Understanding the Impacts of Large-Scale Climate Variability on the Global Carbon Cycle.

David W. J. Thompson, A. Scott Denning (CSU), Nicolas Gruber (UCLA)

Progress report, year two.

Recap of project goals

The principle goal of the research project is to bring together scientists with seemingly disparate expertise to systematically develop and test hypotheses regarding the impact of large scale climate variability on the carbon cycle. The research is largely focused on the dominant patterns of hemispheric scale variability, the so-called Northern and Southern Hemisphere annular modes. This is because both annular modes have marked impacts on surface climate throughout their respective hemispheres, and both annular modes are known to have exhibited low frequency variability over the past few decades. There is considerable evidence that the observed trends in the annular modes are at least partially driven by increased anthropogenic emissions of greenhouse and ozone-depleting gases. Hence, the ongoing research is key for understanding and anticipating the future behavior of not only the carbon cycle, but of the atmospheric general circulation as well.

Progress update

In the second year, we have continued to make progress in better understanding the relationships between the annular modes and the carbon cycle from both observational and modeling perspectives. The research so far has produced ~10 papers which are either accepted in major journals or will be submitted in the next couple of months, an MS thesis, and ~20 talks at meetings and institutes throughout the world.

The coming third year of the project is key. During this time, the PIs will synthesize the research done at UCLA on air-sea CO_2 fluxes with that done at CSU on terrestrial CO_2 fluxes and on the observed relationships between CO_2 and large scale climate variability. The synthesis during the third year will include the submission of several new papers and the completion of a PhD.

The key findings of year 2 are summarized below.

Progress during second year (UCLA)

During the 2nd year of this project, work at UCLA continued along the first year's two avenues, i.e. satellite data analyses and ocean biogeochemical model analyses with a shift toward the latter. The data analysis avenue built on the results of the first year (as published in Lovenduski and Gruber (2005)), producing additional products to consolidate and refine our hypotheses. The model analyses created the basis for a detailed description of the magnitude of the air-sea CO_2 flux variations associated with southern hemisphere climate variability. These results will form the basis for the global synthesis that we plan for the final year of the project and that will incorporate the results from the atmospheric and terrestrial analyses undertaken by the Colorado State University groups.

We expanded and refined our analyses of satellite data in the Southern Ocean by incorporating additional remotely-sensed products. Anomalies in net primary production (computed from photosynthetically active radiation (PAR), SST, and chlorophyll observed by SeaWiFS) are found to be positively correlated with the Southern Annular

Mode (SAM) in the Antarctic Zone (AZ), but little elsewhere. The increased NPP during the positive phase of the SAM in the AZ is driven mostly by an increase in chlorophyll, while PAR exhibits little correlation with SAM.

Sea ice concentrations from SSM/I and model results show good agreement for the overall increase in sea ice extent during positive SAM. The regression of sea surface height anomalies from TOPEX/POSEIDON onto the SAM index is nearly identical to the regression of SST anomalies onto the SAM index, indicating that the primary control on the former is water column expansion and contraction from heat content anomalies associated with the SAM, rather than circulation changes.

We used empirical orthogonal function analysis to extract the dominant modes of natural variability of wind speed, SST, chlorophyll, sea-ice, and NPP anomalies south of 20S. Although the spatial patterns associated with the first principal component (PC) of wind, SST, and chlorophyll appear to have a reasonable agreement with the spatial regression pattern of these quantities with SAM, the timeseries of the principal components show little temporal correlation with the SAM. The exceptions to this are wind speed, where the SAM accounts for 42% of the variance in the first PC, and summertime chlorophyll, where the SAM accounts for 33% of the variance in the first PC. Interestingly, the first PCs of SST and year-round chlorophyll show high correlation with ENSO. This is suggestive of a substantial tropical Pacific-driven teleconnection pattern in the Southern Ocean, such as is typical of the Pacific South-American (PSA) pattern.

We made major advances with regard to model analyses, but did forgo an initially planned model development step. Originally we proposed to couple the Moore & Doney functional group ecosystem model (FGM) to the Upper Ocean Model (UOM). We decided to change our strategy and to use instead the ocean component of NCAR's CCSM climate model, wherein the same ecosystem/biogeochemical model has already been implemented. Not only did this change in strategy permit us to focus more on the analysis of model results, it also provides a better long-term investment strategy, as the UOM model unlikely will receive much future support, whereas the ocean component of CCSM is at the center of NCAR's attention. For our initial analyses, we received existing output from a hindcast simulation (1958- 2004), forced by NCEP reanalysis products and a pre-industrial atmospheric CO_2 concentration (kindly provided by Scott Doney at WHOI). We also ported this model to our computing facilities and will use it for our own sensitivity experiments in the third year.

First results from an evaluation of the hincast model results with satellite observations of SST and other key variables indicate that the model responds to the SAM in a comparable way to the real ocean (Figure 1a). During positive SAM, the model's circulation anomalies show an increase in the meridional overturning circulation of the Deacon cell, with increased upwelling in the AZ, increased northward transport across the Polar Front, and increased convergence and downwelling in the Subantarctic Zone, but no deepening of the mixed layer, as we had expected. Positive phases of the SAM are associated with anomalous outgassing of CO_2, and elevated surface iron concentrations in the AZ (Figure 1b and 1c), likely a result of the increased upwelling, which is insufficiently compensated by increased productivity.

Empirical orthogonal function analysis of the modeled air-sea CO_2 flux anomalies shows that the dominant modes of variability exhibit spatial patterns that are annular in structure, suggestive of the SAM. The SAM accounts for 25% of the variance in the spatially integrated air-sea CO2 flux anomalies south of 20S, and positive phases of the SAM are associated with anomalous CO2 outgassing nearly everywhere in the Southern Ocean (Figure 1c). Variability associated with the SAM contributes to an anomalous CO2 flux of 0.12 PgC/yr. Initial results indicate that the anomalous upwelling during positive SAM in the AZ brings waters rich in DIC to the surface. This process elevates the partial pressure of CO2 in the surface waters and causes anomalous outgassing. A paper outlining these results is currently in preparation.

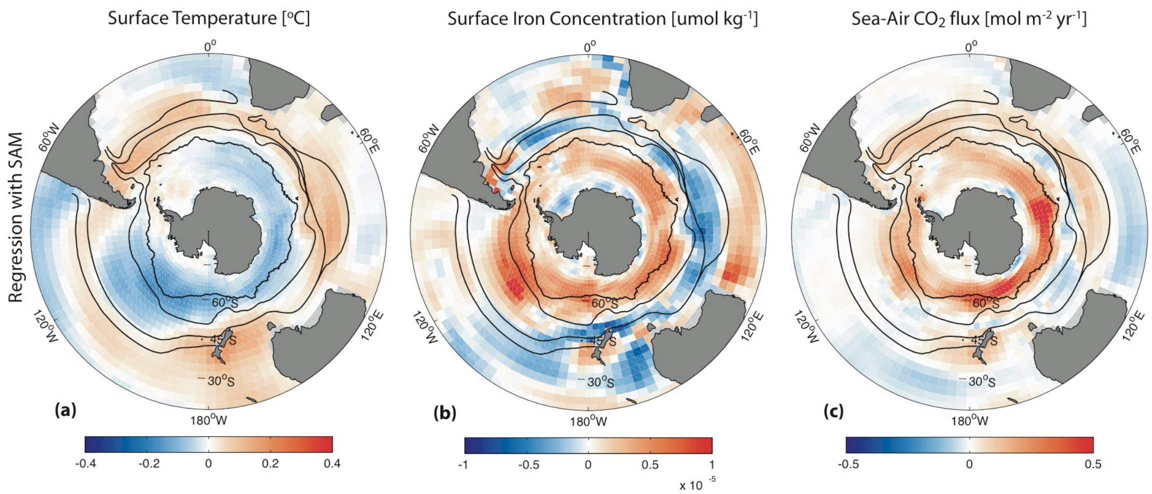

Figure 1. Maps of regressions between the SAM index and (a) surface temperature; (b) surface iron concentration; and (c) sea-air flux of CO2 from the ocean model for the NCEP reanalysis period (1958-2004). The regression coefficients indicate changes in the temperature (degC), iron concentration (umol/kg), and sea-air CO2 flux (mol m^-2 yr^-1) corresponding to one standard deviation change in the SAM index. Black contours mark the location of the Southern Ocean fronts. Positive CO2 fluxes are outgassing from the ocean. Model results are from the ocean component of NCAR CCSM.

Progress during second year (CSU)

Work at CSU also focused on several avenues, in this case 1) investigating the mechanisms by which the Northern Annular Mode (NAM) impacts the seasonal cycle of terrestrial carbon exchange and 2) investigating the relationships between the SAM and observed concentrations of atmospheric CO2 and also estimated fluxes from the TransCom experiment.

[***START SCOTT'S PART***] In the case of the relationships between the NAM and the terrestrial biosphere, we used the simple biosphere model (SiB2) to study the effects of climate variability on the seasonal cycle and trends of terrestrial carbon exchanges throughout the Northern Hemisphere from 1958-2002. Weather was specified every six hours from the NCEP reanalysis, and vegetation properties were specified from normalized difference vegetation index (NDVI) data obtained from the Advanced Very High Resolution Radiometer (AVHRR) for 1983-2002. Simulated years before and after the AVHRR record used the mean seasonal cycle from those years, and we adapted the timeseries of NDVI in springtime using a phenological model parameterized from thermal sums ("growing degree days"). This allowed us to isolate the effects of climate variability on spring onset independently of the NDVI imagery, and to obtain higher temporal resolution for spring onset of photosynthesis than is possible using monthly composite imagery.

We found that the date of predicted leafout over the 45-year period was significantly correlated with variability in the NAM during January-March (JFM) over much of eastern North America and western Europe (Fig. 2, top). This result suggests that slower-changing components of the climate system "remember" wintertime climate anomalies well into springtime in this region, because there is very little persistence in the NAM between winter and summer. We found that soil temperature and the areal extent and water content of snowpack have sufficient heat capacity to accomplish this role. Earlier leaf-out and higher temperatures during years with higher-than-average wintertime values of the NAM index led to higher integrated gross primary production (GPP), due to both longer growing season and more intense early-season photosynthesis over large parts of the Northern Hemisphere (Fig 2, bottom). These regions also exhibited statistically significant trends in January-July GPP over the 45-year period, which is consistent with the increasing amplitude of the seasonal cycle of CO_2 during this period.

Climate variability associated with the NAM also impacted simulated ecosystem respiration during the period. We found that wintertime air temperature anomalies propagated only slowly into deeper soil layers. Significant correlations of simulated soil temperature with winter air temperature persisted well into spring and even summer in some regions, which affected the seasonal timing of soil (root and microbial) respiration months later (figure not shown).

Taken together, the NAM-related changes in springtime GPP and summer respiration led to a secular trend in the simulated amplitude of the seasonal cycle of terrestrial net ecosystem exchange (NEE=Resp-GPP) over the 45-year experiment. This result is consistent with observations of the increasing amplitude of the seasonal cycle of CO_2. Our results suggest that asymmetric responses of GPP and respiration to NAM-related climate variability and trends, modulated by slowly-evolving snowpack and soil temperature, can explain much of the observed change in the seasonality of the terrestrial carbon cycle in recent decades.[***END SCOTT'S PART***]

In the case of the relationships between the SAM and the global carbon cycle, we have made what we consider a major discovery in terms of the observed relationships between concentrations of atmospheric CO_2 and large scale SH climate variability. The discovery is important, as it lays credence to the impacts and modeling work done at UCLA.

Before reviewing the results, it is worth briefly considering the difficulty in isolating the impact of large scale climate variability on observations of atmospheric CO_2. Figure 3 (left) shows time series of atmospheric CO_2 measurements (in parts per million by volume) from Palmer Station, Antarctica from 1980-2004. The variance in the time series is dominated by the long term trend and a comparatively weak seasonal cycle. If the linear trend of ~15 ppm/decade and the seasonal cycle are removed from the data, the resulting time series (not shown) is characterized by a small number of low-frequency variations. However, the amplitude and timing of the low-frequency variations in the resulting time series are sensitive to the manner in which the trend is removed from the data (i.e., whether via an exponential or linear fit), and thus correlations with the SAM are not stable to small changes in the analysis design.

For this reason, our methods have evolved over the past year to focusing instead on the high frequency variability inherent in month-to-month tendencies in CO_2 concentrations. This has the effect of "pre-whitening" the concentration time series, but it also makes physical sense: on monthly timescales, variations in the SAM should be most strongly correlated not with the absolute concentration of CO_2, but the rate of change of CO_2. Similar reasoning has been exploited by *Bacastow* (1976) and *Russell and Wallace* (2005) to examine the relationship between CO_2 and ENSO, but in the latter case the tendencies were smoothed over a 12-month period.

The right panel in Fig. 3 shows the month-to-month anomalous tendencies in CO_2 concentrations, where the tendencies at time *t* are defined as the concentration at *t+1* minus the concentration at time *t-1*, and the seasonal cycle was removed by (1) creating long-term average values for each calendar month and (2) subtracting the long-term values for all calendar months from all time steps in the data. The key statistical aspects of the resulting time series are that 1) The resulting anomalous tendency time series is not strongly impacted by the long term growth of CO2; and 2) the time series has a large number of degrees of freedom (more than 200), which allows us to assess relationships with the SAM with a high degree of confidence.

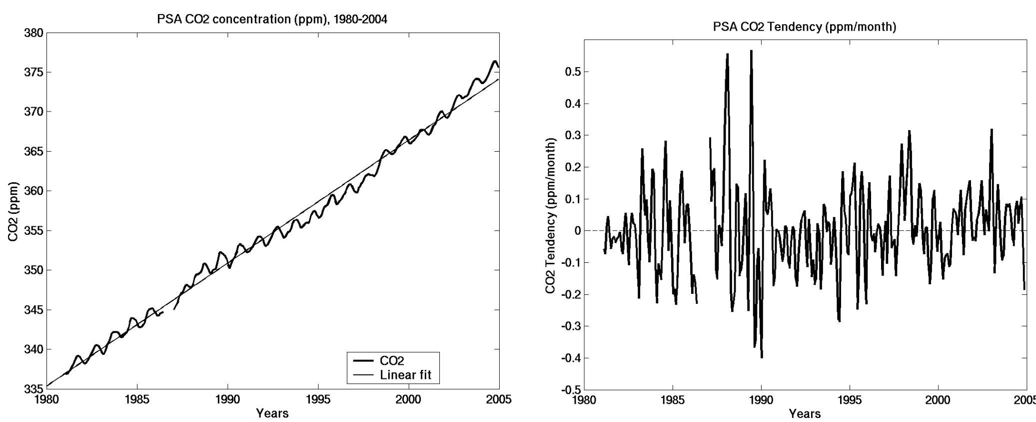

Figure 3. (left) The Palmer Station CO_2 concentration time series in parts per million from 1980-2004. The linear fit to this curve is also shown. (right) The Palmer Station CO_2 tendency time series (in ppm/month) from 1980-2004.

Figure 4 shows the regression of CO_2 tendencies at 5 SH stations with the longest available records onto the SAM time series at zero lag. The amplitudes are highest at Palmer and Syowa Stations, where the regressions are significant at the 99% and 95% levels based on a 1-tailed test using the *t*-statistic. The regression coefficients over the interior of Antarctica are not statistically significant, which suggests only stations that sample the air that encircles the Southern Ocean show a strong linear relationship with the SAM. The robustness of the relationships between CO2 tendencies at Palmer Station and Syowa are further illustrated in Fig. 5, which shows the lag zero regression of 500 hPa geopotential height anomalies onto standardized values of the CO_2 tendency at Palmer Station (left) and Syowa (right). Clearly, the pattern of 500 hPa height anomalies associated with fluctuations in CO2 at both stations bears strong resemblance to the SAM.

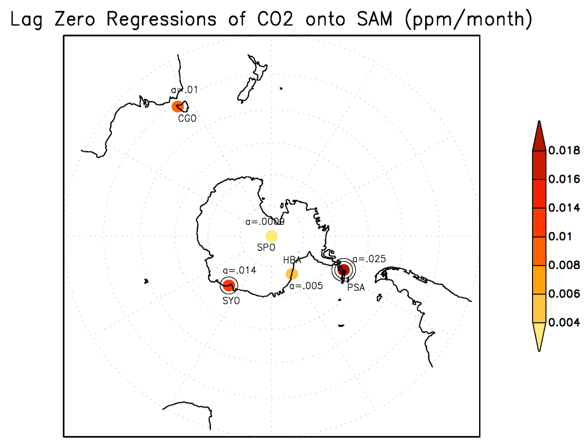

Figure 4. The regression at lag zero of the CO_2 tendency onto the SAM at each of the 5 stations listed in Table 1. The length of the CO_2 tendency time series varies for each station. The double black circles represent a 95% significant correlation using a 2-tailed t-test; the single black circle represents a 95% significant correlation using a 1-tailed t-test.

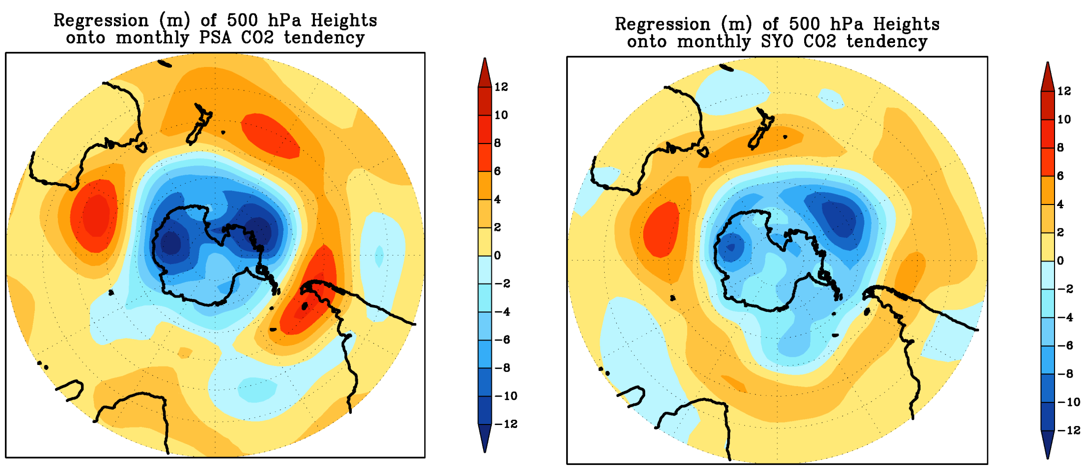

Fig. 5 Regression of the 500-hPa geopotential height field (seasonal cycle removed) onto the **(left)** standardized Palmer Station CO_2 tendency for 1980-2003 and onto the **(right)** standardized SYO CO_2 tendency for 1986-2003. Contours are in meters/standard deviation of the CO_2 tendency time series.

The results in Figs. 4 and 5 provide the first definitive evidence that fluctuations in the SAM are, in fact, evident in local records of CO2 concentrations. The results thus provide a sound observational basis for the ongoing research at UCLA, and add to the growing number of novel findings that will serve as the legacies of this project. The results are also a marked improvement over the status of our understanding a year ago, at which time we were grappling with the limited sample sizes inherent in CO2 concentrations and the competing effects of competing sources of variability in the CO2 record evident in Fig. 3 (left). The strength of the new methodology lies in its simplicity (which often seems obvious in hindsight, but is rarely obvious beforehand) and in the large number of independent samples afforded by the "prewhitened" time series.

We are currently working on understanding the mechanisms that give rise the results in Fig. 4. It is possible they reflect the redistribution of atmospheric CO_2 via anomalous advection, but our findings so far suggest the observed gradients in CO2 are much too small to explain the amplitudes via advective arguments alone. Additionally, results based on Transcom are broadly consistent with the sign and timing of the observations in Fig. 4. Thus, it seems likely the explanation for the observations in Fig. 4 will lie in the anomalous flux of CO2 at the ocean surface. Year 3 of the project will be dedicated in part to synthesizing the relationships found at CSU with the mechanisms currently under investigation at UCLA.

Another avenue of research at CSU is focused on understanding the mechanisms of the ocean response to the SAM, and also the mechanisms through which ENSO impacts the SAM. The research is related to that under investigation at UCLA, but with greater emphasis on the timescale of the ocean response. A key finding so far is that the ocean response to the SAM has a considerably longer timescale than that associated with the Northern Annular Mode in the NH. The increased timescale has implications for the total amplitude of the anomalous flux of carbon at the ocean surface. Another key finding is that ENSO impacts the SAM substantially during the SH summer season. The implications are that a complete understanding of the impacts of ENSO on the global carbon cycle requires consideration of processes in the high latitudes of the SH. Both findings will be examined in detail in the third year of the project.

Peer reviewed publications related to this research

Lovenduski, N.S. and N. Gruber, 2005: Impact of the Southern Annular Mode on Southern Ocean circulation and biology. Geophys. Res. Lett., 32, L11603, doi:10.1029/2005GL022727.

Peylin, P., P. Bousquet, C. Le Quere, S. Sitch, P. Friedlingstein, G. McKinley, N. Gruber, P. Rayner and P. Ciais, 2005: Multiple constraints on regional CO2 flux variations over land and oceans, Global Biogeochem. Cycles, 19(1), GB1011, doi:10.1029/2003GB002214

Hawes, A., 2005: Observed relationships between large scale atmospheric variability and the carbon cycle. Masters Thesis, Colorado State University.

Hawes, Amy, and D. W. J. Thompson, 2006: Observed relationships between the Southern Annular Mode and Measurements of Atmospheric Carbon Dioxide. J. Climate, in preparation.

Brix, H, N. Gruber, D.M. Karl, and N.R. Bates, 2006: On the relationships between primary, net community, and export production in subtropical gyres, Deep Sea Research II, in press.

Ciasto, L. and D. W. J. Thompson, 2006: Large scale atmosphere/ocean interaction in the Southern Hemisphere. J. Climate, in preparation.

Lovenduski, N.S., N. Gruber, S.C. Doney and I.D. Lima, 2006: Enhanced CO2 outgassing in the Southern Ocean from a positive phase of the Southern Annular Mode. Global Biogeochem. Cycles, in preparation.

Sabine, C. L., and N. Gruber, 2006: Introduction to a special section: North Pacific

Carbon Cycle Variability and Climate Change, J. Geophys. Res., in press.

Renwick, J. and D. W. J. Thompson, 2006: The Southern Annular Mode and New Zealand climate. In press, *Water and Atmosphere.*

Select abstracts and talks

Lovenduski, N.S.: Impact of the Southern Annular Mode on Southern Ocean Circulation and Biogeochemistry, poster presentation, Workshop on Modes of Southern Hemisphere Climate Variability, Scott Polar Research Institute, Cambridge, UK, June 2005.

H. Brix and N. Gruber: Carbon and nutrient budget variability in subtropical mode waters -- a model sensitivity study, poster presentation, ASLO 2005 summer meeting, Santiago de Compostela, Spain, June 2005.

Lovenduski, N.S.: Impact of the Southern Annular Mode on Southern Ocean Biogeochemistry, talk, Department of Atmospheric Sciences, Colorado State University, Ft. Collins, September 2005.

N.S. Lovenduski, N. Gruber, A. Hawes, and D.W.J. Thompson: Impact of the Southern Annular Mode on the Southern Ocean Carbon Cycle, poster presentation, 7th International Carbon Dioxide Conference, Boulder, CO, September 2005.

H. Brix and N. Gruber: Biogeochemical changes in subtropical and subpolar mode water: A miner's canary for climate change? Poster presentation, 7th International Carbon Dioxide Conference, Boulder, CO, September 2005.

Lovenduski, N.S.: Impact of the Southern Annular Mode on Southern Ocean Circulation and Biogeochemistry, graded department seminar, Department of Atmospheric and Oceanic Sciences, UCLA, November 2005.

N.S. Lovenduski, N. Gruber, and H. Brix: Impact of the Southern Annular Mode on Southern Ocean Biogeochemistry, Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract OS23G-04, oral presentation, Ocean Sciences Meeting, Honolulu, HI, February 2006.

H. Brix and N. Gruber: Decadal Changes In The Biogeochemistry Of Subtropical And Subpolar Mode Waters, Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract OS53D-01, oral presentation, Ocean Sciences Meeting, Honolulu, HI, February 2006.

Hawes, A.: "Observed relationships between large-scale atmospheric variability and the carbon cycle" UCLA May 2nd- May 6th 2005

Hawes, A.: "Observed relationships between large-scale atmospheric variability and the carbon cycle" International Carbon Dioxide Conference, Boulder, Sept. 26th-30th 2005

Hawes, A.: "Observed relationships between large-scale atmospheric variability and the carbon cycle" AGU, San Francisco, Dec. 5th-9th 2005Thompson, D. W. J., Recent Southern Hemisphere climate change. Gordon Research Conference on Polar Marine Science, Ventura, CA 3/2005 (invited).

Thompson, D. W. J., Large scale climate variability and the cryosphere. Climate and Cryosphere (CLiC) Science Conference, Beijing, China 4/2005 (invited).

Thompson, D. W. J., A new look at the structure of recent climate change. American Geophysical Union Spring meeting, New Orleans, LA 5/2005 (invited).

Thompson, D. W. J., Overview of the Southern Hemisphere annular mode. CLIVAR Modes of SH Climate Variability Workshop, Cambridge, UK 6/2005 (invited).

Thompson, D. W. J., The role of the SAM in recent SH climate change. National Institute for Water and Atmospheric Research, Wellington, NZ 1/2006. (invited).

Thompson, D. W. J., Interpretation of recent SH climate change. Victoria University, Wellington, NZ 2/2006. (invited).

Thompson, D. W. J., Mechanisms for SH climate change. National Institute for Water and Atmospheric Research, Lauder, NZ 2/2006. (invited).

Thompson, D. W. J., The role of the SAM in recent SH climate change. University of Canterbury, Christchurch, NZ 2/2006

Thompson, D. W. J., The Southern Annular Mode. Focus group on abrupt climate change (Changeling), La Jolla, CA 3/2005 (invited).