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Asymmetries in the moisture origin of Antarctic precipitation

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[1] The seasonality of moisture sources for precipitation in Antarctica is studied with a Lagrangian moisture source diagnostic. Moisture origin for precipitation in Antarctica has strongly asymmetric properties, which are related to the Antarctic topography, seasonal sea ice coverage, and the land/ocean contrasts in the mid-latitudes of the southern hemisphere. The highest altitudes of the East Antarctic ice shield, where major ice cores have been drilled, have mean source latitudes of 45–40°S year-round. This finding contrasts to results from previous Lagrangian studies which detected a more southerly moisture origin due to too short trajectories. Now, results from Lagrangian moisture source diagnostics are consistent with findings from general circulation models with tagged tracers. Thus, both approaches can serve as a common benchmark for the interpretation of moisture source indicators based on stable isotopes, such as deuterium excess, in Antarctic ice cores.

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1. Introduction

[2] The interpretation of climatic signals in Antarctic ice cores often relies on stable water isotopes [*Jouzel et al.*, 2003; *Masson-Delmotte et al.*, 2006]. The parameters δ^{18}O and δD reflect the thermal history during the water transport from evaporation source to precipitation area, and can be calibrated as paleo-thermometers [*Lorius et al.*, 1969]. This is possible because the isotopic fractionation during atmospheric transport of water vapor can to first order be described by a (temperature-controlled) Rayleigh distillation process. The initial conditions of this equilibrium fractionation are determined by the location where the moisture evaporated from the ocean surface. Often, the second-order parameter deuterium excess (d-excess) is applied to infer the evaporation conditions of the moisture, and thereby the source itself [*Delmotte et al.*, 2000; *Stenni et al.*, 2001; *Vimeux et al.*, 2001]. *Petit et al.* [1991] for example concluded from a study with a simple isotope box model that moisture sources for Antarctica are on average located at 30–40°S. However, a realistic modelling of processes governing the spatial distribution of d-excess even with isotope-enabled general circulation models (GCMs) still remains a challenge [*Masson-Delmotte et al.*, 2008]. Hence, additional means for determining the moisture origin for Antarctic precipitation are needed.

[3] GCMs with tagged water tracers are one powerful option to determine the moisture origin of Antarctica [*Koster et al.*, 1992; *Delaygue et al.*, 2000; *Werner et al.*, 2001; *Noone and Simmonds*, 2002]. According to GCM studies, moisture sources for the Antarctic land mass are mostly located at mid-latitudes, but also comprise the waters near the sea ice boundary. GCM studies are however limited by, among other biases, the coarse grid resolution which, due to lower orography and larger diffusion, leads to more water transport into the dry interior of Antarctica than observed [*Delaygue et al.*, 2000; *Noone and Simmonds*, 2002].

[4] An alternative approach to determine the moisture origin is to trace air parcels backwards in time, from individual sites [*Reijmer et al.*, 2002; *Schlosser et al.*, 2004; *Suzuki et al.*, 2008] or from the complete Antarctic land mass [*Helsen et al.*, 2007]. These Lagrangian studies consistently point towards moisture sources in the Southern Ocean (south of 50°S), considerably closer to Antarctica than what is derived from GCM studies and stable isotope box models. However, all Lagrangian studies so far have relied on (relatively short) 5-day backward trajectories, and simply considered the back-trajectory end points as the moisture origin.

[5] In order to resolve the discrepancy that currently exists for the different moisture source identification methods, we employ the recently developed Lagrangian moisture source diagnostic of *Sodemann et al.* [2008a] to determine the seasonality of moisture sources for all of Antarctica over a 5-year period. Thereby, we trace water vapor transport for 20 days backward in time, allowing for the identification of long-range moisture transport to Antarctica. Additional advantages of this method are the high spatial resolution at which moisture sources can be diagnosed, the quantitative interpretation of moisture origin, and the use of meteorological analysis data for the calculation.

2. Method and Data

[6] In this study, the Lagrangian moisture source diagnostic of *Sodemann et al.* [2008a] has been applied to air parcel trajectories calculated using the Lagrangian particle transport model FLEXPART [*Stohl et al.*, 2005]. A major advantage of this particular model are the parameterisations for atmospheric turbulence and convection, which increase the total amount of precipitation for which evaporative moisture sources can be identified from this diagnostic. In the boundary layer, Langevin equations for Gaussian turbulence are solved. For moist convective transport, the mass-flux scheme from Emanuel and Zivkovic-Rothman is used. Poleward of 75° latitude FLEXPART advects particles on a polar stereographic projection.

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[7] A global transport simulation with FLEXPART, tracing 1.4 million air parcels, was carried out for the period October 1999 to April 2005. Winds for the transport calculations, as well as specific humidity and temperature at the air parcel locations were derived from the European Centre for Medium-Range Weather Forecast's (ECMWFs) 6-hourly operational analyses. Despite being located in a data-sparse area, ECMWF analyses have been shown to reliably represent the weather over Antarctica [e.g., *Cullather et al.*, 1998]. This study complements the atmospheric transport climatology for Antarctica by *Stohl and Sodemann* [2009] with a view on moisture transport.

[8] The moisture source diagnostic tracks changes in specific humidity (q) along the transport path of air parcels at a 6 h interval. If q increases by the threshold value Δq_c = 0.1 g kg^{-1} 6 h^{-1} or more in an air parcel inside the boundary layer, that moisture increment is attributed to evaporation from the underlying surface area (mostly ocean). All humidity changes lower than Δq_c are considered as random fluctuations and have been excluded from the diagnostic.

[9] Taking the temporal sequence of moisture increases and decreases of an air parcel into account allows for quantitatively estimating each moisture source's contribution to the air parcel's total moisture content, and hence to the precipitation generated from it over Antarctica. In this respect the method is different to the one applied by *Stohl and James* [2004] which diagnoses the joint quantity *E-P* of evaporation (*E*) and precipitation (*P*) rather than separating both quantities. Moisture source contributions are spatially gridded at a 1° × 1° interval for every 6 h time step, and then averaged to monthly and seasonal composite maps.

[10] Precipitation events are identified by selecting situations where the relative humidity with respect to liquid water (below −10°C with respect to ice) exceeds 70%, and where q decreases by at least Δq_c. Since the inland of Antarctica is very cold and dry, actual humidity changes due to precipitation cannot unambiguously be separated from random fluctuations below Δq_c. The diagnostic is therefore biased towards stronger precipitation events at higher latitudes, which however are probably responsible for a large part of total precipitation [*Bromwich*, 1988; *Fujita and Abe*, 2006]. At higher altitudes, an increasing share of the total moisture content is acquired above the boundary layer. Total diagnosed precipitation from the Lagrangian method however agrees reasonably well with forecast ECMWF precipitation and the accumulation maps from *Bromwich* [1988] (not shown). Seasonal mean sea ice cover was constructed from the satellite-based data product of *Comiso* [1990] using monthly data for the years 1999 to 2005.

3. Results

3.1. Moisture Source Region Seasonality

[11] Figure 1 shows seasonal mean maps of moisture source regions for Antarctica during southern hemisphere (SH) summer (DJF, Figure 1a) and winter (JJA, Figure 1b). The shading shows the contribution of local evaporation to precipitation in Antarctica in cm/yr. Figure 1 can be interpreted as the total precipitation in Antarctica during the respective season projected backwards onto the corresponding evaporation sources.

[12] Precipitation in Antarctica (and hence evaporation contribution) is higher during SH winter, corresponding to the higher storminess in the Southern Ocean [*Bromwich*, 1988; *Noone and Simmonds*, 2002]. During both seasons, moisture sources for Antarctic precipitation are distributed annularly in the Southern Ocean, with distinct maxima in the Indian Ocean sector at about 40°S. This corresponds to a maximum of surface wind energy associated with fronts that are related to maxima in cyclone density and baroclinicity further south [*Simmonds et al.*, 2003]. In addition, moisture sources reach well into subtropical latitudes, for example in the Atlantic Ocean during SH summer (Figure 1a), or in the Pacific during SH winter (Figure 1b). An inspection of seasonal mean latent heat flux, surface temperature, and 10 m wind velocity from the ERA-40 Reanalysis data (not shown) indicates that the evaporation contribution maxima in the Indian Ocean and the Pacific sector are associated with maxima in latent heat flux and surface wind velocity.

[13] Noteworthy is the position of the maxima of moisture origin downstream of major land areas. A persistent maximum reaches from the warm waters east of Cape Agulhas southeast of southern Africa into the Indian Ocean. During SH winter, a distinct maximum of moisture origin is present along the Australian south-west coast (Figure 1b). Weaker maxima appear downstream of the southern Andes as well as Tasmania and New Zealand (Figure 1a). In the Pacific sector, moisture sources are distributed more uniformly over a wide range of latitudes. The evaporation contribution maximum off south-west Australia instead appears to be associated with large land-ocean temperature contrasts during SH winter. Moisture evaporating from here is more likely to be transported to Antarctica than average (not shown), indicating preferential N-S transport. The evaporation contribution hot-spots in the lee of New Zealand, Tasmania and southern Chile are at least partly related to anomalously high evaporation at these locations compared to the ERA-40 zonal mean.

[14] The ice edge in the Southern Ocean has a clearly visible influence on the proximity of the moisture origin to Antarctica. In particular during SH winter, the sea ice edge and strong continental katabatic winds [*Stohl and Sodemann*, 2009] impose a clear southern limit to evaporation contributions (Figure 1b, grey line). During summer, the southern moisture source limit is less clear-cut, probably owing to evaporation from leads as the seasonal sea ice retreats (Figure 1a, grey line) as well as weakening katabatic outflow.

3.2. Spatial Distribution of Moisture Origin

[15] Figures 2a and 2b show the spatial distribution of the local moisture source latitude, calculated as a weighted mean from all diagnosed precipitation events. The dominantly blue shading in Figure 2a indicates that during SH summer, the low areas of West Antarctica are on average associated with moisture that evaporated south of ~52°S, corresponding to the minimum in seasonal sea ice extent (Figure 1a, grey line). During the winter season, local moisture source contributions to West Antarctica are shut off due to the expanding sea ice. As a result, the moisture source latitude increases to ~48°S (Figure 2b). In the coastal areas of East Antarctica, moisture sources are on average at latitudes of 46–50°S year round.

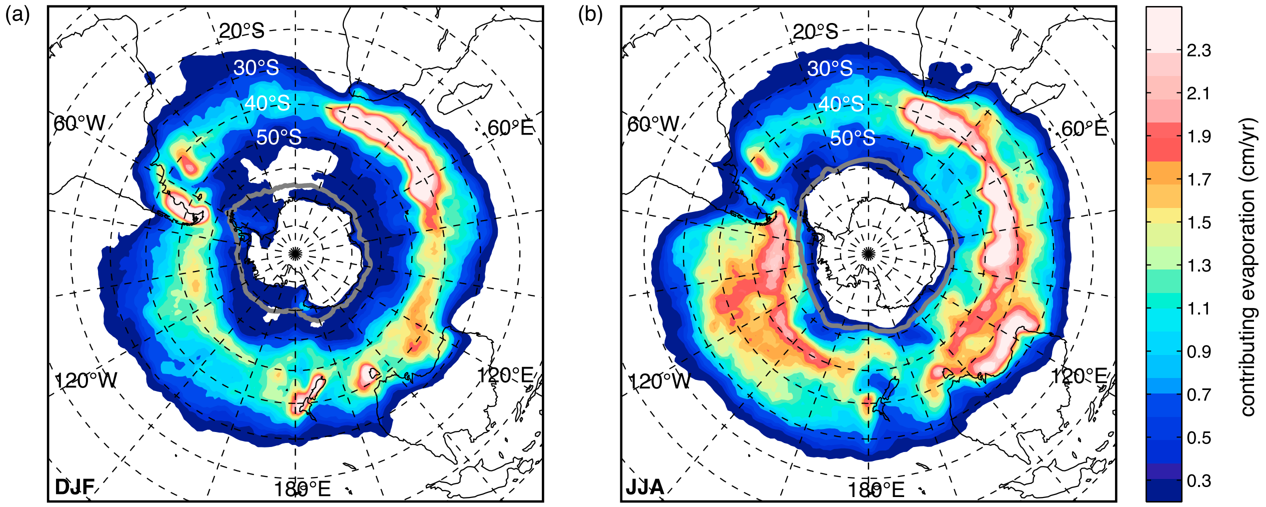

Figure 1. Seasonal mean moisture source regions for Antarctica during (a) summer (DJF) and (b) winter (JJA). Grey line denotes the seasonal mean sea ice boundary.

[16] This is in sharp contrast to the mean moisture source latitudes at higher elevations of (eastern) Antarctica: Areas above ∼2000 m asl (Figures 2a and 2b, contours) have mean moisture source latitudes north of 44°S. Apparently, moisture source latitude is a function of both altitude and distance from the coastline. An interesting anomaly to this general pattern is the decrease to moisture sources at ∼42°S in Victoria Land (150°E) even down to the coast during SH winter. One possible explanation is that this area is associated with the seasonal evaporation contribution maximum south of Australia (Figure 1b).

[17] The finding that moisture sources become more distant from the coastline as one proceeds further into the ice cap may appear somewhat paradoxical at first, but has already been noted in other studies for Antarctica [*Delaygue et al.*, 2000] and Greenland [*Sodemann et al.*, 2008a, 2008b]. Considering isentropic transport towards Antarctica [Stohl and Sodemann 2009, Figure 3] as a first-order estimate for moisture origin supports that due to the slope of the mean isentropes higher Antarctic elevations are linked to the surface of more northerly latitudes. *Noone and Simmonds* [2002] used the Froude number to distinguish air masses that are able to penetrate to higher altitudes from those that will be blocked by the orography. Interestingly, d-excess in Antarctic snow is constant at ∼5 permil below ∼2000 m altitude, and increases to up to ∼18 permil at higher altitudes, indicating different moisture transport processes below and above this altitude threshold [*Masson-Delmotte et al.*, 2008]. This observation agrees with the relatively uniform moisture source latitude distribution in West Antarctica in Figures 2a and 2b. Convective transport could be important to homogenize the moisture origin at lower altitudes.

[18] The spatial distribution of local moisture source longitude does not show an imprint of the orography (Figure 2c). Due to the weak seasonal differences, only the winter mean figure is displayed. Moisture source longitudes are shifted by on average 20–60° westward with respect to a location in Antarctica (Figure 2c, colored ring). Hence, West Antarctica and the Antarctic Peninsula receive moisture from the Pacific sector, Dronning Maud Land (∼0°E) is mainly influenced by moisture sources in the South Atlantic, whereas Queen Mary Land (∼69°E) predominately receives moisture from the Indian Ocean sector. Figure 2c supports also that the moisture source latitude anomaly in Victoria Land (∼150°E) is associated with evaporation off the Australian coast.

3.3. Comparison of Lagrangian and Eulerian Results

[19] In quantitative terms, about 60% of the Antarctic precipitation originate from the latitude band between 30–50°S throughout all seasons, while about 30% evaporate at 50–70°S. The remaining 10% originate from latitudes north of 30°S. In comparison to previous studies, the mid-latitude location of the moisture sources identified here is in agreement with results from tagging GCM studies [*Delaygue et al.*, 2000; *Werner et al.*, 2001; *Noone and Simmonds*, 2002], but in disagreement with previous Lagrangian studies [*Reijmer et al.*, 2002; *Helsen et al.*, 2007]. The reason for this discrepancy is that previous studies relied on rather short 5-day backward trajectories. In a sensitivity experiment, we diagnosed the moisture origin for Antarctica using 5, 10, and 15-day backward trajectories. While 5-day trajectories clearly lead to biased results (only 50% of the total precipitation attributed to a source region), 10 days (∼80% attributed) appears as an acceptable time scale, whereas the differences between 15 and 20 days (∼90% attributed) are small. In particular at higher altitudes, a backward calculation time of more than 10 days appears essential to fully capture long-range moisture transport to Antarctica. Note that there is an increasing degree of uncertainty for longer trajectories, which here is alleviated to some degree by considering a large number of particles.

3.4. Moisture Sources at Ice Core Locations

[20] Figure 2d shows the annual mean moisture source footprints (latitude-longitude range) for five of the major ice-core sites in Antarctica. The precipitation weighted annual mean latitude and longitude for each drilling site has been composited from monthly data in a 100 km radius around each site.

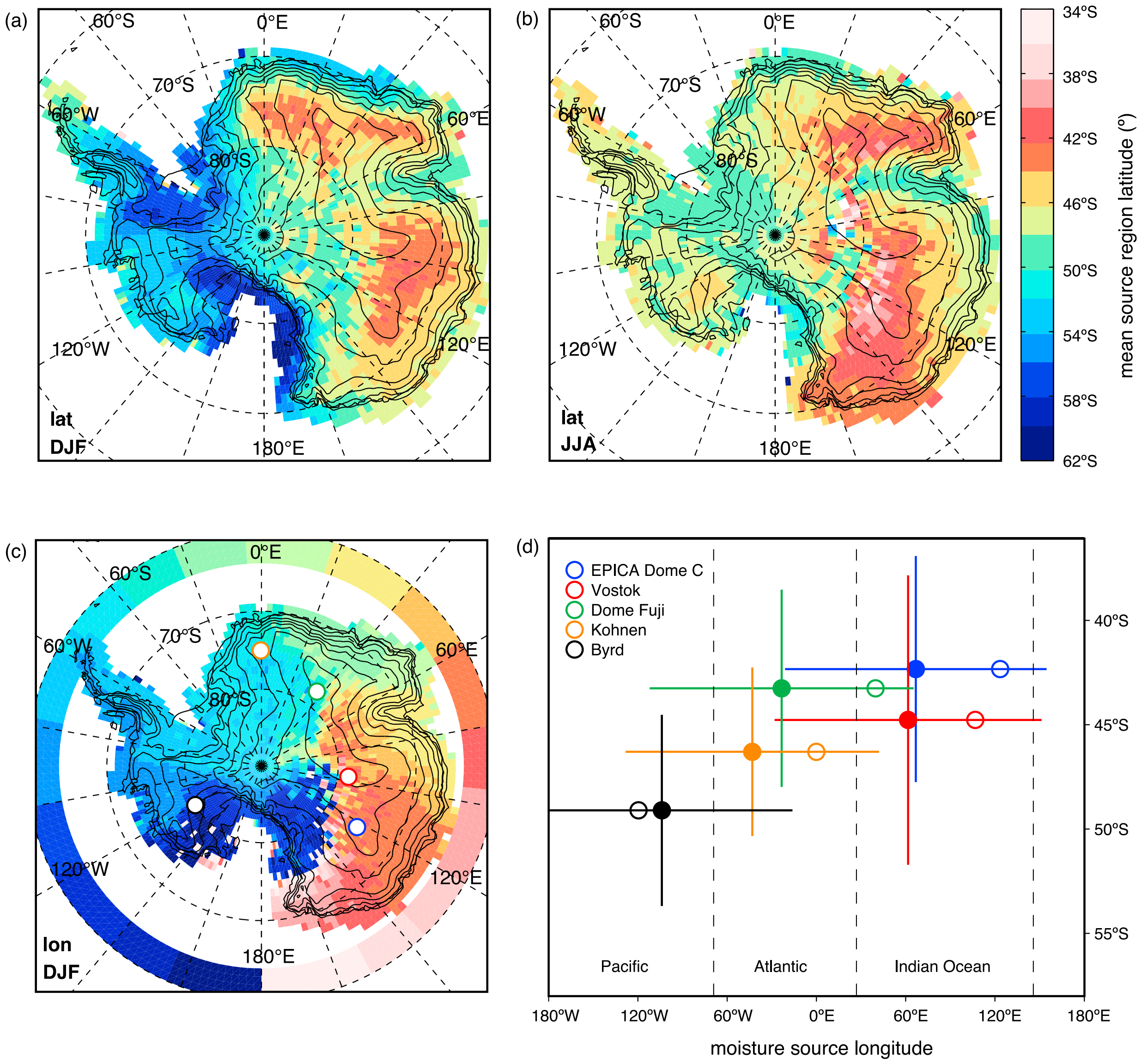

Figure 2. Forward projection of moisture source mean latitude onto Antarctica for (a) summer (DJF) and (b) winter (JJA). Contours denote altitude above sea level according to the ECMWF model orography, contour interval 500 m. (c) Forward projection of moisture source mean longitude onto Antarctica for summer (DJF). (d) Mean moisture source latitude and longitude (solid circles) near the ice core locations EPICA Dome C (123.3°E, 75.1°S), Vostok (106.8°E, 78.5°S), Byrd (119.5°W, 80.0°S), Dome Kohnen (0.1°W, 75.0°S), and Dome Fuji (39.6°E, 77.3°S) and the associated 1-σ standard deviation. Open circles in Figures 2c and 2d denote the respective ice-core longitude.

[21] Remarkable differences exist between the major ice cores: While EPICA Dome C (Figure 2d, blue, 3233 m asl) and Vostok (red, 3488 m asl) have dominant moisture sources in the subtropical and mid-latitude Indian Ocean, Dome Fuji (green, 3810 m asl) is mainly influenced by mid-latitude Pacific and sub-tropical Atlantic moisture. At the new EPICA drilling site Kohnen station (orange, 2892 m asl), moisture originates mainly from the mid-latitude South Atlantic Ocean. The ice core recovered at Byrd polar station (black, 1530 m asl) is one of the few West Antarctic ice cores. Located at lower altitude, Byrd is influenced by more local moisture sources from the Pacific part of the Southern Ocean. Note that the altitude of the drilling site strongly influences the mean latitude of the corresponding moisture source footprint. The longitudinal distance between the moisture source (Figure 2d, solid circles) and the drilling site (open circles) also increases with elevation.

4. Conclusions

[22] The findings of this study with respect to moisture origin in Antarctica differ from previous studies based on trajectories and agree with GCMs and isotope-based source reconstructions. The main reason for the discrepancy with past Lagrangian studies is the use of 5-day backward trajectories, which is insufficient to reveal the actual atmospheric moisture transport characteristics for Antarctica. Hence, Lagrangian and GCM approaches to identify moisture sources now provide consistent results, and serve as a common benchmark for the interpretation of isotopic

signals in Antarctic ice cores by means of simple and complex models.

[23] Our results highlight that moisture origin in Antarctica has strongly asymmetric properties, which are related to the Antarctic topography, seasonal sea ice coverage, baroclinicity, and the land/ocean contrasts in the mid-latitudes of the southern hemisphere. This implies for instance that sea ice seasonality is not equally important in East and West Antarctica.

[24] Antarctic ice cores are mainly influenced by subtropical to mid-latitude moisture due to their high altitude drilling locations, but their moisture sources can be located in different ocean basins. Possibly, this could cause ice cores to reflect lower-latitude climate variability, such as ENSO, differently.

[25] Particularly interesting findings are the increasing distance of moisture origin with increasing elevation only above ∼2000 m asl, which corresponds to surface snow d-excess, and the contribution of local anomalies, such as the seasonal evaporation contribution maximum off south-west Australia, to Antarctic precipitation origin. In future studies it will be insightful to perform a detailed interpretation of d-excess at individual ice core sites, and to examine the spatial coherence of source regions identified here on climatic time scales.

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References

Bromwich, D. H. (1988), Snowfall in high southern latitudes, *Rev. Geophys.*, *26*, 149–168.

Comiso, J. (1990), DMSP SSM/I Daily and Monthly Polar Gridded Bootstrap Sea Ice Concentrations, 1999–2005, edited by J. Maslanik and J. Stroeve, Natl. Snow and Ice Data Cent., Boulder, Colo.

Cullather, R., D. Bromwich, and M. V. Woert (1998), Spatial and temporal variability of Antarctic precipitation from atmospheric methods, *J. Clim.*, *11*, 334–367.

Delaygue, G., V. Masson, J. Jouzel, R. D. Koster, and R. J. Healy (2000), The origin of Antarctic precipitation: A modelling approach, *Tellus, Ser. B*, *52*, 19–36.

Delmotte, M., V. Masson, J. Jouzel, and V. I. Morgan (2000), A seasonal deuterium excess signal at Law Dome, coastal eastern Antarctica: A southern ocean signature, *J. Geophys. Res.*, *105*, 7187–7197.

Fujita, K., and O. Abe (2006), Stable isotopes in daily precipitation at Dome Fuji, East Antarctica, *Geophys. Res. Lett.*, *18*, L18503, doi:10.1029/2006GL026936.

Helsen, M. M., R. S. W. van de Wal, and M. R. V. den Broeke (2007), The isotopic composition of present-day Antarctic snow in a Lagrangian atmospheric simulation, *J. Clim.*, *20*, 739–756.

Jouzel, J., F. Vimeux, N. Caillon, G. Delaygue, G. Hoffmann, V. Masson-Delmotte, and F. Parrenin (2003), Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores, *J. Geophys. Res.*, *108*(D12), 4361, doi:10.1029/2002JD002677.

Koster, R. D., J. Jouzel, R. J. Suozzo, and G. L. Russell (1992), Origin of July Antarctic precipitation and its influence on deuterium content: A GCM analysis, *Clim. Dyn.*, *7*, 195–203.

Lorius, C., L. Merlivat, and R. Hagemann (1969), Variation in the mean deuterium content of precipitations in Antarctica, *J. Geophys. Res.*, *74*, 7027–7031.

Masson-Delmotte, V., et al. (2006), Past temperature reconstructions from deep ice cores: Relevance for future climate change, *Clim. Past*, *2*, 145–165.

Masson-Delmotte, V., et al. (2008), A review of Antarctic surface snow isotopic composition: Observations, atmospheric circulation and isotopic modelling, *J. Clim.*, *21*, 3359–3387.

Noone, D., and I. Simmonds (2002), Annular variations in moisture transport mechanisms and the abundance of δ^{18}O in Antarctic snow, *J. Geophys. Res.*, *107*(D24), 4742, doi:10.1029/2002JD002262.

Petit, J. R., J. W. C. White, N. W. Young, J. Jouzel, and Y. S. Korotkevich (1991), Deuterium excess in recent Antarctic snow, *J. Geophys. Res.*, *96*, 5113–5122.

Reijmer, C. H., M. R. V. den Broeke, and M. P. Scheele (2002), Air parcel trajectories and snowfall related to five deep drilling locations in Antarctica based on the ERA-15 dataset, *J. Clim.*, *15*, 1957–1986.

Schlosser, E., C. Reijmer, H. Oerter, and W. Graf (2004), The influence of precipitation origin on the δ^{18}O-T relationship at Neumayer Station, Ekstromisen, Antarctica, *Ann. Glaciol.*, *39*, 41–48.

Simmonds, I., K. Keay, and E. Lim (2003), Synoptic activity in the seas around Antarctica, *Mon. Weather. Rev.*, *131*, 272–288.

Sodemann, H., C. Schwierz, and H. Wernli (2008a), Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence, *J. Geophys. Res.*, *113*, D03107, doi:10.1029/2007JD008503.

Sodemann, H., V. Masson-Delmotte, C. Schwierz, B. Vinther, and H. Wernli (2008b), Interannual variability of Greenland winter precipitation sources: 2. Effects of North Atlantic Oscillation variability on stable isotopes in precipitation, *J. Geophys. Res.*, *113*, D12111, doi:10.1029/2007JD009416.

Stenni, B., V. Masson-Delmotte, S. Johnsen, J. Jouzel, A. Longinelli, E. Monnin, R. Rothlisberger, and E. Selmo (2001), An oceanic cold reversal during the last deglaciation, *Science*, *293*, 2074–2077.

Stohl, A., and P. James (2004), A Lagrangian analysis of the atmospheric branch of the global water cycle. Part I: Method description, validation, and demonstration for the August 2002 flooding in central Europe, *J. Hydrometeorol.*, *5*, 656–678.

Stohl, A., and H. Sodemann (2009), Characteristics of atmospheric transport into the Antarctic troposphere, *J. Geophys. Res.*, doi:10.1029/2009JD012536, in press.

Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa (2005), Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2, *Atmos. Chem. Phys.*, *5*, 2461–2474.

Suzuki, K., T. Yamanouchi, and H. Motoyama (2008), Moisture transport to Syowa and Dome Fuji stations in Antarctica, *J. Geophys. Res.*, *113*, D24114, doi:10.1029/2008JD009794.

Vimeux, F., V. Masson, G. Delaygue, J. Jouzel, J. R. Petit, and M. Stievenard (2001), A 420,000 year deuterium excess record from East Antarctica: Information on past changes in the origin of precipitation at Vostok, *J. Geophys. Res.*, *106*, 31,863–31,873.

Werner, M., M. Heimann, and G. Hoffman (2001), Isotopic composition and origin of polar precipitation in present and glacial climate simulations, *Tellus, Ser. B*, *53*, 53–71.

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