Impact of latent heat release on polar climate

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[1] In this study we use model output from a range of coupled climate models, as well as, focused AGCM experiments to support the hypothesis that in a warmer climate increased moisture availability will cause a warming of the Polar Regions through increased dynamical heat transports. Projections of climate change due to increased greenhouse gases predict significant warming of the Polar Regions. This change in polar temperatures has been primarily attributed to ice-albedo feedbacks. However, in this study we show that in our AGCM experiments the temporal and spatial coherence between developing extratropical cyclones and latent heat release causes a greater than 2°C warming of the poles. **Citation:** Solomon, A. (2006), Impact of latent heat release on polar climate, *Geophys. Res. Lett.*, *33*, L07716, doi:10.1029/2005GL025607.

1. Introduction

[2] Projections of climate change due to increased greenhouse gases predict significant warming of the Polar Regions [e.g., *Intergovernmental Panel on Climate Change (IPCC)* Third Assessment Report (TAR), 2001]. The TAR concludes that as the climate warms, Northern Hemisphere snow cover and sea-ice extent will decrease, with the Greenland ice sheet being the most vulnerable to climatic warming. For an annual-average warming of 2.7°C, the Greenland ice sheet is projected to gradually disappear [e.g., *Huybrechts et al.*, 1991; *Oerlemans*, 1991; *Van de Wal and Oerlemans*, 1994]. In the Southern Hemisphere, the projected warming of the Polar Region is limited by the uptake of heat by the Southern Ocean [e.g., *Raper et al.*, 2002; *Huang et al.*, 2003; *Barnett et al.*, 2005]. In addition to an increase in sea surface temperatures, projections of climate change due to increased greenhouse gases predict an increase in tropospheric water vapor and the frequency of mid-to-high latitude deep convection [e.g., *Murphy and Mitchell*, 1995; *Brinkop*, 2002], potentially providing more energy for the development of extratropical storms.

[3] Studies of extratropical variability forced by extratropical diabatic heating anomalies due to latent heat release tend to be limited to the impact on individual storms. For synoptic-scale eddies, case studies suggest that latent heat release associated with condensation augments rapid surface cyclogenesis [e.g., *Davis*, 1992; *Davis et al.*, 1993; *Whitaker and Davis*, 1994; *Stoelinga*, 1996] and acts as a source of upper-tropospheric enstrophy over the storm track regions [*Black*, 1998]. Over the North Pacific this contribution is of the same order as the conversion from the mean flow [*Black*, 1998]. This additional energy source has been shown to increase the growth rate and amplitude of baroclinic waves in theoretical [e.g., *Mak*, 1982; *Emanuel et al.*, 1987; *Fantini*, 1995], numerical and diagnostic [e.g., *Gutowski et al.*, 1992; *Reed et al.*, 1992; *Davis et al.*, 1993] studies.

[4] In this study we assess to what extent the projected warming of the Polar Regions is due to changes in dynamical heat transport, which is forced by latent heat release through increased moisture availability. Specifically, we focus on dynamical heat transport due to eddy fluxes—since this is the dominant poleward heat transport mechanism in mid-latitudes [e.g., *Trenberth and Solomon*, 1993; *Trenberth and Stepaniak*, 2003]. Understanding what role these climate feedbacks play in determining the mean climate is critical for predicting future climate change, especially in a warmer climate where more moisture is available for extratropical latent heat release.

2. The Dynamical Response to Latent Heat Release in Developing Cyclones

2.1. Feedbacks in Coupled Climate Model Simulations

[5] We first demonstrate that there is a systematic relationship between precipitation over the extratropical oceans and polar surface temperatures on decadal time scales in 10 coupled climate model simulations of pre-industrial (1870's) climate used in the upcoming IPCC Fourth Assessment Report. An approximate increase of 0.15 mm/day in average precipitation over the North Pacific and North Atlantic Oceans is coincident with an approximate 0.5°C increase in polar surface temperatures on decadal time scales in coupled climate model simulations of pre-industrial climate (Figure 1). It is important to note that this variability is only due to internal processes since the forcing in these model integrations is held fixed at pre-industrial levels. This result indicates that, over a wide range of coupled climate models, there is a systematic relationship between increased precipitation over the extratropical oceans and a warming of the Polar Regions. The rest of this study uses the NCAR Community Atmospheric Model version 2 (CAM2, http://www.ccsm.ucar.edu/models/atm-cam/docs/cam2.0/UsersGuide/).

2.2. Modified Latent Heating Experiments

[6] The dominance of latent heating over radiative cooling results in a net heating in the tropics and the dominance of radiative cooling over latent heating results in a net cooling in the subtropics (Figure 2a). Poleward of the subtropical cooling there is a net heating in the mid-latitudes, which is of the order of the tropical heating in the Northern Hemisphere (NH). This mid-latitude heating is

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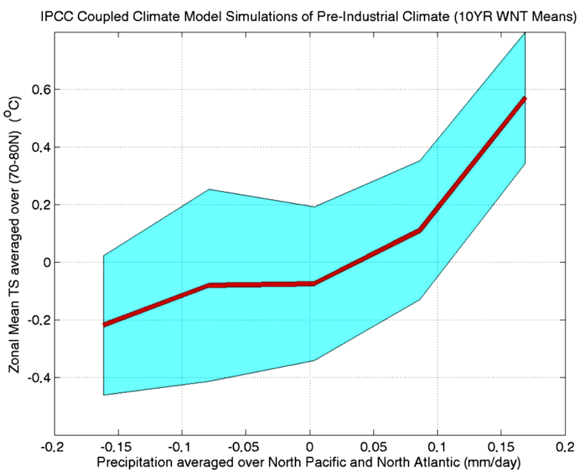

Figure 1. Mean and standard deviation deduced from scatter between precipitation averaged over the North Pacific and North Atlantic versus zonal mean surface temperature (TS) averaged between 70–80°N using 10-year Nov–Mar means from 10 pre-industrial climate simulations (http://www.cdc.noaa.gov/people/amy.solomon/ipcc_models.pdf). The scatter is separated into 5 equally spaced bins from which a mean and standard deviation is calculated. The red line indicates the mean of the scatter and the aqua shading indicates the 0.5 standard deviation of the scatter. The results were calculated by binning the scatter of all of the wintertime 10-year means from all of the model integrations into 5 equally spaced bins from which a mean (red line) and 0.5 standard deviation (aqua shading) were calculated (mean precipitation and polar temperature were removed from each time series prior to this calculation). Precipitation over extratropical oceans was estimated by averaging total precipitation over the North Pacific (32–49°N,142°E–132°W) and North Atlantic (32–49°N,75–24°W). Polar surface temperatures were estimated by averaging zonal mean surface skin temperatures from 70–80°N. November–March monthly mean data was then averaged over 10 years.

primarily due to large-scale condensation in the warm sector of developing cyclones [*Chang et al.*, 2002].

[7] In order to identify why the zonal mean heating in mid-latitudes is larger in the NH than in the Southern Hemisphere (SH), the total wintertime diabatic heating at 600 hPa averaged over the same years as Figure 2a is plotted in Figure 2b. It is seen that the heating in the NH occurs primarily over the Pacific and Atlantic Ocean basins with maximum values in the western oceans. This heating is collocated with poleward heat transport due to meridional eddy fluxes in the storm track regions.

[8] The CAM2 diabatic heating at 600 hPa (Figure 2b) has maximum values over western ocean basins that are over 50% larger than observations (Figure 2c), while the general distribution is well simulated. In addition, the model has organized heating that extends around the globe between 40–60°S (Figure 2b). It is important to note that observed diabatic heating estimates, especially in the Southern Hemisphere, may differ depending upon the data sets and time periods used in the calculation. However, model biases in precipitation may also be impacting the dynamical heat transports in mid-latitudes.

[9] To isolate the impact of latent heat release in extratropical cyclones on climate, we perform another integration in which we disrupt the temporal and spatial coherence between the developing cyclones and the latent heat release over the mid-latitude oceans, while keeping the zonal mean distribution unchanged. This is accomplished by taking the latent heat release generating by storms over mid-latitude ocean basins and distributing this heating zonally in all ocean basins along the same latitude circle and at the same pressure level where it is created (Figure 3b). Therefore, the zonal mean distribution of the latent heat release from the perturbed run (MOD) (Figure 3a) is approximately the same as the control integration (CNT) (Figure 2a).

[10] Disrupting the relationship between the latent heat release and the developing storms results in significant changes in mid-latitude zonal mean transient eddy heat fluxes (VTP), with similar structure in both hemispheres. Maximum poleward heat transport in mid-latitudes is seen to occur over the oceans to the east of continents in both hemispheres. Figure 4b shows the difference in VTP at 700 hPa between CNT and MOD. Locally, over mid-latitude oceans, poleward heat transport increases by up to 12 K m/s (Figure 4b). These results demonstrate that latent heat release in developing cyclones causes an increase in pole-

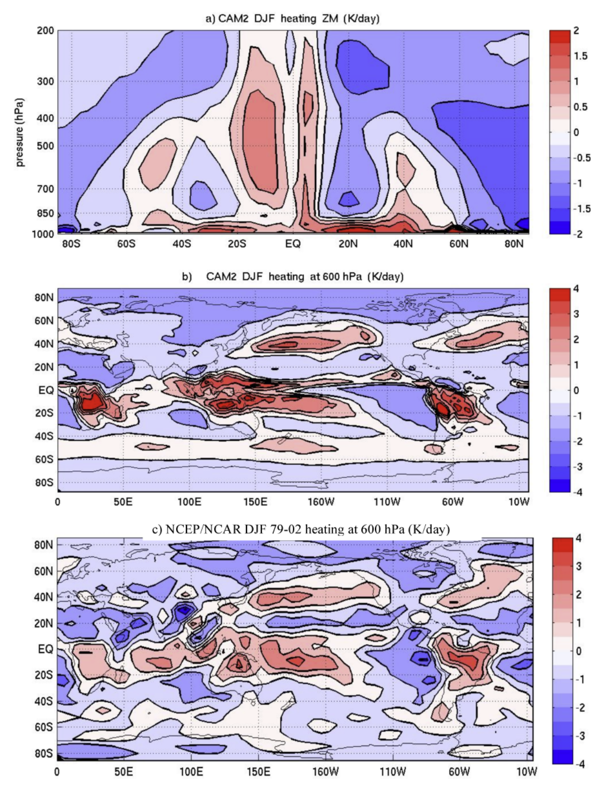

Figure 2. DJF mean diabatic heating field time averaged over 20 years calculated from CAM integration forced by climatological mean SSTs, in units of K/day. (a) Zonal mean. (b) 600 hPa. (c) DJF mean chi-corrected diabatic heating field time at 600 hPa averaged over 1979–2002 calculated using the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996; following *Sardeshmukh*, 1993], in units of K/day.

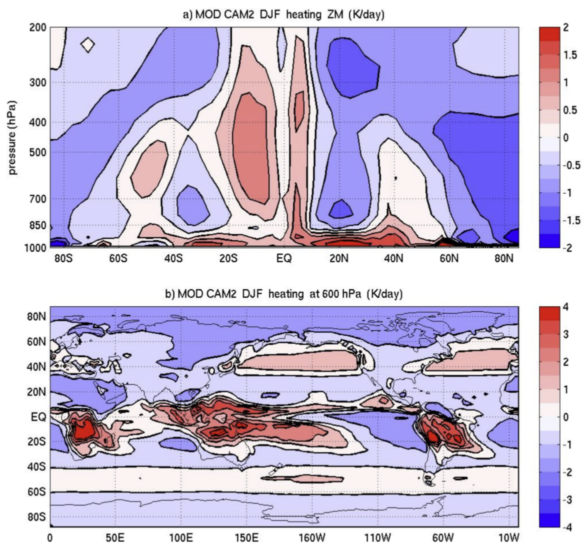

Figure 3. DJF mean diabatic heating field time averaged over 20 years calculated from the modified latent heat release integration forced by climatological mean SSTs, in units of K/day. (a) Zonal mean. (b) 600 hPa.

ward heat transport over regions of the North Pacific, North Atlantic, and Indian Oceans by over 30%.

[11] This change in transient eddy fluxes due to latent heat release significantly modifies the climate mean state by reducing the shear throughout the mid-latitude troposphere (results not shown). Consistently, the resultant impact of disrupting the latent heat release on the climate mean temperature distribution is to reduce the horizontal temperature gradients, cooling the mid-latitudes and warming the poles by approximately 2°C in both hemispheres (Figures 5a and 5b).

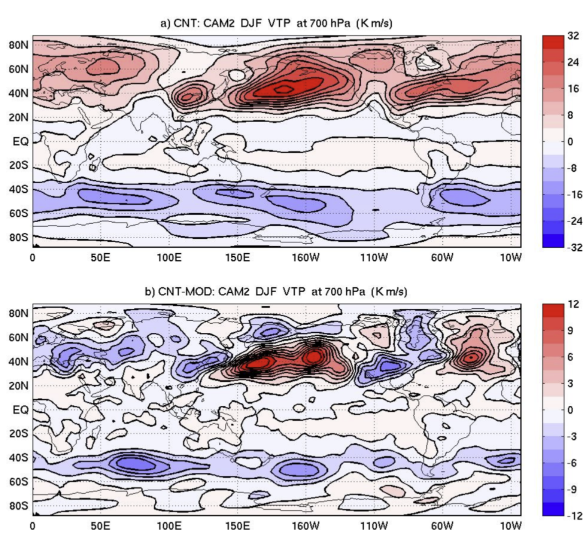

Figure 4. DJF mean transient eddy heat fluxes (VTP) at 700 hPa time averaged over 20 years calculated from the CAM integration forced with climatological SSTs, in units of K m/s. (a) From the control integration (CNT). (b) From the control integration minus the modified latent heat release integration (CNT-MOD) to highlight the impact of latent heat release over the extratropical oceans.

3. Implications for Climate Change

[12] The discussion above clearly demonstrates that diabatic heating due to latent heat release is the dominant diabatic heating term in the mid-latitude mid-troposphere and that variations in this heating significantly impact poleward heat transport and storm track structure. The change in jet strength and structure is larger than El Niño/Southern Oscillation (ENSO) related changes in the western Pacific but smaller in the Eastern Pacific (results not shown). However, the changes in poleward heat transport in mid-latitudes due to extratropical latent heat release (estimated from Figures 4a and 4b) are significantly larger than changes observed at the peak of an ENSO event (results not shown).

[13] An increase in surface temperature locally increases moisture available for condensation. This increase in moisture due to local sources has been shown to increase latent heat release and upper-tropospheric enstrophy using the GEOS-1 assimilated data set [*Black*, 1998] and the NCEP-NCAR reanalyses [*Chang et al.*, 2002]. Coupled climate model simulations using the "Business as Usual" climate scenario indicate that mid-latitude temperatures will increase by 1–2°C by 2090 [e.g., *Boer et al.*, 2000; *Dai et al.*, 2001]. For example, increasing carbon dioxide to 4 times current levels in the NCAR Community Climate System Model version 3 (CCSM3) results in a greater than 2°C increase in surface air temperature in essentially all extratropical ocean basins (http://www.ccsm.ucar.edu/

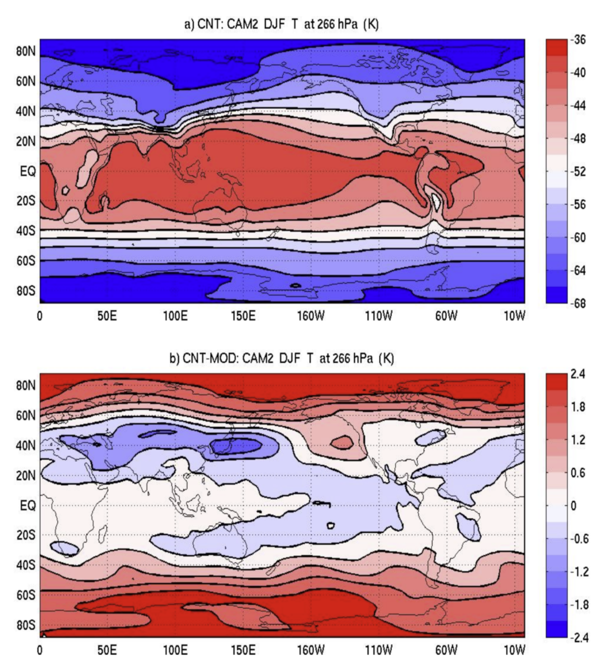

Figure 5. DJF mean temperature (T) time averaged over 20 years at 266 hPa calculated from the CAM integration forced with climatological SSTs, in units of °C. (a) From the control integration (CNT). (b) From the control integration minus the modified latent heat release integration (CNT-MOD).

experiments/ccsm3.0). This relatively small increase in temperature results in a 20–30% increase in specific humidity throughout the mid-latitude troposphere [*Dai et al.*, 2001].

[14] In this paper we have shown that there is a systematic relationship between latent heat release in extratropical storms and poleward heat transport by transient eddies. Our results indicate that these feedbacks may be playing an important role in the dynamical response to an increase in greenhouse gases. Whether or not this results in an amplification of polar variability is the focus of current research.

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