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Article

Contributions to the moisture budget of airmasses over Iceland

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Abstract

Motivated by the excellent skills of a new Lagrangian diagnosis method to identify the contributions to the moisture budget over a region (STOHL and JAMES, 2004, 2005), this study examines the main areas where there is net uptake of moisture in airmasses over Iceland. The method computes budgets of evaporation minus precipitation by calculating changes in the specific humidity along back-trajectories for the previous 10 days. We tracked the origin of all air-masses, including precipitating airmasses, residing over Iceland during a period of five years (2000–2004). Air transported into the Icelandic waters has a large uptake of water over the Norwegian Sea in the preceding first three days and from the Western-North Atlantic in the range of 3–10 days. Concerning the days with observed precipitation in SW-Iceland, it was found that the major net uptake of moisture was the final northward segment of the Gulf Stream and the Atlantic waters immediately surrounding Iceland.

Zusammenfassung

Motiviert durch die ausgezeichneten Fähigkeiten einer neuen Lagrangeschen-Diagnosemethode zur Identifizierung der Beiträge zum Feuchtigkeitshaushalt über einer Region (STOHL und JAMES, 2004, 2005), analysiert diese Studie die Hauptgebiete in denen eine Netto-Feuchtigkeitsaufnahme der Luftmassen über Island stattfindet. Diese Methode berechnet den Nettobetrag der Evaporation abzüglich des Niederschlags, indem sie Änderungen in der spezifischen Feuchte über Rückwärtstrajektorien für die vorhergehenden 10 Tage errechnet. Hiermit haben wir den Ursprung aller Luftmassen, einschließlich regenträchtiger Luftmassen, die sich über Island während einer Periode von fünf Jahren (2000–2004) befanden, zurückverfolgt. Die Luftmassen, die in die isländischen Gewässer transportiert werden, nehmen eine große Menge Feuchtigkeit über dem norwegischen Meer in den vorhergehenden drei Tagen auf, sowie über dem Nordwestatlantik über einen Zeitraum von 3–10 Tagen. Hinsichtlich der Tage mit beobachtetem Niederschlag über Südwest-Island wurde die höchste Nettofeuchtigkeitsaufnahme über dem nördlichsten Abschnitt des Golfstroms und den atlantischen Gewässern, die Island direkt umgeben, gefunden.

1 Introduction

There is considerable interest in the meteorology and hydrology communities on the origin of the moisture and the precipitation that occurs over a given region. This is a topic of clear practical interest because water is essential for life, but it also addresses important scientific questions (TRENBERTH et al., 2003). It is now commonly accepted that the precipitation that falls in a region has one of the following origins: 1) moisture already in the atmosphere, 2) advection of moisture into the region by the winds or, 3) recycling. Moisture recycling refers to the process by which a portion of the precipitated water that evapotranspired from a given area contributes to the moisture over the same area. Over long periods, the first source contributes little, so there are two major sources, evaporation and advection. In general terms, studies dealing with this topic can be grouped into four categories:

a) Studies that calculate recycling ratios, the fraction of precipitation that originates locally within the region (e.g. ELTAHIR and BRAS, 1996; TRENBERTH, 1999). Such studies can be particularly sensitive to both the length scale and the assumption of a well-mixed atmosphere; however their main limitation is that they cannot determine the specific origin of non-local water.

b) Studies that use general circulation models and water vapour tracers to assess the major evaporating regions that contribute to water precipitating in a different region (e.g. NUMAGUTI, 1999; BOSILOVICH et al., 2003). In this approach the source regions must be prespecified and the use of models instead of analyses makes the method very sensitive to errors in the simulation of the hydrological cycle.

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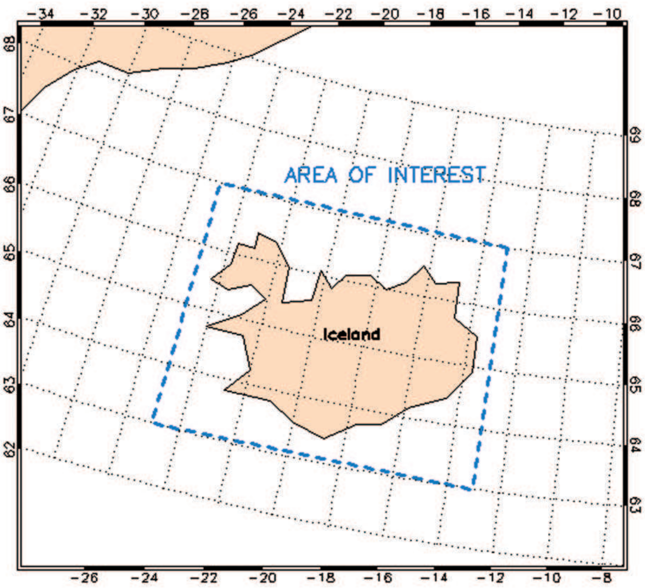

Figure 1: Map of the analyzed region (63°–67°N latitude, 13°–25°W longitude).

c) Studies based on integrating the atmospheric moisture fluxes across the region boundaries (e.g. CHEN et al., 1994; LIU and STEWART, 2003; FERNÁNDEZ et al., 2003). These are able to quantify inflows and outflows of moisture from and into a region but not the geographical sources of the moisture crossing the region boundaries net convergence and divergence that calculate vertically integrated atmospheric moisture.

d) Studies that quantify the transport based on trajectories (e.g., CRIMP and MASON, 1999; KNIPPERTZ and MARTIN, 2005). These studies are capable of providing full 3D details of where the air mass originated, but provide no information on how the moisture increases and decreases along the trajectory affects the moisture in the target region, so the identification of sources is qualitative.

In a two papers work, STOHL and JAMES (2004, 2005) applied a Lagrangian diagnostic method that answers well where the moisture and the water that produced precipitation in a basin came from. It is based on three components; a) a comprehensive meteorological analysis dataset, b) a particle dispersion model and c) a Lagrangian analog to the Eulerian budget method to diagnose the surface moisture flux. Details of the method are provided in the method section of the paper.

To the best of our knowledge there are no specific studies about net uptake of moisture in airmasses residing over Iceland. However, climatological studies on precipitation (PHILLIPS and THORP, 2006) or studies about preferred storm tracks in the North Atlantic (TRIGO, 2006) appoint that air masses follow a track from the southwest. The lack of specific works can be partially replaced by the huge amount of literature concerning the moisture budget over the Arctic region. So, climatological surface moisture fluxes (precipitation and evaporation) have been estimated using data from surface meteorological stations (SERREZE and HURST, 2000), or rawinsonde data (NAKAMURA and OORT, 1988; MASUDA, 1990; SERREZE et al., 1994). Gridded reanalysis dataset from NCEP-NCAR (National Center for Environmental Prediction – National Center for Atmospheric Research) and from ECMWF (European Center for Medium-Range Weather Forecasts) Reanalysis (ERA-40) have also been used to calculate moisture budget products, like precipitable water, precipitation (P), evaporation (E) and $P - E$ (e.g., BROMWICH et al., 2000; SERREZE and HURST, 2000; CULLATHER et al., 2000). The first study using satellite moisture retrievals to examine the Arctic atmospheric budget was made by GROVES and FRANCIS (2002) who have combined these data with reanalysis wind fields to calculate daily moisture transport and convergence throughout the Arctic basin, which cannot be done with only rawinsonde data. In general terms all these studies agree that southwesterly fluxes are the main contribution for moisture over the Arctic. According to previous studies based on isotopes it has been shown that light water, associated with precipitation in cold areas, has typically been sent to the atmosphere by convection, or convection-like processes (e.g. GAT, 1996; SMITH, 1992). In fact, water entering the atmosphere in the tropical regions, and being transported northward, will typically put down such a pattern. Reversely, water entering the atmosphere in the north going southward will most likely leave another signal, reversing the heavy-light water gradient.

This paper applies the new Lagrangian diagnosis method used by STOHL and JAMES (2004, 2005) to identify the main net uptake of moisture ($E - P$) and precipitation ($E - P < 0$) in air masses residing over Iceland. It is important to remark that in this study we identify those regions where the air acquired water vapor when passing over. To do this we will track the air masses residing over Iceland backward in time to see where the air parcels gain or lose moisture. Independently, we have also tracked the origin of air masses when there is precipitation over SW-Iceland.

2 Data and methods

Our study is based in the method developed by STOHL and JAMES (2004, 2005), which uses the Lagrangian particle dispersion model FLEXPART (STOHL et al., 1998) and meteorological analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (WHITE, 2002) to track atmospheric moisture along trajectories. The atmosphere is divided homogeneously into a large number of so-called particles and then these particles are transported by the model using three-dimensional winds, with their positions and their specific humidity (q) being recorded every six hours. The increases (e) and decreases (p) in moisture along the trajectory can be calculated through changes in (q) with the time ($e - p = mdq/dt$), being (m) the mass of the particle. When adding ($e - p$) for all the particles residing in the atmospheric column over an area we can obtain ($E - P$), that is the surface freshwater flux where (E) is the evaporation and (P) the precipitation rate per unit area. The method can also track ($E - P$) from a region backward in time along the trajectories, choosing the appropriate particles for finding regions where those particles gained or lost moisture. It should be stressed that this study is about the water budget of air masses prior to arriving in Iceland. The vast majority of water molecules that entered into the atmospheric system have done so due to strong convection in the tropics and some of them are transported towards the mid-latitude regions by the Hadley and Ferrel cells.

The method has limitations mainly concerning the trajectory accuracy and the fact that it uses a time derivative of the humidity (unrealistic fluctuations in humidity could be considered as moisture fluxes). However the use of large time periods minimizes such effects. The FLEXPART model used ECMWF operational analyses every 6 hours with a 1°x1° resolution on 60 vertical levels. Level density is higher at lower levels, with approximately 14 model levels below 1500 m and 23 levels below 5000 m. To ensure exact mass balance, vertical winds are calculated using spherical harmonics data as part of the data-retrieval procedures at ECMWF. In order to account for turbulence, the FLEXPART model calculates the trajectory of the particles using analyzed winds plus random motions. In the planetary boundary layer (PBL), these random motions are calculated by solving Langevin equations for Gaussian turbulence (STOHL and THOMPSON, 1999). These equations use the Lagrangian timescales and the standard deviations of the wind components, which are computed from ECMWF PBL parameters (HANNA, 1982). PBL height is diagnosed using a combined Richardson number and lifting parcel technique (VOGELEZANG and HOLTSLAG, 1996), while outside the PBL, turbulence is assumed to be very small. Global datasets also do not resolve individual convective cells, although they reproduce the large-scale effects of convection. FLEXPART has a number of options on how particles are generated. In this case, the atmosphere was "filled" homogeneously with particles, each representing a fraction of the total atmospheric mass. Particles were then allowed to move freely (forward in time, but this is arbitrary) with the winds for the duration of the simulation. The Lagrangian diagnostics for E, P and $E - P$ were validated by comparing results with those obtained with the Eulerian method of STOHL and JAMES (2004) (see their Figure 2 for $E - P$ comparison and Figure 4 for precipitation comparison). They found an excellent agreement on a global basis for the year 2000. In a recent work, the authors have used the same FLEXPART model to compute the net uptake of moisture over the Sahelian region (NIETO et al., 2006). In that case, the validation procedure was done for a 2-year period (2000-2001) comparison with Eulerian results computed using data from NCAR-NCEP 2.5°x2.5°. The good agreement shows that results were robust independently of methods, reanalysis and scale choices. NIETO et al. (2006) have done a comparison of P results also for the same 2-year period mentioned (P was calculated based on the computation of $E - P$ whenever $E - P < 0$) obtaining a satisfactory agreement (see Figure 1 on their paper). A comprehensive description of the method is out of the scope of this paper and can be found in STOHL and JAMES (2004, 2005).

In this work we have used the tracks of 1,398,801 particles over a 5-year period (2000–2004) computed using ECMWF operational analysis every 6 hours (00, 06, 12 and 18 UTC) with a 1°x1° resolution and including all the 60 vertical levels of the analysis. We traced ($E - P$) backwards from the Iceland region (63°–67°N latitude, 13°–25°W longitude) limiting the transport times to 10 days. Although the average residence time of water in the atmosphere is different for various locations on the earth, and the residence time varies most likely from case to case we have taken 10 days which is the average residence time of water vapour in the atmosphere (NUMAGUTI, 1999). All the particles residing over the Iceland region (Figure 1) were identified each 6 hours and tracked backwards for 10 days. For the first trajectory time step, all the target particles reside over the Iceland region and ($E - P$) is the region-integrated net freshwater flux. For the following trajectory time steps, ($E - P$) represents the net freshwater flux into the air mass travelling to the Iceland region. We calculated ($E - P$) on a 1°x1° grid and averaged over seasonal, annual and 5-year periods. ($E - P$) values for specific days are labelled $(E - P)_n$ here, so $(E - P)_2$ shows where the particles of air over Iceland gained or lost moisture on the second day of the trajectory. Furthermore, we labelled $(E - P)^n$ to the total ($E - P$) integrated over days 1 to n, so $(E - P)^{10}$ corresponds to the sum of days 1 to 10. In summary, the analysis of ($E - P$) values for various preceding time steps lets us know where and when the moisture over the Icelandic region was received or lost. If we repeat the calculation but only for days with precipitation in a target station and for particles that lost moisture in the Iceland region (particles producing precipitation) we can identify what the air parcels have experienced before coming to start precipitating on Iceland. Both approaches will be used and analysed in the following section.

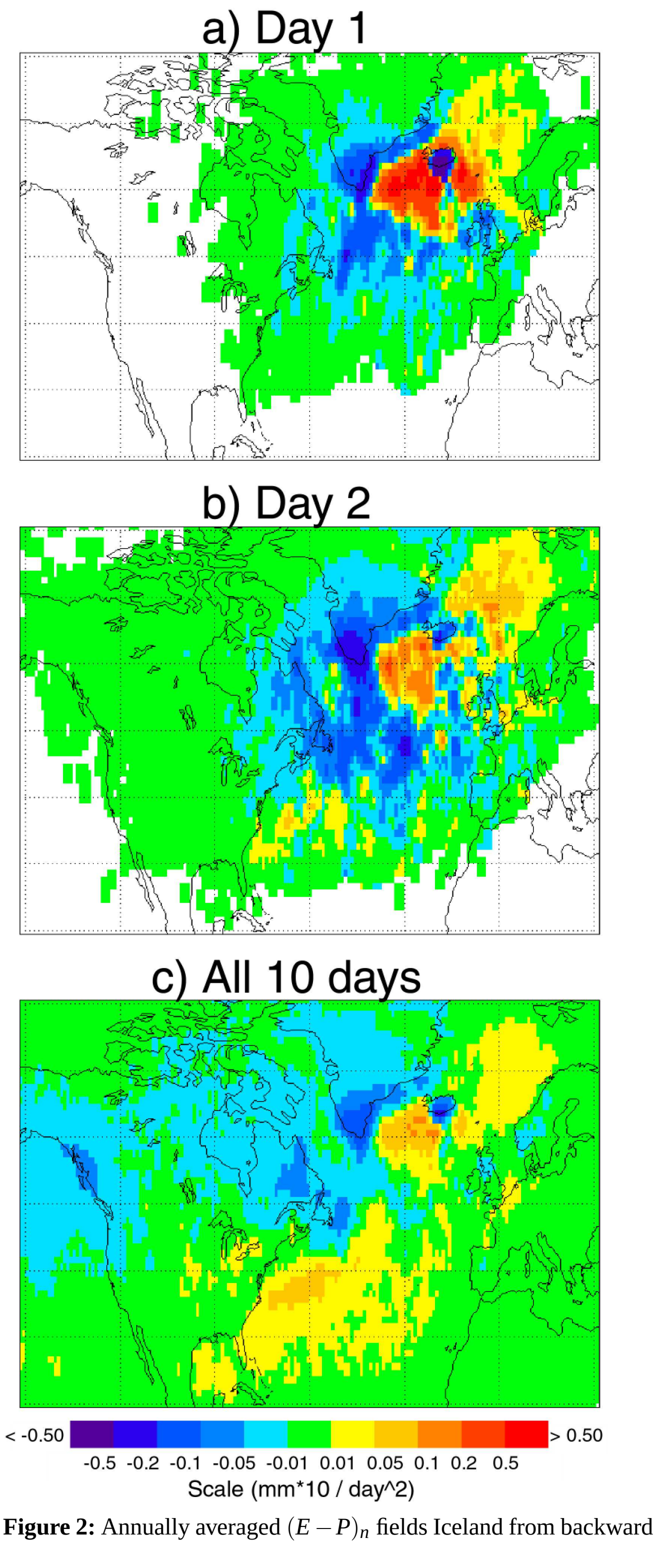

Figure 2: Annually averaged $(E-P)_n$ fields Iceland from backward tracking, a) $(E-P)_1$, b) $(E-P)_2$, and c) $(E-P)^{10}$ (10 days)$^{-1}$, i.e., averaged over 10 days back.

3 Results

3.1 Regions of net uptake of moisture in air masses residing over Iceland

We tracked the air masses residing over the Icelandic region back in time to see where the particles gained or lost moisture. Figure 2 shows the $(E-P)_n$ fields on the first and second day of transport (counting backwards) and also averaged over the 10-day period $(E-P)^{10}$. If we consider only one day back in time, most of the air resides over the North Atlantic Ocean north of 30° latitude or over the Norwegian Sea south of 80° latitude (see Figure 4a). The value $(E-P)_1$ is negative over the Atlantic Ocean, indicating that over this region precipitation dominates over evaporation, a situation that typically occurs in air masses in transit to Iceland (one of the preferred storm tracks identified in the North Atlantic (Trigo, 2006)). The value $(E-P)_1$ is positive over the Norwegian Sea, indicating that particles coming from surrounding oceanic areas located in the opposite direction to the storm-track have a strong contribution from evaporation. A similar pattern in the Norwegian Sea can be observed for $(E-P)_2$ with a logical expansion of the area where air resides. The region with positive values of $E-P$ (reddish) does not indicate the initial origin of the water vapour particles that arrive in Iceland, it refers to an area in which during these previous days the particles gain moisture. The negative/positive values over the Atlantic Ocean to the east (west) of Greenland are due to the rise (drop) of the air over Greenland before reaching Iceland, producing net precipitation windward and net evaporation leeward. Averaged over all 10 days of transport, there is a strong moisture uptake over the Atlantic coast of North America. Positive values of $(E-P)^{10}$ even reach the tropical North Atlantic, the Caribbean and the Gulf of Mexico (hereafter, Western North Atlantic region). However the negative values of $(E-P)_n$ for the first and the second day of the trajectory in these areas indicate that part of the moisture could be lost from the air mass through precipitation during the two days prior to reaching Iceland. To estimate this effect objectively we have quantified the moisture gained from day 10 to day 2 over the Western North Atlantic area (50°–40°N latitude, 47°–30°W longitude and 40°–27°N, 77º–30ºW longitude; see Figure 4a) and subtracted the moisture lost over the Southern region of Iceland (65º–52ºN latitude, 40°–23°W longitude; see Figure 4a) from day 2 to day 1. The amount of moisture injected into the atmosphere in the Western North Atlantic (246.48 km^3/year) is considerably higher than the corresponding loss of moisture over the Southern region of Iceland (–52.1 km^3/year), so we can affirm that the Western North Atlantic is an area where the airmasses gain moisture when passing over in direction to Iceland. The Norwegian Sea, close to the Scandinavian coast, continues being a region where the particles gain moisture over the 10-days period. Although recycling is not expected to be excessively important due to the small size of the analyzed region and its small evaporative capacity, the positive values of $(E-P)^{10}$ over the Icelandic sea to the SW of Iceland (that is included in the studied area, see Figure 1) indicates a non-negligible recycling component, that is also important two days back in time (Fig. 2b). These patterns of the $(E-P)$ fields were very robust, so similar structures appeared when the analysis was done on a seasonal basis. The main differences occurred in summer (JJA) with a lower importance being attributed to the Norwegian Sea as moisture uptake area while a higher recycling component can be observed.

3.2 Regions of net uptake of moisture for precipitation falling over Iceland

In this section we repeated the analysis performed in the previous section but considering only those days when precipitation was observed in Reykjavik (64:08N lat, 21:54W lon, 52 m alt.[1]) and, additionally, considering only those particles that lost moisture in the entire Iceland region $(E-P<0)$. This method is slightly different to that used by STOHL and JAMES (2005) that instead of requiring real precipitation events, added to the condition of "particle losing moisture" the fact that the target grid had $(E-P) < -8$ mm per 3 h time step. We have preferred to use real precipitation days from weather stations because it gives more realistic information about when it rained over a certain place in Iceland – Reykjavik in this case –. Tracing the selected particles backward (Figure 3) shows that $(E-P)_1$ continues to be positive in the Norwegian Sea but now this is not the main region where particles gain moisture for precipitation falling in Iceland. The Atlantic areas surrounding Iceland are now the main evaporative areas for air masses giving precipitation in Reykjavik, SW-Iceland. Similar patterns can be observed for $(E-P)_2$.

Averaged over all 10 days of transport, there is also another strong moisture uptake over the Atlantic Ocean south of 40°N. Again, the region of strongly negative $(E-P)_1$ and $(E-P)_2$ in the North Atlantic Ocean between 40° and 50°N is caused by particles arriving from the Atlantic Ocean south of 40°N and travelling northeastward in the storm track direction producing precipitation already in route to Iceland. In summary, these results indicate two areas where airmasses gain moisture for precipitation falling over Iceland, the nearby Atlantic areas close to the region and transport from the Atlantic Ocean southward of 40°N and the area close to the Atlantic American coast in the final part of the northward branch of the Gulf current (West-Northern Atlantic region).

3.3 Quantification of the water vapour transport

Another interesting possibility with the Lagrangian method is to provide a quantification of the water vapour transport. More precisely it is appealing to evaluate the relative weight of the main regions contributing to the net uptake of moisture, in this case; Southern Iceland,

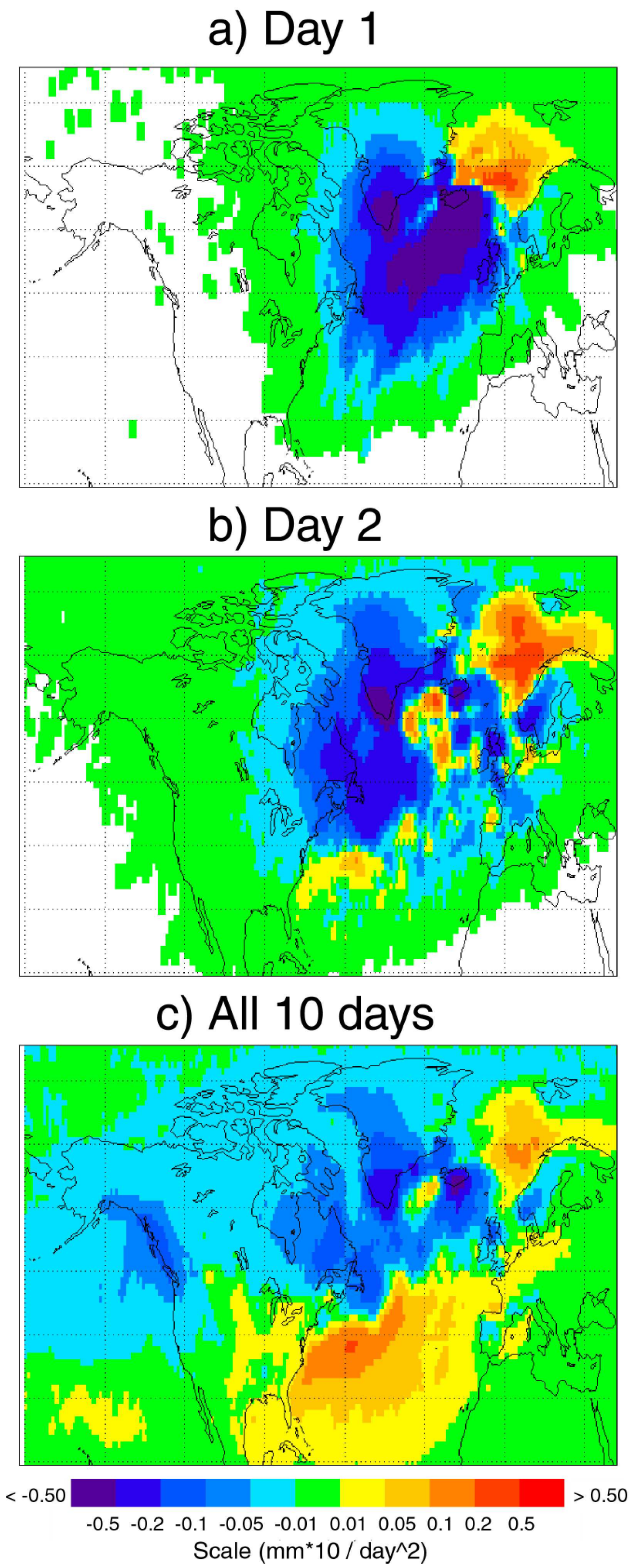

Figure 3: Same as figure 2, but calculated only for precipitation particles with $dq(dt)^{-1} < 0$ g Kg^{-1} (6hr)$^{-1}$ for the days with precipitation in Reykjavik station.

[1]Data available at http://eca.knmi (TANK et al., 2002).

Table 1: $E-P$ computed for the days with precipitation detected in Reykjavik (units in km^3/year).

	Southern Iceland	W-N Atlantic	Norwegian Sea
From day 0 to day 3	2,28	0,08	1,05
From day 3 to day 6	0,83	7,49	0,56
From day 6 to day 10	0,37	6,12	0,24
From day 0 to day 10	3,48	13,69	1,85

Western North Atlantic and Norwegian Sea. We have quantified $(E-P)_n$ series computed backwards from Iceland and integrated over these three regions (Figure 4). Figure 4a shows the limits of the source regions, Figure 4b depicts the values of $(E-P)_n$ without considering the different areas of each region, and Figure 4c shows the corresponding values of $(E-P)_n$ divided by the appropriate area of the regions. A view of Figure 4b shows that the Western North Atlantic is the most important contributing area between days 3 to 10 backward, whereas during the first two days the most relevant region corresponds to the Norwegian Sea. It takes 3 days back for the Southern Iceland to become a net uptake of moisture for Iceland. When we use the normalised time series, $(E-P)_n$ values divided by the area of the region, (Figure 4c) the relative importance of the Norwegian Sea is evident.

An analogue calculation was done for $E-P$ when precipitation falls over Reykjavik station (Table 1). The importance of the Southern Iceland region as moisture uptake area during the first three days of transport is again highlighted in these results.

4 Conclusion and future applications

An analysis of the major regions where air parcels have gained or lost moisture on their way to Iceland has been performed here by means of a Lagrangian diagnostic method. We have studied the average conditions over a 5-year period (2000–2004), which can be considered as typical on a global climate scale, because there were no extremes of any modes of climate variability such as ENSO or NAO. We emphasise again that the concept of net uptake of moisture in this work is restricted to the capacity that the FLEXPART model exhibits to track those regions where an air parcel has either absorbed or expelled water before reaching Iceland. Three main conclusions can be extracted from the results of this study:

Norwegian Sea was found to be the dominant region of net moisture uptake for airmasses in the Icelandic region. This area is important during the first days of transport but also averaged over all 10 days of transport. There is strong moisture uptake over the Western North Atlantic, southward of 45°N averaged over the 10 days of transport, but its net contribution to the moisture over Iceland is not very important because of the loss of moisture by precipitation during the two days before the air reaches the Icelandic region.

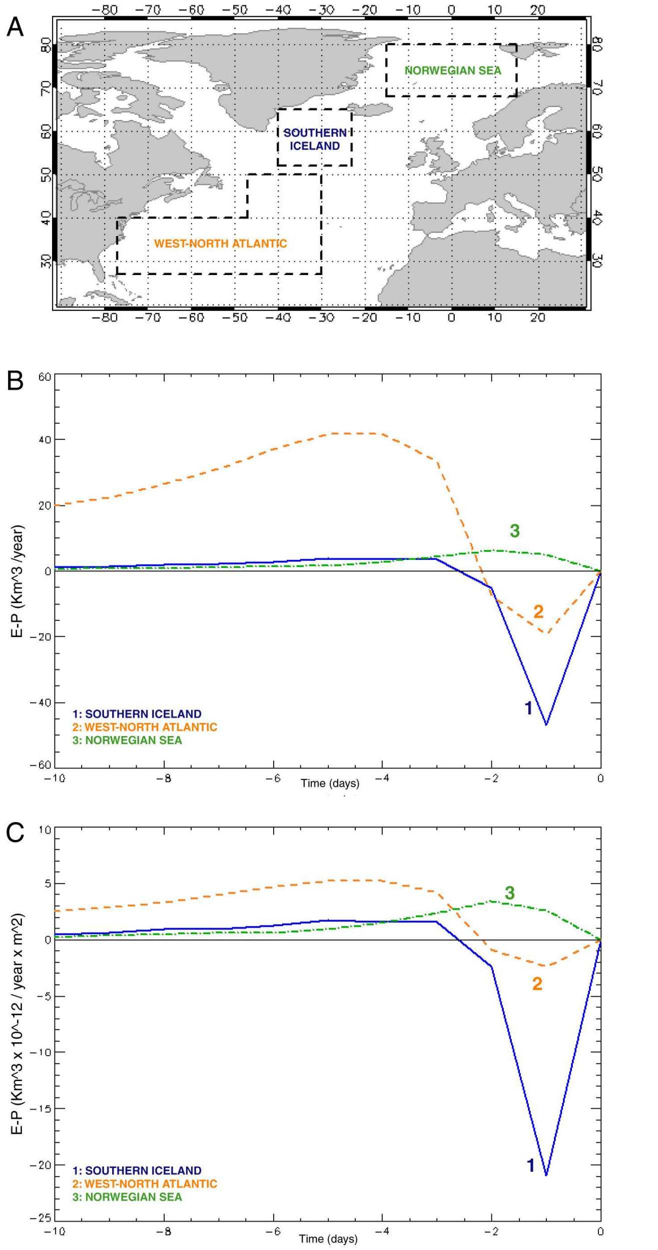

Figure 4: a) Time series of $(E-P)_n$ calculated backward for moisture over the Iceland area and integrated over the regions indicated: Southern Iceland (curve 1), Western North Atlantic coast (curve 2) and the Norwegian Sea (curve 3). b) Absolute values of $(E-P)_n$ time series. c) Relative values of $(E-P)_n$ time series, taking into account to the area of each region (scale multiplied by a factor of 10^{12}).

When analyzing only the regions of net moisture uptake for airmasses in which precipitation is falling in SW-Iceland we found slightly different results. The Norwegian Sea continues being an area where airmasses absorbed moisture but loosing the leading role. In this case, the most important area corresponds to regions in the Atlantic surrounding Iceland along the storm track area and over a region located on the final part of the northward branch of the Gulf Stream. So, the combination of storm track plus warm Atlantic areas is the ultimate net uptake of the moisture-producing precipitation over SW-Iceland.

This study can be considered as an approach to the mean conditions of moisture transport towards Iceland, however the relatively short period analysed does not permit to explore conveniently the seasonal variability and in any case the interannual variability. Recent studies have reported important interannual variability and trends in the precipitation over Iceland and a moderate relationship with the North Atlantic Oscillation (HANNA et al., 2004). Possible changes in the moisture uptake regions linked to anthropogenic forcing and to major modes of climate variability could explain this variability and must be studied.

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