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The influence of climate variability on internal migration flows in South Africa

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ABSTRACT

This work investigates the impact of climate variability on internal migration flows in post-apartheid South Africa. We combine information from South African censuses and climatic data to build a panel database covering the waves 1997–2001 and 2007–2011. The database enables the examination of the effect of spatiotemporal variability in temperature and precipitation on inter-district migration flows defined by five-year intervals. We employ a gravity approach where bilateral migration flows are explained by climate variability at the origin, along with a number of geographic, socio-economic and demographic factors traditionally identified as potential drivers of migration. Overall, we find that an increase in positive temperature extremes as well as positive and negative excess rainfall at the origin act as a push effect and enhance out-migration. However, the significance of the effect of climate on migration greatly varies by migrant characteristics. Particularly, flows of black and low-income South African migrants are strongly influenced by climatic variables whereas those of white and high-income migrants exhibit a weak impact. We also argue that agriculture may function as a transmission channel through which adverse climatic conditions affect migration.

1. Introduction

Environmental factors are increasingly recognized as a possible driver of cross-border and internal human migration (Laczko and Aghazarm, 2009). Indeed, adverse environmental conditions — ranging from natural disasters and extreme weather events, to more gradual variations in climate — might induce people to use migration as an adaptation strategy (McLeman and Smit, 2006). Quantifying the effects of the environment on human migration is crucial to better monitoring and predicting internal and international migration flows and, especially in the context of least developed countries (LDCs), is crucial to effectively managing issues associated with the movement of people. Moreover, a better understanding of the environment-migration link would aid in the development of strategies and policies to cope with the challenges posed by projected climate change.

Environmental factors influence individual migration decisions and shape migration flows through a complex web of causal links. Adverse environmental conditions could reduce, either abruptly or more gradually, the safety of homes or communities, worsen individual health, and decrease household-asset value through land and property degradation. Environmental factors may also interact in non-trivial ways with economic activity and indirectly affect individual migration decisions. For example, changes in climatic conditions may reduce agricultural productivity and raise food-commodity prices (Porter et al., 2014). The impact can be more severe in LDCs lacking sufficient capital to invest in innovative technologies for climate-change mitigation and adaptation (Lybbert and Sumner, 2012). This may negatively affect income and employment opportunities of people working in the agricultural sector (or in industries strongly dependent on it), and influence household consumption, possibly boosting urbanization via rural–urban migration, and ultimately affecting migration decisions of urban households resulting in international migration (Marchiori et al., 2012). Furthermore, recent findings suggest that environmental factors may also limit movement of the most

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vulnerable populations due to financial constraints (Gray and Mueller, 2012).

Motivated by these lines of evidence, we explore whether and how climate variability has affected internal migration flows across South Africa in the post-apartheid period (1996–2001; 2007–2011). Review of the literature (see Appendix B) indicates that the climate-migration link has not been addressed there so far. Nevertheless, South Africa is a relevant case study for a number of reasons. First, it is characterized by high internal migration rates (between 2007 and 2011, approximately 2.3m people, i.e. 5% of the country's population, moved across districts), particularly since the end of the apartheid, when the laws constraining the movement of people on the basis of ethnicity were abolished (see Appendix A). Second, South Africa is already experiencing significant changes in climate. Average annual temperature has exhibited positive trends between 1960 and 2000, with an increase by about 0.13 °C per decade (Kruger and Shongwe, 2004). Average annual rainfall trends are weak, but there is a tendency towards a significant decrease in the number of rainy days combined with an increase of inter-annual variability in precipitation (DEA, 2013). IPCC scenarios (van Oldenborgh et al., 2013) project that these trends will intensify by the end of this century (see Appendix A). Third, South Africa is characterized by persistent poverty and racial inequalities that are partially a consequence of decades of apartheid, and that could potentially make some specific population sub-groups particularly vulnerable to climate change. According to World Bank (http://wdi.worldbank.org), in 2010 the share of population below national poverty line was 53.8%, while the income Gini coefficient was estimated to be 63.4% in 2011, which makes South Africa one of the most unequal countries in the world (see Appendix A). Fourth, although the economy of South Africa is increasingly dominated by the tertiary sector (i.e., service industry), which makes up almost two-thirds of GDP, agriculture is still relevant for the development and stability of the country because of the economic importance of its commercial sector and the ubiquity of subsistence and rainfed, small-holder farming (see Appendix A), Therefore, one could argue that, if climate variability influences migration decisions, this may occur through its impact on people directly or indirectly via the agricultural channel.

In this work, we study the patterns and determinants of South African inter-district bilateral migration flows in the periods 1997–2001 and 2007–2011. In particular, we employ an augmented gravity model where, in addition to geographic, socio-economic and demographic determinants, we introduce a number of covariates to control for the spatiotemporal distribution of climatic factors. We further test climate-migration sensitivity of different demographic sub-groups within South Africa. In particular, we condition migration flows by age, gender, ethnic group and income. Finally, we ask whether agriculture could act as a potential transmission channel from climate to migration, in line with the empirical findings in recent studies (Feng et al., 2012; Mueller et al., 2014).

2. Materials and methods

2.1. Data

The main sources of data are South Africa's 1996, 2001, and 2011 censuses, and the 2007 community survey (CS). Data for 1996 and 2007 are taken from the IPUMS (Integrated Public Use Microdata Series, International) available at https://international.ipums.org (Minnesota Population Center, 2013), whereas the 2001 and 2011 censuses come from Statistics South Africa (statssa.gov.za). A number of migration-related studies have previously employed these data, see for example Kok et al. (2003, 2005), Dinkelman (2013), Facchini et al. (2013), Garcia et al. (2014) and Choe and Chrite (2014). In principle, census and CS data cover the entire universe, but data are only available for a nationally-representative 10% sample together with individual and household weights, which we used throughout our analysis. Census and CS data cover a wealth of information about demographics, general health and fertility, education and employment, mortality, housing, households and services, and migration. In particular, each census wave contains data on current and past residence of individuals. However, the geographic resolution of the past residence data varies widely across waves. The only past residence data that are consistently available are at the province level. Since South Africa only features 9 provinces, this choice would strongly limit the cross-sectional variability of our data. Therefore, we choose to track individual movement from origin to destination at the level of the 52 South African district councils using solely the 2001 and 2011 waves. The data further provides information on the year of last move, which we utilize to determine the migration status of individuals. More precisely, an individual is defined as a migrant if s/he moved between two different district councils within the 5 years prior to the 2001 or 2011 census year included (see Appendix C for more details on the characteristics of migrants and the statistical patterns of migration flows in South Africa). We choose 5-year intervals to compute migration flows because we employ the 1996 census and the 2007 CS to build a set of demographic and socio-economic variables, to be used as lagged covariates in our regression exercises (see Section 2.2).

Climate data (gridded at 0.25° resolution) are taken from the African Drought and Flood Monitor project (hydrology.princeton.edu/monitor/), see Sheffield et al. (2006, 2014). The system monitors hydrological conditions of land surface in Africa employing the Variable Infiltration Capacity (VIC) model and provides data on a variety of climatic indicators including precipitation, temperature, and soil moisture.

2.2. Econometric framework

We explore the determinants of inter-district migration flows with the following panel gravity model, which we estimate using Poisson Pseudo Maximum-Likelihood (PPML) with errors clustered at the dyadic level (ij):

$$m_{ij,t} = \kappa \cdot \exp\{\psi_i + \phi_{j,t} + \boldsymbol{\beta}\mathbf{Z}_{ij} + \boldsymbol{\theta}\mathbf{X}_{i,\tau(t)} + \boldsymbol{\mu}\mathbf{C}_{i,\omega(t)}\} \cdot \varepsilon_{ij,t} \qquad (1)$$

where $i \neq j = 1, \ldots, 51$ are origin and destination district councils (from the list of 52 district councils in 2011 Buffalo Metropolitan Municipality has been removed and its flows have been aggregated with those of Amathole District, which contained Buffalo Metropolitan Municipality in 2001); $t = 2001, 2011$ are census years; $m_{ij,t}$ are 5-year individual migration flows from i to j (i.e. defined for the time interval $[t-4, t]$); κ is a constant; ε_{ij}^{t} is an error term with mean equal to 1; ψ_i are origin fixed effects; ϕ_j^t are time-destination fixed effects; $\mathbf{Z}_{ij}$ is a vector of bilateral variables, i.e. log of geographical distance between i and j and a contiguity dummy; $\mathbf{X}_{i,\tau(t)}$ is a vector of lagged demographic and socio-economic origin controls at year $\tau(t) = 1996, 2007$, and $\mathbf{C}_{i,\omega(t)}$ is a vector of origin climatic variables computed over the 5-year time intervals $\omega(t) = [1996–2000], [2006–2010]$. Since we are mostly interested in assessing the role of climate and other origin covariates as push effects, we do not use any time-varying covariate at the destination, but we control for all cross-section, time-dependent unobserved heterogeneity in pull factors using time-destination fixed effects (ϕ_j^t). We also employ time-independent origin fixed effects (ψ_i) to pick up unobservable spatial heterogeneity across districts that is due to structural differences across origins, including historical climate. Note that our gravity model specifications do not explicitly account for spatial autocorrelation that may be present in the dependent variable, in climatic measures and/or in the errors. We discuss this issue in Section 4.

We develop several climatic variables for the vector $\mathbf{C}_{i,\omega(t)}$. In order to capture the positive observed trends in temperature, we primarily use positive anomalies of 5-year averages of maximum temperature in the district. To compute this variable, we start from 5-year maximum temperature anomalies, calculated as the average of maximum temperature over the 5 years before the census (not included), minus long run mean divided by long run standard deviation, where long run statistics refer to the period 1950–2011. Subsequently, we replace negative values with zero. This allows us to evaluate the effect of heat extremes. In order to test if the effects of temperature excess is symmetric, we also consider negative anomalies of 5-year averages of minimum temperature (in absolute values), computed in the same way as before, but using minimum temperature anomalies and taking absolute values after replacing positive values with zero.

To account for the impact of precipitation extremes, we employ both positive and negative (in absolute values) anomalies of 5-year averages of rainy-season precipitation in the district, computed in the same way as temperature anomalies. We use precipitation in the rainy season as these are the months in which rainfed agriculture can be impacted most heavily by positive or negative extremes in rainfall. For the majority of South African districts, the rainy season lasts from November to March, while for those districts located in the Western part of the country, the rainy season lasts from May throughout August.

Furthermore, we employ a measure of soil moisture, as defined in Sheffield et al. (2004), computed as the average over the 5 years proceeding a census (not included) of relative soil moisture of the top layer (0–10 cm) calculated from the land surface model output (measured in percentage points on a 0–100 scale). In our regression exercises, we always include both a temperature and a precipitation variable, or alternatively our soil-moisture measure alone. The latter is, by definition, a derived indicator accounting for both temperature and precipitation effects.

As is customary in migration gravity models, we also account for the geography of migration flows through the vector $\mathbf{Z}_{ij}$ of bilateral variables: (i) the geographical origin-destination distance, computed as the geographical distance in kilometers between the centroids of origin and destination districts; (ii) geographical contiguity between districts, which is a dummy taking a value of one if two districts share a border. We expect bilateral origin-destination flows to decrease with distance and increase with contiguity.

Finally, we control for a number of lagged demographic and socio-economic factors that are likely to influence migration flows ($\mathbf{X}_{i,\tau(t)}$). With regard to demographic variables, we control for size effects at origin using total district population. This accounts for the fact that highly populated districts are expected to hold larger out-migration flows. Since migration may be affected by the ethnic composition at the origin in the South African context, we include a variable that captures the share of white South Africans in each district. As black and white South Africans together account for the majority of the population, we only include white individuals to avoid multicollinearity. To account for the individual's tendency to migrate towards places offering better labor-market opportunities, we include district unemployment rate (i.e., number of unemployed people over active population, both in the age range 15–64). We also control for educational attainment using the share of people the population 25 and older that has completed primary school at the most. We expect migration flows to increase with unemployment and decrease with our measure of educational attainment.

Summary statistics for our covariates are reported in Appendix C, see Tables C2 and C3, while Fig. C3 shows choropleth maps of temperature and precipitation anomalies, as well as our measure of soil moisture for the years 2001 and 2011.

3. Results

3.1. Main findings

Our main results are shown in Table 1, where each of the columns represents one out of six different model specifications of Eq. (1). More precisely, the first column features a model without climatic variables, and only bilateral and country-specific covariates (in addition to origin and time-destination fixed effects). In columns (2)–(6) alternative combinations of climatic variables (cf. Section 2.2) are added to the specification in column (1). In all regressions, the dependent variable is the inter-district migration flow of adults, that is, of migrants between 15 and 64 years of age,

Table 1
Gravity model estimation.

	(1)	(2)	(3)	(4)	(5)	(6)
Distance	−0.9397***	−0.9395***	−0.9403***	−0.9395***	−0.9399***	−0.9387***
Contiguity	0.5315***	0.5321***	0.5318***	0.5317***	0.5315***	0.5328***
Population	0.3917***	0.5451***	0.3927***	0.5612***	0.4000***	0.3541***
Primary	−7.1186***	−8.1961***	−8.5314***	−6.7194***	−7.1336***	−6.7911***
White	1.9538**	3.4994***	0.9692	4.9012***	2.1328**	0.7318
Unemployment	0.1121	1.0105***	0.4826*	0.4097*	0.0475	−0.0875
Pos $T_{\max}$ anom		0.5212***		0.4975***		
Neg Precip anom		0.6274***	0.5667***			
Neg $T_{\min}$ anom			−0.1678		−0.0624	
Pos Precip anom				0.1341*	0.0557	
Soil moisture						−0.1055***
N	5050	5050	5050	5050	5050	5050
Model DF	157	159	159	159	159	158
Pseudo R^2	0.8378	0.8395	0.8385	0.8388	0.8378	0.8386
Wald Chi^2	8386.6***	9496.9***	10,201.8***	7814.6***	8209.1***	8679.6***

Panel data analysis. Poisson Pseudo Maximum-Likelihood (PPML) estimates. Dependent variable: 5-year district-to-district migration flows of 15–64 year-old people. Constant, time-invariant origin and time-destination fixed effects, demographic and socio-economic origin controls, and bilateral covariates included in all regressions. Regression specifications: (1) without climatic variables; (2)–(6): with climatic variables.

* Significance: $p < 0.10$.

** Significance: $p < 0.05$.

*** Significance: $p < 0.01$.

which should best represent the population at risk of migration. The impact of climate on the whole population of migrants (i.e., no age restrictions), as well as on different subgroups of migrants, is explored in Section 3.2.

As a first observation, the gravity model appears to be well specified and attains comparable goodness of fit levels in all six specifications. Adding climatic variables slightly increases the pseudo R^2 of the fit.

We find that migration flows increase with larger positive maximum temperature anomalies and negative precipitation anomalies, and decrease with lower soil moisture at the origin. Conversely, negative minimum temperature anomalies do not seem to engender a significant effect on migration, and the migration-enhancing effect of positive precipitation anomalies is barely significant. Overall, our results suggest that the effect of temperature is strongly asymmetric, with a significant role played by positive heat extremes that does not have a negative counterpart. The influence of precipitation is instead slightly more symmetric, hinting at an increasing importance of both positive and negative rainfall excess, even though lower-than-normal rainfall seems to be more migration enhancing.

The effect of climate on migration flows in South Africa is not only statistically significant but also relevant in terms of its magnitude. More precisely, a 10% relative increase in positive maximum temperature anomalies and in negative precipitation anomalies, or one percentage point increase in soil moisture, result in a percentage change in migration flow of about 1.9, 2.2 and −5 respectively. A 10% increase in positive precipitation anomalies increases migration flows by approximately 1% (albeit its effect is only marginally significant). Relative percentage changes are computed at the means of the observed pooled distributions. For positive and negative anomalies, the means are calculated excluding the zeros.

With regard to controls, mostly in line with our expectations, we find that migration flows decrease with geographical distance ('Distance') and the share of the population 25 and older that has at most completed primary school ('Primary'). Furthermore, migration increases with population size ('Population') and the share of white individuals ('White') in the district as well as if the origin and destination districts are contiguous ('Contiguity'), with all the coefficients being highly statistically significant. Unemployment ratio ('Unemployment') is however not consistently statistically significant although it has the expected positive effect on migration.

We further explore the climate-migration link under a number of alternative specifications concerning the econometric setup and the definition of dependent and climatic variables. First, the data we use only count the last migration made by surveyed individuals, ignoring any previous moves they made during the 5 year period. In order to account for this possible underestimation of migration flows, we re-run our regressions using 1-year origin-destination migration flows, computed as the number of 15–64 year-olds who left during the year of the census (2001 or 2011). Second, since the time interval used to define climatic variables (i.e. 1996–2000 and 2006–2010) may overlap with that employed to define 5-year migration flows, we use climatic variables referring to the time interval 1992–1996 for the wave 2001 and 2002–2006 for the wave 2011. Third, we cluster errors with respect to origin district and province instead of dyads to account for cross-section autocorrelation among dyads sharing the same origin (across the whole South Africa or within the province the district belongs to). Fourth, we define climatic variables over a 9-year interval instead of a 5-year interval, in order to check whether migration flows are sensitive to a longer time horizon. Fifth, we test additional specifications where we employ temperature anomalies computed in the rainy season, similarly to what we have done with precipitation, instead of considering the whole year. We also check what happens when we include in the same regression both positive and negative temperature and precipitation anomalies (see Table E1 in the Appendix). Overall, all of our main results are robust to such alternative assumptions, in particular the findings concerning the effect of temperature and soil moisture on migration. The effect of rainfall on migration is also robust to these specifications, except in the case of lagged negative precipitation anomalies.

Lastly, we check the robustness of our main results to different setups as to the way push and pull factors are modeled. The foregoing analysis has focused on the identification of push effects (see Eq. (1)), controlling for pull factors with time-destination dummies ($\phi_{j,t}$). It is however instructive to investigate alternative specifications where climatic, demographic and socio-economic covariates at the destination (in addition to time-invariant destination dummies) are explicitly introduced, and where push factors are modeled either with time-origin dummies or a combination of time-invariant fixed effects (ψ_i) and time-varying covariates. Furthermore, one may try to replace origin and destination climatic variables with dyadic measures that are constructed, for example, as the difference between climatic variables at the origin and at the destination (see Appendix D for details). Results of this set of exercises (see Table D1) show, first, that both bilateral variables and origin covariates, including climatic variables, consistently keep the signs and magnitudes already found when estimating Eq. (1). Second, as far as climate at destination is concerned, positive maximum temperature anomalies and soil moisture do not represent significant pull factors. However, taking together the evidence on push and pull factors, our findings suggest that migration tends to flow from districts with higher positive temperature excesses and lower soil moisture to areas characterized by lower positive temperature excesses and higher soil moisture. This is confirmed by the regressions featuring dyadic climatic variables. As for the role of precipitation, holding climate constant at the origin, any increase in both positive as well as negative rainfall anomalies at destination reduces migration flows towards those areas. Coupled with the push effect of rainfall anomalies, this result reinforces the significant role of precipitation extremes in enhancing migration flows.

3.2. Conditioning flows to migrant characteristics

In this section, we explore the influence of climate on migration across different sub-groups of migrants, defined according to their demographic and socioeconomic characteristics. To do so, we disaggregate migration flows by age, gender, marital status, ethnic group, and income. More specifically, we break migrants into five age groups (0–14, 15–30, 31–45, 46–64, 65 and over); males vs. females; married vs. single; black vs. white individuals; and high- vs. low-income individuals (i.e. above vs. below the median individual annual income). All of these characteristics are observed at the year of the census and, except for the age breakdown, we always consider only the adult population (i.e., 15–64 year-old people) for the sake of comparison with results in Table 1. Moreover, we also include results for the whole population (i.e., not only the adults). We then fit the model in Eq. (1) using disaggregated migrant flows as dependent variables.

Results are reported in Table 2. Firstly, we do not find any relevant difference between the impact of climate on adult migrants and that in the whole population. When breaking down flows by age groups, results suggest an inverse U-shaped relationship between age and the climate-migration coefficient, with strongest climate impacts for migrants in the age group 15–30 (typically higher than the one for the whole population). This is particularly true for positive maximum temperature

Table 2
Conditioning bilateral flows to migrant characteristics

	(1)		(2)		(3)
	Pos $T_{\max}$ anom	Neg Precip anom	Pos $T_{\max}$ anom	Pos Precip anom	Soil moisture
All	0.506^{***}	0.578^{***}	0.507^{***}	0.170^{**}	-0.098^{***}
Age					
0–14	0.490^{***}	0.433^{***}	0.587^{***}	0.338^{***}	-0.075^{**}
15–30	0.610^{***}	0.661^{***}	0.603^{***}	0.143^{*}	-0.128^{***}
31–45	0.433^{***}	0.597^{***}	0.366^{***}	0.077	-0.098^{***}
46–64	0.377^{***}	0.612^{***}	0.355^{***}	0.192^{**}	-0.028
65+	0.201^{*}	0.110	0.289^{***}	0.221^{***}	-0.019
Gender					
Female	0.564^{***}	0.577^{***}	0.582^{***}	0.193^{**}	-0.107^{***}
Male	0.479^{***}	0.671^{***}	0.415^{***}	0.081	-0.104^{***}
Marital status					
Married	0.461^{***}	0.594^{***}	0.397^{***}	0.076	-0.097^{***}
Single	0.562^{***}	0.759^{***}	0.516^{***}	0.105	-0.123^{***}
Ethnicity					
Black	0.685^{***}	0.841^{***}	0.666^{***}	0.146^{*}	-0.135^{***}
White	0.213^{*}	0.081	0.287^{*}	0.179^{*}	-0.033
Income					
Low	0.553^{***}	0.663^{***}	0.522^{***}	0.123	-0.113^{***}
High	0.217^{*}	0.004	0.181	-0.070	-0.095^{**}

Coefficient estimates from PPML panel gravity-model regressions. Dependent variable: 5-year migration flows broken down according to age classes, gender, marital status, ethnic group and income (as defined in rows). Columns: regression specifications as to climatic variables entered. All remaining covariates as in Table 1.

[*] Significance: $p < 0.10$.

[**] Significance: $p < 0.05$.

[***] Significance: $p < 0.01$.

anomalies, negative precipitation anomalies and soil moisture. Also, results do not seem to significantly change between male and female migrants, as well as between married and single migrants.

However, conditioning on ethnic group and income reveals significant differences. We find that climatic variables have a more significant and stronger effect on black and low-income migrants compared to white and higher-income ones. Specifically, estimated coefficients for black and low income (respectively, white and high-income) migrants are almost always larger (respectively, lower) than in the case of the whole population. The higher significance of climate coefficients for black migrants compared to white migrants could be partly explained by the fact that, as a consequence of the apartheid, black South Africans are largely located on some of the most marginal agricultural lands, where they have low landholdings/per capita (Durning, 1990; Cousins and Scoones, 2010). Of course, the evidence surrounding income groups must be taken with caution, as migrant income is measured at destination (i.e., on the year of the census) and therefore might not fully capture the economic status of the migrant before migration takes place. Nevertheless, the fact that breaking into ethnic groups gives results in line with those for income is reassuring, as ethnicity provides an exogenous source of variation which is mostly correlated with income.

Overall, these results suggest that a number of defining characteristics exist, which identify groups of migrants (e.g., black and low-income) who are relatively more vulnerable to climate, and who are more likely to use migration as an adaptation response strategy than other groups do. However, this set of findings only concerns, by definition, migrants and does not necessarily apply to non-migrants. In other words, among non-migrants there may be people even more vulnerable to climate variability who cannot afford migration as an option, and therefore remain trapped at the origin despite their migration intentions.

3.3. *Climate, agriculture, and migration*

In this section, we explore the role of agriculture as a potential transmission channel through which climate variability affects migration. This is indeed an important question in the case of South Africa, where agriculture is one of the sectors most affected by climate variations (Turpie and Visser, 2012).

We begin by asking whether the effect of climate on migration flows varies with the importance of agriculture in the district. We measure agricultural importance with lagged share of people employed in the agricultural sector (A) as reported in census 1996 and CS 2007. More formally, we estimate the following model specification where a single climatic variable C is interacted with the agricultural variable A:

$$m_{ij,t} = \kappa\cdot\exp\{\psi_i + \phi_{j,t} + \boldsymbol{\beta}\mathbf{Z}_{ij} + \boldsymbol{\theta}\mathbf{X}_{i,\tau(t)} + \mu C_{i,\omega(t)} + \alpha A_{i,\tau(t)} \\ + \gamma A_{i,\tau(t)}\cdot C_{i,\omega(t)}\}\cdot\varepsilon_{ij,t}.$$

Table 3 shows PPML estimates for the coefficients (μ, α, γ), that is, for the climatic variables, the agricultural variables, and their interaction term, respectively. Results show that all climatic variables retain their signs and, by and large, significance levels observed in the baseline specifications. Furthermore, interaction coefficients suggest that higher positive maximum temperature anomalies and lower values of soil moisture enhance migration more strongly in districts characterized by higher employment in agriculture (see columns 1 and 4).

The relationship between employment in agriculture and the effect of climate on migration is less clearcut as far as precipitation variables are concerned (columns 2 and 3). Indeed, the interaction term between agricultural employment A and negative precipitation anomalies is positive as expected but not statistically significant, whereas the effect of positive precipitation anomalies appears to be weaker in more agriculturally-oriented districts.

Table 3
Gravity model with interaction effects between climate and agriculture.

	(1)	(2)	(3)	(4)
Pos $T_{\max}$ anom	0.378^{***}			
Pos $T_{\max}$ anom × A	3.915^{**}			
Neg Precip anom		0.316		
Neg Precip anom × A		3.132		
Pos Precip anom			0.234^{**}	
Pos Precip anom × A			-6.554^{***}	
Soil moisture				-0.093^{***}
Soil moisture × A				-0.209^{**}
A	4.643^{***}	4.545^{***}	11.444^{***}	15.720^{***}
Pseudo R^2	0.839	0.838	0.840	0.840

Coefficient estimates from PPML panel gravity-model regressions. Dependent variable: 5-year migration flows of 15–64 year-old people.
[*] Significance: $p < 0.10$.
[**] Significance: $p < 0.05$.
[***] Significance: $p < 0.01$.

Table 4
Links between climate, agriculture, and migration.

	(1)	(2)	(3)
Dependent variable: *A*			
Pos $T_{\max}$ anom	-0.027^{***}	-0.027^{***}	
Neg Precip anom	-0.005^{***}		
Pos Precip anom		0.003	
Soil moisture			0.002^{***}
R^2	0.836	0.835	0.820
Dependent variable: migration			
Predicted A	-13.448^{***}	-15.307^{***}	-23.371^{***}
Pseudo R^2	0.838	0.839	0.838

Top panel: OLS estimates from Eq. (2). Bottom panel: PPML estimates from Eq. (3). Columns represent alternative specifications as to the set of climatic variables included in the regressions. Note: Constant included in all regressions.
[*] Significance: $p < 0.10$.
[**] Significance: $p < 0.05$.
[***] Significance: $p < 0.01$.

Note that, in this latter case, the total marginal effect of positive precipitation anomalies on migration flows, computed at the median employment in agriculture, is still positive and significant as found in the main regressions where we do not employ an interaction term. However, for about one-third of all districts, i.e. the most agriculturally-intensive ones, the total marginal effect becomes negative. A possible explanation is that abundant rainfall may have a long-term positive effect on agricultural activity (e.g., because it may alleviate water shortages for several crop seasons), even if in the short term its effect may be detrimental.

We also observe that the coefficient of A is positive. This suggests that people in more agriculturally-oriented districts tend to migrate more, holding constant climate and the other covariates included in the regression, possibly because they belong to the poorest and most rural areas or they are the most dependent on agricultural productivity.

The fact that climate (respectively, agriculture) affects migration flows holding fixed agriculture (respectively, climate), coupled with the result that migration is more sensitive to climate in more agriculturally-oriented districts, does not necessarily imply that climate affects migration through an agricultural channel. However, as we discuss in the literature review (see Appendix B) a growing number of contributions highlight the existence of a causal link between climate, agriculture and migration. In order to test this conjecture in the case of South Africa, we examine whether and how the variability of our agricultural variable, predicted by climatic variables, fixed effects and time trends alone, influences migration flows in a specification not accounting for climate. More precisely, we first estimate via OLS the equation:

$$A_{i,\tau} = \kappa + \psi_i + \delta_\tau + \boldsymbol{\mu}\mathbf{C}_{i,\omega(\tau)} + \nu_{i,\tau}, \tag{2}$$

where τ = 1996, 2007; the time intervals $\omega(\tau)$ that we employ to build climatic variables are, respectively, 1991–1995 and 2002–2006; ψ_i are district fixed effects; δ_τ are time dummies; $\nu_{i,\tau}$ is a zero-mean error; and climatic variables are as in Eq. (1). We then use the predicted values $\hat{A}_{i,\tau}$ from Eq. (2) to fit migration flows via PPML in the regression:

$$m_{ij,t} = \kappa \cdot \exp\{\psi_i + \phi_{j,t} + \boldsymbol{\beta}\mathbf{Z}_{ij} + \boldsymbol{\theta}\mathbf{X}_{i,\tau(t)} + \alpha \hat{A}_{i,\tau(t)}\} \cdot \varepsilon_{ij,t}, \tag{3}$$

that is, in a gravity model as in Eq. (1) without climate and with predicted agricultural variable from Eq. (2).

The top panel of Table 4 presents results of the estimation of Eq. (2) for three combinations of climatic variables: (i) positive maximum temperature and negative precipitation anomalies; (ii) positive maximum temperature and positive precipitation anomalies; (iii) soil moisture. Our findings suggest that adverse changes in climate, in particular positive extremes in maximum temperature, negative rainfall excess and lower soil moisture, may negatively and significantly affect agricultural employment. This parallels results from a number of studies in the context of Sub-Saharan African countries, linking changes in climate to agricultural output (e.g., crop yield, see Schlenker and Lobell, 2010; Müller et al., 2011; Shi and Tao, 2014).

Furthermore, as the bottom panel of Table 4 shows, the predicted decrease in agricultural employment due to adverse climate conditions may increase migration flows, as indicated by the negative and significant signs of the coefficients of $\hat{A}$ in Eq. (3). Note that the negative sign of predicted A obtained here does not contradict the positive effect of A found in Table 3. Indeed, in the latter case we are assessing the overall effect of A, holding constant climatic factors. Conversely, in Eq. (3), the predicted A captures only the variability of agricultural employment explained by climate, thus abstracting from any other factor involved in the causal relationship from agriculture to migration.

The evidence regarding the association between climate-predicted agricultural employment and migration, together with the significant climate–agriculture interaction effects, provide additional support for our hypothesis that the climate-migration link may also take place via an agricultural channel.

4. Conclusions

Our analysis indicates that post-apartheid internal migration flows in South Africa are satisfactorily captured by a gravity specification, where a number of geographical, economic, socio-demographic and environmental factors play a significant role in shaping mobility across districts. Overall, our findings reveal that temperature and precipitation anomalies at origin exert asymmetric push effects in enhancing out-migration, with rainfall shortages and excess temperature showing the strongest impacts. Moreover, soil moisture appears to be an additional important factor to explain migration flows. These results are robust to a number of alternative econometric specifications.

We further find that the relative impact of climatic variables significantly varies across migrant groups, particularly black and low-income South Africans seem to be affected the most. The higher vulnerability to climate variability among these groups may force them to use migration as an adaptation strategy. This raises concerns about the people that might be even more vulnerable to the impact of climate change, but cannot afford migration as an adaptation mechanism.

We further show that agriculture is a possible channel through which harmful climatic impacts may induce population mobility. Support for this assertion lies within the asymmetry of effects that precipitation and temperature anomalies have on migration, which correspond to the differences between droughts and floods, and between cold spells and heat waves, in terms of their potential agricultural impacts. For example, droughts tend to be more temporally persistent than wet periods (Sheffield and Wood, 2009), while cereal crops such as maize and wheat are particularly sensitive to drought stress during the flowering and grain-filling stages (Rosenzweig et al., 2001). Adding to this, drought and high temperature, which tend to co-occur, have a synergistically negative impact on yields (Rosenzweig, 2010; Lobell et al., 2013). Furthermore, maize yields are particularly sensitive to high temperatures, declining non-linearly above 30 °C (Lobell et al., 2011). These temperatures can occur frequently in substantial portions of South Africa's maize growing region (Estes et al., 2013), whereas extreme cold events (which are declining in frequency) do not (New et al., 2006).

The study can be extended in at least three ways. First, as mentioned, our econometric specifications do not take into account spatial autocorrelation possibly existing in climatic data and migration flows. However, the spatial econometrics of gravity model estimation is still in its infancy, especially as far as gravity models of migration are concerned. Therefore, a challenging follow up to this study would entail experimenting with these frontier methodologies in the specific case of internal migration in South Africa. This would not only permit to double check our main conclusions about the influence of climate variability on migration but, more generally, to lay the basis for spatial econometric approaches to gravity models of migration. Second, our estimates indicate that panel gravity models provide a relatively accurate representation of internal migration flows in South Africa (in line with Garcia et al., 2014). This suggests that an interesting exercise would be to employ this econometric specification to predict future migration flows using alternative scenarios as to economic and climatic variables. Third, our macro-level analysis focusing on migration flows could be complemented by a micro-approach, aimed at identifying the environmental and non-environmental determinants of individual migration decisions. For example, a natural follow-up to our analysis would be to further investigate the potential constraints to individual mobility. More generally, using different models and employing different data sources, which allow for the prediction of migration at different scales, will possibly increase the lines of evidence supporting a climate-migration link in South Africa.

Acknowledgements

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Appendix A. Background on South Africa

Economic profile. South Africa is one of the top three African economies and accounts for a large share of Africa's GDP (World Bank data, http://databank.worldbank.org/data/home.aspx). Although the country has been enjoying a more than twofold increase in its GDP from 1996 to 2013, per-capita GDP growth has been more modest, and is lower than the world average. As a result, despite improvements, the extreme levels of poverty, inequality and unemployment persist. According to World Bank, in year 2000 the share of population living on less than 1.90 US$ (respectively, 3.10 US$) a day (PPP) was 35.2% (respectively, 52.5%), whereas in 2011 this share was 16.6% (respectively, 34.7%), cf. http://povertydata.worldbank.org/poverty/country/ZAF. Poverty is distributed unequally among ethnic groups: around 56% of black South Africans (who account for 80% of the whole population) are estimated to be poor, as compared to only 7% of white South Africans (10% of total population). The enduring legacy of the apartheid system is further reflected in an income Gini coefficient of around 63.4% in 2011 (http://data.worldbank.org/indicator/SI.POV.GINI), which makes South Africa one of the most unequal countries in the world. In 2013, the unemployment rate reached 25%, soaring to 55% among young, black South Africans (The World Bank, 2012).

Although the tertiary sector accounts nowadays for almost two-thirds of South Africa's GDP, the agricultural sector remains an important part of the economy. Notwithstanding that a large part of its land is arid and only approximately 11% is suitable for crop cultivation (Hachigonta et al., 2013), South Africa is among the top ten world producers of many agricultural products, e.g., maize, chicory roots and grapefruits in terms of both quantity and value (faostat.fao.org) and, in normal years, is a net food exporter, making it among a few countries in the world capable of exporting food on a regular basis. The commercial, mostly white-controlled, agricultural sector accounts for 5–10% of formal employment (about 1.5m people). However, about 20% of South African households (about 2.9m) are informally involved in subsistence and small-holder farming (Statistics South Africa, 2011).

Administrative divisions. The primary administrative divisions of South Africa are the 9 provinces: Eastern Cape, Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West, Northern Cape and Western Cape. The provinces are divided in 52 district councils, 8 of which are metropolitan municipalities, see Fig. A1 and Table A1.

Climate and agriculture. South Africa can be roughly divided into different climatic zones, ranging from semi-desert to Mediterranean and subtropical conditions, among which: (i) a temperate coastal zone (including Western Cape); (ii) a sub-

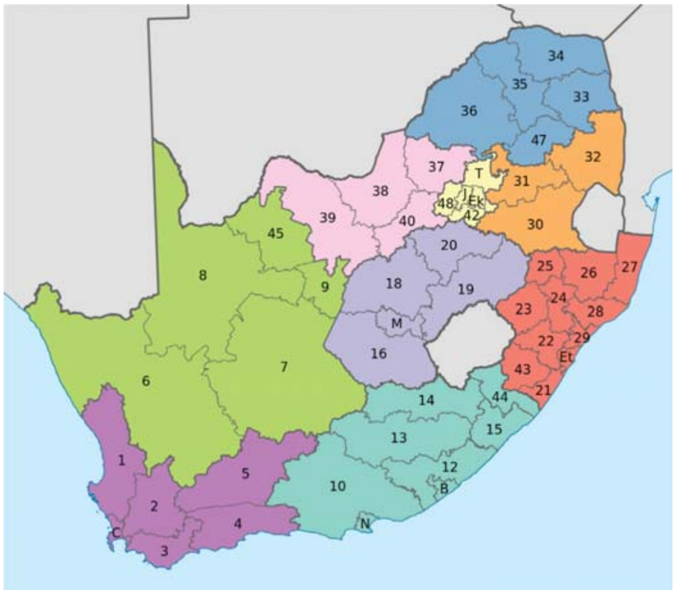

Fig. A1. South African Provinces and Districts. The 9 provinces are depicted in different colors. Districts are numbered. See Table A1 for the complete list of provinces and districts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table A1
South African districts and provinces.

Map code	District name	Province	Map code	District name	Province
10	Cacadu	Eastern Cape	29	iLembe	KwaZulu-Natal
12	Amathole	Eastern Cape	43	Sisonke	KwaZulu-Natal
13	Chris Hani	Eastern Cape	Et	eThekwini[a]	KwaZulu-Natal
14	Joe Gqabi	Eastern Cape	33	Mopani	Limpopo
15	OR Tambo	Eastern Cape	34	Vhembe	Limpopo
44	Alfred Nzo	Eastern Cape	35	Capricorn	Limpopo
B	Buffalo City[a]	Eastern Cape	36	Waterberg	Limpopo
N	Nelson Mandela Bay[a]	Eastern Cape	47	Sekhukhune	Limpopo
16	Xhariep	Free State	30	Gert Sibande	Mpumalanga
18	Lejweleputswa	Free State	31	Nkangala	Mpumalanga
19	Thabo Mofutsanyana	Free State	32	Ehlanzeni	Mpumalanga
20	Fezile Dabi	Free State	37	Bojanala Platinum	North West
M	Mangaung[a]	Free State	38	Ngaka Modiri Molema	North West
42	Sedibeng	Gauteng	39	Dr Segomotsi Mompati	North West
48	West Rand	Gauteng	40	Dr Kenneth Kaunda	North West
Ek	Ekurhuleni[a]	Gauteng	6	Namakwa	Northern Cape
J	City of Johannesburg[a]	Gauteng	7	Pixley ka Seme	Northern Cape
T	City of Tshwane[a]	Gauteng	8	Siyanda	Northern Cape
21	Ugu	KwaZulu-Natal	9	Frances Baard	Northern Cape
22	uMgungundlovu	KwaZulu-Natal	45	John Taolo Gaetsewe	Northern Cape
23	uThukela	KwaZulu-Natal	1	West Coast	Western Cape
24	uMzinyathi	KwaZulu-Natal	2	Cape Winelands	Western Cape
25	Amajuba	KwaZulu-Natal	3	Overberg	Western Cape
26	Zululand	KwaZulu-Natal	4	Eden	Western Cape
27	uMkhanyakude	KwaZulu-Natal	5	Central Karoo	Western Cape
28	uThungulu	KwaZulu-Natal	C	City of Cape Town[a]	Western Cape

Note: Map code: see Fig. A1.

[a] Metropolitan district municipalities.

tropical coastal region, with high temperature and precipitation, mostly coinciding with the KwaZulu-Natal province; (iii) a cold interior, including Gauteng, Free State and part of Northern Cape provinces: (iv) an arid interior (north-western part of Northern Cape); and (v) a hot interior including Limpopo and Mpumalanga provinces, bordering with Mozambique and Zimbabwe.

Fig. A2 depicts long-run (1950–2011) averages of precipitation (per square kilometer) and yearly-average temperature. Rainfall is distributed unevenly across the country, with humid subtropical conditions in the east and dry desert-like conditions in the west. The country's average annual rainfall is 450 mm/year, which is well below the world's average of 860 mm (Turpie and Visser, 2012). Higher temperature is observed in the hot and arid interior, as well as in the sub-tropical coastal region.

Average annual temperature has exhibited positive trends between 1960 and 2000, with an increase by about 0.13 °C per decade (Kruger and Shongwe, 2004). Moreover, high temperature extremes have increased significantly in frequency in most seasons across the country, but particularly in the western and northern interior (DEA, 2013). Annual average rainfall trends are weak, but there is a tendency towards a significant decrease in the number of rainy days in almost all climatic zones, and high inter-annual variability.

According to the IPCC, a widespread and significant pattern of climate change is projected for South Africa (van Oldenborgh et al., 2013). Indeed, temperature is projected to increase by 1.5–2.0 °C under the RCP4.5 scenario in the period 2081–2100 (over the 1986–2005 baseline). Also, precipitation is projected to decrease by about 10% in the same period, especially in the southern and

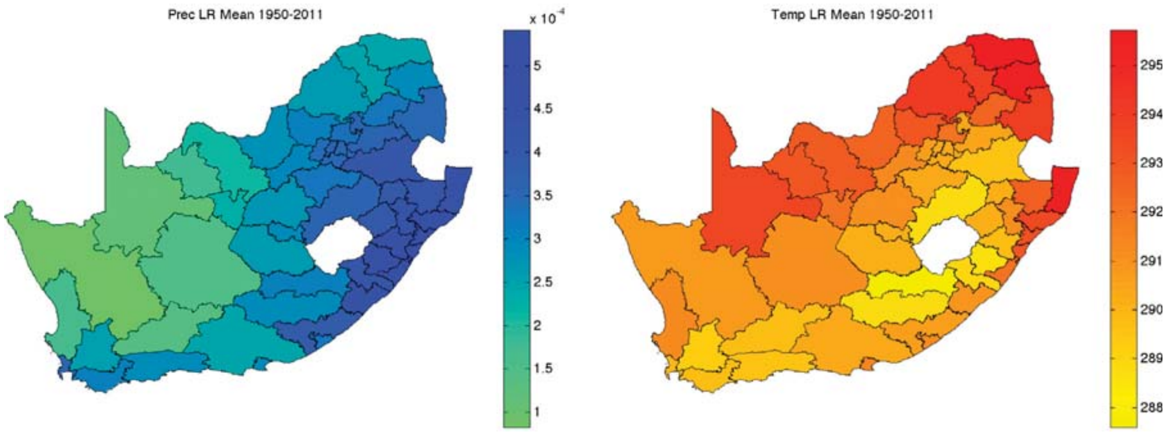

Fig. A2. Choropleth maps of some climatic indicators. Resolution level: South African district councils. Left panel: long run average precipitation per km^2 (1950–2011); right panel: long run average temperature in K degrees (1950–2011).

western areas, thus possibly exacerbating the aridity trends already observed in those zones. For example, the RCP8.5 scenario predicts a substantial increase in the consecutive drought day index for the period 2081–2100 (over the 1986–2005 baseline).

Several studies indicate that climate change is likely to negatively affect agricultural output and performance in African countries (Lobell et al., 2008). For example, net revenues from crop agriculture have been shown to decrease as precipitation falls and temperature increases, especially in small-holder farms (Kurukulasuriya and Mendelsohn, 2007). Therefore, the projected trends for temperature and rainfall could affect the agricultural sector by harming people directly or indirectly involved in agriculture, possibly reducing the areas planted, and eventually inducing already-marginal farming communities to become further impoverished (Turpie and Visser, 2012).

Appendix B. Literature review

Environmental migration. Recent studies have identified environmental factors as a possible driver of human migration, in addition to already-established drivers related to economic, social, political and demographic determinants (Black et al., 2011). Environmental factors that may potentially affect human migration range from extreme, sudden events and natural disasters, to more gradual changes in climate (Raleigh et al., 2008; McLeman, 2013a).

Existing literature has addressed environmental drivers of human migration both from a theoretical perspective (McLeman, 2013b; Marchiori and Schumacher, 2011; Kniveton et al., 2012) and, mostly, using statistical and econometric models (see Piguet, 2010, for a review). This work emphasizes the complexity underlying the relationships between environmental factors and migration, highlighting that environmental and non-environmental drivers are highly interdependent (Perch-Nielsen et al., 2008; Warner et al., 2010; Bie Lilleor and Van den Broeck, 2011). Indeed, environmental factors can affect migration decisions through natural hazards that may displace populations, as well as through pure non-market costs (e.g., the spread of diseases as a result of changing climate may negatively affect health and wellbeing in some regions). Also, adverse environmental changes can negatively impact on household-asset value and income through land and property degradation, and through declines in agricultural performance (e.g., reduction in crop yields). This may in turn negatively influence the well-being of people whose income is directly or indirectly related to the agricultural sector (Feng et al., 2010, 2012; Marchiori et al., 2012).

The role of environmental factors in shaping migration decisions and flows, also through their impact on agricultural output, might be quite relevant in the case of rural–urban migration, and the associated phenomena of circular and return migration (Bilsborrow, 2002; Asfaha and Jooste, 2006; Parnell and Walawege, 2011). This is particularly true for African countries, where rural–urban migration accounts for roughly half of the extraordinary trends in urbanization growth between the 1960s and 1990s (Barrios et al., 2006).

Empirically quantifying the extent to which environmental factors influence internal and international migration may be difficult, not only because of the multi-faceted nature of the phenomenon, but also because people who are more vulnerable to extreme weather events or climate variability could also be the least likely to migrate, due to social, economic and political constraints (Black et al., 2013; McLeman and Hunter, 2010).

Nevertheless, a growing number of contributions find that environmental factors exert a significant effect on both international and internal migration (Bie Lilleor and Van den Broeck, 2011; Obokata et al., 2014). On the one hand, climate has been found to affect international outmigration from poor to rich (OECD) countries (Coniglio and Pesce, 2015). In particular, Cai et al. (2014) show that temperature at origin positively affects outmigration to OECD destinations in agriculturally-dependent countries. The existence of a link between climate, agriculture and migration is confirmed by Marchiori et al. (2012), for the case of sub-Saharan African countries, and by Feng et al. (2010), who find a significant influence of climate-driven variation in crop yields on emigration from Mexico to the United States. Furthermore, Beine and Parsons (2015) identify an indirect effect of environmental factors on bilateral international-migration flows through a wage channel.

Many studies have investigated the relationships between climate and internal migration. Despite the fact that much of migration, whether environmental-induced or not, occurs within national boundaries (McLeman, 2013a), cross-country comparable and reliable data on internal migration are difficult to identify (Bell et al., 2015). Therefore, most of the literature has analyzed country-specific cases, using either a micro or a macro approach. Micro approaches employ individual or household observations and investigate the environmental and non-environmental determinants of their migration choices. Macro approaches instead explore the drivers of internal migration flows, from (and to) administrative units (such as districts and provinces), obtained aggregating observed, individual migration. Overall, internal migration studies identify strong and significant effects of environmental factors on migration. For example, Henry et al. (2004) use an event-history micro approach to study internal migration in Burkina-Faso and find that rainfall deficits increase the likelihood of both temporary and permanent first migrations. Similarly, Gray and Bilsborrow (2013) show that increases in climate variability are likely to result in higher internal household migration rates for rural Ecuador, although more vulnerable, poor internal migrants may find themselves trapped in immobility conditions due to financial constraints. Furthermore, Bohra-Mishra et al. (2014) found a non-linear, permanent response to temperature variation of household internal migration in Indonesia, but a small impact of natural disasters. From a macro, aggregate perspective Feng et al. (2012) study net migration flows among US counties, pointing to a significant correlation with changes in climate-driven crop-yield variation. Adverse conditions concerning rainfall variability and land degradation at origin are likely to influence inter-provincial bilateral migration flows in Burkina-Faso, as suggested by the gravity-model exercises in Henry et al. (2003).

International and internal migration in South-Africa. Historically, South Africa has been one of the most attractive destinations for migrant workers originating in Sub-Saharan Africa countries (e.g., Zimbabwe, Lesotho, Mozambique, and Swaziland). Labor immigration has traditionally concerned both skilled immigrants and less skilled ones who have been entering the country legally and illegally. These workers have largely entered the country temporarily to find a job in the mining industry or in the agricultural sector (Kok et al., 2005). Recent studies show that legal international immigration exerts a significant impact on internal labor market, especially on employment status of natives (Facchini et al., 2013). Whereas immigration has come in waves over the years, international migration from South Africa has followed a relatively stable pattern, at least until 2000, with most out-migration concerning high-skilled workers permanently moving to the UK, the US, Canada, Australia and New Zealand.

Despite its political relevance, international migration is a relatively smaller phenomenon as compared to within-border movements of people in South Africa. Projections by the Department of Home Affairs (2008/9) and Forced Migration Studies Programme (www.migration.org.za) estimate the stockof total (documented and undocumented) foreign population in South Africa to range from 1.6 and 2 million (about 3% of country's population). According to the OECD (oecd.org/els/mig/dioc.htm), the estimated stock of emigrant South African population is 520,000 in

2011. As we discuss below (see Section C), comparable (or higher) figures are observed for total 4-year flows of internal migration across provinces, suggesting that flows of internal migration are by far more relevant in magnitude than international net flows.

During the 20th century, internal migration in South Africa was largely constrained by several measures enacted by the government, which were aimed at restricting the movement of black South African workers (Kok et al., 2005). These policies ranged from systems that compelled African workers to not leave the farms wherein they worked, to laws regulating the circumstances under which Africans were permitted to live in urban areas (influx control). This set of racially-based interventions have been constrained, or even immobilized, certain categories of citizens for a long time, leaving them in vulnerable states. Their long-lasting effects might be at the roots of the relative persistence of internal migration patterns observed in South Africa after the end of the apartheid, when restrictive laws were finally dropped (Kok et al., 2005).

Non-environmental determinants of South African migration have been studied by Kok et al. (2003) using data from the 1996 census. Using a logistic (micro) regression, they find that the probability of becoming a migrant increases with income and education; whether the origin is urban; is higher in Gauteng and Western-Cape provinces; and decreases with age. In their study, Kok et al. (2003) also fit a simple gravity-model to describe province-to-province migration flows from 1992 to 1996, exploring the importance of variables such as relative origin-destination income, unemployment, ethnic dominance, and security (as proxied by reported crimes). Economic and education factors are shown to be relevant also in assessing migration preferences towards alternative locations by black males. Indeed, using the same data, Choe and Chrite (2014) show that individuals prefer higher-wage districts. Furthermore, they suggest that black, highly-educated (respectively, poorly-educated) South Africans tend to migrate to districts with a high (respectively, low) share of highly-educated people.

Appendix C. Descriptive statistics

Characteristics of migrants. According to our definition of migrants, total 5-year migration flows account for about 5% of South African population, resulting in about 2.3m people that moved across districts in both the periods 1997–2001 and 2007–2011. The incidence of migration flows over the total population has therefore slightly decreased due to the increase of South African population from 44.3m to 51.6m people from 2001 to 2011.

Table C1
Characteristics of migrants.

	% of migrants		% migrants/% population	
	1997–2001	2007–2011	1997–2001	2007–2011
Male	50.51	52.64	1.06	1.08
Black	71.02	72.79	0.92	0.93
White	21.13	19.22	1.99	2.07
0–14[b]	14.56	16.28	0.45	0.56
15–64[b]	82.61	81.00	1.31	1.24
Over 65[b]	2.83	2.72	0.57	0.51
Not married	50.56	50.39	0.97	0.93
Married	32.85	31.59	0.98	1.03
No school[a]	9.09	3.28	0.45	0.34
Primary[a]	18.03	9.96	0.75	0.54
Secondary[a]	56.06	61.11	1.20	1.06
University[a]	16.82	25.03	1.90	2.06
Unemployed	22.71	21.73	0.94	0.84
Employed	45.23	57.56	1.33	1.48

Source: Statistics South Africa, censuses 2001 and 2011.

% of migrants: percentage of migrants with characteristic in row over the correspondent total migration flow for each 5-year period in column. % migrants/% population: ratio between percentage in first four columns and correspondent percentage in the reference population (15–64 years old, except for: a = over 25 years old; b = all ages).

Table C1 describes how migrants differ in terms of a number of defining characteristics. Columns (1)–(2) report the percentage of migrants possessing a given characteristic (row) over the corresponding total migration flow for each 5-year period (column). Columns (3)–(4) contain the ratio between the percentages in the first four columns and the corresponding percentage in the reference population. Values larger than one imply that a given characteristic is over-represented among migrants (with respect to the reference population). The table suggests that gender is equally represented among migrants. Also, a larger proportion of migrants tends to be single (as compared to those married). With regard to ethnic groups, black South Africans account for the majority of migrants (about 70%) but white South

Table C2
Socio-economic and demographic variables: summary statistics.

Stat	Population		White		Unemployment		Primary		Agriculture	
	2001	2011	2001	2011	2001	2011	2001	2011	2001	2011
Mean	797,496	913,420	0.102	0.077	0.408	0.428	0.769	0.705	0.042	0.027
Min	33,742	53,737	0.000	0.000	0.113	0.185	0.566	0.469	0.005	0.009
Median	643,253	677,407	0.087	0.074	0.391	0.411	0.780	0.715	0.026	0.022
Max	2,867,889	3,987,334	0.293	0.218	0.731	0.665	0.892	0.827	0.148	0.078
Std. dev.	640,089	854,347	0.077	0.060	0.158	0.110	0.075	0.082	0.038	0.017

Table C3
Climatic variables: summary statistics.

Stat	Pos T_{max} anom		Neg precip anom		Neg T_{min} anom		Pos precip anom		Soil moisture	
	2001	2011	2001	2011	2001	2011	2001	2011	2001	2011
% zeros	52.9	66.7	96.1	25.5	33.3	100.0	3.9	74.5	–	–
Mean	0.346	0.370	0.089	0.374	0.401	–	0.795	0.322	51.514	49.748
Min	0.012	0.047	0.060	0.007	0.028	–	0.013	0.019	35.043	33.844
Median	0.305	0.280	0.089	0.427	0.403	–	0.836	0.333	51.565	49.628
Max	0.957	1.078	0.118	0.658	1.222	–	1.555	0.642	65.792	63.963
Std. dev.	0.249	0.273	0.029	0.183	0.264	–	0.402	0.200	8.093	8.033

Note: Summary statistics for all variables except soil moisture computed excluding zeros.

Africans are largely over-represented (the share of white migrants is two times that in the total population). As far as age structure is concerned, we find, as expected, that people in the age interval 15–64 (adults) make up the large majority of all migrants (about 80%). In addition, they are slightly over-represented as compared to their share in the population.

Furthermore, we report figures about education levels, counting migrants more than 25-years old who completed fully or partially primary school, secondary school, or university. Secondary-school and university migrants account for the largest share (about 86% in the 2007–2011 period), and both are over-represented as compared to the total population. Their shares have been increasing across the two waves at the expense of those of less-educated migrants, which decreased from 27% to 13%. Finally, as for employment status at destination, migrants tend to be mostly employed, indicating that when they reach their target destination, they are likely to find a job.

Immigration and emigration in South African provinces and districts. South African districts exhibit a rather concentrated pattern of immigration and emigration flows, where the attractive role of metropolitan municipalities clearly emerges. About 52% of all immigrants are absorbed by five metropolitan districts, three of them belonging to the Gauteng province (Johannesburg, Tshwane/Pretoria and Ekurhuleni), the city of Cape Town in the Western Cape province, and the city of Durban (eThekwini metropolitan municipality) in the KwaZulu-Natal province (see Fig. C1). These five districts together also account for about 45% of all emigrants. This is partly explained by their large population, which makes up about 34% of the total. Note that the metropolitan districts of Johannesburg, Tshwane/Pretoria and Cape Town also feature the highest emigration and immigration rates (i.e., after having rescaled emigration and immigration flows by district population).

Aggregating the data at the level of provinces, Fig. C2 shows the map of 2007–2011 net migration rates (immigration rate minus emigration rate, where rates are computed as ratios between migration flows and province population). We see that Gauteng and Western Cape turn out to be the provinces with largest and positive net rate. At the opposite, Limpopo and Eastern Cape, which are the two poorest provinces in South Africa, exhibit a preponderance of emigration over immigration. This hints to the importance of economic factors in explaining internal migration patterns in South Africa.

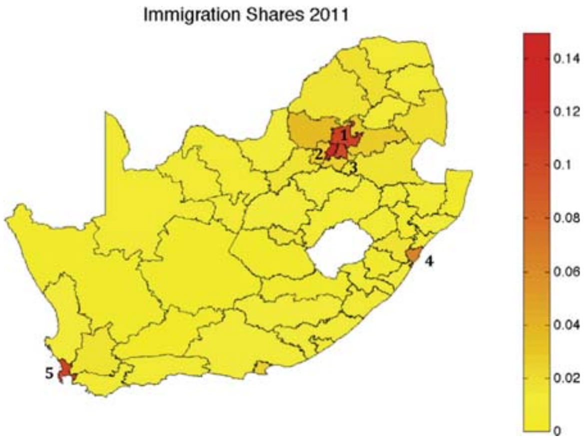

Fig. C1. Choropleth map of districtual immigration shares (2007–2011). Shares computed as districtual immigration flows over total districtual migration flows. *Note*: (1) Tshwane/Pretoria; (2) Johannesburg; (3) Ekurhuleni; (4) Ekurhuleni/ Durban; (5) Cape Town.

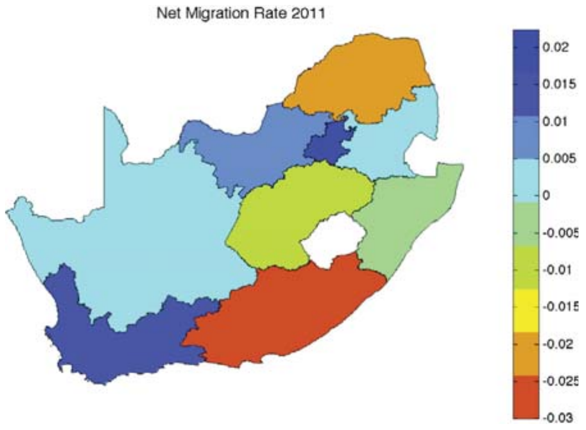

Fig. C2. Choropleth map of provincial net migration rates (2007–2011). Net migration rates computed as immigration rate minus emigration rate; rates computed as ratios between migration flows and province population.

Appendix D. Push vs. pull effects

This section describes additional econometric setups of the gravity equation where we play with alternative specifications of push and pull effects. Our main exercises were performed focusing on push effects and controlling for time invariant and time dependent pull factors using time-destination dummies, see Eq. (1). We now explore two alternative setups where we explicitly control for destination time-variant covariates and time-invariant fixed effects. Furthermore, we introduce a third setup where dyadic climatic variables are employed.

In the first setup, we model push factors using origin time-invariant fixed effects and time-varying origin covariates as follows:

$$m_{ij,t} = \kappa\cdot\exp\{\psi_i + \phi_j + \delta_t + \boldsymbol{\beta}\mathbf{Z}_{ij} + \boldsymbol{\theta}_i\mathbf{X}_{i,\tau(t)} + \boldsymbol{\mu}_i\mathbf{C}_{i,\omega(t)} + \boldsymbol{\theta}_j\mathbf{X}_{j,\tau(t)} + \boldsymbol{\mu}_j\mathbf{C}_{j,\omega(t)}\}\cdot\varepsilon_{ij,t} \tag{4}$$

where (ψ_i, ϕ_j) are origin and destination time-invariant fixed effects; ($\mathbf{X}_{j,\tau(t)}$, $\mathbf{C}_{j,\omega(t)}$) are destination covariates mirroring those for origins; ($\boldsymbol{\theta}_i$, $\boldsymbol{\mu}_i$, $\boldsymbol{\theta}_j$, $\boldsymbol{\mu}_j$) are origin and destination covariate coefficients; and δ_t is a time dummy.

The second setup features a specification specular to Eq. (1), where we fully control for push effects with time-origin dummies and pull factors are modeled using time-invariant fixed effects and time-varying covariates:

$$m_{ij,t} = \kappa\cdot\exp\{\psi_j + \phi_{i,t} + \boldsymbol{\beta}\mathbf{Z}_{ij} + \boldsymbol{\theta}\mathbf{X}_{j,\tau(t)} + \boldsymbol{\mu}\mathbf{C}_{j,\omega(t)}\}\cdot\varepsilon_{ij,t}. \tag{5}$$

Finally, in the third setup we introduce four dyadic climatic variables, defined as the difference between the following origin (i) and destination (j) variables: positive maximum temperature anomalies, negative/positive precipitation anomalies and soil moisture. Note that these dyadic variables vary over the (ijt) dimension. Therefore, we add fixed effects and socio-economic/ demographic covariates at both origin and destination. The equation to be estimated thus reads:

$$m_{ij,t} = \kappa\cdot\exp\{\psi_i + \phi_j + \delta_t + \boldsymbol{\beta}\mathbf{Z}_{ij} + \boldsymbol{\theta}_i\mathbf{X}_{i,\tau(t)} + \boldsymbol{\theta}_j\mathbf{X}_{j,\tau(t)} + \boldsymbol{\mu}\mathbf{C}_{ij,\omega(t)}\}\cdot\varepsilon_{ij,t}, \tag{6}$$

where $\mathbf{C}_{ij,\omega(t)}$ is the vector of dyadic climatic variables.

Results of the estimation of Eqs. (4)–(6) are presented in Table D1 and discussed in the main text.

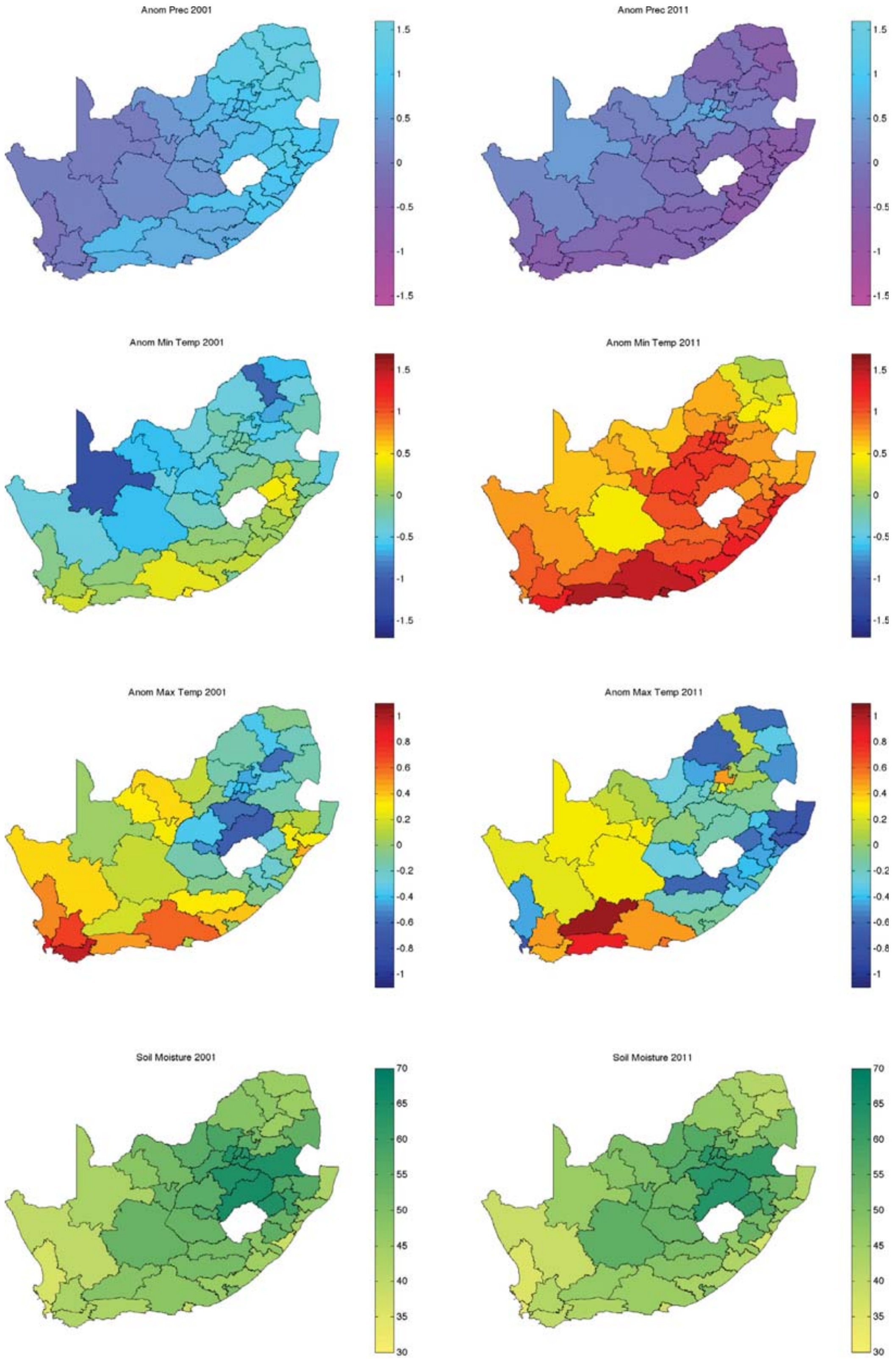

Fig. C3. Choropleth maps of precipitation and temperature anomalies, and soil moisture. Resolution level: South African district councils.

Table D1
Alternative specifications of pull and push effects.

	Push and pull covariates			Pull covariates only			Dyadic climatic variables		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Distance	−0.9419***	−0.9416***	−0.9425***	−0.9432***	−0.9423***	−0.9433***	−0.9431***	−0.9426***	−0.9430***
Contiguity	0.5241***	0.5253***	0.5242***	0.5264***	0.5284***	0.5228***	0.5235***	0.5252***	0.5235***
Population (i)	0.5413***	0.5675***	0.3535***				0.4118***	0.4283***	0.3648***
Primary (i)	-8.2926***	−6.9355***	−7.1310***				−8.5833***	−7.4635***	−7.2476***
White (i)	3.1895***	4.4813***	−0.0388				1.2397	2.0661*	0.3894
Unemployment (i)	0.9390***	0.3899	−0.1426				0.5985**	0.0920	−0.0862
Population (*j*)	0.2046	0.2442*	0.1094	0.1346	0.1979**	0.0658	0.0158	0.0683	0.1190
Primary (*j*)	0.3364	−0.1532	−0.5435	−0.0080	−0.5201	−0.6788	0.4664	−0.3609	−0.9161
White (*j*)	1.6230	1.8902	−0.0458	1.0893	1.2676	−0.1498	−0.8542	−0.7760	0.1575
Unemployment (*j*)	−0.6584*	−0.3030	−0.6978*	−0.7537**	−0.3159	−0.7160**	−1.2924***	−0.7905**	−0.6523*
Pos $T_{\max}$ anom (i)	0.5096***	0.5012***							
Neg Precip anom (*i*)	0.6224***								
Pos Precip anom (*i*)		0.1394*							
Soil moisture (*i*)			−0.1129***						
Pos $T_{\max}$ anom (*j*)	0.1510	0.1766*		0.1027	0.1472				
Neg Precip anom (*j*)	−0.3870***			−0.3523***					
Pos Precip anom (*j*)		−0.1164**			−0.1116***				
Soil moisture (*j*)			0.0232			0.0267			
Pos $T_{\max}$ anom (*ij*)							0.1649**	0.1226*	
Neg Precip anom (*ij*)							0.5717***		
Pos Precip anom (*ij*)								0.1236***	
Soil moisture (*ij*)									0.0772***
Fixed effects	*i* ; *j*	*i* ; *j*	*i* ; *j*	*it* ; *j*	*it* ; *j*	*it* ; *j*	*i* ; *j*	*i* ; *j*	*i* ; *j*
N	5000	5000	5000	5050	5050	5000	5000	5000	5000
Model DF	115	115	113	159	159	157	113	113	112
Pseudo R^2	0.8371	0.8363	0.8355	0.8438	0.8437	0.8432	0.8359	0.8349	0.8353
Wald Chi^2	7459.3***	6613.0***	6888.1***	9346.5***	9754.3***	9119.4***	7388.1***	6796.7***	6897.3***

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

Appendix E. Additional specifications

Table E1
Specifications with alternative climatic variables.

	(1)	(2)	(3)	(4)	(5)	(6)
Distance	−0.9396***	−0.9409***	−0.9394***	−0.9399***	−0.9413***	−0.9412***
Contiguity	0.5318***	0.5314***	0.5316***	0.5316***	0.5306***	0.5310***
Population	0.4151***	0.3603***	0.4352***	0.3889***	0.3899***	0.5936***
Primary	−8.9894***	−7.8546***	−7.4122***	−6.8742***	−9.1268***	−9.0555***
White	1.5875	1.3208	2.8785***	2.2470**	2.0495*	4.4964***
Unemployment	0.6542***	0.4648*	0.0951	0.0701	0.6207***	1.0825***
Neg Precip anom	−0.6339***	−0.4977***			−0.8099***	−1.0521***
Pos Precip anom			0.0885	0.0390	0.2031**	0.3550**
Pos $T_{\max}$ rainy anom	0.7419***		0.6140***		0.8931***	
Neg $T_{\min}$ rainy anom		0.0963		0.0546	0.0555	
Pos $T_{\max}$ anom						0.6778***
Neg $T_{\min}$ anom						0.2716**
N	5050	5050	5050	5050	5050	5050
Model DF	159	159	159	159	161	161
Pseudo R^2	0.8393	0.8384	0.8385	0.8378	0.8398	0.8406
Wald Chi^2	9751.0***	9627.6***	7806.0***	8131.0***	8948.9***	9079.7***

Panel data analysis. Poisson Pseudo Maximum-Likelihood (PPML) estimates. Dependent variable: 5-year district-to-district migration flows of 15–64 year-old people. Constant, time-invariant origin and time-destination fixed effects, demographic and socio-economic origin controls, and bilateral covariates included in all regressions.
* Significance: $p < 0.10$.
** Significance: $p < 0.05$.
*** Significance: $p < 0.01$.

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