Moisture Recycling in the Mississippi River Basin

Seasonal to interannual variability in the Mississippi River Basin

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March 8, 2018

Abstract

Moisture recycling has been known for decades and is used to determine the origin of moisture. The Mississippi catchment has however not been studied specifically in relation to the variation in the precipitation recycling ratio. This study will therefore try to determine the seasonal and interannual variation of the precipitation recycling ratio. With the use of ERA-Interim data and the WAM2-layer model it was possible to identify both its temporal and spatial variation. Beforehand the ERA-Interim data was checked for closure of the moisture balance, which it did. It was found that the precipitation recycling ratio is high during summer and low during winter, with both spring and autumn in between. During the studied period, 1986-2016, there was also a large variation in the annual precipitation recycling ratio, with 1998 being the highest and 2010 being the lowest.

To determine the causes of these variations correlations between the precipitation recycling ratio and the z200 geopotential height were identified. The dominant proces driving the precipitation recycling ratio was the circulation of moisture. On a global scale the ENSO also became clear, indicating an interannual cycle. However, this should be validated in further research as the correlations themselves are only indicators of a possible explanation. Furthermore, two case studies were identified, namely the drought of August 2012 and the Louisiana flash floods of August 2016. This study found that the difference between these two months was minimal, which was unexpected based on the difference in precipitation. Therefore, in future research it should be noted that extreme events are not indicative for the precipitation recycling ratio.

Acknowledgements

At the start of this study I was introduced to the WAM2-layer model and the concept of moisture recycling by Imme Benedict and Wilco Hazeleger. After learning to work with python with the help of Imme Benedict, I was able to determine the moisture balance. The use of the WAM2-layer model for the recycling ratios turned out to be more difficult than anticipated, but after several sessions with Imme Benedict and Wilco Hazeleger, as well as a meeting with the developer of the model, Ruud van der Ent, we were able to use the model properly. After all these struggles I would like to thank Imme Benedict and Wilco Hazeleger for their support and patience throughout this study. Furthermore I would like to thank Chiel van Heerwaarden for his contributions in helping me quantify the divergence of the moisture flux. I would also like to thank the rest of the MAQ department for the overall pleasant atmosphere, and positive working conditions. Throughout this study I also received many comments from the thesis ring of the MAQ department, as well as from my sister, which helped improve this report tremendously.

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Chapter 1

Introduction

The Mississippi catchment is one of the largest catchments in the world, only eclipsed by the Amazon catchment in South America. With its location in North America, it is the largest catchment in the Northern Hemisphere. Together with its main tributaries, the Missouri, Ohio and Arkansas rivers, the Mississippi catchment is crucial for the water availability in nearly 40% of the USA. It ranges from the Rocky Mountains and the Great Plains in the West, the Appalachian mountains in the East, reaches Canada in the North, while its delta can be found in Southern Louisiana (figure 1.1). As shown by the IPCC the chances of droughts and floods will increase in this area (Romero-Lankao et al. (2014)), due to changes in weather patterns. These effects are already noticeable in the Mississippi River basin, as severe extreme events like droughts (2006-2008;Georgakakos et al. (2013)), 2012;Otkin et al. (2016)) and floods (2009;Georgakakos et al. (2013), 2016;Breaker et al. (2016)) have occurred recently. The most recent of these droughts and floods have led to severe damage,- $17 billion (USDA (2013)) and $10.4 billion (NOAA (2017)) in damage for 2012 and 2016 respectively-, to both human society and ecosystems that are located near the Mississippi river.

Due to the importance of the Mississippi River basin for both humans and wildlife, and with the upcoming changes in the hydrological cycle due to climate change, it is important to completely understand what causes the (lack of) water. To check the validity of our current understanding of the atmospheric moisture budget, Benedict [2017] has plotted the annual variability in precipitation. This annual variability follows from the reanalysis outputs of ERA-Interim, and observations, all of which are shown in figure 1.2. As is visible in figure 1.2, the observations do not match the reanalysis data of the ECMWF. The main peak in precipitation both occurs one to two months too early and is too intense for the dataset when compared to the observations. It is thus important to determine the details of the atmospheric moisture balance within the catchment of the Mississippi.

Figure 1.1: The Mississippi catchment, divided in its sub-catchments

To be able to determine these details this study will focus on the feedback between evaporation and precipitation: when moisture evaporates, it will precipitate, and can evaporate again, which leads to the moisture recycling cycle. Based on this cycle two variables can be defined: The precipitation recycling and the evaporation recycling ratio. These two ratios both quantify a different part of the moisture recycling ratio at a chosen location. The precipitation recycling ratio is the ratio of precipitation that is locally generated and the total precipitation. This is in contrast to the evaporation recycling ratio which is the ratio of locally generated evaporation and total evaporation. These two ratios thus give a clear picture of where the moisture in a chosen location originates and where the moisture is going to. Therefore, these two variables can be useful to determine the sources and sinks of moisture in a region.

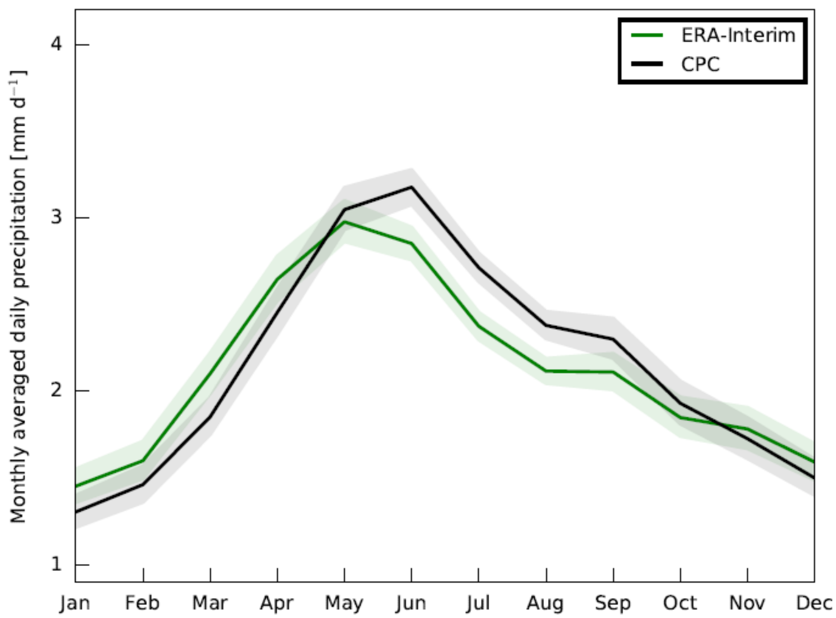


Figure 1.2: Seasonal variation in precipitation averaged over the Mississippi basin [$\frac{mm}{day}$]: Reanalysis data from ERA-Interim, and observations. All datasets were averaged over 30 years. Shaded bands indicate the 95 % confidence intervals.

In recent years the details of the moisture balance have already been the subject of several studies. This was usually done by analyzing the spatial variability of the different terms of the moisture balance. At present, this type of research has already been performed on a global scale (Trenberth and Stepaniak (2003); Lorenz et al. (2014); Trenberth et al. (2011)), and for several subsections of the land mass, such as the Arctic (Dufour et al. (2016)), southeast Asia (Sebastian et al. (2016); Prasanna (2015)), and the United States (Trenberth and Fasullo (2013); Seager et al. (2014)). Apart from these more generalized studies, there also is research available that focuses on shorter time intervals periods, like Betts et al. (2003), who studied a period of only ten years. The studies that focused on North America found a large influence from both the Pacific Ocean and the Gulf of Mexico on the moisture balance in North America. However, none of these studies were conclusive on their influence on the Mississippi catchment.

This study will thus try to use the different terms of the moisture budget, - the evaporation, precipitation and the divergence of the moisture flux - , to determine the precipitation and the evaporation recycling ratios for the Mississippi catchment, which leads to the following research questions:

What are the effects of seasonal and interannual variability of the components of the moisture balance on the sources and sinks of moisture in the Mississippi catchment?
This research question focuses on the seasonal and interannual variability of the three terms of the moisture balance, and the closure of the moisture balance.

What are the seasonal and interannual differences in the precipitation recycling ratio of the Mississippi catchment?
This research question focuses on the climatology of the precipitation recycling ratio in the Mississippi catchment, as well as the processes that drive the precipitation recycling ratio.

What are the spatial patterns of the precipitation recycling ratio and the evaporation recycling ratio during specific events in the Mississippi catchment?
This research question focuses on the drought of August 2012 and Louisiana flash flood of August 2016.

Chapter 2

Theoretical background

This chapter provides a theoretical background of the moisture balance and the regional recycling ratio. In the section of the derivation of the recycling ratio we will provide the definition of the regional recycling ratio, followed by the derivation of both the regional precipitation and the regional evaporation recycling ratios.

2.1 The moisture balance

The four terms in the atmospheric moisture balance are the evaporation, the precipitation, the divergence of the moisture flux and the storage of moisture in the atmosphere (Berbery and Rasmusson (1998); Dufour et al. (2016)). These four terms are visualized in equation 2.1: the first term is the change in storage of moisture in the atmosphere over time, the second is the divergence of the moisture flux, the third is the evaporation and the fourth is the precipitation:

$$\frac{1}{\rho_w g}\int_0^{p_s}\frac{\partial q}{\partial t}dp + \nabla\cdot\frac{1}{\rho_w g}\int_0^{ps} q\vec{V}dp = E - P, \quad [\mathrm{m\,s^{-1}}] \tag{2.1}$$

where ρ_w is the density of water $[\frac{kg}{m^3}]$, g is the gravitational constant $[\frac{m}{s^2}]$, p_s is the surface pressure $[Pa]$, q is the specific humidity $[\frac{kg}{kg}]$, $\vec{V}$ is the horizontal wind velocity $[\frac{m}{s}]$, E is the evaporation $[\frac{m}{s}]$, and P is the precipitation $[\frac{m}{s}]$.

As the change in storage of moisture in the atmosphere is negligible when averaged over time scales longer than a year, we will neglect this term. The divergence of the moisture flux will be calculated by using the second term of equation 2.1. Using Reynolds decomposition in equation 2.1 will be required to ensure that the data is representative for the large-scale flow, as the divergence of the moisture flux fluctuates rapidly over time. This leads to equation 2.2, which will be used in this research, and in which the $\overline{q'\vec{V}'}$ is neglected:

$$\nabla \cdot \frac{1}{\rho_w g} \int_0^{p_s} (\overline{q\vec{V}}) dp = E - P. \qquad [\mathrm{m\,s^{-1}}] \quad (2.2)$$

2.2 The derivation of the recycling ratios

To derive the regional recycling ratio, the moisture balance of equation 2.1 needs to be rewritten in such a way that atmospheric moisture can be tracked over time and space. The start of this derivation is the moisture balance. In this case we need to include the storage term as well, as the tracking of moisture is done on daily and hourly time scales. A finite volume is assumed (equation 2.1). As we are interested in the moisture fluxes we need an equation that represents the change in storage, so the equation has been rewritten, and the terms have been simplified:

$$\frac{\partial S}{\partial t} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} = E - P, \qquad [\mathrm{m^3\,s^{-1}}] \quad (2.3)$$

where S is the storage of moisture in the atmosphere $[m^3]$, $\frac{\partial F_x}{\partial x}$ is the zonal divergence of the moisture flux, and $\frac{\partial F_y}{\partial y}$ is the meridional divergence of the moisture flux. They are defined as:

$$S = \frac{A}{\rho_w g} \int_0^{p_s} q dp, \qquad [\mathrm{m^3}] \quad (2.4)$$

$$F_x = \frac{A}{\rho_w g} \int_0^{p_s} qu dp, \qquad [\mathrm{m^3}] \quad (2.5)$$

$$F_y = \frac{A}{\rho_w g} \int_0^{p_s} qv dp, \qquad [\mathrm{m^3}] \quad (2.6)$$

Where A as the size of the grid cell $[m^2]$. The multiplication with the size of the grid cell is required, to be able to solve the moisture balance in each location of a chosen grid.

It should be noted that these formulas are already specified for a certain grid cell size. This means that the evaporation and the precipitation of equation 2.3 also need to be summed over the same grid cell size. The result is a moisture balance for each grid cell, including the transport between the grid cells.

The zonal and meridional divergences of the moisture flux can be approximated numerically on a grid:

$$\frac{\partial F_x}{\partial x} = \frac{F_x(x+1) - F_x(x-1)}{L}, \qquad [\mathrm{m^3\,s^{-1}}] \quad (2.7)$$

$$\frac{\partial F_y}{\partial y} = \frac{F_y(y+1) - F_y(y-1)}{L}, \qquad [\mathrm{m^3\,s^{-1}}] \quad (2.8)$$

where L is the length of the boundary over which the divergence of the moisture flux occurs. These formulas are going to be adapted later, as by using these formulas we are able to calculate the recycling ratios by tracking moisture.

2.2.1 Precipitation recycling ratio

To derive the forward tracking balance, which results in the precipitation recycling ratio, the different terms are now divided into a regionally generated part and an advected part, which are denoted by r and a respectively (Burde et al. (2006) Dominguez et al. (2006)):

$$\frac{\partial S_r}{\partial t} + \frac{\partial F_{xr}}{\partial x} + \frac{\partial F_{yr}}{\partial y} = \delta E - P_r, \qquad [\mathrm{m^3\,s^{-1}}] \quad (2.9)$$

$$\frac{\partial S_a}{\partial t} + \frac{\partial F_{xa}}{\partial x} + \frac{\partial F_{ya}}{\partial y} = (1-\delta)E - P_a. \qquad [\mathrm{m^3\,s^{-1}}] \quad (2.10)$$

In these formulas it is assumed that $\delta = 1$ for cells inside the region and $\delta = 0$ for cells outside the region. As the evaporation is the source of moisture it is set to zero outside of the chosen region. If a well-mixed atmosphere is assumed, the ratio between regional storage and total storage, and the ratio between regional precipitation and total precipitation should be the same and coincidentally also the precipitation recycling ratio.

$$\frac{S_r}{S_r + S_a} = \frac{P_r}{P_r + P_a} \equiv \rho \qquad [\text{-}] \quad (2.11)$$

The regional zonal and meridional divergence of the moisture fluxes can be numerically approximated by implementing equation 2.11 into equation 2.7 and equation 2.8:

$$\frac{\partial F_{xr}}{\partial x} = \frac{F_x(x+1) \cdot \frac{S_r}{S_r+S_a} - F_x(x-1)}{L}, \qquad [\mathrm{m^3\,s^{-1}}] \quad (2.12)$$

$$\frac{\partial F_{yr}}{\partial y} = \frac{F_y(y+1) \cdot \frac{S_r}{S_r+S_a} - F_y(y-1)}{L}, \qquad [\mathrm{m}^3\,\mathrm{s}^{-1}] \quad (2.13)$$

These two formulas can be solved for each grid cell in a chosen region, which is done by Van der Ent (2014).

2.2.2 Evaporation recycling ratio

The main difference between the precipitation recycling ratio and the evaporation recycling ratio is that the precipitation recycling ratio is determined by tracking forward in time, while the evaporation recycling ratio is determined by tracking backward. Therefore equation 2.9 is rewritten as the precipitation is now :

$$\frac{\partial S_r}{\partial t} + \frac{\partial F_{xr}}{\partial x} + \frac{\partial F_{yr}}{\partial y} = \delta P - E_r, \qquad [\mathrm{m}^3\,\mathrm{s}^{-1}] \quad (2.14)$$

$$\frac{\partial S_a}{\partial t} + \frac{\partial F_{xa}}{\partial x} + \frac{\partial F_{ya}}{\partial y} = (1-\delta) P - E_a. \qquad [\mathrm{m}^3\,\mathrm{s}^{-1}] \quad (2.15)$$

As the precipitation is now the source of moisture instead of the evaporation, it is set to zero outside of the chosen region. This enables us to track moisture backward over time. Just as for the precipitation recycling ratio and when a well-mixed atmosphere is assumed, the ratio between regional storage and total storage should be equal to the ratio between the regional evaporation and total evaporation. This is the evaporation recycling ratio:

$$\frac{S_r}{S_r + S_a} = \frac{E_r}{E_r + E_a} \equiv \epsilon \qquad [\text{-}] \quad (2.16)$$

The same formulas as for the precipitation recycling ratio (equations 2.12 and 2.13) are used to track moisture backwards. The only difference between the forward and backward tracking of moisture is that in the solution the signs of the different components are reversed.

Chapter 3

Data and the Water Accounting Model

This chapter provides a brief description of the used dataset and variables. Thereafter, the model that is used to determine the precipitation and evaporation recycling ratio is discussed.

3.1 Data description

In this study the ERA-Interim dataset is used (Dee et al. (2011)). The ERA-Interim global dataset uses the IFS Cycle 31r2 assimilation system and consists of 79 by 79 [km] grid cells, and 60 height levels up to 0.1 [hPa].

The first part of this research is a comprehensive overview of the more general patterns of the moisture balance variables. In this part we use a 31 year seasonal average; from 1986 until 2016. These years are chosen because these are the most recent complete years that ERA-Interim has available at the start of this study. The variables that are used in this part of the study are: the evaporation, the precipitation, the specific humidity, and the wind velocity. All four variables are used on a 0.75° grid.

The second part of this research consists of the tracking of moisture with the WAM2-layer model. Here we focus on the recycling ratios. The WAM2-layer model requires daily data of a large variety of variables (see Appendix, table 7.1). This data is taken from the validated ERA-Interim dataset, and are again used on a 0.75° grid. As this research focuses on the origin of the moisture, the average precipitation recycling ratio over the 31 years that were mentioned in the first step of this research are analyzed as well.

3.2 The Moisture balance

The different sources and sinks of the moisture balance are examined individually (Chapter 2). For the evaporation and the precipitation this is first done for North America, to be able to identify the more general patterns. After describing the general patterns we zoom in on the Mississippi catchment. The average over the 31 years and the variability between the seasons is calculated to create an overview of the processes behind the moisture balance in the Mississippi catchment.

After establishing the evaporation and the precipitation for the Mississippi catchment, the divergence of the moisture flux is calculated. The calculation of the divergence of the moisture flux can be simplified by using the divergence theorem (Holton and Hakim (2012)):

$$\int_A BndA = \int_V BdV, \tag{3.1}$$

with V as a volume with boundaries A and n is a unit normal on A, and B as a vector. Here we see that the integral of fluxes over an area is equal to the integral of the fluxes over the boundaries over the area. For the closure of the moisture balance this means that the transport over the catchment boundaries should be equal to the evaporation and the precipitation (equation 2.2). As soon as the different aspects of the moisture balance (the evaporation, precipitation and the divergence of the moisture flux) have been determined, the moisture balance can be calculated by using equation 2.2. The difference between the left and right hand side of this equation is a measure of the error of the moisture balance in this region.

3.3 The WAM2-layer model

The second part of this study focuses on the precipitation and evaporation recycling ratios in the Mississippi catchment. These ratios can be calculated by using either a Lagrangian or an Eulerian method. In this study the Eulerian Water Accounting Model 2-layer (WAM2-layer; Van der Ent (2014)) is used to determine the origin of moisture in the Mississippi catchment. In this model, the moisture fluxes are used to track moisture particles. Combined with the evaporation and the precipitation, this results in a moisture balance for each grid cell. These regional moisture balances are then used by the WAM2-layer model to calculate the evaporation and precipitation recycling ratios. While we focus on seasonal to interannual time scales, we also look at the differences in moisture origin during a dry and a wet case: the drought of August 2012, and the Louisiana flash floods of August 2016.

Chapter 4

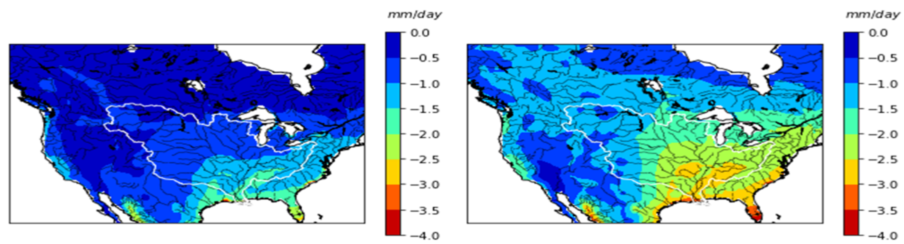
The different terms and closure of the moisture balance

This chapter focuses on the three terms of the moisture balance (equation 2.2), in the following order: evaporation, precipitation and the divergence of the moisture flux. Afterwards we will combine these terms and check for the closure of the moisture balance in the Mississippi catchment.

4.1 Evaporation

As is shown in figure 4.1, the evaporation over land is lower during winter (December, January and February: DJF) than during the summer (June, July and August: JJA). During both DJF and JJA the highest evaporation rates can be found in the Southeast (2.5 $\frac{mm}{day}$ and 4 $\frac{mm}{day}$ respectively), while the lowest evaporation rates can be found in the North and over the Rocky Mountains (<0.5 $\frac{mm}{day}$ during both winter and summer). This is most likely caused by the relatively high temperatures and abundance of water in the Mississippi catchment compared to the cold North and the dry Rocky Mountains.

When zooming in to the Mississippi catchment, it becomes clear that the Great Lakes do not follow the same seasonal cycle as the land surface (not shown). However, this is not the main focus of this research and will therefore not be taken into account. With the focus on the land surface, the overall pattern remains the same, with relatively low evaporation rates during DJF and relatively high evaporation rates during JJA. During DJF the lowest evaporation rates can be found in the Northwestern corner of the Mississippi catchment. These are caused by lower temperatures in the north compared to the south and an overall lack of moisture in this corner of the Mississippi catchment. The highest



(a) DJF (b) JJA

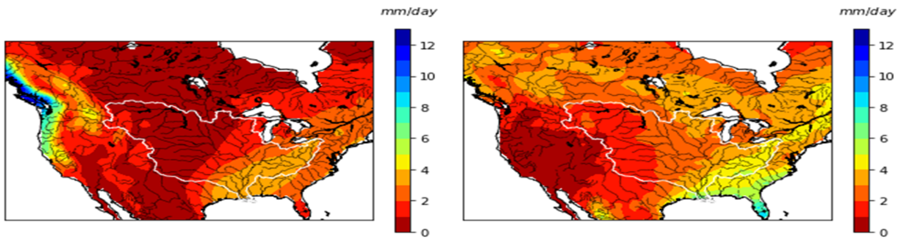
Figure 4.1: Mean evaporation during (a) December, January and February, and (b) June, July and August of 1986 until 2016. The boundaries of the Mississippi catchment are found in white [$\frac{mm}{day}$].

values can be found near the delta of the Mississippi. These are caused by an abundance of moisture and relatively high temperatures compared to the rest of the catchment. During JJA the evaporation rates over land are considerably higher, which is caused by the higher temperatures during summer. However, the spatial pattern has remained the same compared to DJF, with low values in the Northwest and high values in the South/Southeast.

4.2 Precipitation

During DJF the highest precipitation rates are found around the West coast (12 $\frac{mm}{day}$; see figure 4.2a). On the other side of the continent fairly high precipitation rates (up to 4 $\frac{mm}{day}$) can be found as well. In between these two regions a large area with little to no precipitation is found, which coincides with the Great Planes. In JJA this dry area does receive some precipitation (2 $\frac{mm}{day}$) but the biggest difference between DJF and JJA is that the West coast is now completely dry. In contrast the Southeast of the United States is receiving more precipitation during summer than during winter (7 $\frac{mm}{day}$ vs 2 $\frac{mm}{day}$; see figure 4.2b). It is also noticeable that the precipitation during DJF is mostly focused on two regions, while during JJA a spatially more gradual pattern is found.

These patterns are also visible when zooming in to the Mississippi catchment, as during winter the Western part is dry, while the Eastern part does receive precipitation. The highest values that are now encountered in the Mississippi catchment are just below 4 $\frac{mm}{day}$. The overall pattern within the Mississippi catchment itself is that the further East one is, the more precipitation occurs. The same pattern in precipitation holds for JJA, but now high precipitation rates can also be found in the delta of the Mississippi. The maximum value during JJA is higher (7 $\frac{mm}{day}$) than during winter but this is due to convective precipitation. Convective precipitation can be evenly distributed over the Mississippi catchment as we are looking at a 31 year average.

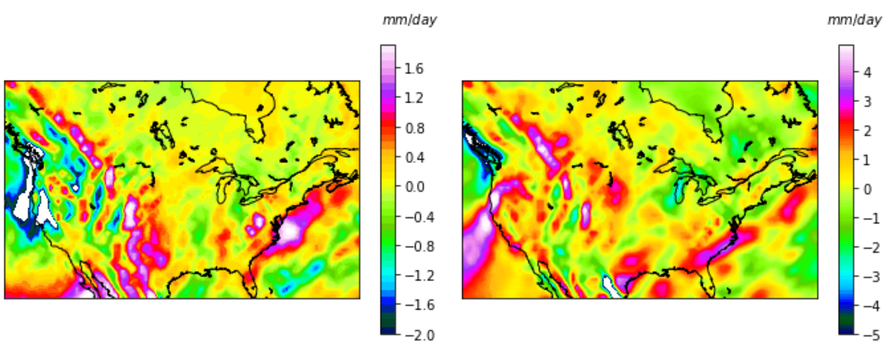


(a) DJF (b) JJA

Figure 4.2: Mean precipitation during (a) December, January and February, and (b) June, July and August of 1986 until 2016. The boundaries of the Mississippi catchment are found in white. Note that the sign of the evaporation and precipitation are opposite $[\frac{mm}{day}]$.

4.3 Divergence of the moisture flux

The divergence of the moisture flux is more variable than the evaporation and the precipitation, as both show a much more spatially gradual pattern than is visible in figure 4.3. The equation of the moisture balance (equation 2.2) already suggests that this would be the case, as the specific humidity and especially the wind velocities are found to be more variable than the evaporation and the precipitation in the central part of the United States. There also appears to be a difference between the seasons as is shown in figure 4.3. The divergence of the moisture flux is much more extreme, both positively and negatively, during JJA than during DJF.



(a) (b)

Figure 4.3: Mean divergence of the moisture flux during (a) December, January and February, and (b) June, July and August of 1986 until 2016.

According to the divergence theorem, it is possible to determine the total flux in an area by determining the fluxes over the boundaries of said area. As this simplifies the calculations, this was applied to the Mississippi catchment. The values themselves vary slightly for each of the four boundaries, with the divergence of the moisture flux being highest at the Eastern and Southern boundaries (-3.507 $\frac{mm}{day}$ and 3.652 $\frac{mm}{day}$ respectively), and lowest at the Western and Northern boundaries (2.765 $\frac{mm}{day}$ and -3.155 $\frac{mm}{day}$ respectively). This suggest that moisture enters mostly through the Southern border, and leaves mostly through the Eastern border. As the wind direction in this area was found to go from the Southwest to the Northeast over this area, these differences between the different boundaries are expected. The annual average of the divergence of the moisture flux in the Mississippi catchment is found to be -0.245 $\frac{mm}{day}$.

4.4 Closure of the Moisture Balance

The previously mentioned terms are now combined to check the closure of the moisture balance in the ERA-Interim data, as the combination of these three variables should be zero. While it will be very difficult to get a perfect fit, it was found that the values were very close to each other: with the average divergence of moisture between 1986 and 2016 being -0.245 $\frac{mm}{day}$, the sum of the evaporation and the precipitation was found to be -0.263 $\frac{mm}{day}$. The difference between the different sides of the moisture balance was thus only 0.018 $\frac{mm}{day}$ which is only a fraction of the three terms themselves (7% for the total divergence, and $<$1% for both the evaporation and the precipitation). Compared to the literature, this is relatively small (e.g. Maurer et al. (2001) found 10 % with ERA-40 and the CRCM model, Berbery and Rasmusson (1998) found 10 % with ERA-Interim and the Eta Model, and Lorenz and Kunstmann (2012) found 1 % with ERA-Interim from 1979 to 2012). These discrepancies are caused by the lack of moisture conservation in ERA-Interim. However, as the discrepancies that we found are small compared to the actual terms of the moisture balance, we can assume that the moisture balance based on ERA-Interim closes and can therefore be used in the next phase of this study.

Chapter 5

The recycling of moisture

This chapter will cover the precipitation and evaporation recycling ratios. The first part will cover the climatological results. Secondly, to determine the large-scale drivers which influence the precipitation recycling ratio, we perform correlations between the precipitation recycling ratio and the temperature at 2 meters (t2m), the surface pressure (sp) and the 200 hPa geopotential height (z200). At the end of this chapter cases of both a drought and a flood are discussed.

5.1 Precipitation recycling ratio climatology

The climatology of the precipitation recycling ratio is determined over the 31 years between 1986 and 2016. Figure 5.1 shows a seasonal cycle for the precipitation recycling ratio. During DJF the recycling ratio is lowest, while it is highest during JJA (average of 0.072 and 0.263 for DJF and JJA respectively). The precipitation recycling ratios of spring (March, April and May: MAM) and autumn (September, October and November: SON) can be found in between the precipitation recycling DJF and JJA values, but there also appears to be a clear distinction between the MAM and SON as the values of the SON are always lower than the values for MAM (average of 0.136 and 0.195 for MAM and SON respectively). The variation within each season also differs between the seasons. The range in precipitation recycling ratio during DJF is 0.059-0.088. This range is significantly smaller than the range during the rest of the seasons, as especially MAM and JJA show a large interannual variability (0.160-0.243 and 0.214-0.302 respectively).

The most likely explanation for the difference in variability is the pattern in which the precipitation itself occurs. During JJA the precipitation is dominated by convective precipitation (chapter 4). This influences the amount and variability of precipitation that is generated, and therefore has an effect on the variability of the precipitation recycling ratio.

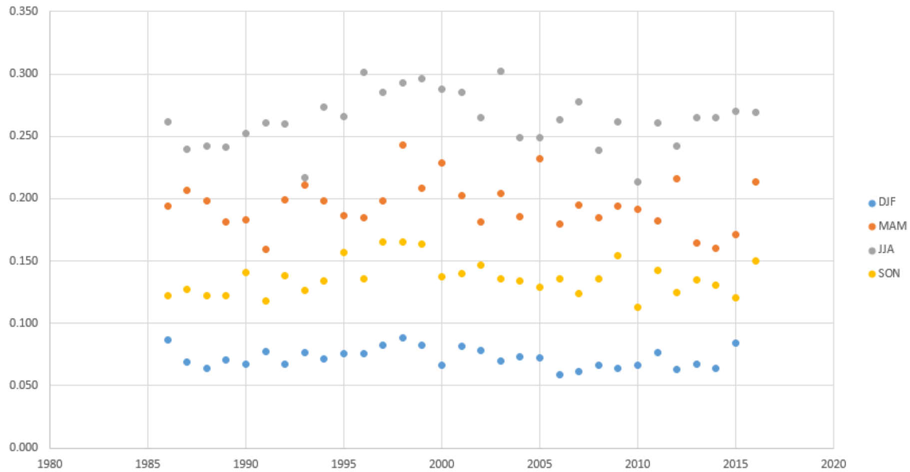


Figure 5.1: The seasonality of the regional precipitation recycling ratio [-] of the moisture during the 31 years between 1986 to 2016. All shown values are the average of the calculated values in the chosen region: the Mississippi catchment (grid cell size = 0.75°).

Apart from the variation in between the four seasons, there also is a variation visible between the annual values of the precipitation recycling ratios (see figure 5.2). This interannual variation was also slightly visible in the seasonal variation (see figure 5.1), which for instance already showed that the high precipitation recycling ratio in 1998 ($\rho = 0.197$) was mostly caused by relatively high values during DJF and MAM, while the low precipitation recycling ratio in 2010 ($\rho = 0.145$) was mostly caused by low precipitation recycling ratios in the JJA and SON. This suggests that the annual precipitation recycling ratio can be heavily influenced by one or two seasons, and that the pattern in annual precipitation recycling ratios needs to be related to all four seasons to determine the causes of the variation.

However, even though all four seasons will be able to influence the annual precipitation cycle, the effects will be more severe in the case of the MAM and JJA values as they are higher than the DJF and SON values. This also coincides with the higher variability in MAM and JJA, which could increase the relative effect these two months have on the annual average even more.

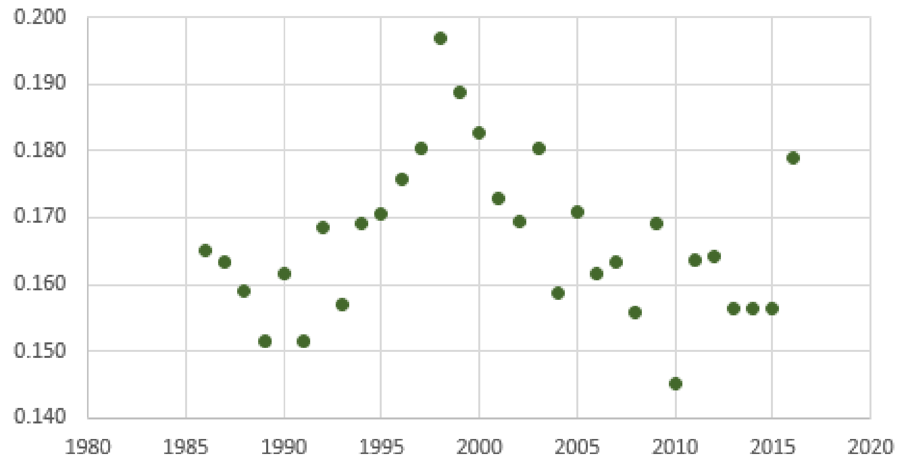
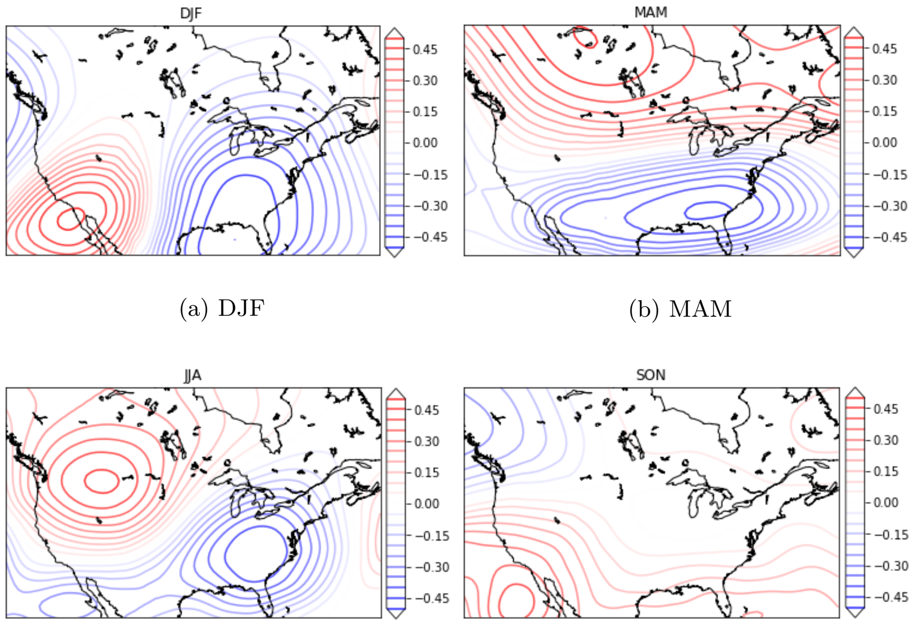


Figure 5.2: The interannual variability of the regional evaporation recycling ratio [-] of the moisture during the 31 years between 1986 to 2016. All shown values are the average of the calculated values in the chosen region: the Mississippi catchment (grid cell size = 0.75°).

5.2 Large-scale drivers of the precipitation recycling ratio

The variability in the precipitation recycling ratio that was found in the previous section, can be caused by different large-scale circulation patterns. This is why the correlations of the average precipitation recycling ratio in the Mississippi and the anomalies of the z200 (figure 5.3), the t2m and the sp (see Appendix figure 7.1 and figure 7.2) can be used to identify the main drivers of the precipitation recycling ratio.

For the z200, we find positive correlations in the Western part of the United States and negative correlations in the Eastern part during DJF and JJA. However, during MAM and SON this pattern is not visible. The Western pattern during DJF and JJA is probably the result of a decrease in overall precipitation instead of an increase in locally generated precipitation. When the z200 in the West is high, the high pressure blocks any low pressure system that may transport moisture from the Pacific to the Mississippi catchment. Therefore, the advected precipitation decreases, while the locally generated precipitation remains the same. This will thus increase the precipitation recycling ratio. On the Eastern coast the reverse is visible, as a high z200 and resulting cyclonic flow will lead to an influx of moisture from the Gulf of Mexico. This will lead to a lower precipitation recycling ratio, as the advected precipitation increases.



(a) DJF

(b) MAM

(c) JJA

(d) SON

Figure 5.3: The correlation between the regional precipitation recycling ratio [-] and the 200 hPa geopotential height anomalies. Each figures depicts a different month: (a) DJF, (b) MAM, (c) JJA, and (d) SON.

In the case of the temperature at 2 m, comparable correlation patterns can be found as for the 200 hPa geopotential height during all four seasons. Only small differences are found, for example the correlation for the t2m in the West is less pronounced than for the z200 during DJF. During DJF and JJA the Western pattern is probably due to an increase in evaporation, which leads to a higher transportation of moisture towards the Mississippi catchment. On the Eastern side of the United States the reverse is visible, as a high temperature leads here to a larger portion of moisture being transported from the Mississippi towards other regions.

For the surface pressure comparable patterns as for the z200 and the t2m are found. The most important difference is that in the case of the z200 the patterns are much more defined. This will be due to the lack of interference from the surface, which plays a large role in the lower parts of the atmosphere.
On top of these drivers over North America, the global correlations were also determined (see Appendix 7.3). Here the more global patterns were determined. During DJF the negative correlations over the Pacific Ocean are shaped in the

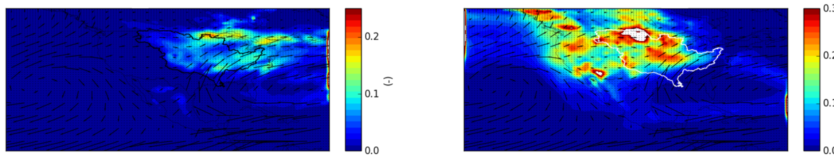
form of a horseshoe. Combined with the positive correlations over the equator to the West of South America, this means that the El Nino Southern Oscillation (ENSO) influences the precipitation recycling ratio. As we have already seen that the circulation of moisture is influencing the precipitation recycling ratio, the influence of ENSO on the recycling of moisture in the Mississippi catchment was to be expected.

5.3 The drought of 2012

Now that the large scale drivers have been identified, we look at two extreme cases to see the variation in precipitation and evaporation recycling ratio in more detail. The first case that was chosen was the drought of 2012. In August 2012 the amount of moisture that precipitated in the Mississippi catchment was considerably lower than average (at least 1.5 standard deviations lower than the climatological mean of 1979 to 2011). Combined with a higher than average surface temperature, and a lower than average soil moisture content this lead to severe impacts on the crop yields of that year (Hoerling et al, 2014). In the months towards this disastrous August, the amount of moisture that was present in the atmosphere above the USA was already depleted. In May and June a high pressure ridge prevented the flow of cold fronts from Canada to the USA, which usually causes widespread rains in the Central parts of the USA. In July an anticyclone had formed over the central parts of the USA, which prevented fronts from coming in. This anticyclone also stabilized the atmosphere and prevented the occurrence of convection. And finally, in August a trough located in Ohio prevented moisture to flow from the Gulf of Mexico (Hoerling, et al, 2014). Individually these conditions could have caused some minor issues, but the combination of these factors in four consecutive months was what lead to the most severe drought in half a century (Hoerling, et al, 2014). As most of the damage was done in August of 2012, we focus only on this month.

It can be seen in figure 5.4a that during August 2012 the moisture from within the Mississippi is moving out of the catchment before it precipitates again. This movement occurs mostly towards the northeast, which was the prevalent wind direction over the continent during the drought (also shown in 5.4a). The movement of moisture out of the catchment also concurs with the weather conditions, as the general flow was from the west to east. There was only a small moisture flux from the Mississippi catchment towards the south due to the trough over Ohio (figure 5.4a).

After having established the positions of the precipitation that originate from the Mississippi catchment, the origin of moisture that precipitates in the Mississippi catchment can also be obtained in the form of the evaporation recycling ratio. During August 2012 there was a trough located over Ohio, which resulted in a lack of moisture flux from the south. This is also visible in figure 5.4b, where it is shown that all the moisture coming into the Mississippi catchment origi-



(a) (b)

Figure 5.4: The regional precipitation recycling ratio [-] of the moisture during (a) the drought of August 2012 and (b) the flood of August 2016. The chosen grid cell size for both (a) and (b) is 0.75°. The arrows show the wind velocity and direction.

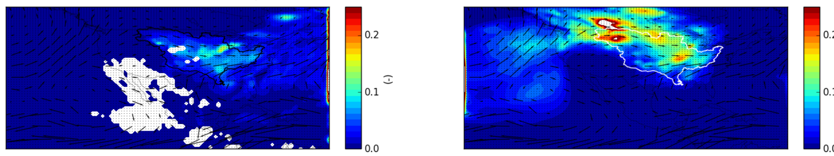
nates either from the Northwest or from the West. It should be observed that most of the moisture originates over land, which might imply that the amount of moisture that comes into the system is quite low.

5.4 The Louisiana flash floods of 2016

Though the drought of 2012 was predicted beforehand, the flash floods that occurred in Louisiana in 2016 were unpredicted by both the Global Forecast System (GFS) and the Climate Forecast System (Wang et al, 2016). This could have been caused by the difficulties that belong to the prediction of subsynoptic low pressure systems, like the tropical cyclone that caused the flash floods. The tropical cyclone in question moved slowly over the Gulf Coast, but remained stationary over Louisiana for a few days. This lead to the continuous formation of thunderstorms, which resulted in precipitation rates that were very high for this region (534.7 mm in three days; Van der Wiel et al, 2017).

The pattern that was found for August 2012 was thus very different than the pattern in August 2016 (figure 6.1b). While quite a large part of the precipitation still originates above North-America, a significant part originates from the ocean. There is also a lack of moisture influx from the Gulf of Mexico, as the weather pattern showed a tropical cyclone moved from the Gulf of Mexico along the Coast. Therefore it would have been expected that there was a flux from the Gulf of Mexico to the Mississippi catchment.

Secondly, the spatial pattern of the regional precipitation recycling ratio during



(a) (b)

Figure 5.5: The regional evaporation recycling ratio [-] of the moisture during (a) the drought of August 2012 and (b) the flood of August 2016. The chosen grid cell size for both (a) and (b) is 0.75°. The arrows show the wind velocity and direction.

the flash floods of 2016 are more surprising (figure 6.1). The white spaces that are visible in figure 6.1 indicate that no precipitation occurred during August. The maximum of the recycling ratio also does not go beyond 0.2. This indicates that the precipitation in the Mississippi either moved out of the model domain, or remained within the catchment.

Chapter 6

Discussion

In this discussion the results from chapters 4 and 5 are put into a broader perspective. The first section focuses on the ERA-Interim data which is used to calculate the different terms of the moisture balance in the Mississippi catchment. The second section contains a sensitivity analysis performed on the precipitation recycling ratio. Finally the WAM 2-layer model (Van der Ent et al. (2010)), and the recycling ratios that were found with this model are discussed.

6.1 The closure of the moisture balance

As was mentioned before, the moisture balance consists of three components (see chapter 2): the precipitation, the evaporation and the divergence of the moisture flux. Thus, these three components will be compared to the literature individually before combining them into the moisture balance. This check is necessary as ERA-Interim does not include moisture conservation.

The precipitation (see Chapter 4) indicated a highly variable precipitation rate at the West coast, as well as in the South East. The driest region was the Great Plains, as it is located on the leeward side of the Rocky Mountains. The Mississippi catchment received a small amount of precipitation during DJF, and a larger amount during JJA. This was also shown by Brubaker et al. (2001) and Lorenz et al. (2014). Brubaker et al. (2001) also showed that in the Western part of the Mississippi catchment (closest to the dry Great Planes) the difference between DJF and JJA is higher, while the East part is more constant over time. This supports figure 4.1, which showed that the Eastern part of the Mississippi catchment received only slightly more precipitation during JJA, while the Western part of the United States received a lot more precipitation.

The evaporation that was shown in Chapter 4 indicated low rates during DJF and high rates during JJA over the Mississippi catchment. This was also found by Brochu and Laprise (2007), who used the Canadian Regional Climate Model

(CRCM) to simulate evaporation between 1987 and 1994. This model was validated with the ERA40 dataset, which is also a product of the ECMWF.

The divergence of the moisture flux is spatially more variable than the evaporation and the precipitation due to the high variability in wind velocity. In the catchment it was visible that the moisture is entering through the Southern and Western boundaries, while the moisture was leaving the system through the Eastern and Northern boundaries. The biggest fluxes of entering and departing moisture are the Southern and Eastern boundaries respectively. This is comparable with the results that were found by Rasmusson (1967) and Seneviratne et al. (2004), who determined that the main flow of moisture over the Eastern part of the Mississippi catchment is parallel to the East coast. Therefore the dominance of the Southern and Eastern boundaries was to be expected.

After calculating the different components of the moisture balance, we found a discrepancy of 0.018 $\frac{mm}{day}$ for the moisture balance in the Mississippi catchment. This discrepancy is <1% of the size of the evaporation and the precipitation. The remaining of 0.018 $\frac{mm}{day}$ indicates that the system has lost 0.018 $\frac{mm}{day}$ during the 31 years. This is most likely due to river runoff, which we chose to neglect in this study. While this is not exactly zero, it is better than most of the values found in the literature. Examples of the values from the literature are: Maurer et al. (2001) who showed a discrepancy between these two terms of 10% by using ERA-40 data and the CRCM model, Berbery and Rasmusson (1998) who also found a discrepancy of 10%, while using ERA-Interim data and the data generated by the Eta Model. These differences can be explained by the difference in both the spatial resolution and the temporal resolution. While I used a 0.75° grid and three hourly data for the evaporation and the precipitation, Maurer et al. (2001) used a 1.5° grid and six hourly data, and Berbery and Rasmusson (1998) even used a 2.5° grid and a varying temporal resolution. However, Berbery and Rasmusson (1998) only use two years instead of a few decades, as was done in this research and by Maurer et al. (2001). Thus, it should come as no surprise that the discrepancy for the moisture balance is larger for these studies compared to mine. However, Lorenz and Kunstmann (2012) found a discrepancy of 1 % with ERA-Interim between 1979 and 2012. The difference with Maurer et al. (2001) and Berbery and Rasmusson (1998) is that Lorenz and Kunstmann (2012) used a 0.75° grid instead of a 1.5° or 2.5° grid. Therefore, we need to continue working with an 0.75° grid as the discrepancy in the moisture balance is lowest in that case.

6.2 Sensitivity Analysis

To ensure that the right parameters were chosen for the model, it is necessary to determine whether the size of the grid cells and the size of the chosen area have an effect on the eventual outcomes of this research. These analyses will only be done for the precipitation recycling ratio, as it has more comparable literature available than the evaporation recycling ratio, and will therefore be easier to validate.

6.2.1 Grid Cells Size

The first variable that may be able to influence the precipitation recycling ratio is the chosen size of the grid cells. The effect this can have is mostly focused on the amount of averaging that occurs while calculating the precipitation recycling ratio. However, while a downward quadratic trend is found (see figure 6.1), the trend itself is not significant as it has an R^2 of 0.59. The choice of a quadratic function was made, as the size of a grid cell influences the amount of grid cells within the Mississippi catchment quadratically.

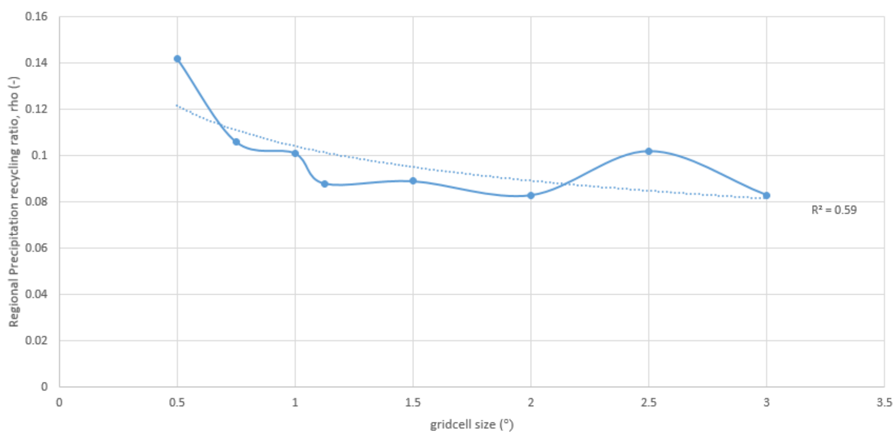


Figure 6.1: Relation between the chosen grid cell size, and the regional precipitation recycling ratio [-]. A single year was chosen (2016), and the mean of the precipitation recycling ratio was calculated for every month.

The same trend as for the annual values can also be found for the monthly values (not shown). These results indicate that while the 0.5° grid cell size is significantly higher than the other values, the rest of the grid cell sizes between 0.75° and 3° are all very close to each other. This is quite strange, as the 0.5° was determined by interpolating the original 0.75° dataset to a finer grid and thus should be comparable to the original dataset. The lack of a correlation between the precipitation recycling ratio and the size of the grid cells was also found by Eltahir and Bras (1994), but it is currently accepted that for global scale studies it is a factor that needs to be taken into consideration (Dirmeyer and Brubaker (2007), Trenberth (1999)). The lack of a correlation between the precipitation recycling ratio and the size of the grid cells is probably due to that while the grid cells change in size, the area over which the ratio is calculated remains the same. The variables that are used to calculate the precipitation recycling ratio remain the same on average, and will thus not lead to a correlation between the size of the grid cells and the average precipitation recycling ratio in the Mississippi catchment.

6.2.2 Area Size

The second variable that might be able to influence the output of the precipitation recycling ratio is the size of the area, as a larger area affects the ratio between the total precipitation and the locally generated precipitation. A larger area incorporates a larger variety of topography, which may lead to differences in precipitation recycling ratio. These effects are found (see figure 6.2), as there appears to be a logarithmic relation between the size of the area and the precipitation recycling ratio.

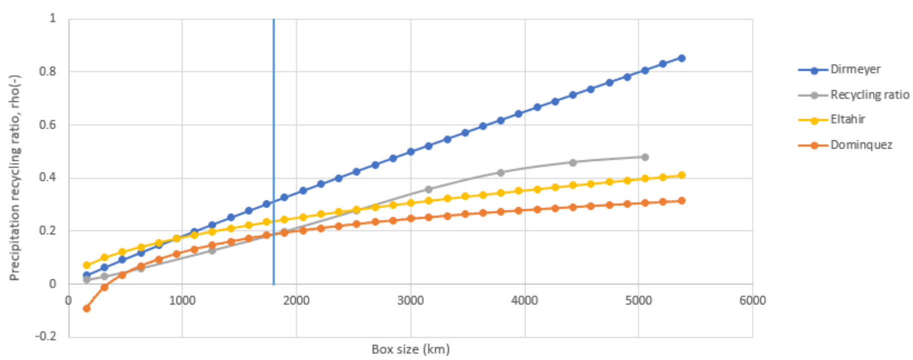


Figure 6.2: Relation between the size of the chosen region, and the regional precipitation recycling ratio [-]. A single year was chosen (2016), and the mean of the precipitation recycling ratio was calculated over the entire year. Dirmeyer (blue), Eltahir (yellow) and Dominquez (orange) are examples of relations found in the literature. The Recycling Ratio (grey) are the values that were found in this study. The size of the box is measured in the length of one side (equal for all sides). The blue vertical line is the size of the Mississippi catchment.

In contrast to the grid cell size there is a correlation between the precipitation recycling ratio and the size of the chosen area ($R^2 = 0.99$). This is also shown in the literature where Eltahir and Bras (1996), Dirmeyer et al. (2009) and Dominguez et al. (2006) all found relations between the size of the chosen area and the precipitation recycling ratio. However, there is a large variation in the formulas of the relations that are found. This could be caused by the chosen region, as Eltahir and Bras (1996) used the Amazon, Dominguez et al. (2006)

used the United States, and Dirmeyer et al. (2009) used the entire Earth to determine their formulas. However, this may not be the only reason behind the difference as there also appears to be a difference in the method used for calculating the precipitation recycling ratio in the same region (Eltahir and Bras (1996)). The exact relation thus mostly depends on the methodology used to calculate the precipitation recycling ratio. Therefore, while each study found that there was indeed a relationship between the precipitation recycling ratio and the size of the area, there is no consensus over the exact formula for this relation.

6.3 The Water Accounting Model

Since the different aspects of the moisture balance have been established, it is now possible to discuss results of the WAM2-layer model. First, the climatology of the precipitation recycling ratio will be discussed, followed by the large-scale drivers of the recycling ratio. And finally, the two cases of the 2012 drought and the 2016 flood are discussed.

6.3.1 The climatology of the precipitation recycling ratio

In the climatology a clear difference between the precipitation recycling ratios in between the seasons was found. JJA has the highest precipitation recycling ratios, while DJF has the lowest precipitation recycling ratios. This was also found by Eltahir and Bras (1996), and Brubaker et al. (2001) for the Amazon and the Mississippi respectively. Within the seasons the largest variation can be found during MAM and JJA, while the smallest variation can be found during the DJF (see also Bosilovich and Schubert (2001) for comparable results). However, these studies are mostly focusing on the (early) summer months, while this study has either focused on the entire year, or August in particular. A variation between the annual values of the precipitation recycling ratio was also found. These variations are caused by the differences within the individual seasons. It depends on the year which season is causing the variation in annual precipitation recycling ratio.

6.3.2 The large-scale drivers of the precipitation recycling ratio

The seasonal variations can be explained by the correlations that were found between the precipitation recycling ratio and the three variables (t2m, sp and z200) that were checked. As the z200 influences the direction of moisture fluxes in the atmosphere, the amount of moisture that becomes available for transportation towards the Mississippi depends on it (Chapter 5). Apart from the effect the circulation has on the precipitation recycling ratio, another factor to consider is the Clausius-Clapeyron relation. This relation states that warm air is able to contain more moisture than cold air. In the Western part of the United States the high positive correlations between the precipitation recycling ratio and the t2m possibly shows this relation. As it is more difficult for warm air to reach saturation it is now harder to precipitate moisture. With the wind moving here from West to East, an increase in potential moisture content leads to less advected precipitation in the Mississippi catchment. However, the Clausius-Clapeyron argument does not hold up in the Eastern United States, as the main wind direction is here away from the Mississippi catchment. If the Clausius-Clapeyron argument were valid in the Eastern region, we would have expected no correlation between the precipitation recycling ratio in the Mississippi catchment and the t2m in this region. As we find a high negative correlation, the Clausius-Clapeyron argument is not valid in this region. Therefore, while the Clausius-Clapeyron argument might contribute to the high positive correlation in the West, the dominant process behind the precipitation recycling ratio in the Mississippi catchment is the circulation.

6.3.3 The 2012 and 2016 case studies

The main differences between the drought of 2012 and the flood 2016 is in the amount of moisture that precipitates within the Mississippi catchment. It was possible to compare the average precipitation recycling ratio of the dry and wet years (0.195 and 0.183 respectively) to the values that are available in the literature. Brubaker et al. (1993) found in the period 1963-1973 that 0.24 of the moisture that evaporates in the Mississippi catchment is recycled. Another example is Bosilovich and Chern (2006) who found in 1946-1996 a value of 0.144. These annual values do seem to indicate that the values we found are in the correct order of magnitude. However, both the drought and the flood occurred during August. Thus we need to the values in the literature for the summer as well. Brubaker et al. (2001) found 0.32 in 1963-1998, Bosilovich and Schubert (2001) found 0.35 in 1990-1995, and Burde et al. (2006) found 0.37 for the summer. The corresponding values found in this study are 0.301 and 0.302 for the dry summer and wet summer respectively. The studies mentioned all use different models and techniques to calculate the precipitation recycling ratio so small variations are expected. Therefore, it can be concluded that the precipitation recycling ratios that were found in this study are comparable to the ones that are presented in the literature.

During the drought of 2012 almost all significant evaporation recycling ratios can be found over North America. This suggests that the Mississippi catchment was mostly fed by moisture that evaporated above land. This is in sharp contrast to the flood of August 2016, during which at least some of the moisture was found to have originated from above the Pacific Ocean. It is also noteworthy that almost no moisture from the Gulf of Mexico is found to precipitate within the Mississippi catchment during both case studies. This is unexpected, as hurricanes are known to move from the Caribbean and make landfall in the United States. However, this movement is not visible at all, which can be caused by the years that were chosen, as it was already established that the weather conditions during the chosen years were not favorable for a moisture flux from the Gulf of Mexico to the Mississippi catchment (see chapter 3). It could however also be caused by the choice of model as the Eulerian WAM2-layer model might have oversimplified the tracking of moisture. As was already mentioned, there are several different methods to calculate the recycling ratios, which can result in very different recycling ratios.

Chapter 7

Conclusion and Recommendations

In this study, the different components of the moisture balance were analyzed for the 31 years between 1986 and 2016. This included the use of the WAM2-layer model, which calculated the precipitation and evaporation recycling ratios. Each research question will now be answered, after which a final conclusion is given.

> *What are the effects of seasonal and interannual variability of the components of the moisture balance on the sources and sinks of moisture in the Mississippi catchment?*

For the Mississippi catchment the evaporation was discovered to be fairly homogeneous during winter, while there were some larger spatial variations during summer. The evaporation was found to be higher during summer, due to higher temperatures. For the precipitation the variation was higher during the winter months, while the total precipitation was higher during summer. The divergence of the moisture flux was found to be more spatially variable, and to have higher convergence and divergence values during summer compared to the winter. The three different components were also combined into the moisture balance, which resulted in a average discrepancy of 0.018 $\frac{mm}{day}$. The remaining of 0.018 $\frac{mm}{day}$ indicates that the system has lost 0.018 $\frac{mm}{day}$ during the 31 years. This is most likely due to river runoff, which we chose to neglect in this study. However, the remainder is small compared to the other components. Therefore, while a seasonal cycle is present, the interannual cycle closes the moisture balance almost perfectly for the ERA-Interim dataset.

> *What are the seasonal and interannual differences in the precipitation recycling ratio of the Mississippi catchment?*

With the aid of the WAM2-layer model the evaporation and precipitation recycling ratios could be determined. A seasonal pattern was discovered, with the highest values in summer and the lowest values in winter. It has become clear from the correlations between the precipitation recycling ratio and the 200 hPa geopotential height and the temperature at 2 m that different things affect the precipitation recycling ratio in the Mississippi catchment. Examples of this are the low pressure systems in the South East, which influence the amount of moisture that is able to move into the Mississippi catchment. Another example are the high temperatures in the Rocky Mountains, which ensure that moisture is incapable to move into the Mississippi catchment. It therefore depends on the specific situation what the main driver influencing the precipitation recycling ratio is. In general, high temperatures in the Rocky Mountains and low pressure systems in the South East lead to more local recycling within the Mississippi, while precipitation usually originates from the Pacific ocean.

> *What are the spatial patterns of the precipitation recycling ratio and the evaporation recycling ratio during specific events in the Mississippi catchment?*

The two case studies that were performed in this project were meant to showcase the most extreme cases, which was why the drought of August 2012 and the Louisiana flash flood of August 2016 were chosen. For the drought in August 2012 the sources appear to be land based, caused by a trough in the South which blocked moisture from coming in. The sinks were found to be mostly located to the North East of the Mississippi catchment due to the prevalent wind direction at the East coast. For the flash floods of 2016 the sources appear to be located over the Pacific ocean and the North Western part of North America. This caused a lot of moisture to accumulate, as the air above the ocean will be a lot more moist than air generated over land. The fact that only a small amount of moisture was found to precipitate outside of the Mississippi catchment will have only compounded the severity of the flash floods in 2016. Combined with the previous research questions we conclude that it greatly depends on the weather conditions whether moisture is flowing towards the Mississippi catchment from the Gulf of Mexico, the Pacific ocean or hardly at all. Therefore the sources and sinks of moisture need to be determined for each case individually, as was done in this study for August 2012 and August 2016.

With the results generated in this study we were able to a answer all three research questions. It was found that ERA-Interim is a viable option to determine a closing moisture balance, even though it does not include moisture conservation. The resulting precipitation recycling ratios from the WAM2-layer model showed a clear seasonality, and an interannual variation throughout the chosen years. It was also clear that the main driver behind the recycling of moisture in the Mississippi catchment is the circulation of moisture over North America. Different drivers might also be identified when looking more in depth into the global correlations. In this study we also found that the ENSO is correlated with the precipitation recycling ratio in the Mississippi catchment. This correlation would be interesting to look at in more detail. However, there was little impact of this driver visible when comparing the precipitation recycling ratios of the drought of 2012 and the flood of 2016. The driver was visible for the evaporation recycling ratio, which shows that (lack of) moisture from the Pacific Ocean can lead to extreme events. In future research on the precipitation recycling ratio it should be taken into account when determining cases that the precipitation recycling ratio is not related to the amount of precipitation. The Eulerian WAM2-layer which was used in this study can in future research be replaced by a large variety of models, like the Lagrangian FLEXpart model. With the help of the different models, the results of this study can be verified further, while also identifying any issues that did not arise during this study but are inherent to an Eulerian model.

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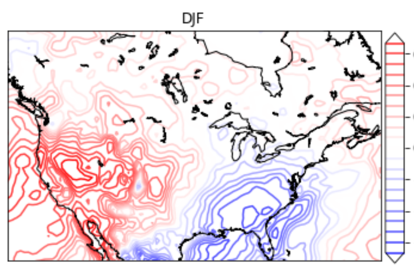
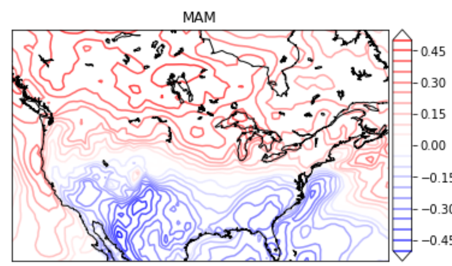
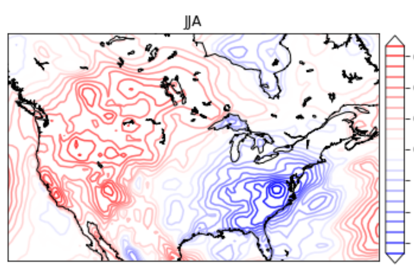
Appendix



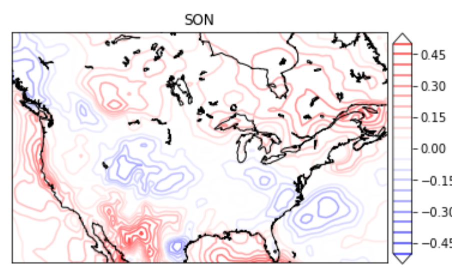
(a) DJF



(b) MAM



(c) JJA

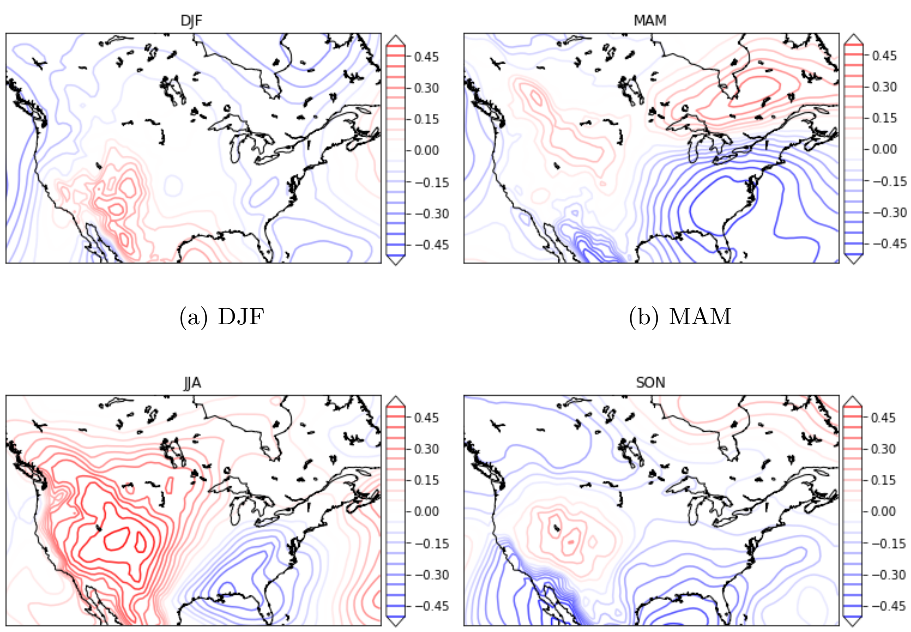


(d) SON

Figure 7.1: The correlations between the regional precipitation recycling ratio [-] and the temperature at 2 meter anomalies. Each figures depicts a different month: (a) DJF, (b) MAM, (c) JJA, and (d) DJF.

Table 7.1: The variables used in the WAM2-layer model, with the units as described in ERA-Interim.

Abbreviation	Variable	units
sp	Surface pressure	Pa
q	Specific humidity	$kg\ kg^{-}1$
tcw	Total column water	$kg\ m^{-}2$
tcwv	Total column water vapor	$kg\ m^{-}2$
u	Zonal wind velocity	$m\ s^{-}1$
v	Meridional wind velocity	$m\ s^{-}1$
ewvf	Vertical integral of eastward water vapor flux	$kg\ m^{-}1\ s^{-}1$
nwvf	Vertical integral of northward water vapor flux	$kg\ m^{-}1\ s^{-}1$
eclwf	Vertical integral of eastward cloud liquid water flux	$kg\ m^{-}1\ s^{-}1$
nclwf	Vertical integral of northward cloud liquid water flux	$kg\ m^{-}1\ s^{-}1$
ecfwf	Vertical integral of eastward cloud frozen water flux	$kg\ m^{-}1\ s^{-}1$
ncfwf	Vertical integral of northward cloud frozen water flux	$kg\ m^{-}1\ s^{-}1$
E	Evaporation	$m\ day^{-}1$
P	Precipitation	$m\ day^{-}1$



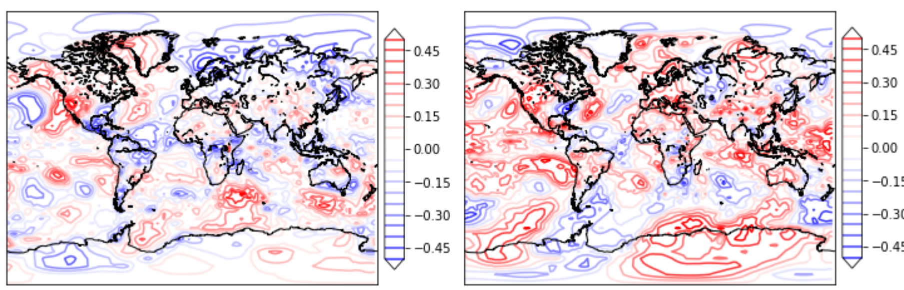
(a) DJF

(b) MAM

(c) JJA

(d) SON

Figure 7.2: The correlations between the regional precipitation recycling ratio [-] and the surface pressure anomalies. Each figures depicts a different month: (a) DJF, (b) MAM, (c) JJA, and (d) DJF.



(a) DJF (b) JJA

Figure 7.3: The global correlations between the regional precipitation recycling ratio [-] and the surface pressure anomalies. Each figures depicts a different month: (a) DJF, (b) DJF.