ON THE HYDROCLIMATE OF SOUTHERN SOUTH AMERICA: WATER VAPOR TRANSPORT AND THE ROLE OF SHALLOW GROUNDWATER ON LAND-ATMOSPHERE INTERACTIONS

by

John Alejandro Martinez Agudelo

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF ATMOSPHERIC SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

DOCTOR OF PHILOSOPHY

WITH A MAJOR IN HYDROMETEOROLOGY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2015
As members of the Dissertation Committee, we certify that we have read the dissertation prepared by John Alejandro Martinez Agudelo, titled On the Hydroclimate of Southern South America: Water Vapor Transport and the Role of Shallow Groundwater on Land-Atmosphere Interactions and recommended that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Francina Dominguez  
Date: 11/23/2015

Xubin Zeng  
Date: 11/23/2015

Peter Troch  
Date: 11/23/2015

Guo-Yue Niu  
Date: 11/23/2015

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director: Francina Dominguez  
Date: 11/23/2015
STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of the requirements for an advanced degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that an accurate acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: John Alejandro Martinez Agudelo
I want to thank the coauthors of this work, Dr. Francina Dominguez and Gonzalo Miguez-Macho, for their support, advise, and contributions (F. Dominguez was my academic advisor, and G. Miguez-Macho developed the groundwater scheme and provided the parameters needed to run the model).

Especial thanks to my advisor Francina Dominguez, who has been a great mentor, an example of discipline and hard work, an excellent academic guide, and a friend.

Funding for this dissertation was provided by the National Science Foundation, award 1045260, for the project “Collaborative Research: The Amazon Groundwater and its Impact on Evapotranspiration and the Climate of South America”.

I also thank the committee members, Professors Xubin Zeng, Peter Troch and Guo-Yue Niu, for reading and contributing with comments to this dissertation.

Especial thanks to Professors James Shuttleworth and Hoshin Gupta, for providing very important feedback during the meetings of Francina Dominguez’ Hydrometeorology group.

Thanks to the Professors, Staff and Students of the Department of Atmospheric Sciences at the University of Arizona, for their orientation, support, help and friendship in multiple aspects of my graduate studies.

I also thank my good friends Erick Rivera, Carlos Carrillo, Huancui Hu, Zhao Yang and Hsin-I Chang for their support and friendship. I learned important lessons from each one of them.

My graduate studies would have not been possible without the support of my family, including my mother, my uncles and aunts. My greatest debt is to my wife, who moved with me from the City of the Eternal Spring (Medellín, Colombia) to the Arizona Desert, and supported me in many ways during my graduate studies. I will always be grateful for her support, companionship, and unbounded love.
DEDICATION

A mi esposa,
fuente de amor y dulzura,
compañera incondicional.
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................... 7

INTRODUCTION ........................................................................................................................ 9

PRESENT STUDY ....................................................................................................................... 14

REFERENCES ............................................................................................................................ 20

APPENDIX A: SOURCES OF ATMOSPHERIC MOISTURE FOR THE LA PLATA RIVER BASIN ................................................................................................................................. 24

APPENDIX B: EFFECTS OF A GROUNDWATER SCHEME ON THE SIMULATION OF SOIL MOISTURE AND EVAPOTRANSPIRATION OVER SOUTHERN SOUTH AMERICA ................................................................................................................................. 72

APPENDIX C: IMPACTS OF A GROUNDWATER SCHEME ON HYDROCLIMATOLOGICAL CONDITIONS OVER SOUTHERN SOUTH AMERICA .... 121
ABSTRACT

The present work focuses on the sources and transport of water vapor to the La Plata Basin (LPB), and the role of groundwater dynamics on the simulation of hydrometeorological conditions over the basin. In the first part of the study an extension to the Dynamic Recycling Model (DRM) is developed to estimate the water vapor transported to the LPB from different regions in South America and the nearby oceans, and the corresponding contribution to precipitation over the LPB. It is found that more than 23% of the precipitation over the LPB is from local origin, while nearly 20% originates from evapotranspiration from the southern Amazon. Most of the moisture comes from terrestrial sources, with the South American continent contributing more than 62% of the moisture for precipitation over the LPB. The Amazonian contribution increases during the positive phase of El Niño and the negative phase of the Antarctic Oscillation.

In the second part of the study the effect of a groundwater scheme on the simulation of terrestrial water storage, soil moisture and evapotranspiration (ET) over the LPB is investigated. It is found that the groundwater scheme improves the simulation of fluctuations in the terrestrial water storage over parts of the southern Amazon. There is also an increase in the soil moisture in the root zone over those regions where the water table is closer to the surface, including parts of the western and southern Amazon, and of the central and southern LPB. ET increases in the central and southern LPB, where it is water limited. Over parts of the southeastern Amazon the effects of the groundwater scheme are only observed at higher resolution, when the convergence of lateral groundwater flow in local topographical depressions is resolved by the model.

Finally, the effects of the groundwater scheme on near surface conditions and
precipitation are explored. It is found that the increase in ET induced by the groundwater scheme over parts of the LPB induces an increase in near surface specific humidity, accompanied by a decrease in near surface temperature. During the dry season, downstream of the regions where ET increases, there is also a slight increase in precipitation, over a region where the model has a dry bias compared with observations. During the early rainy season, there is also an increase in the local convective available potential energy. Over the southern LPB, groundwater induces an increase in ET and precipitation of 13 and 10%, respectively. Over the LPB, the groundwater scheme tends to improve the warm and dry biases of the model. It is suggested that a more realistic simulation of the water table depth could further increase the simulated precipitation during the early rainy season.
INTRODUCTION

Land-atmosphere interactions shape important features of weather and climate (e.g. Cotton and Pielke (2007), Betts (2004, 2009)). The distribution of water vapor in the atmosphere, and the characteristics of the fluxes of energy, matter and momentum in the land-atmosphere interface are fundamental aspects of the hydroclimate of a region. These aspects interact with the patterns and variability of near surface temperature and precipitation. In this work we study aspects of the hydroclimate of the La Plata Basin (LPB). The LPB is the second largest river system in South America (Berbery and Barros, 2002), and it is one of the most densely populated areas of the continent (Lee and Berbery, 2012). The area of the LPB is nearly one third of the area of the conterminous United States, with a mean river discharge that exceeds by nearly 25% that of the Mississippi river (Berbery and Barros, 2002). The LPB is also venue of some of the most powerful storms on earth (Zipser et al., 2006). The economy of the region heavily relies on its water resources for agricultural activities and generation of hydropower (Lee and Berbery, 2012). Therefore, the hydroclimate of the region is of great societal and economical importance, and it responds to both large scale and local drivers. For example, during El Niño conditions there is a change in the regional circulation, which is associated with an increase in precipitation over the southern LPB (Grimm et al., 2000). In addition, land use/land cover changes over the region seem to be associated with local changes in near surface temperature and precipitation (Beltrán-Przekurat et al. (2012), Lee and Berbery (2012), Lee et al. (2013)).

The water vapor content of the atmosphere is one critical ingredient for the distribution
and variability of precipitation. Because of its location in southern South America, the LPB receives water vapor not only from the adjacent oceans (the Pacific and the Atlantic), but also from other regions in South America located upstream of the LPB (Berbery and Barros (2002), Marengo et al. (2004)). It has been estimated that most of the precipitation over the LPB comes from water vapor of terrestrial origin (van der Ent et al., 2010), mostly originated from evapotranspiration from regions in the South American continent, with a significant fraction provided by the Amazon basin (Dirmeyer et al., 2009). The transport of water vapor to the LPB from upstream regions in South America exhibits variability at different time scales, including variations associated with the different phases of the El Niño-Southern Oscillation (e.g. Silva et al., 2009), and the Antarctic Oscillation (Silvestri and Vera, 2003). Despite the general understanding of the transport of water vapor to the LPB, a link between the regional circulation and the estimated contributions from different sources is lacking.

Another fundamental component related to the distribution of water vapor and the local hydroclimate is evapotranspiration (ET). ET is the land surface flux that contributes water vapor to the atmosphere, which then will be transported and redistributed by the atmospheric circulation (e.g. Trenberth et al. (2011), Gimeno et al. (2012)). The water vapor transport between source and target regions estimated by different transport models depends on the estimation of ET (e.g. Bosilovich and Chern (2006), Stohl and James (2004), Dominguez et al. (2006), Dirmeyer et al. (2009), van der Ent et al. (2010)). In addition, ET is associated with the local contribution to water vapor that can favor precipitation, via the availability of moisture and its effects on atmospheric stability (Schär et al. (1999), Findell and Eltahir (2003)). Furthermore, ET is linked to the partitioning of land surface fluxes that shape near surface conditions, like
temperature. Despite its importance, even in satellite estimates and atmospheric reanalyses, ET is mostly a model product, and as such it depends on its representation in the model physics (see e.g. Vinukollu et al. (2011), and Decker et al. (2011)).

A critical component that affects the simulation of ET in Land Surface Models (LSMs) is the distribution of soil moisture. The dependence of ET on soil moisture is particularly important in regions and/or seasons when moisture availability is the major control on ET, as opposed to energy availability (i.e. radiation). Model simulations suggest that the LPB is a region where ET is sensitive to soil moisture content (e.g. Dirmeyer et al. (2009b)). However, the estimation of the soil moisture field for weather and climate studies is itself a difficult task, due to the uncertainties about the hydrologic properties of the subsurface, and limitations in the representation of some critical processes (Koster et al., 2009). Shallow groundwater is one of those components that can affect the distribution of soil moisture and ET (Miguez-Macho and Fan (2012), Fan et al. (2013)). For example, shallow groundwater can reduce the drainage rate of moisture from the soil layers above, producing moister soils during dry periods, which in turn sustains ET. In addition, if the water table is within the reach of the roots, plants can take moisture directly from the shallow aquifer, which also affects ET (Fan et al. (2013), Fan (2015)).

The representation of shallow groundwater in LSMs could be particularly important for the LPB. From a compilation of observations and the use of an equilibrium model, Fan and Miguez-Macho (2010) found that the estimated water table depth in the LPB can be within the top 4 meters of the soil. Kuppel et al. (2015) report water table depths in the range 1-3 m for a region in the southern extreme of the LPB, and a strong coupling between fluctuations in ET and the water table depth. Chen et al. (2010) found an improvement in the simulated terrestrial water
storage in data from the Global Data Assimilation System (which does not include a representation of the groundwater) when combined with groundwater data from observations. In general, several modeling studies have found an increase in the simulated soil moisture and ET over parts of South America when a groundwater scheme is included in the LSM (e.g. Niu et al. (2007), Miguez-Macho and Fan (2012), Koirala et al. (2014)). Despite the importance of shallow groundwater for soil moisture and evapotranspiration in the LPB as suggested from observations, no previous studies have investigated in detail the effects of groundwater schemes within LSMs in simulations for this region.

Because of its potential effects on soil moisture and ET, shallow groundwater could also impact the simulation of near surface conditions and precipitation. Modeling studies have found a decrease in near surface temperature and an increase in precipitation over parts of the United States during the summer season when a groundwater scheme is included in the models (Anyah et al. (2008), Jiang et al. (2009), Barlage et al. (2015)). A similar impact could be observed over the LPB, where the soil moisture field has a noticeable link with precipitation, as suggested by local coupling measures (e.g. Zeng et al. (2010), Sörensson and Menéndez (2011), Spenneman et al. (2015)) and process oriented sensitivity studies (e.g. Collini et al. (2008), Saulo et al. (2010), Doyle et al. (2013), Sörensson and Berbery (2015)). While these sensitivity studies have focused mostly on the initial specification of the soil moisture field, no studies of the effects of the shallow groundwater (affecting both the initial and boundary conditions of soil moisture) on hydrometeorological variables over the LPB have been reported so far. In particular, the potential increase in precipitation and the decrease in temperature that a groundwater scheme could induce over parts of the LPB, could contribute to the improvement of some of the dry and
warm biases observed in current regional climate simulations over the region (Solman et al. 2013).

In this work we study the sources of water vapor, and the effects of a groundwater scheme on the simulation of hydrometeorological variables over the LPB. First we extend the Dynamic Recycling Model (DRM, Dominguez et al. 2006) to study the transport of water vapor to the LPB, with particular interest in its variability, the associated regional circulation, and the contribution from the Amazon. Next we use the groundwater scheme developed by Miguez-Macho et al. (2007) within the Noah-MP LSM (Niu et al., 2011) to assess the effects of shallow groundwater on soil moisture and ET over the LPB in off-line simulations (i.e. with prescribed atmospheric conditions). Finally, we explore the impacts of the shallow groundwater on near surface conditions and precipitation over the LPB in fully coupled land-atmosphere simulations with the Weather Research and Forecasting tool, WRF (Skamarock et al., 2008) coupled with the Noah-MP LSM and the Miguez-Macho et al. (2007) groundwater scheme (Barlage et al. 2015).
PRESENT STUDY

The first part (A) is devoted to the sources and transport of water vapor to the La Plata basin. The second part (B) focuses on the effects of using a groundwater scheme on the simulation of soil moisture and evapotranspiration fields in off-line simulations with a Land Surface Model. The third part (C) is devoted to the impacts of the groundwater component on the simulation of near surface conditions and precipitation via the induced changes in soil moisture and evapotranspiration. In this section we present a summary of the major findings of each study. Details about the methodology and the results of each study can be found in the corresponding Appendix.

A. Sources of Atmospheric Moisture for the La Plata River Basin (See Appendix A)

In this study we address the transport of water vapor to the La Plata river basin from different regions in the South American continent and the nearby oceans (the Pacific and Atlantic). In particular, we are interested in assessing the relative contributions from the oceans and the South American continent, the transport from the Amazon basin to the La Plata basin, and the fraction of moisture in the La Plata basin that originates as evapotranspiration within the same basin (i.e. recycling). As a first step we extend the Dynamic Recycling Model (DRM) developed by Dominguez et al. (2006) to estimate the exchanges of atmospheric moisture among several regions. We define the regions of interest as representations of major hydrologic units in South America (including the Amazon and the La Plata basins) and the nearby portions of the Pacific and Atlantic oceans.
As input for the extended DRM we use data from the ERA-Interim archive (Dee et al., 2011) for the period 1980-2012. We find that the mean transport of moisture to the La Plata basin is dominated by the terrestrial sources from the South American continent, contributing more than 62% of the moisture over the basin. More than 24% of the mean annual precipitation originates from local evapotranspiration (i.e. recycling), while more than 20% comes from moisture from the southern Amazon. The remaining 37% of precipitation is from moisture originated from the oceans.

The variability of the transport of moisture to the La Plata basin is dominated by the variability of the atmospheric circulation instead of changes in evapotranspiration. During the summer season, anomalies in the water vapor content over the La Plata basin can be either of oceanic or terrestrial origin. In fact, we found that the anomalies from terrestrial origin can be as large as those from oceanic origin, and that one of them can compensate the other. In addition, inter-annual modes of variability have a clear signature in the transport of moisture from different sources to the La Plata basin. Compared to La Niña conditions, during El Niño more moisture from Amazonian origin reaches the La Plata basin, while the local contribution is reduced, despite the increase in local evapotranspiration. This is mostly a result of the enhancement of the northerly circulation over the region. Similar differences are observed by comparing conditions under the negative and positive phases of the Antarctic Annular Mode, respectively.

The overall results from this study illustrate the important role of terrestrial sources both in the mean and in the variability of the transport of moisture toward the La Plata basin. This suggests that this transport could be affected by changes in the land surface fluxes in the regions
upstream, e.g. from land cover/land use changes. The estimated transport of moisture might be sensitive to the input data sets, including their estimation of the evapotranspiration field. This is an important issue, as even in atmospheric reanalyses (e.g. ERA-interim) the evapotranspiration is largely model dependent.

B. Effects of a groundwater scheme on the simulation of soil moisture and evapotranspiration over southern South America (See Appendix B)

In this study we investigate the effects of a groundwater scheme on the simulation of water storage and evapotranspiration in the Noah-MP Land Surface Model (Niu et al., 2011). We use the groundwater scheme developed by Miguez-Macho et al. (2007, hereafter MMF scheme), which contains a representation of an unconfined aquifer that interacts with the unsaturated soil layers above. The scheme considers explicitly the lateral flow of groundwater, which is largely shaped by topographic gradients. We run simulations with and without the groundwater scheme using identical atmospheric forcing (i.e. off-line simulations). The simulations are run for 10 years for a domain that includes the southern part of the Amazon basin, the region most affected by the South American monsoon, and most of the La Plata river basin. In the first part of the study the simulations are performed at a resolution typical of climate simulations at the continental scale (grid size is 20 km). In the second part of the study we address the role of the horizontal resolution on the water table depth distribution and its consequent impacts on ET.

Relative to estimates from GRACE, we find that the amplitude of fluctuations in the terrestrial water storage are improved over the southern Amazon and the monsoon regions when the MMF scheme is used. The phase of the mean annual cycle is also improved over the
monsoon region. These results are consistent with previous studies where a much higher horizontal resolution was used (grid size \(\sim 2\text{km}\) was used by Pokhrel et al., 2013), and they also show the potential impact of the groundwater scheme even at the relatively coarser resolutions of current climate simulations. The simulations with the MMF scheme show an increase in soil moisture over those regions where the water table is closer to the surface, including the western and southern Amazon, and the central and southern part of the La Plata basin. The increase in soil moisture induces an increase in ET, mostly over those regions where ET is water limited, including the central and the southern La Plata basin. The differences in soil moisture and ET induced by the groundwater scheme can be in the range of 5-20\% of the absolute values obtained without the groundwater scheme.

The comparison of simulations with grid sizes of 5 and 20 km show that at higher resolution there is a larger impact of the groundwater scheme over parts of the southern Amazon. Of particular interest is the fact that the groundwater scheme has an effect on ET over some parts of the Amazon only at the higher resolution, namely those regions with topographical depressions that cannot be resolved at the lower resolution. These results are consistent with the role of the horizontal resolution suggested by Miguez-Macho and Fan (2012), although here we provide a direct comparison of different resolutions using the same modeling system.

The effects on ET over the La Plata basin and the southern Amazon are associated with different topographical controls. In the case of the La Plata basin, the water table is uniformly shallow, which makes ET larger in the groundwater simulations both at low and high resolutions. On the other hand, the existence of multiple small-scale depressions, only “visible” at higher resolution, is the cause of an increase in ET over the Southern Amazon when the groundwater is
C. Impacts of a groundwater scheme on hydroclimatological conditions over southern South America (See Appendix C)

Previous studies have found a strong coupling between soil moisture and precipitation over parts of the La Plata basin (e.g. Zeng et al. 2010, Sörensson and Menéndez 2011). In the present study we investigate the changes in hydrometeorological variables over the La Plata basin induced by the use of a groundwater scheme in simulations with the Weather Research and Forecasting tool, WRF (Skamarock et al., 2008). We use the groundwater scheme developed by Miguez-Macho et al. (2007, hereafter MMF scheme) within the Noah-MP LSM (Barlage et al., 2015).

We find that the groundwater scheme induces an increase in soil moisture and ET over the La Plata basin, consistent with our previous results from off-line simulations (Martinez et al. 2015a). During the early rainy season October-November-December, the increase in ET due to the groundwater scheme is associated with a decrease in sensible heat flux, which in turn leads to a decrease in the near surface temperature in the range of 0.5-1.0°C. The increase in ET is also associated with an increase in specific humidity, which is more pronounced during the dry season. As a result of the increase in humidity and decrease in temperature, the groundwater scheme produces a small increase in relative humidity, and a decrease in the lifting condensation level of the order of 10% during the early rainy season.

Associated with the decrease in near surface temperature there is a decrease in the height of the boundary layer when the groundwater scheme is included in the simulation. There is also
an increase in the convective inhibition in the southern extreme of the La Plata basin. However, the increase in relative humidity and moist static energy in the lower levels of the atmosphere is associated with an increase in convective available potential energy, more pronounced over the central part of the La Plata basin. In general we found an increase in precipitation over the central and southern parts of the La Plata basin. Part of the extra precipitation over the southern La Plata was of convective origin, due to the increase in convective available potential energy. Over the southern extreme of the region a larger fraction of the precipitation was from the large-scale component (the microphysics) of the model, as there was still moisture available but increased convective inhibition.

The overall increase in ET and precipitation over the southern La Plata during the early rainy season was of 13 and 10%, respectively. The increase in precipitation is not only a consequence of more atmospheric moisture available when the groundwater scheme is used, but also because of the effects of this moisture on the stability of the atmosphere. Over the La Plata basin, the simulation with the groundwater scheme tends to decrease the biases in temperature and precipitation of the model, although the general bias of the model, due to other components and parameters, is larger than the difference introduced by the groundwater scheme. In the present simulations, the water table depth in the La Plata basin seems to be deeper compared with observations reported in previous studies (e.g. Fan and Miguez-Macho (2010), Kuppel et al. (2015)). Therefore, the increase in precipitation due to the groundwater scheme could be larger if more realistic estimates of the water table depth are simulated.
REFERENCES


Jiang, X., G.-Y. Niu, and Z.-L. Yang (2009), Impacts of vegetation and groundwater dynamics on warm season precipitation over the Central United States, J. Geophys. Res., 114, D06109,


Silva, G. A. M., T. Ambrizzi, and J. A. Marengo, 2009: Observational evidences on the


Sörensson, A.A., and E.H. Berbery (2015): A Note on Soil Moisture Memory and Interactions with Surface Climate for Different Vegetation Types in the La Plata Basin. J. Hydrometeor. 16, 716-729. DOI: 10.1175/JHM-D-14-0102.1


Appendix A

Sources of Atmospheric Moisture for the La Plata River Basin

J. Alejandro Martinez\textsuperscript{1} and Francina Dominguez\textsuperscript{1,2}

1. Department of Atmospheric Sciences, University of Arizona.

2. Department of Hydrology and Water Resources, University of Arizona

doi:\url{http://dx.doi.org/10.1175/JCLI-D-14-00022.1}
Abstract

The La Plata River Basin (LPRB) is the second largest basin of South America. In this study we quantify the spatio-temporal variability of sources of moisture for the LPBR using an extended version of the Dynamic Recycling Model. More than 23% of the mean annual precipitation over the LPRB is of local origin, while almost 20% comes from the southern Amazon. The contribution from South America (including the Amazon and the LPRB) is 62.6%, while 37.4% comes from other sources, mostly from the southern Pacific and the tropical Atlantic. The dependence of the LPRB on external sources is greater during the dry (winter) season, when local evaporation reaches a minimum and moisture outflow increases. Variations in the transport of moisture from the Amazon to the LPRB have a stronger dependence on variations of the atmospheric circulation than on evaporation, both at the monthly and daily scale. In particular, weak atmospheric flow allows the accumulation of moisture over the Amazon basin, followed by an above-normal release of moisture downwind when the atmospheric flow strengthens again. Water vapor transport with these characteristics was observed 20% of the days of the summer season during the 1980-2012 period, leading to higher than average convergence of moisture of terrestrial origin over the LPRB. During the positive (negative) phase of the El Niño-Southern Oscillation (ENSO) more (less) moisture from Amazonian evaporation reaches the LPRB. The Amazonian contribution to the LPRB is reduced (increased) during the positive (negative) phase of the Antarctic Oscillation (AAO), when surface pressure over southern South America is above (below) normal.
1. Introduction

The La Plata River Basin (LPRB) extends across one of the most densely populated regions of South America, spreading over parts of Brazil, Argentina, Paraguay, Bolivia and Uruguay, as the second largest river system in South America, (Lee and Berbery, 2012). Water resources of the LPRB are important for human consumption, harvesting and hydroelectric power generation for a large population (Berbery and Barros, 2002). The LPRB is located south of the Amazon basin (Fig. 1), downstream of the mean atmospheric circulation, which favors the transport of moisture evaporated from the Amazon forest to the LPRB (see e.g. Marengo et al., 2004). The transport of atmospheric moisture of Amazonian origin constitutes a significant fraction of the LPRB's precipitation (Dirmeyer et al., 2009). Therefore, estimation of the magnitude and variability of this transport is important for the assessment and management of the water resources of the LPRB.

The transport of atmospheric moisture over South America has been studied using a variety of methods. From analysis of the horizontal atmospheric moisture flux, Berbery and Barros (2002) found that Amazonian moisture contributes to the LPRB throughout the year, with maximum transport during the austral summer. Based on a similar approach, Arraut et al. (2012) estimated the contribution to atmospheric moisture from the Atlantic, the Amazon and from local evaporation for a region between southern Amazon and northern LPRB. They found that the Amazon contribution is of the same order as that from the Atlantic, while the local contribution is smaller but comparable to the other sources. Using a one-dimensional equation to represent
the hydrologic cycle, Lettau et al. (1979) estimated that the precipitation recycling increases from east (~19%) to west (~88%) of the Amazon basin. Drumond et al. (2008) used a 3D Lagrangian model (FLEXPART, Stohl et al., 1998) to study the sources of moisture for regions representing Central Brazil and the LPRB. They found that both regions receive moisture from the Amazon, but the latter was not the dominant source of moisture in either case. By back-tracking air parcels on isentropic surfaces, Dirmeyer et al. (2009) estimated that nearly 23% of the moisture over LPBR is of Amazonian origin (see Moisture Sources by River basin at http://www.iges.org/wcr/). By means of a 2D Eulerian approach, Van der Ent et al. (2010) estimated that 70% of the precipitation over the LPRB is of terrestrial origin. Because of the LPRB's geographical location, most of the terrestrial contribution is presumably of South-American origin. Using the same water accounting method, Keys et al. (2012) found that 57% of the rainfall for a region within the LPRB comes from terrestrial sources during the growing season. Using the same methodology as in Van der Ent et al. (2010) and Keys et al. (2012), Van der Ent (2014, personal communication) estimated the direct contribution from the Amazon to the LPRB to be 22% of LPRB’s precipitation.

The transport of atmospheric moisture exhibits variability at multiple time scales. For example, Silva et al. (2009) and Silvestri and Vera (2003) identified variations in the transport of moisture from the Amazon to the LPRB under different phases of the El Niño-Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO). Despite our improved understanding of the transport of atmospheric moisture to the LPRB on a climatological basis, many lingering questions remain about its variability. In particular, the link between the atmospheric circulation
patterns and the estimated transport of atmospheric moisture is lacking. In this work we extend the Dynamic Recycling Model (DRM), developed by Dominguez et al. (2006), to quantify the transport of atmospheric moisture to the LPRB from multiple sources, with special emphasis on the Amazon basin. We describe the atmospheric circulation associated with the contributions from multiple sources to the LPRB – including the climatological mean, and the variability associated with ENSO and AAO. In addition, we explore the common features in the vertically integrated moisture flux (VIMF) anomalies that determine the dominant role of terrestrial vs. oceanic contributions to atmospheric moisture over the LPRB.

2. Data and Methodology

a. Methodology

From a Lagrangian solution for the equation of conservation of the total column water vapor (i.e. precipitable water), Dominguez et al. (2006) found that the fraction \( R \) of atmospheric moisture collected by an air column along its trajectory between times \( \tau' = 0 \) and \( \tau' = \tau \) is given by:

\[
R(x, y, t) = 1 - \exp \left[ -\int_0^{\tau} \frac{E(x', y', \tau')}{W(x', y', \tau')} d\tau' \right]. \quad (1)
\]

where \( E \) and \( W \) represent the evaporation and the precipitable water, respectively, along the two-dimensional trajectory \( (x'(\tau'), y'(\tau')) \). Based on (1), we have developed a new method to quantify the relative contributions from different sources to the atmospheric moisture over a given sink region. For example, consider the portions of trajectory \( \lambda = 1 \) and \( \lambda = 2 \), crossing regions \( A_4 \) and \( A_3 \), respectively, in Fig. 2. The trajectory starts at time \( \tau_2 \) and reaches the sink point \( (x, y) \) at time \( \tau_0 \). Applying (1) we get:
\[ R = 1 - \exp \left[ - \int_{\tau_1}^{\tau_2} \frac{E}{W} d\tau' \right] = R_1 + \alpha_1 R_2 \quad (2) \]

where:

\[ R_1 = 1 - \exp \left[ - \int_{\tau_1}^{\tau_2} \frac{E}{W} d\tau' \right] \quad (3a) \]

\[ R_2 = 1 - \exp \left[ - \int_{\tau_1}^{\tau_2} \frac{E}{W} d\tau' \right] \quad (3b) \]

\[ \alpha_1 = 1 - R_1 \quad (3c) \]

In (3) \( R_1 \) and \( R_2 \) represent the local collection of moisture from portions 1 and 2 of the trajectory, respectively. Additionally, \( \alpha_1 \) represents that fraction of moisture produced in part 2 of the trajectory that is not lost (via precipitation) in the intermediate part of the trajectory, i.e. part 1. This idea can be generalized to a trajectory with an arbitrary number of portions (e.g. in Fig. 2, we show a trajectory with 5 portions). We refer to the net contribution from each portion \( \lambda \) of the trajectory as \( c_\lambda \). In our example \( c_1 = R_1 \) and \( c_2 = \alpha_1 R_2 \). In general, it can be shown that:

\[ c_\lambda (x, y, t) = \left( \prod_{j=1}^{\lambda-1} a_j (x, y, t) \right) R_\lambda (x, y, t) \quad (4) \]

Finally, we can group the contributions from different portions of the trajectory according to some predefined regions. In our example, the total contribution from region \( A_4 \) to the moisture at point \((x, y)\) is given by \( a_4 (x, y) = c_1 (x, y) + c_2 (x, y) \). In general:

\[ a_4 (x, y, t) = \sum_{\lambda \in A_4} c_\lambda (x, y, t) \quad (5) \]
where the sum is done over all those portions of trajectory $\lambda$ that fall into the region $A_k$. The $a_k(x,y)$ fields provide an estimate of the fraction of moisture on each grid cell $(x,y)$ that originated as evaporation from somewhere in the region $A_k$ (see Fig. 2). Therefore:

$$R(x,y,t) = \sum_{k=1}^{N_A} a_k(x,y,t), (6)$$

where (6) satisfies (1), and $N_A$ represents the total number of regions.

Because (1) is derived from the water balance equation for an atmospheric column, the corresponding trajectories follow an effective 2D wind field, which in the DRM is given by the VIMF divided by the precipitable water (Dominguez et al., 2006). This approach has been the subject of debate because the vertical wind shear of the horizontal winds can produce water transport patterns not accounted for in a vertically integrated moisture flux (Goessling and Reick, 2013 and Van der Ent et al. 2013). Rather than attempting a detailed quantification of the errors associated with the 2D nature of the DRM, we provide a careful comparison of our results with well-established facts about the transport of water vapor associated with major circulation patterns over South America at a range of spatial and temporal scales, as reported by multiple studies based on a broad spectrum of techniques and data sources.

b. Regional Averages

In order to quantify the spatially averaged contributions from each source region to each sink region, we compute regional averages for each day. We quantify the contribution $P_m$ from each source region $A_k$ to the precipitation $P$ over the sink region $A_j$, for each day $t$, as:
where $\delta A(x,y)$ is the area of each grid cell with center at $(x,y)$. Note that according to this definition, $P_m(A_k,A_j,t)$ depends on the spatial covariance between $a_k(x,y,t)$ and $P(x,y,t)$. Similarly, we quantify the contribution $W_m$ from each source region $A_k$ to the total precipitable water $W$ over a sink region $A_j$, for each day $t$, as:

$$W_m(A_k,A_j,t) = \frac{\sum_{(x,y)\in A_k} a_k(x,y,t) W(x,y,t) \delta A(x,y)}{\sum_{(x,y)\in A_j} \delta A(x,y)}$$

Definitions (7) and (8) contain information about the temporal and spatial variability of $P$ and $W$, respectively, in addition to the information about the relative exchange of atmospheric moisture given by the $a_k$ fields. The $a_k$ maps represent fractions of moisture, and these patterns can be different from those of precipitation and precipitable water originating from a particular source region. The existence of enough moisture content is a necessary, but not a sufficient condition for the occurrence of precipitation. Upward movement by large-scale convergence, deep convection or orographic lifting is also needed to produce precipitation.

c. Region of Study

We subdivided the South American continent into 13 regions, and the adjacent oceans into four regions (Fig. 1). These regions are based on the Pfafstetter delineation of basins, level 1, extracted from the GTOPO30/HYDRO1k watershed boundaries data set, developed by the Earth Resources Observation and Science center (Verdin and Verdin, 1999). The data is available

At the continental scale, the level 1 Pfafstetter delineation basically identifies the four major river basins draining to the ocean, and the corresponding five interbasin regions (Verdin and Verdin, 1999). For this study, we modified the HYDRO1k data to better represent the LPRB (based on Lee and Berbery, 2012). We also subdivided the Amazon basin into northern and southern Amazon because the climatic characteristics of each sub-region are different (Marengo 2004, Arias et al. 2010). These modifications produced more regions than present in the original HYDRO1k dataset.

d. Data

We use ERA-Interim fields for the period 1980-2012. Data for the domain of interest was provided by the European Centre for Medium-Range Weather Forecasts at 0.75° resolution from their website at http://data-portal.ecmwf.int/data/d/interim_full_daily. We use evaporation, total column water vapor (or precipitable water), and precipitation. We also use the vertical integral of the moisture flux in the horizontal direction \( \mathbf{Q} = (Q_x, Q_y) \) to obtain the effective horizontal wind components \( U, V \) as \( U = Q_x / W \) and \( V = Q_y / W \). In general, ERA-Interim provides a better representation of the hydrological cycle (Dee et al., 2011) and of the transport of atmospheric moisture than other assimilated products (Trenberth et al., 2011). The largest uncertainties and errors are likely associated with the precipitation and evaporation estimates (Trenberth et al., 2011). ERA-Interim has a wet bias in precipitation over the Amazon and southern South America (see e.g. Betts et al. 2009, and Dee et al. 2011). There is larger uncertainty in the evaporation estimates because of the differences among satellite retrievals (Vinukollu et al.,...
2011) and reanalyses estimates (Decker et al., 2012). The evaluation of the ERA-Interim fields over South America is beyond the scope of this study. We use daily averages for the moisture fields $E$, $W$ and $P$ because our interest is the water budget in the time scale of days and longer. The horizontal wind field is updated every 6 hours in order to compute the trajectories of the air columns. The time step in the kinematic scheme is 30 minutes, and the wind field is assumed to be constant for periods of 6 hours.

We use monthly values of the Oceanic Niño Index (ONI) and the corresponding classification of ENSO years as provided by the Climate Prediction Center (CPC) from their website at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. To quantify the activity of the AAO, we use monthly values of the Antarctic Oscillation index as provided by the CPC from their website at: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao/aao_index.html.

e. Significance test

In this study, we perform statistical significance tests for quantities that represent spatial averages over tens of grid points, and temporal averages over hundreds of time steps. By the Central Limit theorem we expect the corresponding distributions to be nearly Gaussian, and the sampling distributions of their moments (e.g. means) to be close to the Student $t$-distribution. Therefore, we use the $t$-test to assess the significance level of our results.
3. Mean Annual Cycle of Atmospheric Moisture Transport to the LPRB

Moisture from terrestrial origin over the LPRB reaches a maximum during the austral summer and a minimum during the winter (Figs. 3 and 4). Total terrestrial contributions (i.e. from South America) account for approximately 62% of the precipitation over the LPRB (Fig. 3a) (compare to 51% and 29% for southern Amazon and northern Amazon, respectively). Local recycling (i.e. moisture evaporated from the LPRB that precipitates within the basin) is the single most important terrestrial contribution to atmospheric moisture over the LPRB. The mean annual contribution to precipitation by local recycling is 0.87mm/day, which is 23.5% of the total mean annual precipitation (Fig. 3a). As a reference, the mean recycling estimated by the DRM for northern and southern Amazon is 17.3% and 25.5%, respectively. In terms of precipitable water over the LPRB, the local contribution is 26%, almost twice as large as the second largest contribution (Fig. 3b). Moisture from the LPRB does not reach regions far upwind of the mean VIMF (Figs. 4a and 4d). This is consistent with a vertical profile of moisture flux that is mostly northerly over the northern LPRB (see e.g. Berbery and Barros, 2002; and Fig. 11 in Van der Ent et al., 2013). Most of the moisture of local origin stays within the basin, especially during the DJF season, (Fig. 4a). Consequently, the local recycling of precipitation is highest during the LPRB’s wet season (DJF), with a peak value of almost 30% during January (1.8 mm d⁻¹). During DJF, both large scale convergence and net radiation are enhanced, increasing the atmospheric instability, precipitation and evaporation. During the dry season (austral winter) recycled precipitation is the lowest in fraction (12%) and absolute value (~0.18 mm d⁻¹). Average precipitation is reduced in the dry season (Fig 3a), which reduces the probability of local
evaporation to precipitate back over the LPRB. Consequently, while the ratio of precipitation of local origin to the local evaporation is nearly 0.40 during January (wet season) it is 0.17 during July (dry season), (see Fig. 3a). This suggests that the LPRB is relatively more dependent on external sources for its dry season precipitation. However, errors in our estimates could be larger during the winter, when the atmosphere is more stratified, and the well-mixed atmosphere assumption in the DRM is less valid. During this season the effects of the vertical wind shear are expected to be larger (Goesling and Reick, 2013; Van der Ent et al., 2013). Our estimates of the local contribution during winter are lower than those of previous studies (~30% according to Dirmeyer et al., 2009, see Moisture Sources by River basin at http://www.iges.org/wcr/).

The annual average Amazonian contribution to the LPRB (sum of the northern and southern Amazon, see Fig. 1) is 23.9% (Fig. 3a), which is very close to the 23% estimated by Dirmeyer et al., 2009 (as reported at www.iges.org/wcr/). Most of this moisture comes from the southern Amazon, and reaches the LPRB all year-round. The southern Amazon contributes more to precipitation over the LPRB during the dry season (~24%) than the LPRB itself (Fig. 3a). However, the southern Amazon and the LPRB contribute almost the same amount of precipitable water to the LPRB in this season (~5 mm in July, Fig. 3b). This suggests that moisture of Amazonian origin is more efficiently converted to precipitation over the LPRB, than moisture originating from the LPRB. Compared to the large seasonal changes of the LPRB as a moisture source, the contribution from the southern Amazon is very consistent throughout the year, which means this region is a quasi-permanent source of moisture for the LPRB. This contribution is especially important during the dry season in the LPRB, when the local contribution to
precipitable water is less than half the local contribution during the wet season (~11 mm in the wet season).

The northeastern and central Brazil (NORD and TOCA in Fig. 1, respectively) are also important terrestrial contributors to the LPRB. Together they account for 7.3% (7.7%) of the mean annual LPRB precipitation (precipitable water). Note that the contributions from each of these regions are equal to or larger than those from the northern Amazon (Fig. 3). The oceanic contributions to the LPRB come mostly from the adjacent southern Pacific, tropical Atlantic, and southern Atlantic, (SOPA, NOAT and SOAT regions in Fig. 5, respectively). The adjacent southern Pacific contributes with 7.1% (7.6%) of the mean annual precipitation (precipitable water) over the LPRB (Fig. 3), and this contribution takes place mostly during the austral winter. Due to the westerly mean VIMF and eddy transport by baroclinic disturbances, between 10 and 30% of the moisture over southwestern LPRB comes from the southern Pacific during the austral winter (Fig. 5d). The tropical Atlantic contributes 6.1% (5.6%) of the mean annual precipitation (precipitable water) over the LPRB, and this contribution is larger in absolute value during the austral summer (Fig. 3). This transport is associated with cross-equatorial flow during the austral summer (Fig. 5b), while the large fractional contribution during the austral winter coincides with minimum values of precipitation and precipitable water (Fig. 3), making this contribution negligible in absolute value. The southern Atlantic contributes nearly 1.5% of the mean annual precipitation over the LPRB, but almost 5.4% of the precipitable water (Fig. 3). Moisture from the southern Atlantic reaches the LPRB primarily during the austral summer (Fig. 5). This transport is not associated with the mean VIMF (Fig. 5) but rather with eddy transport by
transient low pressure patterns that produce southeasterly flow off the coast of Uruguay and southern Brazil. The effect of transient systems, and of those associated with the transport from the southern Pacific (both in the time scales of hours to days), seem to be well captured in our calculations by the use of 6-hourly wind fields. The contribution from the tropical Pacific (NOPA) is less than 0.7% and is mainly associated with the mean VIMF (see Fig. 4 for VIMF patterns, and Supplemental material).

4. Variability of moisture transport to the LPRB

In the following subsections we analyze the variability of the transport of precipitable water to the LPRB at several time scales. The analysis is primarily based on precipitable water because in ERA-Interim this field is more constrained by observations (e.g. specific humidity), while precipitation is generated by the forecast (Dee et al. 2011).

a. Interannual Variability: ENSO

ENSO is one of the modes of climate variability that most affects the precipitation and temperature patterns over South America (see e.g. Garreaud et al., 2009). In general, it has been found that there is a strong correlation between precipitation over northeastern and southeastern South America and the sea surface temperature in the El Niño 3.4 region (Van der Ent and Savenije, 2013). Figure 6a shows the regional monthly anomalies of the contributions to precipitable water over the LPRB originating from select subregions. The contributions are
grouped according to the two extreme phases of ENSO, according to the classification of the CPC following the ONI (as in Silva et al., 2009). In Fig. 6 the “+” (“−”) sign represents the El Niño (La Niña) phase of ENSO. The differences of means for different ENSO phases are statistically significant beyond the 99% level (see Table 1). Note that, even when the values on Fig. 6a may seem small, an anomaly of 0.5 mm over the entire LPRB corresponds to an equivalent of 1.75 Gt (where 1 Gt = 1 gigatonne = \(10^{12}\) kg) of liquid water. Furthermore, the contributions from each source do not spread uniformly over LPRB, so the local anomalies can be much larger.

We find that during El Niño the anomalies in total \(W\) and in the contributions from the Amazon and southern Pacific tend to be positive, while those from the LPRB and the southern Atlantic tend to be negative (Fig. 6). The opposite is observed during La Niña events. The anomalies in total \(W\) are consistent with the correlation between ENSO and precipitation over southeastern South America (e.g. Garreaud et al., 2009). There is also an enhanced southward transport of moisture from Brazil to southeastern South America (Fig. 7). Because of the anomalous circulation, the Amazonian contribution to the mean monthly precipitable water over the LPRB is almost 1 mm higher during El Niño than during La Niña months (see Table 1). Figure 7 shows that during El Niño, the excess precipitable water is concentrated over central and northern LPRB, consistent with its Amazonian origin, while during La Niña, the deficit in precipitable water is larger over southern LPRB, as the reduced moisture arriving from the Amazon stays mostly over northern LPRB.
The same anomalies in the circulation produce a reduction of 0.65 mm in the contribution from the LPRB to its own monthly mean precipitable water during El Niño compared to La Niña. Even when the average evaporation over the LPRB is 0.087 mm/d higher during El Niño compared to La Niña (this difference is significant at the 99% level), the stronger northerly VIMF during El Niño takes that moisture originated as local evaporation out of the LPRB at a faster rate. The same circulation patterns produce a decrease in the contribution from the southern Atlantic of nearly 0.62 mm during El Niño compared to La Niña. Increased transport from the southern Atlantic during La Niña months might be the result of larger and more frequent eddy transport associated with cyclonic circulations off the coast of southeastern South America. On the other hand, there is an increase in the contribution from the southern Pacific of nearly 0.44 mm during El Niño compared to La Niña. Enhanced transport from the southern Pacific is a combination of both a strengthening in the mean westerly VIMF in the band 20°S-30°S (Fig. 7) and the increase in the baroclinic activity over southern South America during El Niño events (Grimm et al., 1998).

Composites analogous to those in Fig. 6a were realized for the DJF and September-October-November (SON) seasons separately (not shown), when the effects of ENSO on southeastern South America are stronger (e.g Garreaud et al., 2009). In general the results are the same as those presented above. All the anomalies are larger in magnitude during DJF, except those associated with the southern Pacific, which are larger during the spring season SON due to the anomalous activity of extra-tropical cyclones during each of the ENSO phases. Results in Fig. 6a show that the sign of the anomalies are present all year-round, which is
consistent with previous studies (e.g. the sign of the correlations in Garreaud et al. (2009) is the same for all seasons).

b. Interannual Variability: AAO

The Antarctic Oscillation (AAO) is the leading pattern of tropospheric variability south of 20°S. During the AAO, positive (negative) anomalies in pressure over the Antarctic are associated with negative (positive) anomalies over the latitudinal band around 40-50°S (Thompson and Wallace, 2000). Gong and Wang (1999) found variability in the AAO at inter-monthly (periods of 2.7 and 4.2 months) and inter-annual (period of 45.7 months) timescales. The positive AAO phase is associated with increased pressure and temperature, and less precipitation over southern South America (e.g. Garreaud et al. 2009 and Gillett et al. 2006). The correlation between the AAO index and precipitation over southern South America is larger during the late spring season, particularly during November-December (Silvestri and Vera, 2003). Therefore, during this season we expect to see noticeable changes in the transport of water vapor to the LPRB that are associated with the AAO. In this study we have classified the contributions to precipitable water over the LPRB according to the sign of the average AAO index for the November-December period. The present analysis focuses on the inter-annual variability of the late spring season because only the November-December periods of different years are compared.

In general, negative anomalies in total precipitable water over the LPRB during the positive phase of the AAO are related to decreased transport from the southern Amazon and the southern Pacific, while anomalous contributions from the LPRB and the southern Atlantic tend to be
positive (see Fig. 6B and Table 1). The negative anomalies in total precipitable water and the increased saturation vapor pressure associated to higher temperatures in the positive phase of the AAO lead to reduced precipitation over the LPRB. At the same time, the contributions from the LPRB and the southern Atlantic tend to be larger, due to the weakening of the mean eastward flow associated with the poleward shift of the westerlies, and the subsequent increase in the westward eddy transport from the east (Fig. 7). However, these positive anomalies are in general not large enough to lead to positive anomalies in the total precipitable water. During the negative phase of the AAO the signs of the anomalies just described change as a consequence of the opposite changes in the circulation. Note that the anomalies during the negative phase of the AAO are similar to those of El Niño months (Fig. 7). However, the anomalous circulation is stronger in the higher latitudes for the AAO, whereas during El Niño tropical anomalies have the meridional component associated with the change in the Hadley circulation. In addition, less than half of the negative AAO years are El Niño years. Something analogous happens when comparing the La Niña and the positive AAO composites.

c. Interannual Variability: Covariability of Precipitation, Evaporation and Precipitable Water

In an effort to understand how moisture contributions from different sources affect the variability of precipitation and precipitable water over the LPRB, we performed a correlation analysis for the monthly anomalies in precipitation ($P'$), precipitable water ($W'$) and the contributions from different regions (see Table 2). For economy in the notation, in this section $P'_k$ represents the anomaly in the contribution to precipitation ($P_m(A_k, A_j)$) over the LPRB ($A_j$: LPRB) from different sources (regions $A_k$), (see section 2b). An analogous definition of $W'_k$ is used for
precipitable water, while $E_k'$ represents the anomalous evaporation in region $A_k$. The regions $A_k$ for this part of our analysis are listed in the columns of Table 2.

The correlations between $P'$ and $W'$, and the anomalies from different sources are shown in the first two lines of Table 2. Note that the correlations are higher for the contributions from upwind regions like the southern and northern Amazon, northeastern Brazil and the tropical Atlantic. In particular, the correlation of total precipitation over the LPRB with the contribution from the southern Amazon is much larger (0.82) than the correlation with the contribution from the LPRB itself (0.47). The correlations with the contributions from the southern Atlantic are negative. Analysis at the daily time scale shows that when moisture from the southern Atlantic reaches the LPRB, usually the other contributions are smaller and total precipitation and precipitable water decrease (see section 4d). At the monthly time scale, the contributions from the southern Pacific show a lower co-variability with $P$ and $W$ over the LPRB than the contributions from tropical South America. However, anomalous contributions from the southern Pacific, especially during the winter-spring season, can be as large as those from the southern Amazon (see Fig. 6b).

The correlations between the anomalous contributions to precipitation and precipitable water over the LPRB from each source are shown in the third row of Table 2. These correlations capture the frequency of events when anomalous contributions to precipitable water from each source are converted into a corresponding contribution to precipitation. These values suggest that anomalous precipitable water arriving to the LPRB from all external sources in Table 2 is more linked to precipitation events than contributions from the LPRB itself. For example, the
anomalous contributions from the southern Pacific can be smaller than those from the LPRB, but the former are more likely to fall as precipitation than the local contributions. This effect is even more pronounced for some remote regions such as the northern Amazon. Similarly, note that anomalous precipitable water arriving from the southern Atlantic is highly and positively correlated with the contribution to precipitation from that region to the LPRB, even when the corresponding relationships with the total anomalies (i.e. $P$ and $W$) are small and negative. The higher correlations between the remote contributions to precipitable water and the corresponding precipitation contributions show the role of large-scale convergence in the generation of precipitation over the LPRB (as represented by ERA-Interim).

The last two rows in Table 2 show the correlations between the anomalies in the contributions to precipitation and precipitable water over the LPRB, and the anomalous evaporation in each source. Most of them are smaller in magnitude than the correlations in the previous rows, and some of them are not significant. These correlations are relatively larger for upwind regions, but still small in magnitude. Comparison of the correlations in the first three rows of Table 2 with those in the last two rows suggest that, at the monthly time scale, the effect of the circulation on the contributions from each source is larger than effect of the variability of the evaporation field in each source region.

\emph{d. Daily Variability}

In order to identify the relative roles of the South American (SA) and non-South American (No-SA) contributions to daily anomalies of total precipitable water in the LPRB during the wet
season, we classified each of the 2970 days in DJF (between 1980 and 2012) as belonging to one of eight types (Table 3). In the discussion that follows we will refer to South American sources as “terrestrial” and non-South American sources as “oceanic”, but keep in mind that while non-South American sources are dominated by oceans, there could be small terrestrial contributions from other continents. The classification in Table 3 encompasses all the combinations in which the anomalous contributions from two sources (terrestrial vs. oceanic) can add up to produce the total anomaly over a target region (total anomaly in precipitable water over the LPRB). We use this decomposition for several tasks: i) to quantify the frequency of occurrence of events when both major sources add “constructively” (same sign of anomaly) or “destructively” (opposite sign of anomaly); ii) to identify South American sources that add constructively or destructively to the total terrestrial anomalous contribution; and iii) to identify the patterns of moisture flux and evaporation associated with opposite contributions from terrestrial and oceanic sources.

The anomalies used to obtain the results in Table 3 are computed as the value of regional averages for each day minus the average value for the corresponding Julian day over the 1980-2012 period. We selected the wet season DJF because that is when the largest mean contributions from the South American continent are observed (Figs. 3 and 4) and the wind shear effects are expected to be smaller (Goessling and Reick, 2013; Van der Ent et al., 2013). In Table 3 the first sign in the parenthesis in the first column represents the sign of the oceanic anomalous contribution. Similarly, the sign in the second part of the parenthesis represents the sign of the terrestrial anomalous contribution. The double sign indicates which of these two
sources is dominant in the total $W$ anomaly. As an example, (−,+++) indicates a day when oceanic sources were below average, but terrestrial sources were anomalously high, and overall there was anomalously high precipitable water. The second column in Table 3 contains the frequency of occurrence of each case. The other columns show the average value of the anomalous contributions to precipitable water over the LPRB from selected source regions. We will analyze in detail only cases II and VI. These represent conditions of above average precipitable water where either oceanic sources dominate with negative terrestrial anomalies (II) or terrestrial sources dominate with negative oceanic anomalies (VI).

Case II groups 442 days when anomalous $W$ is positive and determined by the oceanic contribution, while the terrestrial anomaly is negative. The associated precipitation is 1.06 mm d$^{-1}$ above average with an oceanic contribution of 0.81 mm d$^{-1}$ above normal. The corresponding VIMF and evaporation anomalies are shown in Fig. 8, for the corresponding case II day, and two and four days before. Only those anomalies that are significant at the 99.5% level are plotted. In this case the contributions from the Amazon are slightly above normal while the LPRB contributes less than in case I (hence the negative anomaly of terrestrial sources). The VIMF composites suggest that the strengthening of the subtropical circulation is common in case II (specially in the 13°S-23°S band, close to the adjacent Atlantic), but anomalies in the cross-equatorial flow do not show a preferred direction. Fig. 8 also shows that the anomalous circulation is noticeable 4 days before the case II day (similar patterns are observed up to 9 days before, but they are not statistically significant). Note that the positive evaporation anomalies over southeastern Brazil are mostly outside the Amazon, and the northerly flow is so strong that
moisture is transported southeastward beyond the LPRB region, producing very small Amazonian anomalies, and negative LPRB anomalies. On the other hand, the transport from the southern Atlantic has two components: decreased eddy transport of moisture from the exit region of the circulation anomalies, and the increased moisture coming from northern region of the southern Atlantic.

The largest South American contributions to the LPRB take place during case VI, when the anomalous $W$ is positive despite reduced oceanic contributions. The continental contribution is larger than in other cases, with average excess close to 4 mm (more than 10% of the mean $W$, see Fig. 3b). The resulting precipitation is an excess of 0.83 mm d$^{-1}$, with a terrestrial contribution of 0.90 mm d$^{-1}$ above normal (the largest among all cases), and a decrease of oceanic contribution of -0.07 mm d$^{-1}$. During case VI days, the Amazon plays an important role, with a contribution to precipitable water of almost 1.5 mm above normal (equivalent to 5.25 Gt of extra liquid water), while the excess contribution from the LPRB is 2.1 mm (7.35 Gt of extra liquid water), (see Table 3). Case VI is important also because it is the most common among all eight cases (602 days). In this case the anomalous contributions from the LPRB, and southern and northern Amazon tend to be positive simultaneously. This combination is produced by an interesting change in the circulation during the days prior to the case VI day (Fig. 8). Four days prior to the case VI day, the anomalous circulation is southerly over the LPRB and Brazil. A similar pattern is observed up to 9 days before the case VI day, but they stop being statistically significant at the 7$^{\text{th}}$ day before the case VI day. Two days before the case VI day the significant anomalies in the VIMF are mostly over the southern Atlantic, and suggest weaker outflow from the LPRB to the
Atlantic. The accumulation of moisture from continental origin over the Amazon region is due to the sustained weakening of the mean flow and not due to evaporation, as we see that anomalous evaporation over Brazil is relatively small. The contribution to precipitable water from the southern Amazon to the southern Amazon itself (the accumulation of evaporation in the overlying atmosphere) is almost 1 mm larger than average during the 5th to 2nd days before the case VI day. This increase in the contribution from the southern Amazon is the largest among all the cases. Finally, during the day of arrival of the moisture to the LPRB (Day 0), the VIMF from the southern Amazon to the LPRB is enhanced while the flow over the south of the LPRB is close to average, leading to an accumulation of moisture of Amazonian origin. The weakening of the flow over the LPRB also leads to an accumulation of moisture of local production, despite the fact that local evaporation anomalies are small. In addition, an anticyclonic anomaly in the VIMF over the southern Atlantic starts to form. The weaker northerly flow over the LPRB on the previous days and the anticyclonic anomaly during the case VI day allow for a slightly larger contribution from the southern Atlantic to the LPRB compared to case V.

Once a given anomaly type takes place, it can persist for several days. On average, cases II and VI last for 2.2 and 2.6 days, respectively, while all other cases do not last longer than 2 days. Our results suggest that terrestrial contributions can help support positive anomalies in both precipitable water and precipitation over the LPRB during several days, even when the oceanic contribution decreases (case VI).

Interestingly, there are some similarities between the anomalous patterns in Fig. 8 and the low
level circulation associated with different configurations of the South Atlantic Convergence Zone (SACZ) (see Fig. 8 in Carvalho et al., 2004). In particular, case II might be associated with a SACZ that is weak or confined over southeastern South America, while the case VI might be associated with a SACZ that is more intense over the Amazon, or that travels from the north of the LPRB eastward to the South Atlantic. The explicit role of the SACZ in the anomalous terrestrial contribution to precipitable water over the LPRB would require a date by date comparison with the different configurations of the SACZ, which is beyond the scope of this study.

5. Summary and Discussion

We present an extended version of the DRM for estimating the exchange of atmospheric moisture among different regions. This method is computationally efficient and has been used to study the transport of atmospheric moisture to the LPRB for the period 1980-2012. The largest errors in our estimates are likely related to the effect of the vertical wind shear. The transport of moisture of local origin and that of remote origin can be in different directions when there is substantial vertical wind shear, (Goessling and Reick (2013) and Van der Ent et al., 2013). In our study, the potential errors given by the wind shear are expected to be relatively small as shear is not too large over most of South America, especially over the LPRB (e.g. see Figure 11 in Van der Ent et al., 2013). Accordingly, Goessling and Reick (2013) found that the differences in the absolute values of recycling and transport of moisture from 2D and 3D moisture tracking methods is around 10% (5%) during winter (summer) over South America.
We acknowledge that the DRM is not able to explicitly capture the dynamics associated with the wind shear. However, the transport of moisture to southern South America as estimated by the DRM is in general agreement with a number of previous studies that have used different methodologies. We think that, in combination with a sound analysis of the atmospheric circulation in the region of interest, the DRM can be used as an efficient tool to diagnose first order patterns and magnitudes of moisture transport at continental and regional scales.

We find that local recycling (i.e. precipitation originated as evaporation from the same region) is the most important terrestrial contribution to atmospheric moisture over the LPRB, accounting for 23.5% of the mean annual precipitation over the region. The southern Amazon contributes almost 20% of the annual mean precipitation over the LPRB, with little seasonal variability in the contribution to absolute precipitation and precipitable water. Interestingly, during the dry season, the moisture of Amazonian origin seems to be more efficiently converted to precipitation over the LPRB, than moisture originating from the LPRB. This might be the case when more Amazonian moisture is transported and precipitated over the LPRB during the passage of synoptic disturbances, while larger contributions from the LPRB take place during days with no precipitation. This is consistent with the southward moisture flow over the LPRB and the precipitation events over southeastern LPRB associated with baroclinic waves during the cold season, as found by Vera et al., 2002. Other important sources for the LPRB are the southern Pacific and southern Atlantic. South Pacific moisture is also consistent with the patterns resulting from westward propagating synoptic-scale waves during the cold season (Vera et al., 2002).
During El Niño, we find positive anomalies in total precipitable water and in the corresponding contributions from the adjacent southern Pacific and southern Amazon regions, while less moisture comes from the LPRB itself and the adjacent southern Atlantic. The opposite tendencies are observed during La Niña. During El Niño events, the weakening of the Walker circulation in the vicinity of South America induces anomalous subsidence over Brazil, which coincides with anomalous upward motion at mid-levels over southeastern South America (Andreoli and Kayano, 2005). This dipolar pattern is also evident in the negative anomalies of precipitable water over northeastern South America and positive anomalies over southeastern South America (Fig. 7), which coincide with reduced precipitation over Brazil and increased precipitation over southern South America, (Grimm et al., 2000; Vera et al., 2004). The resulting weakening of the lower branch of the Hadley circulation between tropical and subtropical South America (Wang, 2005) is associated with an enhanced southward transport of moisture from Brazil to southeastern South America. There is also evidence of more SALLJ events during El Niño than during La Niña years (Silva et al., 2009). We also find that there is an increase in the contribution from the southern Pacific during El Niño compared to La Niña. This could be due, in part to anomalous upper-level circulation patterns (200 hPa) during El Niño, where stronger subtropical westerlies occur (Ropelewski and Halpert, 1987), and an anomalous cyclone is observed over the southern Pacific along with an anomalous anticyclone over the southern Atlantic, both features off the coasts of southern South America (Grimm et al., 1998; Vera et al., 2004; Andreoli and Kayano, 2005). Some anomalously high contributions from the adjacent southern Pacific are also observed during La Niña, which could be related to transport events from the southeastern Pacific and southern Argentina, as reported by Silva et al. (2009). Silva et
al. suggest these events could be produced by the weakening of the SALLJ during La Niña, and the co-existence of anticyclonic and cyclonic anomalies on the west and east sides of southern South America, respectively.

During the positive AAO phase in the late spring the contributions from the LPRB itself and the adjacent southern Atlantic tend to be larger, as a consequence of the weakening of the mean northwesterly flow. During the positive AAO phase, the westerlies are shifted poleward (Garreaud et al., 2009), which in general decreases the transport from the Pacific. Additionally, the increased pressure over the LPRB reduces flow from the Amazon region towards the south of the continent (Silvestri and Vera, 2003). Consequently, despite the positive contribution from the LPRB, the decreased transport from the Pacific and the Amazon lead to a decrease in total precipitable water over the LPRB. During the negative phase of the AAO we find the opposite tendencies.

Linear correlation analysis suggests that the variability in precipitation and precipitable water over the LPRB is more related to the variability in the contributions from upstream regions than with the variability of the local contribution. We also find that the variability of moisture contributions from different source regions depends on atmospheric circulation, rather than on the regions’ evaporation variability. This behavior is also evident at the daily scale during the wet season DJF, when 20% of the days have positive anomalies in the transport from continental upstream regions that is not associated with positive anomalies in evaporation. During the days leading to the moisture contribution of continental origin event, there is an accumulation of
evaporated moisture over the Amazon because of weaker flow, which is then suddenly “released” downwind, when the large-scale circulation from the Amazon to the LPRB gets stronger. Conversely, relatively higher evaporation can occur simultaneously with close to average local moisture contributions, because the excess moisture can be transported out of the source. Thus, evaporation anomalies over a particular region do not determine the anomalies in the local contributions to atmospheric moisture from that region. Therefore, we expect evaporation changes to be important to the contributions to the LPRB only if there is a relatively large variation in the mean evaporation, which could happen under dramatic land use/land cover changes (see e.g. Pires and Costa, 2013; and Lee and Berbery, 2012). Particularly, important land cover changes have been observed and projected over the southern Amazon (Soares et al., 2006).

Our present results rely on the ERA-Interim estimates of evaporation over South America. However, important differences in the mean evaporation over South America are present among satellite-derived products (e.g. Vinukollu et al. 2011), reanalysis (Decker et al. 2011) and land surface models (e.g. Miguez-Macho and Fan 2012). Comparison of atmospheric moisture pathways from different datasets is an important task that needs further research. Nevertheless, the analysis presented in this study shows the importance of terrestrial sources for water vapor content and precipitation over the LPRB, both as components of the mean state and also to balance the deficits of oceanic origin. In this sense, atmospheric moisture over the LPRB is particularly sensitive to the mean evaporation in source regions like the southern Amazon and the northern LPRB, and also to the variability of the atmospheric circulation that brings moisture
from these regions.

Acknowledgements

We acknowledge the ECMWF for providing the ERA-Interim data, and the CPC for providing the ONI and AAO index data. We also acknowledge James Shuttleworth, Hoshin Gupta, Carolina Vera, Ruud van der Ent, Gustavo Gonçalves, and the reviewers for their insightful comments. This research was supported by NSF Grant 1045260.
References


Table 1. Differences between the mean values of the anomalies in precipitable water between different ENSO and AAO phases (see Figure 6). $\Delta_{\text{ENSO}}$ corresponds to the mean value during the positive ENSO phase (El Niño) minus the mean value during the negative ENSO phase (La Niña). $Z(\Delta_{\text{ENSO}})$ and $p(\Delta_{\text{ENSO}})$ are the Z score and the p-value (probability of occurrence) of each difference $\Delta_{\text{ENSO}}$. Analogous definitions hold for the AAO.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>LPRB</th>
<th>Southern Amazon</th>
<th>Southern Atlantic</th>
<th>Southern Pacific</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{\text{ENSO}}$</td>
<td>1.66 mm</td>
<td>-0.65 mm</td>
<td>0.76 mm</td>
<td>-0.62 mm</td>
<td>0.44 mm</td>
</tr>
<tr>
<td>$Z(\Delta_{\text{ENSO}})$</td>
<td>5.07</td>
<td>-3.95</td>
<td>6.20</td>
<td>-3.96</td>
<td>3.57</td>
</tr>
<tr>
<td>$p(\Delta_{\text{ENSO}})$</td>
<td>&lt; 0.0001</td>
<td>0.0002</td>
<td>&lt; 0.0001</td>
<td>0.0002</td>
<td>0.0009</td>
</tr>
<tr>
<td>$\Delta_{\text{AAO}}$</td>
<td>-1.55 mm</td>
<td>1.14 mm</td>
<td>-0.88 mm</td>
<td>0.83 mm</td>
<td>-0.29 mm</td>
</tr>
<tr>
<td>$Z(\Delta_{\text{AAO}})$</td>
<td>-2.08</td>
<td>4.16</td>
<td>-3.29</td>
<td>3.96</td>
<td>-3.59</td>
</tr>
<tr>
<td>$p(\Delta_{\text{AAO}})$</td>
<td>0.0673</td>
<td>0.0011</td>
<td>0.0081</td>
<td>0.0016</td>
<td>0.0033</td>
</tr>
</tbody>
</table>
Table 2. Correlation coefficients between time series of monthly anomalies. \((P',P_k')\): correlations between anomalies in total precipitation over LPRB \((P')\) and the corresponding contributions from each source \(P_k'\) (columns). \((W',W_k')\): same as \((P',P_k')\) but for precipitable water. \((P_k',W_k')\): correlations between the contributions from each source to precipitation \((P_k')\) and precipitable water \((W_k')\). \((P_k',E_k')\) as \((P_k',W_k')\) but \(E_k'\) refers to anomalies in evaporation in the corresponding source region \(k\) (columns). \((W_k',E_k')\): same as \((P_k',E_k')\) but for precipitable water. All correlations are statistically significant at the 99% level, except those values in italics.

<table>
<thead>
<tr>
<th></th>
<th>LPRB</th>
<th>NAMZ</th>
<th>SAMZ</th>
<th>NOAT</th>
<th>SOAT</th>
<th>NOPA</th>
<th>SOPA</th>
<th>NORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>((P',P_k'))</td>
<td>0.47</td>
<td>0.62</td>
<td>0.82</td>
<td>0.72</td>
<td>-0.17</td>
<td>0.34</td>
<td>0.47</td>
<td>0.54</td>
</tr>
<tr>
<td>((W',W_k'))</td>
<td>-0.22</td>
<td>0.47</td>
<td>0.68</td>
<td>0.69</td>
<td>-0.42</td>
<td>0.21</td>
<td>0.23</td>
<td>0.54</td>
</tr>
<tr>
<td>((P_k',W_k'))</td>
<td>0.57</td>
<td>0.90</td>
<td>0.71</td>
<td>0.71</td>
<td>0.79</td>
<td>0.86</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>((P_k',E_k'))</td>
<td>0.07</td>
<td>0.31</td>
<td>0.27</td>
<td>0.21</td>
<td>0.09</td>
<td>0.32</td>
<td>0.28</td>
<td>0.17</td>
</tr>
<tr>
<td>((W_k',E_k'))</td>
<td>-0.08</td>
<td>0.28</td>
<td>0.33</td>
<td>0.23</td>
<td>0.10</td>
<td>0.31</td>
<td>0.40</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Table 3. Composites of precipitable water anomalies (mm) contributed by different sources to LPRB during the season December-January-February. The first (second) sign in the parenthesis in the first column represents the sign of the oceanic (terrestrial) anomalous contribution. The double sign indicates which of these two sources is dominant in the total $W$ anomaly. All values are significant at the 95\% level or higher, except those in italics.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Freq.</th>
<th>Tot</th>
<th>No-SA</th>
<th>SA</th>
<th>LPRB</th>
<th>SAMZ</th>
<th>SOAT</th>
<th>NOAT</th>
<th>NAMZ</th>
<th>SOPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I:</td>
<td>9.4</td>
<td>4.29</td>
<td>3.10</td>
<td>1.19</td>
<td>-1.52</td>
<td>1.61</td>
<td>-0.84</td>
<td>1.02</td>
<td>0.55</td>
<td>0.21</td>
</tr>
<tr>
<td>II:</td>
<td>14.9</td>
<td>2.34</td>
<td>4.45</td>
<td>-2.10</td>
<td>-2.59</td>
<td>0.18</td>
<td>-0.79</td>
<td>0.65</td>
<td>0.08</td>
<td>0.22</td>
</tr>
<tr>
<td>III:</td>
<td>13.4</td>
<td>-1.70</td>
<td>-3.35</td>
<td>1.65</td>
<td>2.26</td>
<td>-0.37</td>
<td>0.04</td>
<td>-0.52</td>
<td>-0.24</td>
<td>-0.15</td>
</tr>
<tr>
<td>IV:</td>
<td>8.7</td>
<td>-4.24</td>
<td>-2.93</td>
<td>-1.31</td>
<td>1.16</td>
<td>-1.54</td>
<td>0.47</td>
<td>-0.82</td>
<td>-0.43</td>
<td>-0.12</td>
</tr>
<tr>
<td>V:</td>
<td>9.4</td>
<td>4.14</td>
<td>1.09</td>
<td>3.05</td>
<td>0.08</td>
<td>1.65</td>
<td>-0.79</td>
<td>0.93</td>
<td>0.74</td>
<td>0.01</td>
</tr>
<tr>
<td>VI:</td>
<td>20.3</td>
<td>2.05</td>
<td>-1.99</td>
<td>4.04</td>
<td>2.06</td>
<td>1.28</td>
<td>-0.44</td>
<td>0.06</td>
<td>0.21</td>
<td>-0.09</td>
</tr>
<tr>
<td>VII:</td>
<td>11.9</td>
<td>-2.26</td>
<td>1.93</td>
<td>-4.20</td>
<td>-2.07</td>
<td>-1.33</td>
<td>0.83</td>
<td>-0.29</td>
<td>-0.28</td>
<td>0.10</td>
</tr>
<tr>
<td>VIII:</td>
<td>11.9</td>
<td>-5.77</td>
<td>-1.53</td>
<td>-4.24</td>
<td>-0.42</td>
<td>-2.10</td>
<td>1.79</td>
<td>-0.98</td>
<td>-0.60</td>
<td>-0.13</td>
</tr>
</tbody>
</table>
Figure 1. Regions of study. Conventions are: CEAM: Central America (except Guatemala) NOSA: Northern South America; ORIC: Orinoco; GUYN: Guianas; PECH: Peru-Chile coastal region; NAMZ: Northern Amazon; SAMZ: Southern Amazon; TOCA: Tocantins river; NORD: Northeastern Brazil; ANDS: Subtropical Andes; LPRB: La Plata River Basin; SBRU: Southern tip Brazil and east of Uruguay; SOSA: Southern South America; NOPA: Adjacent Tropical Pacific; SOPA: Adjacent Subtropical and Extratropical Pacific; NOAT: Adjacent Tropical Atlantic; SOAT: Adjacent Southern Subtropical and Extratropical Atlantic.
Figure 2. Schematics of the trajectory of an ideal air column. In this example, the rectangular domain has been divided arbitrarily into 4 regions $A_1$, $A_2$, $A_3$ and $A_4$. According to the traversed region, the trajectory can be decomposed into 5 portions labeled by $\lambda = 1, 2, ..., 5$. The trajectory goes backwards in time, from time $t$, to time $\tau_5$, traversing the points $(x'(\tau_i), y'(\tau_i))$, where $i = 1, 2, ..., 5$. 
Figure 3. Mean annual cycle of contributions to (a) precipitation, and (b) precipitable water over the LPRB. In (a), the dark blue (light green) line represents total precipitation (evaporation), and the mean annual values (in mm d$^{-1}$) are shown in the small legend inside the plot. In (b) the dark blue line represents total precipitable water, and the mean annual value is shown in the small legend (in mm). The dotted line (“Terr”) is the sum of the contributions from South American sources. The long term contributions from each source are shown in the larger legends as percentages of the mean annual value of total (a) precipitation, and (b) precipitable water.
Figure 4. Mean VIMF (vectors) and mean moisture fraction (colors) originated from the LPRB (left column), southern Amazon (central column), and northeastern Brazil (right column). Monthly averages for January (top) and July (bottom) for the period 1980-2012. Units of the VIMF are kg m$^{-1}$ s$^{-1}$. Source regions different from the LPRB are delineated in blue. The LPRB is delineated in red. For the contribution from the northern Amazon, see the Supplemental Material.
Figure 5. Same as Figure 4 but for moisture originated from the adjacent portions of the Southern Pacific (left column), tropical Atlantic (central column), and Southern Atlantic (right column). For the contribution from the tropical Pacific, see the Supplemental Material.
Figure 6. Composites of anomalies of the contribution to monthly precipitable water (mm) over the LPRB by different regions during the extreme phases of (a) ENSO, and (b) AAO. The “+” (“−”) sign denotes the positive (negative) phase for ENSO and the AAO. The positive whisker extends from $q_{0.75}$ to $q_{0.75} + 1.5(q_{0.75} - q_{0.25})$ and the negative whisker extends from $q_{0.25} - 1.5(q_{0.75} - q_{0.25})$ to $q_{0.25}$, where $q_{0.25}$ and $q_{0.75}$ are the 25th and 75th percentiles, respectively.
Figure 7. Composites of anomalies in the monthly VIMF (vectors, (kg m\(^{-1}\) s\(^{-1}\))) and monthly precipitable water (colors, (mm)) fields associated with the different phases of ENSO (top) and the AAO (bottom). The vectors and the colored grid cells represent ENSO (AAO) anomalies that are statistically significant at the 99.5% (90%) level. The contours represent the anomalies in the monthly precipitable water, even if not significant.
Figure 8. Composites of anomalies in the VIMF (vectors, (kg m\(^{-1}\) s\(^{-1}\))) and evaporation (colors, (mm d\(^{-1}\))) fields associated with positive anomalies of \(W\) over the LPRB at \(t = \text{Day 0}\) during the wet season DJF. Top: case II, when oceanic sources dominate total \(W'\). Bottom: case VI, when terrestrial sources dominate total \(W'\). Composites for the day of the anomaly in \(W\) (Day 0) and 2 (Day -2) and 4 (Day -4) days before. See Table 3 and text for details. Only those anomalies significant at the 99.5% level are shown.
Figure Supp.1. Same as Figure 4, but for moisture originated from the adjacent tropical Pacific (top) and the northern Amazon (bottom).
Supplementary Material 2: Derivation of Equation (4)

In what follows, it must be understood that \( E = E(x'(\tau'), y'(\tau')) \) is evaluated along the trajectory. The same applies to \( W \). Equation (1) can be written as:

\[
R(\tau_i) = 1 - \exp \left( -\int_{\tau_i}^{\tau_0} \frac{E}{W} d\tau' \right) = 1 - \exp \left( -\int_{\tau_i}^{\tau_{i-1}} \frac{E}{W} d\tau' \right) \exp \left( -\int_{\tau_{i-1}}^{\tau_0} \frac{E}{W} d\tau' \right)
\]  

(1)

where \( R(\tau_i) \) is the \( R(x, y, t) \) fraction of atmospheric moisture at a given time \( t = \tau_0 \) and the integral is evaluated between a present moment \( \tau_0 \) and a previous time \( \tau_i \). The atmospheric moisture contributed by the portion of trajectory traversed between times \( \tau_i \) and \( \tau_{i-1} \) (where \( \tau_i < \tau_{i-1} \)) is given by:

\[
R(\tau_i) - R(\tau_{i-1}) = \exp \left( -\int_{\tau_{i-1}}^{\tau_0} \frac{E}{W} d\tau' \right) \left[ 1 - \exp \left( -\int_{\tau_i}^{\tau_{i-1}} \frac{E}{W} d\tau' \right) \right]
\]  

(2)

We can define some \( \alpha \) terms such that:

\[
\alpha_i = \exp \left( -\int_{\tau_i}^{\tau_{i-1}} \frac{E}{W} d\tau' \right) \rightarrow \exp \left( -\int_{\tau_i}^{\tau_0} \frac{E}{W} d\tau' \right) = \prod_{j=i}^{j=i-1} \exp \left( -\int_{\tau_j}^{\tau_{i-1}} \frac{E}{W} d\tau' \right) = \prod_{j=1}^{j=i-1} \alpha_j
\]  

(3)

Thus, the contribution form the portion of trajectory traversed between times \( \tau_i \) and \( \tau_{i-1} \) (i.e. the \( i \)th portion of the trajectory, going backwards in time) is given by:

\[
RC_i = R(\tau_i) - R(\tau_{i-1}) = \prod_{j=1}^{j=i-1} \alpha_j R_i
\]  

(4)

where \( R_i = 1 - \alpha_i \). By induction, the total fraction of moisture collected between times \( \tau_i \) and \( \tau_0 \) can then be written as:
where \( \lambda \) runs over all the portions of the trajectory. These portions can be defined according to the region that they traverse, which then leads to equations (5) and (6) as presented in the “Data and Methodology” section.
Appendix B

Effects of a Groundwater Scheme on the Simulation of Soil Moisture and Evapotranspiration over Southern South America

J. Alejandro Martinez¹, Francina Dominguez², and Gonzalo Miguez-Macho³

1. Department of Atmospheric Sciences, University of Arizona
2. Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois
3. Faculty of Physics, Universidad de Santiago de Compostela, Galicia, Spain

Manuscript prepared to be submitted to the Journal of Hydrometeorology
Abstract
The effects of groundwater dynamics on the representation of water storage and evapotranspiration (ET) over southern South America are studied from simulations with the Noah-MP Land Surface Model. The model is run with two different configurations: one including the Miguez-Macho and Fan groundwater scheme, and the other with free drainage at the bottom of the soil column. The first objective is to assess the effects of the groundwater scheme using a grid size typical of regional climate model simulations at the continental scale (20km). The phase and amplitude of the fluctuations in the Terrestrial Water Storage over the southern Amazon are improved with the groundwater scheme. An increase in the moisture in the top 2 meters of the soil is found in those regions where the water table is closer to the land surface, including the western and southern Amazon and the La Plata basin. This induces an increase in ET over the southern La Plata basin, where ET is water limited. There is also a seasonal increase in ET during the dry season over parts of the southern Amazon. The second objective is to assess the role of the horizontal resolution on the effects induced by the groundwater scheme. From simulations with grid sizes of 5 and 20km, it is found that over the La Plata basin, the 5km simulation exhibits an even larger increase in ET in areas where the groundwater scheme already has effects at the coarser resolution. However, the groundwater scheme increases ET over parts of the Amazon only at the higher resolution.
1. Introduction

The continuous exchanges of momentum, energy and mass between the land and the atmosphere shape weather disturbances and regional climates in different ways, depending in part on the geographical location (see e.g. Pielke (2001), Betts (2004), Cotton and Pielke (2007), Seneviratne et al. (2010)). A number of studies have shown the important role of soil moisture and land surface fluxes on weather and climate over South America. For example de Goncalves et al. (2006a) and Doyle et al. (2013) obtained better weather forecasts when using more realistic initial conditions of soil moisture (Doyle et al. also used an updated map of soil properties). Collini et al. (2008) found that precipitation over the South American Monsoon region is particularly sensitive to the soil moisture field at the onset of the monsoon. Sörensson and Menéndez (2011) found a strong coupling between summer precipitation and evapotranspiration (ET) over the La Plata basin. Therefore, a good representation of the storage and fluxes of moisture in the land component of a weather or climate model might be critical for the simulation of precipitation patterns over parts of South America.

In spite of the tremendous advances in the representation of many processes in Land Surface Models (LSMs), the simulation of the storage (e.g. soil moisture) and fluxes of moisture (e.g. ET) require further improvement. Despite the high temporal co-variability of soil moisture among different LSMs in their study, Koster et al. (2009) state: “It is possible that land surface models are, indeed, all “wrong in precisely the same way”, reducing their usefulness for such a real-world application. For example, they all lack, to some degree, sophisticated treatments of
certain hydrological processes (e.g. baseflow, interflow), and most share similar simple representations of other hydrological processes [...].” In the case of South America, Chen et al. (2010) found that GLDAS-NOAH does not give account of some of the amplitude of the monthly-scale fluctuations in the Terrestrial Water Storage (TWS) field over the southern La Plata basin, maybe due to the lack of a representation of groundwater processes. Ferreira et al. (2011) found that GLDAS-NOAH and WRF-NOAH both underestimate soil moisture over northeastern Argentina. The comparison was made both using absolute values and after normalizing by the dynamic range of each data set. From the simulation of the water balance of the Amazon basin with 14 LSMs, Getirana et al. (2014) also suggest that there are still several aspects where the LSMs need improvement, in particular the simulation of ET. Both surface characteristics (e.g. the parameterization of surface resistances) and the simulated soil moisture affect the ET estimates.

One fundamental component affecting soil moisture dynamics is the distribution of shallow groundwater (Fan et al., 2013, Fan 2015). Shallow unconfined aquifers have an effect on the content of moisture in the layers closer to the land surface (e.g. the critical zone), as the downward flux (drainage) might be reduced and even reversed by the presence of groundwater. In addition, where groundwater is shallow, or where roots are deep enough, the groundwater can directly be used by plants, affecting the land surface fluxes of moisture and energy via effects on transpiration (Fan 2015). By studying the water balance components measured on an Amazonian micro-catchment, Tomasella et al. (2008) found strong memory features of the groundwater component, in the form of anomalies that persist in the scale of years. The authors suggest that
the memory of the groundwater affects the moisture content in the unsaturated zone and ET, which are very important for understanding the variability of the weather and climate of the region. Pfeffer et al. (2014) estimated the depth of the water table for the central Amazon using satellite data for the period 2003-2008. They also found strong memory features at the basin scale, in particular in the response of the central Amazon to the drought of 2005: the negative anomalies in the water table persisted until 2007. Studying the Argentine Pampas (southern La Plata Basin), Kuppel et al. (2015) found significant correlations between the water table depth and TWS, and between TWS and ET. There is also a monotonic relationship between the water table depth and the surface water cover. Thus, groundwater in this region is also a critical factor for flood dynamics and ET anomalies. In the modeling study by Chen et al. (2010), the authors found a better representation of the fluctuations of TWS when they combined the GLDAS-NOAH data with groundwater observations over the southern La Plata Basin.

Given its importance for surface hydrology, and its corresponding impact on the fluxes of energy and moisture at the land-atmosphere interface, schemes to represent groundwater processes and water table dynamics have been developed in the last 10-15 years as new components of LSMs for weather and climate studies. Some examples include the studies by Niu et al. (2007), Miguez-Macho et al. (2007), Choi and Liang (2010), Decker and Zeng (2009) and Koirala et al. (2014). Niu et al. (2007) found that a groundwater scheme increased the simulated soil moisture and ET over parts of South America, including the southern half of the Amazon basin, western La Plata basin, and northeastern Brazil. The simulations with groundwater also produce fluctuations in the TWS consistent with GRACE estimates. Miguez-Macho and Fan (2012b)
estimate that the water table is less than 2 meters deep over 20-40% of the Amazon basin. The shallow groundwater reduces drainage during the wet season, and even supports capillary rise over parts of the Amazon during the dry season; both effects increase dry season soil moisture and ET. On the third paper of that series, Pokhrel et al. (2013) also find a better agreement with TWS from GRACE when the dynamic groundwater is included. Koirala et al. (2014) found an improvement in the simulation of the discharge of the Amazon river (in phase and amplitude). They also found an increase of soil moisture and ET over parts of South America, but their increase in ET is much smaller than that reported by Miguez-Macho and Fan (2012b).

Shallow water tables are found not only in the Amazon basin, but also in other parts of South America, and in particular in the La Plata basin (Fan and Miguez-Macho (2010), Fan et al., (2013)). This suggests that groundwater dynamics might have an important role on the water balance and its variability over this region. Furthermore, given the strong land-atmosphere coupling in southern South America (see e.g. Sörensson and Menéndez (2011), and Dirmeyer et al. (2009)), the representation of groundwater dynamics on LSMs might also have potential impacts on the simulation of the atmospheric processes - including precipitation.

From previous studies (with some examples cited above) it is clear that: i) there is a strong coupling between precipitation and land states in southern South America; ii) there are characteristics of the simulation of soil moisture dynamics that still need improvement and analysis in weather and climate models; and in particular iii) the shallow groundwater is a component of the water balance that affects soil moisture and ET, however it is a relatively new
component in LSMs whose effects are still an area of research. Consequently, there is a critical need to study the role of groundwater on the water balance over central and southern South America.

Therefore, the goal of this study is to explore the effects of a groundwater scheme on the simulation of the storage and fluxes of moisture over a region that includes the southern Amazon and the La Plata basins. In addition to studying the groundwater effects at resolutions typical of regional circulation models (RCMs), we explore the role of the horizontal resolution on a groundwater scheme that explicitly includes the lateral flow of groundwater. Specifically we ask a) What are the spatial and seasonal differences in the simulation of TWS, soil moisture and ET when a groundwater scheme is included?; b) do the effects of the groundwater scheme change at the inter-annual time scale (including climatic extremes like the 2008-2009 drought in southern La Plata)?; and c) what is the effect of the horizontal resolution of the groundwater scheme on the simulation of ET? To do this, we use the groundwater scheme developed by Miguez-Macho et al. (2007). To address questions a) and b), we perform 10-year simulations in offline mode (i.e. with prescribed atmospheric conditions) using a grid size of 20km. We compare a simulation that uses the groundwater scheme with a simulation that has free drainage as boundary condition at the bottom of the resolved soil layers. We assess the effects of the groundwater by comparing the TWS, soil moisture and ET in both simulations, with a focus on features at the regional scale. To address question c) we perform simulations with grid sizes of 20 and 5 km. While the results of simulations with 20 km grid size are relevant for the interpretation of current climate simulations, the comparison of the lower and higher resolution simulations provide a picture of
those regions where higher resolution or additional parameterizations are needed.

2. Methodology

a. Region of study

The model domain includes parts of the La Plata river basin (LPB), the southern half of the Amazon basin, and central-eastern Brazil (Figure 1). The LPB extends over parts of five countries, is the second largest system in South America, and its water resources are a key component of the economy of the region, which is one of the most densely populated areas in South America (Berbery and Barros, 2002). The southern Amazon and central-eastern Brazil play important roles in the local and regional climate, in particular because of its connection with the South American Monsoon System (e.g. Marengo et al. (2012), Collini et al. (2008), Vera et al., 2006), and the transport of water vapor to the La Plata basin (e.g. Marengo et al. 2004, Martinez and Dominguez, 2014).

b. The Miguez-Macho and Fan (MMF) groundwater scheme

In the present study, we use the groundwater scheme developed by Miguez-Macho et al. (2007), as currently implemented in the Noah-MP LSM (Barlage et al., 2015). This scheme (hereafter the Miguez-Macho and Fan or MMF groundwater scheme) includes a representation of the
interaction of the shallow groundwater with the unsaturated zone by adding an unconfined aquifer below the lowest resolved soil layer. The water balance for this aquifer includes the interaction with the unsaturated zone (vertical fluxes) and with the river network (horizontal fluxes). The vertical fluxes represent the gravitational drain and the capillary fluxes, and Darcy's law is used to represent the resulting flux. There is also a representation of the lateral movement of the groundwater, given by the horizontal flow between each grid cell and its 8 neighboring grid cells. These fluxes are estimated via Darcy's law with the Dupuit-Forchheimer approximation (Fan and Miguez-Macho, 2010). Lateral flow between the groundwater and the river network is also represented by a Darcy's law-type equation.

c. Model Configuration

The Land Surface Model (LSM) used in this study is the Noah land surface model with multiparameterization options, Noah-MP (Niu et al., 2011). We use the Noah-MP Version 1.6 in offline mode (i.e. with prescribed atmospheric conditions) by using the driver code High-Resolution Land Data Assimilation System (HRLDAS). The code has been provided by the Research Applications Laboratory (RAL) from their website http://www.ral.ucar.edu/research/land/technology/noahmp_lsm.php. We run the model at two different grid sizes (20 and 5 km, see details below), with a time step of 30 minutes (see e.g. Getirana et al., 2014). We have modified the soil column to have 14 layers extending from the land surface to 4 meters below, using the same configuration as Miguez-Macho and Fan (2012a).
The offline simulations require initial conditions of the state of the soil (moisture and temperature) and atmospheric forcing (including downward short (SWDOWN) and longwave radiation, precipitation (P), humidity, temperature and winds). The initial conditions and the atmospheric forcing were obtained from the ERA-Interim archive (Dee et al., 2011). This reanalysis has some known biases over South America. For example, Betts et al. (2009) found that the clear-sky downward shortwave radiation has a negative bias over the Amazon with respect to International Satellite Cloud Climatology Project (ISCCP) data set. Betts et al. (2009) also found a negative bias in the 2 m temperature over the Amazon. Figure 2 shows the average SWDOWN and P fields from ERA-Interim during the period 2004-2013 (right panels). As a reference data set, we show the forcing fields used for the Global Land Data Assimilation System (GLDAS, Rodell et al. (2004), Rui (2011)) for the same period (Figure 2, left column). Over the region, ERA-Interim has a negative bias in SWDOWN compared with GLDAS, which is more pronounced over the Amazon region and southeastern Brazil. In addition, the ERA-Interim forcing has a positive bias in P over the southern Andes, and the northern and southern parts of the domain. In this study, we focus mostly on the differences among simulations with and without a groundwater scheme, and the role of the horizontal resolution.

*d. Assessing the role of the Groundwater: “Groundwater” (GW) vs. “Free Drainage” (FD) simulations*

In order to assess the effects of the representation of the groundwater dynamics in the Noah-MP LSM, we run the model with two different configurations. In the first configuration, the
Miguez-Macho and Fan groundwater scheme (Miguez-Macho et al., 2007) is activated; we will refer to simulations with this configuration as the GW simulations. In the second configuration, the soil moisture is allowed to freely drain from the bottom layer of the soil column under the action of gravity solely, i.e. no interaction with a groundwater reservoir is taken into account; we will refer to simulations with this configuration as the FD simulations. Initial conditions and parameters for the groundwater scheme come from equilibrium conditions with the recharge simulated by Noah-MP, using the same methods as in Fan and Miguez-Macho (2010) and Fan et al. (2013).

In this study we seek regional scale patterns of soil and land-surface conditions induced by the groundwater scheme that could be simulated by fully coupled land-atmosphere models at horizontal resolutions that represent current continental-scale regional climate modeling studies over South America (e.g. Solman et al. (2013), Lee and Berbery (2012), and Müller et al. (2014)), and that could affect the state of the atmosphere (e.g. affecting precipitation). Accordingly, we run a set of simulations with a grid size of 20 km. We first run a simulation for the period 1994-2003 with the MMF scheme. This simulation is regarded as a spin-up of the model, as the time of spin-up of soil variables over South America is no longer than a few years (de Goncalves et al., 2006a). Then, the final state is used as initial condition for two simulations (GW and FD) for the period 2004-2013. These two simulations are compared in terms of Terrestrial Water Storage (TWS), soil moisture in the top 2 meters of the soil column (SM2m) and evapotranspiration (ET).
e. Assessing the role of the horizontal resolution: 20 vs. 5 km simulations

Other objective of the present study is to assess the sensitivity of the effects of the MMF groundwater scheme to the horizontal resolution of the model. This scheme has an explicit representation of the lateral flow of groundwater to/from each grid cell from/to each of its 8 neighboring cells. We run a second set of simulations that include two runs with a grid size of 20 km (GW20 and FD20) and two runs at 5 km grid size (GW05 and FD05). All simulations start from the same initial condition on December 1st, 2003, and run through December 31st, 2005. In this case, no spin-up is considered (except for excluding the first month of simulation from the analysis). The focus is on the difference between two spatial resolutions, i.e. differences of the type (GW05-FD05) vs. (GW20-FD20). The outcome will provide a picture of those regions where the groundwater scheme has an impact that depends on the resolution of the model.

Table 1 presents a summary of some of the details of the studied simulations.

3. Results

a. Effects of the MMF groundwater scheme with grid size of 20 km

Over most of the domain, the rainy season is from October-November through March-April
The dry season peaks in July-August. To facilitate our analysis, we define four regions of interest: the Southern Amazon (“SOAM”, [68-55°W, 20-8°S]), the South American Monsoon region (“SAMS”, [55-45°W, 20-8°S], similar to Collini et al., 2008), the “Upper La Plata” (“UPLP”, [64-54°W, 28-20°S]) and the “Lower La Plata” (“LOLP”, [64-54°W, 36-28°S]). The amplitude of the precipitation cycle is larger for the monsoon region, while the southern Amazon receives some precipitation even during the dry season. Precipitation over the La Plata basin is less than over the north of the domain, with larger values over the south of the basin.

1) Water table depth

The simulated water table is relatively deep compared with the estimates obtained by Fan and Miguez-Macho 2010, and Fan et al. 2013 (Figure 3, bottom panels). Over the UPLP and LOLP regions the water table is mostly below the 5 m depth, with some regions above the 4 m depth (i.e. where the water table is within the resolved soil layers). In contrast, Fan et al. 2013 found equilibrium values around 2.5 m for the same region. Analogously, the water table over the SOAM and SAMS regions is deeper than reported by Fan and Miguez-Macho (2010). Two major factors contribute to these differences: i) in this study we are using a much coarser resolution (20km) compared with Fan and Miguez-Macho 2010 (~ 270 m) and Miguez-Macho and Fan 2012a,b (~ 2km), which affects the simulation of the lateral movement of the groundwater toward small scale depressions; and ii) in our simulations ET seems to be too high (see below), which is likely to dry up the soils and lower down the water table. However, the
GW simulation still shows a relevant fraction of the domain where the water table depth is within the top 4 m of the soil column (i.e. within the resolved layers). Figure 3 also shows that there is a seasonal cycle of the water table depth over parts of the southern Amazon and the monsoon region, with the water table depth lagging precipitation by nearly 2-3 months.

2) Terrestrial Water Storage (TWS)

We estimated the monthly fluctuations in the TWS in both simulations (Figure 4). For the FD simulation we add the moisture in the canopy and the soil column (14 levels, bottom at 4m) to obtain the total water storage. The fluctuations in TWS are obtained by subtracting the mean water storage during the 10 years of simulation (2004-2013). For the GW simulation we add the moisture in the canopy, the resolved soil layers, and in the soil below, assuming a hypothetical constant bedrock at 100 m below the land surface. This arbitrary bedrock depth has no consequence because we remove the long term mean of the water storage. Thus, the fluctuations in TWS in the GW simulation are independent of the bedrock depth, and capture the role of the fluctuations in the water table depth (Pokhrel et al., 2013). For reference, we compare with the fluctuations in TWS from the Gravity Recovery and Climate Experiment (GRACE) data (Landerer and Swenson (2012), Swenson and Wahr (2006)). The GRACE TWS fluctuations are deviations from the mean value for the 2004-2009 period. The large scale patterns in Figure 4 are similar among the data sets. Over the north of the domain, the TWS is larger during April, after the end of the rainy season; then the TWS decreases during the dry season and reaches the lowest values at the onset of the new rainy season. Over the south of the domain, the highest
TWS is seen during the dry season (winter) and the beginning of the rainy season. Part of the reason seems to be the decrease of ET during the dry winter season, while moisture is still collected from winter precipitation (extratropical systems).

Both for the southern Amazon and the monsoon region the GW simulation produces a longer lag in the response of the TWS to the cycle of precipitation (Figure 5). In the case of the monsoon region (SAMS) and the southern Amazon (SOAM), after the first years of simulation, the amplitude in the GW simulation is closer to GRACE than the amplitude of FD. In addition, for the SAMS region, the phase of GW is closer to GRACE. Thus, the GW simulation seems to produce a better amplitude and phase than FD, even at this “coarse” resolution of 20 km (Pohkrel et al. 2013 found analogous results using ~ 2 km). Figure 5 shows a jump around 2006 in the TWS for SOAM in the Noah-MP simulations. A similar jump is observed in soil moisture (Figure 7), both in our simulations and in ERA-Interim. These abrupt changes around 2006 are a result of a jump in the ERA-Interim precipitation over the region, which seems to be an artifact of the reanalysis when compared with TRMM (not shown).

In the case of the La Plata basin, the differences between our simulations and GRACE are more notorious. First, note the relatively large year to year variability on each time series, and how the smaller fluctuations are some times out of phase between our simulations and GRACE. Second, the resulting mean annual cycle is noticeably different between our simulations and GRACE, while the GW and FD simulations are very close to each other. The timing of the largest fluctuations seems to be well depicted by our simulations, probably because the variations of the
forcing (e.g. SWDOWN and P) are larger or more relevant than the corresponding biases. This is the case during the drought over the southern La Plata basin in 2008-2009 (see e.g. Chen et al., 2010). Starting around October 2007, all three time series (GRACE, GW and FD) show the same fluctuations throughout 2008 and 2009. One interesting difference is that GW seems to overestimate the fall in TWS in this period. This decrease seems to have sustained higher values in ET in the GW simulation compared with the FD simulation in response to the lack of precipitation (see below). Finally, note that both the long-term decline and the largest fluctuations of TWS in the GW simulation are more pronounced than in the FD simulation over the southern La Plata basin (i.e. LOLP). In general, our simulations suggest that the groundwater scheme affects the amplitude, phase and long-term behavior of the fluctuations in TWS.

The largest discrepancies between GRACE and our simulations were found for the central La Plata (UPLP, Fig. 5). In particular, the difference between the first and second half of the year is much smaller in the simulations than in the GRACE estimates, which seems to be associated with an overestimation of the runoff over the UPLP region, which would be unrealistic given the flat terrain and other hydrologic characteristics of the region. Further discussion of the simulation of runoff and its relation to TWS is included in section 5), where different components of the water budget for the Paraná basin are presented.

3) Soil moisture in the top 2 meters (SM2m)

The largest values of soil moisture (Figure 6) are found over the Amazon (north of the domain),
where precipitation is larger (Figure 3). The amplitude of the seasonal cycle is also larger over this region. The model produces local maxima of soil moisture over southern Brazil and southern La Plata (LOLP), and intermediate values over the north-central part of the La Plata basin (including UPLP). The middle panels in Figure 6 show the absolute difference between the GW and FD simulations. The differences are positive, which means that the GW scheme increases the soil moisture content in the top layers of the soil. This increase is not homogeneous over the domain, but is larger where the water table is shallower (Figure 3). SM2m is larger not only in regions where the water table is above the 2 m depth, but also in regions where it is even below the resolved soil layers (4 m). Including a representation of the shallow aquifers reduces the downward flux of soil moisture in the GW simulation compared with the FD simulation. In some regions, the moisture flux can even reverse, going upwards from the aquifer to the soil column. The largest differences are seen over the northwest of the domain, reaching values larger than 0.12 m$^3$/m$^3$. A permanent difference is observed over the southern La Plata (LOLP), with mean values between 0.02 and 0.04 m$^3$/m$^3$. The differences over the southern Amazon (SOAM) and the monsoon region (SAMS) have a more visible seasonal cycle, which peaks at the end of the rainy season. This is due to the reduced drainage in the GW simulation. The bottom panels in Figure 6 show the fractional differences between FD and GW, defined as (GW-FD)/FD. These maps show that the differences over the northwestern part of the domain can be larger than 40%. Similar values are observed over parts of the southern Amazon and the monsoon region. Over La Plata, the differences in soil moisture between both simulations are in the range 5-20%.
Time series of the regional averages of soil moisture in the top 2 m from the simulations are
compared with SM2m derived from ERA-Interim (Figure 7). Note that a free drainage
condition is also used in ERA-Interim, whose land-surface scheme has 4 layers, with the bottom
at 2.55 m (Balsamo et al., 2009). The comparison of “soil moisture” variables between different
models is not straightforward, as some properties of this variable (e.g. its dynamic range) depend
on intrinsic properties and formulations of each model (Koster et al., 2009). However, we make
some comments to add in the description of our simulations. In general, ERA-Interim has
smaller values of SM2m, except over SOAM, where it nearly coincides with the FD simulation.
The annual cycle over SAMS is more pronounced in ERA-Interim, probably because
ERA-Interim produces larger ET in that region during the dry season (see below). In general, the
phase of the annual cycle over the Amazon is similar between our simulations and ERA-Interim.
As for the TWS, the case of La Plata is more complex. For both regions in the La Plata basin
(UPLP and LOLP), the timing of the largest fluctuations in GW and FD is similar to
ERA-Interim. However, this is not the case for the smaller variations. The mean annual cycle
over this region is different between Noah-MP and ERA-Interim. In particular, our simulations
show a local minimum around January-February (which is not evident in ERA-Interim) that
could be related to the relatively high ET during the previous months (see below).

The annual cycle over the Amazon is more regular, while over La Plata the inter-annual
variations are larger. The time series for the southern Amazon (SOAM) and the monsoon region
(SAMS) show that the SM2m field lags precipitation by about one month (compare to 2-3
months for the TWS). Note also that the difference between GW and FD are a smaller fraction
of the amplitude of the annual cycle over the Amazon, but a larger fraction over the La Plata basin. For all four regions, the phase of both time series (GW and FD) seems to be the same, in contrast with the TWS fluctuations. Thus, the groundwater scheme is not introducing temporal effects on SM2m in these offline simulations (i.e. where the same atmospheric forcing is used in both simulations). The situation could be different in fully coupled land-atmosphere simulations (e.g. with WRF), where larger values of SM2m in the GW simulation could increase precipitation, modifying the surface forcing in magnitude and timing.

Over the southern La Plata (LOLP) the time series shows some interesting features during some of the anomalously dry rainy seasons. One example is the drought of 2008-2009. By October 2007, both the GW and FD simulations have relatively similar values of average soil moisture. However, the decrease in soil moisture between October-2007 and February-2008 is stronger in the FD simulation, while the groundwater scheme reduces the drainage. Other example is the wet season between 2010 and 2011. The difference in soil moisture between both simulations is larger in March-2011 than in September-2010. Thus the FD simulation exhibits a sharper drop in soil moisture as a response to the largest negative anomalies in precipitation. In contrast, large positive anomalies in precipitation can make the moisture in the top 2 meters of the soil nearly equal in both simulations, like in the second half of 2012. During those wet events the soil layers closer to the land surface are very moist, contributing more to SM2m, which therefore takes very similar values in both simulations between September and November of 2012. However, at the end of the anomalous wet period, the FD simulation dries up faster due to its free drainage boundary condition.
4) Evapotranspiration

Large values of ET are observed over the southeastern part of the domain during the rainy (summer) season (Figure 8). These values decrease sharply during the dry (winter) season. Around July, ET over the monsoon region is too low. It is important to point out that no calibration of Noah-MP has been made, which is reflected on the simulated values of different variables. The simulated ET tends to be lower than the ET from ERA-Interim over the northeast of the domain during the dry season (where ET is more energy limited). To first order, this bias in ET seems to be consistent with the biases in the SWDOWN and P fields (see Figure 2). The simulated ET over the Amazon recovers by October.

The GW simulation produces more ET than the FD simulation over parts of the La Plata basin and the southern Amazon (Figure 8), which is a result of moister soils in the GW simulations (Figure 6). Note that there are no ET differences over the northwestern part of the domain, despite the significant differences in soil moisture (Figure 6); in that region ET is mostly limited by radiation. The differences over the southern Amazon peak during the dry and before the onset of the rainy seasons, when ET tends to be more water limited. Over the La Plata region the difference in ET is larger at the onset of the rainy season (~ October), due to the combination of enough radiation and water available. Over the monsoon region the difference in ET has two peaks during the year, around the end and the onset of the rainy season. During the peak of the dry season the difference in ET has a local minimum, which seems to be caused mostly by the
bias in SWDOWN (as in the case of total ET, see Figure 8). The largest fractional differences (Figure 8, bottom) are found during the dry season (when absolute ET is smaller), reaching values larger than 40%. Note that during the onset (~October) and demise (~April) of the rainy season, the fractional differences over the southern La Plata are larger than 10%. Even in the middle of the rainy season (e.g. January), the GW simulations produce around 10% or more ET over the southern La Plata, which could enhance precipitation in coupled simulations via recycling.

The regional averages of ET show that the differences between both simulations are much smaller than the amplitude of their seasonal cycle (Figure 9). The phase of the fluctuations is virtually the same in both simulations for all regions (as in the case of SM2m). For reference, we also plotted the regional averages of ET from ERA-Interim (which does not include a groundwater scheme). In the case of SOAM and SAMS, there is a big difference between ERA-Interim and our simulations between ~March-September, likely due to the biases in SWDOWN and the lack of calibration described above. For SOAM, the GW simulation produces more ET during the dry season and the first part of the rainy season (June-November), which shows the buffering effect of the groundwater scheme when precipitation decreases. In the case of the monsoon region (SAMS), the regional average from the GW simulation is almost identical to that from FD simulation, because the differences are limited to a small region and for a limited time during the year (see Figure 8).

In the case of La Plata, our simulations are closer to ERA-Interim (Figure 9), with the GW
simulation producing higher values at the end of the dry (August) season and the early stages of the rainy season (October). The difference GW-FD is somewhat larger around October-November, but it can be seen throughout the year. The effect of the groundwater scheme on the increase in ET is larger over the southern La Plata (LOLP). Total ET is significantly reduced over this region during the drought of 2008-2009. In both simulations, the reduction in ET is due to the reduction of soil moisture in the top 2 meters of the soil (which is the root zone of the model), (Figure 7). During the rainy season of 2009-2010 there is a sharp recovery of ET in both simulations, as a response to the anomalously wet rainy season. On the other hand, ET is almost the same in both simulations during the second half of 2012. In particular, peak values during October-January are very large and virtually the same in both simulations as a response to the anomalously wet second half of 2012 (which also induced similar peak values in SM2m in both simulations, see above).

5) The Paraná basin

The region formed by the Paraná and the Paraguay sub-basins constitutes most of the LPB (Berbery and Barros, 2002). The resulting sub-basin of the LPB is shown in Figure 10 as defined by the GRDC (http://www.compositerunoff.sr.unh.edu/html/Stn/B6.html), and following their definition we will refer to it as the Paraná basin. In this section we describe some characteristics associated with different components of the water budget for the Paraná basin. Observations of river discharge for a location close to the outlet of the basin were obtained from the Base de Datos Hidrológica Integrada, via the website
Observations are recorded at the Timbues station (coordinates (60.7°W, 32.6°S), red dot in Fig. 10B), and mean monthly river discharge for the period January-2004 to December-2013 was used to compute the mean annual cycle shown in Figure 10 (labeled as BDHI in Fig. 10B). The total runoff, ET and TWS fields were averaged over the Paraná basin as defined in Figure 10A.

The river discharge from the model is too large between January and April, during the mature and demise stages of the precipitation season over the basin. In the GW simulation the overestimation of river discharge is associated in part with a lack of calibration of the river-groundwater exchange. The real Paraná basin has little drainage as large portions of the basin are very flat. In addition, the Noah-MP model used in this study does not include a flooding scheme (e.g. like the one used by Miguez-Macho and Fan (2012) for the Amazon), despite the fact that a substantial portion of the Paraná basin is formed by flooded areas, wetlands and marshes, including the Pantanal. Finally, the model does not include a routing scheme, which is important to simulate the delayed response of the river system to the precipitation regimes in different parts of the basin. In this respect, Berbery and Barros (2002) found that the phase differences between the LPB sub-basins (including the Paraguay and the Paraná) are a key factor in the small seasonal changes in the river discharge of the LPB.

Compared to ERA-Interim, Noah-MP underestimates ET during the dry season (~May-September), and overestimates ET during the early wet season (~October-January). On the other hand, the ERA-Interim precipitation over the basin seems to be close to observations,
as suggested by comparison with TRMM estimates (not shown). Therefore, the differences in
the simulated TWS fluctuations between the model and GRACE (Figure 10D) seem to be
associated with limitations in the simulation of runoff and ET. For example, between December
and February, the TWS from GRACE increases faster than the Noah-MP estimates because of
excess ET and runoff in the model. Conversely, during the dry season, the model has low ET
(compared to ERA-Interim) and runoff, which slows down the decrease in TWS compared to
GRACE. Despite the limitations of the model, the GW scheme seems to improve the amplitude
and phase of the TWS fluctuations, while reducing the peak river discharge and increasing the
dry season ET.

b. Role of the horizontal resolution

At higher resolution, finer details of the topographical gradients are captured, which in turn leads
to larger lateral flows of groundwater toward local (as opposed to regional) topographic
depressions. In turn, this induces shallower water tables over a larger area in the higher
resolution simulation compared with the lower resolution (Figure 11). This effect, however, is
not homogeneous in space, as it is more pronounced where the topographical gradients are larger.
In our region of interest, the difference is more noticeable over the north and east of the domain,
including the southern Amazon (SOAM) and the monsoon region (SAMS). On the contrary, the
topographical gradients are smoother in the 20km simulation, reducing the lateral flow as
represented in the MMF groundwater scheme. The differences of the water table depth over the
La Plata region (including UPLP and LOLP) are not as pronounced as over the Amazon, because the small-scale topographical gradients are relatively smaller (see Figure 1).

As a result of having more grid cells with a shallower water table, the 5km simulations produce more regions where the groundwater scheme increases ET that are not observed in the 20 km simulations (Figure 12). For example, during the wet season (January), the 5km simulation induces an increase in ET over parts of the southern Amazon (SOAM), Uruguay and Southern Brazil. By the end of the rainy season (April) over the monsoon region (SAMS) the groundwater effects in the 5km simulation are also visible. During the dry season (July), the northwest corner of the box representing the monsoon region, and the northeast of the southern Amazon, show an increase in ET, which in the 5 km simulations is greater than 0.5 mm/day, while a smaller area, with lower values, is observed in the 20 km simulations. During October, the effects of the groundwater scheme over the monsoon region span a larger area in the high resolution simulation.

For all four regions of interest, the simulations with 5km grid size show a larger increase in ET (i.e. larger ΔET) due to the groundwater scheme (Figure 13). During the peak of ΔET, the groundwater scheme plays a major role on ET, and the scale effects are more pronounced due to the existence of a larger area with shallow water table in the high resolution simulations. On the contrary, during the peak of the rainy season, the groundwater scheme has a smaller role on ET, and the differences due to resolution are consequently smaller. The horizontal resolution does not introduce differences in the timing of ΔET, but increases its magnitude. The effects of the
higher resolution can be very large over disconnected but nearby grid cells, and its widespread
distribution is visible even at the regional scale, as seen both from the monthly maps (Figure 12)
and the spatial averages (Figure 13) of ΔET. In general, the comparison of the 5 and 20 km
simulations, suggests that the resolution effects of the MMF scheme on ET are neither spatially
homogeneous, nor negligible at spatial scales relevant to the current use of RCMs for climate
simulations at the continental scale. In particular, the regions most affected by the groundwater
scheme at higher resolution can span hundreds of kilometers, and the increase in ET can be
larger than 1 mm/day, like in the case of the southern Amazon during the dry season. A
difference of this magnitude in the land surface fluxes might have an impact on the simulation of
the atmosphere in RCMs, even with a grid size of the order of 20 km, although their land surface
model would not be able to capture the groundwater effect in the first place. Finally, note the
differences between both resolutions is of the same type throughout the simulation over the
southern Amazon and the monsoon region. This is not the case for the La Plata basin, where the
simulations at both resolutions show similar effects of the groundwater scheme in the last year of
simulation.

4. Summary and Discussion

The role of groundwater on water storage and evapotranspiration over parts of South America
was studied using the Noah-MP LSM. Simulations with the groundwater scheme developed by
Miguez-Macho and Fan (Miguez-Macho et al. 2007) were compared with simulations that use
free drainage as boundary condition at the bottom of the soil column. The role of the groundwater scheme was assessed in terms of the differences in terrestrial water storage, moisture in the top 2 meters of the soil, and evapotranspiration between the simulations with groundwater and those with free drainage. In addition, the role of the horizontal scale on the effects of the groundwater scheme was also investigated.

The groundwater scheme improves the simulated amplitude of the seasonal cycle of terrestrial water storage (TWS) over parts of the Amazon and central-eastern Brazil (i.e. what we call in this paper the “monsoon region”, SAMS), as compared with GRACE estimates. Over these regions, there is also a change in the phase of the TWS, characterized by a delay in the peaks and valleys of TWS with respect to the simulation with free drainage (which is also a delay with respect to the precipitation cycle). The changes in phase also improve the simulated TWS over the monsoon region. Over the La Plata basin, the groundwater scheme induces a larger long-term decline in the TWS, as well as larger monthly fluctuations (like in the case of the drought of 2008-2009, see Figure 5).

The groundwater scheme also induces an increase in the simulated moisture in the top 2 meters of the soil over those regions where the water table is closer to the surface. Over the northwest of the domain the increase can be as large as 40%. Over parts of the southern Amazon, the monsoon region, and the La Plata basin, the increase in soil moisture is mostly in the range 5-20%. The increase in soil moisture in the top 2 meters (the root zone of the model) induces in turn an increase of evapotranspiration, but mostly over those regions/seasons where ET is more
water limited. This is the case for the southern La Plata (throughout the year) and parts of the
southern Amazon and the monsoon region (between the dry and the onset of the rainy seasons).
In particular, during the onset and demise of the rainy season over the La Plata basin, the
groundwater scheme can increase ET in the order of 10%, which might have an impact on
precipitation recycling in fully coupled simulations. In contrast to the TWS fluctuations over the
Amazon region, no changes in phase are observed in the fluctuations of soil moisture and
evapotranspiration in these offline simulations.

Comparison of simulations with grid sizes of 20 and 5 km show that the latter depict
significantly more grid cells where the water table is shallower. A higher resolution
representation of the topography induces larger lateral flows of groundwater toward local (as
opposed to regional) topographic depressions, which produces a shallower water table in those
regions. In turn, the groundwater scheme affects the simulation of ET over a larger area in the
higher resolution simulations. The most dramatic effects are observed over parts of the southern
Amazon and the monsoon region. At higher resolution there is also a further increase in ET over
the La Plata basin, especially during the onset of the rainy season.

The atmospheric forcing from ERA-Interim has some biases over South America (e.g. Betts et
al., 2009), which are also visible with respect to the GLDAS forcing data (Figure 2). The model
used in this study was not calibrated according to the input forcing. Instead, following the
approach of Miguez-Macho and Fan (2012a,b) we focused on the differences induced by the
groundwater scheme relative to simulations with a free drainage boundary condition. However,
if the objective is to obtain realistic estimates of variables like evapotranspiration, one can make use of a more realistic dataset of atmospheric forcing (e.g. the GLDAS data set) and/or take advantage of the multiparameterization options of Noah-MP (Niu et al., 2011).

The improvement in the simulation of the terrestrial water storage over the Amazon region due to the MMF groundwater scheme has also been reported by Pokhrel et al. (2013). In their study (which is part of the series of studies by Miguez-Macho and Fan, 2012a,b) Pokhrel et al. (2012) use a much higher resolution (~2 km grid size) compared with this study (20km). It is therefore interesting to note that the MMF groundwater scheme can improve the simulation of TWS over the Amazon at grid sizes typical of continental-scale regional climate model (RCM) simulations. In general, over both the Amazon and the La Plata basins, we found that the groundwater scheme affects the monthly amplitude and phase, as well as the long-term behavior of the TWS fluctuations. These effects were observed in the 20km grid size simulations, which suggests that the groundwater impacts on the TWS could be visible in the variability produced by RCMs.

The groundwater scheme induces a significant increase in soil moisture and ET, but does not introduce significant changes in the phase of the fluctuations of soil moisture and ET in our offline simulations. This suggests that the atmospheric forcing plays a more important role on the variability of these variables than the groundwater scheme. However, in fully coupled land-atmosphere simulations (e.g. with WRF) the atmospheric conditions driving the land (including precipitation and downward short-wave radiation) could respond to the changes in soil moisture and ET induced by the groundwater scheme. In particular, the extra 10% of ET induced
by the groundwater scheme over the southern La Plata around the onset of the rainy season could enhance the precipitation over the region, which in turn could increase soil moisture and ET, potentially enhancing the recycling of precipitation. A similar mechanism could mitigate the intensity of droughts, like in the case of the 2008-2009 drought over the southern La Plata. Our simulations with a 20 km grid size suggest that an RCM could be used to test the role of the groundwater on the simulation of precipitation over the southern La Plata.

On the contrary, relatively high resolution is needed in order to detect effects of the MMF groundwater scheme over the Amazon region, as suggested by the comparison between 5 and 20 km simulations in the present study. This is supported by the high-resolution offline simulations of Miguez-Macho and Fan (2012a,b). This suggests that groundwater flows at the scale of a few kilometers can affect the simulation of evapotranspiration patterns at the regional scale over the Amazon and other regions in South America. The next generation of climate simulations with grid sizes of 1-5 km (see e.g. Hazenberg et al., 2015) could explicitly resolve the type of the groundwater effects discussed by Miguez-Macho and Fan (2012a,b) and in this study.

The present study is intended to be a contribution to the general understanding of the effect of a groundwater scheme on the simulation of the hydrological cycle over part of South America, in the context of climate studies. In particular, the La Plata basin has been identified as a region where a groundwater scheme could induce significant impacts on the simulation of the soil moisture and evapotranspiration. In our simulations, the impacts of the groundwater scheme on soil moisture and ET are larger than those reported by Niu et al. (2007) and Koirala et al. (2014).
However, the impact could be even larger if the simulated water table would have the same shallow profile as estimated by Fan and Miguez-Macho (2010) and Fan et al. (2013). As discussed by Miguez-Macho and Fan (2012b), the real impact of shallow groundwater on the hydrologic systems of South America has to be assessed via field measurements, and a more detailed representation of the soil characteristics in LSMs. Our study suggests that, taking into account the strong coupling of surface conditions and precipitation over the La Plata basin (Sörensson et al., 2011), a groundwater scheme could also impact the simulation of the rainy season in climate simulations, including the precipitation recycling during droughts. This is the focus of our ongoing research.

Acknowledgments

We acknowledge the Research Applications Laboratory (RAL) from NCAR-UCAR for providing the HRLDAS driver from their website

http://www.ral.ucar.edu/research/land/technology/noahmp_lsm.php. We also acknowledge Dr. Michael Barlage, at NCAR, for providing support to install and run the HRLDAS driver. We also acknowledge the ECMWF for providing the ERA-Interim data and GRCTellus for providing the GRACE data. GRACE land are available at http://grace.jpl.nasa.gov, supported by the NASA MEaSUREs Program. We are grateful to James Shuttleworth and Hoshin Gupta for their insightful comments. This research was supported by NSF Grant 1045260.
References


Table 1. Configurations of the simulations with the Noah-MP LSM in offline mode. GW denotes simulations with the MMF groundwater scheme. FD denotes simulations with free drainage. The soil column will have 14 layers, with bottom at 4 m, for all simulations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Grid Size</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD</td>
<td>20km</td>
<td>2004-2013 (spin-up 1994-2013)</td>
</tr>
<tr>
<td>GW05</td>
<td>5km</td>
<td>2004-2005</td>
</tr>
<tr>
<td>FD05</td>
<td>5km</td>
<td>2004-2005</td>
</tr>
<tr>
<td>GW20</td>
<td>20km</td>
<td>2004-2005</td>
</tr>
<tr>
<td>FD20</td>
<td>20km</td>
<td>2004-2005</td>
</tr>
</tbody>
</table>
Figure 1. Model domain and topography at 20km grid size. Red contour represents the La Plata river basin. Blue contour represents the Amazon basin.
Figure 3. Top: Mean monthly precipitation from ERA-Interim interpolated to the Noah-MP grid. Bottom: Depth to water table as simulated by the Miguez-Macho and Fan groundwater scheme. Grid size is 20 km.
Figure 4. Seasonal fluctuations in TWS from GRACE (top) and the GW (middle) and FD (bottom) simulations. Base period for GRACE is 2004-2009. Base period for Noah-MP is 2004-2013. See text for details.
Figure 5. Monthly fluctuations in TWS averaged over the regions in Fig. 4. Base period for GRACE is 2004-2009. Base period for Noah-MP is 2004-2013. See text for details.
Figure 6. Top: soil moisture in top 2m in FD simulation. Middle: absolute difference GW-FD. Bottom: fractional difference.
Figure 7. Soil moisture in top 2 m (curves) and precipitation (bars) averaged over the regions in Fig. 6. See text for details.
Figure 8. Top: Evapotranspiration in FD simulation. Middle: absolute difference GW-FD. Bottom: fractional difference.
Figure 9. Evapotranspiration (curves) and precipitation (bars) averaged over the regions in Fig. 8. See text for details.
Figure 10. A: “Paraná” basin as defined by the GRDC (figure modified from http://www.compositerunoff.sr.unh.edu/html/Stn/B6.html). B: River discharge from observations at a location marked by red dot in A (BDHI), and by integrating the surface and subsurface runoff of Noah-MP over the basin. C: ET from ERA-Interim and the Noah-MP model. D: TWS fluctuations from GRACE and the Noah-MP model. GW and FD are the simulated values with and without the groundwater scheme, respectively.
Figure 11. Depth to water table as simulated by the Miguez-Macho and Fan groundwater scheme in the second year of simulation. Top: grid size is 20 km. Bottom: grid size is 5 km.
Figure 12. Difference in ET between the GW and FD simulations, in the fourth year of simulation. Top: grid size is 20km. Bottom: grid size is 5 km.
**Figure 13.** Difference in ET (curves) and input precipitation (bars) averaged over the regions in Figure 12.
Appendix C

Impacts of a Groundwater Scheme on Hydroclimatological Conditions over Southern South America

J. Alejandro Martinez¹, Francina Domínguez², and Gonzalo Miguez-Macho³

1. Department of Atmospheric Sciences, University of Arizona
2. Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois
3. Faculty of Physics, Universidad de Santiago de Compostela, Galicia, Spain

Manuscript prepared to be submitted to the Journal of Hydrometeorology
Abstract

A sensitivity study of the impact of a groundwater scheme on hydrometeorological variables in coupled land-atmosphere simulations over southern South America is presented. The analysis focuses on the effects on soil moisture, evapotranspiration, near surface atmospheric conditions and precipitation over the La Plata basin. It is found that shallow water tables in the groundwater scheme lead to reduced drainage and even upward capillary fluxes over parts of the central and southern La Plata basin. This leads to an increase in the simulated moisture in the root zone, which in turn produces an increase in evapotranspiration over the southern part of the domain, where evapotranspiration tends to be limited by the availability of water. There is also a decrease in the near-surface temperature, in the range 0.5-1.0°C. During the dry season, the increase in ET and relative humidity over the central La Plata coincide with an increase in precipitation downstream, over Uruguay and southern Brazil. During the early rainy season October-November-December, there is also an increase in precipitation over parts of the central and southern La Plata basin – in a region where the simulation without groundwater has a larger dry bias when compared to observations. The overall increase in evapotranspiration and precipitation over the southern La Plata basin during the early rainy season is 13 and 10%, respectively. The additional precipitation comes from both an increase in the availability of atmospheric moisture when the groundwater scheme is used, and its effect on the atmospheric instability. The simulated water table is somewhat deeper than observations reported in previous studies. This suggests that a more shallow and realistic water table could enhance the effect of the groundwater scheme on the simulated precipitation over the La Plata basin.
1. Introduction

Land surface conditions and soil moisture patterns play an important role on some of the characteristics of local and regional climates, including the diurnal cycle of near surface conditions, the structure of the boundary layer, the stability of the atmosphere and the probability of precipitation (e.g. Betts 2004, 2009; Pielke 2001, Cotton and Pielke 2007, Seneviratne et al. 2010). From a synthesis of observations and modeling studies, Betts (2009) show some characteristics of the warm season coupling between soil moisture, land surface fluxes, boundary layer development, the cloud field and precipitation. Betts (2009) finds a tendency to an increase in precipitation when the relative humidity near the surface is higher from enhanced evapotranspiration (ET), which in turn produces a lower lifting condensation level and favorable conditions for the development of instabilities in the atmosphere. However, Pan et al. (1996) suggest that the increase in ET might enhance precipitation if the convective boundary layer is already relatively dry and well developed. This suggestion is supported by the study by Findell and Eltahir (2003), who find that even over wet soils the probability of precipitation is low if the atmosphere is very stable. Findell and Eltahir (2003) also find that convective precipitation develops over both wet and dry soils under similar instability conditions, with larger precipitation amounts over wet soils. In a modeling study, Schär et al. (1999) describe how an increase in soil moisture can lead to an increase in precipitation via several and possibly simultaneous mechanisms, including the increase of moisture in the atmosphere from enhanced ET, the increase of moist static energy in the lower levels and the ensuing increase in convective instability, and the decrease of radiative cooling of the surface, which further increases the moist
entropy flux into the boundary layer. As shown by Findell and Eltahir (2003), the sign of the feedback between soil moisture and precipitation depends on the different factors, including the moisture available at low levels, the atmospheric stability, and the large-scale circulation.

The role of soil moisture in the evolution of atmospheric conditions has also been found to be important for the weather and climate of South America. In a modeling study, de Goncalves et al. (2006) obtain improved 7-day weather simulations when more realistic soil moisture fields are used as initial conditions as opposed to mean climatological estimates. Saulo et al. (2010) found a larger sensitivity in the 10-day forecasts of precipitation for a low-pressure event over Argentina when drier initial conditions were used for the soil moisture field. Doyle et al. (2013) obtain an improvement in the simulation of a Mesocale Convective System over northern Argentina by updating the map of soil properties and improving the initial condition of the soil moisture field. At the seasonal time scale, Collini et al. (2008) find that during the early stages of the South American monsoon, precipitation over the south American monsoon region is more sensitive to dry soil moisture anomalies, showing a decrease in precipitation due to the reduced moisture contribution from both local and upstream sources. Sörensson and Berbery (2015) find that seasonal simulations with the Weather Research and Forecasting Tool – Noah Land Surface Model (LSM), WRF-Noah system, are better initialized during the wet season (September-February), when the difference between the initial soil moisture (obtained from a reanalysis product) and the equilibrium state of the WRF-Noah system for that time of the year is smaller. On the contrary, simulations initialized during the dry season (June-August) show pronounced biases in the surface and near surface variables. In general, regions within and in the
vicinity of the La Plata river basin have been considered a hot spot for land-atmosphere feedbacks (e.g. Dirmeyer et al., 2009b), that exhibit a positive and substantial feedback between soil moisture and precipitation (e.g. Zeng et al. (2010), Sörensson and Menéndez (2011), Spenneman et al. (2015)).

Shallow unconfined aquifers are a fundamental component of the hydrologic cycle that may affect the soil moisture content in the layers close to the surface, including the root zone (Fan et al., 2013, Fan 2015). Kuppel et al. (2015) show how shallow water tables (1-3 m. deep) in the Argentinean Pampas are strongly coupled with the variations in the Terrestrial Water Storage (TWS), which in turn is highly correlated with ET over the region. Using data from the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004), Chen et al. (2010) find a trend in TWS closer to observations from the Gravity Recovery Climate Experiment (GRACE) when they combine the original model output (from the Noah model, which does not include a representation of the groundwater) with groundwater storage data from wells within the southern La Plata basin. Several modeling studies have shown that a representation of groundwater dynamics within models for weather and climate studies can substantially affect the simulation of soil moisture and evapotranspiration over South America (e.g. Niu et al. (2007), Miguez-Macho and Fan (2012), Koirala et al. (2014)). In particular, the La Plata basin is one of the regions where the groundwater impact on other simulated hydrologic variables is expected to be larger, as the estimated water table is relatively shallow over this region (e.g. Fan and Miguez-Macho (2010), Fan et al., (2013)). This is consistent with the physical picture provided by observations, as suggested by the studies from Kuppel et al. (2015) and Chen et al. (2010). This hypothesis
has been confirmed in a modeling context by Martinez et al. (2015), who found an increase in the simulated root zone moisture and ET over parts of the La Plata basin and the southern Amazon from offline simulations with the Noah model with multiparameterization options (Noah-MP, Niu et al. 2011) and the Miguez-Macho et al. (2007) groundwater scheme.

Modeling studies over the U.S. suggest that the increase in ET and soil moisture induced by groundwater schemes can in turn modify near-surface conditions such as 2 meter temperature, and the patterns of precipitation (Anyah et al. (2008), Jiang et al. (2009), Barlage et al. (2015)). Given the strong coupling between soil moisture and precipitation over southern South America, and the impact of groundwater schemes on the simulation of soil moisture and evapotranspiration, in this study we address the effects of a groundwater scheme on the simulation of near-surface conditions and precipitation over the region. In particular we describe the magnitude and distribution of the changes in soil moisture, evapotranspiration, near surface temperature and humidity, atmospheric stability and precipitation over the La Plata basin. In addition, we relate the observed effects of the groundwater scheme to the general biases in temperature and precipitation of the atmospheric model used in this study when compared to observations. The paper is organized as follows: section 2 describes the model configuration; section 3 describes the effects of the groundwater scheme on different variables from the subsurface, the surface, and the lower levels in the atmosphere; finally, section 4 presents a summary and discussion of our results.
2. Methodology

a. Model configuration

The modeling system used in this study is the Weather Research and Forecasting Tool WRF version 3.4.1 (Skamarock et al 2008). The model domain includes the La Plata basin and most of the Amazon basin (Figure 1). Three boxes are drawn and used throughout the text to represent the “southern Amazon” (68-54°W, 20-8°S), the “central part of the La Plata basin” (64-54°W, 28-20°S) and the “southern La Plata basin” (67-54°W, 38-28°S). These boxes are not exact representations of each region, but they are useful to identify and separate some effects representative of each region. Some details of the configuration of the model are shown in Table 1. The physical parameterizations are the same as in previous studies of the hydrometeorology of the La Plata basin, which have proved to provide a consistent representation of the temperature and precipitation fields over southern South America (Lee and Berbery (2012), Lee et al. (2013), Müller et al. (2014), Sörensson and Berbery (2015)). Spectral nudging is used in the simulations, forcing wavelengths of 1467 km (wavenumber 3) and longer, similar to Lee et al. (2013). The idea is to preserve characteristics of the large-scale circulation (Miguez-Macho et al. 2004), while allowing for the development of perturbations at smaller scales due to the land-atmosphere interactions. The default spectral nudging scheme used in WRF does not nudge the moisture fields, which means that water is conserved (Miguez-Macho et al. 2004, Anyah et al. 2008). In addition, we extended the soil column to a depth of 4 meters, and divided it into 14 layers, according to the configuration used by Miguez-Macho and Fan (2012).
configuration, the top 2 meters of the soil column (which is the root zone in the model) contain 10 layers, instead of the default 4 layers of the Noah-MP and Noah LSMs.

The horizontal grid size is 20 km, which is similar to recent process studies over the region of interest (between 12 and 36 km in Lee and Berbery (2012), Müller et al. (2014), Sörensson and Berbery (2015)), and it represents a higher resolution compared with recent climate simulations for South America (~50 km in Solman et al. (2013)). In addition, 20 km is the grid size used in our previous study of the role of the groundwater using off-line simulations (Martínez et al., 2015). The period of simulation is January 1st 2006 to December 31st 2009 (4 years). This period includes the drought period over the southern La Plata basin during 2008-2009 (Chen et al. (2010), Müller et al. (2014), Küppel et al. (2015)). The analysis of de Goncalves et al. (2006b) suggests that the spin-up time for soil moisture in the region of interest is between 12 and 18 months. On the other hand, Sörensson and Berbery (2015) found that the skill in seasonal predictions improves if the model is initialized during the wet season September-February. In this study only the first 5 months of simulation are excluded from the analysis. However, the observed effects of the groundwater scheme during and after the first simulated dry season (June-July-August, 2006) are very similar to those observed in 10-year long simulations in off-line mode (i.e. with prescribed atmospheric conditions, Martínez et al. 2015). In this study the Leaf Area Index (LAI) and vegetation fraction are not computed dynamically according to the current climate conditions, but come from tables (dynamic vegetation option is off).

The groundwater scheme used in this study (hereafter the MMF groundwater scheme) was developed by Miguez-Macho et al. (2007) and implemented in the land surface scheme
Land-Ecosystem-Atmosphere Feedback model (LEAF2) of the Regional Atmosphere Modeling System RAMS. More recently, the MMF scheme was implemented in the Noah-MP land surface model as one of the “runoff” options (Barlage et al. 2015). The MMF groundwater scheme includes a representation of a shallow aquifer, and its interaction with the soil column above. The groundwater storage in each grid cell of the aquifer is determined by the balance between the vertical flux to/from the unsaturated soil layers, the lateral fluxes with its 8 nearest coplanar neighbors, and subsurface runoff (Miguez-Macho et al. 2007). The MMF groundwater scheme has been previously used in several studies using off-line simulations (i.e. with prescribed atmospheric conditions), (e.g. Miguez-Macho et al. 2007, Miguez-Macho and Fan 2012), and in coupled land-atmosphere simulations (e.g. Anyah et al., 2008). Recently, Martinez et al. (2015) have used the MMF scheme in off-line simulations with the Noah-MP model for a region that includes parts of the La Plata and the Amazon basins. In the present study, fully coupled land-atmosphere simulations with the MMF groundwater scheme are compared with simulations that have free drainage as boundary condition at the bottom of the soil column in order to assess the effects of the groundwater scheme on soil moisture, evapotranspiration, near surface conditions and precipitation over southern South America. We will refer to the simulations with the MMF groundwater scheme as the GW simulations, and to those with the free drainage bottom boundary condition as FD simulations. The slope parameter in the FD simulations has been changed from its default value of 0.1 (Barlage et al. 2015) to 1.0 (i.e. full drainage under the action of gravity), in order to assess the full effect of the groundwater scheme. The initial condition of the water table depth, and the parameters of the groundwater scheme, were obtained by Fan and Miguez-Macho (2010) assuming equilibrium conditions among long
term estimates of evapotranspiration, precipitation, run-off and the lateral flow of groundwater over South America.

b. Diagnostic variables

In order to have an idea of the effects of the near surface changes on the atmospheric structure and stability, we use some measures of the lifting condensation level, the convective available potential energy, and the convective inhibition, as estimated for an air parcel with the largest equivalent potential temperature in the lowest 3 km of the atmosphere. These parcels are usually in the lowest levels. The corresponding estimates of the lifting condensation level, the convective available potential energy and the convective inhibition are referred to as LCL, MCAPE, and MCIN, respectively (see NCL documentation at https://www.ncl.ucar.edu). These diagnostics do not correspond necessarily to parameters used in the model during the integration. Moreover, they are unable to synthesize all the complexity of the vertical structure of the simulated atmosphere, and the corresponding details leading to stable or unstable conditions. Therefore these diagnostics do not map directly into the spatial distribution and evolution of variables like the simulated precipitation. However, an analysis of the LCL, MCAPE and MCIN is useful in the interpretation of the potential mechanisms behind the changes in precipitation from our simulations. These diagnostics have been also used in previous studies (e.g. Lee and Berbery 2012, Lee et al. 2013).
In order to identify some of the biases of our WRF simulations, we compare near surface temperature and precipitation from the FD simulations with two reference data sets. For temperature, we use the CRU TS3.21 product (University of East Anglia CRU, Jones and Harris, 2013), and for precipitation the TRMM-3B43 product (Huffman et al. (2007), Huffman and Bolvin (2014)). The averages during the June-July-August (JJA) and October-November-December (OND) seasons throughout the 2006-2009 period are shown in figures 2 and 3 for temperature and precipitation, respectively. The temperature fields in the FD simulation are in general similar to those from the CRU during both seasons (Figure 2). WRF tends to underestimate near surface temperatures over northwestern Brazil in both seasons. During JJA, the FD simulation produces higher temperatures over the southern La Plata basin. During OND, the FD run also tends to simulate higher temperatures over both the central and southern La Plata. The overall seasonal patterns and changes in precipitation are also well represented by WRF (Figure 3). During JJA, the FD simulation tends to underestimate precipitation over northern Bolivia, southern Brazil and Uruguay. A similar bias is found by Solman et al. (2013) when comparing observations with 7 simulations that follow the protocol from the Coordinated Regional Climate Downscaling Experiment (CORDEX), (see their figure 3c). During OND, the FD simulation underestimates precipitation over the central and southern La Plata basin. The spatial location of this bias is similar to that reported by Solman et al. (2013) for the DJF season (see their figure 3f).

WRF exhibits biases in different variables over South America (e.g. Ruiz et al. (2010), Lee
2010), likely due to problems with different components of the model, as is the general case for different Regional Climate Models (RCMs) over the region (e.g. Solman et al., 2013). For example, previous studies report good skill of some parameterizations in some regions of South America, but a poor performance in other regions of the continent (see Solman and Pessacq (2012) for a comprehensive sensitivity study with the MM5 model). Despite the importance of reducing biases in the model, the present sensitivity study focuses on the differences between two model configurations (namely with and without a groundwater scheme). In particular, no attempt to calibrate the model has been made. Some comments about the biases in the GW and FD simulations with respect to the reference data sets CRU-TS3.21 and TRMM-3B43 are included at the end of the Results section.

3. Results

Two continuous simulations have been performed for the period 2006-2009, with and without the MMF groundwater scheme. The use of continuous, as opposed to multi-year simulations for a particular season, responds to the need of allowing the groundwater scheme to operate during the dry season and assess its accumulated impact during transition seasons. This strategy has been suggested but not explored in previous studies (e.g. Anyah et al., 2008). The analysis of the dry season itself also allows the identification of the effects of the groundwater scheme on soil moisture and evapotranspiration when the effects of precipitation on these variables are at a minimum. The general patterns of the differences between the simulations for different variables, including soil moisture, evapotranspiration and near surface temperature are very similar among
different years (not shown). Therefore, the present analysis is based on seasonal means averaged during the four years of simulation. At the end of this section we present spatial averages of the simulated precipitation during each of the OND months, for each of the four years, which provide a picture of the inter-annual variability of the simulated precipitation, and of the differences between both simulations.

a. Recharge and water table depth

The MMF scheme introduces a dynamic water table depth (ZWT), and a vertical flux between the shallow aquifer and the unsaturated soil layers (RECH). Seasonal averages of both variables (which are exclusive of the GW simulation) are shown in Figure 4. The water table can be within the resolved soil layers, and the RECH flux can be upward, from the aquifer to the soil layers above due to capillary forces, depending on the vertical gradient of moisture content. In contrast, in the FD simulation the flow of moisture in the bottom of the deepest soil layer is only downward, and solely determined by the action of gravity and the hydraulic conductivity of the soil. In the GW simulation, the interaction with the shallow aquifer makes the drainage of moisture from the soil layers above it to be slower compared with the FD simulation, where no aquifer is included. In those regions where the flow is from the aquifer to the soil layers above, the soil moisture in the unsaturated layers can increase in the GW simulation, while it may be decreasing in the FD simulation as a result of continuous draining (see e.g. Miguez-Macho and Fan, 2012, for a detailed analysis of these fluxes).
Over the La Plata basin, the vertical flux between the aquifer and the unsaturated layers is upward over some regions, due to capillary forces in the GW simulation (blue regions in Figure 4, most pronounced during the dry season). Both the reduction of the drainage rate, or the existence of an upward capillary flux, increase soil moisture in the GW simulation with respect to the FD simulation. Upward capillary fluxes are larger during the dry season, due to a decrease in the moisture content of the unsaturated soil layers (from evapotranspiration and runoff) above the shallow aquifer, and the consequent increase in the moisture gradient. The largest effects take place in regions and seasons where the water table is more shallow, and where the evapotranspiration is predominantly limited by the availability of water (as opposed to radiation), including parts of Bolivia, the Pantanal (both regions included in the box we are calling “southern Amazon”), and the central and southern La Plata basin during the dry season JJA (Fig. 4 bottom).

Kuppel et al. (2015) report water table depths mostly in the range 1-3 m over the western Pampas (64-61°W, 36-34°S), where the current simulation shows values deeper than 5 m. Observations compiled by Fan and Miguez-Macho (2010) show values smaller than 2.5 m for other regions in the La Plata basin. Their model results also suggest a water table depth shallower than 2.5 m over northern Bolivia, the Pantanal region, and the La Plata basin (Fan and Miguez-Macho, 2010). The closer the water table is to the land surface, the slower is the soil moisture drainage or the larger the upward capillary flux. On the contrary, the deeper the water table, the more the decoupling between the groundwater and soil moisture in the unsaturated zone. Because the vertical flux of moisture depends on the depth to the water table, our simulations may
underestimate the effect of the groundwater over the La Plata basin by simulating a deeper water table distribution compared with a more realistic distribution. The overestimation of the water table depth (i.e. deeper than in reality) could be a result of the lack of calibration of Noah-MP and/or the groundwater parameters. While no attempt to calibrate Noah-MP to improve the estimates of ET has been made, the groundwater parameters were obtained from long term conditions (~ 30 years) of ET, precipitation and runoff (Fan and Miguez-Macho 2010) that are not necessarily representative of WRF long term means, which are not available for this study due to computational constraints.

b. Dry season

As mentioned in the previous paragraph, as a consequence of the reduced drainage of soil moisture, or the existence of an upward flux of moisture from the aquifer to the unsaturated soil layers above, the moisture SM2m in the top 2 meters of the soil (root zone of the model) is larger in the GW simulation compared to the FD simulation (Figure 5). The largest increase is observed over those regions where the water table is shallower (see Figure 4). The increase can be larger than 20% of the absolute value in the FD simulation over parts of the La Plata basin. As a direct result of more moisture in the root zone, there is an increase in evapotranspiration (ET) in the GW simulation (Figure 5). This increase is larger over the central La Plata basin, the Pantanal region and northern Bolivia, where ET is predominantly limited by water availability. On the contrary, no evident increase in ET is observed over northwestern Brazil (western Amazon), where ET is limited by radiation (e.g. Fisher et al., 2009). Due to the small values of
the simulated ET during the dry season over these regions, the relative increase in the GW simulation can be as large as 50% of the values in the FD simulation. However, absolute values of more than 0.5 mm/day extra ET are also observed over the central La Plata Basin in the GW simulation.

The increase in ET is associated with a decrease in sensible heat flux (not shown), which in turn decreases the near surface temperature (e.g. the 2 meter temperature, T2m, Figure 5). The decrease in T2m can be larger than 1°C over those regions where ET increases the most (central La Plata, Pantanal and northern Bolivia). The increase in ET also induces an increase in near surface specific humidity (e.g. the specific humidity at 2 meters AGL, Q2m, Figure 5). The near surface winds seem to play a role in the distribution of the excess of specific humidity, producing an accumulation of moisture over the west of the central La Plata, and some transport to the northwest of the southern La Plata region. Note that the increase in specific humidity over the central La Plata is a substantial fraction of its total value in the FD simulation. During the dry season, this extra moisture is not consumed by precipitation, due to the seasonal minimum in local rainfall.

The dry season JJA corresponds to the austral winter, with relatively high values of the lifting condensation level (LCL), and low values of downward shortwave radiation (SWDOWN), convective available potential energy (e.g. MCAPE), and precipitation (RAINRATE) over the La Plata basin, (Figure 6). The decrease in near surface temperature and the increase in near surface humidity lead to a decrease in the LCL and SWDOWN (from increased cloudiness) in
the GW simulation. However, both changes are a small fraction of the absolute values of LCL and SWDOWN in the FD simulation. Over the southern Amazon, there is also a visible increase in MCAPE, with values larger than 10% relative to the FD simulation. Some increase in MCAPE is also observed over the southern La Plata basin. In addition, there is increase in precipitation in the GW simulation over southeastern South America (including Uruguay and southern Brazil), which seems to be co-located with the dry bias in the FD simulation (see Figure 3), downstream of the regions in the southern Amazon and the central La Plata where an increase in ET and near surface moisture is observed (see ET and Q2m in Figure 5, and the 850hPa winds in Figure 6). The magnitude of the increase in precipitation is small in absolute value, but larger than 10% relative to the FD simulation values (compare the absolute precipitation FD and the difference GW-FD in Figure 6).

c. October-December (OND) season

We describe now the observed changes in hydroclimatological conditions during the OND season, when the largest difference in precipitation between the FD and GW simulations was observed. Figure 7 shows the mean absolute values of SM2m, ET, T2m and Q2m in the FD simulation (top panels) and the corresponding differences with the GW simulations (GW – FD, bottom panels). The differences in SM2m are larger than during the dry season, due to the accumulated effect of weaker drainage/upward fluxes during the dry season JJA, plus the reduced drainage of the moisture coming from precipitation during the OND season. The location of the largest differences in SM2m is still determined by the water table depth (see
Figure 4). With the increase in SM2m in the GW simulation relative to the FD simulation, there is an increase in ET. The difference in ET during OND is also larger than the difference in JJA, because of the larger difference in SM2m during OND. There is no increase in ET over the northwest of the domain (western Amazon basin), despite the extra SM2m, because in that region ET is predominantly radiation limited. The increase in ET in the GW simulation is a significant fraction of the ET from the FD simulation. For example, the extra ET in the GW simulation can be in the range 0.5-1.0 mm/day over parts of the southern La Plata basin, where the total ET in the FD simulation is in the range 2.5-3.0 mm/day. As it was observed during the dry season, with the increase in ET there is a decrease in T2m, mostly in the range of 0.5 to 1.0°C. The increase in Q2m associated to the extra ET is much smaller compared with the values observed during the dry season (note the difference in scales in Figures 5 and 7 for Q2m). This difference could be due to the higher consumption of moisture by the extra precipitation in the GW simulation during the OND season (see below). The increase in Q2m during OND, although small, contributes to an increase in the moist static energy (see below).

The observed changes in the land-surface fluxes and in the near surface conditions lead to changes in the LCL, the planetary boundary layer height (PBLH) and, to a lesser degree, in the SWDOWN (Figure 8). The increase in moisture and decrease in temperature lead to a decrease in the LCL in the GW simulation with respect to the FD simulation. This decrease can be of the order of 10% and larger over parts of the La Plata basin. The changes in the downward shortwave radiation associated a decrease in LCL (more clouds) are small, and mostly confined to the eastern slopes of the Andes. This suggests that the increase in cloudiness from the
lowering of the LCL does not contribute substantially to a potential decrease in the incident solar radiation upon the surface. Such a decrease could potentially decrease ET, but the small magnitudes of the differences in SWDOWN between both simulations suggest that this is not happening for the current decrease in LCL. On the other hand, the increase in ET, and the associated decrease in sensible heat flux (see decrease in T2m in Figure 7) lead to a decrease in the boundary layer height. This decrease is also larger than 10% of the PBLH in the FD simulation over the La Plata basin. Thus, we have two changes contributing in opposite ways to potential convection and precipitation over the region: the decrease in the LCL (and a corresponding decrease in the level of free convection) and the decrease in the boundary layer height (reducing the chances of near surface thermals to reach higher levels in the atmosphere). Note that the decrease in LCL is larger than the decrease in PBLH.

Vertical profiles of relative humidity (RH) and moist static energy (MSE) averaged over the boxes representing the central and southern parts of the La Plata basin are shown in Figure 9. The increase in moisture and the decrease in temperature (see e.g. Q2m and T2m in Fig. 7) lead to an increase in RH. However, this increase is small, (maximum difference is of the order of 3-5%). In both regions (central and southern La Plata), the RH profiles in both simulations (GW and FD) are virtually identical above the 800hPa level. Similarly, despite the decrease in temperature, there is a net small increase in the MSE in the lower levels of the atmosphere over both regions. This is due to the large value of the latent heat of vaporization: a small amount of extra moisture contains a large amount of moist static energy, compensating for the decrease from the lower temperature. Over both regions, the increase of MSE in the lower levels is
associated with an increase in CAPE, although this increase is smaller over the southern La Plata (LOLP), (see below). The vertical profiles in Figure 9 illustrate how the overall largest effects of the groundwater scheme are confined to the lowest layers of the atmosphere.

Despite the increase in relative humidity and moist static energy, and the decrease in the lifting condensation level, the decrease in sensible heat flux and temperature in the lowest levels could have a negative impact on the potential development of convection over the region. The role of the two competing mechanisms in the development of convection in the present simulations (increase in moisture and reduction of sensible heat flux) is different throughout the La Plata basin, as can be seen in Figure 10. In the GW simulation, the convective inhibition (MCIN) increases over parts of the southern La Plata basin, due to the reduction in the low level temperatures, from the increase in ET. Thus, the decrease in temperature overcompensates the potential positive effect of a lower LCL for the generation of moist convection and precipitation over these regions. Note that the increase in MCIN can be as large as 10% of the value from the FD simulation. Over the central La Plata basin, such increase in MCIN is not observed.

At the same time, there is a general increase in MCAPE (Figure 10), associated with the increase in moist static energy in the lowest levels (Fig 9). The increase is more pronounced in parts of the central La Plata basin, although a smaller increase is also seen over the southern La Plata basin (in the range 10-40 J kg$^{-1}$, not shown). As a result of the distribution of the convective inhibition and convective available potential energy (as suggested by the MCIN and MCAPE diagnostics), the cumulus scheme tends to produce more convective precipitation (RAINC)
downstream of the central La Plata basin, but less over the southern extreme of the southern La Plata. However, over this region, there is a significant contribution to precipitation from the microphysics scheme (non-convective precipitation, RAINNC), due to the extra relative humidity in the GW simulation that is not “used” by the cumulus scheme due to the increased convective inhibition. Note that over the southern La Plata, the contribution of convective (from RAINC) and large scale (from RAINNC) to total precipitation (top panels, Fig. 10) is of the same order.

As a result of the availability of moisture and/or the increase of convective instability, the GW simulation yields an increase in total precipitation (i.e. convective + non-convective or large scale precipitation) over different parts of the La Plata basin (Figure 11). (The total precipitation from the FD simulation is the same as in Figure 3, reproduced here for easier comparison with the changes due to the GW scheme). The second panel in Figure 11 shows a spatially uniform increase (i.e. in sign, not in magnitude) in precipitation over the southern La Plata basin, with a more noisy pattern in the rest of the domain. The third panel shows the fractional differences between the simulations, estimated as (GW-FD)/FD for each grid cell. The largest fractional differences are found over the southern La Plata basin, and parts of the central La Plata basin. The local relative differences over the La Plata basin can reach values as large as 30%, although the absolute magnitudes are rather small (mostly in the 0.1-0.5 mm/day range). The map of fractional differences also shows the relatively less important changes in other parts of the domain, like the southern Amazon region.
A more general view of the regional changes in precipitation (P) and ET due to the groundwater scheme can be derived from the regional averages for the southern La Plata box, as shown in Figure 12. Panels (a) and (b) show that the regional averages of ET and P, respectively, are very similar between the GW and FD simulations. These monthly averages also show the variations from year to year during the 4 years of simulation, which includes a period of drought over the southern La Plata during 2008-2009 (Chen et al. 2010, Müller et al. 2014). The reduction in precipitation in both simulations is clear between November-2007 and October-2009. Despite the similarities in the values of ET and P, and their year to year variations, the GW simulation invariably produces more ET and precipitation in the OND months during the 4 years of simulation. The use of dynamic vegetation could modify the LAI and the vegetation fraction, which in turn could affect ET (Jiang et al. 2009), e.g. during drought years (e.g. Müller et al., 2014) Further differences in ET and P between the FD and GW simulations, could arise from the use of a dynamic vegetation scheme (which we do not include), but such effects are beyond the scope of the present study.

The absolute differences between both simulations (Figure 12(c)) show that the extra precipitation in the GW simulation tends to be less than the extra ET (except in November-2006, and October-2007). However, the extra precipitation tends to be a relatively large fraction of the extra ET. For example, during December 2006, the extra ET from the GW simulation is nearly 0.32 mm/day, while the extra P is 0.22 mm/day; thus, the extra P is nearly 69% of the extra ET during this month. In general, the observed ratio of extra P to extra ET during the OND months is in the range ~30-120%. The estimated recycling ratio for the region is in the range 23-42%
(Dirmeyer et al. 2009, Martinez and Dominguez 2014). Thus, the extra precipitation in the GW simulation seems to be coming not only from direct recycling of the extra ET, but from the effects of ET on the stability of the local and upstream atmosphere, likely enhancing the indirect local production of precipitation (from the increase in local instability) and the transport from upstream regions (e.g. the central La Plata). This is consistent with the observed increase in moisture content, relative humidity and convective available potential energy over the region (Figures 7, 9 and 10). These mechanisms have been found to operate simultaneously in other regions, as described and discussed in previous studies (e.g., Schär et al. 1999).

On the other hand, the regional average of the increase in ET and precipitation in the GW simulation relative to the FD simulation values is shown in Figure 12(d). The overall fractional increase is in the range 2-23%. The mean relative increase in ET is 13%, while the mean increase in precipitation is 10% relative to the FD simulation. The local increase in ET (both absolute and relative) could actually be larger if computed only over the region where the largest increase in SM2m is observed, instead of the larger box representing the southern La Plata (see Figure 7).

Finally, we compare the mean temperature and precipitation from both the GW and FD simulations with the estimates based on CRU and TRMM products (Figure 13). It is common practice for the mean temperature in CRU products to be computed from the maximum and minimum temperatures during the day, and the result is not necessarily equal to the mean temperature estimated from, say, hourly data (Wang and Zeng, 2013). On the other hand, the
mean monthly temperature from our simulations is computed from 6-hourly output from WRF (at 00, 06, 12 and 18z). Therefore, instead of using CRU temperature products directly, we use the adjusted temperature data set developed by Wang and Zeng (2013), which is based on different reanalyses products, constrained by information of the hourly evolution of the temperature field as represented by the MERRA reanalysis, and the monthly field as estimated by a CRU temperature product. Here we show the comparison of WRF estimates of 2 meter temperature to the adjusted ERA-Interim fields from Wang and Zeng (2013) (available at http://rda.ucar.edu/datasets/ds193.0/). The ERA-Interim adjusted product was chosen because it shows the smallest deviations from the CRU products over South America (Wang and Zeng, 2013). The adjusted ERA-Interim temperature is available at 00:30z, 01:30z, etc. To obtain estimates for 00z, we averaged the 00:30z and the 23:30z estimate from the previous day. A similar procedure was performed to obtain estimates at 06, 12 and 18z. Finally, these estimates were averaged to obtain a daily average that we can unambiguously compare to our WRF averages.

The general biases of WRF in temperature and precipitation (Figure 13) are larger than the differences between the GW and the FD simulations (Figures 5, 6, 7 and 11), which is evident in the common patterns for the different simulations in Figure 13. The differences in temperature tend to be smaller over the La Plata basin, where Figure 13 suggests a decrease in the warm bias. However, there is some extra cooling in the southern Amazon, in particular over the northeast corner of the box. Table 2 shows that the biases over the La Plata basin decrease in magnitude (with some extra cooling over the southern La Plata), while there is an increase in the magnitude
of the cold bias over the Southern Amazon. A comparison between WRF temperatures and adjusted temperatures from MERRA (Wang and Zeng, 2013) and the daily averages from the CRU-TS3.21 product show the same improvement of the temperature bias due to the groundwater scheme (not shown).

On the other hand, the differences in the precipitation fields are not as evident as in the temperature fields. Only a small decrease in the dry bias over the southern La Plata basin in the GW simulation is suggested by Figure 13. From Table 2 we see that there is a slight decrease in the magnitude of the dry bias over the both the central and southern parts of the La Plata basin. However, the wet bias over the southern Amazon increases.

4. Summary and Discussion

A sensitivity study of hydrometeorological variables over southern South America to the use of the MMF groundwater scheme in fully coupled land-atmosphere simulations is presented. The study includes an analysis of the impacts on soil moisture, ET, near surface temperature, convective available potential energy and precipitation. In general we find that the groundwater scheme leads to an increase in the simulated soil moisture over those regions where the water table is shallower. The increase in soil moisture leads to an increase in ET and relative humidity, and to a reduction of the lifting condensation level and the boundary layer height. During the dry season the groundwater scheme helps sustain larger values of soil moisture because of a
reduction in drainage and even the existence of upward moisture fluxes from the underlying shallow aquifer to the unsaturated soil layers. The extra moisture in the atmosphere (from ET) seems to be linked to an increase in precipitation downstream, where both the current simulations and other regional climate models have a dry bias when compared to observations.

During the early rainy season (October-November-December) the changes in ET and convective instability are larger than during the dry season. Over parts of the central and southern La Plata the changes in moisture and instability lead to an increase in the simulated convective precipitation. Over the southern extreme of the La Plata region, the cooling effects from the enhanced ET lead to enhanced convective inhibition. Over these regions however, an increase in rainfall is still observed, but it comes mostly from large-scale precipitation, due to the increase in relative humidity. The regional change in ET and precipitation over the southern La Plata changes from month to month, and from year to year, but the use of the groundwater scheme invariably increased the simulated ET and precipitation over the region. The mean regional increase in ET over the southern La Plata is 13%, while the increase in precipitation is 10%, relative to the simulated values without the groundwater scheme. The increase in precipitation is of the same order as the increase found by Müller et al. (2014) from the use of Ecosystem Functional Types instead of fixed LAI and vegetation fraction. Lee and Berbery (2012) also found an increase in precipitation with maximum values of ~10% on a study of the sensitivity to land cover changes over the LPB. We also find that the extra precipitation is a larger fraction of the extra ET compared with expected values from the estimated recycling ratios from previous studies. This is additional evidence that suggests that the increase in precipitation when the
groundwater scheme is used is due not only to the use of more moisture from local origin (recycling) but also to the effects of this extra moisture on the stability of the atmosphere. Both mechanisms have been described in previous studies, like Schär et al. (1999).

The present sensitivity study attempts to illustrate the potential impacts of a groundwater scheme on the simulation of near surface conditions and precipitation over southern South America. Therefore we do not attempt to reduce the biases of the model in the simulation of the regional South American climate: this would require longer simulations than those presented here, and a calibration procedure. In particular, the parameters of the groundwater scheme are sensitive to the mean balance between precipitation, evapotranspiration and runoff, which varies from model to model (see e.g. Fan and Miguez-Macho 2010). In the present study, the lack of calibration of the parameters of the MMF scheme could be part of the reason behind the overly deep water table simulated over the La Plata basin. The calibration of the parameters of the MMF scheme would require long-term (several years) estimates of precipitation, ET and runoff from the model (WRF in our case). Such calibration procedure was beyond the scope of the present sensitivity study. Other aspects of the modeling system that must be calibrated and carefully selected are the multi-physics options of the Noah-MP model (Niu et al., 2011).

The primary modification of the soil moisture distribution due to the groundwater scheme is not homogeneous, but a result of the estimated effect of the topography and the local climate on the distribution of the water table of shallow unconfined aquifers (Fan et al., 2013). In contrast, in other sensitivity studies more idealized tests are performed, e.g. modifying the soil moisture field
in some fixed fraction (Schär et al. 1999, Collini et al. 2008). Once the equilibrium water table
distribution has been estimated, we have more a boundary value problem, instead of being an
initial value problem, which is the case of other studies of the sensitivity to soil moisture
conditions (e.g. Sörenson and Berbery (2015)). Therefore, the present sensitivity study presents
plausible modifications to the simulation of the hydroclimate of southern South America when
one of the boundary conditions is changed throughout the simulation, according to a physically
based estimation of the shallow aquifers over the region. The results from the present fully
coupled land-atmosphere simulations are consistent with results from offline simualtions (i.e.
with prescribed atmospheric forcing) by Martinez et al. (2015). This means that the increase in
ET due to the groundwater scheme observed in the offline simulations is not only preserved in
the coupled land-atmosphere simulations, but in addition can affect the near surface atmospheric
conditions and the simulated precipitation patterns. These modifications could be larger, if the
water table is actually shallower, as suggested from observations (Fan and Miguez-Macho 2010,
Kuppel et al 2015).

The largest sensitivity to the effects of the groundwater scheme are found in parts of the La Plata
basin, where previous studies have shown a substantial sensitivity of atmospheric conditions,
including precipitation, to characteristics and dynamics of the soil moisture field (e.g. Saulo et al.
2010), land use and land/cover change (Beltrán-Przekurat et al. 2012, Lee and Berbery, 2012),
land cover and vegetation properties (Lee et al. 2013, Müller et al. 2014), soil texture properties
(e.g. Doyle et al., 2013), and the coupling between soil moisture and precipitation (e.g. Zeng et
al. 2010, Sörensson and Menéndez (2011), Spenneman et al. (2015)). This study, along with
other previous studies, suggests that the climate of southern South America is particularly sensitive to surface and subsurface hydrological conditions.

In order to have a more accurate picture of the real need and impacts of groundwater schemes in weather and climate studies, a better estimation of the components of the hydrologic cycle is needed. For example, more and better estimates of the evapotranspiration (Wang and Dickinson, 2012) and soil moisture (e.g. Koster et al. 2009) fields are needed. Other aspects include, but are not limited to: effective characteristics of the soil in South America (e.g. Doyle et al. 2013), the estimated distribution of shallow water tables (e.g. Fan et al. 2013), the distribution of roots (e.g. Fan 2015, Wang and Dickinson 2012), the effects of dynamic vegetation schemes (e.g. Jiang et al. 2009, Müller et al 2014), and the distribution and representation of the lateral flow of groundwater at the hillslope scale (Hazenberg et al., 2015). Important improvements in the modeling of the land-surface and subsurface for weather and climate studies has been made (e.g. Niu and Zeng 2012). There is still a pressing need for field campaigns and routine measurements, especially in South America, where they are scarce. A better and more extended set of observations of hydrometeorological variables over South America are essential for a better understanding and modeling of the hydroclimate of the region.

Acknowledgments

We acknowledge the ECMWF for providing the ERA-Interim data used as boundary and initial conditions for the WRF simulations. We also acknowledge the Centre for Environmental Data Archival for providing the CRU-TS3.21 data, from their website at
The TRMM-3B43 data was provided by the Goddard Earth Sciences Data and Information Services Center, through the website http://mirador.gsfc.nasa.gov. We are grateful to James Shuttleworth and Hoshin Gupta for their insightful comments. This research was supported by NSF Grant 1045260.
References


Sörensson, A.A., and E.H. Berbery (2015): A Note on Soil Moisture Memory and Interactions with Surface Climate for Different Vegetation Types in the La Plata Basin. J. Hydrometeor. 16, 716-729. DOI: 10.1175/JHM-D-14-0102.1

DOI: 10.1002/joc.4274.


Wang, A., and X. Zeng, (2013): Development of Global Hourly 0.5° Land Surface Air Temperature Datasets. J. Climate, 26, 7676-7691, DOI: 10.1175/JCLI-D-12-00682.1


### Table 1. Model configuration options.

<table>
<thead>
<tr>
<th><strong>Option</strong></th>
<th><strong>Model Configuration</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>WSM 6-class</td>
</tr>
<tr>
<td>Long wave radiation scheme</td>
<td>RRTM</td>
</tr>
<tr>
<td>Short wave radiation scheme</td>
<td>Dudhia</td>
</tr>
<tr>
<td>Surface Layer</td>
<td>Monin-Obukhov (Janjic)</td>
</tr>
<tr>
<td>Planetary Boundary Layer</td>
<td>Mellor-Yamada-Janjic</td>
</tr>
<tr>
<td>Cumulus Convection</td>
<td>Betts-Miller-Janjic</td>
</tr>
<tr>
<td>Land Surface Model</td>
<td>Noah-MP</td>
</tr>
<tr>
<td>Horizontal grid size</td>
<td>20 km</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>39</td>
</tr>
<tr>
<td>Soil layers</td>
<td>14, bottom at 4 m BGL</td>
</tr>
<tr>
<td>Bottom boundary condition</td>
<td>Free Drainage, FD (opt_run = 3),</td>
</tr>
<tr>
<td></td>
<td>MMF groundwater scheme, GW(opt_run = 5)</td>
</tr>
</tbody>
</table>
Table 2. Area averages of differences between WRF simulations and reference data sets. T2m: temperature at 2 meters in WRF simulations. TMP: near surface temperature in the ERA-Interim T2m adjusted dataset (Wang and Zeng, 2013). P: precipitation.

<table>
<thead>
<tr>
<th></th>
<th>Southern La Plata (LOLP)</th>
<th>Central La Plata (UPLP)</th>
<th>Southern Amazon</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2m(FD) – TMP(ERAi_WZ) [°C]</td>
<td>0.51</td>
<td>1.09</td>
<td>0.11</td>
</tr>
<tr>
<td>T2m(GW) – TMP(ERAi_WZ) [°C]</td>
<td>-0.01</td>
<td>0.43</td>
<td>-0.20</td>
</tr>
<tr>
<td>P(FD) – P(TRMM) [mm/day]</td>
<td>-0.81</td>
<td>-0.40</td>
<td>0.39</td>
</tr>
<tr>
<td>P(GW) – P(TRMM) [mm/day]</td>
<td>-0.54</td>
<td>-0.16</td>
<td>0.59</td>
</tr>
</tbody>
</table>
Figure 1. Model domain and definition of regions of interest. Red (blue) contour represents the La Plata river basin (Amazon basin). Boxes are used as reference to represent the southern Amazon (top), the central La Plata basin (middle) and the southern La Plata basin (bottom).
**Figure 2.** Near surface temperature according to the CRU TS3.21 data set (left) and the FD simulation (right) averaged during June-July-August (JJA, top) and October-November-December (OND, bottom).
Figure 3. Precipitation according to the TRMM3B43 data set (left) and the FD simulation (right) averaged during June-July-August (JJA, top) and October-November-December (OND, bottom).
Figure 4. Top: Average moisture flux between the shallow aquifer and the soil layers above (RECH) for the June-August (left) and October-December (right) seasons. Negative values represent upward flux. Bottom: Average water table depth (ZWT) for the June-August (left) and October-December (right) seasons.
Figure 5. Top: average soil moisture in top 2 meters of the soil (SM2m), evapotranspiration (ET), 2 meter temperature (T2m) and specific humidity (Q2m) from the FD simulation for the June-August season. Bottom: average differences in SM2m, ET, T2m and Q2m between the GW and the FD simulations for the June-August season. The total 10 meter winds from the GW simulation are drawn on top of the ET differences.
Figure 6. Top: average lifting condensation level (LCL), downward shortwave radiation (SWDOWN), maximum convective available potential energy (MCAPE) and precipitation (RAINRATE) from the FD simulation for the June-August season. Bottom: average differences in LCL, MCAPE, SWDOWN, and RAINRATE between the GW and the FD simulations for the June-August season. The total 850 hPa winds from the GW simulation are drawn on top of the MCAPE differences.
Figure 7. Same as Figure 5, but for the October-December season. Note the difference in scale in the difference in specific humidity GW-FD Q2m.
Figure 8. Top: average downward shortwave radiation (SWDOWN), lifting condensation level (LCL) and boundary layer height (PBLH) during the OND season. Bottom: average differences in SWDOWN, LCL and PBLH between the GW and FD simulations during the OND season.
Figure 9. Vertical profiles of relative humidity (RH, left) and moist static energy (MSE, right) averaged over the central (UPLP, top) and southern (LOLP, bottom) La Plata basin during the October-December season.
Figure 10. Top: average convective inhibition energy (MCIN), convective available potential energy (MCAPE), rain rate from cumulus convection scheme (RAINC) and rain rate from the microphysics scheme (RAINNC) during the OND season. Bottom: average differences in MCIN, MCAPE, RAINC and RAINNC between the GW and FD simulations during the OND season.
Figure 11. Left: Total precipitation (RAINC+RAINNC) from the FD simulation. Middle: Difference in total precipitation between GW and FD simulations. Right: Fractional difference in total precipitation between GW and FD simulations.
Figure 12. (a): Average ET over the southern La Plata basin (LOLP) for each month of the October-December season during the 4 years of simulation. (b): same as (a) but for average precipitation. (c): Absolute differences GW-FD in ET (blue) and precipitation (red). (d): Differences GW-FD in ET (blue) and precipitation (red) relative to FD averages (%).
Figure 13. Top: difference in near surface temperature between the ERA-Interim T2m adjusted dataset (Wang and Zeng, 2013) and the FD and GW simulations for the October-December season. Bottom: difference in total precipitation between the TRMM-3B43 data set and the FD and GW simulations for the October-December season.