1. Introduction

Isotopes are one of the most useful and innovative tools for understanding complex processes in the atmospheric water cycle, paleoclimate, biogeochemistry and chemistry on many timescales. An increasing variety of isotope data is now available, and active research on isotopic physics and chemistry continues to expand the data collected and the species examined. A workshop on isotopes in the climate system was held in Boulder, CO from January 13-15th 2004. The workshop, funded by a special grant from the National Science Foundation, had two goals. First, to bring together scientific leaders in observing and modeling isotopes to discuss the most interesting and important state-of-the-art science using isotopes. Second, the workshop participants discussed modeling isotopes specifically in the context of the Community Climate System Model (CCSM) and developed a plan for the implementation of isotopes within the CCSM.

This summary report provides an overview of the workshop. Included are a discussion of science issues and opportunities regarding isotopes and climate (section 2), as well as specific priorities and plans for implementing isotopes in CCSM (section 3). The agenda and participants list are attached as appendices.

2. Science Issues and Opportunities

The workshop discussions were broadly organized around different isotopic species, and what can be learned from each one. Various isotopologues of water (H$_2$O), carbon dioxide (CO$_2$) and carbon monoxide (CO) were discussed, with some discussion of sulfur and nitrogen atmospheric species (HNO$_3$ and H$_2$SO$_4$). Discussions were wide ranging, focusing on both observations and modeling, and what can be learned from isotopes.

In general, isotopes or isotopologues are valuable tracers in the earth system because their physical properties are slightly different than their parent species. The difference in molecular mass between an isotope and its parent may result in different behaviors during physical and chemical transformations, fluxes between reservoirs or phase changes. This different behavior is known as ‘fractionation’: the ratio of the isotope to its parent changes for a given process. For example, the vapor pressure of water is different for its different isotopes, such that the heavier isotopes (HDO, H$_2$O$_{18}$) preferentially go to the condensed phase at equilibrium. The result is that due to this ‘fractionation’ the vapor is depleted in the heavy isotope, and the condensate enriched. Fractionation is usually recorded as a ratio of isotope to parent species relative to some standard. In the case of water, this standard is a ‘standard mean ocean water’. Depletion or enrichment is often reported in percent terms (or per mil) so that -100 per mil is a 10% depletion (and denoted as ‘δ’ or delta notation). For water vapor, this fractionation is mainly a function of temperature, which provides a record of a wide range of condensation processes in the climate system.
In general the isotopic fractionation for similar species (such as H$_2^{17}$O and H$_2^{18}$O) is similar and proportional to their mass. Effects not proportional to mass are known as ‘mass independent fractionation’, and because they only occur for certain processes, are useful tracers of those processes. For oxygen, the gas phase reaction creating Ozone (O$_2$+O+M $\rightarrow$ O$_3$) has a mass independent fractionation for $^{17}$O and $^{18}$O, creating a signal which is imparted to oxygen containing species (H$_2$O, CO, CO$_2$) that react with ozone, mostly in the stratosphere.

2.1 H$_2$O isotopes

Several isotopologues were discussed. Most prominent were H$_2$HO (or HDO) and H$_2^{18}$O. Also discussed were H$_2^{17}$O, and some discussion of H$^3$HO (or HTO). The discussions were focused on several themes. Water vapor isotopes are widely known as paleoclimate temperature and ice sheet mass proxies. Their relationship to model and data-based climate reconstructions was also discussed. Water vapor isotopes can also serve as diagnostics of ocean and land surface transport and processes. Much of the discussion focused on the atmospheric hydrologic cycle, and how isotopes can help improve the representation of condensation and evaporation processes in climate system models. There was also discussion of uncertainties in our understanding of isotopic fractionation of water vapor.

![Diagram of water cycle with δD and δ$^{18}$O values](image)

Figure 1: Illustration of the water cycle, δD and δ$^{18}$O values in the atmosphere (courtesy of Gavin Schmidt.) Values indicate isotopic fractionation observed in various locations or for processes for δ$^{18}$O and (δD) in per mil units.
Figure 1 presents an overview of the atmospheric hydrologic cycle, with the fractionation observed for the two most important isotopologues of H$_2$O: HDO and H$_2^{18}$O. The fractionation is measured relative to standard mean ocean water. Large depletions are found in the stratosphere and upper troposphere, as well as at high latitudes. Several key processes in the upper troposphere are still uncertain.

2.1.1 Paleoclimate

The goal of many paleoclimate researchers is to simulate directly isotopes in climate system models so that transfer functions (e.g. conversion of isotope data to proxy temperature records) are not necessary. Isotopes also enable a better understanding of processes, and provide a new class of validation for paleoclimate models. Paleoclimate isotope effects occur in precipitation, in groundwater, and in ocean carbonates. In precipitation, isotopic fractionation is mainly due to the temperature of evaporation and condensation and to the amount of precipitation ($\delta^{18}$O is negatively correlated with precipitation in the tropics). Paleoclimate records thus convolve many processes, including source region, transport, temperature, quantity and seasonal timing of precipitation. Since many of the paleoproxies in oceans involve biological organisms, fractionation within ecosystems also impacts the marine $\delta^{18}$O observed.

Examples of paleoclimate records include ice cores from tropical glaciers as well as from polar ice caps. Tropical glaciers can record decadal variability, but the signals are often difficult to separate between isotopic variations due to the amount of precipitation or its seasonality and temperature. Carbonate in corals records $^{18}$O in seawater and is sensitive to temperature and rainfall. Interannual correlations with ENSO cycles are found. Cave speleothems (stalactites and stalagmites) also preserve a record of $^{18}$O from precipitation ending up in groundwater calcium carbonates. These records are starting to allow new types of paleoclimate reconstruction of drought patterns in the southwest United States, for example.

The deuterium excess (HDO v. H$_2^{18}$O) can also be used as a long term climate proxy. Unfortunately, while the current generation of climate system models is able to correctly simulate the present day deuterium excess, the models still have problems simulating observations of deuterium excess in paleo-climate records such as ice cores. The result is an interesting remaining question for interpreting and modeling the paleo record, and isotope modeling in general.

2.1.2 Stratospheric Transport

Water isotopes can also be used to understand atmospheric transport, and in particular, the exchange of air between the stratosphere and the troposphere. New analyses presented at the workshop help narrow the uncertainties in the isotopic composition of the stratosphere, mostly by new understanding about the isotopic composition of stratospheric hydrogen. The stratosphere is ‘underdepleted’ relative to a simple Rayleigh fractionation model, in which as an air parcel cools and water condenses, the condensate H$_2$O and isotopes are removed from the parcel. Understanding this discrepancy may
provide useful information on the processes that transport air into the stratosphere. Active laboratory work is also occurring to understand low temperature fractionation processes, kinetic fractionation effects and pure evaporation processes, which may be important for understanding low temperature and low pressure fractionation in the upper troposphere and polar regions. Most participants do not think the uncertainties in these low temperature processes are large enough to explain the observed discrepancies. Most analyses conclude that significant quantities of lofted ice evaporating are necessary to understand the isotopic composition of the stratosphere.

Initial modeling results with water vapor isotopes in global models and analytic models do seem to be able to correctly simulate observations of water isotopes in the upper troposphere and stratosphere. This is encouraging for diagnoses of the hydrologic cycle (see below).

2.1.3 Ocean Circulation

Unstable water vapor isotopes, such as HTO (water with Tritium) have been used effectively as tracers of ocean circulation. Significant quantities of Tritium were injected into the climate system during nuclear bomb tests in the 1950s and 1960s. HTO is now useful because it was absorbed into natural reservoirs (such as the southern ocean) and these reservoirs are now emitting HTO, revealing timescales of the ocean uptake of atmospheric gases (e.g. carbon dioxide). Stable isotopes in ocean waters leave records in carbonates (like corals) that are a useful proxy of temperature and precipitation, as discussed above in the section on paleoclimate.

2.1.4 Hydrology

The focus of the workshop discussions on hydrology were related to isotopic processes in precipitation, chiefly H$_2^{18}$O in precipitation. There are currently active global and North American networks to measure isotopes in precipitation. The US network is not well developed, but is being augmented. The current network is able to pick out basic temperature signals, but the variance of isotopes in precipitation is not strongly related to local temperature at midlatitudes. It is rather related to the amount of precipitation, and trajectories which govern the source water. In studies of North America, for example, there are strong isotopic signals that occur with individual storms depending on their source and trajectory, and the seasonal anomalies are corrected with the phase of the ENSO cycle. The workshop did not focus explicitly on the surface water budget, runoff and the surface hydrologic cycle, but participants noted that this is an area of active research, although outside of the research of most of the participants.

There was considerable discussion about how isotopes can be used to improve simulations and understanding of the hydrologic cycle. Water vapor isotopes record an integrated history of condensation and evaporation processes. This makes isotopes useful for several types of diagnosis within the hydrologic cycle that are difficult to observe by other means. In bulk, isotopes are useful for understanding the atmospheric water budget, particularly in the upper troposphere where few observations exist. Isotopes are
particularly valuable as a diagnostic for models. Simulated isotopic distributions of HDO and H$_2^{18}$O can be used to validate whether moisture arrives in the upper troposphere by the right set of processes in a model. This process oriented approach can assist in validating model simulations of water vapor and cloud radiative feedbacks on climate.

There was mention that the vertical profile of water itself is not known well in the middle and upper troposphere. Better isotopic observations of water vapor are also needed, particularly vertical profiles. Observations of isotopes in the upper troposphere are difficult. There was some discussion of remote sensing and in-situ techniques. HDO is a tractable measurement problem, H$_2^{18}$O is a much more difficult observation. Few vertical profiles of water isotopes in the atmosphere exist, and a reasonable climatology is not complete.

In addition to the atmospheric water budget, isotopes are useful for understanding the sources of water in precipitation. Models can explicitly calculate where water comes from, but validating model results with observations is difficult. Isotopes provide a good diagnostic for validation of models. The source regions or ‘fetch’ of precipitation are an important and uncertain part of the atmospheric hydrologic cycle. Different source regions (high latitude oceans, low latitude continents, lakes) have different isotopic signals, and these can be traced in precipitation. In addition, isotopes of water can also be used as a detailed diagnostic of cloud condensation and evaporation in models. This can occur both on a global basis, to examine the integrative effect of condensation, or on a cloud scale. Both global models and cloud resolving models can be tested with isotopic observations. Few sets of detailed vertical profiles near clouds exist, and it was urged that isotopic observations become standard in campaigns to observe convective clouds.

2.2 CO$_2$ isotopes

The chief isotopologues of CO$_2$ discussed were $^{13}$CO$_2$, $^{14}$CO$_2$ and C$^{18}$O. These isotopes provide useful information about various aspects of the global carbon cycle, and are particularly useful for understanding various sources and sinks of carbon, as well as carbon fluxes and exchanges between the atmosphere, oceans and biosphere. $^{13}$CO$_2$ is a useful diagnostic of the atmospheric CO$_2$ budget, and can assist in partitioning the terrestrial and oceanic sinks of atmospheric CO$_2$. C$^{18}$O can help elucidate the gross exchanges between the atmosphere and the biosphere and is linked to the water cycle. $^{14}$CO$_2$ provides a useful diagnostic of the age of carbon respired from the biosphere.

2.2.1 Land/Ocean Carbon Sink

$^{13}$CO$_2$ is a critical tool for trying to understand the sources and sinks of carbon in the earth system. Various sources of CO$_2$ have different $^{13}$CO$_2$ signatures (fossil fuel carbon is depleted in $^{13}$C for example), and there are different $^{13}$C burdens in reservoirs. The total flux of carbon to/from each reservoir, and the total flux of $^{13}$C provide two ways to distinguish various reservoirs and the fluxes between them. This closure of the carbon budget using $^{13}$C isotopes is illustrated in Figure 2. Given sources and sinks of carbon, as
well as the $^{13}$C composition, the magnitude of the net land and ocean sink can be
determined. Observations of CO$_2$ and isotopes over time allow us also to discern
interannual variability in carbon sources and sinks.

Figure 2: Illustration of how isotopes can be used as an additional piece of information to
distinguish between carbon reservoirs to help determine sources and sinks. If the isotopic
composition of a flux is known, then this constrains the magnitude of the flux. (figure
from C. Still)

In addition, C$^{18}$OO provides a linkage between the global water and carbon cycles as
indicated in Figure 3. $^{18}$O in CO$_2$ is a function of photosynthesis (which enhances C$^{18}$OO)
and soil respiration (which depletes C$^{18}$OO). It is also modulated by the H$_2$O$^{18}$O in the
water cycle (precipitation mostly). CO$_2$, in the presence of leaf enzymes, isotopically
equilibrates with H$_2$O (H$_2$O$^{18}$O). Thus constraints on the gross primary production (GPP)
are possible by examining the isotopes. These results indicate that fluxes in and out of
leaves are huge: roughly 1/3 of atmospheric CO$_2$ molecules interact with leaves each
year. This also highlights the necessity of understanding the role of the water cycle in
regulating the carbon cycle.
Figure 3: Interactions between the global water and carbon cycles for Oxygen 18 (courtesy of Chris Still). As noted in the text, C\textsuperscript{18}OO isotopic ratios equilibrate with the \textsuperscript{18}O ratios in leaves, ‘resetting’ the isotopic ratio of C\textsuperscript{18}OO. Exchange may also occur in soils, and in root uptake of groundwater.

There exist observations of C\textsuperscript{18}OO for the 1980’s and 1990’s which indicate lags with respect to CO\textsubscript{2} cycles, and interannual variability. In the tropics, such variability is correlated with ENSO cycles (likely due to precipitation). In high latitudes, there may be interannual anomalies in C\textsuperscript{18}OO which are linked to high latitude circulation patterns (the Arctic Oscillation), due to effects on H\textsubscript{2}\textsuperscript{18}O in the water cycle.

\subsection*{2.2.2 Carbon cycle Disequilibria & paleo C cycle}

Currently there exists a ‘disequilibrium’ between the \textsuperscript{13}C going into plants and the \textsuperscript{13}C coming out, because of fossil fuel emissions of carbon dioxide emitted into the atmosphere are more depleted in \textsuperscript{13}C than other parts of the system. This disequilibrium is illustrated graphically in Figure 2. Note that in Figure 2, changes in the total mass of \textsuperscript{13}C can occur even with no changes in total mass of carbon as a result of this ‘disequilibrium’. The extra constraints on the \textsuperscript{13}C budget from the \textsuperscript{12}C budget thus provide a useful extra constraint on understanding the global carbon cycle, and perturbations to the cycle over time. We may also think of constructing a diagram like Figure 2 for different time scales.
Because of its equilibration in plants, isotopes of oxygen in carbon dioxide can also potentially be an indicator of the paleo-carbon cycle. If we can use it now to discern GPP, then perhaps we can use records of $^{18}$O and $^{17}$O to understand GPP in the past. The stratospheric production of ozone produces a mass independent anomaly in $^{17}$O in O$_2$. Because the biosphere removes the isotopically anomalous stratosphere-derived O$_2$ by respiration, and replaces it with isotopically 'normal' oxygen by photosynthesis, the magnitude of the tropospheric $^{17}$O anomaly can be used as a tracer of global biosphere production on paleo timescales.

2.2.3 Ocean Biogeochemistry

Radiocarbon CO$_2$ ($^{14}$CO$_2$) is useful for understanding oceanic carbon reservoirs. Radiocarbon from bomb tests in the 1960’s is now being outgassed from ocean reservoirs into the atmosphere similarly to HTO, providing useful information on the age of carbon in the upper ocean. Some ocean regions (high latitude southern ocean) have been isolated from $^{14}$CO$_2$ as well, and are depleted in natural and bomb radiocarbon.

2.2.4 Land Use/Carbon sources

Radiocarbon CO$_2$ ($^{14}$CO$_2$) has natural cosmogenic sources as well as nuclear bomb sources and is also useful for understanding terrestrial carbon reservoirs. This source provides useful information on carbon reservoirs in tropical forests for example, which differ from fossil fuel CO$_2$ sources (depleted in radiocarbon). Given knowledge of the natural background of cosmogenic $^{14}$CO$_2$, it may provide a useful tracer of stratosphere-troposphere exchange. Given assumptions about the stratospheric source, $^{14}$CO$_2$ is then a useful discriminant between various terrestrial and oceanic reservoirs of $^{14}$CO$_2$ (some of which fixed it at higher levels during the 1960s bomb tests, and are now outgassing it).

In addition there was discussion that the mass independent fractionation of C$^{17}$OO can also be used as an indicator of stratosphere-troposphere exchange. A mass independent fractionation signature is imparted to stratospheric CO$_2$ during its reaction with stratospheric ozone, which has more $^{17}$O than mass dependent theory would presume. This large isotope effect, with known rates of reaction, is a good test of stratospheric models. There are some observations from aircraft and rockets of the $^{17}$O anomaly in stratospheric CO$_2$. The signal is ‘reset’ in the terrestrial biosphere by equilibration of CO$_2$ with the much larger H$_2$O reservoir as indicated in Figure 3. In this sense the ‘reset’ itself may be used as a tracer of the biosphere CO$_2$ source.

Finally, there was discussion of how changes in CO$_2$ isotopologues over time can be used to understand changes in land use. C$^{18}$OO can help us understand the balance of different types of plants (C3 respiration pathway plants vs. C4 plants), this also may change with changes in the local hydrologic cycle (H$_2$O and H$_2$O$^{18}$O variations). Also, $^{13}$C can help us separate biomass burning from fossil fuel emissions over time.
2.3 CO

Several isotopes of carbon monoxide were discussed during the workshop. $^{13}\text{CO}$ (or C$^{18}\text{O}$ and C$^{17}\text{O}$) is a useful tracer for discriminating the sources of CO since the fossil fuel, C3 and C4 plant biomass burning, and organic compound oxidation sources of CO have different isotopic signatures. Seasonal variations in the isotopic composition of CO at several sites (e.g. Barbados) indicate changes in the sources of CO over the course of a year.

In addition, $^{14}\text{CO}$ provides a useful tracer of stratosphere-troposphere exchange and chemistry in models. $^{14}\text{CO}$ is produced in the stratosphere, and is basically a stable isotopomer over the lifetime of CO (months). Because the $^{14}\text{CO}$ production rate is well known, then the concentration of $^{14}\text{CO}$ can also be used to infer stratosphere-troposphere exchange and OH oxidation of CO.

2.4 Summary of scientific priorities

Based on the wide ranging discussions above the participants condensed the discussions into a series of summary tables for each of the isotopes. For each isotope, key science questions were described. A summary is provided here.

H$_2$O

1. Paleo-Climate. Models can be used to directly produce isotopic signatures from past temperature and precipitation patterns to aid in the interpretation of paleoclimate records from ice cores, ground water, corals, etc. This requires an appropriate hydrologic cycle, and H$_2$O and HDO.

2. Stratospheric Water Vapor and Transport. Understanding isotopic observations of H$_2$O and HDO in the upper troposphere and lower stratosphere can provide additional information to understand how air and humidity enter the stratosphere. These isotopes provide another constraint on model condensation processes, cloud microphysics and transport.

3. The Atmospheric Water Budget. The large scale humidity budget of the atmosphere is critically important both for understanding the source water for precipitation on weather scales, as well as global scale feedbacks and coupling to radiation on climate scales. Isotopes of water (HDO and H$_2$O) can help discriminate sources of precipitation, and validate global model simulations of upper level humidity for climate purposes.

4. Simulating and understanding Cloud Processes. There are several related areas of research that are actively concerned with understanding cloud microphysics and condensation processes. Cloud processes are coupled to radiation, latent heat
release and large scale dynamics that are important for organizing clouds in the atmosphere. Isotopes in cloud resolving models and global models (HDO and H$_2^{18}$O) provide strong tests of model performance for various processes. More observations are needed.

5. Ocean Circulation. HTO (tritium), emitted by nuclear tests in the 20th century, is an important tracer of oceanic transport and ventilation of the ocean on decadal scales. Ocean model transport can be tested with HTO isotope observations, exploring how ocean water comes back into contact with the atmosphere.

**CO$_2$**

1. Changing Land/Ocean Sinks. Isotopes of carbon dioxide ($^{14}$CO$_2$ and $^{13}$CO$_2$) coupled with C$^{18}$OO and water isotopes provide a powerful suite of tracers to understand the current sources and sinks of carbon dioxide. This includes gross photosynthesis and respiration, as well as fire and anthropogenic sources with different isotopic signatures. By properly modeling the different fluxes and reservoirs of both carbon and isotopes in the system, land surface and biogeochemical models can be better constrained.

2. Age Distribution of Carbon Sinks. The current disequilibrium in both radiocarbon ($^{14}$CO$_2$) and $^{13}$CO$_2$ from fossil fuels provides a wealth of information about the age of surface (terrestrial and oceanic) carbon sources and sinks, and allows us to close the carbon cycle. Simulations of this cycle are useful for testing the source and sink distributions in models.

3. Ocean Biogeochemistry. As noted, radiocarbon is a useful tracer of ocean carbon reservoirs, as well as transport. Simulations with $^{14}$CO$_2$ and HTO can be used to understand ocean transport, and uptake and emission from marine biological reservoirs.

4. Paleo Productivity. Interannual variations in carbon isotope sources and sinks ($^{13}$CO$_2$, C$^{18}$OO and C$^{17}$OO) provide an integrated view of the variations in the earth system and interactions between carbon and water cycles when coupled with HDO, H$_2^{17}$O and H$_2^{18}$O. Being able to simulate this system is useful for interpreting paleo isotopic records (as it is for water isotopes) and for testing the coupled variability of the simulated carbon cycle.

5. Land use changes. CO$_2$ isotopes ($^{13}$CO$_2$) change with fossil fuel emissions and the distribution of C3 and C4 pathways of respiration in plants. So changing land use and land cover, by changing forests to grassland or crops, can change CO$_2$ isotopes. Biomass burning sources also have unique isotopic signatures. Correctly simulating these pathways will give us more confidence in projecting future carbon cycle changes, and also assist with paleo record interpretation.
CO

1. Biomass Burning. $^{13}$CO isotopes provide a strong and unique signature of biomass burning that is important for models to be able to simulate, this helps constrain the overall source of carbon from fires.

2. Stratosphere-Troposphere Exchange. $^{14}$CO has a known and calculable stratospheric source, and can be used as an indicator of the transport of CO from the stratosphere into the upper troposphere. This provides a unique way to quantify a process that models have trouble with: exchange across the tropopause.

3. Combustion v. Oxidation. The combination of $^{14}$CO and $^{13}$CO provides insight into the balance of combustion sources of CO and oxidation of CO by OH in the atmosphere. Variations of the distribution of isotopes in time and space help us understand and simulate sources and sinks of CO.

2.5 Summary of Previous Modeling Work

There was a brief discussion among several of the participants of previous global modeling work on isotopes. To date, there have been several successful efforts to model isotopes in global models. To date, these efforts have focused on water isotopologues. The first efforts were with the French Laboratoire de Météorologie Dynamique (LMD) general circulation model (Joussaume et al., 1984). Other efforts have included the Goddard Institute for Space Studies (GISS) model (Jouzel et al 1987, Jouzel et al 1991). A second generation of the GISS model with isotopes is currently being developed by G. Schmidt (personal communication). Water vapor isotopes have also been added to the Max Plank Institute Hamburg GCM, ECHAM (Hoffmann, 1998). Isotopes of water have also been added to the Melbourne University GCM (MUGCM) by Noone and Simmonds (2002). The GENESIS model also now has an isotope module (Mathieu et al., 2002). Finally, efforts are underway to add isotopes to the Hadley Center model HadCM2 by P. J. Valdes.

References:


3. CCSM

3.1 Past and Present isotope work with CCSM

There has been some preliminary work using isotopes in the CCSM framework. A version of the land surface model (LSM) from the CSM has been developed with isotopes, the ISOLSM. This effort has been lead by W. Riley (LBL). In addition, some preliminary work on implementing isotopes in the Community Climate Model, version 3 (CCM3) has been completed by Noone (CU-Boulder). Incorporating isotopes into the ocean model is a task for future work.

3.2 Statement of Priorities for CCSM

There was a clear statement of priorities from the workshop. Water isotopes are clearly the first set of isotopes to implement in the model. Given the dependence of other processes and species (such as CO$_2$ isotopes) on water isotopes, as well as other modeling efforts, this is a logical place to start. Because of the many applications, the atmosphere is the highest priority, followed by the land surface and terrestrial biosphere. The latter effort has not be extensively modeled, though some efforts are currently underway with other coupled models.

While some of the work has been partially completed in CCM3 and ISOLSM, there is still much to do to upgrade these code to the CAM3 and CLM3 versions. In particular, it was pointed out that there are several aspects of the atmospheric physics parameterizations which are not explicit enough in their description of condensation processes for proper treatment of isotopic fractionation. This is an important area where isotopes can serve as a diagnostic for the atmospheric hydrologic cycle, but a difficulty for modeling isotopes in the near term.
Carbon dioxide isotopes are an area of importance, and a new frontier for isotope modeling. Properly treating these isotopes requires interactions with the isotopologues of water (for $^{18}C\text{O}_2$), and thus this is a second task. Fewer modeling efforts have successfully been able to model CO$_2$ isotopes. Given the details of the CCSM carbon cycle, there is a great potential for cutting edge science here.

### 3.3 CCSM work plan and tasks

The work plan discussed during the workshop focuses on the next 6 months, at which time progress will be re-assessed. The plan is dictated by three milestones. First, the March 2004 CCSM atmosphere and biogeochemistry working group meetings are a good opportunity to raise issues related to isotopes. These issues include (among others); potential future directions for transport schemes in the atmosphere, requirements of conservation for future atmospheric physics packages, and conservation of water substance (through runoff) in the land model. Second, the CCSM annual meeting in July 2004, where it would be nice to be able to illustrate progress. Third, software engineering resources within the CCSM project at NCAR are occupied until the May 2004 release date of CCSM3. After July, it may be possible to get some assistance in developing an isotope implementation in CCSM.

Interaction with the IPCC process was also discussed, but it was decided that given the IPCC timeline, it is unlikely that working isotope code will be ready for the planned paleoclimate runs starting soon. It may be possible, but ambitious, to have some paleoclimate simulations performed for science in the IPCC report (submitted by summer 2005 or so).

The outline of tasks is detailed below, in approximate order of priority.

**Tasks: Water isotopes**

**Atmosphere:** Goal end of 2004 have working code (not public)
1. Move from ccm3 to cam3 (software)
2. Precip flux negative in convective mass flux scheme (kludge now, fix later)
3. Prognostic water in moist processes different/large scale precip
4. Evaporation under convective clouds new
5. New generic water tracers in atm (software)
6. Debugging + tuning +understanding?

**Atmosphere Resources**

Near Term: Group from CU, UCB, UMD and NCAR.
After May 18: Possible CCSM assistance for software engineering
Land (2nd priority)

- Move from LSM to CLM–Plan is in place for this to occur.
- New generic water tracer scheme in clm
- Leaf water—may need development in next version of CLM
- Resources there for next 6 months?? Perhaps done by July
- More development (longer develop with CO₂)
- Need river tracers (longer term) possible to add tracer without too much trouble?? but to do right need lakes (longer time-need new version of runoff)

Other model components

- Ocean model (advection of del18O, HDO, HTO in POP)? (kludge rivers or do right?) ~1 week) Coding easy, spinup problems
  - Advection issues?? Fresh water vs. isotopes consistent funky adjustments
- Sea ice tracers (multi layer snow and sea ice –may not matter) (longer term) (new model has some tracers, vague plan currently

CO2 isotopes

1. CLM-CN integrations of CLM work by CSU
   1. Scheme similar to the water isotopes
   2. Move CSU into CLM-CN ¹³C
   3.
2. ISO/LSM → CLM-CN: entrepreneurial
   1. Soil diffusion
   2. Leaf water
3. Need plan for ¹⁴C passive tracer (relatively easy but no plan)
4. for all isotope applications, new state, new flux, new diagnostics—BGC meeting discuss again. Chose which to include.
Appendix 1: Workshop agenda

AGENDA
Workshop on Isotopes in the Earth System
at
Mesa Lab, Walter Orr Roberts Board Room, Fleischmann Building
Boulder, Colorado
January 13-15, 2004

PHASE I: ISOTOPES AS A TOOL FOR UNDERSTANDING THE EARTH SYSTEM
Each session has two speakers focusing on current status and future directions, with plenty of time for discussion.

Tuesday, January 13, 2004, Walter Orr Roberts Board Room
Day 1, AM: Water isotope data: Interesting questions, innovative new data approaches

8:00 Continental Breakfast
8:30-9:00 Introductions
9:00-10:30 Betty Otto-Bliesner, NCAR, Chair
Speakers:
Evaporation and condensation of water (Ronald Cohen, University of California, Berkeley)
Stable isotopes in paleoclimate and climate modeling (Julia Cole, University of Arizona)
Isotopic patterns and processes in precipitation: Recent findings and future directions (Jeffrey Welker, Colorado State University)
10:30-10:45 Break
10:45-12:30 Other Speakers (1-2 slides), discussion
12:30-1:45 Lunch

Day 1, PM: Water isotope modeling: Results and future modeling approaches

1:45-3:15 David Noone, University of Colorado, Boulder, Chair
Speakers:
Water stable isotopes using GCMs: an overview (Martin Werner, Max Planck Institute for Biogeochemistry)
Water isotope modeling: Land surface and plants (William Riley, Lawrence Berkeley National Laboratory)
Coupled modeling of isotopes in the GISS GCM (Gavin Schmidt, NASA Goddard Institute for Space Studies)

3:15-3:30  Break

3:30-5:30  Other Speakers, discussion

5:30-7:30  Reception

Wednesday, January 14, 2004, Walter Orr Roberts Board Room
Day 2, AM:  Carbon dioxide data and modeling

8:30-10:30  Inez Fung, University of California, Berkeley, Chair
Speakers:
Oxygen-18 in atmospheric CO2: a linkage between the global cycle of carbon and water (Christopher Still, University of California, Berkeley)
Why do we want carbon isotopes in the CCSM? (Neil Suits, Colorado State University)
Isotopic fractionation of CO2 in the stratosphere (Kristie Boering, University of California, Berkeley)
Estimating carbon sources and reservoir lifetimes with C13 & C14 (Jim Randerson, University of California, Irvine)

10:30-10:45  Break

10:45-12:30  Other Speakers, discussion

12:30-1:45  Lunch

Day 2, PM:  Other isotopes and approaches?

1:45-2:45  Andrew Gettelman, NCAR, Chair
Speakers:
Observations of carbon isotopes in CO (John Mak, State University of New York)
Oxygen mass independent fractionation in sulfur and nitrogen compounds (Mark Thiemens, University of California, San Diego)

2:45-3:00  Break

3:00-5:00  Other Speakers, discussion

PHASE II:  ISOTOPE S IN THE CCSM
Goal: Establish plan for implementing isotopes into CCSM, including identifying resources required and persons responsible for specific tasks.
Thursday, January 15, 2004, Walter Orr Roberts Board Room

Day 3, AM:  Isotopes in CCSM

8:00     Continental Breakfast

8:30-9:45 Natalie Mahowald, NCAR, Chair
Discussion of Priorities for Isotopes in CCSM

9:45-10:00 Break

10:00-12:00 Current Status of “Entrepreneurial” Work in CCSM
Individual (10 minute) presentations

12:00-1:00 Lunch

Day 3, PM:  Discussion of future work: Plan for needs and assign tasks

1:00-3:00 Andrew Gettelman, NCAR, Chair
Discussion of Work Plan and Wrap Up
Appendix 2: List of Participants

Workshop on Isotopes in the Earth System
Participant List

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