PCAS 19 (2016/2017)

Critical Literature Review

(ANTA602)

Climate change tipping points in Antarctica and what this means for the Antarctic Circumpolar Current

Name: Nicolette Marks

Student ID: 53406278

Word count: 3,036

Abstract

The Antarctic region is like no other place on Earth. In Antarctica and the Southern Ocean there are large-scale components which may pass critical tipping points within the next century. Anthropogenic climate change pushes the fragile physical and chemical mechanisms of climate sensitive regions into new territory. Minor changes in annual ice duration or light availability could cause radiating ecological responses to Antarctic systems. The Antarctic Circumpolar Current is a critical system within the Antarctic and global environment which joins the waters of the major oceans with a strong current unimpeded by any land mass. The impact of reaching or breaching critical tipping point thresholds in Antarctica and the Antarctic Circumpolar Current could be disastrous to the local and global environment.

Contents

Abstract 1

Introduction 2

Climate change tipping points in Antarctica 3

The effects of climate change on the Antarctic Circumpolar Current 4

The outlook for Antarctica in a warmer future 6

Conclusions 7

References 9

Introduction

The world is undergoing many anthropogenic changes with the main variation being global temperatures, in the oceans and on the continents, increasing (Scheffer *et al.,* 2009). It is a unique era in the Earth's timescale where scientists have the capacity to observe ongoing changes and build on knowledge through understanding processes and influences behind the changes (National Research Council, 2011). Antarctica and the Southern Ocean (SO), principally the Antarctic Circumpolar Current (ACC), are linked tightly with global systems which have the potential to provide key evidence that can improve the current understanding of the drivers and reactions behind the changes (Bracegirdle *et al.*, 2008). As the global climate changes, Antarctica's fragile environment is placed under increasing pressure from climatic variations. This literature review endeavours to obtain an in-depth understanding of possible outcomes that may occur in Antarctica if the continent reaches or surpasses critical tipping points (Bracegirdle *et al.,* 2008; Lenton *et al.,* 2008). As the globe continues to warm, insight into localised and widespread consequences of Antarctic climate change will be invaluable to the science community and the world. These changes have the potential to extensively reduce biodiversity and cause irreversible ecological impacts, rendering the Antarctic ecosystems acutely vulnerable to climate-induced tipping points (Clarke *et al.,* 2013).

Environmental tipping points are events where a small change in driver or perturbation, such as global mean temperature, can qualitatively alter the state or development of a system, resulting in disproportionate and detrimental outcomes. They occur when conditions breach critical environmental thresholds – where the pressure becomes greater than the tolerance levels of the natural systems – causing the ecosystems to switch states (Clarke *et al.,* 2013; Kriegler *et al.,* 2009). Nature generally moves through gradual changes with smooth transitions however, with increasing anthropogenic warming this process is being interrupted, resulting in sudden drastic switches to a contrasting state (Scheffer *et al.,* 2001). Assessing the knowledge of climate change tipping points in Antarctica and the impact they will have on the ACC is crucial to understand where the global environment is headed (Levermann, & Mengel, 2014; National Research Council, 2011).

The SO is a unique global climate system which is zonally unrestrained by continents and land masses (Meredith *et al.,* 2004). Part of the SO system is the ACC, which is the dominant feature of present-day ocean circulation and climate, being the world's only unimpeded global current. The unique and hostile environment of the SO includes continuous storm-forced westerly winds, with the closed current flowing strongly eastwards around Antarctica. The flow of the ACC is often referred to as the 'great ocean conveyer belt' as it connects the Pacific, Indian and Atlantic Ocean basins, allowing water, salt, heat and other properties to move from one ocean to another. The ACC is the most powerful current in the world ocean, responsible for the thermal isolation of the Antarctic from the tropical waters, with a volume transport of 130-140 Sv (1 Sv = the estimated flow of the combined global river systems or $10^6 m^3/s$) (Fyfe & Saenko, 2006; Lefebvre *et al.,* 2012).

Disturbing the equilibrium of the ACC could destabilise the Earth's processes as it plays a crucial role in maintaining a healthy global environmental due to its unique ecology. The ACC systems and processes are defined and specialised to support its unique environment (Lefebvre *et al.,* 2012). Direct climatic changes, including increased temperature and lower albedo have the potential to disrupt this complex zone, altering the water column mixing and nutrient loading. These are crucial factors which could have a severe impact on a variety of aspects in the SO, including the food web, breeding patterns and migration (Clarke let al., 2013). It is crucial to look in-depth at the themes which define climate change tipping points, showing the benefits of extended climate research in Antarctica to learn how these can affect the ACC. The aim of this literature review is to determine whether tipping points exist in Antarctica and what affect they have on the ACC and global ecological systems. To achieve this aim, a review of current literature will be used to assess and contrast academic perspectives on climate change tipping points in Antarctica. This is done with the outlook of interpreting how climate tipping points will affect the ACC, and to comprehend the local and global consequences of Antarctica reaching or surpassing climate tipping points.

Climate change tipping points in Antarctica

The Intergovernmental Panel on Climate Change (IPCC) reported that the risks associated with crossing a tipping point increase with temperature rise and may cause the transition of large-scale components of the Earth's system into a different state. The Antarctic sea ice and the West Antarctic ice sheet (WAIS) have been identified by numerous studies (Kriegler *et al.,* 2009; Lenton *et al.,* 2008; Thomas *et al.,* 2004) as top candidates for tipping points, which may be triggered within this century. If these environmental thresholds surpass their tipping points, triggering irreversible change, they could contribute to extensive sea level rise and mass extinction of species (Reid & Croxall, 2001). In 2004, satellite observations showed that the Pine Island glacier, one of many glaciers on the outskirts of the WAIS, had significantly reduced and the resulting ice flow into the Amundsen Sea was 25 per cent faster than in the 1970s (Barley, 2010). Lenton *et al.* (2008) estimated that the WAIS, and its associated glaciers, are losing 60% more ice mass than they are gaining, contributing considerably to sea-level rise and freshwater fluctuations. These observations reinforce the suggestion that the WAIS is poised to reach a tipping point and enter a period of accelerated shrinking, raising the sea levels by more than 0.2 millimetres per year and altering the water buoyancy properties (Lenton *et al.,* 2008; Thomas *et al.,* 2004).

The rate at which tipping points change the environment after the threshold is surpassed is widely debated. Lenton *et al.* (2008) described a broad definition of a tipping point and its tipping threshold to include gradual transitions, however Clarke *et al.* (2013) classified the ecological reaction to tipping points as causing rapid change. There is no consensus in the literature reviewed around whether sensitivity to increased temperatures from global warming are successful identifying indicators of ecological systems reaching a critical threshold.

Although diverse events can trigger these climatic shifts, Scheffer *et al.* (2001) explained that recent studies show a loss of resilience is the starting point for a major shift to an alternative state. This advocates for environmental management to focus on maintaining ecosystem resilience, so that critical tipping points are not reached (Lenton *et al.,* 2008).The dramatic loss of ice from the WAIS and Pine Island glacier is only the beginning of a trend in increased melt and massive sea level rise (Wang *et al.,* 2011). Levermann and Mengel (2014) used topographical data and simulations of ice dynamics to investigate parts of Antarctica's vulnerability to climate change. While they are not the first to try and model the tipping points, the challenges surrounding developing models and methods to pinpoint ecosystem thresholds make accurate predictions difficult (Lenton *et al.,* 2008).

The effects of climate change on the Antarctic Circumpolar Current

Meredith *et al.* (2004) found that the ocean transport through the Drake Passage is susceptible to long-term climate variability quantified through studies on the seasonal correspondence changes in the Southern Annular Mode. The paper concluded that the changes and vulnerabilities observed are from anthropogenic processes, meaning that these climate change mechanisms have the potential to directly impact ocean circulation on a global scale. Toggweiler & Russell (2008) reinforce this by discussing how in the past, the hydrological cycle became stronger with anthropogenic additions of CO_2

to the atmosphere, which ultimately threatened the oceans processes and circulation. Current climate-system models explained by Gregory *et al.* (2005) uses data to support these arguments saying that over the next century, the ocean's processes and circulation will weaken. However, these predications may be unfounded as suggested by Toggweiler & Russell (2008) that the models failed to anticipate the change in climate and wind dynamic that have occurred as a result of recent global warming. Therefore, even though climate models predict that ocean circulation will respond to global warming, by becoming weaker in the future, the information from the past suggests increasingly stronger oceanic circulation as the climate warms (Toggweiler & Russell, 2008).

Over the past two centuries the ACC has accounted for approximately 40% of the global oceanic uptake of anthropogenic CO_2, making it one of the biggest carbon sinks in the world (Böning *et al.,* 2005). This suggests that any shifts in the ACC would require significant re-organisation of the global dynamics in regards to greenhouse gas emissions, particularly in the Southern Hemisphere (Saenko *et al*., 2005). Model simulations (Lenton & Matear, 2007; Lovenduski *et al.,* 2008; Zickfeld *et al.,* 2007) suggest that the future of this carbon sink depends on the response of the ACC circulation system to the strengthening of the westerlies projected by IPCC climate scenarios for the twenty-first century. The ACC exchanges carbon dioxide, oxygen and other gasses with the atmosphere and also redistributes heat and other ocean properties through the connected ocean basins. A reduction in the SO CO_2 uptake, relative to expectations, from atmospheric observations and attributed to an increase in outgassing of natural carbon dioxide as a result of this mechanism (Böning *et al.,* 2008).

Research (Saenko *et al.,* 2005; Toggweiler & Russell, 2008) shows that the atmospheric winds are the main drivers of ocean circulation, which is particularly important for the ACC. The strong westerly winds over the SO are crucial for the deep and surface water interactions, which is continuously being overturned as the water makes its way around the globe (Lefebvre *et al.,* 2012). The volume and mass of water transported by the ACC makes it the world's strongest current, with approximately 70% of the oceans wind energy going directly into its system (Meredith *et al.,* 2004; Toggweiler & Russell, 2008). It is critical to understand the overturning system in the SO, as changes to the process alters the acidification and changes the balance of anthropogenic CO_2 which, in-turn, alters the seasonal carbon dynamics (McNeil & Matear, 2008).

A number of observational studies (Böning *et al.,* 2008; Meredith *et al.,* 2004; Rintoul & Sokolov, 2001) show that changes in the SO circulation will be significant as they will have lasting effects on heat uptake, the global meridional overturning circulation, and the global carbon budget. Modelling studies (Fyfe & Saenko, 2006; Meredith & Hogg, 2006; Saenko *et al.,* 2005) have presented findings that the ACC is a critical component in the SO circulation due to its high sensitivity to atmospheric changes

(Wang *et al.,* 2011). Böning *et al.* (2008) discusses the implications for ACC dynamics based on ocean models, which implies that there will be an increased upwelling of deep water that is rich in dissolved inorganic carbon south of the circumpolar flow.

The outlook for Antarctica in a warmer future

Light is a key driver of community structure in Antarctic ecosystems, with seasonal ice-covered areas receiving direct sunlight for only a portion of the year. This results in limited growing and reproduction, with most primary producers attaining their annual light needs during the summer when their habitat is ice-free. These organisms rely on consistent dynamics in their annual light, including the timing of the ice free periods in relation to the annual solar cycle and the length of time that the ecosystem is ice-free (Reid & Croxall, 2001). Clarke *et al.* (2013) provides data that demonstrates the strength of the dependant relationship with light, which proves that any changes may cause severe imbalance the Antarctic ecosystem equilibrium and have expanding consequences. Glacier or sea-ice melt could switch marine conditions from dark underneath the ice, to bright light influencing the ecological processes and cause disturbances. Algae use light to photosynthesise and a potential increase in the light availability could see the plant outcompete other organisms in the habitat. Consequently, these processes induce a strong ecological response from relatively minor changes in annual ice duration.

There is increased warming off the coast of Antarctica, which is connected to the loss of sea ice, estimated to be approximately 25% by the end of the 21st century (Böning *et al.,* 2008) . The largest annual average increase in temperature is over the Weddell Sea region and areas at high altitude, however the warming is projected to become more uniform over the entire Antarctic continent (Lenton *et al.*, 2012). The climate variables are broken down into large scale patterns to understand the individual and complex roles that each regional aspect plays in the predicted climate changes. This is done by using changes observed in the past to assess the known patterns of evolution with the variables which occur over the 21st century (Bracegirdle *et al.,* 2008).

Climate projections indicate that anthropogenic changes in the atmospheric circulation are likely to continue into the future, resulting in significant changes to the ACC and global ocean circulation (Jacobs *et al.,* 2011). One of the reasons for this occurring is the melting of glaciers in Antarctica, most prominently the West Antarctic glacier. Antarctica regions that have the most rapid melting all share a commonality in that they are all located in areas where the ACC flows near the Antarctic continent. This has led scientists (Bracegirdle *et al.,* 2008; The National Academy of Sciences, 2011; Smale *et al.,* 2008) to speculate that the ACC properties and dynamics have already drastically changed, resulting in warm deep water being delivered to the Antarctic marginal seas. Consequentially, this results in increased melt and even more changes to the Antarctic environment (Gille, 2014). The changes to the ACC are consistent with anthropogenic change, with the fluctuation of water properties in the ACC, warming and freshening, being represented in climate models (Böning *et al.,* 2008).

Conclusions

Antarctica and the SO comprise an unparalleled natural laboratory for climate forecasting both short and long term changes (National Research Council, 2011). The complex environmental forces need to be studied so that early warning signs of Earth approaching a critical climatic tipping point can be predicted, before the critical threshold is reached (Lenton *et al*., 2012). Some studies (Lenton *et al.,* 2008) have been able to identify tipping points in certain vulnerable climate systems, however new research (Allison *et al.,* 2011) has included abrupt anthropogenic climate changes to the data collective, which highlighted the concern that larger future nonlinear changes pose a significant risk. Additionally, assessments undertaken by Smith *et al.* (2009) show that 'large-scale discontinuities' are closer than previously thought, due to the present state of the climate. This is concerning as the state of a system approaching a threshold has a slow response to distress as it transitions through an unstable state and into an altered, often contrasting dynamical regime (Lenton *et al.,* 2012; Scheffer *et al.,* 2009).

Antarctica and the SO provide extraordinary opportunities to study climate change tipping points and improve the robustness of early warning methods (Lenton *et al.,* 2012). However, the models of the complex Antarctic systems do not have a precise enough accuracy to consistently predict where the critical tipping point threshold occurs (Scheffer *et al.,* 2009). Lengthy time series measurements and high-resolution modelling is needed to better understand how large-scale physical processes influence smaller scale ecological processes, which is crucial for interpreting natural ecosystem variability (Jacobs *et al.,* 2011; Reid & Croxall, 2001).

The large-scale consistency of trends supports the conclusion that climate change poses a global risk. There is potential for numerous, high probability tipping points during this century. The IPCC term 'large-scale discontinuities' reflect the literal threshold responses in parts of the climate system. (Lenton & Ciscar, 2013). The reasons for concern represents the likelihood that certain tipping points would occur, any of which may be accompanied by very large impacts. It is now possible to better identify specific climate vulnerable systems based on their distribution of impacts and their reaction to multiple stresses (Smith *et al.,* 2008).

One example that requires further research is how the dynamics of the oceans thermohaline circulation works within the climate change scenarios (Saenko *et al.,* 2005). Antarctica is considered one of the most significant baseline environments to study global climate change as its effects are expected to impact the high latitudes first and the most severely (Robinson *et al.,* 2003). A way these studies could be undertaken is with a large-scale observation network that how scientific research in this region can yield insights into global changes, by constructing models that have the potential for constant change and expansion (National Academy of Sciences, 2011).

A potential source of error is the assumption that all potential tipping points have been identified. There needs to be a comprehensive understanding of the Antarctic region, to allow scientists to better predict possible tipping points and how reaching these critical thresholds will affect the local area and the rest of the planet. As warming continues, ecosystem functioning-the physical and chemical processes in each environment-that have, until now, dominated the region's ecosystems have been able to be used as baseline measurements. Moving forward, a critical step will need to be taken in verifying whether these baselines are correct in the relative global carbon cycle.

This synthesis of present knowledge through academic literature suggests that a variety of tipping points could pass their critical threshold within this century under current anthropogenic climate change. From the literature it can be deduced that not all potential tipping points have been identified, meaning that a systematic search for further tipping points should be undertaken. Given the large uncertainty that remains around tipping points, there is urgent need to improve understanding of the underlying mechanisms that determine their behaviour.

The literature review highlighted several areas, such as the ACC overturning process, of Antarctic science where conducting research is logistically challenging, due to the harsh environmental conditions. It was also interesting to assess how well the collaboration between nations, and across disciplines, in both the public and private sector. From the current knowledge database, it can be deciphered that there needs to be improvements made in the collection, management and exchange of information.

References

Allison, I., Bindoff, N., Bindschadler, R., Cox, P., de Noblet-Ducoudre, N., England, M., … Weaver, A. (2011). *The Copenhagen Diagnosis: Updating the World on the Latest Climate Science*. Sydney, Australia: The University of New South Wales Climate Change Research Centre.

Aoki, S., Bindoff, N. L., & Church, J. A. (2005). Interdecadal water mass changes in the Southern Ocean between 30°E and 160°E. Geophysical Research Letters, 32(7). doi: 10.1029/2004GL022220

Barley, S. (2010). Major Antarctic glacier is 'past its tipping point'. *New scientist,* doi: 10.1098/rspa.2009.0434

Böning, C. W., Dispert, A., Visbeck, M., Rintoul, S. R., & Schwarzkopf F. U. (2008). The response of the Antarctic Circumpolar Current to recent climate change. *Nature Geoscience,* 1: 864-869. doi:10.1038/ngeo362.

Bracegirdle, T. J., Connolley, W. M., & Turner, J. (2008). Antarctic climate change over the twenty first century. *Journal of Geophysical Research,* 113(D3). doi: 10.1029/2007JD008933.

Clarke, G. F., Stark, J. S., Johnston, E. L., Runcie, J. W., Goldsworthy, P. M., Raymond, B., & Riddle, M. J. (2013). Light-driven tipping points in polar ecosystems. *Global change Biology*, 19(12): 3749-3761.

National Research Council. (2011). Chapter 2: Fundamental Questions of Global Change. *Future Science Opportunities in Antarctica and the Southern Ocean* (pp.23-74). Washington, DC: The National Academies Press. doi: 10.17226/13169.

Fyfe, J. C., & Saenko, O. A. (2006). Simulated changes in the extratropical Southern Hemisphere winds and currents. *Geophysical Research Letters,* 33(6). doi: 10.1029/2005GL025332.

Gille, S. T. (2014). Meridional displacement of the Antarctic Circumpolar Current. *Philosophical Transactions of the Royal Society A,* 13(2019). doi: 10.1098/rsta.2013.0273.

Gregory, J.M. Dixon, K. W., Stouffer, R. J., Weaver, A. J., Driesschaert, E., Eby, M., … Thorpe, R. B. (2005). A model intercomparison of changes in the Atlantic thermohaline circulation in response to increase in atmospheric CO_2 concentrations. *Geophysical Research Letters,* 32(12). doi: 10.1029/2005GL023209.

Jacobs, S. S., Jenkins, A., Giulivi, C. F., & Dutrieux, P. (2011). Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience,* 4: 519-523. doi:10.1038/ngeo1188.

Kriegler, E., Hall, J. W., Held, H., Dawson, R., & Schellnhuber, H. J. (2009). Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, 106(13): 5041–5046. doi: 10.1073/pnas.0809117106

Lefebvre, V., Donnadieu, Y., Sepulchre, P., Swingedouw, D., & Zhang, Z. (2012). Deciphering the role of southern gateways and carbon dioxide on the onset of the Antarctic Circumpolar Current. *Paleoceanography,* 27(4). doi: 10.1029/2012PA002345.

Lenton, T. M., & Ciscar, J. C. (2013). Integrating tipping points into climate impact assessments. *Climatic Change,* 117(3), 117-585. doi:10.1007/s10584-012-0572-8.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. H., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *PNAS,* 105(6): 1786-1793. doi:10.1073/pnas.0705414105.

Lenton, A., & Matear, R. J. (2007). Role of the Southern Annular Mode (SAM) in Southern Ocean CO 2 uptake. *Global Biogeochemical Cycles,* 21(2). doi: 10.1029/2006GB002714.

Lenton, T. M., Livina, V. N., Dakos, V., van Nes, E. H., & Scheffer, M. (2012). Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness. *Journal of Philosophical Transactions of the Royal Society.* doi: 10.1098/rsta.2011.0304.

Levermann, A., & Mengel, M. (2014). Tipping points for Antarctic melting. *Nature,* 509(7499):136.

Lovenduski, N. S., Gruber, N., & Doney, S. C. (2008). Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink. *Global Biogeochemical Cycles,* 22(3). doi:10.1029/2007GB003139.

McNeil, B., & Matear, R. J. (2008). Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO_2. *PNAS*, 105(48), 18860-18864. doi:10.1073/pnas.0806318105.

Meredith, M. P., & Hogg, A. M. (2006). Circumpolar response of the Southern Ocean eddy activity to a change in the Southern Annular Mode. *Geophysical Research Letters,* 33(16). doi: 10.1029/2006GL026499.

Meredith, M. P., Woodworth, P. L., Hughes, C. W., & Stepanov, V. (2004). Changes in the ocean transport through the Drake Passage during the 19080s and 1990s, forced by changes in the Southern Annular Mode. *Geophysical Research Letters,* 31(21). doi: 10.1029/2004GL021169.

Reid, K., & Croxall, J. P. (2001). Environmental Response of Upper Trophic-Level Predators Reveals a System Change in an Antarctic Marine Ecosystem. *Proceedings: Biological Sciences,* 268(1465): 377-384.

Rintoul, S. R., & Sokolov, S. (2001). Baroclinic transport variability of the Antarctic Circumpolar Current south of Australia. *Geophysical Research Letters,* 106: 2815-2832.

Robinson, S. A., Wasley, J., & Tobin, A. K. (2003). Living on the edge – plants and global change in continental and maritime Antarctica. *Global Change Biodiversity,* 9(12): 1681-1717. doi: 10.1046/j.1365-2486.2003.00693.x.

Saenko, O. A., Fyfe, J. C., & England, M. H. (2005). On the response of the oceanic wind-driven circulation to atmospheric CO2 increase. *Climate Dynamics,* 25(4): 415-426. doi: 10.1007/s00382-005-0032-5.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., … Sugihara, G. (2009). Early-warning signals for critical transitions. *Nature,* 461: 53-59. doi: 10.1038/nature08227.

Scheffer, M., Carpenter, S., Foley, J. A., Folkes, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, 413(6856): 591-596.

Smale, D. A., Brown, K. M., Barnes, K. A., Fraser, K. P., & Clarke, A. (2008). Ice Scour Disturbance in Antarctic Waters. *Science,* 321(5887): 371.

Smith, J. B., Schneider, S. H., Oppenheimer, M., Yohe, G. W., Hare, W., Mastrandrea, M. D., … van Ypersele, J. P. (2008). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) “reasons for concern”. *PNAS,* 106(11): 4133-4137.

Thomas, R., Rignot, E., Cassassa, G., Kanagaratnam, P., Acuña, C., Akins, T., … Zwally, J. (2004). Accelerated Sea-Level Rise from West Antarctica. *Science,* 306(5694): 255-258.

The National Academy of Sciences. (2011). Future Science Opportunities in Antarctica and the Southern Ocean. *Polar Research Board.*

Toggweiler, J. R., & Russell, J. (2008). Ocean circulation in a warming climate. *Nature,* 451: 286-288. doi:10.1038/nature06590.

Wang, Z., Kuhlbrodt, T., & Meredith, M. P. (2011). On the response of the Antarctic Circumpolar Current transport to climate change in coupled climate models. *Journal of Geophysical Research: Oceans,* 116(8). doi:10.1029/2010JC006757.

Zickfeld, K., Fyfe, J. C., Saenko, O. A., Eby, M., & Weaver, A. J. (2007). Response of the global carbon cycle to human-induced changes in the Southern Hemisphere winds. *Geophysical Research Letters*, 34(12). doi:10.1029/2006GL028797.