

Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources

Final Report, Synthesis and Assessment Product 4.4

U.S. Climate Change Science Program
And the Subcommittee on Global Change Research

Editors

Susan Herrod Julius, U.S. Environmental Protection Agency
Jordan M. West, U.S. Environmental Protection Agency

Authors

Jill S. Baron, U.S. Geological Survey and Colorado State University
Linda A. Joyce, U.S.D.A. Forest Service
Brad Griffith, U.S. Geological Survey
Peter Kareiva, The Nature Conservancy
Brian D. Keller, National Oceanic and Atmospheric Administration
Margaret Palmer, University of Maryland
Charles Peterson, University of North Carolina
J. Michael Scott, U.S. Geological Survey and University of Idaho

FEDERAL EXECUTIVE TEAM

Acting Director, Climate Change Science Program:	William J. Brennan
Director, Climate Change Science Program Office:	Peter A. Schultz
Lead Agency Principal Representative to CCSP, National Program Director for the Global Change Research Program, U.S. Environmental Protection Agency:	Joel D. Scheraga
Product Lead, Global Ecosystem Research and Assessment Coordinator, Global Change Research Program, U.S. Environmental Protection Agency:	Susan Herrod Julius
Chair, Synthesis and Assessment Product Advisory Group Associate Director, National Center for Environmental Assessment, U.S. Environmental Protection Agency:	Michael W. Slimak
Synthesis and Assessment Product Coordinator, Climate Change Science Program Office:	Fabien J.G. Laurier
Special Advisor, National Oceanic and Atmospheric Administration	Chad A. McNutt

EDITORIAL AND PRODUCTION TEAM

Editor, U.S. Environmental Protection Agency:	Susan Herrod Julius
Editor, U.S. Environmental Protection Agency:	Jordan M. West
Technical Advisor, Climate Change Science Program Office:	David J. Dokken
Technical Editor, ICF International:	Susan Asam
Technical Editor, ICF International:	Anne Choate
Copy Editor, ICF International:	Brad Hurley
Reference Coordinator, ICF International:	Sarah Shapiro
Logistical and Technical Support: ICF International:	Joe Herr, Kathryn Maher, Sandy Seymour

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

Disclaimer: This document, part of the Synthesis and Assessment Products described in the U.S. Climate Change Science Program (CCSP) Strategic Plan, was prepared in accordance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and the information quality act guidelines issued by the U.S. Environmental Protection Agency pursuant to Section 515. The CCSP Interagency Committee relies on U.S. Environmental Protection Agency certifications regarding compliance with Section 515 and Agency guidelines as the basis for determining that this product conforms with Section 515. For purposes of compliance with Section 515, this CCSP Synthesis and Assessment Product is an “interpreted product” as that term is used in U.S. Environmental Protection Agency guidelines and is classified as “highly influential”. This document does not express any regulatory policies of the United States or any of its agencies, or provides recommendations for regulatory action.



June 2008

Members of Congress:

On behalf of the National Science and Technology Council, the U.S. Climate Change Science Program (CCSP) is pleased to transmit to the President and the Congress this Synthesis and Assessment Product (SAP), *Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources*. This is part of a series of 21 SAPs produced by the CCSP aimed at providing current assessments of climate change science to inform public debate, policy, and operational decisions. These SAPs are also intended to help the CCSP develop future program research priorities. This SAP is issued pursuant to Section 106 of the Global Change Research Act of 1990 (Public Law 101-606).

The CCSP’s guiding vision is to provide the Nation and the global community with the science-based knowledge needed to manage the risks and capture the opportunities associated with climate and related environmental changes. The SAPs are important steps toward achieving that vision and help to translate the CCSP’s extensive observational and research database into informational tools that directly address key questions being asked of the research community.

This SAP focuses on adaptation options for climate-sensitive ecosystems and resources on Federally owned and managed lands. It was developed with broad scientific input and in accordance with the Guidelines for Producing CCSP SAPs, the Federal Advisory Committee Act, the Information Quality Act, Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (Public Law 106-554), and the guidelines issued by the Environmental Protection Agency pursuant to Section 515.

We commend the report’s authors for both the thorough nature of their work and their adherence to an inclusive review process.

Sincerely,

Carlos M. Gutierrez
Secretary of Commerce

Samuel W. Bodman
Secretary of Energy

John H. Marburger III
Director, Office of Science
and Technology Policy
Executive Director, Committee
on Climate Change Science and
Technology Integration

Chair, Committee on
Climate Change Science
and Technology Integration

Vice Chair, Committee on
Climate Change Science
and Technology Integration

AUTHORS TEAM FOR THIS REPORT

- Chapter 1 **Lead Authors:** Susan Herrod Julius, U.S. EPA; Jordan M. West, U.S. EPA
Contributing Authors: Geoffrey M. Blate, AAAS Fellow, U.S. EPA; Jill S. Baron, USGS and Colo. State Univ.; Linda A. Joyce, USDA Forest Service; Peter Kareiva, The Nature Conservancy; Brian D. Keller, NOAA; Margaret A. Palmer, Univ. Md.; Charles H. Peterson, Univ. N. Car.; J. Michael Scott, USGS and Univ. Id.
- Chapter 2 **Lead Authors:** Susan Herrod Julius, U.S. EPA; Jordan M. West, U.S. EPA; Geoffrey M. Blate, AAAS Fellow, U.S. EPA
- Chapter 3 **Lead Author:** Linda A. Joyce, USDA Forest Service
Contributing Authors: Geoffrey M. Blate, AAAS Fellow, U.S. EPA; Jeremy S. Littell, JISAO CSES Climate Impacts Group, Univ. Wa.; Steven G. McNulty, USDA Forest Service; Constance I. Millar, USDA Forest Service; Susanne C. Moser, NCAR; Ronald P. Neilson, USDA Forest Service; Kathy O’Halloran, USDA Forest Service; David L. Peterson, USDA Forest Service
- Chapter 4 **Lead Author:** Jill S. Baron, USGS and Colo. State Univ.
Contributing Authors: Craig D. Allen, USGS; Erica Fleishman, NCEAS, Univ. Southern Calif.; Lance Gunderson, Emory Univ.; Don McKenzie, USDA Forest Service; Laura Meyerson, Univ. Rhode Is.; Jill Oropeza, Colo. State Univ.; Nate Stephenson, USGS
- Chapter 5 **Lead Authors:** J. Michael Scott, USGS and Univ. Id.; Brad Griffith, USGS
Contributing Authors: Robert S. Adamcik, USFWS; Daniel M. Ashe, USFWS; Brian Czech, USFWS; Robert L. Fischman, Indiana Univ. School of Law; Patrick Gonzalez, The Nature Conservancy; Joshua J. Lawler, Univ. Wa.; A. David McGuire, USGS; Anna Pidgorna, Univ. Id.
- Chapter 6 **Lead Author:** Margaret A. Palmer, Univ. Md.
Contributing Authors: Dennis Lettenmaier, Univ. Wa.; N. LeRoy Poff, Colo. State Univ.; Sandra Postel, Global Water Policy Project; Brian Richter, The Nature Conservancy; Richard Warner, Kinnickinnic Consulting
- Chapter 7 **Lead Author:** Charles H. Peterson, Univ. N. Car.;
Contributing Authors: Richard T. Barber, Duke Univ.; Kathryn L. Cottingham, Dartmouth College; Heike K. Lotze, Dalhousie Univ.; Charles A. Simenstad, Univ. Wa.; Robert R. Christian, East Car. Univ.; Michael F. Piehler, Univ. N. Car.; John Wilson, U.S. EPA
- Chapter 8 **Lead Author:** Brian D. Keller, NOAA
Contributing Authors: Satie Airamé, Univ. Ca. Santa Barbara; Billy Causey, NOAA; Alan Friedlander, NOAA; Daniel F. Gleason, Ga. Southern Univ.; Rikki Grober-Dunsmore, NOAA;

- Johanna Johnson, Great Barrier Reef MPA; Elizabeth McLeod, The Nature Conservancy; Steven L. Miller, Univ. N. Car. Wilmington; Robert S. Steneck, Univ. Maine; Christa Woodley, Univ. Ca. Davis
- Chapter 9 **Lead Author:** Peter Kareiva, The Nature Conservancy
Contributing Authors: Carolyn Enquist, The Nature Conservancy; Ayana Johnson, Univ. Ca. San Diego; Susan Herrod Julius, U.S. EPA; Joshua Lawler, Oregon State Univ.; Brian Petersen, Univ. Ca. Santa Cruz; Louis Pitelka, Univ. Md.; Rebecca Shaw, The Nature Conservancy; Jordan M. West, U.S. EPA
- Annex A **Editors:** Susan Herrod Julius, U.S. EPA; Jordan M. West, U.S. EPA;
Lead Authors: Jill S. Baron, USGS and Colo. State Univ.; Brad Griffith, USGS; Linda A. Joyce, USDA Forest Service; Brian D. Keller, NOAA; Margaret A. Palmer, Univ. Md.; Charles H. Peterson, Univ. N. Car.; J. Michael Scott, USGS and Univ. Id.
- National Forests Case Studies**
- Tahoe National Forest*
Constance I. Millar, USDA Forest Service; Linda A. Joyce, USDA Forest Service; Geoffrey M. Blate, AAAS Fellow, U.S. EPA
- Olympic National Forest*
David L. Peterson, USDA Forest Service; Jeremy S. Littell, JISAO CSES Climate Impacts Group, Univ. Wa.; Kathy O’Halloran, USDA Forest Service
- Uwharrie National Forest*
Steven G. McNulty, USDA Forest Service
- National Parks Case Study**
- Rocky Mountain National Park*
Jill S. Baron, USGS and Colo. State Univ.; Jill Oropeza, Colo. State Univ.
- National Wildlife Refuges Case Study**
- Alaska and the Central Flyway*
Brad Griffith, USGS; A. David McGuire, USGS
- Wild and Scenic Rivers Case Studies**
- Wekiva River*
- Rio Grande River*
- Upper Delaware River*
Margaret A. Palmer, Univ. Md.; Dennis Lettenmaier, Univ. Wa.; N. LeRoy Poff, Colo. State Univ.; Sandra Postel, Global Water Policy Project; Brian Richter, The Nature Conservancy; Richard Warner, Kinni Consulting
- National Estuaries Case Study**
- The Albemarle-Pamlico Estuarine System*
Robert R. Christian, E. Car. Univ.; Charles H. Peterson, Univ. of N. Car.; Michael F. Piehler, Univ. of N. Car.; Richard T. Barber, Duke Univ.; Kathryn L. Cottingham, Dartmouth College; Heike K.

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

Lotze, Dalhousie Univ.; Charles A. Simenstad, Univ. Wa.; John W. Wilson, U.S. EPA

Marine Protected Areas Case Studies

The Florida Keys National Marine Sanctuary

Billy Causey, NOAA; Steven L. Miller, Univ. N. Car. Wilmington; Brian D. Keller, NOAA

The Great Barrier Reef Marine Park

Johanna Johnson, Great Barrier Reef Marine Park Authority

Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument

Alan Friedlander, NOAA

The Channel Islands National Marine Sanctuary

Satie Airamé, Univ. Ca. Santa Barbara

Annex B

Editors: Susan Herrod Julius, U.S. EPA; Jordan M. West, U.S. EPA;

Lead Authors: Jill S. Baron, USGS and Colo. State Univ.; Brad Griffith, USGS; Linda A. Joyce, USDA Forest Service; Brian D. Keller, NOAA; Margaret A. Palmer, Univ. Md.; Charles H. Peterson, Univ. N. Car.; J. Michael Scott, USGS and Univ. Id.

ACKNOWLEDGMENTS

Federal Advisory Committee: Adaptation for Climate-Sensitive Ecosystems and Resources Advisory Committee (ACSERAC)

We would like to thank the following members of ACSERAC who provided excellent reviews of this report that resulted in an improved document, and to the Designated Federal Officials:

Chair

Paul G. Risser, University of Oklahoma

Elizabeth Malone, Joint Global Change
Research Institute

Vice-Chair

Reed F. Noss, University of Central Florida

David Patton, University of Arizona
Daniel Tufford, University of South Carolina
Robert Van Woesik, Florida Institute of
Technology

Members

Joe Arvai, Michigan State University

Eric Gilman, IUCN Global Marine

Programme

Carl Hershner, Virginia Institute of Marine
Science

George Hornberger, University of Virginia

Designated Federal Officials

Joanna Foellmer

Janet Gamble (back-up)

Thank you to Sharon Moxley (EPA) and to
Versar, Inc for their support to the
ACSERAC.

Additional External (Public) Reviewers

We would like to thank the many individuals who provided useful comments during the public review period. The draft manuscript, public review comments, and response to public comments are publicly available at: <http://www.climatescience.gov/Library/sap/sap4-4/default.php>
Stakeholder workshop participants and key reviewers are acknowledged in individual chapters.

US Environmental Protection Agency Internal Reviewers

We would like to thank the following internal reviewers who provided valuable comments on this report in preparation for external and public review:

Peter Beedlow, Office of Research and
Development

Paul Bunje, American Association for the
Advancement of Science Fellow

David Burden, Office of Research and
Development

Barry Burgan, Office of Water

Ben DeAngelo, Office of Air and Radiation

Dominic Digiulio, Office of Research and
Development

Anne Fairbrother, Office of Research and
Development

Bill Fisher, Office of Research and
Development

Eric Jorgensen, Office of Research and
Development

Chris Laab, Office of Water

Michael Lewis, Office of Research and
Development

Jeremy Martinich, Office of Air and
Radiation

Larry Merrill, Region 3

Dave Olszyk, Office of Research and
Development

Kathryn Parker, Office of Air and Radiation

Amina Pollard, Office of Research and
Development
Jackie Poston, Region 10

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

Kathryn Saterson, Office of Research and Development

Karen Scott, Office of Air and Radiation

Jim Titus, Office of Air and Radiation

Jim Wigington, Office of Research and Development

Wendy Wiltse, Region 9

Steve Winnett, Region 1

Jeff Yang, Office of Research and Development

3 anonymous reviewers, Office of Research and Development

National Center for Environmental Assessment (NCEA), Global Change Research Program

We would like to thank our colleagues in the Global Change Research Program who contributed thoughtful insights, reviewed numerous drafts, and helped with the production of this report: Amanda Babson (AAAS Fellow), Britta Bierwagen, Geoffrey Blate (AAAS Fellow), Anne Grambsch, Thomas Johnson, Chris Pyke^{*}, Michael Slimak, Chris Weaver. We would also like to acknowledge the administrative support and oversight provided by the National Center for Environmental Assessment.

ICF International (support contractor to NCEA)

We would like to thank our colleagues at ICF International for their logistical and technical support for this report, with special thanks to: Susan Asam, Anne Choate, Randall Freed, Joseph Herr, Bradford Hurley, Kathryn Maher, Sandra Seymour, and Sarah Shapiro. Stakeholder workshops were organized by ICF and facilitated by Bill Dennison of the University of Maryland, Center for Environmental Science.

It was an honor and a pleasure to work with all of the people above as well as the many other colleagues we have encountered in the science and management communities who are working to address climate change impacts. We hope that this document will be a positive step forward in our collective effort to apply adaptation principles for climate-sensitive ecosystems and resources.

^{*} Currently with CTG Energetics.

RECOMMENDED CITATIONS

Note: The page numbers included below are specific to the pre-layout draft of the report. These page numbers will change in the final printed version.

For the Report as a Whole:

CCSP, 2008: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, 873 pp.

For Chapter 1:

Julius, S.H., J.M. West, G.M. Blate, J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott, 2008: Executive Summary. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 1-1 to 1-6.

For Chapter 2:

Julius, S.H., J.M. West, and G.M. Blate, 2008: Introduction. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection

Agency, Washington, DC, USA, pp. 2-1 to 2-24.

For Chapter 3:

Joyce, L.A., G.M. Blate, J.S. Littell, S.G. McNulty, C.I. Millar, S.C. Moser, R.P. Neilson, K. O'Halloran, and D.L. Peterson, 2008: National Forests. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 3-1 to 3-127.

For Chapter 4:

Baron, J.S., C.D. Allen, E. Fleishman, L. Gunderson, D. McKenzie, L. Meyerson, J. Oropeza, and N. Stephenson, 2008: National Parks. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 4-1 to 4-68.

For Chapter 5:

Scott, J.M., B. Griffith, R.S. Adamcik, D.M. Ashe, B. Czech, R.L. Fischman, P. Gonzalez, J.J. Lawler, A.D. McGuire, and A. Pidgorna, 2008: National Wildlife Refuges. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P.

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 5-1 to 5-100.

For Chapter 6:

Palmer, M.A., D. Lettenmaier, N.L. Poff, S. Postel, B. Richter, and R. Warner, 2008: Wild and Scenic Rivers. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 6-1 to 6-73.

For Chapter 7:

Peterson, C.H., R.T. Barber, K.L. Cottingham, H.K. Lotze, C.A. Simenstad, R.R. Christian, M.F. Piehler, and J. Wilson, 2008: National Estuaries. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 7-1 to 7-108.

For Chapter 8:

Keller, B.D., S. Aïramé, B. Causey, A. Friedlander, D.F. Gleason, R. Grober-Dunsmore, J. Johnson, E. McLeod, S.L. Miller, R.S. Steneck, and C. Woodley, 2008: Marine Protected Areas. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change

Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 8-1 to 8-95.

For Chapter 9:

Kareiva, P., C. Enquist, A. Johnson, S.H. Julius, J. Lawler, B. Petersen, L. Pitelka, R. Shaw, and J.M. West, 2008: Synthesis and Conclusions. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. 9-1 to 9-66.

For Annex A:

Julius, S.H., J.M. West, J.S. Baron, B. Griffith, L.A. Joyce, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott, 2008: Annex A: Case Studies. In: *Preliminary review of adaptation options for climate-sensitive ecosystems and resources*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. A-1 to A-170.

For Annex B:

Julius, S.H., J.M. West, J.S. Baron, B. Griffith, L.A. Joyce, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott, 2008: Annex B: Confidence Estimates for SAP 4.4 Adaptation Approaches. In: *Preliminary review of adaptation options for climate-*

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

sensitive ecosystems and resources. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Julius, S.H., J.M. West (eds.), J.S. Baron, B. Griffith, L.A. Joyce, P. Kareiva, B.D. Keller, M.A. Palmer, C.H. Peterson, and J.M. Scott (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, pp. B-1 to B-36.

TABLE OF CONTENTS

Preface

1. Executive Summary

2. Introduction

- 2.1 Goal and Audience 2-4
- 2.2 Stakeholder Interactions 2-5
- 2.3 Approach for Reviewing Adaptation Options for Climate-Sensitive Ecosystems and Resources 2-5
- 2.4 Climate Variability and Change 2-7
 - 2.4.1 Increases in Surface Temperature 2-7
 - 2.4.2 Changes in Precipitation 2-8
 - 2.4.3 Warming of the Oceans 2-8
 - 2.4.4 Sea Level Rise and Storm Intensity 2-8
 - 2.4.5 Changes in Ocean pH 2-9
 - 2.4.6 Warming in the Arctic 2-9
 - 2.4.7 Changes in Extreme Events 2-10
 - 2.4.8 Changes in Hydrology 2-10
 - 2.4.9 Observed Ecological Responses 2-10
 - 2.4.10 Future Anticipated Climate Change 2-11
- 2.5 Treatment of Uncertainty 2-11
- 2.6 The Adaptation Challenge: The Purpose of This Report 2-12
- 2.7 References 2-14
- 2.8 Boxes 2-18
- 2.9 Figures 2-20

3. National Forests

- 3.1 Summary 3-3
- 3.2 Background and History 3-6
 - 3.2.1 Historical Context and Enabling Legislation 3-6
 - 3.2.2 Evolution of National Forest Mission 3-6
 - 3.2.3 Interpretation of Goals 3-8
- 3.3 Current Status of Management Systems 3-9
 - 3.3.1 Key Ecosystem Characteristics Upon Which Goals Depend 3-9
 - 3.3.2 Stressors of Concern on National Forests 3-11
 - 3.3.3 Management Approaches and Methods Currently in Use to Manage Stressors 3-19
 - 3.3.4 Sensitivity of Management Goals to Climate Change 3-21
- 3.4 Adapting to Climate Change 3-35
 - 3.4.1 The Need for Anticipatory Adaptation 3-35
 - 3.4.2 Approaches for Planning in the Context of Climate Change 3-42
 - 3.4.3 Approaches for Management in the Context of Climate Change 3-45
 - 3.4.4 Prioritizing Management Responses in Situations of Resource Scarcity 3-56
 - 3.4.5 Barriers to Adaptation Approaches 3-57
- 3.5 Conclusions and Recommendations 3-58

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

- 3.5.1 Climate Change and National Forests 3-58
- 3.5.2 Management Response Recommendations 3-59
- 3.5.3 Research Priorities 3-63
- 3.6 References 3-68
- 3.7 Acknowledgements 3-102
- 3.8 Boxes 3-103
- 3.9 Case Study Summaries 3-109
- 3.10 Figures 3-116

- 4. National Parks**
- 4.1 Chapter Summary 4-3
- 4.2 Background and History 4-6
 - 4.2.1 Legal History 4-8
 - 4.2.2 Interpretation of Goals 4-10
- 4.3 Current Status of Management Systems 4-12
 - 4.3.1 Key Ecosystem Characteristics on Which Goals Depend 4-12
 - 4.3.2 Stressors of Concern 4-13
 - 4.3.3 Current Approaches to NPS Natural Resource Management 4-20
 - 4.3.4 Sensitivity of NPS Goals to Climate Change 4-25
- 4.4 Adapting to Climate Change 4-26
 - 4.4.1 Coming to Terms with Uncertainty 4-26
 - 4.4.2 Approaches to Management Given Uncertainty 4-27
 - 4.4.3 Incorporating Climate Change Considerations into Natural Resource Management 4-31
- 4.5 Conclusions 4-38
- 4.6 References 4-40
- 4.7 Acknowledgements 4-49
- 4.8 Boxes 4-50
- 4.9 Case Study Summaries 4-59
- 4.10 Figures 4-61

- 5. National Wildlife Refuges**
- 5.1 Summary 5-3
- 5.2 Background and History 5-7
 - 5.2.1 Introduction 5-7
 - 5.2.2 Mission, Establishing Authorities, and Goals 5-10
 - 5.2.3 Origins of the NWRS 5-11
 - 5.2.4 The 1997 NWRS Improvement Act 5-12
- 5.3 Current Status of the NWRS 5-15
 - 5.3.1 Key Ecosystem Characteristics on Which Goals Depend 5-15
 - 5.3.2 Challenges to the NWRS 5-17
 - 5.3.3 Ecoregional Implications of Climate Change for the NWRS 5-26
- 5.4 Adapting to Climate Change 5-33
 - 5.4.1 Adaptive Management as a Framework for Adaptation Actions 5-34
 - 5.4.2 Adaptation Strategies within Refuge Borders 5-35
 - 5.4.3 Adaptation Strategies Outside Refuge Borders 5-38

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

- 5.4.4 Steps for Determining Research and Management Actions 5-46
- 5.5 Conclusions 5-55
- 5.6 References 5-61
- 5.7 Acknowledgements 5-78
- 5.8 Appendix: Actions to Assist Managers in Meeting the Challenges Posed by the Challenge of Climate Change 5-79
- 5.9 Boxes 5-86
- 5.10 Case Study Summaries 5-88
- 5.11 Tables 5-90
- 5.12 Figures 5-91

6. Wild and Scenic Rivers

- 6.1 Summary 6-3
- 6.2 Background and History 6-6
- 6.3 Current Status of Management System 6-7
 - 6.3.1 Framework for Assessing Present and Future Status 6-8
 - 6.3.2 Hydrogeomorphic Context 6-8
 - 6.3.3 Present Human Context 6-11
 - 6.3.4 The Policy Context: Present Management Framework Legal and Management Context 6-16
- 6.4 Adapting to Climate Change 6-22
 - 6.4.1 Climate Change Impacts 6-22
 - 6.4.2 Future Human Context: Interactive Effects of Multiple Stressors 6-25
 - 6.4.3 Ecosystem Goods and Services Assuming Present Management 6-27
 - 6.4.4 Options for Protection Assuming New Management 6-29
- 6.5 Conclusions 6-35
- 6.6 References 6-37
- 6.7 Acknowledgements 6-45
- 6.8 Boxes 6-46
- 6.9 Case Study Summaries 6-52
- 6.10 Figures 6-56

7. National Estuaries

- 7.1 Summary 7-3
- 7.2 Background and History 7-7
 - 7.2.1 Historical Context and Enabling Legislation 7-7
 - 7.2.2 Interpretation of National Estuary Program Goals 7-9
- 7.3 Current Status of Management Systems 7-10
 - 7.3.1 Key Ecosystem Characteristics on Which Goals Depend 7-10
 - 7.3.2 Current Stressors of Concern 7-12
 - 7.3.3 Legislative Mandates Guiding Management of Stressors 7-15
 - 7.3.4 Sensitivity of Management Goals to Climate Change 7-24
- 7.4 Adapting to Climate Change 7-40
 - 7.4.1 Potential for Adjustment of Traditional Management Approaches to Achieve Adaptation to Climate Change 7-41
 - 7.4.2 Management Adaptations to Sustain Estuarine Services 7-44

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

- 7.4.3 New Approaches to Management in the Context of Climate Change 7-56
- 7.4.4 Prioritization of Management Responses 7-60
- 7.5 Conclusions 7-61
 - 7.5.1 Management Response 7-61
 - 7.5.2 Research Priorities 7-64
- 7.6 Appendix 7-68
- 7.7 References 7-93
- 7.8 Acknowledgements 7-94
- 7.9 Boxes 7-95
- 7.10 Case Study Summaries 7-102
- 7.11 Tables 7-104
- 7.12 Figures 7-107

8. Marine Protected Areas

- 8.1 Summary 8-3
- 8.2 Background and History 8-6
 - 8.2.1 Introduction 8-6
 - 8.2.2 Historical Context and Origins of National Marine Sanctuaries and Other Types of Marine Protected Areas 8-9
 - 8.2.3 Enabling Legislation 8-11
 - 8.2.4 Interpretation of Goals 8-13
- 8.3 Current Status of Management System 8-14
 - 8.3.1 Key Ecosystem Characteristics on Which Goals Depend 8-14
 - 8.3.2 Stressors of Concern 8-17
 - 8.3.3 Management Approaches and Sensitivity of Management Goals to Climate Change 8-27
- 8.4 Adapting to Climate Change 8-29
 - 8.4.1 Ameliorate Existing Stressors in Coastal Waters 8-29
 - 8.4.2 Protect Apparently Resistant and Potentially Resilient Areas 8-31
 - 8.4.3 Develop Networks of MPAs 8-32
 - 8.4.4 Integrate Climate Change Into MPA Planning, Management, and Evaluation 8-36
- 8.5 Conclusions 8-40
 - 8.5.1 Management Considerations 8-40
 - 8.5.2 Research Priorities 8-42
- 8.6 References 8-43
- 8.7 Acknowledgements 8-72
- 8.8 Boxes 8-74
- 8.9 Case Study Summaries 8-79
- 8.10 Tables 8-87
- 8.11 Figures 8-91

9. Synthesis and Conclusions

- 9.1 Summary 9-3
- 9.2 Introduction 9-5

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

- 9.3 Assessing Impacts to Support Adaptation 9-6
 - 9.3.1 Mental Models for Making Adaptation Decisions 9-6
 - 9.3.2 Elements of an Impact Assessment 9-7
 - 9.3.3 Uncertainty and How to Incorporate it Into Assessments 9-13
- 9.4 Best Practices for Adaptation 9-16
 - 9.4.1 Resilience 9-16
 - 9.4.2 Adaptation Approaches 9-18
 - 9.4.3 Confidence 9-21
 - 9.4.4 Adaptive Management 9-22
- 9.5 Barriers and Opportunities for Adaptation 9-24
 - 9.5.1 Legislation and Regulation 9-25
 - 9.5.2 Management Policies and Procedures 9-26
 - 9.5.3 Human and Financial Capital 9-29
 - 9.5.4 Information and Science 9-30
- 9.6 Advancing the Nation’s Capability to Adapt 9-32
 - 9.6.1 Re-Evaluate Priorities and Consider Triage 9-33
 - 9.6.2 Manage at Appropriate Scales 9-34
 - 9.6.3 Manage for Change 9-35
 - 9.6.4 Expand Interagency Collaboration, Integration, and Lesson-Sharing 9-36
- 9.7 Conclusions 9-38
- 9.8 References 9-41
- 9.9 Appendix: Resources for Assessing Climate Vulnerability And Impacts 9-48
- 9.10 Boxes 9-50
- 9.11 Tables 9-57
- 9.12 Figures 9-66

10. Glossary and Acronyms

11. SAP Workshop Participants

Annex A: Case Studies

- A1 National Forests Case Studies A-4
 - A1.1 Tahoe National Forest A-4
 - A1.2 Olympic National Forest A-16
 - A1.3 Uwharrie National Forest A-26
- A2 National Parks Case Study A-30
 - A2.1 Rocky Mountain National Park A-30
- A3 National Wildlife Refuges Case Study A-36
 - A3.1 Alaska and the Central Flyway A-36
- A4 Wild and Scenic Rivers Case Studies A-47
 - A4.1 Wekiva River A-47
 - A4.2 Rio Grande A-54
 - A4.3 Upper Delaware River A-59
- A5 National Estuaries Case Study A-63
 - A5.1 The Albemarle-Pamlico Estuarine System A-63
- A6 Marine Protected Areas Case Studies A-73

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

A6.1 The Florida Keys National Marine Sanctuary A-74

A6.2 The Great Barrier Reef Marine Park A-83

A6.3 Papahānaumokuākea (Northwestern Hawaiian Islands) Marine National Monument
A-90

A6.4 The Channel Islands National Marine Sanctuary A-99

A6.5 Conclusions About Marine Protected Areas Case Studies A-107

A7 References A-109

A8 Boxes A-140

A9 Tables A-147

A10 Figures A-149

Annex B: Confidence Estimates for SAP 4.4 Adaptation Approaches

B1 Introduction B-3

B2 Adaptation Approach: Protecting Key Ecosystem Features B-3

B3 Adaptation Approach: Reducing Anthropogenic Stresses B-8

B4 Adaptation Approach: Representation B-12

B5 Adaptation Approach: Replication B-15

B6 Adaptation Approach: Restoration B-17

B7 Adaptation Approach: Refugia B-21

B8 Adaptation Approach: Relocation B-24

B9 References B-27

Preface

The U.S. Government’s Climate Change Science Program (CCSP) is responsible for providing the best science-based knowledge possible to inform management of the risks and opportunities associated with changes in the climate and related environmental systems. To support its mission, the CCSP has commissioned 21 “synthesis and assessment products” (SAPs) to advance decision-making on climate change-related issues by providing current evaluations of climate change science and identifying priorities for research, observation, and decision support. This Report— SAP 4.4— focuses on federally managed lands and waters to provide a “Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources.” It is one of seven reports that support Goal 4 of the CCSP Strategic Plan to understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.

The purpose of SAP 4.4 is to provide useful information on the state of knowledge regarding adaptation options for key, representative ecosystems and resources that may be sensitive to climate variability and change. As its title suggests, this report is a preliminary review, defined as “the process of collecting and reviewing available information about known or potential adaptation options.” The Intergovernmental Panel on Climate Change (IPCC) notes that there are few demonstrated examples of ecosystem-focused adaptation options (see IPCC Fourth Assessment Report, 17.4.2.1 and 4.6.2). Thus, the authors of this SAP found it necessary to examine adaptation options in the context of a desired ecosystem condition or natural resource management goal, as set forth by the resource management entity. Therefore, this report explores potential adaptation options that could be used by natural resource managers within the context of the legislative and administrative mandates of the six systems examined: National Forests, National Parks, National Wildlife Refuges, Wild and Scenic Rivers, National Estuaries, and Marine Protected Areas. Case studies throughout this report examine in greater detail some of the issues and challenges associated with implementation of adaptation options, but are not intended to be geographically comprehensive or representative of the full breadth of ecosystems that exist or adaptation options that are available.

The management systems selected for this report are meant to be representative of a variety of ecosystem types and management goals, in order to be useful to managers who work at different spatial and organizational scales. Time and resource constraints do not allow for a comprehensive coverage of all federally owned and managed lands and waters, which means that some important management systems (*e.g.*, Bureau of Land Management lands, Department of Defense lands, tribal lands, research reserves) are not featured in this report. However, this preliminary review of existing adaptation knowledge does contain science-based adaptation strategies that are broadly applicable to not only other federal lands, but also state, local, territorial, tribal, and non-governmental holdings. Adaptive Management, a key tool recognized in this report, is an important concept within the Department of the Interior, and an Adaptive Management Technical Guide² was released in the spring of 2007. It provides a robust analytical

² Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2007. Adaptive Management: The U.S. Department of the Interior Technical Guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

SAP 4.4. Adaptation Options for Climate-Sensitive Ecosystems and Resources

framework that is based on the experience, in-depth consultation, and best practices of scientists and natural resource managers. The information in this SAP combined with Interior's Technical Guide is available for managers to consider and discuss. Additional work is needed to refine and add to this body of knowledge, including conducting detailed analyses of adaptation options on a case-by-case basis.

It must be noted that a discussion of the cost and benefits of implementing the adaptation options, either individually or collectively, was not a component of the SAP prospectus and is not included in this report. Relative to ecosystems, the IPCC noted that information is very limited on the economic and social costs and benefits of adaptation measures, especially the non-market costs and benefits of adaptation measures involving ecosystem protection, among others. Since this is a preliminary report, additional information on the costs and benefits is certainly warranted.

While SAPs 4.1, 4.2 and 4.3 analyze the impacts literature, this report focuses on the current science available on adaptation responses. This report synthesizes climate change research with the experience of on-the-ground ecosystem and resource managers to suggest adaptation options that consist of: 1) adjustments to current practices to ensure their effectiveness given climate change interactions with "traditional stressors," and 2) creation of new practices. The level of confidence in each of the adaptation approaches was evaluated by the authors based on their experience and assessment of the peer-reviewed literature on climate change impacts, current management techniques, and ecological responses. The adaptation approaches and measures suggested in this report are presented as options, not as prescriptive directives, standards, or rules.

/Signature/

Michael W. Slimak
Associate Director for Ecology
National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency