors, damages reflect the expenditures required to maintain current levels of service and allow infrastructure to remain functional through the intended design lifespan. In the case of permafrost, where repair approaches are limited, damages represent only the expenditures required for infrastructure replacement. Damages are calculated by first determining the extent of damage caused by each environmental stressor and then applying a monetary value of those damages based on known construction and maintenance costs. These calculations are unique to each stressor–response relationship and detailed in the following sections. Modeled damages represent only those costs attributed to the incremental change in expenditures caused by the projected climate change. Estimates presented here do not include operation and maintenance costs from normal wear and tear, damages caused by factors other than the evaluated climate variables, or replacement costs of structures resulting from infrastructure reaching the end of its design lifespan.

Modeling adaptation costs. The IPSS models proactive adaptation for infrastructure type–climate stressor combinations where effective adaptation methods exist and costs are quantifiable. Adaptation is applied in the form of upgrades to units of infrastructure when structures are determined to be vulnerable to a climate change stressor. In some cases, adaptation is determined to be cost-effective (i.e., adaptation costs < estimated damages), but in other instances, adaptation costs may be more than estimated damages. For instance, for permafrost thaw, no adaptation measures were identified that were less expensive than infrastructure reconstruction. Generally, the extent of adaptation required for a given unit of infrastructure is determined by the projected change in each individual stressor through the design lifespan of the infrastructure. After a unit of infrastructure is adapted, it is assumed that future vulnerability to climate damages is minimal and no additional climate-related costs or damages are incurred in the model through the end of the intended design lifespan.

Historical baseline. We calculated the difference between our estimated damages (and adaptation costs) and damages that would have been incurred in a historical baseline period (1986–2005). Information in the historical baseline represents weather impacts captured historically that we do not attribute to climate change. By reporting the difference between these values, the effects of climate change are isolated from historical baseline maintenance costs. Detailed methods for generating the historical baseline are outlined in *SI Text*.

IPSS Considerations for Northern Latitudes. Assessing potential infrastructure damages at high latitudes requires specific considerations and model modifications for extreme low temperatures. This study incorporated these cold weather conditions in three specific stressor categories: pavement temperature, FTCs, and near-surface permafrost thaw. Weather conditions in Alaska can lead to costs that are two to three times the typical construction, operations, and maintenance costs found in the contiguous United States across infrastructure types (RSMeans 2015; https://rsmeansonline.com/), and consideration of these higher costs was incorporated into the damage estimates. However, design standards modeled here are assumed to be comparable with those used in the contiguous United States.

Pavement temperature impacts on roads. An important factor in determining whether pavement damage will occur with climate change is the ability of the pavement to withstand changes in temperature. Pavements are designed for specific minimum and maximum temperature limits, and environmental changes beyond these limits have the potential to damage pavement surfaces. For this study, when climate projections indicated a potential threshold change from the baseline climate temperature range, it was assumed that pavement was more likely to be damaged, and a cost was applied at the time that the threshold was crossed to account for pavement binder reconstruction expenditures. Specific road surface temperature and binder thresholds were determined from changes in minimum (1 d) and maximum (7-d average) temperatures using equations and research reported in the work by Mills et al. (52). These temperature functions were also used to analyze climate change impacts on asphalt runways for airports.

FTCs. FTCs affect the long-term durability of paved roads and asphalt runways because of the impact that repeated freezing and thawing have on the stability of the base supporting the pavement surface. We used two methods to calculate FTC impacts on road and runway maintenance costs and damages. We determined whether changes in precipitation and temperature placed the infrastructure within a given climate grid cell in a new pavement performance zone. These zones were characterized by the Freezing Degree Index and mean annual precipitation, which were combined to place the grid cells in wet or dry zones and high or low FTC environmental zones (31) (detailed in *SI Text*). When projected climate change indicated that a geographic area crossed into a new zone, specific increases were applied to the maintenance costs for the affected road and runway segments. We used a second method when climate change did not cause a threshold crossing into a different zone, but increased FTC could still result in damages. For this approach, we quantified climatic changes based on the percentage increase in frequency of FTC for a rolling 5-y period relative to the historic baseline. Costs were estimated based on corresponding increases in routine maintenance to repair freeze–thaw-related road and runway damages (31, 53).

Near-surface permafrost thaw. Near-surface permafrost thaw affects all types of infrastructure but in different ways depending on whether the infrastructure is located above or below the ground and the potential for underlying permafrost to thaw if permafrost is present (20, 54). Permafrost thaw impacts the soil bearing underneath structures and may weaken foundations, creating risks directly related to the capacity of the soil to bear the weight of the support structures for the infrastructure. The broad foundations of buildings may be affected differently than linear elements, like rail and pipelines, which have specific support points that hold the infrastructure in place. If near-surface permafrost thaws and GIC is reduced, soil will subside, and infrastructure failure will occur when the subsidence amount exceeds the allowance of the construction materials to bend to the stresses (55).

We assessed changing vulnerability from near-surface permafrost thaw for roads, buildings, rail, and pipelines. First, we overlaid the infrastructure inventory with current and projected ALT and GIC maps. For buildings, we developed a risk assessment that assigns potential risk because of near-surface permafrost thaw based on a spatially centered value in each climate grid cell. Second, we implemented a threshold approach based on permafrost distribution, GIC, and projected change in MAGT to determine when critical foundation damage was likely to occur (detailed in *SI Text* and Tables S4 and S5) that would require rebuilding or retrofit of the entire building. For roads, railroads, and pipelines, we determined where thaw settlement was likely to cause asset failure and the lengths of pipe and rail where replacement would be required, thereby incurring costs (56). Costs were applied based on total estimated cost of replacement using specific inventory data and RSMeans cost estimates (2016; https://rsmeansonline.com/), with customized adjustments made for the Arctic conditions based on available data. When near-surface permafrost was lost for a given location, no additional damages to infrastructure were incurred from this environmental stressor. Methods for adapting infrastructure to near-surface permafrost thaw are limited and costly. Approaches modeled in the IPSS after the damage threshold was crossed included modifying the base of the infrastructure and installing thermosyphons to maintain lower soil temperatures.

Previously Developed Stressor–Response Relationships Applied in this Study. Precipitation and flooding damages and adaptation costs have been modeled previously in the IPSS (38, 57, 58) and were not modified specifically for this study. Similarly, underlying assumptions in the model related to these environmental stressors were not changed for this analysis.

Precipitation. Precipitation damages to paved and unpaved roads and runways were triggered when projected maximum monthly precipitation increased by 10 cm above the historical baseline, with incremental increases in damages applied for each subsequent 10-cm increase (57). Modeled damages result from the vertical impact of precipitation on road surfaces. For paved roads and runways, increased precipitation causes rutting, which reduces the time until resurfacing is required. For unpaved surfaces, precipitation increases erosion (while also making considerations for traffic levels and road slope, which influence the erosion rate), and damage estimates are generated from refilling, compacting, and aligning the road or runway surface to restore function (38).

For paved roads and runways, modeled adaptation measures include changing the sealant or binder to better withstand the projected increase in precipitation as well as modifying the base layer to enhance drainage below the pavement surface. Limited adaptation approaches are available for unpaved surfaces, and therefore, the accepted approach is to pave roads and runways that were previously unpaved (when it is cost-effective to do so based on projected damages). In these instances, the adaptation costs are comparable with construction costs for the alternative surface type.

Precipitation-driven damages to buildings quantified in the IPSS are specific to roof drainage systems (59). When drainage systems are not adequately sized, water is modeled to pool, resulting in material and sealant failure and increased repair expenses. The IPSS triggers roof damages when the monthly precipitation exceeds the historic design standard referenced in relevant building codes. Roof adaptation for increased precipitation includes the installation of larger drainage systems. These costs are quantified based on the known construction costs associated with drainage installation (59).

Flooding. Precipitation-induced flooding damages to roads and runways result from the lateral movement of water, which creates washouts, erosion, and/or surface degradation depending on the level of increased flow (57). The extent of damages is determined based on the recurrence interval of the projected flooding. As the recurrence interval increases, the level of damage increases, which reflects the greater damage that the flood can cause to roadways and culverts. For events with a recurrence interval of 15 y or less, no additional damage is calculated for paved roads, because the standard base is designed to withstand floods up to a 15-y recurrence interval. When the recurrence interval reaches 50 y, damages are estimated to be double those of the 20-y recurrence to account for impacts on riverside floodplains and nonculvert washouts. For a 100-y event, damages are estimated to be 50% larger than those of the 50-y event.

Costs quantified for adapting roads and runways to projected flooding focus on the installation of larger-diameter road drainage systems. However, additional adaptations include strengthening the structure of the roadway through an increased base layer as well as wider shoulders in areas that have repeated floods projected.

Coastal Erosion. The presence of coastal sea ice buffers Arctic coastlines against wave energy, thus naturally mitigating erosion (46). Climate change is predicted to slow the advance of the seasonal sea ice in fall and reduce the overall extent of the Arctic sea ice sheet in winter, which may lengthen the ice-free season in coastal areas (60, 61). It has also been suggested that the increased length of the ice-free season is a good first-order indicator of coastal erosion (46). Our analysis relies on the assumption that, as the ice-free season along Alaska's coastline increases, erosion rates will increase proportionally. First, we divided the coastline into three coarse latitudinal regions: south (56°N to 60°N), central (60°N to 65°N), and north (>65°N). For these regions, we projected changes in the length of the ice-free season this century using observed changes in coastal sea ice cover and observed and projected future changes in sea ice extent. Second, we combined this information with measured coastal erosion rates in 12 coastal communities to determine cumulative coastline losses to 2095 for RCP8.5 and RCP4.5.

Current length of coastal ice-free season and extent of sea ice sheet. We used satellite data to reconstruct the coastal open water season and the corresponding extent of the Northern Hemisphere sea ice sheet during recent years (2006, 2008, 2010, and 2012) to serve as a baseline. We also extracted the areal extent of the Arctic sea ice sheet at the times that sea ice advanced to cover the coast in fall and retreated to expose the coast in the spring in each of the designated regions. Daily sea ice extent and ice edge boundary data were obtained from Multisensor Analyzed Sea Ice Extent–Northern Hemisphere maps (nsidc.org/data/G02186) and the National Snow & Ice Data Center (NSIDC; nsidc.org/). Data were imported into Google Earth Pro at semimonthly intervals for the ice advance (September to January) and ice retreat (March to July) seasons for years 2006, 2008, 2010, and 2012. These years reflect a reasonable characterization of interannual variability in sea ice extent and duration of cover and include both cold and warm years in the Bering Sea (62). Using visual inspection, we determined whether sea ice covered the coastline length in each region for each time interval and coded the interval as yes, no, or partial. The area of the sea ice sheet at the date of coastal sea ice cover/retreat for each region and year was also extracted and then, averaged across the 4 y evaluated (Tables S6–S8).

Projected lengthening of coastal ice-free season. Projected sea ice extent was manually extracted from CMIP5 ensemble means at decadal intervals for September (RCP8.5 and RCP4.5) and March (RCP4.5 only) from 2000 to 2100 (17, 61). To estimate extent for March RCP8.5, the March RCP4.5 rate was scaled proportionally to the relationship between the September RCP8.5 and RCP4.5 rates. Projected decadal reduction rates were then applied to mean monthly historical (1979–2015) sea ice extent values from the NSIDC Sea Ice Index data from 1979 to 2015 (nsidc.org/data/G02135) (*SI Text*) to project monthly sea ice extent through the end of the century at decadal intervals. The projected monthly sea ice extent values were then compared with current mean sea ice extent at the dates of coastal sea ice cover and retreat to determine the length of the coastal ice-free season through the end of the century (Table S2).

Projected monthly sea ice extent values for each RCP were then compared with the current average sea ice extent at the date of coastal sea ice cover and the date of sea ice retreat for each of three regions. In the sea ice advance months of September to February, the projected sea ice extent was compared with the current average sea ice extent at the date of coastal sea ice cover for each region. When the projected value exceeded the average, ice cover began for the respective region. Similarly, in the ice retreat months of March to August, the projected sea ice extent was compared with the current average sea ice extent at the time of coastal ice retreat for each region, and when the projected value was less than the average value, the ice-free season began for the respective region. These comparisons were used to estimate the length of the ice-free season in each decade for each of three regions through the end of the century (Fig. S3).

Estimation of coastal erosion rates in coastal communities. Finally, we projected cumulative coastal erosion to 2095 for 12 coastal communities identified as extremely vulnerable to erosion (33). We assumed that erosion rates will increase proportionally with lengthening of the coastal ice-free season and then, applied the percentage increase in the decadal projections of coastal ice-free season to current erosion estimates obtained from the US Army Corps of Engineers Baseline Erosion Assessment (33) and the National Oceanic and Atmospheric Administration Fisheries Alaska Fisheries Science Center (Individual Profiles; www.afsc.noaa.gov/REFM/Socioeconomics/Projects/cpu.php). Cumulative erosion estimates through the end of century for each coastal community for both RCP8.5 and RCP4.5 are presented in Table S3.

As detailed here and in *SI Text*, many of the datasets used as inputs to this analysis are publicly available (including the downscaled climate model projections, current coastal erosion rates, and others). Datasets generated as part of this analysis are available from J.M. by request.

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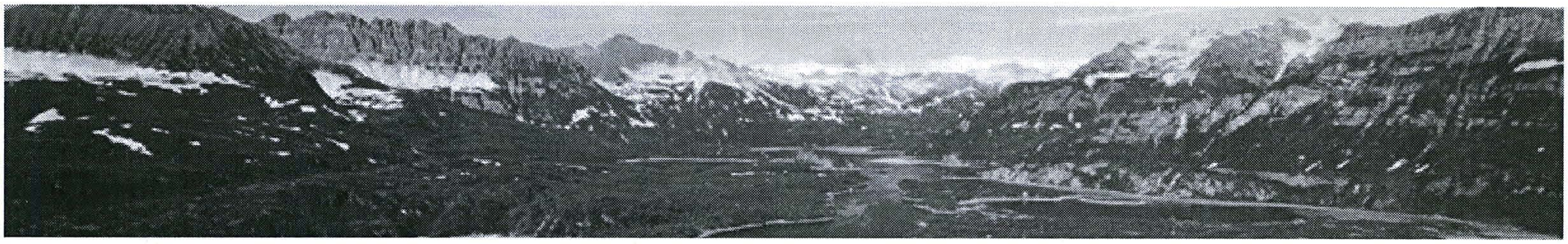
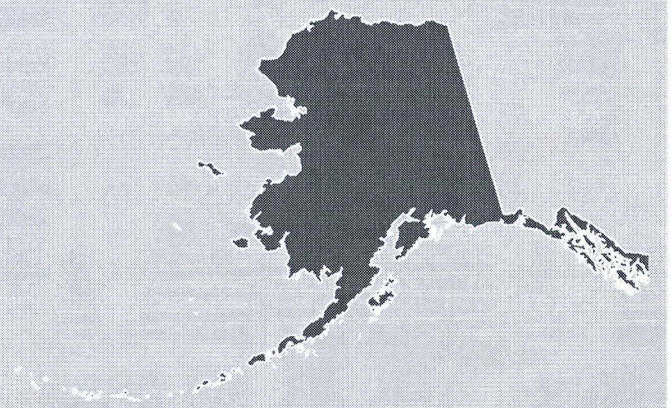


Climate Change Impacts in the United States

CHAPTER 22
ALASKA



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22 ALASKA

Key Messages

1. **Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.**
2. **Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.**
3. **Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.**
4. **Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.**
5. **The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.**

Alaska is the United States' only Arctic region. Its marine, tundra, boreal (northern) forest, and rainforest ecosystems differ from most of those in other states and are relatively intact. Alaska is home to millions of migratory birds, hundreds of thousands of caribou, some of the world's largest salmon runs, a significant proportion of the nation's marine mammals, and half of the nation's fish catch.[1]

Energy production is the main driver of the state's economy, providing more than 80% of state government revenue and thousands of jobs.[2] Continuing pressure for oil, gas, and mineral development on land and offshore in ice-covered waters increases the demand for infrastructure, placing additional stresses on ecosystems. Land-based energy exploration will be affected by a shorter season when ice roads are viable, yet reduced sea ice extent may create more opportunity for offshore development. Climate also affects hydropower generation.[3] Mining and fishing are the second and third largest industries in the state, with tourism rapidly increasing since the 1990s.[2] Fisheries are vulnerable to changes in fish abundance and dis-


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tribution that result from both climate change and fishing pressure. Tourism might respond positively to warmer springs and autumns[4] but negatively to less favorable conditions for winter activities and increased summer smoke from wildfire.[5]

Alaska is home to 40% (229 of 566) of the federally recognized tribes in the United States.[6] The small number of jobs, high cost of living, and rapid social change make rural, predominantly Native, communities highly vulnerable to climate change through impacts on traditional hunting and fishing and cultural connection to the land and sea. Because most of these communities are not connected to the state's road system or electrical grid, the cost of living is high, and it is challenging to supply food, fuel, materials, health care, and other services. Climate impacts on these communities are magnified by additional social and economic stresses. However, Alaskan Native communities have for centuries dealt with scarcity and high environmental variability and thus have deep cultural reservoirs of flexibility and adaptability.

Observed Climate Change

Over the past 60 years, Alaska has warmed more than twice as rapidly as the rest of the United States, with state-wide average annual air temperature increasing by 3°F and average winter temperature by 6°F, with substantial year-to-year and regional variability.[7] Most of the warming occurred around 1976 during a shift in a long-lived climate pattern (the Pacific Decadal Oscillation [PDO]) from a cooler pattern to a warmer one. The PDO has been shown to alternate over time between warm and cool phases. The underlying long-term warming trend has moderated the effects of the more recent shift of the PDO to its cooler phase in the early 2000s.[8] The overall warming has involved more extremely hot days and fewer extremely cold days (Ch. 2: Our Changing Climate, Key Message 7).[7,9]

Because of its cold-adapted features and rapid warming, climate change impacts on Alaska are already pronounced, including earlier spring snowmelt, reduced sea ice, widespread glacier retreat, warmer permafrost, drier landscapes, and more extensive insect outbreaks and wildfire, as described below.

Projected Climate Change

Average annual temperatures in Alaska are projected to rise by an additional 2°F to 4°F by 2050. If global emissions continue to increase during this century, temperatures can be expected to rise 10°F to 12°F in the north, 8°F to 10°F in the interior, and 6°F to 8°F in the rest of the state. Even with substantial emissions reductions, Alaska is projected to warm by 6°F to 8°F in the north and 4°F to 6°F in the rest of the state by the end of the century (Ch. 2: Our Changing Climate, Key Message 3).[7,10]

Annual precipitation is projected to increase, especially in northwestern Alaska,[7] as part of the broad pattern of increases projected for high northern latitudes. Annual precipitation increases of about 15% to 30% are projected for the region by late this century if global emissions continue to increase (A2). All models project increases in all four seasons.[7] However, increases in evaporation due to higher air temperatures and longer growing seasons are expected to reduce water availability in most of the state.[11]

The length of the growing season in interior Alaska has increased 45% over the last century[12] and that trend is projected to continue.[13] This could improve conditions for agriculture where moisture is adequate, but will reduce water storage and increase the risks of more extensive wildfire and insect outbreaks across much of Alaska.[14,15]

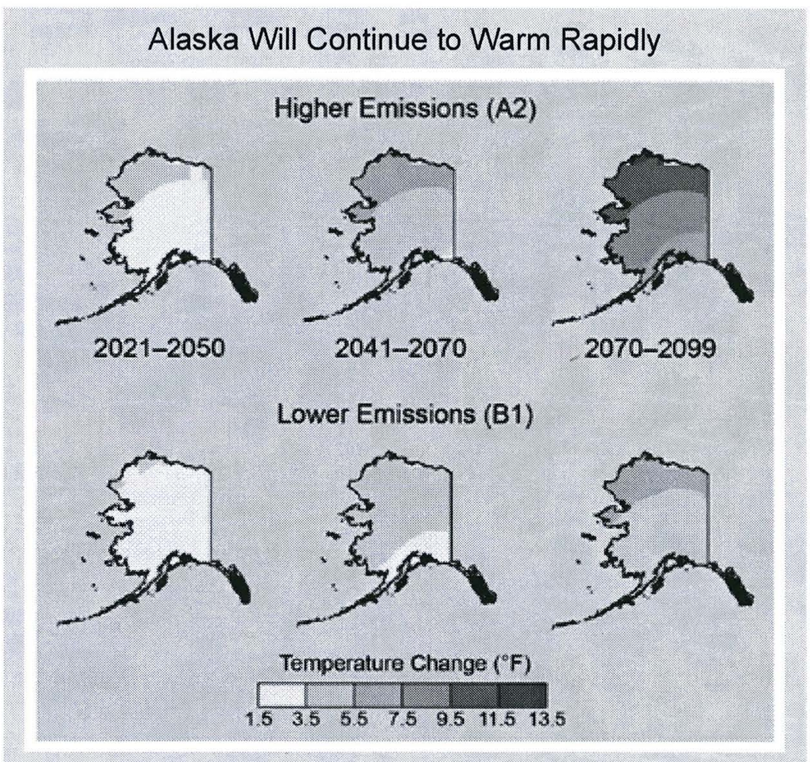


Figure 22.1. Northern latitudes are warming faster than more temperate regions, and Alaska has already warmed much faster than the rest of the country. Maps show changes in temperature, relative to 1971-1999, projected for Alaska in the early, middle, and late parts of this century, if heat-trapping gas (also known as greenhouse gas) emissions continue to increase (higher emissions, A2), or are substantially reduced (lower emissions, B1). (Figure source: adapted from Stewart et al. 2013[7]).

Changes in dates of snowmelt and freeze-up would influence seasonal migration of birds and other animals, increase the likelihood and rate of northerly range expansion of native and non-native species, alter the habitats of both ecologically important and endangered species, and affect ocean currents.[16]

Key Message 1: Disappearing Sea Ice

Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Arctic sea ice extent and thickness have declined substantially, especially in late summer (September), when there is now only about half as much sea ice as at the beginning of the satellite record in 1979 (Ch. 2: Our Changing Climate, Key Message 11).[17,18] The seven Septembers with the lowest ice extent all occurred in the past seven years. As sea ice declines, it becomes thinner, with less ice build-up over multiple years, and therefore more vulnerable to further melting.[18] Models that best match historical trends project northern waters that are virtually ice-free by late summer by the 2030s.[19,20] Within the general downward trend in sea ice, there will be time periods with both rapid ice loss and temporary recovery,[21] making it challenging to predict short-term changes in ice conditions.

Reductions in sea ice increase the amount of the sun's energy that is absorbed by the ocean. This leads to a self-reinforcing climate cycle, because the warmer ocean melts more ice, leaving more dark open water that gains even more heat. In autumn and winter, there is a strong release of this extra ocean heat back to the atmosphere. This is a key driver of the observed increases in air temperature in the Arctic.[23] This strong warming linked to ice loss can influence atmospheric circulation and patterns of precipitation, both within and beyond the Arctic (for example, Porter et al. 2012[24]). There is growing evidence that this has already occurred[25] through more evaporation from the ocean, which increases water vapor in the lower atmosphere[26] and autumn cloud cover west and north of Alaska.[27]

With reduced ice extent, the Arctic Ocean is more accessible for marine traffic, including trans-Arctic shipping, oil and gas

Declining Sea Ice Extent

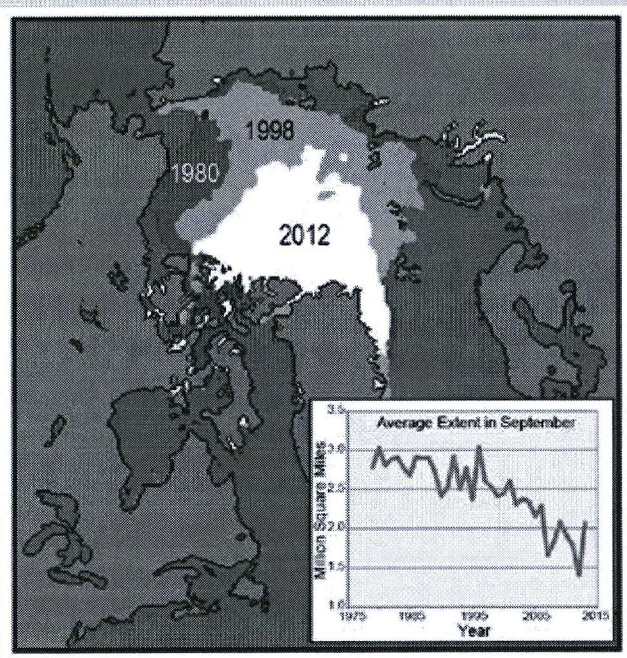


Figure 22.2. Average September extent of Arctic sea ice in 1980 (second year of satellite record and year of greatest September sea ice extent; outer red boundary), 1998 (about halfway through the time series; outer pink boundary) and 2012 (recent year of record and year of least September sea ice extent; outer white boundary). September is typically the month when sea ice is least extensive. Inset is the complete time series of average September sea ice extent (1979-2013). (Figure source: NSIDC 2012; Data from Fetterer et al. 2013[22]).

Sea Ice Loss Brings Big Changes to Arctic Life

Figure 22. 3. Reductions in sea ice alter food availability for many species from polar bear to walrus, make hunting less safe for Alaska Native hunters, and create more accessibility for Arctic Ocean marine transport, requiring more Coast Guard coverage. (Photo credits: (top left) G. Carleton Ray; (bottom left) Daniel Glick; (right) Patrick Kelley).

exploration, and tourism.[28] This facilitates access to the substantial deposits of oil and natural gas under the seafloor in the Beaufort and Chukchi seas, as well as raising the risk to people and ecosystems from oil spills and other drilling and maritime-related accidents. A seasonally ice-free Arctic Ocean also increases sovereignty and security concerns as a result of potential new international disputes and increased possibilities for marine traffic between the Pacific and Atlantic Oceans.[10]

Polar bears are one of the most sensitive Arctic marine mammals to climate warming because they spend most of their lives on sea ice.[29] Declining sea ice in northern Alaska is associated with smaller bears, probably because of less successful hunting of seals, which are themselves ice-dependent and so are projected to decline with diminishing ice and snow cover.[30] Although bears can give birth to cubs on sea ice, increasing numbers of female bears now come ashore in Alaska in the summer and fall[31] and den on land.[32] In Hudson Bay, Canada, the most studied population in the Arctic, sea ice is now absent for three weeks longer than just a few decades ago, resulting in less body fat, reduced survival of both the youngest and oldest bears,[33] and a population now estimated to be in decline[34] and projected to be in jeopardy.[35] Similar polar bear population declines are projected for the Beaufort Sea region.[36]

Walrus depend on sea ice as a platform for giving birth, nursing, and resting between dives to the seafloor, where they feed.[37] In recent years, when summer sea ice in the Chukchi Sea retreated over waters that were too deep for walrus to feed,[38] large numbers of walrus abandoned the ice and came ashore. The high concentration of animals results in increased competition for food and can lead to stampedes when animals are startled, resulting in trampling of calves.[39] This movement to land first occurred in 2007 and has happened three times since then, suggesting a threshold change in walrus ecology.

Living on the Front Lines of Climate Change

"Not that long ago the water was far from our village and could not be easily seen from our homes. Today the weather is changing and is slowly taking away our village. Our boardwalks are warped, some of our buildings tilt, the land is sinking and falling away, and the water is close to our homes. The infrastructure that supports our village is compromised and affecting the health and well-being of our community members, especially our children."

– Alaska Department of Commerce and Community and Economic Development, 2012[44]

Newtok, a Yup'ik Eskimo community on the seacoast of western Alaska, is on the front lines of climate change. Between October 2004 and May 2006, three storms accelerated the erosion and repeatedly "flooded the village water supply, caused raw sewage to be spread throughout the community, displaced residents from homes, destroyed subsistence food storage, and shut down essential utilities."[45] The village landfill, barge ramp, sewage treatment facility, and fuel storage facilities were destroyed or severely damaged.[46] The loss of the barge landing, which delivered most supplies and heating fuel, created a fuel crisis. Saltwater is intruding into the community water supply. Erosion is projected to reach the school, the largest building in the community, by 2017.

Recognizing the increasing danger from coastal erosion, Newtok has worked for a generation to relocate to a safer location. However, current federal legislation does not authorize federal or state agencies to assist communities in relocating, nor does it authorize them to repair or upgrade storm-damaged infrastructure in flood-prone locations like Newtok.[42] Newtok therefore cannot safely remain in its current location nor can it access public funds to adapt to climate change through relocation.

Newtok's situation is not unique. At least two other Alaskan communities, Shishmaref and Kivalina, also face immediate threat from coastal erosion and are seeking to relocate, but have been unsuccessful in doing so. Many of the world's largest cities are coastal and are also exposed to climate change induced flood risks.[47]

Newtok, Alaska

Figure 22.4. Residents in Newtok, Alaska are living with the effects of climate change, with thawing permafrost, tilting houses, sinking boardwalks, in conjunction with aging fuel tanks and other infrastructure that cannot be replaced because of laws that prevent public investment in flood-prone localities. (Photo credit: F. S. Chapin III).

With the late-summer ice edge located farther north than it used to be, storms produce larger waves and more coastal erosion.[10] An additional contributing factor is that coastal bluffs that were "cemented" by ice-rich permafrost are beginning to thaw in response to warmer air and ocean waters, and are therefore more vulnerable to erosion.[40] Standard defensive adaptation strategies to protect coastal communities from erosion, such as use of rock walls, sandbags, and riprap, have been largely unsuccessful.[41] Several coastal communities are seeking to relocate to escape erosion that threatens infrastructure and services but, because of high costs and policy constraints on use of federal funds for community relocation, only one Alaskan village has begun to relocate (see also Ch. 12: Indigenous Peoples).[42,43]

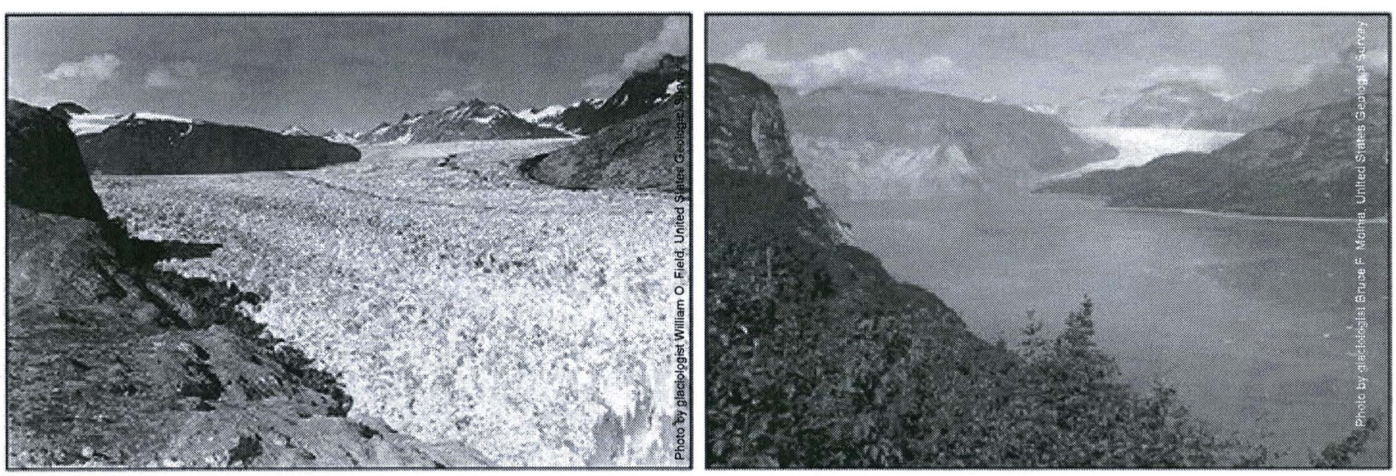
Key Message 2: Shrinking Glaciers

Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.

Alaska is home to some of the largest glaciers and fastest loss of glacier ice on Earth.[48,49,50] This rapid ice loss is primarily a result of rising temperatures (for example, Arendt et al. 2002, 2009[51,52,53]; Ch. 2: Our Changing Climate, Key Message 11). Loss of glacial volume in Alaska and neighboring British Columbia, Canada, currently contributes 20% to 30% as much surplus freshwater to the oceans as does the Greenland Ice Sheet – about 40 to 70 gigatons per year,[49,54,55,56] comparable to 10% of the annual discharge of the Mississippi River.[57] Glaciers continue to respond to climate warming for years to decades after warming ceases, so ice loss is expected to continue, even if air temperatures were to remain at current levels. The global decline in glacial and ice-sheet volume is predicted to be one of the largest contributors to global sea level rise during this century (Ch. 2: Our Changing Climate, Key Message 10).[58,59]

Water from glacial landscapes is also recognized as an important source of organic carbon,[60,61] phosphorus,[62] and iron[63] that contribute to high coastal productivity, so changes in these inputs could alter critical nearshore fisheries.[61,64]

Glaciers supply about half of the total freshwater input to the Gulf of Alaska.[65] Glacier retreat currently increases river discharge and hydropower potential in south central and southeast Alaska, but over the longer term might reduce water input to reservoirs and therefore hydropower resources.[3]



On the left is a photograph of Muir Glacier in Alaska taken on August 13, 1941; on the right, a photograph taken from the same vantage point on August 31, 2004. Total glacial mass has declined sharply around the globe, adding to sea level rise. (Left photo by glaciologist William O. Field; right photo by geologist Bruce F. Molnia of the United States Geological Survey.)

Key Message 3: Thawing Permafrost

Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.

Alaska differs from most of the rest of the U.S. in having permafrost – frozen ground that restricts water drainage and therefore strongly influences landscape water balance and the design and maintenance of infrastructure. Permafrost near the Alaskan Arctic coast has warmed 4°F to 5°F at 65 foot depth[66,67] since the late 1970s and 6°F to 8°F at 3.3 foot depth since the mid-1980s.[68] In Alaska, 80% of land is underlain by permafrost, and of this, more than 70% is vulnerable to subsidence upon thawing because of ice content that is either variable, moderate, or high.[69] Thaw is already occurring in interior and southern Alaska and in northern Canada, where permafrost temperatures are near the thaw point.[70] Models project that permafrost in Alaska will continue to thaw,[71,72] and some models project that near-surface permafrost will be lost entirely from large parts of Alaska by the end of the century.[73]

Uneven sinking of the ground in response to permafrost thaw is estimated to add between $3.6 and $6.1 billion (10% to 20%) to current costs of maintaining public infrastructure such as buildings, pipelines, roads, and airports over the next 20 years.[74] In rural Alaska, permafrost thaw will likely disrupt community water supplies and sewage systems,[75,76,77] with negative effects on human health.[78] The period during which oil and gas exploration is allowed on tundra has decreased by 50% since the 1970s as a result of permafrost vulnerability.[11]

On average, lakes have decreased in area in the last 50 years in the southern two-thirds of Alaska,[80,81,82] due to a combination of permafrost thaw, greater evaporation in a warmer climate, and increased soil organic accumulation during a longer season for plant growth. In some places, however, lakes are getting larger because of lateral permafrost degradation.[81] Future permafrost thaw will likely increase lake area in areas of continuous permafrost and decrease lake area in places where the permafrost zone is more fragmented.[71]

A continuation of the current drying of Alaskan lakes and wetlands could affect waterfowl management nationally because Alaska accounts for 81% of the National Wildlife Refuge System and provides breeding habitat for millions of migratory birds that winter in more southerly regions of North America and on other continents.[83] Wetland loss would also reduce waterfowl harvest in Alaska, where it is an important food source for Alaska Natives and other rural residents.

Both wetland drying and the increased frequency of warm dry summers and associated thunderstorms have led to more large fires in the last ten years than in any decade since record-keeping began in the 1940s.[14] In Alaskan tundra, which was too cold and wet to support extensive fires for approximately the last 5,000 years,[84] a single large fire in 2007 released as much carbon to the atmosphere as had been absorbed by the entire circumpolar Arctic tundra during the previous quarter-century.[85] Even if climate warming were curtailed by reducing heat-trapping gas (also known as greenhouse gas) emissions (as in the B1 scenario), the annual area burned in Alaska is pro-

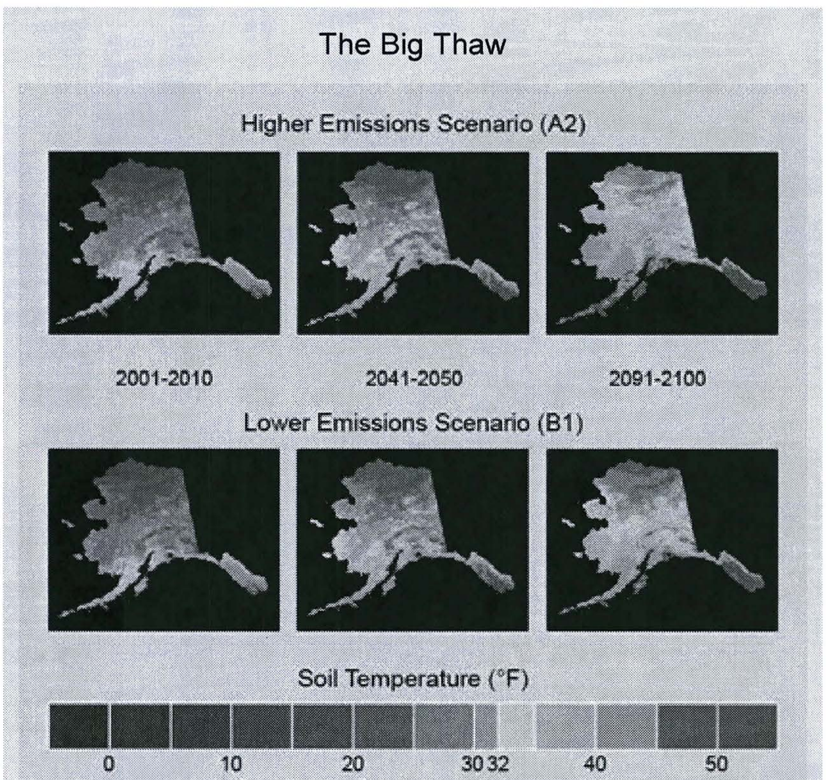


Figure 22.5. Projections for average annual ground temperature at a depth of 3.3 feet over time if emissions of heat-trapping gases continue to grow (higher emissions scenario, A2), and if they are substantially reduced (lower emissions scenario, B1). Blue shades represent areas below freezing at a depth of 3.3 feet, and yellow and red shades represent areas above freezing at that depth, based on the GIPL 1.0 model. (Figure source: Permafrost Lab, Geophysical Institute, University of Alaska Fairbanks).

jected to double by mid-century and to triple by the end of the century,[86] thus fostering increased emissions of heat-trapping gases, higher temperatures, and increased fires. In addition, thick smoke produced in years of extensive wildfire represents a human health risk (Ch. 9: Human Health). More extensive and severe wildfires could shift the forests of Interior Alaska during this century from dominance by spruce to broadleaf trees for the first time in the past 4,000 to 6,000 years.[87,88]

Wildfire has mixed effects on habitat. It generally improves habitat for berries, mushrooms, and moose,[58,89] but reduces winter habitat for caribou because lichens, a key winter food source for caribou, require 50 to 100 years to recover after wildfire.[90] These habitat changes are nutritionally and culturally significant for Alaska Native Peoples.[89,91] In addition, exotic plant species that were introduced along roadways are now spreading onto river floodplains and recently burned forests,[92] potentially changing the suitability of these lands for timber production and wildlife. Some invasive species are toxic to moose, on which local people depend for food.[93]

Changes in terrestrial ecosystems in Alaska and the Arctic may be influencing the global climate system. Permafrost soils throughout the entire Arctic contain almost twice as much carbon as the atmosphere.[94] Warming and thawing of these soils increases the release of carbon dioxide and methane through increased decomposition. Thawing permafrost also delivers organic-rich soils to lake bottoms, where decomposition in the absence of oxygen releases additional methane.[95] Extensive wildfires also release carbon that contributes to climate warming.[86,96] The capacity of the Yukon River Basin in Alaska and adjacent Canada to store carbon has been substantially weakened since the 1960s by the combination of warming and thawing of permafrost and by increased wildfire.[97] Expansion of tall shrubs and trees into tundra makes the surface darker and rougher, increasing absorption of the sun's energy and further contributing to warming.[98] This warming is likely stronger than the potential cooling effects of increased carbon dioxide uptake associated with tree and shrub expansion.[99] The shorter snow-covered seasons in Alaska further increase energy absorption by the land surface, an effect only slightly offset by the reduced energy absorption of highly reflective post-fire snow-covered landscapes.[99] This spectrum of changes in Alaskan and other high-latitude terrestrial ecosystems jeopardizes efforts by society to use ecosystem carbon management to offset fossil fuel emissions.[94,100]

Mounting Expenses from Permafrost Thawing

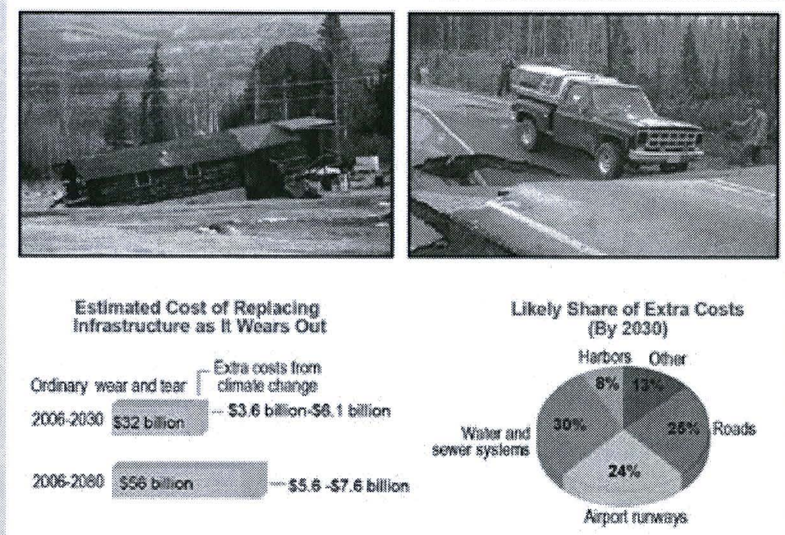


Figure 22.6. Effects of permafrost thaw on houses in interior Alaska (2001, top left), roads in eastern Alaska (1982, top right), and the estimated costs (with and without climate change) of replacing public infrastructure in Alaska, assuming a mid-range emissions scenario (A1B, with some decrease from current emissions growth trends). (Photo credits: (top left) Larry Hinzman; (top right) Joe Moore. Figure source: adapted from Larsen and Goldsmith 2007[79]).

Drying Lakes and Changing Habitat

Figure 22.7. Progressive drying of lakes in northern forest wetlands in the Yukon Flats National Wildlife Refuge, Alaska. Foreground orange area was once a lake. Mid-ground lake once extended to the shrubs. (Photo credit: May-Le Ng).

Key Message 4: Changing Ocean Temperatures and Chemistry

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes interact to affect the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence.[101,102,103] These changes have allowed some near-surface fish species such as salmon to expand their ranges northward along the Alaskan coast.[104] In addition, non-native species are invading Alaskan waters more rapidly, primarily through ships releasing ballast waters and bringing southerly species to Alaska.[10,105] These species introductions could affect marine ecosystems, including the feeding relationships of fish important to commercial and subsistence fisheries.

Overall habitat extent is expected to change as well, though the degree of the range migration will depend upon the life history of particular species. For example, reductions in seasonal sea ice cover and higher surface temperatures may open up new habitat in polar regions for some important fish species, such as cod, herring, and pollock.[106] However, continued presence of cold bottom-water temperatures on the Alaskan continental shelf could limit northward migration into the northern Bering Sea and Chukchi Sea off northwestern Alaska.[107] In addition, warming may cause reductions in the abundance of some species, such as pollock, in their current ranges in the Bering Sea[108] and reduce the health of juvenile sockeye salmon, potentially resulting in decreased overwinter survival.[109] If ocean warming continues, it is unlikely that current fishing pressure on pollock can be sustained.[110] Higher temperatures are also likely to increase the frequency of early Chinook salmon migrations, making management of the fishery by multiple user groups more challenging.[111]

The changing temperature and chemistry of the Arctic Ocean and Bering Sea are likely changing their role in global ocean circulation and as carbon sinks for atmospheric CO_2 respectively although the importance of these changes in the global carbon budget remains unresolved. The North Pacific Ocean is particularly susceptible to ocean acidification (see also Ch. 2: Our Changing Climate, Key Message 12; Ch. 24: Oceans).[112] Acidifying changes in ocean chemistry have potentially widespread impacts on the marine food web, including commercially important species.

Ocean Acidification in Alaska

Ocean waters globally have become 30% more acidic due to absorption of large amounts of human-produced carbon dioxide (CO_2) from the atmosphere. This CO_2 interacts with ocean water to form carbonic acid that lowers the ocean's pH (ocean acidification). The polar ocean is particularly prone to acidification because of low temperature[113,114] and low salt content, the latter resulting from the large freshwater input from melting sea ice[115] and large rivers. Acidity reduces the capacity of key plankton species and shelled animals to form and maintain shells and other hard parts, and therefore alters the food available to important fish species.[113,116] The rising acidity will have particularly strong societal effects on the Bering Sea on Alaska's west coast because of its high-productivity commercial and subsistence fisheries.[102,117]

Shelled pteropods, which are tiny planktonic snails near the base of the food chain, respond quickly to acidifying conditions and are an especially critical link in high-latitude food webs, as commercially important species such as pink salmon depend heavily on them for food.[118] A 10% decrease in the population of pteropods could mean a 20% decrease in an adult pink salmon's body weight.[119] Pteropod consumption by juvenile pink salmon in the northern Gulf of Alaska varied 45% between 1999 and 2001, although the reason for this variation is unknown.[120]

At some times of year, acidification has already reached a critical threshold for organisms living on Alaska's continental shelves.[121] Certain algae and animals that form shells (such as clams, oysters, and crab) use carbonate minerals (aragonite and calcite) that dissolve below that threshold. These organisms form a crucial component of the marine food web that sustains life in the rich waters off Alaska's coasts. In addition, Alaska oyster farmers are now indirectly affected by ocean acidification impacts farther south because they rely on oyster spat (attached oyster larvae) from Puget Sound farmers who are now directly affected by the recent upwelling of acidic waters along the Washington and Oregon coastline (Ch. 24: Oceans; Ch. 21: Northwest).[122]

Key Message 5: Native Communities

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

With the exception of oil-producing regions in the north, rural Alaska is one of the most extensive areas of poverty in the U.S. in terms of household income, yet residents pay the highest prices for food and fuel.[123] Alaska Native Peoples, who are the most numerous residents of this region, depend economically, nutritionally, and culturally on hunting and fishing for their livelihoods.[124,125,126] Hunters speak of thinning sea and river ice that makes harvest of wild foods more dangerous,[127] changes to permafrost that alter spring run-off patterns, a northward shift in seal and fish species, and rising sea levels with more extreme tidal fluctuations (see Ch. 12: Indigenous Peoples).[128,129] Responses to these changes are often constrained by regulations.[77,129] Coastal erosion is destroying infrastructure. Impacts of climate change on river ice dynamics and spring flooding are threats to river communities but are complex, and trends have not yet been well documented.[130]

Major food sources are under stress due to many factors, including lack of sea ice for marine mammals.[131] Thawing of near-surface permafrost beneath lakes and ponds that provide drinking water cause food and water security challenges for villages. Sanitation and health problems also result from deteriorating water and sewage systems, and ice cellars traditionally used for storing food are thawing (see also Ch. 12: Indigenous Peoples).[75,78] Warming also releases human-caused pollutants, such as poleward-transported mercury and organic pesticides, from thawing permafrost and brings new diseases to Arctic plants and animals, including subsistence food species, posing new health challenges, especially to rural communities.[132] Positive health effects of warming include a longer growing season for gardening and agriculture.[10,133]

Development activities in the Arctic (for example, oil and gas, minerals, tourism, and shipping) are of concern to Indigenous communities, from both perceived threats and anticipated benefits.[126] Greater levels of industrial activity might alter the distribution of species, disrupt subsistence activities, increase the risk of oil spills, and create various social impacts. At the same time, development provides economic opportunities, if it can be harnessed appropriately.[134]

Alaska Native Elders say, "We must prepare to adapt." However, the implications of this simple instruction are multi-faceted. Adapting means more than adjusting hunting technologies and foods eaten. It requires learning how to garner information from a rapidly changing environment. Permanent infrastructure and specified property rights increasingly constrain people's ability to safely use their environment for subsistence and other activities.

Traditional knowledge now facilitates adaptation to climate change as a framework for linking new local observations with western science.[124,135] The capacity of Alaska Natives to survive for centuries in the harshest of conditions reflects their resilience.[91] Communities must rely not only on improved knowledge of changes that are occurring, but also on support from traditional and other institutions – and on strength from within – in order to face an uncertain future.[124]

Alaska Coastal Communities Damaged


Figure 22.8: One effect of the reduction in Alaska sea ice is that storm surges that used to be buffered by the ice are now causing more shoreline damage. Photos show infrastructure damage from coastal erosion in Tuntutuliak (left) and Shishmaref, Alaska (right). (Photo credits: (left) Alaska Department of Environmental Conservation; (right) Ned Rozell).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for developing key messages

A central component of the assessment process was the Alaska Regional Climate assessment workshop that was held September 12-15, 2012, in Anchorage with approximately 20 attendees; it began the process leading to a foundational Technical Input Report (TIR).[10] The report consists of 148 pages of text, 45 figures, 8 tables, and 27 pages of references. Public and private citizens or institutions were consulted and engaged in its preparation and expert review by the various agencies and non-governmental organizations (NGOs) represented by the 11-member TIR writing team. The key findings of the report were presented at the Alaska Forum on the Environment and in a regularly scheduled, monthly webinar by the Alaska Center for Climate Assessment and Policy, with feedback then incorporated into the report.

The chapter author team engaged in multiple technical discussions via regular teleconferences. These included careful expert review of the foundational TIR[10] and of approximately 85 additional technical inputs provided by the public, as well as the other published literature and professional judgment. These discussions were followed by expert deliberation of draft key messages by the writing team in a face-to-face meeting before each key message was selected for inclusion in the Report. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities" (Ch. 26: Decision Support).

Key message #1 Traceable Account

Arctic summer sea ice is receding faster than previously projected and is expected to virtually disappear before mid-century. This is altering marine ecosystems and leading to greater ship access, offshore development opportunity, and increased community vulnerability to coastal erosion.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska TIR.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Although various models differ in the projected rate of sea ice loss, more recent CMIP5 models[20] that most accurately reconstruct historical sea ice loss project that late-summer sea ice will virtually disappear by the 2030s, leaving only remnant sea ice.

Evidence is strong about the impacts of sea ice loss.[10] Because the sea ice cover plays such a strong role in human activities and Arctic ecosystems, loss of the ice cover is nearly certain to have substantial impacts.[17]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

Evidence from improved models (for example, Wang and Overland 2012[20]) and updated observational data from satellite, especially new results, clearly show rapid decline in not only extent but also mass and thickness of multi-year ice,[18] information that was not available in prior assessments.

Nearly all studies to date published in the peer-reviewed literature agree that summer Arctic sea ice extent is rapidly declining and that, if heat-trapping gas concentrations continue to rise, an essentially ice-free summer Arctic ocean will be realized before mid-century. However, there remains uncertainty in the rate of sea ice loss, with the models that most accurately project historical sea ice trends currently suggesting nearly ice-free conditions sometime between 2021 and 2043 (median 2035).[20] Uncertainty across all models stems from a combination of large differences in projections among different climate models, natural climate variability, and uncertainty about future rates of fossil fuel emissions.

Ecosystems: There is substantial new information that ocean acidification, rising ocean temperatures, declining sea ice, and other environmental changes are affecting the location and abundance of marine fish, including those that are commercially important, those used as food by other species, and those used for subsistence.[101,102] However, the relative importance of these potential causes of change is highly uncertain.

Offshore oil and gas development: A key uncertainty is the price of fossil fuels. Viable avenues for improving the information base include determining the primary causes of variation among different climate models and determining which climate models exhibit the best ability to reproduce the observed rate of sea ice loss.

Coastal erosion: There is new information that lack of sea ice causes storms to produce larger waves and more coastal erosion.[10] An additional contributing factor is that coastal bluffs that were "cemented" by permafrost are beginning to thaw in response to warmer air and ocean waters, and are therefore more vulnerable to erosion.[40] Standard defensive adaptation strategies to protect coastal communities from erosion such as use of rock walls, sandbags, and riprap have been largely unsuccessful.[41] There remains considerable uncertainty, however, about the spatial patterns of future coastal erosion.

Assessment of confidence based on evidence
Given the evidence base and remaining uncertainties:

Very high confidence for summer sea ice decline. **High** confidence for summer sea ice disappearing by mid-century.

Very high confidence for altered marine ecosystems, greater ship access, and increased vulnerability of communities to coastal erosion.

High confidence regarding offshore development opportunity.

KEY MESSAGE #2 TRACEABLE ACCOUNT

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise.

Description of evidence base
The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence that glaciers in Alaska and British Columbia are shrinking is strong and is based on field studies,[56] energy balance models,[59] LIDAR remote sensing,[51,52] and satellite data, especially new lines of evidence from the Gravity Recovery and Climate Experiment (GRACE) satellite.[48,52,55]

Evidence is also strong that Alaska ice mass loss contributes to global sea level rise,[58] with latest results permitting quantitative evaluation of losses globally.[49]

Numerous peer-reviewed publications describe implications of recent increases, but likely longer-term declines, in water input from glacial rivers to reservoirs and therefore hydropower resources.[3,10,65]

Glacial rivers account for 47% of the freshwater input to the Gulf of Alaska[65] and are an important source of organic carbon,[60,61] phosphorus,[62] and iron[63] that contribute to the high productivity of near-shore fisheries.[61,64] Therefore, it is projected that the changes in discharge of glacial rivers will affect ocean circulation patterns and major U.S. and locally significant fisheries.

New information and remaining uncertainties
Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

As noted above, major advances from GRACE and other datasets now permit analyses of glacier mass loss that were not possible previously.

Key uncertainties remain related to large year-to-year variation, the spatial distribution of snow accumulation and melt, and the quantification of glacier calving into the ocean and lakes. Although most large glaciated areas of the state are regularly measured observationally, extrapolation to unmeasured areas carries uncertainties due to large spatial variability.

Although there is broad agreement that near-shore circulation in the Gulf of Alaska is influenced by the magnitude of freshwater inputs, little is known about the mechanisms by which near-term increases and subsequent longer-term decreases in glacier runoff (as the glaciers disappear) will affect the structure of the Alaska Coastal Current and smaller-scale ocean circulation, both of which have feedback on fisheries.

The magnitude and timing of effects on hydropower production depend on changes in glacial mass, as described above.

Assessment of confidence based on evidence
High confidence that glacier mass loss in Alaska and British Columbia is high, contributing 20% to 30% as much to sea level rise as does shrinkage of the Greenland Ice Sheet.

High confidence that due to glacier mass loss there will be related impacts on hydropower production, ocean circulation, fisheries, and global sea level rise.

Key message #3 Traceable Account

Permafrost temperatures in Alaska are rising, a thawing trend that is expected to continue, causing multiple vulnerabilities through drier landscapes, more wildfire, altered wildlife habitat, increased cost of maintaining infrastructure, and the release of heat-trapping gases that increase climate warming.

Description of evidence base
The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Previous evidence that permafrost is warming[66] has been confirmed and enhanced by more recent studies.[70] The most recent modeling efforts (for example, Avis et al. 2011; Jafarov et al. 2012[71,73]) extend earlier results[72] and project that permafrost will be lost from the upper few meters from large parts of Alaska by the end of this century.

Evidence that permafrost thaw leads to drier landscapes[81,82] is beginning to accumulate, especially as improved remote sensing tools are applied to assess more remote regions.[71]

Satellite data has expanded the capacity to monitor wildfire across the region, providing additional evidence of wildfire extent.[87] This new evidence has led to increased study that is beginning to reveal impacts on ecosystems and wildlife habitat, but much more work is needed to understand the extent of natural resilience.

Impacts of permafrost thaw on the maintenance of infrastructure[11,74,75,76,77] is currently moderate but rapidly accumulating. Evidence that permafrost thaw will jeopardize efforts to offset fossil fuel emissions is suggestive (Ch. 2: Our Changing Climate).[94,100]

New information and remaining uncertainties
Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

This evidence included results from improved models and updated observational data. The assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm the relevance and significance of the key message for local decision-makers.

Key uncertainties involve: 1) the degree to which increases in evapotranspiration versus permafrost thaw are leading to drier landscapes; 2) the degree to which it is these drier landscapes associated with permafrost thaw, versus more severe fire weather associated with climate change, that is leading to more wildfire; 3) the degree to which the costs of the maintenance of infrastructure are associated with permafrost thaw caused by climate change versus disturbance of permafrost due to other human activities; and 4) the degree to which climate change is causing Alaska to be a sink versus a source of greenhouse gases to the atmosphere.

Assessment of confidence based on evidence
Very high confidence that permafrost is warming.

High confidence that landscapes in interior Alaska are getting drier, although the relative importance of different mechanisms is not completely clear.

Medium confidence that thawing permafrost results in more wildfires. There is **high** confidence that wildfires have been increasing in recent decades, even if it is not clear whether permafrost thaw or hotter and drier weather is more important.

High confidence that climate change will lead to increased maintenance costs in future decades. **Low** confidence that climate change has led to increased maintenance costs of infrastructure in recent decades.

Very high confidence that ecological changes will cause Alaska to become a source of greenhouse gases to the atmosphere, even though evidence that Alaska is currently a carbon source is only suggestive.

Key message #4 Traceable Account

Current and projected increases in Alaska's ocean temperatures and changes in ocean chemistry are expected to alter the distribution and productivity of Alaska's marine fisheries, which lead the U.S. in commercial value.

Description of evidence base
The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10]

Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe evidence that ocean temperatures are rising and ocean chemistry, especially pH, is changing.[10] New observational data from buoys and ships document increasing acidity and aragonite under-saturation (that is, the tendency of calcite and aragonite in shells to dissolve) in Alaskan coastal waters.

Accumulating strong evidence suggests that these changes in ocean temperature and chemistry, including pH, will likely affect major Alaska marine fisheries, although the relative importance of these changes and the exact nature of response of each fishery are uncertain.[101,102,103]

Alaska's commercial fisheries account for roughly 50 percent of the United States' total wild landings. Alaska led all states in both volume and ex-vessel value of commercial fisheries landings in 2009, with a total of 1.84 million metric tons worth $1.3 billion.[1]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

The new evidence included results from improved models and updated observational data. The assessment included insights from stakeholders collected in a series of distributed engagement meetings that confirm the relevance and significance of the key message for local decision-makers.

A key uncertainty is what the actual impacts of rising temperatures and changing ocean chemistry, including an increase in ocean acidification, will be on a broad range of marine biota and ecosystems. More monitoring is needed to document the extent and location of changes. Additional research is needed to assess how those changes will affect the productivity of key fishery resources and their food and prey base.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

High confidence of increased ocean temperatures and changes in chemistry.

Medium confidence that fisheries will be affected.

Key message #5 Traceable Account

The cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

Description of evidence base

The key message and supporting chapter text summarize extensive evidence documented in the Alaska Technical Input Report.[10] Technical input reports (85) on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence exists in recorded local observational accounts as well as in the peer-reviewed scientific literature of the cumulative effects of climate-related environmental change on Native communities in Alaska; these effects combine with other socioeconomic stressors to strain rural Native communities (Ch. 12: Indigenous Peoples).[124,125,126,131] Increasing attention to impacts of climate change is revealing new aspects, such as impacts to health and hunter safety (for example, Baffrey and Huntington 2010; Brubaker et al. 2011[78,134]). There is also strong evidence for the cultural adaptive capacity of these communities and peoples over time.[91,130,135]

New information and remaining uncertainties

Important new evidence confirmed many of the findings from a prior Alaska assessment (http://nca2009.globalchange.gov/alaska), which informed the 2009 NCA.[136]

The precise mechanisms by which climate change affects Native communities are poorly understood, especially in the context of rapid social, economic, and cultural change. Present day responses to environmental change are poorly documented. More research is needed on the ways that Alaska Natives respond to current biophysical climate change and to the factors that enable or constrain contemporary adaptation.

Alaska Native communities are already being affected by climate-induced changes in the physical and biological environment, from coastal erosion threatening the existence of some communities, to alterations in hunting, fishing, and gathering practices that undermine the intergenerational transfer of culture, skill, and wisdom. At the same time, these communities have a long record of adaptation and flexibility. Whether such adaptability is sufficient to address the challenges of climate change depends both on the speed of climate-induced changes and on the degree to which Native communities are supported rather than constrained in the adaptive measures they need to make.[124]

Assessment of confidence based on evidence

There is **high** confidence that cumulative effects of climate change in Alaska strongly affect Native communities, which are highly vulnerable to these rapid changes but have a deep cultural history of adapting to change.

Environment

What climate change looks like in Alaska now

Author: Yereth Rosen Updated: September 28, 2016 Published August 29, 2015

Long before the terms "global warming" and "climate change" became part of the national dialogue, Alaska's indigenous people noticed that things were going askew in the natural world.

"Ice cellars were sweating because we were losing the permafrost," said Patricia Cochran, an Inupiaq from Nome who is the executive director of the Alaska Native Science Commission. Berries were ripening two to three weeks earlier than normal, and beavers, once unknown in the treeless tundra regions, began showing up in rivers and streams as woody plants sprouted farther north, she said.

Elders in North Slope whaling communities also called attention to strange things happening at sea, said Edward Itta, a Barrow whaling captain and former mayor of the North Slope Borough.

"They had noticed 30, 35 years ago that the multiyear ice was getting different, and they didn't see the huge *ivus* anymore," said Itta, using the Inupiaq term for jumbled ice piles pushed to shore by currents or winds. "Sure enough, here I am, 35 years later, seeing now that these guys were way ahead of us. They knew things were changing, which is not surprising because they were masters of observation."

Winter 6.3 degrees warmer

The mainstream scientific community that once relegated such traditional knowledge to anecdotal footnotes now has data confirming the indigenous reports.

Since the mid-20th century, Alaska and the Arctic have been warming about twice as fast as the global rate.

Over the past five decades, average Alaska temperatures have increased by 3.4 degrees Fahrenheit, with the increases most pronounced in winter at 6.3 degrees.

That warming can have drastic consequences here: open water rather than solid ice at sea or on rivers traditionally used for travel, or soft and collapsing soil instead of hard-frozen ground, or rain instead of snow.

It also means that warming creates more warming and explains the phenomenon known as "Arctic Amplification" — the self-reinforcing process that warms the Arctic and subarctic far faster than the rest of the world.

"As ice melts, you have less white ice to reflect heat and more dark ground to absorb heat, and that makes ice melt faster," said Nancy Fresco, a research professor at the University of Alaska Fairbanks' International Arctic Research Center. Quicker melt of sea ice, land ice and snow cover lead to yet more melt. Heat-stoked, lightning-sparked wildfires char the ground and also can feed into the cycle. Clouds created from water vapor released from seas no longer covered by ice help trap atmospheric warmth. Permafrost thaw releases carbon, some of it thousands of years old, that also feeds the warming cycle.

With the Arctic crucial to the Earth's climate and much of its wildlife, and with new evidence coming in that links the rapid Arctic warming to extreme weather events in highly populated latitudes far south, the rest of the world should pay attention to the changes first noticed by Alaska's indigenous residents, scientists say.

"The Arctic is not like Vegas. What happens in the Arctic doesn't stay in the Arctic," Howard Epstein, an environmental scientist at the University of Virginia, said when the National Oceanic and Atmospheric Administration released a 2013 Arctic Report Card showing profound changes.

Weather changes, weather extremes

Alaska in the past few years has been posting some of its warmest temperatures on record, with new marks in various places for all-time highs, daily highs, high daily lows and lack of snow.

That is part of a global pattern. The world's 10 hottest years on record have occurred since 1998, and last year was the hottest ever measured. July was the hottest month on record and 2015 — with the help of the brewing El Nino system in the Pacific — is poised to break the annual record.

It can be difficult to parse out the differences between the chaos of daily weather from medium-term cycles from long-term climate change, experts say.

"Weather is what clothing you put on in the morning, and climate is what clothing you have in your closet," Fresco said. "Weather is still a day-to-day thing that can vary enormously."

Beyond the day-to-day and year-to-year fluctuations, some long-term trends have emerged.

The Arctic as a whole has gotten warmer and wetter since the start of the 21st century, a change attributed to sea-ice reduction. Other forces like reduced snow cover — which this year hit a near-record June low in the Northern Hemisphere — and cloud formation amplify the warming. Records show that Alaska's North Slope has warmed dramatically, most so in autumn, the time of minimal ice when more summer heat absorbed by the ocean is emitted into the atmosphere, thanks to ever-bigger areas of open water in that season.

Lack of sea ice means fall storms are more destructive. On the Bering Sea coast, storms are sending seawater far inland, as much as 20 miles in southwestern Alaska's Yukon-Kuskokwim region, the U.S. Geological Survey reports.

For Alaska, history is being used to make predictions about what appears to be a vastly different future. UAF's Scenarios Network for Alaska and Arctic Planning, led by Fresco, gives community-by-community predictions for higher temperatures and shifts to rain rather than snow.

Melt and thaw — glaciers and permafrost

Alaska's glaciers pale in comparison to the Greenland ice sheet and Antarctica, but they have become major contributors to sea level rise, scientists say.

Mountain glaciers hold only 1 percent of the world's glacial ice, but they are contributing 30 percent of the water that is increasing sea levels, said Shad O'Neel of the USGS. Alaska holds 11 percent of the world's mountain glaciers but contributes about a quarter of the world's mountain glacier meltwater, O'Neel said. "We're the most disproportionate region," he said.

In all, Alaska's glaciers are losing 75 billion tons of ice a year, and almost all of that comes from the glaciers on land rather than those spilling into tidewater. The alpine glaciers in western Alaska's Ahklun Mountains, already shrunken, are expected to disappear entirely by the end of the century.

Glacial melt affects more than sea levels. The increasing amount of fresh water pouring off them changes marine salinity and currents and, ultimately, circulation in the Arctic Ocean, O'Neel said.

Permafrost is dwindling in its southern range in Alaska and Canada and warming even in its northern range, where the frozen layer is thickest. At Prudhoe Bay, temperatures last year edged to just a few degrees below thaw, compared to a temperature of 17.6 degrees Fahrenheit in the 1980s, according to UAF's Vladimir Romanovsky, one of the world's top permafrost experts.

Forests, fires and plants

Wildfires are a natural part of the forest ecosystem, but the increased frequency of large fires and expanded duration of the Alaska fire season is not. There were twice as many large Alaska wildfires in the 2000s as in the 1950s and 1960s, and the state is winding up what has turned out to be the second-biggest fire season on record, with nearly 5.2 million acres burned. Coupled with vast and fierce wildfires in neighboring parts of Canada, this year's fires are part of a broad upheaval of the northern boreal forest.

In the short term, that means property damage costs and health and safety hazards from smoke. In the long term, it means a transformation of what has been a spruce-dominated forest into something else.

It is not yet clear what that future landscape will be, said Epstein, who researches northern forests and tundra vegetation. As spruce trees wither and burn, deciduous birch, aspsen and willows seem to be taking their place, he said. Grasslands are another future possibility.

Farther north, tall, woody shrubs are expanding northward into the tundra, and vegetation that already existed there is growing more vigorously, Epstein said.

Could that new plant life become a carbon sink offsetting atmospheric emissions? No, Epstein says. The carbon dioxide consumption is "really minor" compared to other effects, such as darkening of the land surface.

"I don't think that anybody believes that increased vegetation in the Arctic is going to be a savior in terms of carbon dioxide uptake," he said.

Wildlife on thin ice

The ice-dwelling polar bear, the first animal granted Endangered Species Act protections because of climate change, has been the icon of global warming. But it is not the only animal species that faces an uncertain future as the summer and fall sea ice disappears, federal biologists say.

Bearded and ringed seals, also dependent on the diminishing summer and fall sea ice and the snow atop it, are listed as threatened. Pacific walruses, which have in recent years crowded the Chukchi Sea shoreline because they can't find floating sea ice in late summer and fall, are also candidates for Endangered Species Act protections.

Land animals have their own problems with the ecosystem changes.

The northward expansion of shrubs is bad for caribou, musk oxen and other animals that depend on tundra habitat, Epstein said. Caribou herds across North America have declined, and some biologists point to winter rain events that coat forage food with hard ice as a persistent problem. Earlier springs are causing timing problems for some migrating birds. If they arrive in Alaska too late, they will miss the most nutritious vegetation growth.

But not all animals are losing out. There are some climate change winners, like North Slope black brant, geese that are thriving as they feed on salt-tolerant plants growing in the place of upland vegetation that dies as permafrost sags, shorelines erode and saltwater seeps in.

Erosion, villages and culture

Much of the world has seen photographs of homes slumping into the sea in the Inupiat village of Shishmaref in Northwest Alaska. But Shishmaref is just one of several Alaska villages struggling as thawing permafrost and stronger waves eat away at its coasts.

Two others — Newtok and Kivalina — are working on relocations, with the move already started in the former. In all, 26 communities have erosion problems that are bad enough to warrant major and immediate response, ranging from aggressive shore bolstering projects to total relocation, according to a 2009 report by the U.S. Army Corps of Engineers.

Some of the fastest erosion is on Alaska's North Slope, where an average 4.6 feet has been lost each year since the mid-20th century, according to a U.S. Geological Survey report. That puts oil field infrastructure at risk, along with the villages.

Even past generations are affected. In Barrow, archaeologists excavated ancient and eroding gravesites, transferring bodies to the more modern local cemetery. In the Yukon-Kuskokwim region, archaeologists have embarked on an ambitious project to save relics from an eroding settlement site that dates back to the 1300s. Erosion is threatening important sites in Northwest Alaska, where the Bering Land Bridge once connected Asia to North America and was a pathway for human migration.

Food security, health and safety

Years ago, said Aleut leader Larry Merculieff, elders pointed to lesions appearing on salmon skins and predicted hard times ahead for the fish that is a staple of traditional diets and rural household incomes.

It turns out that there is a climate explanation, Merculieff said. Faster and earlier snowmelt has changed hydrology patterns, flushing rivers and streams early but leaving water levels lower than they would be if snowmelt were gradual, he said. Low water means salmon have little space to swim, and the lesions came from "salmon going against rock and not water," he said.

Warmer conditions, changing weather patterns and extreme weather events have myriad effects on Alaskans who depend on wild foods for their nutrition and income.

Rivers that were once dependably frozen for winter travel are treacherous when ice is thin. Lack of snow strands rural travelers.

Warmer waters also mean a northward movement of disease-carrying pathogens.

A stomach-turning ailment that struck tourists who ate Prince William Sound oysters in 2004 turned out to be the northernmost documented case of *Vibrio parahaemolyticus*-caused illness among humans. Algal blooms proliferate in warm conditions, and it is suspected that 30 dead whales found this summer in the western Gulf of Alaska succumbed to toxins produced by such a bloom. Ripple effects of paralytic shellfish poisoning appear to be spreading through the marine food web, new research shows.

Warming also allows contaminants to be released into the food system. Thawing permafrost and eroding soils free sequestered elemental mercury that adds to pollution carried in the atmosphere and oceans from faraway industrial and coal burning operations. Persistent organic pollutants like pesticides and PCBs that were once trapped in sea ice are being released into the water column as the ice thaws.

Ocean acidification pronounced in Alaska waters

Nearly a third of the carbon released into the atmosphere winds up absorbed by the oceans, according to NOAA. That process slows the greenhouse effect and the resulting climate warming, but it comes at a cost — changes to the oceans' chemistry makes their waters more acidic. More acidic waters degrade the calcium that is needed by a variety of shell-building organisms — from tiny pteropods that form much of the base of the ocean food web to big king crabs that fetch premium prices in seafood markets.

Globally, the oceans have become 30 percent more acidic since the start of the Industrial Age, according to NOAA. For Alaska, the characteristics that make the marine waters rich with fish and wildlife — and a major global seafood harvesting center — put it at enhanced risk for acidification.

Cold waters that benefit salmon and other fish hold more carbon dioxide. Alaska's marine waters, underlain by a broad continental shelf, are relatively shallow, allowing absorbed carbon to concentrate in the water column. The rich supply of sea life emits yet more carbon through processes of decay. And ocean currents carry carbon from around the world to waters off Alaska

Come winter, the Bering Strait holds the world's most acidic ocean waters, partly because of natural characteristics and partly because of ongoing changes. Changes have been particularly rapid in the Beaufort Sea, where waters have already become so altered that they hold, on average through the year, too little calcium to support shell-building organisms. Waters in the Chukchi and Bering seas, for now buffered a bit by plentiful carbon-consuming phytoplankton blooms, are expected to reach similar milestones in the future.

Accelerated glacier melt contributes to the changes. The outpouring of freshwater into the ocean dilutes natural calcium, and the glacial melt carries carbon that contributes to the load in the water.

'Cold Rush'

When Swedish scientist Svante Arrhenius theorized more than a century ago that carbon emissions from fossil-fuel burning would warm the Earth significantly, he believed that would be a good thing. The "hothouse effect," he hypothesized, would stimulate plant growth and usher in a global agricultural boom.

Some Alaskans are also embracing what they see as the upside of northern climate warming.

They look forward to the thousands of jobs and billions of barrels of new oil that might be produced if Royal Dutch Shell, drilling this summer in the Chukchi Sea, is successful in its Arctic offshore exploration program. They hope that Northwest Alaska, and possibly the hub city of Nome, could emerge as a thriving port, providing much-needed maritime assistance while generating jobs and income in a region that has struggled with poverty. Members of the Alaska Legislature are touting sea ice melt as an opportunity to open up more northern mines, including those extracting coal, considered the most polluting of fossil fuels.

But new economic development carries its own complications. Increased ship traffic and oil drilling means increased likelihood of spills in a remote region where emergency response is difficult and where the U.S. Coast Guard takes extraordinary measures to maintain a seasonal presence. It means:

• Air pollution and industrial noise that can harm sea life;

• Expected Arctic shipping routes that overlap precisely with the well-used seabird migratory routes there;

• The specter of black carbon from ship exhaust darkening melting sea ice, though that issue was not addressed in the International Maritime Organization's new Polar Code for shippers;

• The United States and four other Arctic nations are trying to persuade the rest of the world to refrain from commercial fishing in the yet-unexploited and little-understood international waters of the Arctic Ocean.

Development "has its blessings and its curses, that's for sure," said Merculieff, who served as a state commerce commissioner, among other positions in government and in Native organizations. He sees in the new commercial "Cold Rush" echoes of the past, when armies of commercial whalers and fur traders converged on Alaska to exploit its resources for riches. The industrial-scale hunts of centuries past triggered a cascade of ill effects, some of which linger today, Merculieff said.

"They didn't have a clue as to what they were doing," he said.

Could history repeat itself? He worries that too much development too fast will alter the future of an already-stressed region. "Things have changed so quickly, we can't grasp what is happening now," he said. "To plan these types of activities when we don't know what effects there are going to be and when we don't know what effects the current activities have, it's not good."

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About this Author

Yereth Rosen

Yereth Rosen has been a journalist in Alaska since 1987. For most of that time, she was the sole Alaska-based reporter for Reuters. She has been reporting on energy issues, the environment, politics and all things Alaska – from oil spills to sled-dog races. She enjoys running, skiing and other outdoors pursuits. She lives in Anchorage with her family.

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Global Landscape of Climate Finance 2015

November 2015

A CPI Report

Authors

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Descriptors

Sector	Climate Finance
Region	Global
Keywords	Climate Finance, Private Finance, Public Finance, Tracking, Climate Policy
Related CPI Reports	• The Landscape of Climate Finance 2011 • The Landscape of Climate Finance 2012 • The Global Landscape of Climate Finance 2013 • The Global Landscape of Climate Finance 2014
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About CPI

Climate Policy Initiative works to improve the most important energy and land use policies around the world, with a particular focus on finance. An independent organization supported in part by a grant from the Open Society Foundations, CPI works in places that provide the most potential for policy impact including Brazil, China, Europe, India, Indonesia, and the United States.

Our work helps nations grow while addressing increasingly scarce resources and climate risk. This is a complex challenge in which policy plays a crucial role.

Global Landscape of Climate Finance 2015

As 2015 draws to a close, there is a strong hope that the Paris Climate Summit could represent a turning point in the global fight against climate change. A transformation of global financial and energy systems is needed to make a low-carbon and climate-resilient global economy the 'new normal', and to support the implementation of the climate actions already proposed by more than 150 countries.[1]

Global climate finance flows reached at least USD 391 billion in 2014 as a result of a steady increase in public finance and record private investment in renewable energy technologies.

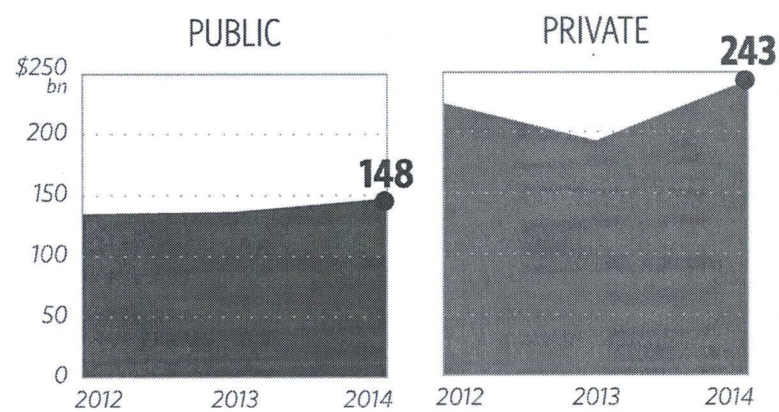
The Global Landscape of Climate Finance 2015 presents the most comprehensive information available about which sources and financial instruments are driving investments, and how much climate finance is flowing globally. It aims to provide an updated picture on how, where, and from whom finance is flowing toward low-carbon and climate-resilient actions globally, and to improve understanding of how public and private sources of finance interact. With this global outlook, it provides a complementary, though broader perspective to a recent report prepared by CPI in collaboration with the OECD (OECD, 2015) to track progress towards commitments made by developed country Parties to the UNFCCC to mobilize USD 100 billion annually for climate interventions in developing countries by 2020.

After levelling off in 2012, and declining in 2013, the amount of climate finance invested around the world in 2014 increased by 18%, from USD 331 billion to an estimated USD 391 billion.[2]

Public climate finance is on the rise, with contributions by governments and intermediaries reaching at least USD 148 billion (range of USD 144-152 billion) in 2014, an 8% increase from 2013 levels, and a 10% rise from 2012. Public actors are increasingly recognizing the benefits of climate action for achieving their goals, and that managing climate change is in their national economic interest.

Private investment in renewable energies grew by 26% in 2014 after two years of decline, resulting in record volumes of new installed capacity (103 GW). With USD 243 billion, private investment remained the largest source (62%) of global climate finance captured in *Landscape 2015*. Policy and market signals, predictable and stable profits, and the strategic potential of investments are key determinants of private actors' financing behavior. Obtaining the requisite technical expertise, gaining access to finance, and managing project risks remain key challenges for enabling shifts in the patterns of private climate finance investments.

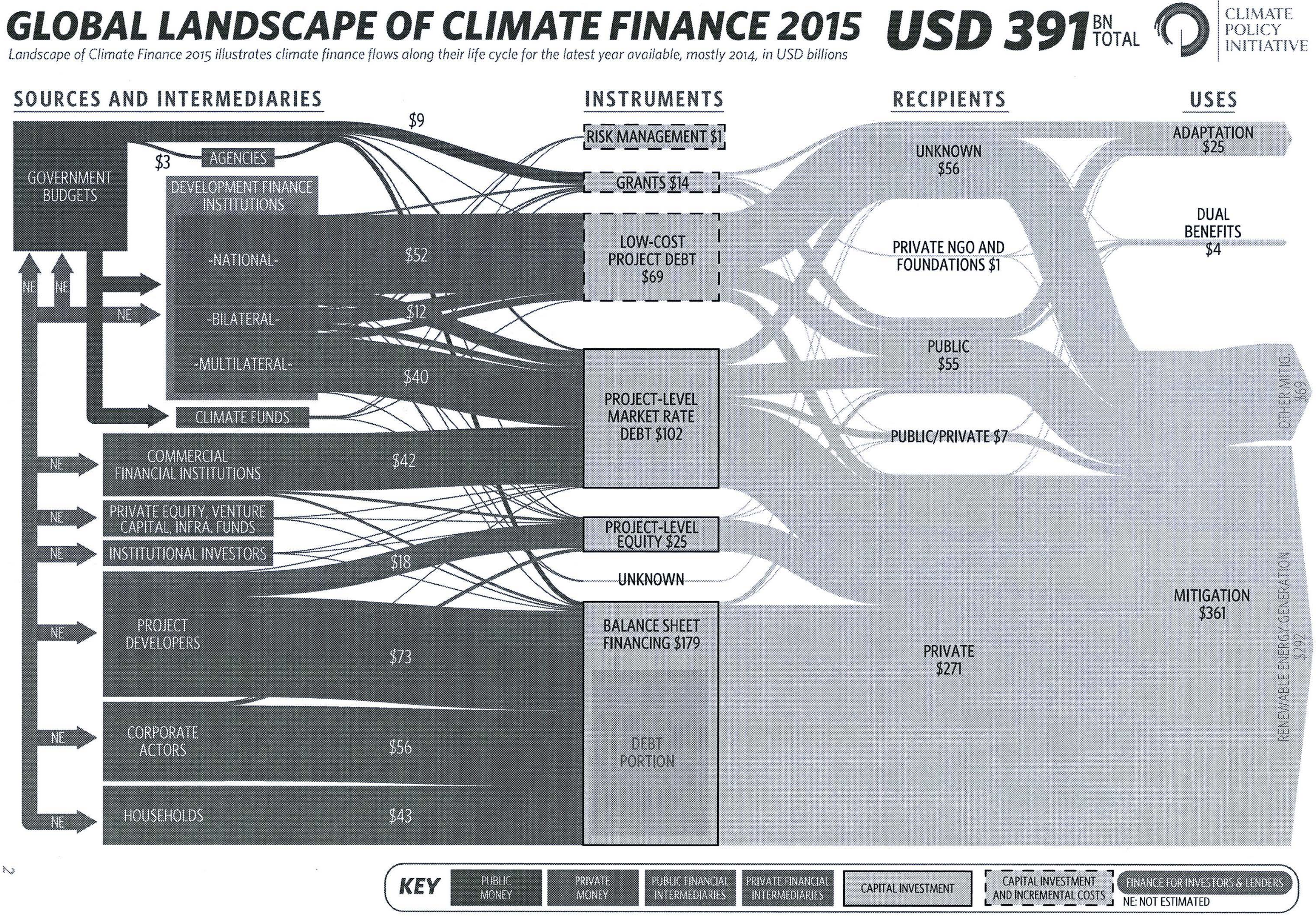
Figure 1. The evolution of total public and private finance, 2012-2014, in USD billion



Source: CPI analysis.

1 So-called 'Intended Nationally Determined Contributions (INDCs)".
2 Figures represent annual flows for the latest year available, variable according to the data source. Flows are rounded to produce whole numbers and, as a result, the figures may not add up exactly. Throughout the document, the mid-point is presented where ranges of estimates are available.

Figure 2. The Global Landscape of Climate Finance 2015



Sources and Intermediaries

PUBLIC SOURCES AND INTERMEDIARIES

In 2014, public actors and intermediaries committed USD 148 billion, or 38% of total climate finance flows.

Public actors including governments, bilateral aid agencies, Climate Funds, multilateral, bilateral and national Development Finance Institutions (DFIs) drive the global climate finance system by reducing the costs and risks of climate investments, strengthening knowledge and technical capacity, and building the track record needed to enhance confidence in such investments.

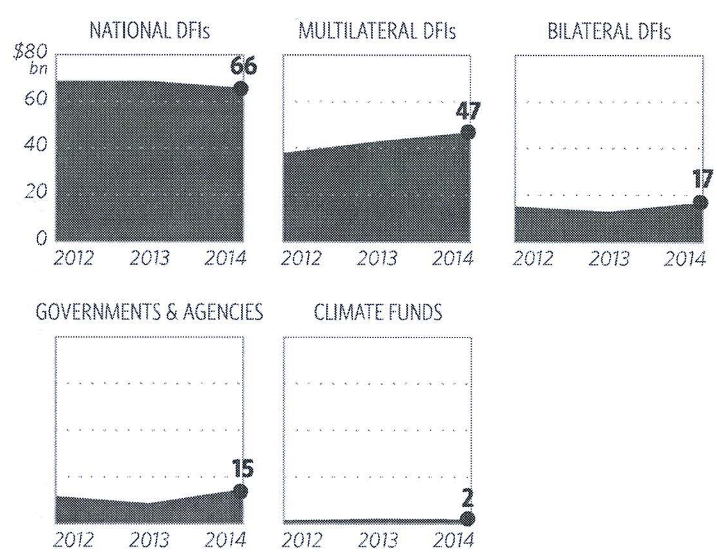
In 2014, DFIs' commitments reached USD 131 billion - 33% of total climate finance flows - the highest one-year total since we began mapping flows of global climate finance in 2011, with the possibility that the actual rise is higher than what is captured by our numbers.[3]

National DFIs contributed more than half of total DFI flows, USD 66 billion, mostly through concessional loans. Multilateral DFIs committed USD 47 billion[4] while bilateral DFIs provided almost USD 17 billion. 2014 data signal an upward trend in DFIs' commitments notwithstanding year-to-year fluctuations.

Climate finance commitments represent a growing share of DFIs' business volume, highlighting that climate change considerations are increasingly integrated into their operations. For the DFIs surveyed, climate finance commitments ranged from 11% to more than 50% (27% on average) of their total 2014 investments. These DFIs have made progress toward, or in some instances surpassed, their respective investment targets for climate action, which range between 20% and 50% of new annual investments.[5] Some of these DFIs recently announced more ambitious targets,[6] and one multilateral DFI reported that investments in renewables overtook those for thermal power generation for the first time in 2014.[7]

Multilateral and national Climate Funds approved around USD 2 billion for projects with adaptation and mitigation benefits. The longer term trend shows that their funding commitments have grown notably since 2011,[8] and the expectations are that this trend is likely to continue considering that the Green Climate Fund (GCF) is set to fund its first projects.[9]

Figure 3. Breakdown of total public finance by actor, 2012-2014 in USD billion



Source: CPI analysis

3 Figures do not fully reflect the evolution of DFIs' climate actions because due to a lack of 2014 data for a group of national DFIs at the time of preparing the study (April-October 2015), we assumed that a number of national and sub-regional DFIs committed the same amount as in 2013 (USD 83 billion) (see methodology document, available here). The increase observed in our numbers could be higher considering that, for instance, according to CDB (2014 and 2015) the Chinese Development Bank - which is one of the banks for which 2014 data was unavailable at the time of writing - increased its green finance lending by 18% in 2014.

4 Our number is not the same as the one in the MDBs joint report (AfDB et al. 2015). This is because of the different geographic coverage, the inclusion of the Development Bank of Latin America (CAF) among the multilateral DFIs, and the exclusion of external resources managed by MDBs and of financing extended in the form of risk management instruments; (see methodology document, available here).

5 See e.g. (IFC, 2015a); AFD (2015) and EBRD (2015a).

6 See ADB (2015); AfDB (2015); EBRD (2015b) and IDB (2015).

7 See EBRD (2015a).

8 See Section 4 of the methodology document, available here.

9 In November 2015, at its 11th meeting, the GCF's Board approved funding for eight proposals. See GCF (2015).

We captured a further **USD 15 billion on average (USD 12-19 billion) of direct public contributions from governments, ministries, and bilateral agencies to climate projects**, mostly directed to low- and middle-income countries.[10] In line with the trends observed in development aid,[11] these flows rose steadily over the past few years, both in absolute terms and as a proportion of total bilateral Overseas Development Assistance (ODA).[12]

PRIVATE SOURCES AND INTERMEDIARIES

Private actors, who range from single households to multinational corporations and their intermediaries,[13] hold the resources to drive the shift towards low-carbon and climate-resilient growth.

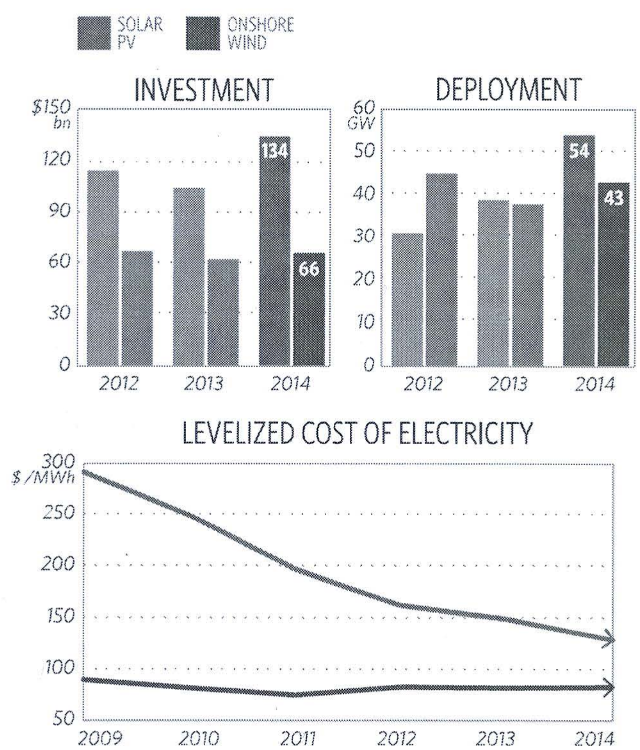
In 2014 private actors invested USD 243 billion in renewable energies, up 26% on the previous year's total thanks to a record 98 GW of solar PV and onshore wind capacity installed.[14] A significant portion of this increase reflects a 36% (USD 22 billion) growth in new renewable energy investment in China, which accounted for 34% of all private finance in 2014 and was driven by supportive government policies, incentives, and ambitious targets.[15]

Energy investments are achieving record levels of deployment at lower cost than ever. The 26% increase in investment observed in 2014 is noteworthy considering the decreasing costs for some technologies and that a strengthening dollar in 2014 likely diminished private climate finance estimates as measured in USD.[16]

Private finance increased by nearly USD 50 billion in 2014 driven mainly by a record amount of new renewable energy deployment, particularly in China.

Some renewable energy technologies are edging closer to becoming fully cost competitive with fossil fuels around the world. The levelized cost of electricity (LCOE) for utility-scale solar photovoltaics (PV), for instance, has fallen by around half in the past five years while solar PV module prices decreased by three-quarters between 2009 and 2014; the LCOE of onshore wind has fallen by about 8%-15% since 2009.[17] Across all technologies, our data show that the unit costs of deployed capacity fell from USD 2.3 million/MW installed in 2013, to USD 2.2 million/MW in 2014.

Figure 4. Private investments in onshore wind and solar PV, 2012-2014 in USD billion and LCOE (in USD/MWh)



Source: CPI analysis based on IRENA (2015); Bloomberg (2015) and BNEF (2015a; 2015b)

10 The lower bound includes ODA and Other Official Flows marked as having 'climate change mitigation' or 'adaptation' as its principal objective; the upper bound includes activities with a 'significant' climate change objective as reported in OECD-DAC CRS (2015b). To avoid double counting, our estimate includes bilateral commitments only and excludes USD 8.4 billion of finance provided by bilateral DFIs (the French Development Agency [AFD], Japan International Cooperation Agency [JICA], and Germany's KfW Development Bank), or channeled through Climate Funds (USD 180 million), which are tracked in different sections of the Landscape.

11 With a total of USD 134.8 billion in net ODA in 2013, development aid rose by 6.1% in real terms marking a rebound after two years of falling volumes (OECD, 2014a).

12 In the period 2011-2013, total bilateral climate-related ODA commitments represented 15% of total bilateral ODA, compared to 11% over the 2008-2010 period (see OECD, 2015e)

13 See methodology document for further details, available here.

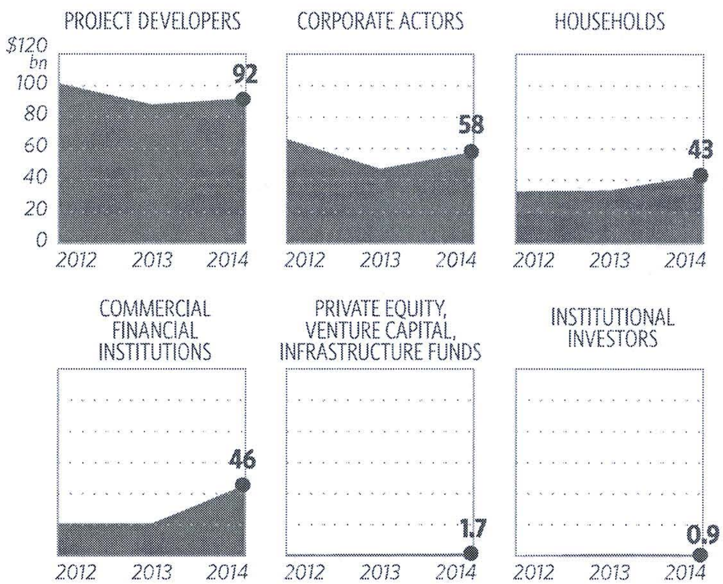
14 Due to data availability issues, the Landscape 2015 only captures private investments in renewable energies sourced from BNEF (2015a), BNEF (2015b). Solar Heating Systems data are derived from Mauthner et al. (2015), REN21 (2015). See methodology document for details, available here.

15 See FS-UNEP (2015) and REN21 (2015) for more details on the policies and targets in place.

16 BNEF (2015e).

17 IRENA (2015) and Bloomberg (2015). For onshore wind, the lower bound refers to the global average, while the upper bound excludes Asia, China in particular, whose cost developments drive the global average LCOE (IRENA, 2015).

Figure 5. Breakdown of total private investment by actor, 2012-2014 in USD billion



Source: CPI analysis

Note: A significant portion of the increase observed in commercial banks' financing, is likely due to a change in BNEF's accounting for Chinese wind and solar projects in 2014, which now assumes certain debt-to-equity ratios when total project values are known, but financial details are not disclosed. These projects now assume a 70%/30% ratio for solar projects and an 80%/20% ratio for wind projects, reflecting their respective levels of state support (personal communications with BNEF staff in June 2015). This more accurate approach is likely to have more correctly classified debt finance that might once have been allocated to equity providers as "balance sheet financing" - BNEF's default classification when information is missing.

Project developers remained the most prominent private investor class in 2014, with USD 92 billion, or 38% of total private climate finance.[18] Most project developers' financing targeted onshore wind projects (USD 45 billion or 49% of their total) and originated from, and was invested in, East Asia and the Pacific region (46%), Western Europe (25%) and the Americas (15%).

Corporate actors (non-energy corporations and manufacturers) invested USD 58 billion, up from 2013 by almost USD 11 billion, representing about 24% of overall private finance. Solar PV attracted most of their resources. Households' investments accounted for USD 43 billion (18% of the total), and grew roughly in the same proportion as overall private climate finance since 2013.[19] Households invested almost their entire resources in solar PV and thermal systems, typically rooftop and other small-scale solar installations (< 1 MW). Mostly, such investments took place in China, Japan, and the US, driven by policy support schemes and declines in installation costs.[20]

Commercial financial institutions provided USD 46 billion or 19% of total private climate finance in 2014, mostly for established-technology renewable energy projects (solar PV and onshore wind) in East Asia and Pacific and the Americas. Only 13% of their financing went to other technologies.

DFIs have increasingly involved commercial local banks in on-lending or co-financing energy efficiency, renewable energy, and climate-resilient projects by building their technical capabilities for assessing environmental standards and risks of such projects, as well as demonstrating their attractiveness.[21] Commercial banks' engagement in climate action is critical given their important intermediary role in originating investments and lending to corporates and households for small-scale projects.

Finally, we also tracked about USD 2.6 billion of direct investment from private equity, venture capital, infrastructure funds, and institutional investors, slightly (USD 0.4 billion) lower than in 2013. While this is partly due to data limitations,[22] institutional investors' direct primary investments in renewable energy projects remain small (less than USD 1 billion) compared to the scale of their assets globally and their growing fossil fuel divestment commitments.[23]

18 The category "project developers" refers to dedicated energy project developers, engineering, procurement and construction (EPC) contractors, utilities and independent power producers.

19 The "household" category refers to family-level economic entities, high-net-worth individuals, and their intermediaries.

20 See REN21 (2015); IEA (2015).

21 See e.g., the EBRD's Medium Size Sustainable Energy Finance Facility (MidSEFF) (EBRD, 2015c and Oliver and Stadelmann, 2015); the EBRD recent structuring of two credit lines with Turkish commercial banks for, inter alia, the provision of finance for water-efficient technologies (EBRD, 2014); or IFC's Climate Assessment for Financial Intermediaries investment (IFC, 2015b).

22 The global Landscape reports focus on project-level primary financing data thereby excluding activities that are more typical for institutional investors, such as re-financing, or equity and debt investments into project developers, manufacturing companies, and aggregation vehicles like funds. The UNSG (2015) states that leading Pension Funds (CalSTERS, APG and PensionDanmark) have collectively made about USD 29 billion in low-carbon investments, and are thereby on track to achieve the commitment made at the UN Secretary-General's Climate Summit in 2014 to allocate more than USD 31 billion to such investments by 2020. The report does not specify whether these USD 29 billion represent primary or secondary transactions.

23 OECD (2014b) estimates that in 2013 institutional investors, including public and private pension funds, insurance companies, Sovereign Wealth Funds, mutual funds and foundations, held an estimated USD 93 trillion of assets. Recently, prominent institutional investors have joined fossil fuel divestment movement see Schwartz (2015), Chabria (2015), UNSG (2015) and UN (2014).

Box 1. Accounting gaps

Due to data limitations, *Landscape 2015* does not capture:

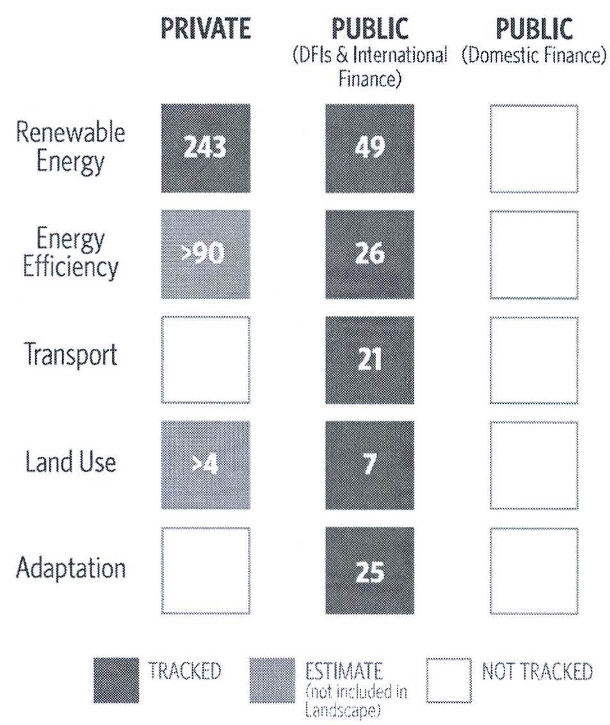
- The value of public budgets dedicated to domestic climate action beyond some national DFIs' commitments and financing tracked in BNEF,[1] as well as the level of climate finance that governments contribute as shareholders of companies;[2]
- Private investments in energy efficiency, including transport, land use and adaptation.

These gaps can be significant and have substantial implications on our findings, for example, by skewing the sectoral spread of total climate finance toward renewable energies.

Existing analysis and estimates help to get a sense of the probable magnitude of these gaps, highlighting that:[3]

- Energy efficiency investments range globally between USD 90-365 billion;[4]
- Land use (forestry) investments are estimated to be around USD 4.2 billion annually;[5]
- Adaptation investments data remain elusive, but early evidence from the portfolio of MDBs highlights that USD 270 million of their financing made 26 private projects with a total value of USD 5.5 billion more climate-resilient;[6]
- Domestic public budget for climate-related development not captured in our report could reach at least USD 60 billion a year,[7] and range between 0% and 15% of national budgets,[8] or represent about 7.5% of total national capital formation.[9]

Figure 6. Finance captured by Landscape 2015 and estimates of the size of data gaps (in USD billion)[10]



Source: CPI analysis

1 Identified through the project-level assessment of BNEF (2015a) (see methodology document).

2 This year we identified at least USD 10 billion of direct investment from state-owned enterprises, mostly in China and India which, for consistency with past years' editions of the global Landscape reports and data limitations, we classified as private finance. We acknowledge that based on insights from past years' data analyses, this could be significantly higher.

3 We don't include those estimates in this report because of the lack of reliable project-level data for these sectors.

4 The lower bound refers to IEA (2015b) estimate of global energy efficiency investment in buildings only, while the upper bound to HSBC (2014) for investment in buildings, industry and transport. There are three main challenges for tracking energy efficiency investment: first, it is difficult to assess a baseline for energy efficiency, second, energy efficiency investments are integrated into larger transactions (e.g. new buildings) and are difficult to disaggregate, and third, these investments are decentralized and often taking place at household or small enterprise level.

5 This estimate refers to investments in selected commodities only. See Falconer et al. (2015 p. 22) for further details.

6 This refers to MDB private sector-oriented adaptation finance in 2013-14. See Vivid Economics (2015).

7 Buchner et al. (2014) estimate based on national estimates for a small number of countries.

8 See CPEIR (2015) database and UNDP (2015) which compile data from the Climate Public Expenditure Review undertaken by UNDP in a number of developing countries. The range presented refers to the average of the latest available four years per country. Drawing on research from three countries in sub-Saharan Africa, Bird (2014) shows that domestic spending can be significantly higher on adaptation than on mitigation.

9 I4CE (2015); this report presents the landscape of climate finance in France, estimating that climate-related investments in France in 2013 amounted to EUR 32 billion.

10 The "land use" figure under public budgets covers projects qualifying as mitigation, adaptation and dual benefits in alignment with Falconer et al. (2015).

Instruments

Available data continues to show that private actors rely primarily on their own balance sheets to finance renewable energy projects (corporate and households' financing), which accounted for USD 175 billion or 72% of total private investment in 2014. Mostly, they relied on balance sheet financing to invest in solar PV projects in high-income and upper-middle income countries such as Japan, the US and China.[24]

The reasons for investors' reliance on balance sheets can vary, including the size of the project (it can make more sense to finance small projects internally), difficulties in securing debt, high costs of capital, and other factors. However, the predominance of balance sheet financing in our figures also reflects the data to which we had access, the quality of which can be affected by incomplete financial disclosures for many private climate finance transactions.[25]

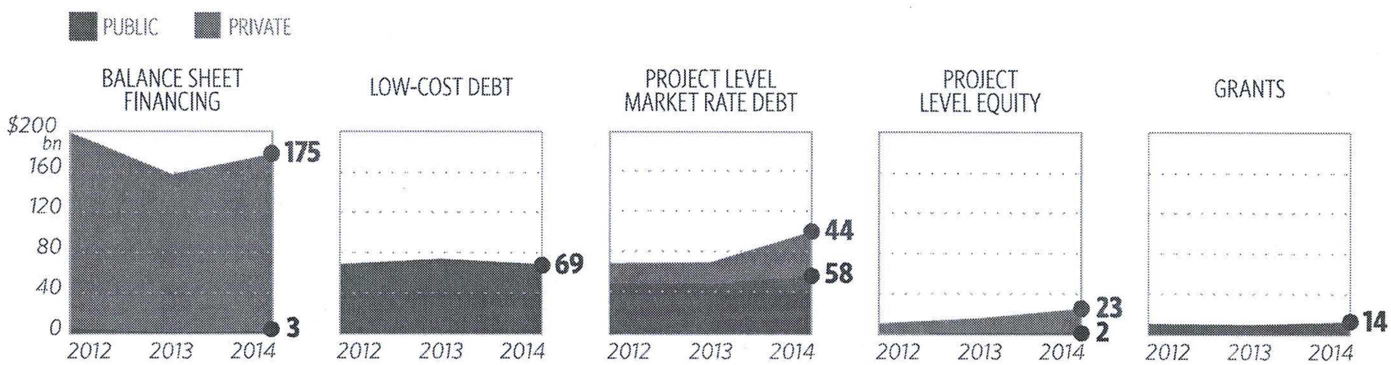
Public actors delivered more than half of their financing in the form of grants and low-cost loans, which accounted for 10% (USD 14 billion) and 47% (USD 69 billion) of total public finance respectively. Over the past three years, grants' share of total public finance averaged 9% (USD 13 billion), while the share of low-cost loans averaged around 50% (USD 71 billion), both with a +/- 10% from 2012 levels attributable to data uncertainties.

Well-established instruments financed the bulk of projects in 2014, but investors are experimenting with new approaches.

Grants made up more than half of government entities' and Climate Funds' respective commitments, and most of those for which we had project-level detail supported projects in low and lower-middle income countries - 34% of total grants (USD 5 billion).[26] Low-cost loans (including concessional loans) accounted for the majority of bilateral and national DFIs' financing - 64% (USD 11 billion) and 78% (USD 52 billion) respectively. 43% of low-cost loans (USD 30 billion) helped reduce the capital costs of mitigation and/or adaptation projects in high- and upper-middle income countries.[27]

Public concessional or lower-than-market-rate finance, including loans with longer tenors and grace periods, play a catalytic role by supporting the establishment of policy frameworks, strengthening technical capacity, lowering investment costs, and reducing investment risks for the first movers in a market. Country macroeconomic and institutional conditions and the existence and level of project-level revenues are key determinants of the appropriate combination of grants versus loans.

Figure 7. Breakdown of total climate finance by instrument, 2012- 2014 in USD billion.



Source: CPI analysis
Note: We do not have details on instruments for about USD 0.5 billion.

24 Due to data availability issues, we could not allocate 8% of total private finance per countries level of income.

25 Improvements in BNEF accounting methodology have helped to shed light on significant financing for Chinese renewable projects that would once have been classified as balance sheet finance, the default option when information are lacking.

26 While we were able to allocate 100% of total public finance to a specific regional or transregional destination, due to data limitations we could not allocate 41% of the total by country.

27 Ibid 26.

Multilateral DFIs provided 84% (USD 40 billion) of their commitments as market-rate loans - often blended with governments and Climate Funds' concessional resources - primarily for sustainable transport and renewable energy generation projects (35% or USD 14 billion and 26% or USD 10 billion of total market debt extended respectively). Around one third of the about USD 2 billion external resources managed by multilateral DFIs for which we have details, supported the financing of greenfield renewable energy generation, and mostly targeted projects in Sub-Saharan Africa, East Asia and the Pacific, and Latin America and the Caribbean.

Multilateral DFIs also provided a significant portion of climate finance, around USD 1.5 billion of their resources, in the form of risk management instruments.[28] These instruments, which can encompass credit guarantees, political risk insurance, and contingency recovery grants, can play a critical role in enabling private investments in the context of political uncertainty, or to back private equity and debt financing in countries with more challenging investment environments.[29] Due to the risk of double counting, these are not captured as part of our total estimate and are not officially supported export credit guarantees.[30]

Investors are also experimenting with new approaches to finance climate-relevant projects. YieldCos, green bonds, and the instruments developed under the *Global Innovation Lab for Climate Finance* are among the most significant examples. The emergence and rapid growth of some of these instruments highlights that investors have unfulfilled needs for risk diversification and revenue/cost savings certainty.[31]

28 DFIs also delivered an additional USD 71 million in Climate Funds' resources. Overall, in our assessment of international climate flows we identified, but excluded USD 2.5 billion extended in the form of risk management instruments.

29 See e.g. Micale, Trabacchi and Boni (2015).

30 OECD (2015e) states that Official Export Credit support for renewable energy generation in 2013 amounted to USD 2.6 billion globally, more than 50% of which to projects in low and middle-income countries, mostly for wind generation. These can encompass officially insured, guaranteed or directly provided credit and are not accounted in Landscape 2015 due to the risk of double counting, and the lack of project-level data that does not allow us to carve out the credit portion.

31 Fifteen US and European YieldCos grew in value from USD 12 billion in 2013 to more than USD 20 billion in 2015 (see BNEF, 2015c). Despite this, however, recent market contractions highlight that additional adjustments to this new financing vehicle may be needed in order to meet the needs of a variety of different investor classes (see BNEF, 2015f and Abramskiehn et al. 2015). Green bonds issuance reached USD 36 billion in 2014 - over a threefold increase from the previous year, 37% of which from corporate issuance (CBI, 2015). See also ClimateFinanceLab.org for further details on Lab instruments.

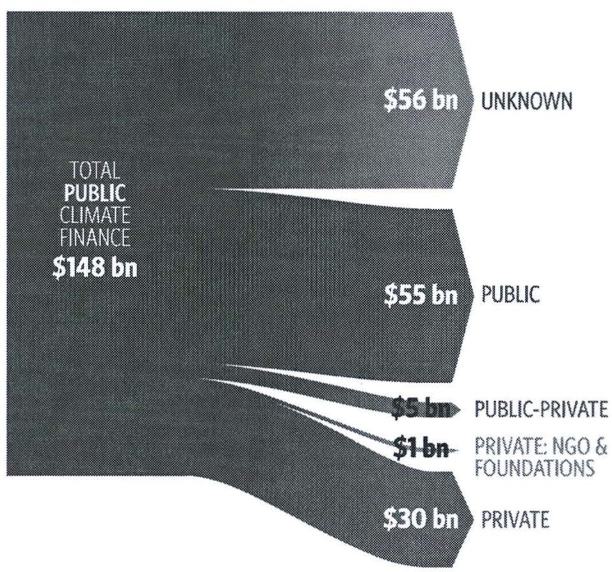
Recipients

At least USD 31 billion or 21% of public finance went to private entities (including NGOs). 41% (USD 61 billion) went to public or public-private entities. Private-oriented finance went mostly to mitigation projects in upper-middle or high- income countries.[32] 4% (about USD 1.4 billion) went to adaptation projects.

Our understanding of the links between public and private finance across the lifecycle of flows has progressed, but is hindered by incomplete information. Details on recipients are not yet consistently tracked or reported across data sources. As a result, we could not identify the initial recipients of USD 56 billion of public finance (38% of the total). Outstanding methodological and definitional issues about the public vs. private nature of recipients still hinder tracking efforts.

It is worth noting that recent efforts on developing standards for measuring mobilized private finance[33] will help to further enhance our understanding of the impact of public interventions on private climate action.

Figure 8. Total public climate finance breakdown by type of recipient, 2014, in USD billion



Source: CPI analysis

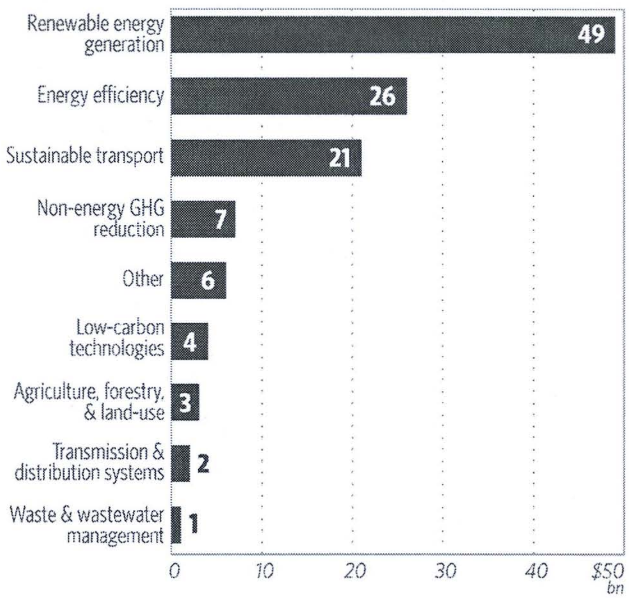
32 This is for projects where we had country-level details. We could not allocate by country level of income 20% or USD 6.2 billion of private-oriented mitigation finance originating from public sources.

33 For tracking progress see International Financial Consulting (2015 [unpublished]); Stumhofer et al. (2015); TWG (2015); OECD Research Collaborative on Tracking Private Climate Finance and, for preliminary estimates, OECD (2015a).

Final Uses

Mitigation accounted for 93% of total climate finance in 2014, or USD 361 billion, 81% of which went toward renewable energy. The heavy bias toward renewable energy reflects the lack of data for private investments beyond this sector.

Figure 9. Breakdown of total public mitigation finance by sector, 2014, in USD billion



Source: CPI analysis

Large and small-scale solar PV and onshore wind projects attracted the majority of renewable energy private investment, totaling USD 134 billion and USD 66 billion respectively. We estimate that the implementation of large-scale projects was financed for USD 71 billion off balance sheets, through special purpose vehicles (SPV) which imply limited or no recourse to the sponsors of the project.

Public climate finance focused on three main sectors: renewables, representing 33% of the total (USD 49 billion), energy efficiency (18% or USD 26 billion), and sustainable transport (14% or USD 21 billion). Projects in these sectors benefited from most of the low-cost loans we captured. Renewables benefited from the largest single share of grants.

Adaptation finance reached USD 25 billion or 17% of all public climate finance in 2014. This figure, roughly the same as last year, represents a partial and uncertain estimate as it is affected by the different accounting approaches used for tracking finance, and tracking gaps for domestic budgets and private investment.

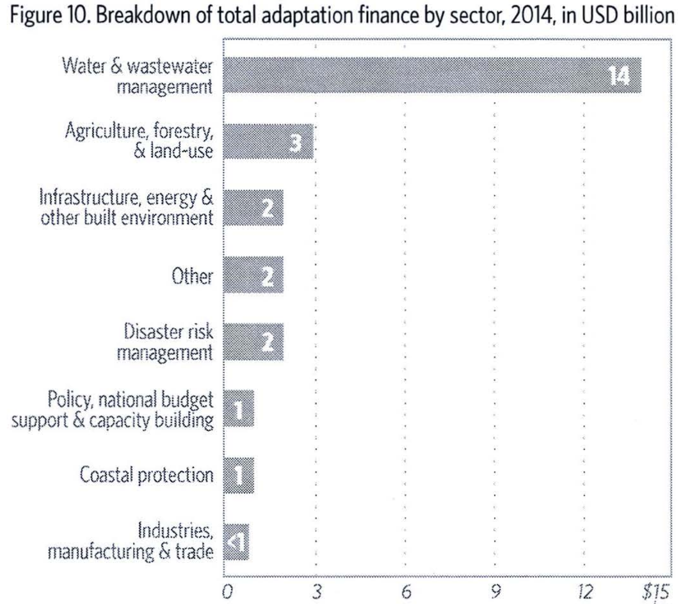
Increased climate finance flows in 2014 funded record levels of low-carbon activities.

Nevertheless, there are two noteworthy developments to flag:

- First, the number of private sector-oriented adaptation projects in DFIs' portfolios has increased since our mapping began, and progress has been made in designing approaches and business models to drive private investment in climate resilience.[34]
- Second, the adoption of *Common Principles for Climate Change Adaptation Finance Tracking* from a number of bilateral, national, and multilateral DFIs as well as the fine-tuning of the OECD's Rio marker definition to reflect the criteria applied by MDBs, represents a significant milestone towards harmonization.

Investments in land use mitigation and/or adaptation reached USD 7 billion on average (USD 6-8 billion). Agriculture, forestry and other forms of land use generate around a quarter of global greenhouse gas emissions.[35] Understanding land use finance flows can help identify how to redirect public and private finance towards practices that can enhance agricultural productivity, while maintaining or enhancing GHG sinks and reservoirs.

Figure 10. Breakdown of total adaptation finance by sector, 2014, in USD billion



Source: CPI analysis.
Note: Difficulties comparing different accounting approaches for adaptation may distort this sectoral distribution.

34 See Trabacchi and Mazza (2015) and Vivid Economics (2015).
35 IPCC (2014).

Geographies

The majority of finance flows remained within the country of origin.

About 74% of total climate finance flows, and up to 92% of private investments were raised and spent within the same country, confirming the strong domestic preference of investors identified in previous years' *Landscape* reports and highlighting the importance of domestic frameworks for attracting investment.

East Asia and the Pacific remained the largest destination of climate finance flows, accounting for 31% of the total or USD 119 billion, up by 22% from 2013. China alone accounted for 22% (USD 84 billion) of total finance.[36] Western Europe was the second main destination with 24% of the total or USD 93 billion, up by 3% from 2013 despite the challenges faced by renewables in some countries due to policy changes or uncertainties.[37] The Middle East and North Africa region and South Asia experienced a significant increase in climate finance investments from 2013, up by 114% and 33% respectively.

The bulk of adaptation investments target the climate change vulnerabilities of countries in East Asia and the Pacific region, Sub-Saharan Africa and Latin America and Caribbean, 46% (USD 12 billion), 13% (USD 3.3 billion) and 12% (USD 3 billion) of total adaptation finance respectively.

The Way Forward

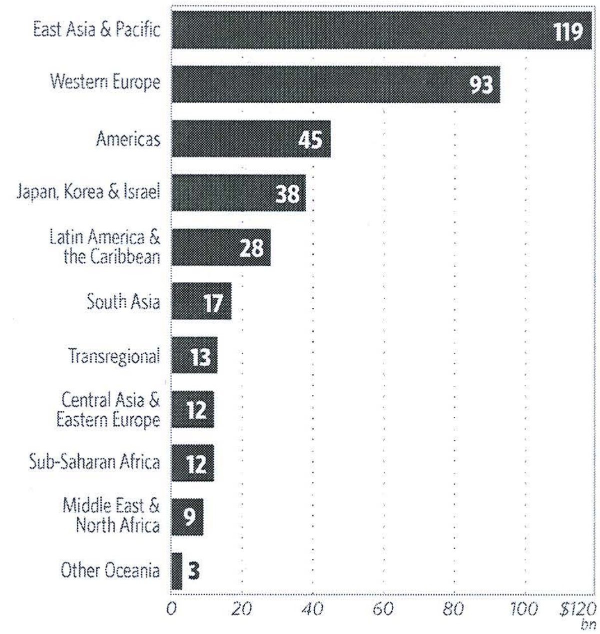
With at least USD 391 billion invested in low-carbon and climate-resilient actions more climate finance than ever flowed in 2014. Nevertheless, efforts need to continue and must expand their geographic spread. Around USD 16.5 trillion are required from 2015 to 2030[38] to reorient the global energy system to one that is consistent with the 2°C goal, and more would be needed to reduce land use emissions and enable societies and economies to adapt to the impacts of climate change.

36 This reflects the data for which we had country-level details.

37 See REN21 (2015).

38 IEA (2015).

Figure 11. Total climate finance breakdown by region, 2014 in USD billion



Source: CPI analysis.

The good news is that there are opportunities to scale up climate finance and shift the pattern of growth:

First, enhance tracking efforts to further improve the transparency, comprehensiveness, and consistency in accounting approaches. Since the first edition of the *Global Landscape of Climate Finance* in 2011, significant progress has been made towards getting a comprehensive picture of climate finance. The ongoing efforts[39] across the climate finance tracking community have laid the foundation for further collaborative work to address outstanding comparability issues and gaps. Agreement on what counts and how it should count can help to strengthen trust and international cooperation. Ultimately, a proper measurement, tracking, and reporting system is a critical building block to ensure finance is used efficiently and targeted where it is needed the most.

39 This refers to: the activities within the UNFCCC Standing Committee on Finance and the OECD (the DAC and the OECD-hosted Research Collaborative); the work of 19 bilateral climate finance providers on a common understanding of mobilized climate finance, and the common principles for tracking mitigation and adaptation finance by a group of Multilateral Development Banks and of bilateral, national and sub-regional DFIs under the International Development Finance Club.

Second, get domestic investment policy and support frameworks right. *Landscape 2015* shows that three-fourths of global climate finance, and more than 90% of private investment, originates in the same country in which it is spent.

Deficient frameworks can inhibit the incentives for investment by, for instance, sending unclear or uncertain policy signals or by failing to put an adequate price on the risk of inaction on climate change.

A clear understanding of where investments take place and what their underlying drivers are can help to identify and overcome the remaining barriers to climate-relevant private investment.

Improved tracking at the national level can help strengthen climate change policy-making processes and ensure effective management of public resources to deliver on national climate change policy goals.

Third, innovate to develop or refine financial instruments that meet the needs of investors. The experience of the *Global Innovation Lab for Climate Finance* has shown that creative collaborations help to identify new ways for addressing the outstanding needs of investors and countries. The process of building a coalition of actors from across the financial system and coordinating their efforts through a systemic platform has shown The Lab's ability to accelerate the development of promising ideas for financial instruments to investment-ready projects.

Fourth, enhance the integration of climate change considerations into the financial system. Public actors have the opportunity to drive investment from the wider financial system, by providing other investors and financiers with the needed confidence to participate in climate projects. DFIs, for instance, can enhance private actors' awareness of and ability to understand, appraise, and manage climate change risks (or opportunities), and thereby engage investors currently still at the sidelines of climate finance.

Further, an enhanced integration of environmental, social, and governance (ESG) factors in investment decision-making processes can help investors to better understand risks and engage further in climate action.

CPI remains committed to improving the understanding and transparency of today's climate finance landscape. By shedding light on the intersection between public policy, finance and private investment, it aims to help decision makers optimize the use of their resources.

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EPA United States Environmental Protection Agency

Climate Impacts in Alaska

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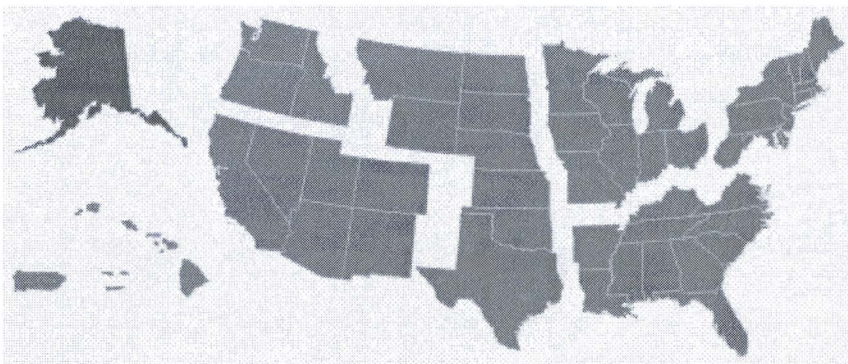


Overview

Key Points

- Warming in Alaska is already thawing permafrost, decreasing Arctic sea ice, changing ecosystems, and threatening the traditional livelihoods of native Alaskans.
- Extensive permafrost thaw is expected by the end of this century, increasing the risk of infrastructure damage.
- Arctic sea ice is projected to continue to decline, with nearly ice-free periods possible by mid-century.
- Changes are expected in the extent, location, and productivity of critical marine and terrestrial habitat for fish and wildlife.
- Native Alaskans are expected to experience declining availability of traditional foods and reduced access to sea ice hunting grounds.

Alaska is the largest state in the United States, accounting for about 20% of the total area of the United States and more than twice the land area of Texas. Alaska includes lands on both sides of the Arctic Circle, which makes the United States an Arctic nation. The state spans a wide range of climatic and ecological conditions that include rainforests, glaciers, boreal forest, tundra, peatlands, and meadows. Alaska contains 16 national wildlife refuges spanning 76 million acres and hosts 60% of the total area managed by the National Park Service, including the largest U.S. National Park (Wrangell-St. Elias with 13.2 million acres).[1][2]

Over the past 60 years, the average temperature across Alaska has increased by approximately 3°F.[3] This increase is more than twice the warming seen in the rest of the United States. Warming in the winter has increased by an average of 6°F [3] and has led to changes in ecosystems, such as earlier breakup of river ice in the spring. As the climate continues to warm, average annual temperatures in Alaska are projected to increase an additional 2 to 4°F by the middle of this century.[3] Precipitation in Alaska is projected to increase during all seasons by the end of this century. Despite increased precipitation, the state is likely to become drier due to greater evaporation caused by warming temperatures and longer growing seasons.[3]

Rising temperatures may provide some benefits in Alaska, such as a longer growing season for agricultural crops, increased tourism, and access to natural resources that are currently inaccessible due to ice cover, like offshore oil. However, climate change is also having adverse effects on many ecosystems and species, and is creating new hardships for Native Alaskans.

Permafrost

Related Links

EPA:

- National Climate Assessment: Alaska
- EPA Region 10 (including AK, ID, OR, and WA)
- Environmental Protection in Indian Country
- EPA Climate Change Indicators: Arctic Sea Ice
- EPA Climate Change Indicators: River Ice Breakup in Alaskan Rivers

Other:

- Alaska Department of Commerce: Climate Change Office EXIT
- State of Alaska: Climate Change in Alaska
- The Alaska Climate Research Center EXIT
- U.S. Arctic Research Commission
- ITEP, Tribes & Climate Change EXIT

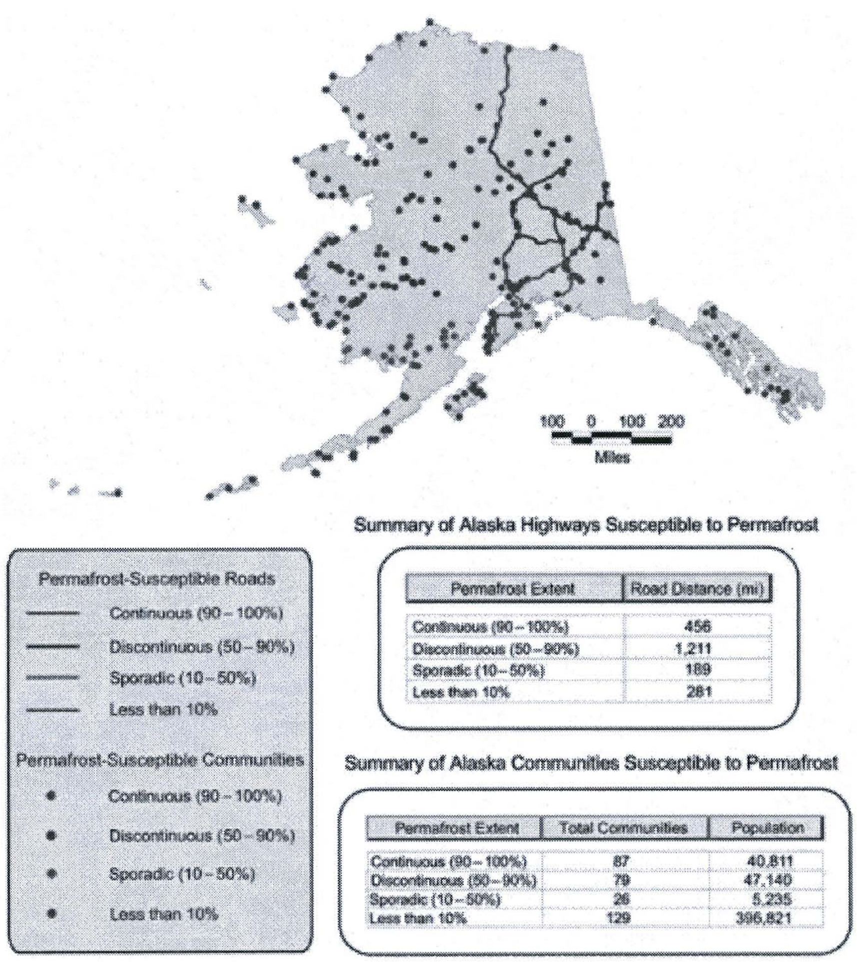
Permafrost is frozen ground that is typically located a few feet below the soil surface in extremely cold regions. Eighty percent of Alaska's surface lies above permafrost.[3] Permafrost typically remains frozen year-round, but as air temperatures rise, permafrost is thawing in many areas. As permafrost thaws, ice in the permafrost melts and can cause the soil above to sink, resulting in ground subsidence and damage to roads, homes, and other structures. The impacts of melting permafrost on transportation, forests, other ecosystems, and the economy could have widespread implications for Alaskans.

Transportation and Infrastructure Impacts

Climate change leads to more permafrost thaw and disruptions to freeze-thaw cycles that can increase frost heaves and subsidence. This can potentially cause damage to transportation infrastructure in Alaska, including highways, railroads, and airstrips.[4] Uneven sinking of the ground in response to permafrost thaw is likely to add significant costs to the maintenance and repair of transportation infrastructure and buildings.[3] Many of Alaska's highways are built in permafrost areas and are subject to damage if the permafrost thaws. Additionally, warming leads to a shorter period when ice roads are usable and a shorter season during which oil and gas exploration on the tundra can occur.[3]

For more information on climate change impacts on transportation, please visit the Transportation Impacts page.

Ecosystems



Summary of Alaska Highways Susceptible to Permafrost

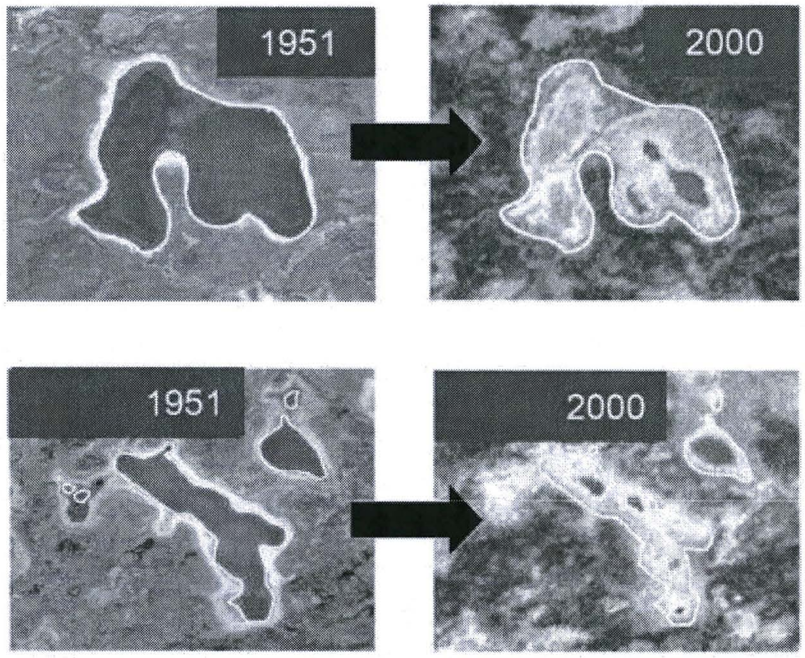
Permafrost Extent	Road Distance (mi)
Continuous (90 – 100%)	456
Discontinuous (50 – 90%)	1,211
Sporadic (10 – 50%)	189
Less than 10%	281

Summary of Alaska Communities Susceptible to Permafrost

Permafrost Extent	Total Communities	Population
Continuous (90 – 100%)	87	40,811
Discontinuous (50 – 90%)	79	47,140
Sporadic (10 – 50%)	26	5,235
Less than 10%	129	396,821

Alaska highways susceptible to permafrost. Source: U.S. Arctic Research Commission (2003)[4]

Click the image to view a larger version.



Two pairs of aerial photographs of pond areas in Alaska. The two images on the left show the pond areas in 1951 and images on the right show the same pond areas in 2000. The pond areas shown on top shrunk from 180 to 10 acres, and the pond areas shown in the bottom went from 90 to 4 acres in size. Source: USGCRP (2009)[9]

Climate change is causing changes in lakes, ponds, wetlands, plant composition, and wildfires that impact human health, wildlife, and ecosystems.[3] Lakes are changing size, with most lakes shrinking in area in the southern portion of the state.[3] Surface waters and wetlands provide breeding habitat for millions of waterfowl and shorebirds that winter in the lower 48 states. These wetland ecosystems and wildlife resources are also important to Alaska Natives who hunt and fish for food.

Lakes get smaller through a combination of increased evaporation caused by warmer temperatures, permafrost thaw which allows lakes to drain more readily, and greater accumulation of decomposing plant material on lake bottoms caused by greater plant growth.[3] In areas where permafrost is discontinuous or fragmented across the landscape, lakes are expected to continue shrinking in area. Some lakes are growing in area because of lateral permafrost thaw, which causes the edges of the lake to collapse inward, thereby increasing the area of the lake. Lake growth is expected to continue in areas underlain with continuous permafrost.[3]

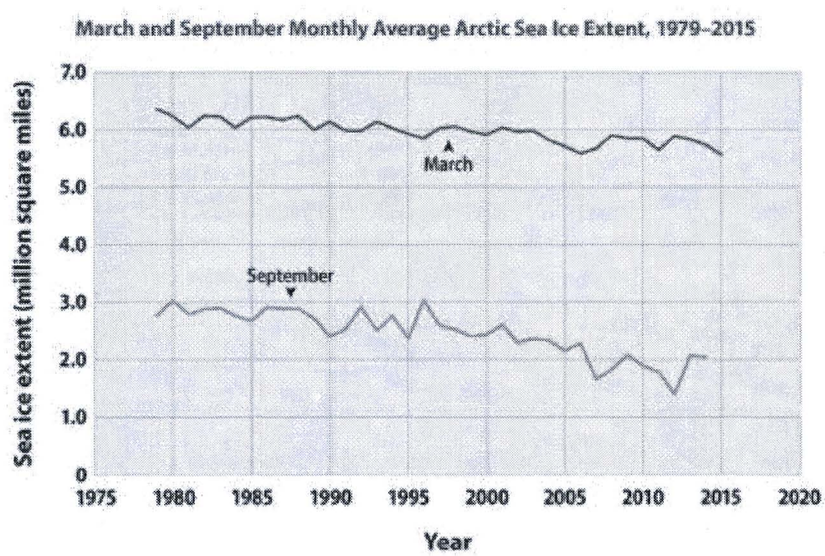
As the climate warms, shrubs are expanding into the tundra. In some areas, shrubs are replacing lichens and other tundra vegetation. Lichens are an important winter food source for caribou, and the loss of lichens can lead to declines in the growth and abundance of these animals. Caribou, in turn, are a critical food source for predators such as bears and wolves, as well as for some Alaska Natives.[5]

In recent years, an increase in large wildfires has been seen in Alaska. Credit: USGCRP (2014)

Higher temperatures and drier conditions increase the risks of drought, wildfire, and insect infestation. Large wildfires have consumed more boreal forest in Alaska in the last ten years than in any other decade recorded, and the area burned annually is projected to double by 2050.[3] Fires change forest habitat, improving conditions for moose and some plant species, but reducing the lichen that caribou rely on in winter. Warmer temperatures are also expected to worsen insect damage to forests across much of the state, which may increase the area of standing dead, highly flammable trees that are especially vulnerable to wildfire.[6]

Oceans and Coasts

Sea ice is frozen seawater that floats on the surface of the ocean. Some sea ice persists from year to year (known as perennial sea ice), often getting thicker as it piles up against Arctic shorelines. Other sea ice is seasonal, melting during the summer and refreezing in winter.



Sea ice extent has, on average, been declining in recent decades. This figure shows the extent from 1979 to 2015. Source: US EPA (2015) [10]

Click the image to view a larger version.

Over the past several decades, perennial sea ice has declined. This decline is, in part, a result of extended periods of above-freezing air or water temperatures. Ocean currents and wind patterns have also played an important role. [7] September 2012 had the lowest sea ice extent (or area of ocean covered by ice) on record, 49 percent below the 1979-2000 average for that month. The September 2014 sea ice extent was nearly 700,000 square miles less than the historical 1979-2000 average for that month - a difference more than twice the size of Texas.[10] The thickness and age of sea ice is also declining throughout the Arctic, with recent measurements indicating a loss of 50% of sea ice since 1979. [3] Climate models project that sea ice will continue to decrease and indicate that the Arctic could be nearly ice free during the late summer by the 2030s.[3]

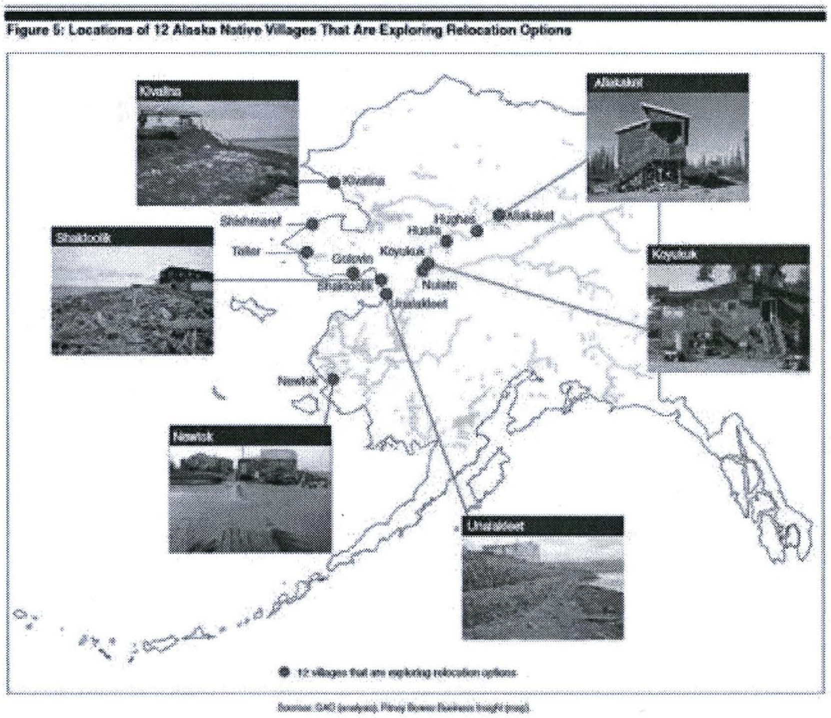
Diminishing sea ice is opening new opportunities for shipping, oil and gas exploration, tourism, and other economic activities. However, it also creates a pathway for invasive species and habitat loss for a variety of ice-dependent species, including walruses and polar bears.[3] Changes in sea ice can also affect the timing and location of plankton blooms, which can in turn affect the areas where commercial fisheries can thrive. Sea ice along the shoreline and permafrost in coastal areas help to protect human settlements from flooding and erosion. As coast erosion increases due to declining sea ice, residents are becoming more vulnerable.[3]

For more information on climate change impacts on coasts, please visit the Coastal Impacts page.

Alaska Natives

The ground under a home in Shishmaref, Alaska collapses from erosion.
Image credit: The Alaska Conservation Foundation (2010) EXIT

Alaska is home to 229 federally recognized tribes that are already experiencing the impacts of climate change in their everyday lives.[3] Alaska Native peoples depend economically, nutritionally, and culturally on fishing and hunting animals, including polar bears, walruses, seals, caribou, and fish. As the supply of fish and game decline, they are likely to travel onto thinning ice in search of food and are being forced to seek alternative food sources. Arctic plants and animals, including those harvested as subsistence food, are also at higher risk for diseases in a warming climate, further affecting food availability and human health.[3]



Locations of 12 Native Villages considering relocation. Source: GAO (2009)[11]

The health of native communities is also threatened by loss of clean water, saltwater intrusion, and sewage contamination from thawing permafrost, as well as by the northward expansion of diseases. Warming also increases exposure to pollutants, such mercury and organic pesticides, that have been transported to Arctic regions and are released from thawing soils.[3]

Thawing permafrost, loss of coastal sea ice, sea level rise, and more intense extreme weather events are also increasing erosion and flooding along Alaska's northwestern coast. More than 30 Native villages are either in the process of or in need of relocating their entire village. In Shishmaref, Kivalina, and Newtok, for example, erosion is causing extensive damage, creating new dangers to residents, and deepening pressure to relocate.[8] However, due to high costs and land constraints, tribal communities in Alaska have been experiencing difficulty relocating to safer areas.

For more information on climate change impacts on society, please visit the Society Impacts page.

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[8] USGCRP (2014). Bennett, T. M. B., N. G. Maynard, P. Cochran, R. Gough, K. Lynn, J. Maldonado, G. Voggesser, S. Wotkyns, and K. Cozzetto, 2014: *Ch. 12: Indigenous Peoples, Lands, and Resources. Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 297-317.

[9] USGCRP (2009). *Global Climate Change Impacts in the United States.*

[10] US EPA (2015). *Climate Change Indicators in the United States.*

[11] GAO (2009). *Alaska Native Villages: Limited Progress Has Been Made on Relocating Villages Threatened by Flooding and Erosion* (53 pp, 2.2 MB, About PDF).

LAST UPDATED ON JANUARY 13, 2017

ALASKA STATE LEGISLATURE

REPRESENTATIVE ANDY JOSEPHSON

MEMORANDUM

Date: March 27, 2017

To: Representative Jonathan Kreiss-Tomkins
Chair, House State Affairs Committee

From: Representative Andy Josephson

Re: Hearing Request for HB 173

I respectfully request a hearing in the House Committee on State Affairs for HB 173, creating the Climate Change Response Commission within the Office of the Governor.

Please find attached a copy of the bill and a sponsor statement, and we will provide additional documentation prior to any scheduled hearing. If you have any questions, contact my office at 465-4939.

Andy Josephson

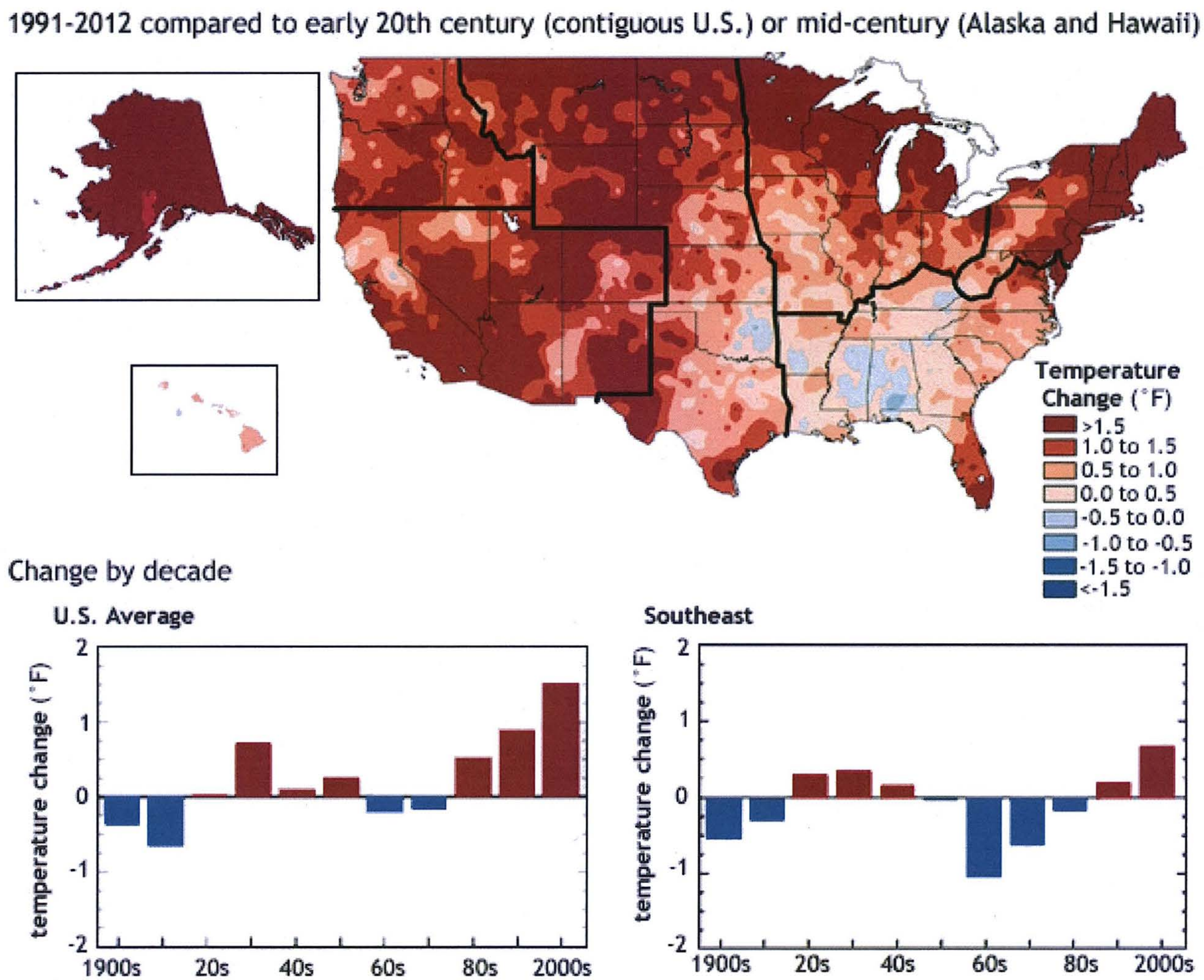
State Capitol – Juneau, Alaska 99801 – (907) 465-4939 – 1(800) 465-4939 – Fax (907) 465-2418
Rep.Andy.Josephson@akleg.gov – Facebook.com/RepAndyJosephson – Twitter.com/RepAndyJ

House Bill 173 – Climate Change Response Commission

Representative Josephson

Purposes of the bill

1. Coordinate climate change adaptation and mitigation strategy state-wide
2. Give rural communities an active role
3. Help local entities secure funding
4. Establish and generate revenue for a Climate Change Response Fund



Temperature changes over the past 22 years (1991-2012) compared to the 1901-1960 average, and compared to the 1951-1980 average for Alaska and Hawai'i. The bars on the graphs show the average temperature changes by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 was warmer than any previous decade in every region. Map from Chapter 2 of the 2014 National Climate Assessment, adapted for web. Original graphic provided by NOAA NCDC / CICS-NC.

"U.S. average temperature has increased by 1.3°F to 1.9°F since 1895, and most of this increase has occurred since 1970…In general, temperatures are rising more quickly in the north. Alaskans have experienced some of the largest increases in temperature between 1970 and the present."
– U.S. National
Climate Assessment.

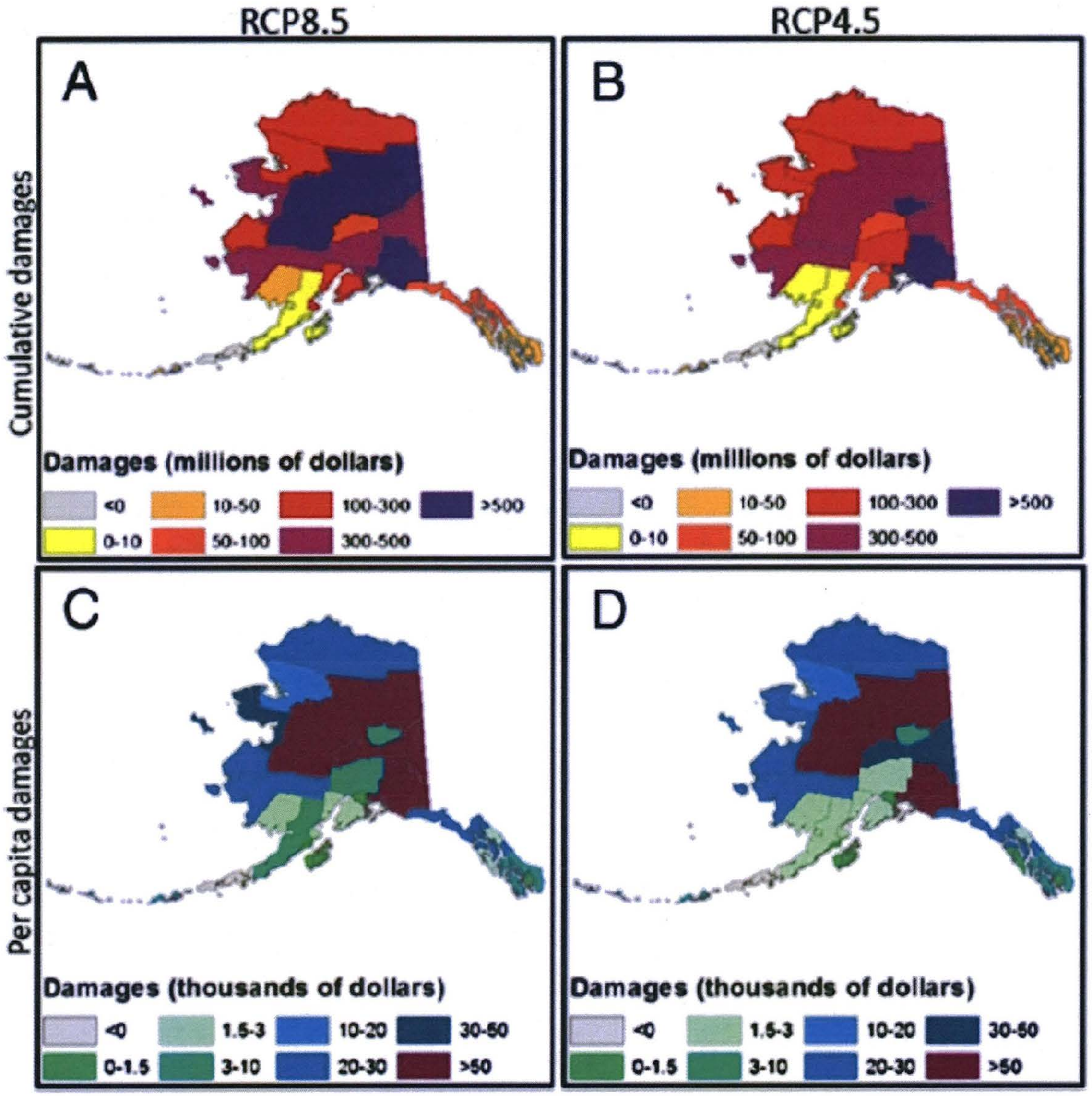
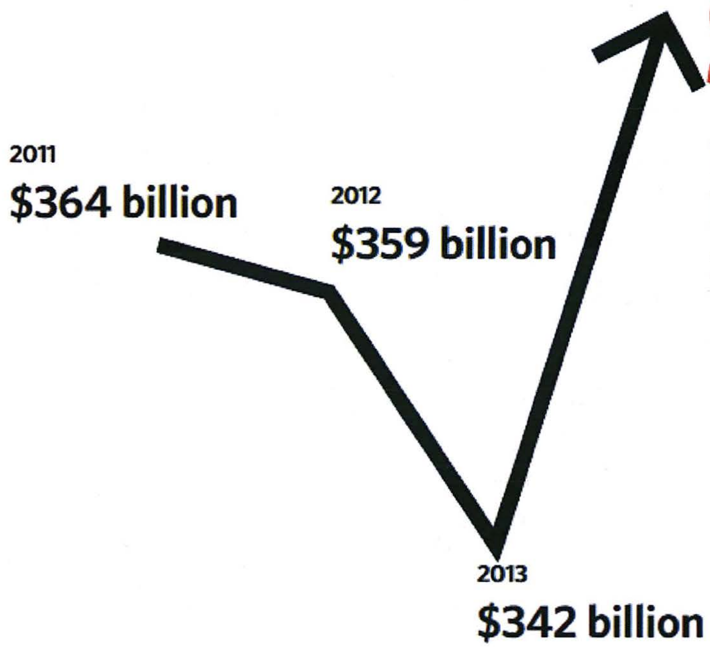


Fig. 3. (*A* and *B*) Cumulative damages (2015–2099; 3% discount) to infrastructure and (*C* and *D*) per capita damage estimates for each borough across Alaska for (*A* and *C*) RCP8.5 and (*B* and *D*) RCP4.5. Values for each borough represent the mean of five GCMs included in this analysis.

Climate change damages to Alaska public infrastructure and the economics of proactive adaptation, Melvin et. Al, 2016

Global climate finance increased by 18% in 2014



TOTAL CLIMATE FINANCE IN 2014

$392 billion

More money than ever before was invested in low-carbon and climate-resilient growth in 2014.

Climate Policy Initiative, Landscape of Global Climate Finance, 2015