The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

Analysed and observed moisture transport as a proxy for snow accumulation in East Antarctica

Ambroise Dufour[IGE], Claudine Charrondière[IGE], and Olga Zolina[IGE, IORAS]
[IGE]Institut des Géosciences de l'Environnement, CNRS/UGA, Grenoble, France
[IORAS]P. P. Shirshov Institute of Oceanology, Russian Academy of Science, Moscow, Russia
Correspondence to: Ambroise DUFOUR (ambroise.dufour@univ-grenoble-alpes.fr)

Abstract.

Atmospheric moisture convergence on ice-sheets provides an estimate of snow accumulation which is critical to quantify sea level changes. In the case of East Antarctica, we computed moisture transport from 1980 to 2016 in five reanalyses and in radiosonde observations. Moisture convergence in reanalyses is more consistent than net preciptation but still ranges from 72 to 96 mm per year in the four most recent reanalyses, ERA Interim, NCEP CFSR, JRA 55 and MERRA 2. The representation of long term variability in reanalyses is also inconsistent which justified the resort to observations.

Moisture fluxes are measured on a daily basis via radiosondes launched from a network of stations surrounding East Antarctica. Observations agree with reanalyses on the major role of extreme advection events and transient eddy fluxes. Although assimilated, the observations reveal processes some reanalyses cannot model due to a lack of horizontal and vertical resolution especially the oldest, NCEP DOE R2. Additionally, the observational time series are not affected by new satellite data unlike reanalyses. We formed pan-continental estimates of convergence by aggregating anomalies from all available stations. We found no statistically significant trend neither in moisture convergence nor in precipitable water.

1 Introduction

East Antarctica stores the equivalent of 53.3 m of sea level rise out of the 58.3 for the whole continent (Fretwell et al., 2013). The mass of the ice-sheet decreases when icebergs are calved off the coast and increases when snow accumulates inland. The surface mass balance should become more positive as precipitation increases due to higher humidity (Bengtsson et al., 2011; Palerme et al., 2017) though not as fast as the loss of ice thus leading to net sea-level rise (Collins et al., 2013). However, as we shall see, the additional accumulation has yet to be observed.

The in situ methods to determine snow accumulation are reviewed in Eisen et al. (2008). The most reliable consist in measuring the emergence of stakes on a yearly basis or annual snow layers in firn cores (Favier et al., 2013). To make up for their limited spatial coverage, the ground-based observations can be combined with remote sensing data as in Arthern et al. (2006) or with regional climate models (Monaghan et al., 2006; Agosta et al., 2012). Lately, both satellites and models have been used without the need for surface data : the snowfall measurements from CloudSat (Palerme et al., 2014) and the high resolution calibration-free model of Lenaerts et al. (2012).

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

Not all the aforementioned methods yield accumulation time series. Among those that do, none present statistically significant trends in accumulation on a continental scale e.g. Lenaerts et al. (2012) or Monaghan et al. (2006) for East Antarctica in particular. The situation is more contrasted on a local scale (Fyke et al., 2017) with recent increases in Dronning Maud Land (Boening et al., 2012; Medley et al., 2018) and Law Dome (Van Ommen and Morgan, 2010), mixed trends on the traverse to Dome A (Ding et al., 2015) and none in Adélie Land (Agosta et al., 2012).

The accumulation can also be measured upstream, as moisture blown from the oceans onto the continent. To compute Antarctica's atmospheric moisture budget, one needs vertical wind and moisture fields along its coast including locations with few research stations, like West Antarctica. Reanalyses synthesize historical observations and short term weather forecasts and provide gridded atmospheric fields constrained by observations even in such remote regions (Genthon and Krinner, 1998; Bromwich et al., 2011; Tsukernik and Lynch, 2013). The analyses will shift to accomodate for new observations sources making the interpretation of time series equivocal. This issue was raised in the case of Antarctica by Nicolas and Bromwich (2011) under a telling title : "Precipitation changes in high southern latitudes from global reanalyses: A cautionary tale."

To reduce the ambiguity, we cross-examined the reanalysis moisture transport with the only in situ measurements of humidity and wind - radiosondes - in the footsteps of Connolley and King (1993) and Bromwich et al. (1995). Rather than compute the climatological moisture budget, our contribution will be to investigate the temporal variability of the transport. Radiosoundings cannot provide an independent validation of reanalyses but they will yield more homogeneous time series. Like our predecessors, we restrict ourselves to East Antarctica due to the lack of long-term upper-air measurements in West Antarctica and in the Peninsula.

2 Data and methods

We build upon a similar study in the Arctic (Dufour et al., 2016) and the reanalyses presented herewith. NCEP NCAR was not included due to a well known moisture diffusion problem over Antarctica (Cullather et al., 1998) as well as unrealistic evaporation (Hines et al., 1999). We left out JRA 25 and MERRA 1 because they were not extended up to 2016. Our period of study starts in 1980 to adjust to the new reanalysis from NASA, MERRA 2. Among other things, the data assimilation system from MERRA 1 was improved to take into account data from satellites launched after NOAA-18 (2005) for instance the hyperspectral infrared radiances of EOS Aqua (Gelaro et al., 2017).

The methods to compute the fluxes are described in Dufour (2016) along with the effects of the various approximations (pressure levels, vapour phase only, 200 hPa cutoff), all of which were limited. Trends are considered statistically significant for p-values higher than 95 % on a two-tail Student t-test.

The domain of study is constrained by the location of stations running long term radiosonde programs which restricts us to East Antarctica (Fig. 1). SANAE (east of Neumayer) and Molodeznaja (east of Syowa) had practically no humidity soundings available inside our time window. Inland, the radiosonde program at Vostok Station stopped in 1992 ; it began at Dome C in 2006 only. The boundary between East and West Antarctica is the transect between the Ross and Filchner-Ronne ice sheets. We excluded ice shelves because they do not contribute to sea level rise. We smoothed the boundary to make inward fluxes at

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

stations more representative of their surroundings. The largest gaps are at the boundaries between the Ross and Filchner-Ronne ice shelves and around Dumont d'Urville.

Radiosondes can measure moisture advection directly as it is the product of humidity by the horizontal wind. IGRA 2 provided the sounding data (Durre et al., 2006). We applied climatological checks to the wind and specific humidity variables similar to Dufour et al. (2016). Based on monthly distributions, they exclude values further than three times the interquartile range from the median. Due to the persistence of unrealistic values, we removed the data from Syowa above 400 hPa.

The temporal availability of the soundings after filtering is shown in Figure 2. The temporal sampling is biased against the early eighties and winters. To build time series and compute trends, we only kept the monthly data of a station if it involved at least ten valid soundings per month for at least ten years. As in Dufour et al. (2016), we co-located the gridded reanalysis data with the stations via bi-linear interpolation to compare them with observations. For an observation-based estimate of the East Antarctic surface mass balance, we averaged the station data along the boundary of the ice sheet using trapezoidal integration. Our aim was to investigate trends rather than absolute amounts so we integrated anomalies with respect to each station's monthly climatology as in Jones (1994). We could thus consider the whole 1980-2016 period and not be as affected by the biased temporal and spatial sampling.

The hygrometers on board radiosondes suffer from known biases some of which can be compensated retrospectively (Miloshevich et al., 2004). For instance, at low temperatures, the hygrometer can no longer adjust to sharp variations of humidity, leading to the so-called time-lag bias. Moreover, the default calibration model of the sensor is inaccurate below -20°C ("temperature-dependence error"). Unfortunately, the suggested corrections apply only to specific radiosonde models and require metadata and high resolution vertical data absent from IGRA. However, as we shall see, in Antarctica most of the transport of humidity occurs near the surface, often in warm storm conditions. Finally, solar heating of the sensor also can generate errors which were documented in the case of Antarctica in Rowe et al. (2008) with the help of an Atmospheric Radiance Emitted Interferometer.

3 Assessment of reanalyses

The map of mean moisture convergence in ERA Interim (Fig. 3.a) is broadly similar to the accumulation map of Arthern et al. (2006). The convergence is highest over the Peninusula where the easterlies intersect the orography. The lower altitude of West Antarctica allows moisture advection further inland than in the eastern half. The area stretching from Dome Fuji to Dome C receives less than 20 mm of moisture a year.

Along the coast of East Antarctica and in the Transantarctic Mountains, there are zones of net moisture divergence neighbouring local maxima in excess of 1000 mm per year. In comparison, the accumulation from Arthern et al. (2006) is always positive and peaks at 500 mm equivalent water per year. The important wind contrasts in mountain ranges and outlet glaciers is a likely source of numerical artefacts. Theoretically at least, strong winds erode and sublimate snow which is a genuine cause of moisture divergence but these processes are not represented in most climate models (Amory et al., 2015). However, reanalyses do assimilate moisture profiles and these are known to be affected by blowing snow events (Barral et al., 2014).

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

Generally speaking, the ensemble standard deviation is proportional to the mean convergence, being highest in the Peninsula and along the coast (Fig. 3.b). The inter-dataset spread is disproportionately high in the Transantarctic Mountains and the East Antarctic Plateau. The 100 km scale inhomogeneities on the plateau are due to JRA 55. Neither the precipitation nor the evaporation exhibit these features (not shown). Unlike the other datasets, in JRA 55, evaporation is on average negative (net deposition) above 2000 m.

Given the dispersion between datasets on a local scale, we cannot expect the datasets to converge to a common estimate of convergence on the scale of East Antarctica (Fig. 4.a, magenta bars). This is all the more true for evaporation and precipitation, which are forecasted variables and thus even less constrained by observations (light and dark blue bars, respectively). One issue with reanalyses is the non-closure of their moisture budget, witnessed by the gap between upper and lower bars in Figure 4 (a). The small mismatch in NCEP DOE R2 is illusory, a consequence of its excessively high sublimation (Bromwich et al., 2011). The 4D-Var reanalyses exhibit the smallest residual. For comparison, we also give the breakdown of the moisture budget in the case of the whole continent (still excluding ice-shelves). West Antarctica and the Peninsula are more exposed to moisture fluxes and indeed the convergence is higher for the whole continent. The ranking between reanalyses remains the same.

The interannual variability in reanalyses are doubtful due to the discontinuities introduced by changes in the observation system (Bengtsson et al., 2004). This is especially the case in Antarctica where analyses rely heavily on satellite data as opposed to conventional observations (Nicolas and Bromwich, 2011). The changes in the components of the moisture budget over time are summarized as linear trends in Figure 4 (b). Generally speaking, the trends are weak and inconsistent. Precipitable water has not significantly changed in the modern reanalyses yet it is the purported mechanism for the future increase in moisture fluxes.

4 Comparison with observations

The coastal profile in the upper panel of Figure 5 was built by interpolating the mean moisture flux field on the smoothed boundary of the East Antarctic ice sheet (lower panel). Overall, the moisture transports are positive over East Antarctica with occasional negative values in valleys where the katabatic winds are channelled e.g. on the Amery ice shelf (70°E). NCEP DOE R2 is oblivious to these local effects and is frequently outside of the ensemble envelope. On the other hand, NCEP CFSR, whose spectral resolution is the highest (T382), shows stronger offshore fluxes at these locations than ERA Interim, MERRA 2 and JRA 55.

Above the launch sites, the reanalysis profiles can be compared with the radiosoundings (black stars in Fig. 5). The observations are within the plus or minus one standard deviation envelope. In several cases (Syowa, Mawson, Casey), the presence of the radiosounding coincides with an extremum in the reanalysis profile, perhaps a deviation to accomodate for the observation. The reanalysis climatology is built on six hourly data whereas there are two radiosoundings a day at the very best with extensive gaps in the data. To correct the sampling bias, we now only consider the reanalysis timesteps that coincide with a radiosounding and we interpolate the reanalyses on the launch location (only relevant for South Pole Station which is not on the domain boundary). The resulting time averages are shown as dots in Figure 5. As expected, there is a gap between profiles

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

and dots at South Pole Station, a measure of the sampling bias. Same goes for Mirniyj as well as Novolazarevskaja in the case of NCEP CFSR. Otherwise, the subsampled reanalyses are quite representative of the year-round values including the summer-only data at Mario Zuchelli Station surprisingly.

This is likely a coincidence : the annual cycle of moisture convergence experiences a twofold increase during the austral winter (Fig. 6.a). In the Southern Hemisphere, the lower winter humidity is more than compensated by the stronger storm activity (Oshima and Yamazaki, 2006). NCEP DOE R2 has a much weaker convergence cycle perhaps due to the unrealistic evaporation in summer. When the reanalyses are interpolated on the stations and masked in time to match the radiosonde launches, the annual cycle is quite different (Fig. 6.b). The transition from summer to winter is no longer as sharp in most datasets and it is altogether absent from NCEP DOE R2 and IGRA.

In the vertical, the moisture flux profiles demonstrate two different regimes (Fig. 7, a). In most datasets including observations, the transport changes sign around 900 hPa : into the continent above and away from it below. The level of the transition is higher in ERA Interim (850 hPa) and higher still in NCEP DOE R2 (750-700 hPa). Both datasets have stronger surface fluxes. The surface fluxes are weaker above stations (solid lines) than in the continental average (dashed lines).

The interdataset spread also increases near the surface in the case of humidity (Fig. 7, b). The IGRA observations exhibit a shallow inversion only present in MERRA 2 and JRA 55 but at a much higher altitude. There is practically no wind on average in altitude but below 800 hPa the prevailing winds blow out from the ice-sheet. This is the signature of katabatic flows. There is quite a difference between the reanalyses both sampled in time and interpolated in space and the originals. We suggest that the stations are not representative of their surroundings because they were generally built in places sheltered from the winds. Only the high resolution datasets can represent both the katabatic outflow and the relative haven of the station. What's more, the radiosonde launch is more likely to be cancelled or the balloon lost during a strong katabatic event which biases the observations against these conditions.

Due to the correlation between wind and humidity, the mean moisture flux ($\overline{q\mathbf{v}}$) is more than the product of the mean wind ($\bar{\mathbf{v}}$) and the mean humidity ($\bar{q}$). The residual is the transient eddy term of the Reynolds decomposition : $\overline{q'\mathbf{v}'} = \overline{q\mathbf{v}} - \bar{q}\bar{\mathbf{v}}$. Two mechanisms should show up under this term : the previously mentioned katabatic conditions and extratropical cyclones. The former involves exceptionally strong downslope wind along with exceptionally dry air from the plateau. In the latter case, the cyclone's warm sector advects exceptionally moist air inland and vice-versa in its cold sector. The sum of these two phenomena fits with panel (d) of Figure 7.

We finish the intercomparison with the statistical distributions of vertically integrated moisture transport, both in the non-sampled and sub-sampled cases (Fig. 8, a and b). The positive (inward) transport dominates, particularly the last decile but the negative (outgoing) fluxes are nonetheless important : more than a third of the absolute transport. The inter-dataset variability is as strong for the positive and the negative transport, highlighting once more the role of katabatic winds. In the sub-sampled case, the observations fall within the reanalysis enveloppe but the inter-dataset variability is also greater.

To sum up, radiosondes and reanalyses diverge in narrow valleys and near the ground especially for low resolutions models. Otherwise, since radiosondes are assimilated into reanalyses, the difference between the two is predictably small. The added value of radiosondes is the study of time series.

5 Interannual variability

Time series from reanalyses reflect modifications to the observation system in addition to changes in the climate. The radiosonde record also has its homogeneity issues e.g. when instruments are upgraded. These events are recorded in the IGRA2 metadata and we found no association with discontinuities in the times series. We will therefore interpret sudden divergences between observations and reanalyses as artefacts of the data assimilation. From Figure 9, the most conspicuous ones are in NCEP DOE R2 followed by JRA 55 but they do not take the form of the shifts we would expect with, say, the introduction of a new satellite. Rather, anomalies are amplified intermittently compared to observations or one reanalysis departs for several years from the ensemble. At Amundsen Scott Station (South Pole), observations exhibit variations of higher amplitude than the reanalyses. The extreme climate in our only inland station must have been a test to both measurements and reanalyses.

We now examine the long term evolution of moisture transport in terms of linear trends, this time analysed along the horizontal dimension (Fig. 10). Most longitudes show no statistically significant change in the advection. Among those that do, even fewer display an agreement between datasets. Mirniy station and its surroundings to the east has seen less moisture travelling inland according to observations, NCEP CFSR and MERRA 2. The other reanalyses agree in sign but not in significance. There has been a similar decrease over the Amery ice shelf in between Davis and Mawson stations. The radiosondes and the interpolated reanalyses at Mawson station present an opposite trend which is greater in magnitude than the un-interpolated reanalyses indicating a sampling bias. This increase evokes the accumulation measurements of Ding et al. (2015) on the eastern side of the nearby Lambert Glacier but it is unrelated : the timing of the rise is off by a decade. Radiosondes at Syowa station report an increase of the onshore moisture flux stronger than the reanalyses. Syowa station is located at the edge of the domain surrounding Kohnen station identified in Boening et al. (2012) and where ice cores have revealed a similar increase in accumulation. In Adélie Land, trends are incoherent in sign. The positive trend in radiosondes is not significantly different from zero, in line with the findings of Agosta et al. (2012). Van Ommen and Morgan (2010) recorded anomalous precipitation at Law Dome that peaked in the mid-1970s before returning to normal by the turn of the century but there is no trace of this trend in the observed transport at the nearby station of Casey.

At the scale of the ice-sheet, we know from Figure 4 that the transport series from reanalyses will be offset by up to 30 mm year^{-1} and that they will present contradictory trends. In Figure 11 (a), ERA Interim, JRA 55 and MERRA 2 are grouped together especially after 2000. NCEP DOE R2 is once again the outlier. It is the only dataset not to peak in 1980. Surprisingly, NCEP CFSR diverges from the other modern reanalyses in the 1980s.

When we restrict the reanalyses to the locations and times of radisonde launches, they display a more consistent behaviour (Fig. 11, b) : a downward trend in the 1980s and an upward trend in the two following decades. Observations follow the same pattern with comparatively higher fluxes in the 1980s and 2000s. During the same period, precipitable water above the launch sites has remained constant both in observations and analyses (not shown). The interdecadal pattern in transport is therefore a consequence of variable winds rather than thermodynamics.

6 Conclusions

We have compared moisture transport to Antarctica in five reanalyses and over the 1980-2016 period. For East Antarctica, estimates of moisture convergence range from 65 to 96 mm per year and net precipitation from 60 to 123 mm per year (respectively 72-96 and 91-123 mm per year when excluding NCEP DOE R2). The sign of the linear trend for moisture convergence is not consistent. In any case, changes are not driven by precipitable water increases.

The scarce situ observations and the unreliable satellite observations (Bouchard et al., 2010) make Antarctica a fitting object of study for reanalyses. The differences we found between the datasets remind their familiar limitations : model dependence in the absence of observations and unreliable time series (Bromwich et al., 2011; Nicolas and Bromwich, 2011). Additionally, the non-closure of their atmospheric hydrological budget is an issue to estimate accumulation over the ice-sheet. Fortunately, the gap between moisture convergence and net precipitation is reduced by 4D-Var assimilation.

Although radiosondes are assimilated by reanalyses, lower resolution models have difficulties to take into account observations near the surface and on irregular terrain. This is relevant to represent the humidity inversion and how valleys funnel moisture offshore during katabatic events. Most of the moisture transport inland occurs above 950 hPa as transient eddy fluxes and in winter. This consistently represented in all but the oldest reanlysis.

Changes in the observing system confounds the interpretation of temporal variability in reanalyses. At the cost of spatial coverage, the original observations provide homogeneous time series that can be used as a proxy for accumulation. The seasonal resolution of stake farms and ice cores is not enough to study short and intense accumulation events such as described in Gorodetskaya et al. (2014) but radiosondes are launched on a daily basis. The distribution of moisture transport highlights both positive and negative extreme events. Regarding exports, the conflation of net precipitation with accumulation ignores post-deposition processes in particular blowing snow which has a net negative effect on the Antarctic surface mass balance.

On the long term and averaged over all the selected East Antarctic stations, there has been no statistically significant increase in neither incoming moisture nor precipitable water. In contrast, surface temperature trends are much stronger in West Antarctica and the Peninsula (Steig et al., 2009) with probable consequences on the moisture budget. It remains to be seen whether the limited radiosonde data in these regions can provide corresponding evidence.

Acknowledgements. The reanalysis datasets were available by courtesy of ECMWF, NASA, NCEP and JMA. The IGRA sounding data were made available by the NOAA National Centers for Environmental Information (NCEI). This work was supported by the project "Mechanisms of moisture advection in high latitudes in the present and future climate" funded by CNRS, IGE and UGA and partly through the BELMONT Forum Fund ARCTIC-ERA project funded by ANR. OZ also benefited from the project 14.613.21.0083 (ID RFMEFI61317X0083) funded by the Ministry of Education and Science of Russia. Finally, we thank the Météo France team during the 2014 winter-over at Dumont d'Urville for sharing their field experience and particularly Didier Lacoste for investigating the station's present weather archives on our behalf.

References

Agosta, C., Favier, V., Genthon, C., Gallée, H., Krinner, G., Lenaerts, J. T., and van den Broeke, M. R.: A 40-year accumulation dataset for Adelie Land, Antarctica and its application for model validation, Climate dynamics, 38, 75–86, 2012.

Amory, C., Trouvilliez, A., Gallée, H., Favier, V., Naaim-Bouvet, F., Genthon, C., Agosta, C., Piard, L., and Bellot, H.: Comparison between observed and simulated aeolian snow mass fluxes in Adélie Land, East Antarctica, The Cryosphere Discussions, pp. 1373–1383, 2015.

Arthern, R. J., Winebrenner, D. P., and Vaughan, D. G.: Antarctic snow accumulation mapped using polarization of 4.3-cm wavelength microwave emission, Journal of Geophysical Research: Atmospheres, 111, 2006.

Barral, H., Genthon, C., Trouvilliez, A., Brun, C., and Amory, C.: Blowing snow in coastal Adélie Land, Antarctica: three atmospheric-moisture issues, The Cryosphere, 8, 1905–1919, 2014.

Bengtsson, L., Hagemann, S., and Hodges, K. I.: Can climate trends be calculated from reanalysis data?, Journal of Geophysical Research: Atmospheres (1984–2012), 109, 2004.

Bengtsson, L., Hodges, K. I., Koumoutsaris, S., Zahn, M., and Keenlyside, N.: The changing atmospheric water cycle in polar regions in a warmer climate, Tellus A, 63, 907–920, 2011.

Boening, C., Lebsock, M., Landerer, F., and Stephens, G.: Snowfall-driven mass change on the East Antarctic Ice Sheet, Geophysical Research Letters, 39, 2012.

Bouchard, A., Rabier, F., Guidard, V., and Karbou, F.: Enhancements of satellite data assimilation over Antarctica, Monthly Weather Review, 138, 2149–2173, 2010.

Bromwich, D. H., Robasky, F. M., Cullather, R. I., and Van Woert, M. L.: The atmospheric hydrologic cycle over the Southern Ocean and Antarctica from operational numerical analyses, Monthly Weather Review, 123, 3518–3538, 1995.

Bromwich, D. H., Nicolas, J. P., and Monaghan, A. J.: An Assessment of Precipitation Changes over Antarctica and the Southern Ocean since 1989 in Contemporary Global Reanalyses*, Journal of Climate, 24, 4189–4209, 2011.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A., and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, book section 12, p. 1029–1136, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Connolley, W. and King, J.: Atmospheric water-vapour transport to Antarctica inferred from radiosonde data, Quarterly Journal of the Royal Meteorological Society, 119, 325–342, 1993.

Cullather, R. I., Bromwich, D. H., and Van Woert, M. L.: Spatial and Temporal Variability of Antarctic Precipitation from Atmospheric Methods*, Journal of Climate, 11, 334–367, 1998.

Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, P., et al.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, 2011.

Ding, M., Xiao, C., Li, C., Qin, D., Jin, B., Shi, G., Xie, A., and Cui, X.: Surface mass balance and its climate significance from the coast to Dome A, East Antarctica, Science China Earth Sciences, 58, 1787–1797, 2015.

Dufour, A.: Transport de vapeur d'eau vers les hautes latitudes : Mécanismes et variabilité d'après réanalyses et radiosondages, Ph.D. thesis, Grenoble Alpes, 2016.

Dufour, A., Zolina, O., and Gulev, S. K.: Atmospheric Moisture Transport to the Arctic: Assessment of Reanalyses and Analysis of Transport Components, Journal of Climate, 29, 5061–5081, 2016.

Durre, I., Vose, R. S., and Wuertz, D. B.: Overview of the Integrated Global Radiosonde Archive, Journal of Climate, 19, 53–68, 2006.

Ebita, A., Kobayashi, S., Ota, Y., Moriya, M., Kumabe, R., Onogi, K., Harada, Y., Yasui, S., Miyaoka, K., Takahashi, K., et al.: The Japanese 55-year reanalysis "JRA-55": an interim report, Sola, 7, 149–152, 2011.

Eisen, O., Frezzotti, M., Genthon, C., Isaksson, E., Magand, O., van den Broeke, M. R., Dixon, D. A., Ekaykin, A., Holmlund, P., Kameda, T., et al.: Ground-based measurements of spatial and temporal variability of snow accumulation in East Antarctica, Reviews of Geophysics, 46, 2008.

Favier, V., Agosta, C., Parouty, S., Durand, G., Delaygue, G., Gallée, H., Drouet, A.-S., Trouvilliez, A., and Krinner, G.: An updated and quality controlled surface mass balance dataset for Antarctica, Cryosphere, 7, p–583, 2013.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J., Barrand, N., Bell, R., Bianchi, C., Bingham, R., Blankenship, D., Casassa, G., et al.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 2013.

Fyke, J., Lenaerts, J. T., and Wang, H.: Basin-scale heterogeneity in Antarctic precipitation and its impact on surface mass variability, The Cryosphere, 11, 2595, 2017.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C., Darmenov, A., Bosilovich, M. G., Reichle, R., et al.: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Journal of Climate, 2017.

Genthon, C. and Krinner, G.: Convergence and disposal of energy and moisture on the Antarctic polar cap from ECMWF reanalyses and forecasts, Journal of climate, 11, 1703–1716, 1998.

Gorodetskaya, I. V., Tsukernik, M., Claes, K., Ralph, M. F., Neff, W. D., and Van Lipzig, N. P.: The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, Geophysical Research Letters, 41, 6199–6206, 2014.

Hines, K. M., Grumbine, R. W., Bromwich, D. H., and Cullather, R. I.: Surface Energy Balance of the NCEP MRF and NCEP-NCAR Reanalysis in Antarctic Latitudes during FROST*, Weather and forecasting, 14, 851–866, 1999.

Jones, P. D.: Hemispheric surface air temperature variations: a reanalysis and an update to 1993, Journal of Climate, 7, 1794–1802, 1994.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J., Fiorino, M., and Potter, G.: NCEP-DOE AMIP-II Reanalysis (R-2), Bulletin of the American Meteorological Society, 83, 1631–1643, 2002.

King, J. C. and Turner, J.: Antarctic meteorology and climatology, Cambridge University Press, 2007.

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., et al.: The JRA-55 reanalysis: general specifications and basic characteristics, Journal of the Meteorological Society of Japan. Ser. II., 93, 5–48, 2015.

Lenaerts, J., Den Broeke, M., Berg, W., Meijgaard, E. v., and Kuipers Munneke, P.: A new, high-resolution surface mass balance map of Antarctica (1979–2010) based on regional atmospheric climate modeling, Geophysical Research Letters, 39, 2012.

Medley, B., McConnell, J., Neumann, T., Reijmer, C., Chellman, N., Sigl, M., and Kipfstuhl, S.: Temperature and snowfall in western Queen Maud Land increasing faster than climate model projections, Geophysical Research Letters, 45, 1472–1480, 2018.

Miloshevich, L. M., Paukkunen, A., Vömel, H., and Oltmans, S. J.: Development and validation of a time-lag correction for Vaisala radiosonde humidity measurements, Journal of Atmospheric and Oceanic Technology, 21, 1305–1327, 2004.

Monaghan, A. J., Bromwich, D. H., Fogt, R. L., Wang, S.-H., Mayewski, P. A., Dixon, D. A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., et al.: Insignificant change in Antarctic snowfall since the International Geophysical Year, Science, 313, 827–831, 2006.

Nicolas, J. P. and Bromwich, D. H.: Precipitation changes in high southern latitudes from global reanalyses: A cautionary tale, Surveys in geophysics, 32, 475–494, 2011.

Oshima, K. and Yamazaki, K.: Difference in seasonal variation of net precipitation between the Arctic and Antarctic regions, Geophysical research letters, 33, 2006.

Palerme, C., Kay, J., Genthon, C., L'Ecuyer, T., Wood, N., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577–1587, 2014.

Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, Climate Dynamics, 48, 225–239, 2017.

Rowe, P. M., Miloshevich, L. M., Turner, D. D., and Walden, V. P.: Dry bias in Vaisala RS90 radiosonde humidity profiles over Antarctica, Journal of Atmospheric and Oceanic Technology, 25, 1529–1541, 2008.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., et al.: The NCEP Climate Forecast System Reanalysis, Bulletin of the American Meteorological Society, 91, 1015–1057, 2010.

Steig, E. J., Schneider, D. P., Rutherford, S. D., Mann, M. E., Comiso, J. C., and Shindell, D. T.: Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year, Nature, 457, 459–462, 2009.

Tsukernik, M. and Lynch, A. H.: Atmospheric meridional moisture flux over the Southern Ocean: A story of the Amundsen Sea, Journal of Climate, 26, 8055–8064, 2013.

Van Ommen, T. D. and Morgan, V.: Snowfall increase in coastal East Antarctica linked with Southwest Western Australian drought, Nature Geoscience, 3, 267–272, 2010.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

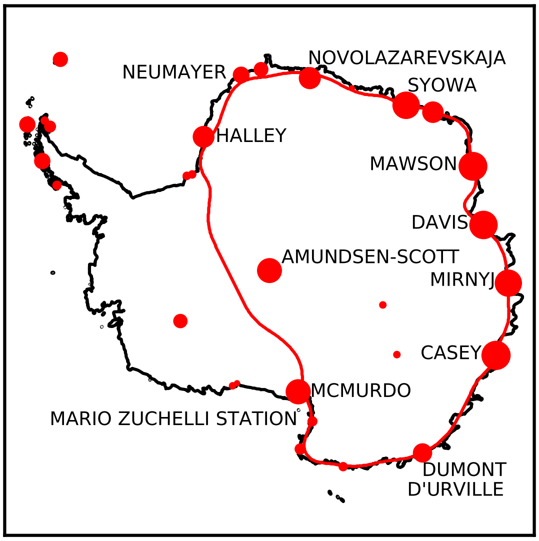

Figure 1. Location of the radiosonde launch sites and boundary of the East Antarctic ice-sheet. The diameter of the dots is proportional to the number of archived soundings (maximum is Casey with 39 000 soundings between 1957 and 2016). Only the sites selected for the study are labelled.

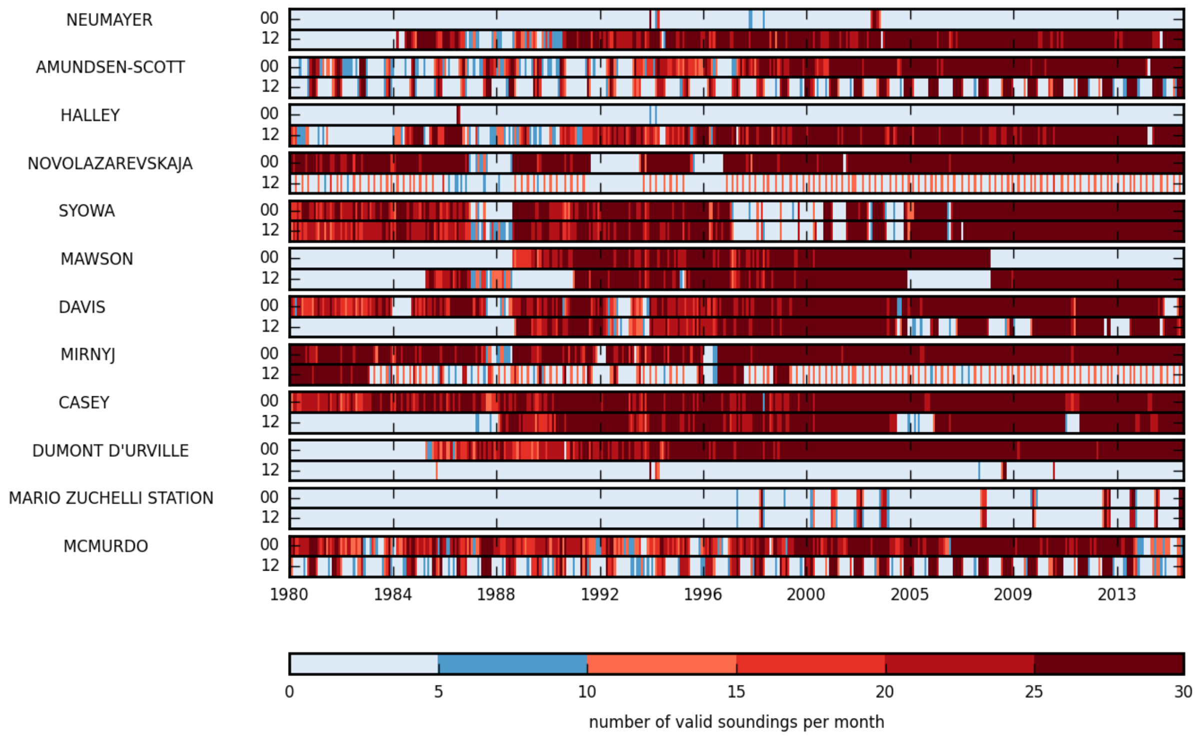

Figure 2. Monthly density of valid humidity and wind soundings per station and per synoptic time (midnight and noon GMT)

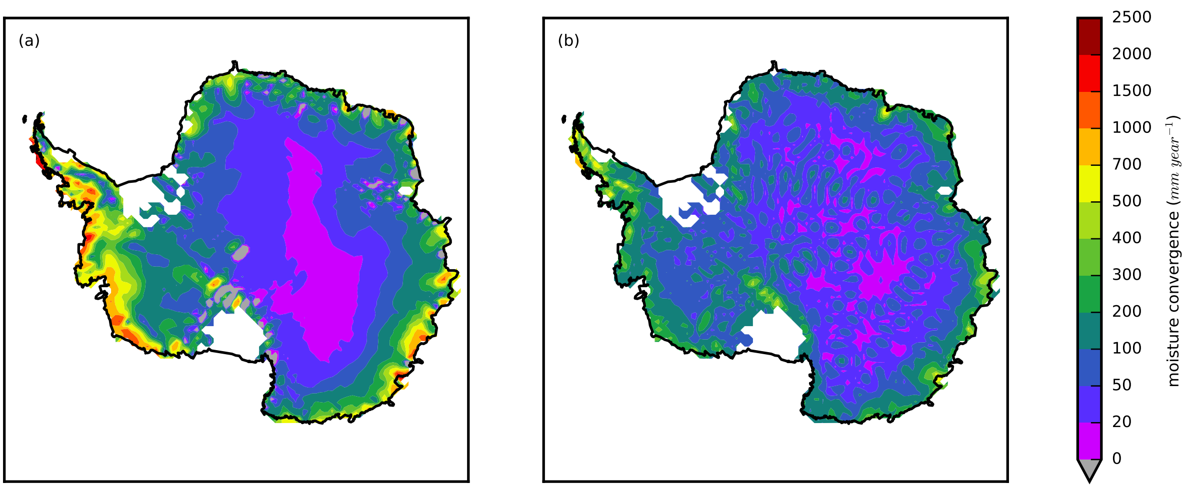

Figure 3. Mean vertically integrated moisture flux convergence over Antarctica in ERA Interim (a) and the standard deviation of that variable for all the studied reanalyses (b).

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

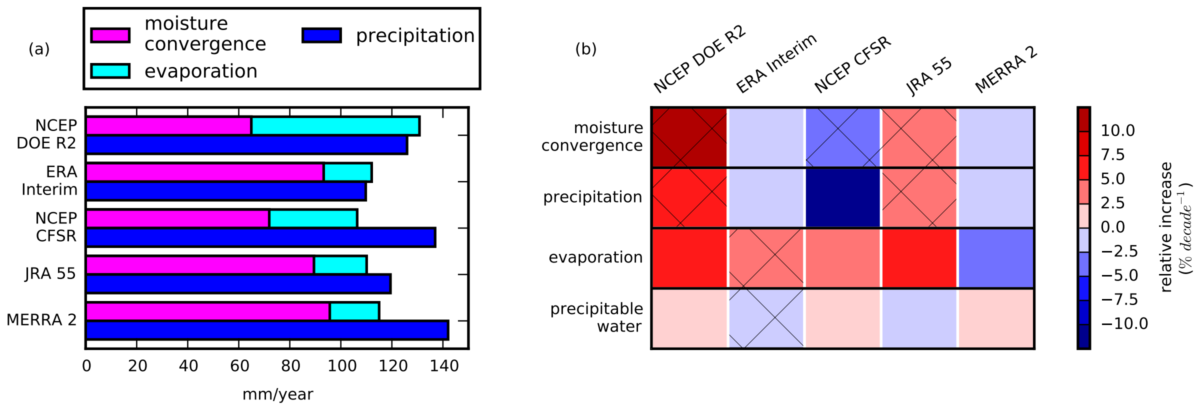

Figure 4. Magnitude of the long-term averaged (1979-2016) atmospheric moisture budget terms of the East Antarctic ice sheet (a). Linear trends of the moisture budget terms (b) : colour indicates rate of change and hatches statistical significance.

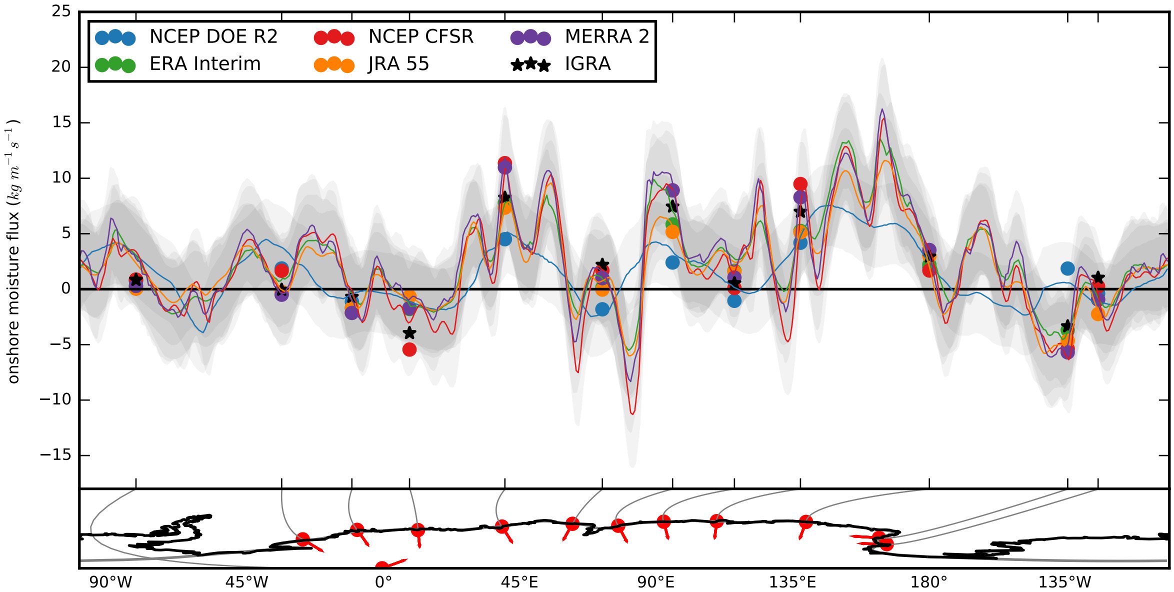

Figure 5. Distribution of the mean incoming vertically integrated moisture flux on the boundary of the Antarctic ice sheet in different reanalyses. The grey shaded bands indicate the ranges corresponding to plus or minus one interannual standard deviation from the mean. Stars represent the radiosonde and dots the reanalyses interpolated over the launch sites and with the same temporal sampling as the observations. The red dots in the lower panel indicate the location of the sites and the arrows the direction normal to the boundary.

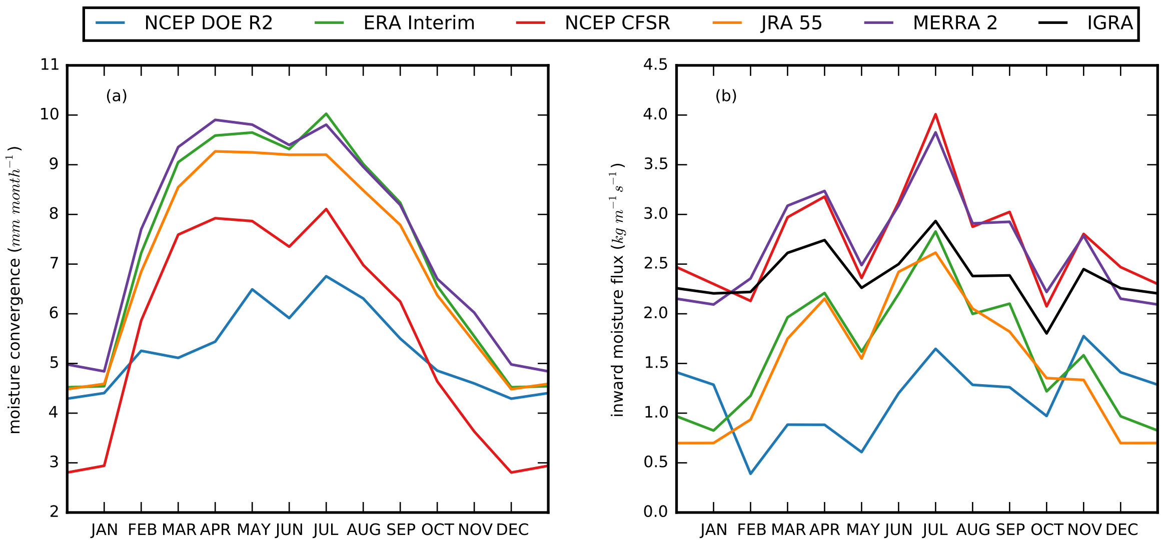

Figure 6. Annual cycle of moisture transport into East Antarctica : (a) computed from reanalyses averaged over East Antarctica (b) observations and reanalyses (with the same spatial and temporal sampling) averaged over all stations

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

The Cryosphere
Discussions
Open Access

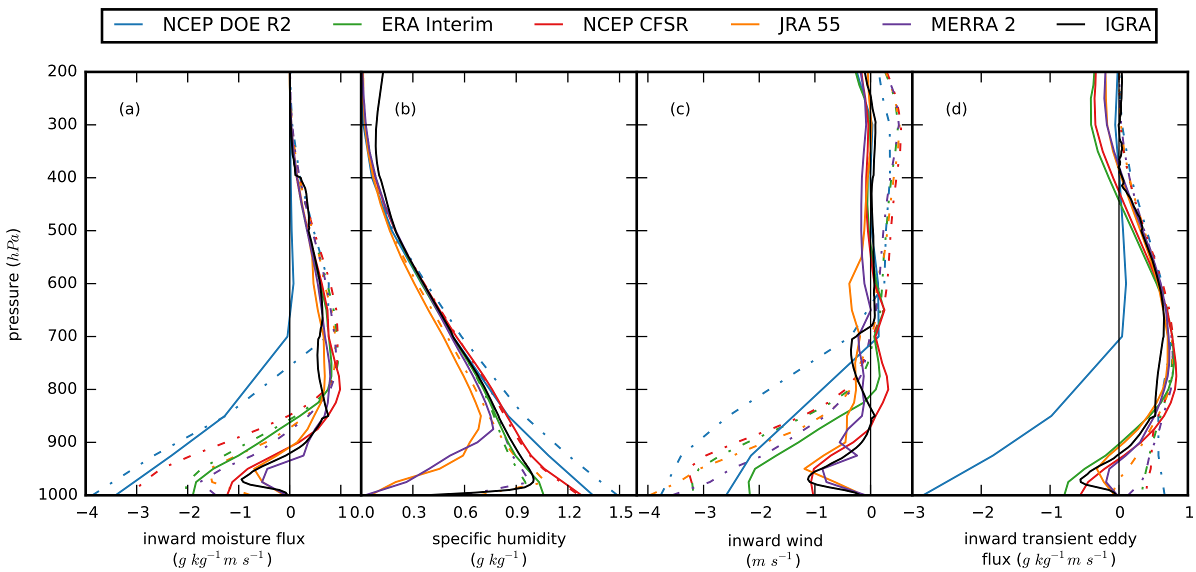

Figure 7. Mean vertical profiles : over radiosonde sites, simultaneously with observations (solid lines) ; along the coast of the East Antarctic ice sheet for the whole 1980-2016 period (dashed lines). The variables displayed in the panels are : moisture flux (a), specific humidity (b), mean wind (c) and transient eddy fluxes (d).

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

The Cryosphere Discussions
Open Access

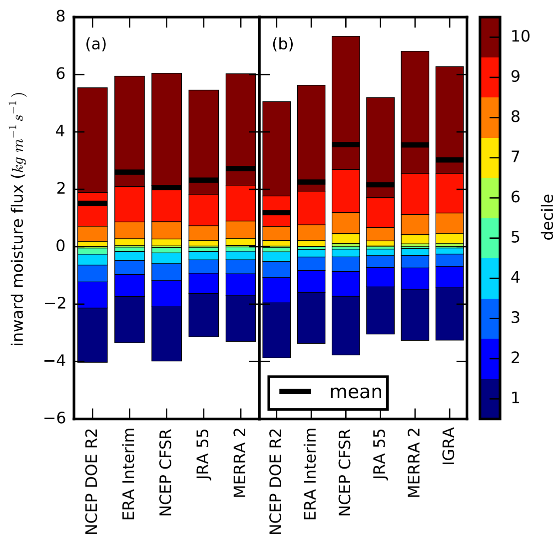

Figure 8. Breakdown of the climatological vertically integrated moisture flux into the contribution of its different deciles. When a decile is represented below the origin, its contribution is negative. The top of the bar indicates the mean transport when negative values are set to zero. The difference between the top and bottom is the mean transport, symbolised by the bold black line. In panel (a), the flux deciles are averaged over the East Antarctic boundary whereas in panel (b) the deciles are computed by aggregating the data over stations only with the same temporal sampling as IGRA.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

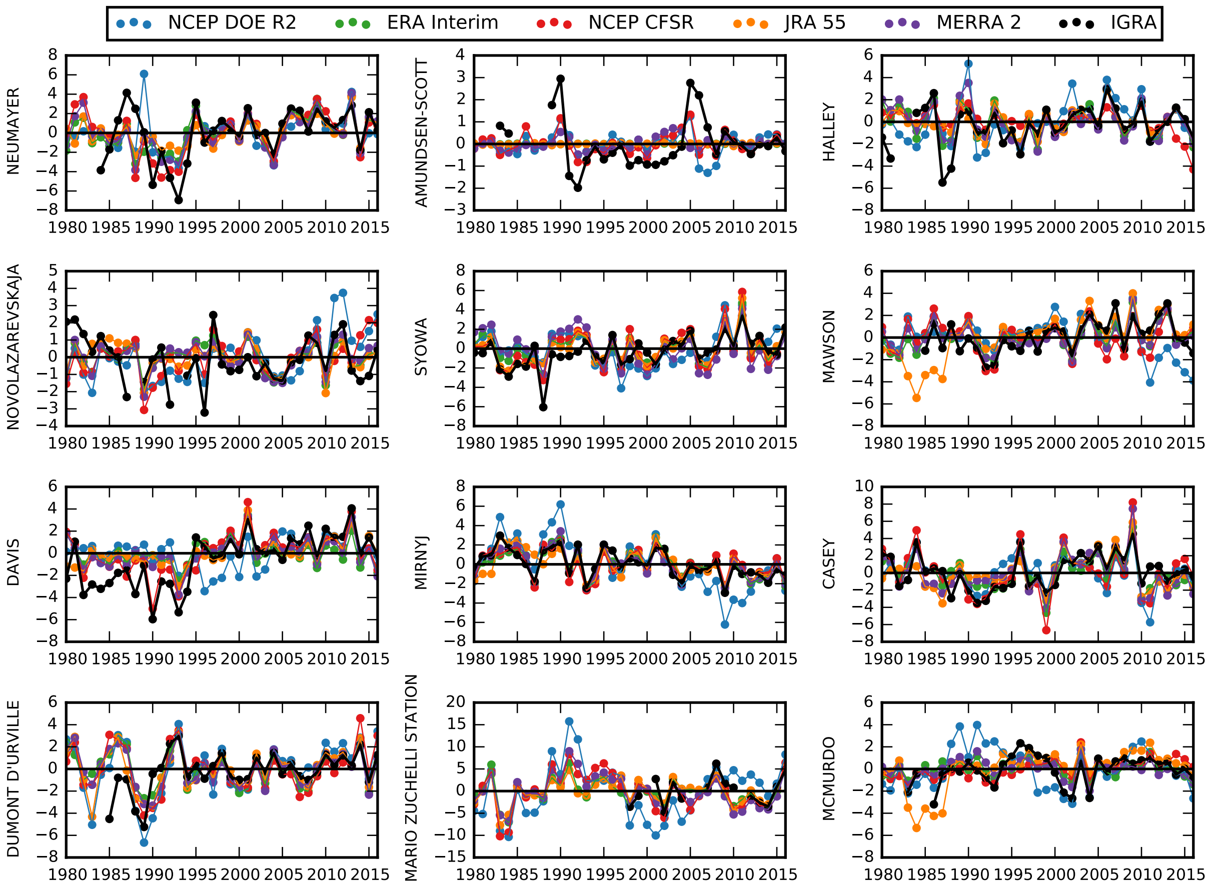

Figure 9. Time series of vertically integrated moisture transport anomalies into East Antarctica (in kg $m^{-1}s^{-1}$) at the location of the selected stations in observations and reanalyses.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

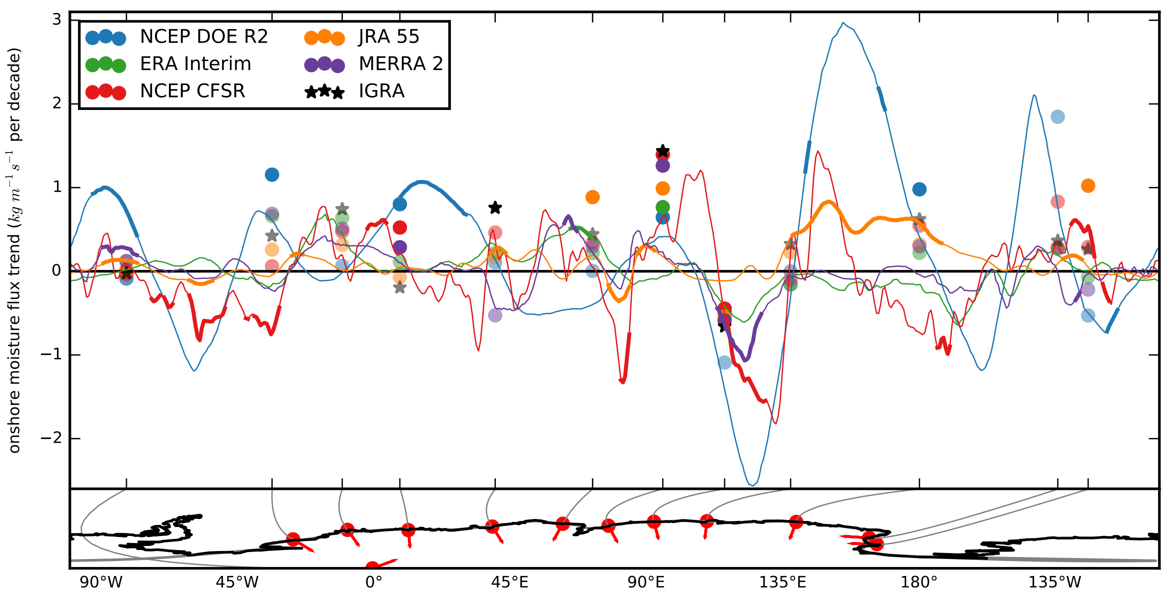

Figure 10. Linear trends of vertically integrated moisture transport into East Antarctica. The profiles are built from reanalyses over the 1980-2016 period interpolated along the domain boundary whereas the dots are computed from reanalyses with the same temporal sampling as the observations. The stars correspond to trends computed from observations. The bold sections of the profiles and the solid dots and stars indicate statistically significant changes.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-156
Manuscript under review for journal The Cryosphere
Discussion started: 27 August 2018

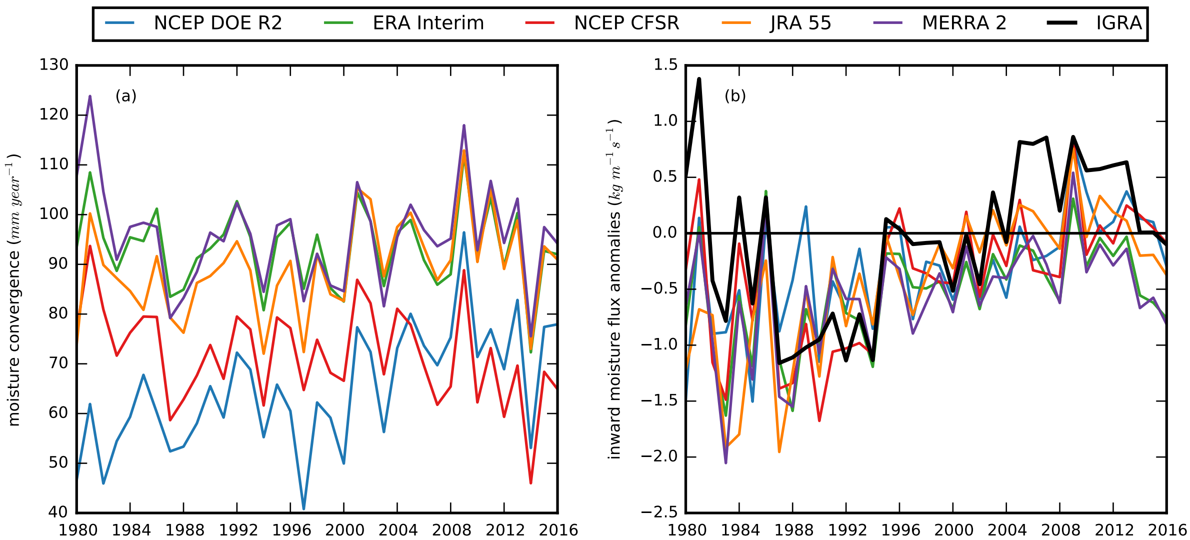

Figure 11. Time series of transport into East Antarctica : (a) absolute amounts computed from reanalyses averaged over the domain boundary (b) anomalies of observations and reanalyses (with the same spatial and temporal sampling) averaged over all stations

Reanalysis	reference	model vintage	model resolution	available resolution	data assimilation
NCEP DOE R2	Kanamitsu et al. (2002)	2001	T62 L28	2.5° L10	3D-Var
ERA Interim	Dee et al. (2011)	2006	T255 L60	0.75° L23	4D-Var
NCEP CSFR	Saha et al. (2010)	2009	T382 L64	0.5° L23	3D-Var + FOTO
JRA 55	Ebita et al. (2011) Kobayashi et al. (2015)	2009	T319 L60	0.5° L23	4D-Var
MERRA 2	Gelaro et al. (2017)	2012	$\sim$ 50 * 50 km L72	0.5° * 0.625° L23	3D-Var + IAU

Table 1. Major characteristics of reanalyses compared during the study

	East Antarctica					Antarctica				
Reanalysis	P	E	P-E	C	P-E-C	P	E	P-E	C	P-E-C
NCEP DOE R2	126	66	60	65	-5	172	64	108	115	-7
ERA Interim	110	19	91	93	-2	159	19	140	138	3
NCEP CFSR	137	34	102	72	31	196	38	158	120	39
JRA 55	119	21	99	89	9	175	21	154	140	15
MERRA 2	142	19	123	96	27	204	20	184	143	42

Table 2. Magnitude of the long-term averaged (1979-2016) atmospheric moisture budget terms in mm per year for the East Antarctic ice sheet and the whole Antarctic continent (ice-shelves excluded). The columns stand for : precipitation (P), evaporation (E), convergence (C), net precipitation (P-E) and residual (P-E-C).