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Title: A broader view of North American climate over the past two millennia: Synthesizing paleoclimate records from diverse archives

Short Title: North American Climate

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Project Summary: Regional- to continental-scale paleoclimate syntheses of temperature and hydroclimate in North America are essential for understanding long-term spatiotemporal variability in climate, and for properly assessing risk on decadal and longer timescales. However, existing syntheses rely almost exclusively on tree-ring records, which are known to underestimate low-frequency variability and rarely extend beyond the last millennium. Meanwhile, many additional records from a variety of archives are available and hold the potential of broadening and enhancing our understanding of past climate in North America over the past two thousand years. We propose to bring together a diverse group of with expertise that spans the relevant natural archives for North America to, for the first time, pull together these disparate paleoclimate records into a unified database with a common format. This will enable us to take advantage of emerging multiproxy and time-uncertain reconstruction techniques to produce multiple-archive climate reconstructions for North America over the past two millennia.

Proposed Start and End Dates: August 2013 to July 2015, with two 4-day meetings at the Powell Center

Proposed Data Release Date: July 2015

Total Requested Budget: [redacted]

Is this a resubmission? No

Conflicts of Interest with Reviewers: Pederson collaborates with Gregory McCabe

Keywords: Climate and land use change

1 Problem Statement

Instrumental records are too short to fully characterize climate variability on timescales of decades and longer. This makes it difficult to understand how forcing mechanisms and climate dynamics interact to drive natural climate variability, which in turn limits our ability to accurately project future climate change. Natural resource managers are also hindered as they strive to plan for, and adapt to, an appropriate range of potential future climate conditions. Therefore, climate scientists and resource managers are increasingly turning to paleoclimatic information to better understand these dynamics and utilize a more complete distribution of climate variability. Reconstructing the climate of the past two thousand years has been a primary effort of the paleoclimate community over the past decade, mostly on a hemispheric or global scale (e.g. *Mann et al.*, 1998; *Jones and Mann*, 2004; *Moberg et al.*, 2005; *Mann et al.*, 2008). Recently, renewed emphasis has been placed on regional to continental scale syntheses (e.g. *Cook et al.*, 2004; *Kaufman et al.*, 2009; *Emile-Geay et al.*, 2013; *PAGES 2k Consortium*, 2013), which are more relevant for most stakeholders.

With this goal in mind, The International Geosphere Biosphere Programme's (IGBP) Past Global Changes (PAGES) project coordinates the 2k Network, nine groups of primarily volunteer researchers working to synthesize climate variability over the past two millennia for each of the seven continents as well as the oceans and the Arctic. The PAGES 2k consortium (led by PIs Kaufman and McKay), just published its first synthesis of temperature over the past two thousand years for seven of the nine regions (Pages 2k Consortium, 2013). The North American working group relied primarily on published tree-ring (*Wahl and Smerdon*, 2012) and pollen (*Viau et al.*, 2012) reconstructions volunteered by working group members rather than performing a comprehensive inventory of available records for North America. Consequently, the North American reconstruction is limited in several ways. Because the reconstruction relies almost exclusively on tree ring records, it is prone to the loss of low-frequency climate variability (*Cook et al.*, 1995), and only extends back to 1200 AD (Figure 1). Furthermore, because of spatial biases in the previous reconstructions, the North American reconstruction could only be calibrated at decadal rather than annual resolution. Tree-ring based hydroclimate and drought reconstructions for North America have a longer history (e.g. *LaMarche and Fritts*, 1971; *Stahle and Cleaveland*, 1992; *Woodhouse and Overpeck*, 1998), and are extremely well-developed (*Cook et al.*, 2004). These reconstructions are spatially-resolved and extend throughout the past 2 kyr; however they also likely underestimate low-frequency variability in hydroclimate (*Cook et al.*, 1995). Despite this focus on tree ring records, there are abundant North American paleoclimatic records for the past 2 kyr from terrestrial and marine sediments (e.g. *Dean*, 1997; *Fritz et al.*, 2000; *Cronin et al.*, 2005; *Marcott et al.*, 2013, and references therein), speleothems (*Asmerom et al.*, 2007; *Bernal et al.*, 2011; *Lachniet et al.*, 2012), glaciers (e.g. *Wiles et al.*, 2008; *Barclay et al.*, 2009; *Koch and Clague*, 2011; *Maurer et al.*, 2012), ice cores (e.g. *Fisher et al.*, 2004; *Vinther et al.*, 2009, and references therein), geomorphic evidence (e.g. *Forman et al.*, 2001; *Mason et al.*, 2004), and corals (e.g. *Swart et al.*, 1996; *Vásquez-Bedoya et al.*, 2012). Like tree rings, each of these archives has its own strengths and weaknesses, but a multiproxy approach provides the ideal means to reconstruct North American climate of the past 2 kyr.

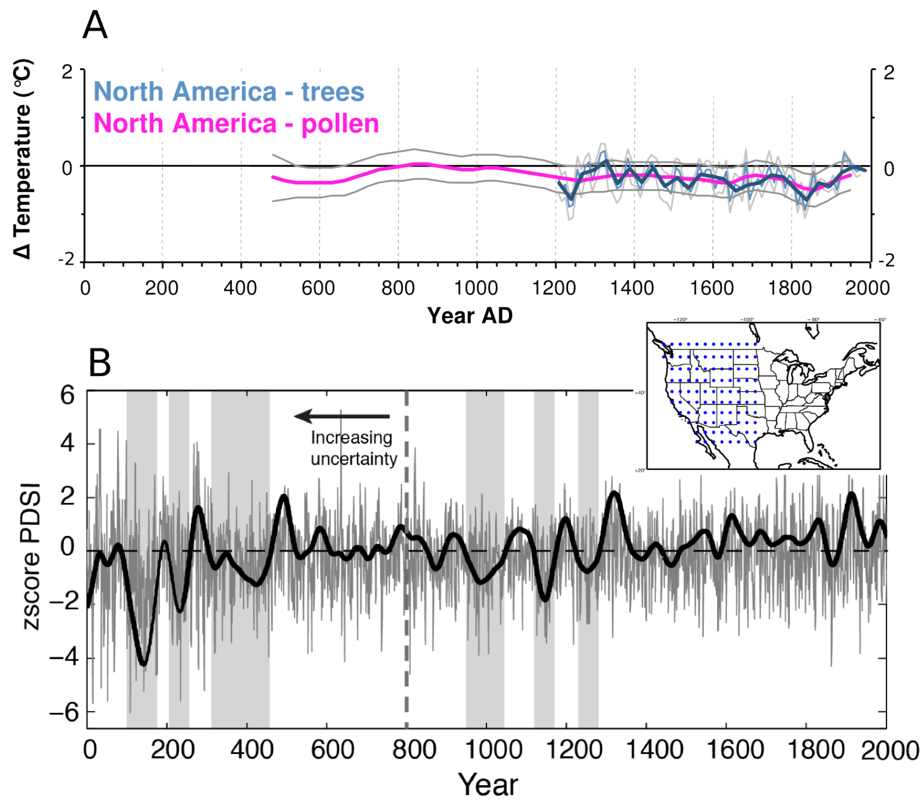

Figure 1: A) North American pollen- and tree ring-based temperature reconstructions (*Trouet et al.*, 2013; *PAGES 2k Consortium*, 2013) and B) Reconstructed Palmer Drought Severity Index (PDSI) over the Western United States (*Cook et al.*, 2004)

Integrating climate-sensitive records from diverse archives is challenging for several reasons. Outside of tree-rings and coral archives, most records have coarser-than-annual time resolution, as well as uncertainty in their chronologies. The majority of climate reconstruction techniques cannot properly incorporate records with time uncertainty and/or variable sampling resolutions, so these records are often excluded from syntheses. When they are included, large assumptions are typically required about the accuracy of the chronologies, or to interpolate records to a common timescale. In addition to these sampling and chronological uncertainties, each archive filters climate in unique ways. The relationships between proxy records and climate are often evaluated by comparison and calibration with instrumental records; however this is more difficult with coarsely-resolved records, and even with annual records the stability of modern relationships back in time is uncertain. An alternative and complementary approach is to rely on expert knowledge of how each record filters the climate signal. This becomes increasingly complicated when recognizing that different proxies record different aspects of climate, with some providing estimates of mean annual temperature, others mirroring seasonal temperatures, others reflecting various aspects of the hydrologic cycle, all with varying spatial and temporal scales.

Fortunately, approaches are emerging to deal with these issues. A new reconstruction method was recently developed to handle variable sampling resolution and reduce assumptions about how records are related to climate (*Hanhijärvi et al.*, In press). The Pairwise Comparison (PaiCo) method inputs records in their original resolution, and reduces assumptions about how the records are related to climate (the sign of the relationship, and that it is monotonic, but not necessarily linear). Other advances are beginning to illuminate how to handle time-uncertainty in records (*Anchukaitis and Tierney*, 2012; *Tierney et al.*, 2013). In response to this issue, a new working group within PAGES program is forming, to bring together leading experts on paleoclimate reconstruction to address the challenge of multi-proxy, time-uncertain climate field reconstruction, and PIs McKay and Kaufman are integrally involved in this effort.

Perhaps the larger challenge is incorporating expert knowledge that spans the breadth of relevant paleoclimate archives for North America. To do this properly, a diverse group of paleoclimate experts must be closely integrated with those working to aggregate and synthesize the data. This will be the primary focus of the working group meetings at the Powell Center, to bring together a comprehensive database that incorporates all of the raw proxy and chronological data, as well as a robust and concise description of how each record filters the climate system. Such an effort is, to our knowledge, unprecedented in the field, and will represent a major step forward.

The time is right for such an effort. Many high-quality paleoclimate records for North America have been published in recent years, and the community has yet to perform a comprehensive inventory of existing records; a task that will only grow more difficult the longer we wait. Furthermore, the next phase of the PAGES 2k network project is beginning, with a focus on multiproxy and spatially resolved reconstructions, especially of precipitation and pressure fields in addition to temperature. This synthesis will bring together researchers from the USGS, universities and the Department of Interior's Regional Climate Centers to advance the North American contribution to a global network.

Extending the length and expanding the scope of North American climate reconstructions will enable us to address important science questions that cannot be fully answered with shorter and single-proxy reconstructions, such as: How have multi-century to millennial scale trends in climate forcing (e.g., orbital variability, volcanism, solar irradiance) interacted with the interannual to decadal-scale modes of climate variability that exert important influences over North America (i.e, the El Niño/Southern Oscillation, the Northern Annular Mode, and the North American Monsoon)? How stable are the associated teleconnection patterns? Furthermore, by incorporating speleothem and lake sediment records, which better record low-frequency variability, with tree-ring based drought reconstructions, we will be able to evaluate the full range of natural hydrologic variability in the American Southwest, providing more realistic baseline distributions for water managers preparing for future changes in the region. Pulling together a well-formatted, community-standard database that includes expert knowledge of each proxy will also allow for intercomparison with upcoming ensemble and single-forcing climate model experiments for the past millennium, and more generally, for new investigations in the related fields of ecology, climatology, archeology and resource management that cannot be listed or predicted here.

2 Proposed Activities

PIs Kaufman and McKay led the recently published first synthesis of the continental-scale temperature records in the PAGES 2k Network (*PAGES 2k Consortium*, 2013), and know firsthand the challenges associated with assimilating and synthesizing paleoclimate data. The North American reconstruction was an exclusively volunteer effort, and thus relied primarily on published reconstructions without comprehensively assimilating all of the records. Our experience with this and other synthesis efforts have taught us that expanding the scope of this synthesis (in terms of proxies, duration and reconstructed parameters) will require a dedicated researcher to lead the data compilation effort. Therefore, we are requesting funding for a Powell Fellow to lead the data assimilation, formatting and synthesis efforts.

2.1 Data Synthesis

The first major goal of this proposal is aggregating all existing data on North American paleoclimate over the past two thousand years into a well-structured database that will be broadly useful to the community. Identifying, screening, aggregating, and reformatting records is a time-consuming, and occasionally tedious task. The Powell Fellow will lead this process, relying on the group members and their expertise throughout.

2.1.1 Record Selection

An initial task for the assembled group will be to establish criteria for selecting records for inclusion. The details will be decided by the group, but will likely include cutoffs for resolution, age control, and evidence for a robust relationship to an aspect of past climate. Additionally, a list of records that don't meet the criteria for resolution or age control, but that would be useful if resampled or with additional analyses, will be identified as high-value targets for future research.

2.1.2 Data Sources

The group will then begin identifying and aggregating the data. Many of the group members have accumulated small databases specific to their field and expertise, and thus we expect to quickly aggregate a large portion of the available records (Table 1). Many of these datasets will be lacking geochronological data and important pieces of metadata, most notably, the relationship between the measured values and climate. The Powell Fellow will add these components to the datasets by returning to the original publication, contacting the authors, and when necessary, getting expert input from the appropriate members of the group. After this initial inventory has been completed, the group will identify remaining targets and contact researchers with records not archived in public databases.

2.1.3 Data Formatting

For the database to be widely useful, the data must be uniformly formatted and machine-readable. The paleoclimate community has yet to agree to such a format, however, efforts

Table 1: Available records by archive type

Archive	Records in current temperature syntheses	Estimated records available
Tree-ring	146	150 to 200
Lake sediment (pollen)	4*	up to 500†
High-resolution lake sediment (non-pollen)	0	30 to 50
Marine sediment	0	10 to 20†
Speleothem	0	10 to 20
Coral	0	5 to 15
Ice core	0	10 to 20
Glaciers and landforms	0	10 to 50†

*Four regional syntheses, consisting of 466 pollen records, were used in the PAGES 2k Synthesis
†Number of records greatly depends on resolution constraints

to do so are beginning, most notably through the NSF's EarthCube initiative[1]. The PIs are engaged in this progress, however, this is unlikely to be finalized during the duration of this project. Consequently, the group, which includes a scientist from the World Data Center for Paleoclimatology[2] (Gene Wahl), along with input from the Powell Center Technical Staff, will decide on an interim data format that will serve our needs, and that will aim to be compatible with, and easily converted to, future standards. This interim data format will need to accommodate each record's 1) metadata, including expert climate interpretation, 2) raw measurements, 3) transformation to a climate variable (if appropriate), and 4) chronological data. The Powell Fellow will work with the Powell Center Staff to convert the aggregated data into the new data format, and ultimately, into a well-structured database that conforms with the Powell Center's Data Guidelines.

2.2 Analysis

2.2.1 North American temperature time-series

The first application of the newly assembled database will be to expand the recently published North American temperature reconstruction to 1) span the full past 2,000 years, and 2) make use of more than tree-ring and pollen evidence. The Powell Fellow will lead this effort, once again relying the diversity of expertise within the group. We will implement a modified version of the recently developed Pairwise Comparison (PaiCo) technique (*Hanhijärvi et al.*, In press). PaiCo was designed to reconstruct climate from records with multiple resolutions, and with minimal assumptions about the relationship with climate, and is thus well-suited for our needs. Because the database will include original geochronological data for all records, we will further expand PaiCo to consider age-uncertainty in the records, by analyzing time-uncertain ensembles of proxy records, rather than best-estimate single time series. These ensembles will be produced from the

[1] http://www.nsf.gov/geo/earthcube/
[2] http://www.ncdc.noaa.gov/paleo/paleo.html

original geochronological data in consultation with group members with expertise in each archive type (cf. *Anchukaitis and Tierney*, 2012; *Tierney et al.*, 2013).

2.2.2 Spatial reconstructions

Whereas extending and broadening the North American temperature reconstruction is a good initial goal, a larger focus will be on developing spatial reconstructions of other facets of climate system, especially hydroclimate. The impacts of changes in precipitation and drought in coming decades are likely to be more severe than changes in temperature, and also have more complex spatial patterns. Using the full breadth of relevant archives and the group's expertise has the potential to greatly improve our understanding on long-term changes in hydroclimate. We anticipate that multiproxy hydroclimate field reconstructions will be particularly interesting to compare with the well-developed tree-ring based drought reconstructions for the past 2,000 years (Figure 1b). Existing climate field reconstruction (CFR) techniques are not designed to appropriately integrate multiple-resolution or time-uncertain records, but this project will parallel a new working group within PAGES tasked with implementing solutions to these challenges in new and existing CFR algorithms. We will work closely with this partially overlapping group, applying emerging techniques to the North American 2k database, that will be designed to, in part, meet the needs of the next generation of reconstruction techniques.

In addition to hydroclimate reconstructions, we will aim to take advantage of our diverse database to work towards reconstructions of other climate parameters, especially pressure fields, circulation patterns and climate modes.

3 Participants

We have assembled a group of participants whose expertise spans the breadth of paleoclimate archives relevant to the past two millennia in North America, and who have specific expertise in North American paleoclimate (Table 2). The participants are diverse: of the 17 listed in Table 2, five are women, seven are early career scientists (two of whom are postdocs), and several ethnicities and nationalities are represented.

The proposed Powell Fellow is Dr. Nicholas McKay, a postdoctoral scholar at Northern Arizona University. McKay is an expert in climate reconstructions from lake sediments, and is well-qualified to be the fellow for this project, having been integrally involved in a several paleoclimate synthesis projects that span a range of regions, proxies and timescales (*Kaufman et al.*, 2009; *McKay et al.*, 2011; *PAGES 2k Consortium*, 2013). McKay is currently funded through next year; Powell Fellow funding would allow his support to be spread over most of two years while he splits his time on his current project (Arctic-Holocene paleoclimate synthesis) and this project.

To help limit the cost to the Powell Center, we are also applying for supplemental funding from PAGES to offset the expenses of international participants. If this proposal is funded, it is very likely that PAGES will support this project (pers. comm. Thorsten Kiefer; see letter of support).

Table 2: Working group members

Participant	Expertise
*† ‡ §**Nicholas McKay**, Northern Arizona University	Paleoclimate synthesis and paleolimnology
***Darrell Kaufman**, Northern Arizona University	Paleolimnology, glaciers and paleoclimate synthesis
***Debra Willard**, U.S. Geological Survey, Reston, VA	Paleoecology, marine sediments, paleoclimate synthesis
***Greg Pederson**, U.S. Geological Survey, Bozeman, MT	Dendroclimatology
***Ray Bradley**, University of Massachusetts	Paleolimnology and paleoclimate synthesis
***Julie Cole**, University of Arizona	Speleothems, corals, 2k climate model simulations
***Ed Cook**, Lamont-Doherty Earth Observatory, Columbia University	Dendroclimatology and paleoclimate synthesis
***Mike Evans**, University of Maryland	Dendroclimatology, corals, marine sediments and synthesis
***Sheri Fritz**, University of Nebraska-Lincoln	Paleolimnology and diatoms
***Virginia Iglesias**, U.S. Geological Survey, Bozeman, MT	Paleoecology
***Steve Jackson**, Southwest Regional Climate Science Center	Palynology and paleoecology
***Brian Menounos**, University of Northern British Columbia	Glaciers and glacier fed lakes
***Casey Saenger**, University of Alaska-Anchorage	Marine sediments
*⋆**Valerie Trouet**, University of Arizona	Dendroclimatology
*⋆**Andre Viau**, University of Ottawa	Palynology
Bo Vinther, University of Copenhagen, or other ice core specialist	Ice cores
*⋆**Gene Wahl**, NOAA World Data Center for Paleoclimatology	Dendroclimatology and paleoclimate synthesis

*Confirmed participant

†Technical liaison to Powell Center computing staff

‡Party responsible for adherence to Powell Center Data and Information Policy

§Powell Fellow

⋆Leader of original NAm2k Project

4 Timetable of Activities

This is a large and ambitious project, and many scientists outside of the core group of Powell Center working group participants will be interested in contributing to this next phase of the PAGES North American 2k project. Therefore, substantial coordination and communication will be required throughout, primarily by means of email and newsletters, but also through occasional web conferences and meetings. We will take advantage of the working group meetings at the Powell Center to focus the assembled expertise to make the difficult choices that might stall a larger group, and then get feedback from the larger community. If possible and appropriate, we're also interested in taking advantage of the Powell Center facilities to host electronic meetings or webinars during parts of the meetings where the participants can interact electronically with the larger community. The bulk of the effort, especially during the first year of the project, will likely be spent aggregating and reformatting data and metadata, as reflected in the timeline below.

August to November 2013 Initial email exchanges, finalize participant lists, begin aggregating data, refine project goals

November 2013 First meeting, four days: Discuss and agree to common data format, including format for specifying expert interpretation of climate sensitivity. Identify status of data collection, and the extent to which already collected records include sufficient geochronological data and author/expert interpretation. Target sites where data have not yet been acquired and assign responsibility for collecting needed data/metadata. Begin initial interpretation of results, primarily to identify data needs.

December 2013 to August 2014 Continue aggregation and formatting of data, initial synthesis efforts and interpretation of results. Email exchanges and conference calls as needed. Write first drafts of manuscripts.

September 2014 Second meeting, four days: Finalize version 1 of the database and identify any remaining data not yet aggregated or formatted for immediate inclusion. Finalize methodological choices for version 1 of the 2,000-year multiproxy reconstruction. Evaluate progress towards spatial reconstructions of other climate fields, and assign tasks moving forward. Evaluate manuscript drafts and assign tasks for manuscript completion.

October 2014 to February 2015 Finish collecting and formatting of data and finalize database. Use the database to evaluate emerging methods of multiproxy and time-uncertain reconstructions.

March to July 2015 Complete manuscripts, submit for publication. Release database to Powell Center, and the World Data Center for Paleoclimatology.

5 Anticipated Results and Benefits

The most important result of this project will be the comprehensive, uniformly formatted database released to the community. A standardized database produced and approved by the paleoclimate community will be extremely useful for 1) evaluating emerging reconstruction techniques with a uniform set of paleoclimate data, 2) climate modelers interested in evaluating model performance in light of paleoclimate evidence, 3) natural resource managers interested in better understanding the full range of natural climate variability, and 4) paleoclimatologists interested in placing new records in context with other regional results.

Furthermore, we expect at least four publications to result from these efforts:

1. A 2,000-year-long multi-proxy reconstruction of North American temperature aimed at a high-profile journal a high-profile journal, such as *PNAS*,

2. A publication presenting and describing the database, how it was assembled and is meant to be used, for a more focused audience, perhaps in *Climate of the Past*,

3. An in-depth study comparing the performance of emerging multiproxy and time uncertain reconstruction techniques, using the North American data as a test bed in a climate focused journal, such as *Journal of Climate* or *Climate Dynamics*,

4. A comparison of tree-ring-only and multiproxy hydroclimate reconstructions, focusing on the severity of past droughts and pluvials, and what this implies about the full range of hydroclimate variability in the Western US, depending on the results, this could also be aimed at high-profile journal.

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Powell Center Summary Data Management Plan

Summary Data Management Plan for Proposed Working Groups

(Repeat table for each data input, provide information for each element, submit with proposal)

Data Inputs	
Title	Paleoclimate data (from a number of different sources; but since one component of this proposal is formatting the data into a format that is consistent across all datasets, I'll describe them together, rather than separately)
Description	A complete paleoclimate dataset consists of three components: 1) metadata (including a range of geographical and other information; in this project it will also include author or expert interpretation of the relationship between the parameters and climate), 2) measurements (can be of various biological, physical, or chemical parameters) typically along a transect across a sample (depth in a sediment or ice core, along tree-ring indices, etc.), and 3) chronological data (this varies by proxy type, can be layer counting for tree-rings, ice cores, corals and varved lakes, but is more typically a table that includes depth and age information from some kind of dating method with associated errors.
Format	Paleoclimate data are typically archived as text files or spreadsheets, for this project however, The data will likely be formatted as a marked-up ascii file or xml.
Source	Various sources, many records are archived online in non-uniform formats at the World Data Center for Paleoclimatology

	(http://www.ncdc.noaa.gov/paleo/paleo.html) others will be acquired directly or second-hand from the original authors
Restrictions	No, only published and publicly available data will be used
Data Volume Estimate	*100 to 1000 Mb*
Link or identifier	There isn't a unique identifier for each record, although adding one should be a goal for this project
Data Processing	
Transformation and processing needs	Ideally, most data will be archived with a minimal amount of processing (raw measurements) and then any transformations that are needed (detrending (tree-rings), calibration, age modeling, transformation to temperature) will be done locally, to allow for standardization of methods across the database. For the synthesis, considerable processing will be required that varies by reconstruction algorithm
Special technology needs	Some reconstruction algorithms require (or at least benefit from) high performance computing. Although these resources are available among the participants if needed.
Data Publishing	
Title	Pages 2k North America climate database
Description	The new database will be a comprehensive collection of 2k-relevant records for North America, formatted in a uniform and machine-readable way that includes chronological data and expert interpretation of the climate-sensitivities.
Format	A collection of marked-up ascii or xml files along with software that allow querying and extraction of the data into other formats
Data Volume Estimate	100-1000 Mb

CVs and budget have been purposefully omitted.