# Toward A High Resolution Southern Hemisphere Climate Reconstruction: Mapping the Antarctic Ice Sheet in Space and Time

Submitted by the Members* of the United States Contribution to the International Trans Antarctic Scientific Expedition (US ITASE)
*The members of US ITASE include: Mary Albert, Steve Arcone, Roger Bales, David Bromwich, Daniel Dixon, Andrea Isgro, Markus Frey, Tony Gow, Gordon Hamilton, Cobi Harris, Carl Hess, Bob Jacobel, Susan Kaspari, Ursula Leeman, Kirk Maasch, Paul Mayewski (Chief Scientist), Joe McConnell, Debra Meese, Steve Niles, Lynn Peters, David Schneider, Chris Shuman, Blue Spikes, Leigh Stearns, Eric Steig, Brian Welch, James White, Mark Wumkes, Betsy Youngman and Ann Zielinski

**Abstract**
On 2 January 2003 the United States component of the International Trans Antarctic Scientific Expedition (US ITASE) arrived at South Pole having completed, over the period 1999-2003, >5000 km of over snow traverses that included much of West Antarctica and a portion of East Antarctica. During the traverses US ITASE focused on the collection of data that will allow the reconstruction of sub-annual scale climate variability and changes in the chemistry of the atmosphere for the last 200+ years. In the process US ITASE collected an integrated, multi-disciplinary assemblage of data extending from the bed of the ice sheet (>3000 m) to >20 km in the atmosphere. Forthcoming results from US ITASE will offer new insights into the understanding of Southern Hemisphere environmental variability, with particular emphasis on atmospheric teleconnections between the Pacific Ocean and West Antarctica.

**Introduction**
Antarctica is encircled by the world's most biologically productive oceans, is the largest reservoir of fresh water on the planet, is a major site for the production of the cold deep water that drives global ocean circulation, is a significant influence (through albedo effects) on Earth's energy budget, and is a crucial driving component for Southern Hemisphere atmospheric circulation. Antarctica thus plays a pivotal role in the coupling of critical components in Earth's complex climate system. Yet despite its importance, Antarctica is the most poorly documented continent, in a climate sense, over the instrumental era of climate monitoring. Fortunately, it has the potential, through ice core sampling, glacier geophysics, and atmospheric chemistry programs, to be the best understood over multi-decadal to centennial and longer time scales.

The International Antarctic Scientific Expedition (ITASE) is a nineteen-nation strong, multi-disciplinary research program endorsed by the Scientific Committee on Antarctic Research (SCAR) and the International Geosphere Biosphere Program (IGBP) (Mayewski and Goodwin, 1997). It is designed to reconstruct the recent climate history of Antarctica through ice coring and related observations along a network of extensive intra-continental traverses (Figure 1).

**West Antarctica and Phase One of US ITASE**
The first four years of the United States contribution to ITASE (1999-2003) have focused on a series of traverses extending over West Antarctica (Figure 1). West Antarctica is of particular importance because this region is strongly linked with climate variability at lower latitudes and therefore offers an opportunity for understanding regional to global scale climate variability. In particular, the El Niño-Southern Oscillation (ENSO) phenomenon in the tropical and the

subtropical Pacific Ocean is known to impact West Antarctica from the Ross Sea to the Weddell Sea as part of the Pacific-South American (PSA) teleconnection pattern. The "ENSO teleconnection" exhibits substantial seasonal to decadal scale variability.

The suite of sub-annually resolved climate records retrieved by US ITASE will allow climate variability over West Antarctica to be established on inter-annual through centennial timescales. In combination with deep ice cores – some already completed, others to be drilled in the near future – US ITASE will also contribute to the understanding of climate on millennial time scales. Information about climate variability in the middle and high latitudes of the Southern Hemisphere is obtained, through calibrations developed between US ITASE ice core records and direct atmospheric observations collected over the last 45 years. A primary goal of the calibration work is to document variation in the ENSO teleconnection and to better understand the relationship between global scale variability and regional Antarctic climate. This will establish a record of natural fluctuations of ENSO frequency and amplitude prior to the beginning of anthropogenic influence on climate, and will help in determining whether the frequency of El Niños changed in the late 20$^{th}$ century relative to earlier periods. This is a question of great importance because climate models indicate El Niño frequency may be enhanced due to global warming. Another important goal is to better understand the Antarctic Oscillation (AAO) (also known as the Southern Annular mode or the high latitude mode). It is the dominant atmospheric teleconnection pattern in West Antarctica after ENSO, and may be the most important for the rest of the continent. Recent changes in the AAO have been related to anthropogenic ozone destruction (Thompson and Solomon, 2002), but the existing record is too short to establish whether those changes are unprecedented. ITASE research will contribute important data to resolving this question.
US ITASE also contributes to our knowledge of current and future projected changes in sea level by improving understanding of ice sheet mass balance. The US ITASE logistics platform provides a base for the collection of field mass balance measurements for large portions of West Antarctica, an area which currently accounts for the greatest uncertainty in global estimates of ice sheet contributions to sea level change. US ITASE is examining two of the major West Antarctic ice drainages (Ross Sea catchment and Amundsen Sea catchment) where existing studies indicate contrasting styles of behavior (Shepherd and others, 1998; Joughin and Tulaczyk, 2002).

**US ITASE Program Description**

US ITASE has developed a suite of field experiments and observations utilizing an over snow traverse platform (Figure 2) that has now covered >5000 km (Figure 3) with studies at a variety of spatial scales extending from the subglacial bedrock (>3000 m), through the surface of the ice sheet, to >20 km into the atmosphere (Figure 4). For each of several stations, spaced approximately 100-200+ km apart (Figure 3), we have obtained high-resolution isotopic, geochemical, and physical measurements from numerous ice core and snowpit profiles ranging in depth from 15-115m (typical sites 60-70m). At each site, global positioning system (GPS) measurements of differential vertical velocity are gathered to study mass balance variations. Calculated rates of ice sheet thickness change from the GPS work are used for interpreting the ice core records of snow accumulation, and as ground-truthing for surface elevation histories derived from NASA's ICESat laser altimetry mission.

In addition to the ice core and GPS measurements, we have obtained high resolution radar records of the entire firn structure to reveal the spatial variation in annual layering and to interpolate accumulation rates between coring sites. This radar work is unprecedented in its combination of high resolution (<35 cm) and depth (>100 m). At each site, detailed snow stratigraphy measurements are also made, including annual layering, grain growth, permeability and microstructure profiles which are important for understanding the influence of vertical and horizontal mass transport on the geochemical species used in the climate reconstruction. This is complimented by measurements, both in the snow and in situ in the atmosphere, of reactive chemical species (eg., formaldehyde, hydrogen peroxide), that may be only partly preserved in the ice, yet are critical to our understanding of global atmospheric chemistry. Finally deep radar soundings are used to correlate surface and bottom topography, to assess basal melting, and to aid in the selection of specific sites for future deep coring projects.

**Results**

Although the final field season for the first phase of US ITASE has just been completed and there remains much data processing and laboratory work to do, initial results from US ITASE are impressive. A few examples are given below:

**Shallow radar**

Variable accumulation rates and ice movement can deform stratigraphy and thus affect the vertical density distribution of annual layers. However, field measurements show that slow variation of amplitude in these parameters (eg., Figure 3) along the US ITASE traverse routes allow single ice cores to be representative well beyond local scales.

Internal stratigraphy in both shallow and deep (discussed below) radio echo sounding records represent isochronal events. This has been validated by sub-annual scale dating of ice cores penetrating these layers, providing therefore a record of depositional and ice flow history along the traverse.

Horizons detected by shallow, short-pulse radar transmitting near 400 MHz are particularly continuous along or near ice divides, are continuous within 2 m of the surface, get stronger into the firn, and still persist beneath the firn, although they weaken with greater depth (Arcone, 2002). Away from ice divides, they may plunge up to 35 meters yet maintain their amplitude. For this latter reason, and since they are continuous where density is highly variable (near-surface), and where there should be no density contrasts (beneath the firn), they do not appear to be responses solely to density contrasts, as is the current paradigm for firn. Comparisons between radar horizons and ice core chemical series are in progress.

**Deep radar**

The bedrock topography and geothermal flux beneath West Antarctica strongly influence ice flow and the overall stability of the ice sheet. Continuous ground-based low frequency radar (eg., Figure 3) characterizes bedrock topography, internal ice stratigraphy, and provides the potential to determine regions of cold and warm based ice. Ice thickness measurements (up to 3200 m depth) contribute to ice flow models that characterize the dynamics in ice core sites.

As with the shallow radar, internal ice reflectors represent isochronal regions, but due to the longer wavelength, are probably longer duration events. Internal ice stratigraphy is mapped along the traverse route with layers as deep as 2200 m.

**Ice coring**

US ITASE utilizes spatially distributed (Figures 3 and 4), multi-parameter ice core measurements to develop climate proxy records (Figure 5). A depth-age scale for each core is produced using the multi-parameter procedure developed for the Greenland Ice Sheet Project 2 (Meese et al, 1997). Parameters containing an annual signal include: visible stratigraphy, major ions, oxygen isotopes, and hydrogen peroxide. The accuracy of the dating within each core and between cores is determined using sulfate peaks from known volcanic eruptions. The presence of several major events in all of the U.S. ITASE ice cores allows precise calibration of annual layer counting between cores (eg., Meese and Gow, 2002).

Temperature dependence of crystal growth rates investigated thus far is consistent with previous measurements across Antarctica and Greenland. However, there is a large gap between $-30^0$C to $-50^0$C in previous studies that we will be able to address with US ITASE data. Snow and firn physical characteristics show large site-to-site variations both on the surface and with depth (Leeman and Albert, 2002). A feedback exists between air-snow vapor transport processes and the physical properties of snow that can induce large site-to-site differences in metamorphism (Albert, 2002). Variations in permeability and microstructure can cause differences in the dynamics of the air-snow transport processes between sites for reversible chemical species. Sites where the air-snow exchange is dominated by ventilation will likely show much greater post-depositional change in reactive species concentrations, while sites where interstitial transport is dominated by diffusion will show better preservation of chemical records. In addition, changes in climate at a given site could make the snow and firn more or less likely to retain the climate signal for reversible species As illustrated in Figure 5, stable isotopes are poorly preserved in the highly permeable firn from a site visited in 1999-2000, but are well preserved elsewhere.

Ice core parameters (eg., methane sulfonate, stable isotopes) and ice sheet surface climate are very closely linked to large-scale atmospheric circulation patterns such as ENSO (Meyerson et al., in press) and the AAO (Schneider and Steig, 2002). Reconstruction of these patterns prior to the instrumental record, which would not be possible with a single ice core, will be achievable with the multi-site, multi-proxy records gathered by US ITASE, As Figure 6a illustrates, data from the ice sheet surface alone (in this case, temperature data derived from satellites) provides sufficient information to reconstruct the ENSO teleconnection pattern over West Antarctica. We have not yet compiled data from all ice cores, but the results are extremely promising, as illustrated by the confirmation with new US ITASE data of the original finding of Kreutz et al. (2000) at Siple Dome, that low pressure anomalies – which may also be related to ENSO forcing – can be detected with ice core sodium concentration data, because advection of sea salt to the ice sheet is enhanced when the Amundsen Sea Low is strong. Using relationships such as these, US ITASE surface climate reconstructions for West Antarctica will ultimately allow for large-scale reconstructions of Southern Hemisphere climate variability for sub-annual to multi-decadal and low frequency modes of the climate system, extending far beyond the available instrumental record.

**Mass balance**

The calculation of local rates of change relies on accurate long term accumulation rate averages derived from ice core stratigraphy. In addition, the interpretation of satellite altimeter derived surface elevation changes in terms of ice equivalent thickness changes requires that temporal variability in accumulation rate be known. Snow accumulation is a standard parameter derived from ice core records. For ice core sites not located on flow divide,s accumulation rate patterns

are convolved with ice flow effects due to ice motion through an undulating topography. Local accumulation rates can exhibit variability because of this effect. At each of the US ITASE core sites (eg., Figure 3), we have measured local topography, ice flow, and accumulation rate for the distance up-flow corresponding to the length of the record.

Surface glaciology results from US ITASE sites where data are complete indicate that the interior portion of the ice sheet is close to steady state and is not currently contributing to changes in global sea level. Lower elevations of the Ross Sea drainage, show net thinning of about 10 cm/yr. Repeat GPS occupations of sites in the Amundsen Sea drainage are used by US ITASE to confirm the presence of rapid thinning in this region of WAIS as implied from repeat satellite radar altimetry (Shepherd and others, 1998).

**Atmospheric chemistry**

Contributions to the understanding of polar atmospheric chemistry and its reconstruction over the past centuries through ice cores include: the characterization of summer boundary layer levels of hydrogen peroxide, organic peroxides, formaldehyde, acetaldehyde and acetone in air above the snow pack and in the interstitial pore space in the firn. Data will be used to estimate the $HO_x$ radical budget with photo-stationary state models.

US ITASE has undertaken the first quantitative measurements of higher organic peroxides over West Antarctica and demonstrated that they consist exclusively of methylhydroperoxide. Trifluoroacetate (a product of atmospheric degradation of HFCs and HCFCs) is also measured in snow pits to develop a better understanding of the processes that control deposition of trifluoroacetate in polar snow because there is concern that this highly stable, man-made molecule will accumulate in the hydrosphere.

Results from US ITASE atmospheric studies will further elucidate the impact of the upper snow pack on levels of atmospheric trace gases in the boundary layer. Measurements of hydrogen peroxide and formaldehyde in air, snow pits, and ice cores are used to validate existing physical atmosphere-snow transfer models and to develop a spatial picture of preservation of these species in snow and firn, Initial results from U.S. ITASE cores demonstrate that the seasonal signal of hydrogen peroxide is preserved at sites where the accumulation rate is sufficiently high and the mean annual temperature sufficiently low.

**Conclusions**

US ITASE offers the ground-based opportunities of traditional style traverse travel coupled with the modern technology of GPS, crevasse detecting radar, satellite communications and multi-disciplinary research. By operating as an over snow traverse US ITASE offers scientists the opportunity to experience the dynamic range of the Antarctic environment. US ITASE also offers an important interactive venue for research (currently eleven integrated science projects – Table 1) similar to that afforded by oceanographic research vessels and large polar field camps, without the cost of the former or the lack of mobility of the latter. Most importantly, the combination of disciplines represented by US ITASE provides a unique, multi-dimensional (x, y, z and time) view of the ice sheet and its history. In its current four year cycle, US ITASE has sampled the environment of West Antarctica over spatial scales of >5000 km, depths of >3000 m, heights in the atmosphere of >20 km, and time periods of several hundred years (sub-annual scale) to hundreds of thousands of years (millennial scale).

Continued US ITASE research, future proposed US ITASE traverses (Figure 1), and collaboration with our international ITASE colleagues, will, in the next several years, provide unprecedented knowledge of past Antarctic climate and ice sheet variability and improve prediction capability.

**Acknowledgements**

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**Table 1 - US ITASE PROJECTS**

| Research Team Members | Institution | Projects |
|---|---|---|
| Mary Albert | CRREL | Snow and firn microstructure |
| Ursula Leeman | | |
| Steve Arcone | CRREL | High resolution radar profiling |
| Roger Bales | U Arizona | Hydrogen peroxide |
| Markus Frey | | and formaldehyde |
| Joe McConnell (DRI) | | |
| David Bromwich | OSU | Meteorology |
| Gordon Hamilton | U Maine | Mass balance and satellite image |
| Blue Spikes | | analysis |
| Ian Whillans (OSU) | | |
| Bob Jacobel | St. Olaf | Deep radar |
| Brian Welch | | |
| Paul Mayewski | U Maine | Glaciochemistry and |
| Dan Dixon | | calibration with |
| Susan Kaspari | | instrumental records |
| Paul Mayewski | U Maine | Science management |
| Joe McConnell | DRI | Tri-fluoroacetate |
| Deb Meese | CRREL | Stratigraphy and grain growth |
| Tony Gow | | |
| Eric Steig | U Washington | Stable isotopes and satellite |
| David Schneider | | observations of surface |
| James White (U Colorado) | temperature | |
| Chris Shuman (NASA) | | |

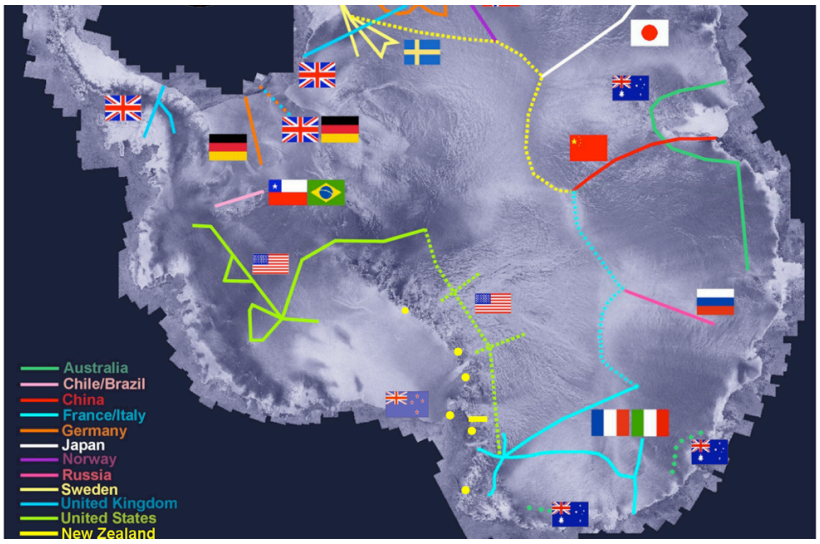


Figure 1 - ITASE traverse routes – completed (solid), proposed (dashed).

Figure 2 – US ITASE traverse tractors and sleds. Crevasse detection equipment mounted on lead tractor. Sleds contain berthing, kitchen, fuel drums, scientific equipment, and ice cores.

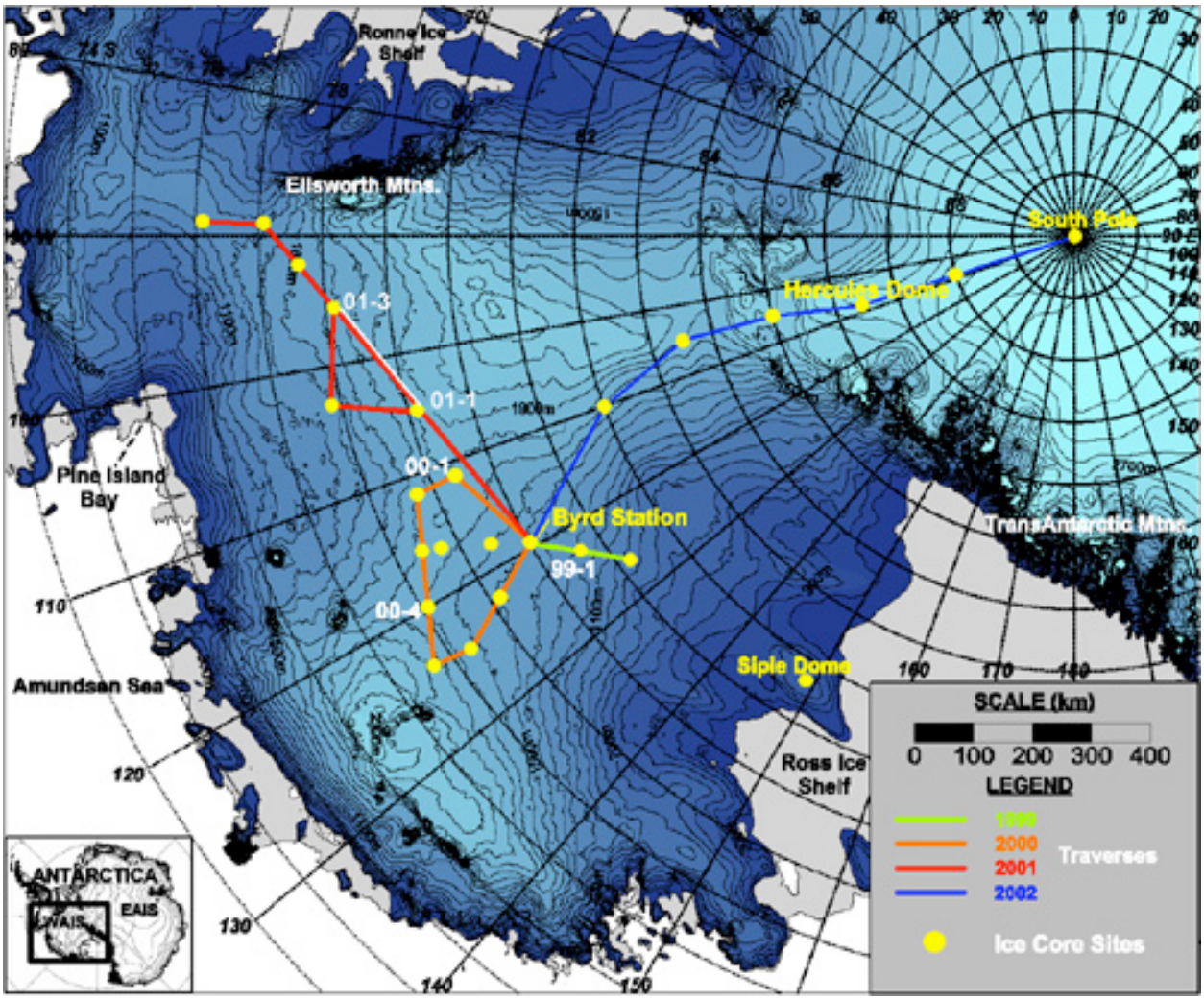


Figure 3 – US ITASE traverse routes, WAIS topography and core sites. Data from sites 99-1, 00-1, 00-4, 01-1, and 01-3 are presented in Figures 4 and 5

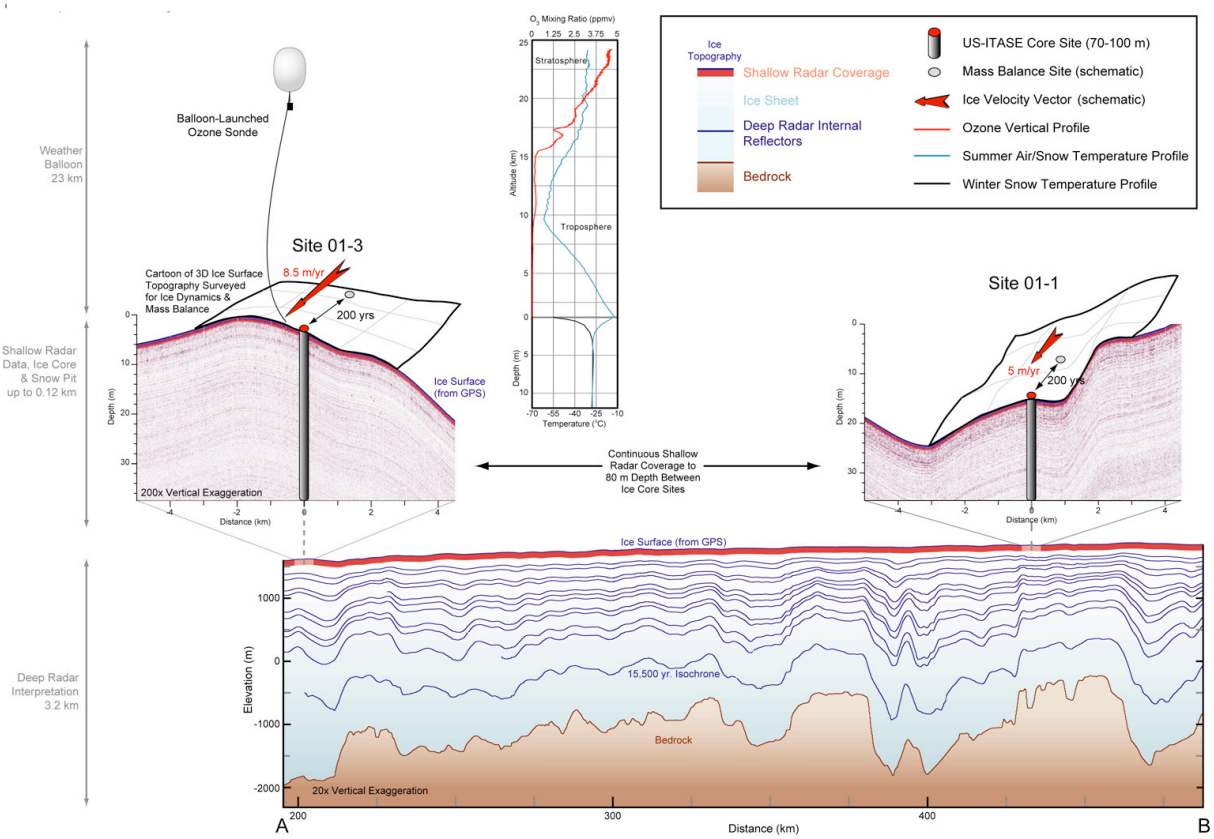


Figure 4: Multi-dimensional approach to the multi-discipline US-ITASE objectives. Studies at a variety of spatial scales extend from the subglacial bedrock surface to over 20 km into the atmosphere. Ice core sites along each traverse route yield 200+ year annually dated climate records. Ice core site selection is determined by field interpretation of shallow radar data. Numerous measurements are made at each core site to provide context for the ice core climate records. These measurements include: high resolution surface topography maps; snow pit measurements of density, chemistry, and temperature; and meteorological data. Ice mass balance and horizontal velocity studies located 200 years upstream provide past ice flow history for the ice cores. Shallow and deep-penetrating radio echo sounding data tie the ice cores together and provide large-scale context for US-ITASE cores and future deep ice core climate records. Internal stratigraphy in both radio echo sounding records represent isochronal events and a record of depositional and ice flow history along the traverse. The radar data and interpretation, ozone sonde data, and ice topography along the radar profiles shown here are actual examples from the 2001 US-ITASE season. Ice topography, mass balance sites, and ice velocity vectors are shown in schematic to represent results obtained once repeat analyses are completed. See Figure 3 (01-1 and 01-3) for locations of the datasets presented in this figure.

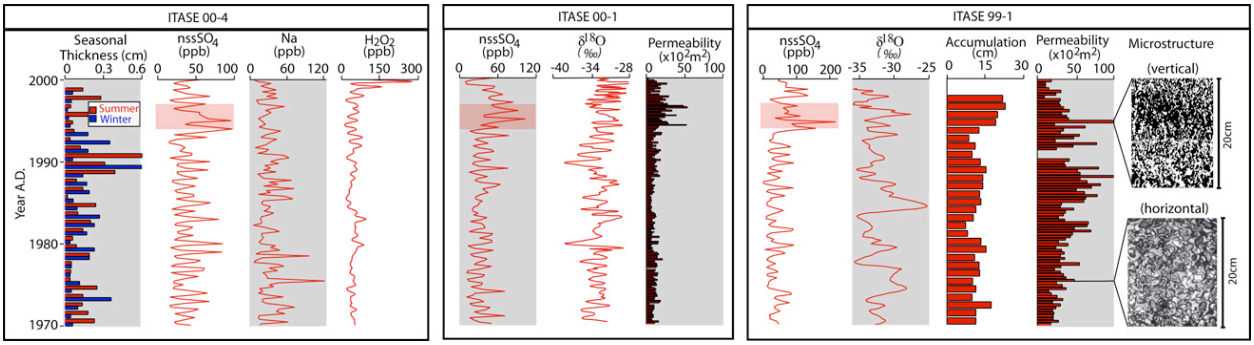


Figure 5 – High-resolution US ITASE ice core records are analyzed for a variety of parameters including: major ion chemistry ($Na^+$, $NH_4^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, $Cl^-$, $NO_3^-$, $SO_4^{2-}$), stable isotopes, reversibly deposited species ($H_2O_2$, HCHO) and physical properties. Annual layers are determined through high resolution sampling (minimum 10 samples per year to significantly greater sampling) and identification of seasonality in a variety of parameters (eg., Na, non seasalt (nss) $SO_4$, seasonal thickness, and where not post-depositionally altered stable isotopes and $H_2O_2$). Annual layer dating is calibrated using known volcanic events identified by $SO_4$ spikes traced from site to site. Volcanic eruptions in mid 1990's are picked up in all three locations as highlighted in the figure. Changes in accumulation rate are derived from measurements of density (not shown) and annual layer thickness. Changes in other climate parameters such as temperature and sea level pressure are developed from calibration between instrumental and ice core records of stable isotopes and major ions, respectively (eg., Figure 6). Measurements of permeability and microstructure are used to assess post-depositional changes in the firn and snow and their effects on reversibly deposited chemical species. Significant site to site variations exist in permeability and microstructure. The data shown come from the upper sections of ice cores collected during the 99-00 and 00-01 field season. See Figure 3 for locations of the datasets (99-1, 00-1, 00-4) presented in this figure.

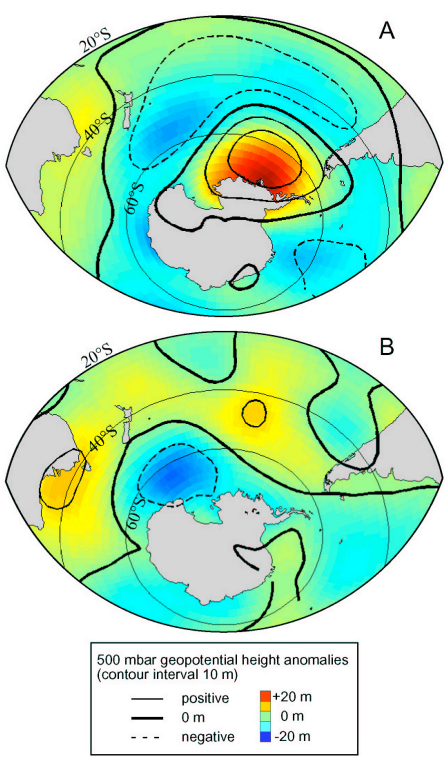


Figure 6 – Covariance of atmospheric circulation with time series from the Antarctic ice sheet surface and from global climate indices. A) Contours show covariance of annual 500 mbar geopotential height (NCEP/NCAR reanalyses) with the Southern Osciallation Index (sign reversed to illustrate the typical pressure anomaly pattern characteristic of an El Niño year). Colors show covariance with the 2nd principal component (time variation of the spatial pattern) of ice sheet surface temperature derived from passive microwave satellite observations (Schneider and Steig, 2002). B) Contours and colors show covariance of springtime 500 mbar geopotential height with sodium concentrations in ITASE core 2000-01 (central West Antarctica) after Kreutz et al. (2000).