March 2007 Workshop Summary of Talks

Konrad Steffen: “Cryospheric Contributions to Sea-Level Rise and Variability”

Of the 1.26 mm/a sea level rise occurring today, 70% coming from glaciers; 20% from Greenland; 10% from Antarctica.

Of the total accumulation per year, approx. 66% goes to Antarctica; 22% to glaciers; and 16% to Greenland.

Average rate of sea level rise (from satellite altimetry) for the period 1993-2006 is 3.5 mm/year. Thermal expansion accounts for 1.2-1.6 mm/yr; mountain glaciers 0.9 mm/year; Greenland ice melt 0.5 mm/yr; Antarctic ice melt 0.4 mm/yr. The average from land water storage for this period is not known.

IPCC sea level rise projections are too conservative.

NASA GRACE (Gravity Recovery and Climate Experiment) satellites show dramatic ice loss from Greenland ice sheet. Trend over the last several year is a loss of 154 Gt/year. Cannot be explained solely by melting. Ice dynamics play a role. Currently, ice dynamics not included in IPCC model estimates.

Regions above 2000m are gaining; regions below 2000m losing.

Southern Greenland losing mass twice as fast as Northern Greenland.

Western Greenland melting more than Eastern Greenland.

Increasing trend in the total area of melting bare ice from the late 70s forward: 13% per year.

Runoff from Greenland increasing. 2005 was record high (478 km3 water equivalent), more than two standard deviations above the long-term mean annual (1958-2005). Increase of 38 km3 per year from 1958-2005.

Antarctica: From 1992 to 2003 72% of Antarctica ice sheet is gaining a total mass of 27Gt per year. This equals a sea level reduction of 0.08mm per year (ERS satellite altimetry).

Antarctica shows increase in elevation over the interior. Decreasing near the coast. East Antarctica gains a bit; west Antarctica is losing mass.

Antarctic peninsula showing thinning in response to break-up of glaciers (accelerated up to 8 times). Antarctic ice sheet can respond rapidly to climate change.

Mass balance summary: Greenland thickening above 2000m; thinning at lower levels. Net loss since 2000. Antarctica has been slowly thickening in central regions and southern Antarctic Peninsula since 1990. Localized thinning at accelerating rates of glaciers in Antarctic Peninsula and Amundsen Sea region. Probably net loss, but close to balance.

Glacier retreat has increased since at least 1960, at rates that more than doubled after 1990. Net loss of almost 300 Gt/a.

Robert Thomas: "Ice Sheet Contributions to Sea Level Change"

Techniques for measuring ice-sheet mass balance include 1) traditional compares snow accumulation to losses from melting/runoff and ice discharge; 2) altimetry infers rates of volume change from time series surface-elevation surveys, and converts them to mass flux; 3) temporal changes to Earth's gravity field: interprets gravity changes as changes in ice mass after correcting for gravity changes from other causes, particularly mass distribution beneath the ice.

Most published mass-balance estimates fail to include all potential errors, particularly biases, in uncertainty estimates.

Recent mass-balance of Greenland and Antarctica. Since 1990 Greenland has been thickening above 2000m, at an accelerating rate; thinning at lower elevations, also at an accelerated rate. Net loss from the ice sheet of > 100 Gt/a after the late 1990s. Antarctica has been slowly thickening in central regions and southern Antarctic Peninsula since the early 1990s. Probably a long-term net loss. Recent localized thinning because of accelerating rates of glaciers in Antarctic Peninsula and Amundsen Sea, rising to probably > 100 Gt/a by 2005.

Ice loss is accelerating from Antarctica, Greenland and most glaciers in Alaska, South America and the Himalayas. Greenland glaciers may be starting to behave more like those in Alaska and Patagonia.

Jakobshavn: thinning very dramatically. Area of very rapid thinning doubled from 2002-2005. Cant melt all away. Must be dynamic response. This glacier used to have a large floating ice tongue which no longer exists (tongue started to thin in 1997 and was toast within the last few years). "Cork out of the bottle analogy".

Helhelm, Kangerdlugssuaq and Eqalorutsit East glaciers are also retreating and shrinking dramatically.

Ikerssuaq has not thinned but the bedrock is above sea level. Suggests melt induced lubrication has some effect but can't explain the rapid retreat.

Possible reasons for accelerating glaciers: 1) weakening/breakup of floating ice tongues, or progressive ungrounding and then breakup of seaward parts of the glaciers – loosening the cork in a tilted bottle; 2) lubrication of glacier beds by increased summer meltwater that drains down crevasses and moulins to the bed – greasing the skids.

Ice shelves getting thinner in Antarctica. On Antarctic peninsula break up of ice shelves have lead to speed up of ice retreat. Crane Glacier flowed into Larsen B after breakup. The ice thinned between 60-70 meters.

Base of glaciers in Greenland hilly, but relatively flat in Antarctica. If "pulling of the cork" is an important factor, then there is some hope in Greenland, as ice flow may stop flowing behind a mountain base. All of the west Antarctic can "pull cork out of bottle". Once the cork is pulled, it will flow back dramatically.

Ice sheet mass balance key questions:

Importance of ice shelves as regulators of ice discharge: develop quantitative relationships between ice-shelf dimensions and tributary-glacier velocities, and for distance inland that glacier acceleration will extend.

Ice-shelf/ocean interactions: develop models able to quantify basal melt rates on real ice shelves under prescribed ocean conditions; identify causes for ongoing ocean changes at high latitudes, and develop models able to predict ocean changes in a range of future climate scenarios.

Assess impact on outlet-glacier velocities of changing surface melt rates: compare existing observations on a range of accelerating glaciers; seek possible model approaches.

Surface mass balance. This is fairly well understood, and requires mainly progressive improvement through continued time series observations of meteorology and surface-balance response, along with continued model improvement.

Ice-sheet modeling. Existing models are totally incapable of simulating outlet-glacier response to changed conditions, and improvement must await substantial improvement in the first 3 bullets above.

Observations: Convergence is needed between mass-balance estimates based on different techniques, with emphasis on quantifying impacts of implicit assumptions in analyses of satellite radar altimetry; realistic error estimates for all techniques including impact of crustal motion on GRACE estimates.

Shawn Marshall: "Sea Level Rise Past, Present and Future: the Perspective from Ice Sheet Models"

North American glacier melting dramatically. Coast and Alaska glaciers the most dramatic; Canadian Arctic the least; Rockies in between.

Insights from the Quaternary period: During the last interglacial (Eemian, 130-120 ka BP) there was an orbitally-driven Arctic warming; global sea-level was 4-6m higher than present; most of the glaciers and ice fields in the Arctic melted, including much of the Greenland ice sheet.

Using Otto-Bleisner NCAR CCSM temperatures to drive an ice sheet model. Over the last interglacial period from 120-130 Kyr BP, if you raise temperature 3-4 degrees, Greenland goes away over 1000-2000 years.

Insights from the Quaternary: Deglaciation. There were periods of ice-sheet fluctuation throughout the glaciation: meltwater pulses during deglaciation; ice sheet surges (Heinrich events); millennial-scale ice sheet advance/retreat. These are not fully understood but must arise from a combination of response to climate variability and internal ice sheet dynamics.

Summary of Quaternary:

- At low latitudes, high melt rates occurred in response to interstadial warming, with several meter per century of sea level rise possible.
- A few degree C change can initiate this, and resultant ice dynamical response extends the response and impact beyond the initial perturbation.
- Greenland is vulnerable to this, but the amount of ice (hence sea level impact) is much less and the latitude/T will soften the response.

Recent and future ice sheet behavior:

Too much confidence been given to the IPCC upper bounds. IPCC gives range 0.18 to 0.59 m at end of 21st century (excludes future rapid dynamical changes in ice flow).

Limitations of ice sheet models:

- Unresolved fast-flow features (ice streams)
- Absence of subglacial process physics
- Absence of marine processes – calving, basal melt, grounding line migration
- Lack of longitudinal stress coupling.

Summary:

The main sources of uncertainty in the models are all in one direction: Underestimation of ice sheet sensitivity. IPCC (2007) estimates don’t represent the upper bounds, and probably underestimate the “most likely” sea-level rise scenario.

David Archer: “Methane Hydrates and Global Warming: A Risk Analysis”

Potential radiative capacity of methane: Assuming 10% of the ocean inventory as methane, we would have
500 Gt C
250 ppm CH4
12 W/m2
~ 10 x atmospheric pCO2

Rising ocean temperature leads to thinner hydrate stability zone.

Increase from 1% to at least 2.5% organic carbon in sediment reduces depth for the base of the clathrate stability zone and creates a steeper methane diffusion gradient (higher methane loss per unit of depth).

Ocean warming and shallowing of stability zone increases potential for destabilization and landslides.

A landslide can release hydrate to the water column, but at most ~ 1 Gt carbon. Smaller radiative impact than a volcanic eruption.

Methane gas escaping through stability zone doesn’t get very far: a few hundred meters.

Only place where bubbles could make it to the atmosphere are continental shelf and, perhaps, polar regions (Siberian shelf).

Arctic: Cold, so hydrates are shallow. Hydrates warm quickly and produce greater bubble volumes. High latitudes, so intense warming. Lots of shelf area. Relic permafrost in Siberia may be a concern.

The Late Paleocene/Eocene thermal maximum at 55Ma. Warming lasted 100,000 years. Warming likely from CO2.

Paleocene	CO2	600 ppm	Ocean Carbon 50,000 Gt C
PETM	CO2	1200-2400 ppm	Ocean Carbon 70,000 Gt C or more

Hydrates in Permafrost: melting from the sides. There are observations of elevated methane in Siberian shelf waters (Shakhova 2005.)

Permafrost melts and peat begins to decompose. Mostly produces CO2, not as much CH4. CH4 production inhibited by SO4 deposition. Ongoing, chronic increase rather than catastrophic.

CH4 sink by atmospheric oxidation increasing as a result of anthropogenic perturbations (NOx, Ozone, OH production).

Conclusions:
- No proposed mechanism for catastrophic methane release. Evidence for it in the past is equivocal.

- Oxidation sink appears to be self-stabilizing, a flickering flame.

Ed Brook: The Ice Core Record of Abrupt Changes in Atmospheric Methane"

Modeled a hypothetical abrupt methane event in the atmosphere and as trapped in ice. An atmospheric release of 5,000 ppb translates to ~ 1800 ppb in ice core. Slight offset in onset and decline in ice versus atmosphere. (Brook et al., GBC, 2000).

Last 20,000 years, recorded methane responses in Antarctic and Arctic ice cores (100-300 year transitions).

Other fast events:

- The 8.2 ka. An abrupt cooling occurred in the ice core. There is a 30-40 year transition.

- D-O 19-21. Rapid methane increase around 84 ka.

Methane versus temperature timing. Severinghaus et al. (1998) pointed out the temperature leads methane by a few decades. Very certain that methane is not causing the warming or cooling. Approach has been applied to 17 different events and in each of these, T leads methane.

Mechanisms for past abrupt methane changes:

- Climate driven methane emissions from freshwater wetlands
- Clathrate decomposition in marine sediments (warming/submarine landslides)
- Melting permafrost

Conclusions:

Things we know pretty well:
- Abrupt methane transitions have century to slightly quicker time scale
- No really large “catastrophic” methane releases in the ice core record
- Methane lags, or is synchronous with, temperature change
- No large events in the Holocene, except the 8.2 ka cooling/methane decrease

Things we know a little less well:
- Isotopic evidence inconsistent with marine clathrates
- Both NH and tropical sources change during abrupt events, NH change may be larger

Further questions:
- Is there a viable mechanism for unforced (by climate) or forced large-scale marine clathrate release?
- How likely is it that this methane would get to the atmosphere?
- What will the hydrologic balance be like in the boreal regions in the future?
- How high did methane concentrations get at glacial terminations?

David Lawrence: Vulnerability of Permafrost and Peatland Carbon Pools to High-Latitude Warming: Amplifying Feedbacks to Climate Change?”

CCSM3 projection (Holland, et al., 2007) shows abrupt change in September sea ice extent. Widespread across AOGCMs in terms of when and how fast sea-ice retreats.

Strong evidence exists that soil temperature and permafrost are responding to Arctic warming.

How much permafrost though to we expect during the 21st century? CCSM3 does a reasonable job simulating contemporary permafrost area. Shows a dramatic and rapid decline in permafrost area. True for most scenarios and there is also a strong commitment.

CCSM3 model limitations:
- No organic soil
- Soil too shallow
- No excess soil ice
- No subsidence, thermokarst
- Vegetation dynamics

CCSM3 model since corrected for organic soil and soil depth components. These factors slow the rate of permafrost degradation, but not enough to alter the general prediction that large-scale changes to near-surface permafrost are likely under the anticipated Arctic warming.

Thermal and hydrologic properties of organic soils are vastly different to those of mineral soil.

CLM3.5 shows most deep permafrost persists through the 21st century.

Other models show significant expansion of permafrost active layer (Sazanova, 2003; Anisimov and Poliakov, 2003; Buteau, 2004; Zhang et al., 2003; Chen et al., 2003).

Amplifying climate feedbacks associated with Arctic warming and permafrost degradation:
- Vegetation – the albedo feedback due to the expansion of shrublands across Arctic tundra and to a lesser extent northward forest migration
- Hydrologic cycle – freshwater discharge to Arctic Ocean; lake and wetland expansion/contraction.
- Carbon cycle – decomposition of carbon stored in peatland soils; release into the atmosphere as CH4 or CO2 depending on the local hydrologic response to permafrost degradation.

Shrub cover increasing at 1.2% per decade since 1950.

- Impacts of conversion of Arctic tundra to shrubland:
- More snow drifting
- Warmer winter soil temperature
- Increased microbial activity
- More plant-available nitrogen
- Summer shading, cooler soil temperature
- Lower albedo, earlier snowmelt

Smith et al. (2005) have detected changes in lakes in Siberia. They found total number and area of lakes decrease in discontinuous permafrost; increase in continuous permafrost regions.

What happens to soil carbon as soil temperatures warm and permafrost thaws? Dry, well drained soils result in aerobic decomposition and CO2 emission. Wetlands result in anaerobic conditions and CH4 emission. Numerous field studies support this (Walter et al., 2006; Zimov et al., 2006; Christensen et al., 2004; Turetsky et al., 2002; Goulden et al., 1998).

Estimates of carbon stored in permafrost soil: 200-800 Pg carbon (not including methane hydrates); ~ 74 Pg carbon in West Siberia peatlands alone; ~500 Pg in yedoma. (atmospheric carbon: ~750 Pg carbon.)

Future carbon balance of Arctic: Source or Sink? Arctic may become a net source, although there are many uncertainties. Fertilization experiments show that increase nitrogen fertilization increases surface vegetation carbon storage, but also increases microbial activity which releases soil carbon.

Summary (amplifying feedbacks):
- Large-scale degradation of near-surface permafrost likely
- Large stocks of labile soil carbon are vulnerable

- Albedo and carbon cycle feedbacks may amplify warming
- Arctic appears likely to be a net source of carbon, +GWP

Jean Lynch-Stieglitz: Atlantic MOC: Evidence for Past Variability and Relationship to Abrupt Climate Change During the Last 80,000 years"

Atlantic MOC past variability

1. LGM Atlantic

Low nutrient waters above 2 km in North Atlantic today; higher nutrient waters below 2 km. Different proxies (delta 13C, Cd/Ca, radiocarbon, Nd isotopes) show same stratificiation.

Shallower Atlantic MOC in Last Glacial Maximum (LGM) indicated by some coupled Ocean-Atmosphere models (e.g. Otto-Bliesner et al., 2006).

East-West density gradient gives shear in Atlantic meridional transport (Marotzke et al., 1999). For a LGM overturning strong but shallower than present, would expect an increase in this gradient.

Oxygen isotope data implies that LGM Eastern margin no longer has higher density than the western margin at 30°S. This implies cross basin density contrast is no longer existing so weakened AMOC at this latitude (Lynch-Stieglitz et al., 2006). Also, ^{231}Pa/^{230}Th ratios infer a reduced MOC (i.e. longer residence time than today.)

LGM summary:
Circulation not enhanced version of today's (N. Atlantic SST, deep water divide)
If surface to deep overturning existed it was probably weaker than today (cross basin density, Pa/Th, Florida Straits geostrophy)
Circulation not "drop dead" (Pa/Th, presence of 2 water masses)

2. Cool Climate Abrupt Change

Heinrich events occur during some DO stadials. Massive purges of ice sheets. (for review see Hemming, 2005)

Three paleo-modes of MOC (e,g, Rahmstorf, 2002)
Holocene – D-O WARM events
LGM – D-O COLD events
Heinrich events – Ice sheet purges – OFF

Rapid shifts of North Atlantic fronts during deglaciation indicated by Ruddiman and McIntyre (1981). Rapid shifts during D-O events as well (Bond et al., 1993).

Changes in deep water properties over D-O events are not clearly expressed even in cores which can resolved the surface water changes, but there are clear changes on the Heinrich events (e.g. Skinner and Elderfield , 2007).

Florida Straits data: consistent with weak MOC during Younger Dryas. H1 is drop dead for Pa/Th.

Relationship between climate, circulation and melt water is not necessarily simple (e.g. Stanford et al., 2006).

Cool climate abrupt change summary:
- Strength of MOC reducing during H1, YD and many other H events (carbon isotopes, FS geostrophy, Pa/Th, grain size).
- No compelling evidence for a direct relationship between D-O events, deep water properties or Atlantic MOC.

Holocene

Been some work trying to see if the MOC has varied during the Holocene, summarized in Hall et al. (2004). Some hints of MOC variations during the Holocene. 8000 year record of transport through the Florida Straits does not show any evidence for any substantial MOC reduction.

Lund et al. (2006) looked at 100yr resolution over the last 1000 years. Only a small change.

8.2 kyr event. Overturning may have weakened but it stayed weak after the Greenland and SST records return. (Ellison et al., 2006)

MOC Variability on centennial/millennial timescale likely to be small in the Holocene (compared to deglacial/glacial changes).

Bill Johns: The Atlantic MOC: Modern Observations, variability and detection of change”

Equilibrium of MOC reflects a balance between sinking and upwelling branches. Upwelling branch governed by large-scale, slowly evolving processes (deep interior mixing, southern ocean upwelling, water mass conversions in tropical oceans). Sinking branch governed by localized air-sea interaction; most likely to experience abrupt changes. Pathways are complex and turbulent.

What do we know about MOC variability on different time scales? Intraannual, decadal and multidecadal variability can introduce “noise” that can mask the detection of longer term MOC trends.

We have very limited direct measurement of MOC variability. Need to use other measurements, such as RAPID observations, repeated hydrographic sections, ocean synthesis / reanalysis products.

RAPID is monitoring the MOC at 26.5°N with good success (Hirschi, 2005). Proposed continuation until 2014 will provide a 10 year MOC time series.

From the 1syt year, At 25°N mean is 18.1±5.6 Sv over first year of RAPID array.

The Bryden et al. (2005) hypothesized MOC "slowdown" actually falls within the measured one year transport range as measured by RAPID.

Reanalysis models with global data assimilation. Mean MOC at 25N ranges from 14-22Sv.

Simulated MOC variability in forced OGCMs: decadal variability = 10-15% of the mean. Current thinking is there may even have been a small increase in the MOC strength during the past two decades.

What causes variability:

Intraanuual: Wind-driven Ekman variability, Rossby and Kelvin (boundary) waves (Hirschi et al.,2007)
Interannual to Decadal: Variability in Labrador Sea convection related to North Atlantic Oscillation (NAO) variability; wind-driven baroclinic adjustment. (Boning et al., 2006)
Multidecadal: Interhemispheric SST anomalies and correlated MOC variability (Atlantic Multidecadal Oscillation, AMO) (Knight et al., 2005; Zhang and Delworth, 2006; Kohl and Stammer, 2007)

Detecting MOC change. How can we detect anthropogenically-produced MOC changes, and whether the MOC's "trajectory" is consistent with climate model predictions?
- Detection of change will depend on the magnitude of the underlying trend vs. the variance of the natural variability.
- Signal to noise ratio.
- Need to know the spectrum of natural variability.
- Detection depends on both frequency and accuracy of MOC observations.

Approaches:
Bayesian models (e.g., Keller et al., 2007)
Climate model ensembles (Drijfhout and Hazeleger, 2007; Baehr et al., 2007)

MOC collapse would be detected within 50 years for annual MOC estimates with uncertainties typical of RAPID (Keller et al., 2007). Drijfhout and Hazeleger (2007) give 35 years detection and Baehr et al. (2007) give 50 years.

Conclusions:
- A system is now in place to provide accurate, long-term, continuous observations of the Atlantic MOC (strategy: RAPID, ocean synthesis/reanalysis models).
- Natural MOC variability occurs on a wide variety of time-scales. We don't yet understand all the mechanisms.
- Best estimate of the amplitude of the natural variability on subannual time scales is 2-3 Sv. With expected observational errors, the "detection" time for a change in the MOC is ~ 50 years. (Mitigation efforts require a shorter time scale.)
- Decadal to multidecadal variability modes – in which MOC changes are implicated – have significant climate impacts in themselves.

Ron Stouffer: Modeling Abrupt Climate Change

Global warming can disrupt the deep convection and deep water formation
- Freshening in high latitudes of the North Atlantic (Increased P-E+r and melting sea ice; melting of Greenland ice sheet and mountain glaciers)
- Surface ocean warming

IPC AR4 quote: It is very unlikely that the MOC will undergo a large abrupt shift during the 21st century. Longer-term changes in the MOC cannot be assesses with confidence. (AR4 WG1 10.3, 10.7)

The CMIP coordinated experiments

"Partially-Coupled" experiment
- Study the impact of the surface flux anomaly projected under "realistic" CO2 scenario on the stability of the THC.
- Determine the relative contribution of the anomalous heat and freshwater surface fluxes to the weakening of the THC
- Reference: Gregory et al. (GRL 2005)

"Water-Hosing" experiment (co-sponsored by PMIP)
- Study the sensitivity of the THC to freshwater fluxes in the high latitudes of the North Atlantic.
- Investigate the climate changes induced by a slowdown/shutdown of the THC. Reference: Stouffer et al. (J of Climate, 2006)

Results of "water-hosing" experiment:
0.1 Sv freshwater perturbation over 50-70 degrees N of the North Atlantic for 100 years. Perturbation removed and THC allowed to recover. Numerous models participated. Weakening of all models during the hosing period. Recovery after the end of the hosing. Models with the most THC weakening need the longest recovery time. 2.0 Sv reduction gives you 1°C cooling.

Multi-model mean SAT: Cooling south of Greenland; “bipolar seesaw” anomaly pattern; large uncertainty over the Barents and Nordic Seas.

The SSS response: Different magnitude of freshening; maximum freshening can occur a the western, middle or eastern part of the perturbation region.

The Atlantic ITCZ: Impact on the Amazon region, Sahel region and low-latitude SSS; Southward shifts in the AOGCMs; Induced by the interhemisphere seesaw-pattern SST anomalies; AOGCM vs. EMIC differences.

Sea Surface Temperatures: Bipolar Seesaw 3 degrees C decrease in North Atlantic; extension of icy seawater and sea ice coverage in North Atlantic; spread of warmer seawater via ACC; feedback on the THC intensity.

Sea Surface Salinity: 1.2 psu decrease in 50-70 degree N belt; South Atlantic and Gulf of Mexico become more saline; sharp SSS gradient at 40 degrees N. Labrador Sea: the most susceptible region to freshwater perturbation.

Sea ice: Thickness increases and coverage extends in the Labrador Sea; thickness decreases in the Nordic Seas and Barents Sea and the Weddell Sea due to enhancement of deep convection.

Precipitation: Dipole pattern over the tropical Atlantic; reduction in the North Atlantic induced by the temp increase; large uncertainty in the tropics and north Atlantic.

P-E+R: Perturbation freshwater flux dominates in the northern North Atlantic; drying in the tropical-subtropical North Atlantic; influence on the behavior of the THC.

Sea Level Pressure: Weakening of the Icelandic low; stimulates wave-like pattern in the high-latitude NH.

Conclusion:
Models are able to simulate at least some types of abrupt climate change. More “realistic” forcing experiments needed. Models can generate relatively large abrupt events without external forcing changes.

Ed Cook: Large-Scale Hydroclimatic Variability and Change Over North America for the Past 1000 Years.”

Epic drought of past few years has not gone away. It has just morphed itself into different regional expressions (see U.S. Drought Monitor).

Drought reconstructions based on 835 annual tree-ring chronologies along 285 2.5° x 2.5° grid points.

Past Droughts of note:

North American Drought Atlas. 50% of North America for AD 951 dry period and 75% coverage for AD 1380 dry period.

El Ano de Hambre drought. Intense 3-year North American drought from 1785-1787. Famine and disease killed 300,000.

17th Century Pueblo Drought. Six-year drought and famine. 1666-1671

Great Pueblo Drought. 1276-1297. Theory for Anasazi abandonment. Climate reconstructions indicate 20 of 22 years dry from 1276-1297. Erosion/arroyo cutting. Warfare. Disease. Social system collapse.
What can drought reconstructions tell us about the current drought in the west? Cook et al Science, (2004). 900-1300 was a mega drought in the Western USA; Medieval climate anomaly. Big droughts in 936, 1034, 1150 and 1253.

Past droughts were not more severe each year, but they lasted longer. Why? Duration is what separates current droughts versus 1000-year old droughts. New paper coming out on droughts of the last millennium in Journal of Climate (Herweijer, et al., in press).

Do climate models have the answers? Good correlation between dust bowl precipitation anomaly and GCMs forced by historical tropical Pacific SSTs (POGA) and global SSTs (GOGA) since 1856. (Seager models.)

1998-2004 precipitation anomaly reasonably-well captured by POGA and GOGA. Model runs also made for 1856-1865, 1870-1877 and 1890-1896 droughts.

Mann et al (2005) forced Zebiak-Cane with volcanic and solar reconstructions. High solar radiance/low volcanism – results lead to La Nina like condition in Eastern Tropical Pacific. Such a condition is known to produce droughts in western North America.

Coral records also indicate cooler conditions ~1200 AD.

Conclusion was that Irradiance up ➔ Eastern Equatorial pacific SSTs go down ➔ drought.

Other reconstructions Rein et al show same thing.

Conclusions:

Major events of hydrologic history of the American West – the current drought, the 1930s “Dust Bowl” drought and other in the 20th century, 3 mid-to-late 19th century droughts, and even two periods of Medieval drought – can be forced by weak but persistent La Ninas in the POGA-ML and GOGA models.

Increased solar irradiance and reduced explosive volcanism over the tropics can also induce a La Nina-like response during the MWP in the Zebiak-Cane ENSO model.

So future increased radiative forcing over the tropical Pacific from any source (natural or anthropogenic) is potentially not a good thing for drought formation in the West.

Richard Seager (talk given by Ed Cook): "Near Term Rapid Climate Change: The Case of Imminent Drying of Southwestern North America."

The Dust Bowl drought for the 1930s was (mostly) caused by a sea-surface temperature anomaly (1932-1939) with a cold La Nina-like tropical Pacific Ocean.

Conclusion based on 3 ensembles of CCM3 atmosphere model simulations by observed sea surface temperatures (SSTs):
- Tropical Pacific SSTs only, ocean ML elsewhere (POGA-ML)
- Global SSTs (GOGA)
- Tropical Atlantic SSTs only (TAGA)

16 ensemble members, all simulations cover 1856-2005.

The Dust bowl: cooperative Pacific and Atlantic SSTs. Forcing by tropical Atlantic SSTs does almost as well as forecasting with topical Pacific SSTs.

North American droughts associated with a characteristic zonal mean dynamical context. During drought regimes:
- Cold tropical troposphere
- Warm mid-latitudes
- Poleward shifted subtropical jet streams

IPCC AR4 simulations predict a rapid drying of the US Southwest beginning now to a perpetual state of 1950s drought- style aridity.

Substantial agreement on SW drying amongst all 19 IPCC models.

SW drying is part of general subtropical drying.

The primary cause of SW drying is a shift in the atmospheric circulation regime, induced by surface warming and orchestrated by transient eddy-mean flow interaction. The ocean is largely passive.

What improvements in observations may allow early detection of abrupt change?

- Continued satellite monitoring for assimilation into reanalyses.
- Rebuilding the radiosonde and weather station network in developing countries
- Extend the reanalyses back into the 19th century.

Research needs:
- A coordinated effort in atmospheric dynamics, from GCMs down to analytic models, to understand the changing character of circulation regimes.
- Almost three centuries after Hadley, we still don't have an adequate theoretical understanding of general circulation!

What are the current gaps and deficiencies in understanding?
- We do not understand the causes of the Medieval North American megadroughts.

Do we know enough to build an early warning system?
- Yes, it comes down to patterns of atmospheric circulation that are distinct for historical and future droughts.

Important issues concerning imminent rapid climate change and elevated aridity:
- Changes in atmospheric circulation regimes – based on eddy-mean flow interaction – will shift the SW North America and subtropics to an even more arid climate in the near future.
- Ocean only passively involved – need to get out of the current THC-think on abrupt climate change – the climate system is much richer than that.
- The past, including unexplained Medieval megadroughts, cannot be the only guide to a future unlike any seen before – dynamical understanding has to be our verification of model projections.
- Discrimination of forced and free climate change requires initialized climate change projections that can account for both.
- Bottom line: A new program for climate change prediction is required to model climate evolution over the next few years to decades and to predict rapid change to greater subtropical aridity.

Pat Bartlein: "Abrupt Hydrologic Response to Gradual Forcing During the Holocene: the Role of Land-Surface Feedback in Amplifying Hydrologic Extremes."

Two Holocene drought stories:

North Africa
- End of African humid period (ca. 5ka)
- "Collapse" of monsoon
- Initiation of Sahara (desert) biome

North America

- Mid-continent drought (8ka to 4ka)
- Enhanced southwestern monsoon

Common Features: 1) ultimately related to gradual decrease in Northern Hemisphere summer insolation during Holocene; 2) feedback from land-surface (vegetation) response is apparently required for both magnitude and abruptness of hydrological changes.

Africa Drought

An abrupt end of the humid period recorded by multiple paleo-indicators.

PMIP-1 results (Joussaume, et al., 1999):
- Stronger than present monsoon, but
- Not strong enough or northward enough
- Basic mechanism ok, but specific mechanisms that amplify abruptness of collapse not described

Abruptness is relationship between precipitation and vegetation. Claussen et al. (1999) show abrupt vegetation response to changing orbital variation.

Post-PMIP-1 simulations: AOGCM and EGVM (Kutzback and Liu, 1997; Texier, et al., 1997; Wohlfahrt, et al., 2004)

- Vegetation feedback apparently necessary for getting amplitude of monsoon right, and
- Probably also necessary for abruptness of change.

Current focus is on mechanisms for monsoon amplification and abruptness of decline (Clauseen et al., 2006; Chikira, et al., 2006; Hales and Neelin, 2006; Held, et al., 2006)

Further refinement of mechanism: 1) strong positive vegetation-climate feedback and multiple equilibria, vs. 2) low-frequency precipitation variability (Liu, et al., 2006)

Summary of African drought story:
- Ultimate forcing was amplification of annual cycle of insolation, and gradual decrease in summer insolation during Holocene
- Amplification of monsoon was dependent on vegetation feedback (and nonlinear relationship between vegetation cover and precipitation)
- Abruptness of collapse was likely also mediated by vegetation, either through the existence of multiple stable states, or through response to low-frequency climate variations.
- Net effect of gradual external forcing and land-surface feedback was abrupt end of humid period

Mid-Holocene “Prairie Period”

Mid-Holocene drought over mid-continent of North America
- Abrupt initiation is likely related to 8.2ka event (ice sheet collapse)
- Termination does not have an apparent external driver

Great Plains/mid-continent drought accompanied by dry conditions in Pacific Northwest and wet conditions in SW (Mock and Brunelle-Daines, 1999; Thompson et al., 1993)

Bartlein et al. (1998) and Webb et al. (1998) models simulate with insolation forcing only…but pretty bad data/model comparisons (wet mid-continent).

Harrison et al. (2003) mid-Holocene climates of the Americas. AOGCM simulations.
- Simulation of dynamical linkage between enhanced monsoon (uplift) and subsidence in PNW and Great Plains apparent in present-day monsoon
- Amplified by ocean-atmosphere coupling, but
- Still a mismatch between simulations and paleo observations of mid-continent aridity (too wet).

SST variability improves the simulations but magnitude too low (Shin, et al.).

AOGCM (CCSM3) also gets good pattern but amplitude of North America drought is too small and pattern too coarse (Otto-Bliesner, et al).

Diffenbaugh et al. (2006) used SSTs from RegCM3. 55 km resolution.
CCSMe >> CAM3 >> reg CM3 experimental design. Still not quite big enough magnitude P anomalies, although soil moisture simulations were good.

Went further still to add in vegetation feedback (Diffenbaugh, et al., in preparation). Things get very close to paleo reconstruction.

Summary of mid-continent aridity story:
- Ultimate forcing again was the amplification of the annual cycle of insolation and decline of summer insolation during the Holocene (with assistance by the ice sheet in onset of aridity)
- Maintenance of drought conditions assisted by SST variability and vegetation feedback
- Importance of model resolution and coupling in simulating drought conditions
North American system appears to be a bit more episodic than African one, but later-Holocene wet-dry episodes still significant and involve land-cover variations (and likely feedbacks).

Issues and questions:

- What is the likelihood of future amplification of hydrological variations by land-surface changes driven either by the response to climate change or to human activities (or both)?
- What is the appropriate hierarchy of models to employ for making that assessment, and how can they be tested?
- How well do we really understand the coupled climatological-hydrological-ecological system?
- Is amplification by land-cover change as important in topographically complex regions like western North America as it seems to be in eastern North America?
- What was actual duration of transitions (years, decades)?
- What is the potential for organizing the paleoflood record (and other hydrological indicators) on decadal-to-millennial scales?