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Mechanism study of the ENSO and southern high latitude climate teleconnections

Jiping Liu,[1,2] Xiaojun Yuan,[3] David Rind,[1,2] and Douglas G. Martinson[2,3]

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[1] Evidence of El Niño-Southern Oscillation (ENSO) teleconnections in the southern high latitude climate has been identified, although the mechanisms that might lead to such far-reaching teleconnections remain unresolved. Here we propose one such mechanism-the regional mean meridional atmospheric circulation (the regional Ferrel Cell)-responsible for the covariability of the ENSO and Antarctic Dipole (ADP; a predominant interannually-varying signal in the southern high latitudes). It is found that the altered storm tracks associated with the ENSO variability influence the regional Ferrel Cell indirectly by changing the meridional eddy heat flux divergence and convergence, and shifting the latent heat release zone. The changes of the regional Ferrel Cell then influence the southern high latitude climate by modulating the mean meridional heat flux. *INDEX TERMS:* 3319 Meteorology and Atmospheric Dynamics: General circulation; 4522 Oceanography: Physical: El Niño; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] The ENSO signal in the southern high latitudes has been investigated in many studies [*Fletcher et al.*, 1982; *Trenberth*, 1991; *Smith and Stearns*, 1993; *Gloersen*, 1995; *Simmods and Jacka*, 1995; *Kwok and Comiso*, 2002]. Statistically significant polar-extrapolar (tropics and mid-latitudes) and circumpolar teleconnection patterns were recently quantified by investigating the relationship between the Antarctic sea ice edge (SIE) and global surface air temperature (SAT) as well as other climate indices [*Yuan and Martinson*, 2000, hereafter as *YM00*]. The strongest circumpolar teleconnection is the ADP pattern characterized by a seesaw in SAT, sea ice and sea level pressure [*YM00*, *Yuan and Martinson*, 2001, hereafter as *YM01*; *Harangozo*, 2000] between the eastern Pacific and Atlantic sectors of the Antarctic. This ADP pattern is closely associated with tropical ENSO events [*YM00, YM01*]. Even with the knowledge that the ENSO signal propagates to high latitudes through both atmosphere and ocean, we do not yet well understand the mechanisms leading to the connectivity of the very disparate components of the climate system. This study proposes one such mechanism—the regional mean meridional atmospheric circulation (the regional Ferrel Cell)—to demonstrate how polar and extrapolar climate communicate nearly simultaneously through the covariability of the ENSO and ADP phenomena.

2. Evidence of Teleconnections

[3] We averaged the monthly Niño3 index [*Cane et al.*, 1986; *NOAA/CDC*] from June of the first year to May of the second year to define interannual ENSO variability (a typical El Niño cycle features slight warming in spring, reaching its peak by the end of the first year or the early spring of the second year). Study of the composite SAT differences between El Niño and La Niña years from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] shows a strong warming of 1–2.5°C in the central Pacific sector of the Antarctic (*Region 1*) and a cooling of 1–2°C in the Bellingshausen and western/central Weddell Seas (*Region 2*), which are of the same magnitude as the SAT variability in the central/eastern tropical Pacific (Figure 1a). Similarly, the composite sea surface temperature (SST) differences based on the Reynolds SST [*Reynolds and Smith*, 1994] also show that the ocean surface warms by 0.5–1.5°C in *Region 1* and cools by 0.5°C in *Region 2*, which is half of the magnitude of the tropical SST variability (Figure 1b). It appears that the ENSO and ADP covariability is the most pronounced signal in the Southern Hemisphere, even in the globe, which is in agreement with the leading Empirical Orthogonal Function SAT modes [*YM01*]. The consistence between the NCEP/NCAR SAT and Reynolds SST gives us more confidence about the NCEP/NCAR reanalysis data. The instantaneous correlation between the Niño3 index and Antarctic SIE suggests that the SIE is displaced poleward in *Region 1* and equatorward in *Region 2* during El Niño years, and vice versa during La Niña years (Figure 1c), which is consistent with the earlier study in the Weddell Sea [*Carleton*, 1988].

3. Mechanism for Teleconnections

[4] How are the ENSO and the ADP variability connected across a hierarchy of spatial scales? *Peterson and White* [1998] suggested a slow oceanic propagation of the tropical ENSO signal to the Southern Ocean where the signal becomes a source of Antarctic Circumpolar Waves [*White and Peterson*, 1996], though the instantaneous correlation results in recent studies [*Martinson and Iannuzzi*, 2000; *YM01*] and Figure 1c suggest that the propagation proceeds much faster, implying an atmospheric mechanism. Through numerical experiments with the NASA/Goddard Institute for Space Studies general circulation model, *Rind et al.* [2001] found that the Hadley Cell in the eastern equatorial Pacific is intensified due to an increased pole-to-equator meridional temperature gradient

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[1] NASA/Goddard Space Flight Center, Institute for Space Studies, USA.

[2] Department of Earth and Environmental Sciences, Columbia University, USA.

[3] Lamont-Doherty Earth Observatory of Columbia University, USA.

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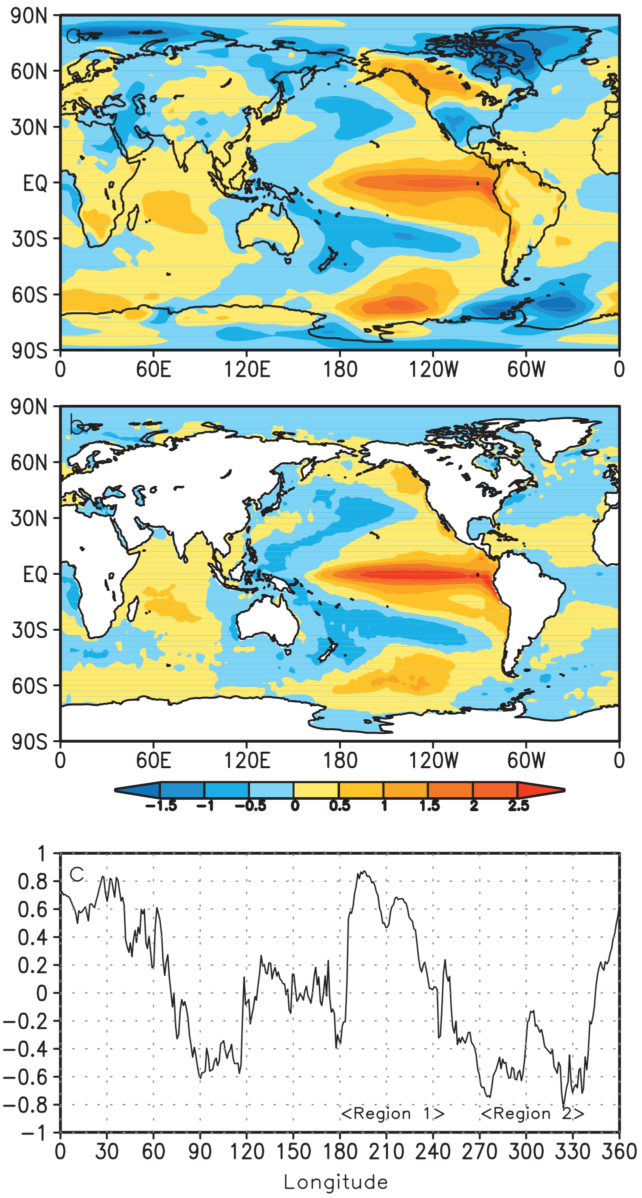

Figure 1. (a) The composite differences of SAT (°C) between El Niño (1982–83, 86–87, 87–88, 91–92, 97–98) and La Niña (1984–85, 85–86, 88–89, 95–96, 98–99, 99–2000) years spanning 1979–2000 from the NCEP/NCAR reanalysis; (b) Similar to (a), except the Reynolds SST (°C) spanning 1981–2000; (c) The instantaneous correlation between the normalized monthly Niño3 index greater (less) than positive (negative) one standard deviation and corresponding Antarctic SIE in each longitude spanning 1979–1999 derived from SMMR/SSMI satellites.

during El Niño years. This leads to an equatorward shift of the subtropical jet (STJ), which moves the storm track equatorward and reduces storm activity in *Region 1*. By contrast, the simultaneous relaxation of the Hadley Cell in the tropical Atlantic is accompanied by a poleward shift of the STJ, which enhances storm activity in *Region 2*. The alternation of the strength of the storms in these two regions is consistent with observational results [*Yuan et al.*, 1999].

[5] The logical question is how the ENSO signal manifests itself in the sea ice through the storm changes: a) sea ice dynamics (direct impacts of the storm changes) or b) atmospheric dynamics associated with altered heat flux (indirect impacts of the storm changes). The more southerly storm track is thought to lead to a northward extension of the Antarctic SIE, since increased storm activity may enhance the dispersion of sea ice and provide more open water for new ice formation. However, *Simmonds*'s study [1996] indicated that the spatial distribution of cyclogenesis is not significantly correlated with variations in the Antarctic SIE. To confirm this, we constructed the joint frequency distribution (JFD) between the storm frequency [*Chandler and Jonas*, 2000] and Antarctic sea ice concentrations (SIC) in the ADP region (Figure 2a). It seems that they do not have an obvious relationship since the slope is mainly parallel to the SIC axis, even when SIC is shifted longitudinally by 2.5–10 degrees with respect to the storm frequency to take into account the storm's downstream effect (not shown).

[6] This leaves b) atmospheric dynamics associated with altered heat flux. The atmospheric circulation can be decomposed into two components: the mean meridional circulation (MMC) and eddy (storm) component. What is the role of the regional MMC in the connectivity between the ENSO and sea ice? Figure 3a shows the instantaneous correlation between the Niño3 index and mean meridional heat flux. The northward (southward) heat flux is positive (negative). During El Niño (La Niña) years, heat is transported into (out of) *Region 1*, which limits (encourages) sea ice growth, while heat is transported out of (into) *Region 2*, which encourages (limits) sea ice growth. To further identify the relationship between the mean meridional heat flux and sea ice, we calculated JFD between the mean meridional heat flux and SIC in the ADP region (Figure 2b). It appears that SIC is linearly linked with the mean meridional heat flux.

[7] Since the mean meridional heat flux in Figure 3a is associated with the regional MMC, we plotted the meridional wind anomalies as well as the meridional and vertical wind anomaly vectors to show the fluctuations of the regional MMC (especially the regional Ferrel Cell) from El Niño to La Niña conditions. The mean Ferrel Cell rises in the high latitudes and sinks in the mid-latitudes. In the central Pacific sector of the Antarctic (Figures 4a and 4b), an anomalous southward (northward) air advection appears near the surface south of ~43°S (~55°S) during El Niño (La Niña) events. Also, there is an anomalous upward (downward) motion in the rising branch of the regional Ferrel Cell (~82°S to ~70°S) during El Niño (La Niña) events. This indicates that the poleward segment of the regional Ferrel cell (triangle labeled "**P**") strengthens (weakens) during El Niño (La Niña) events. At the same time, the anomalous southward (northward) air advection extends from the surface to the top of the atmosphere, and there is anomalous rising (sinking) air between ~55°S and ~40°S (~52°S and ~35°S). Both tend to weaken (strengthen) the equatorward segment of the regional Ferrel cell (triangle labeled "**E**"), which limits (encourages) northward air mass advection in the upper level of the regional Ferrel Cell during El Niño (La Niña) events. The combined effect of these dynamical changes in **P** and **E** leads to a build-up (depletion) of warm air in **P** during El Niño (La Niña) events.

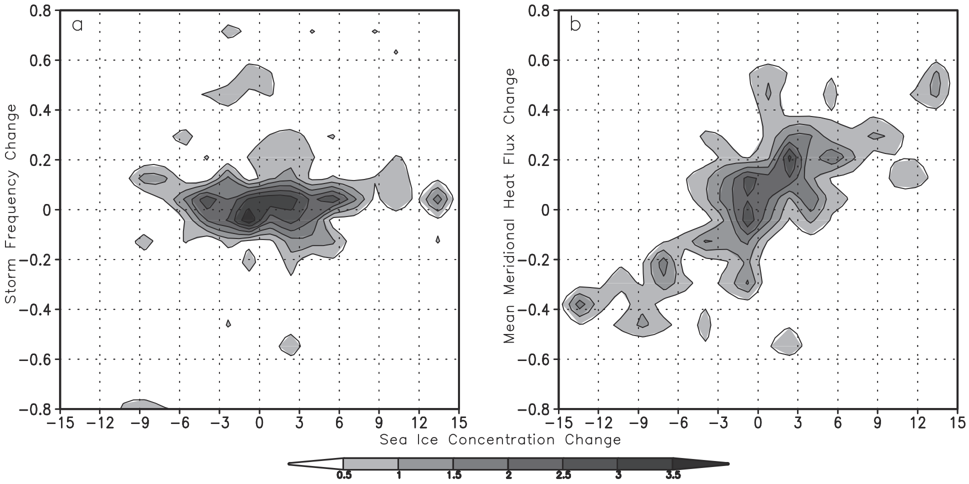

Figure 2. (a) The joint frequency distribution between the storm frequency (%) and Antarctic SIC (%) for the composite differences between El Niño and La Niña years in the ADP region (180–0°W; 90°S–45°S); (b) Similar to (a), except between the mean meridional heat flux (mK/s) and Antarctic SIC (%).

[8] There are two processes responsible for the aforementioned regional Ferrel Cell changes. i) The eddy heat flux in the lower atmosphere determines the variations (intensity and location) of the regional Ferrel Cell [*Holton*, 1992]. The meridional eddy heat flux divergence (convergence) between $\sim$70°S and $\sim$60°S and convergence (divergence) between $\sim$80°S and $\sim$70°S in *Region 1* intensify (weaken) the **P** segment of the regional Ferrel Cell during El Niño (La Niña) events (Figure 3b). ii) In contrast, we see an anomalous counter-clock wise (clock wise) regional MMC in **E** for the El Niño (La Niña) cases, which weakens (intensifies) the regional Ferrel Cell there (Figures 4a and 4b). The equatorward (poleward) shift of the storm track in *Region 1* represented by upward motion centered at $\sim$47° ($\sim$58°) associated with El Niño (La Niña) events moves the latent heat release zone equatorward (poleward), which helps to drive the above anomalous regional MMC in **E**. The overall effects of i) and ii) lead to a strengthening (weakening) of the **P** segment of the regional Ferrel Cell, and a weakening (strengthening) of the **E** segment of the regional Ferrel Cell for the El Niño (La Niña) cases. These changes result in the aforementioned anomalous southward (northward) mean meridional heat flux in the sea ice zone during El Niño (La Niña) events. In the Bellingshausen and western/central Weddell Seas, the circulation patterns for the El Niño (La Niña) cases are qualitatively similar to those described for the central Pacific sector of the Antarctic for the La Niña (El Niño) cases, but the strength of the anomalies in *Region 2* is relatively weaker than that of *Region 1* (not shown). These changes of the circulation patterns provide one mechanism to generate the ADP variations in *Region 1* and *2*.

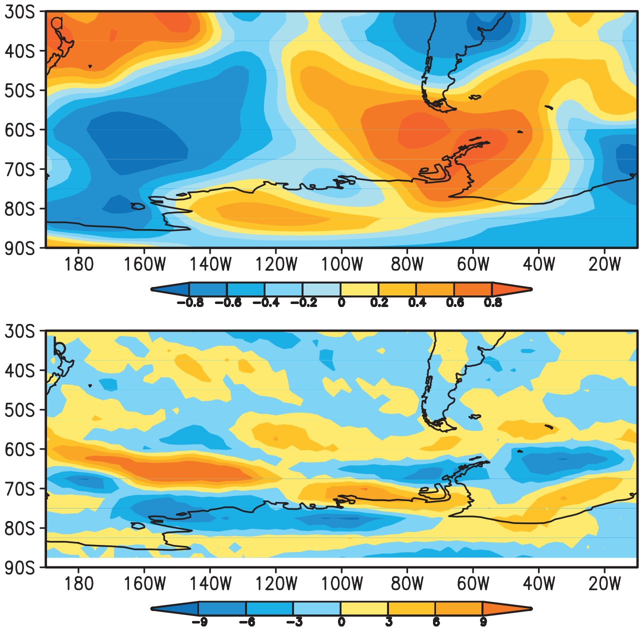

Figure 3. (a) The instantaneous correlation between the normalized monthly Niño3 index greater (less) than positive (negative) one standard deviation and corresponding mean meridional heat flux (mK/s) integrated from the surface to the top of the atmosphere for 1979–1999; (b) the convergence (negative) and divergence (positive) of the meridional eddy heat flux (K/s × 10^{-6}) for the composite differences between El Niño and La Niña events derived from four times daily NCEP/NCAR reanalysis.

4. Discussion and Conclusion

[9] To summarize, the changes of the regional Ferrel Cell in *Region 1* and *2* are a consequence of i) changing the meridional eddy heat flux divergence and convergence and ii) shifting the latent heat release zone associated with the storm changes. Antarctic sea ice variations in *Region 1* and *2* are primarily due to the changes of the regional Ferrel Cell associated with the altered mean meridional heat flux, rather than the changes in storm spatial distribution itself (sea ice dynamics). Additionally, early studies show that the interannual variations in surface temperature are directly linked to air mass variations and associated alterations in warm or cold thermal advection [*Barry and Perry*, 1973]. The SAT warming associated with the regional Ferrel Cell changes reduces the temperature gradient between the air and ocean, which leads to less sensible heat release from the ocean to the

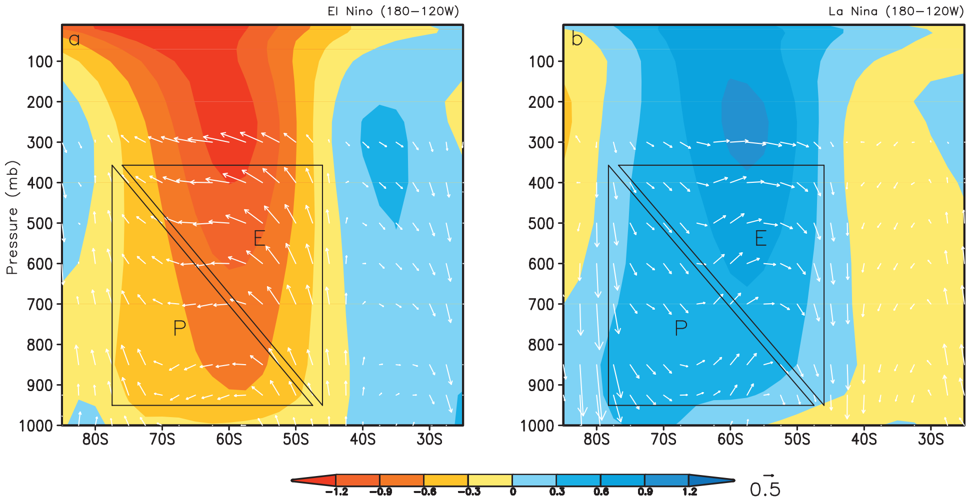

Figure 4. The 180–120°W averaged longitude-pressure cross sections of meridional wind anomalies (shaded, m/s), meridional (m/s) and vertical wind anomaly (pa/s × 300) vectors for El Niño (a) and La Niña (b) cases.

atmosphere based on the bulk aerodynamic formulas. This implies that the ocean retains more heat to melt sea ice and increase ocean surface temperature.

[10] We suggest that the regional MMC changes (the regional Ferrel Cell) are one such mechanism leading to polar and extropolar communicate nearly simultaneously by modulating the mean meridional heat flux. Numerical experiments show that the significant modifications to MMC induced by Antarctic sea ice anomalies can extend into the tropics of the Northern Hemisphere [*Bromwich et al.*, 1998]. This mechanism implies that any change to the regional MMC, either induced by variations of tropical SST or sea ice in the polar regions, may establish teleconnections across a full range of spatial scales. We focus on the meridional mechanism in this paper. Further research into investigating the zonal mechanism for the ADP pattern is currently being undertaken. Our results further suggest that in order to better understand how sea ice may change as climate warms, we must also learn what will happen to tropical temperature, and El Niño/La Niña occurrences.

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References

Barry, R. G., and A. H. Perry, *Synoptic Climatology: Methods and Applications*, Methuen & Co.Ltd, London, P.555, 1973.

Bromwich, D. H., B. Chen, K. M. Hines, and R. I. Cullather, Global atmospheric responses to Antarctic forcing, *Annals of Glaciology*, 521–527, 1998.

Cane, M. A., S. E. Zebiak, and S. C. Dolan, Experimental forecasts of El Nino, *Nature*, *322*, 827–832, 1986.

Chandler, M., and J. Jonas, The atlas of extratropical cyclones (1961–1998), NASA/Goddard Institute for Space Studies open data set CD-ROM, 2000.

Carleton, A. M., Sea ice-atmosphere signal of the southern oscillation in the Weddell Sea, Antarctica, *J. Climate*, *1*, 378–388, 1988.

Fletcher, J. O., U. Radok, and R. Slutz, Climatic signals of the Antarctic Ocean, *J. Geophys. Res.*, *87*, 4269–4276, 1982.

Gloersen, P., Modulation of hemispheric sea-ice cover by ENSO events, *Nature*, *373*, 503–504, 1995.

Harangozo, S. A., A search for ENSO teleconnections in the west Antarctic Peninsula climate in austral winter, *Int. J. Climatol.*, *20*, 663–679, 2000.

Holton, J. R., *An Introduction to Dynamic Meteorology*, 3rd ed., Academic Press, San Diego. 1992. Http://www.cdc.noaa.gov/Correlation/details.html.

Kalnay, E. C., et al., The NCEP/NCAR reanalysis project, *Bull. Am Meteor. Soc.*, *77*, 437–471, 1996.

Kwok, R., and J. C. Comiso, Southern Ocean climate and sea ice anomalies associated with the southern oscillation, *J. Climate*, *15*, 487–501, 2002.

Martinson, D. G., and R. A. Iannuzzi, Spatial/temporal patterns in Weddell gyre characteristics and their relationship to global climate, *J. Geophys. Res.*, in press, 2000.

Peterson, R. G., and W. B. White, Slow oceanic teleconnections linking the Antarctic Circumpolar Wave with the tropical El Nino-Southern Oscillation, *J. Geophys. Res.*, *103*, 24,573–24,583, 1998.

Reynolds, R. W., and T. M. Smith, Improved global sea surface temperature analyses using optimum interpolation, *J. Climate*, *7*, 929–948, 1994.

Rind, D., M. Chandler, J. Lerner, D. G. Martinson, and X. Yuan, The climate response to basin-specific changes in latitudinal temperature gradients and the implications for sea ice variability, *J. Geophys. Res.*, *106*, 20,161–20,173, 2001.

Simmonds, I., and T. H. Jacka, Relationships between the interannual variability of Antarctic sea ice and the southern oscillation, *J. Climate*, *8*, 637–647, 1995.

Simmonds, I., Climatic role of Southern Hemisphere extratropical cyclones and their relationship with sea ice, *Papers and proceedings of the royal society of Tasmania*, *130*, 95–100, 1996.

Smith, S. R., and C. R. Stearns, Antarctic climate anomalies surrounding the minimum in the Southern Oscillation Index, in *Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations, Antarct. Res. Ser.*, 61, edited by D. H. Bromwich and C. R. Stearns, pp. 149–174, AGU, Washington, D.C., 1993.

Trenberth, K. E., General characteristics of El Nino-Southern Oscillation, in *teleconnections linking worldwide climate anomalies*, edited by M. H. Glanz, R. W. Katz, and N. Nicholls, pp. 13–42, Cambridge Univ. Press, New York, 1991.

White, B. W., and R. G. Peterson, An Antarctic circumpolar wave in surface pressure, wind, temperature and sea ice extent, *Nature*, *380*, 699–702, 1996.

Yuan, X., D. G. Martinson, and W. T. Liu, Effect of air-sea -ice interaction on winter 1996 Southern Ocean subpolar storm distribution, *J. Geophys. Res.*, *104*, 1991–2007, 1999.

Yuan, X., and D. G. Martinson, Antarctic sea ice variability and its global connectivity, *J. Climate*, *13*, 1697–1717, 2000.

Yuan, X., and D. G. Martinson, The Antarctic dipole and its predictability, *Geophys. Res. Lett.*, *28*, 3609–3612, 2001.

J. Liu and D. Rind, NASA/Goddard Space Flight Center, Institute for Space Studies, 2880 Broadway, New York, NY, 10025, USA. (jliu@giss.nasa.gov)

X. Yuan and D. G. Martinson, Lamont-Doherty Earth Observatory of Columbia University, USA.