Moisture Sources for the 2008 Midwest Floods

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1 Abstract

This project was conducted during a summer internship with the Laboratory of the Atmospheres at the NASA Goddard Space Flight Center and made possible by the GEST Center Graduate Student Summer Program (GSSP). The main focus of this project was on water vapor transport and sources of moisture for precipitative events. A case study was made of the floods which affected the Midwestern U.S. in June 2008. The study was conducted using atmospheric gridded data sets from the Goddard Earth Observing System (GEOS-5) produced by the Data Assimilation System (DAS) to assess the sources of moisture for the floods. A synoptic analysis was conducted prior to and during the flooding event to understand atmospheric conditions at those times. Analysis of the 500 hPa geopotential heights and sea level pressure showed an anomalous high over the Atlantic. This forced the atmospheric flow over the Midwest to come from the Gulf of Mexico and tropical Atlantic, in a non-precipitating environment. This pattern persisted for two weeks prior to the start of the floods. An analysis of the vertically integrated moisture divergence, over the flood domain, showed a strong period of negative values in the days preceding the flood. These findings suggest that the floods were only possible because of strong moisture advection into the domain prior to their start. Future work using the water vapor tracing scheme developed by Dirmeyer and Brubaker (1999) is needed to quantify the temporal and spatial scales of moisture transport for the floods.

2 Introduction

2.1 Background

This internship, with the Laboratory of the Atmospheres at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), was initiated with a period of intensive scientific training on: 1) general atmospheric dynamics; 2) synoptic analysis: 3) moisture transport mechanisms; 4) flood dynamics; 5) the use of the Graphical Analysis and Display System (GrADS) to analyze gridded atmospheric data sets. This initial training was necessary to build the foundation for the research project which was focused on water vapor transport; specifically the back-tracing of moisture from sink (precipitation) to source (evaporation).

The global hydrologic cycle (GHC) involves the transport of water throughout the Earth system. The GHC is a closed system and thus a balance must be maintained between the quantity of water that flows into the oceans (either as runoff or laterally moving groundwater) and the quantity that is advected within the atmosphere and converges over land as precipitation. The nature of this balance can be upset by changes in climate, land-use and water-use which can result in a shift in local water resources. In order to better understand this balance it is important to both know where the water is being transported to as well as the location of its source. Specifically, due to the importance of local precipitation, it is critical to understand the sources of moisture for precipitative events (Dirmeyer and Brubaker, 2007.)

The moisture available for a given precipitative event has two potential sources: local evaporation and moisture advection. The importance of local evaporation for precipitation events is often measured using a quantity called the recycling ratio. The recycling ratio is loosely defined as the fraction of moisture falling in a given region that has its most recent source of evapotranspiration within that same region. Regions with high recycling ratios have the potential to maintain moisture inside of the region for longer periods of time due to the reduced impact of moisture advection. Moisture advection is the transport of moisture from one location to another due the wind. In non-precipitating environments it is possible for moisture to be transported across long distances from its initial evaporative source. Thus it is possible to have large quantities of moisture transported into a continental interior from a tropical ocean (Dirmeyer and Brubaker, 2007.)

2.2 Floods

A flood is a hydrologic event that occurs when a body of water, usually a river, overflows its banks and spills into its floodplain. The National Weather Service (NWS) declares a river to be flooding when the river height reaches a level called the flood stage. The flood stage is an artificially determined height at which the water level becomes high enough to cause damage to structures. This level is usually at the height of the floodplain but can be lower if there are docks or other structures closer to the water surface. Floods are caused by an accumulation of water, at a given location, that occurs faster

than the water can be discharged. The floodwave moves downstream with the flow and thus regions remote from the source of the precipitation can experience the flooding as well (Perry, 2000).

Flooding can occur on different spatial and temporal scales. Flash floods typically occur when heavy precipitation falls over a short period of time into an area that is incapable of discharging the water quickly enough. In addition to causing local flooding, the rapidly accumulating water can travel downstream as a wave and strike areas remote from the precipitation event. Due to their small scale nature and rapid onset, flash floods can be very difficult to predict and thus can cause significant damage and loss of life (Perry, 2000.) Large-scale floods are caused by an accumulation of precipitation over a period of time. The size of the flood and the amount of precipitation it takes to cause a flood are highly variable and depend on the size of the watershed as well as the flow velocity of the river. Large rivers collect water from a large drainage area and thus are prone to large scale precipitation events. If a prolonged rainfall event occurs over much of the drainage area this water will be collected and eventually channeled into the river both directly and from its tributaries. The total accumulation of water that the river experiences is a sum of the accumulations experienced over the entire drainage area. The large flow velocity of these rivers prevents them from experiencing a rise in water level initially but as the water accumulates from all over the drainage area the water eventually becomes too much for the river to discharge and the water level rises. If the accumulation of precipitation is sufficient enough

the river will reach flood stage (O'Connor and Costa, 2003).

Large-scale floods can only occur when there is a significant enough amount of moisture in the air to produce prolonged precipitation over a large enough area. In mid-latitude continental interiors it is very difficult to find conditions conducive to produce enough moisture for a large-scale flood from local evapotranspiration, mainly due to an insufficient supply of surface water. As a result, large-scale floods are usually a result of moisture accumulation due to moisture advection.

2.3 2008 Midwest Flood

In June of 2008 a series of major floods occurred in the Midwestern United States. These floods affected the states of Iowa, Illinois, Missouri, Wisconsin, and Indiana. The flooding resulted from a period of prolonged precipitation which occurred between June 3 and 13 (peaking on June 9) over these areas. The amount of precipitation falling over this region during these dates was enough to cause the accumulated precipitation for the month of June to be over 300 mm above normal in many locations (NWS, 2008a). Accumulated precipitation, between June 3 and 13, for a few locations was 199 mm in Waterloo, IA, 220 mm in Bloomington, IN, and 262 mm in Madison, WI (NWS, 2008b). The floods, which affected many of the small to intermediate sized tributaries of the Mississippi River, peaked between June 9 and 15 for the various rivers experiencing flooding. This event produced many record breaking gauge heights and discharge rates in the state of Iowa including

readings of 17.95 ft and 33,600 $ft^3\,s^{-1}$ on the Upper Iowa River at Decorah, IA, 31.10 ft and 150,000 $ft^3\,s^{-1}$ on the Cedar River at Cedar Rapids, IA, and 20.07 ft and 60,100 $ft^3\,s^{-1}$ on the Shell Rock River at Shell Rock, IA (USGS, 2008a). For comparison, flood stage at all three stations is 12 ft (USGS, 2008b). The flood was considered to be a 500 year flood by the USGS which is a statistical measure that states that a flood of this magnitude has only 0.2% probability of occurring in a given year (Horvath, 2008.)

3 Methodology

3.1 Synoptic Discussion: Tools and Data sets

At NASA GSFC a global forecasting model, called the Goddard Earth Observing System (GEOS-5) and a full Data Assimilation System (DAS) are run operationally by the Global Modeling and Assimilation Office (GMAO) and are made available to the NASA Earth Sciences community. GEOS-5 combines the Gridpoint Statistical Interpolation (GSI) analysis algorithm co-developed by the National Centers for Environmental Predictions (NCEP) Environmental Modeling Center (documented by Wu et al. [2002]) with the NASA atmospheric global forecast model [Bosilovich et al., 2006] which shares the same dynamical core [Lin, 2004] with the so-called finite-volume General Circulation Model (fvGCM). The DAS is a state-of-the-art assimilation system that assimilates all conventional and satellite observations with the same exhaustive data sets that are used by major operational centers worldwide.

We have had access to the global gridded datasets produced by the GEOS-5 DAS which are at a $\frac{2}{3}^o$ x $\frac{1}{2}^o$ resolution. The analysis fields used in this study were surface pressure, geopotential height, u and v component winds, and specific humidity.

The major diagnostic tool used in this study is a very sophisticated, state-of-the-art software package called the Graphical Analysis and Display System (GrADS) which is able to perform a wide variety of diagnostics on

gridded atmospheric and environmental data sets. We have used GrADS to try to asses the major atmospheric forcings which preceded and caused the catastrophic series of floods which affected the Midwestern U.S. in June 2008. Particular emphasis was placed on understanding the atmospheric conditions which allowed the advection of large quantities of moisture into the Midwest.

Daily synoptic maps of the following fields were produced using GrADS with the GEOS-5 DAS analysis fields: sea level pressure and 500 hPa geopotential heights (Figures 1 and 2) for the period between 00Z 03 Jun and 00Z 13 Jun 2008, and 850 hPa level winds (streamlines) with specific humidity (values shaded above 0.01 $kg\,kg^{-1}$) (Figure 3) for the period between 00Z 22 May and 00Z 31 May 2008.

3.2 Large Scale Bulk Calculations

To determine the importance of the different moisture sources for the Midwest flood, a few gross moisture calculations were performed following Turato et al. (2004.) The spatial domain under which these gross moisture calculations were conducted was determined analytically by finding the region where the flooding, precipitation and moisture convergence domains, for this event, overlapped. This region, which we named MW, encompassed most of the area which experienced the floods, and extended from 96° to 83° W and 38° to 46° N.

The divergence of the moist wind (moisture weighted wind) is a measure of the amount of moisture that is transported and concentrated into a region,

with the atmospheric flow. This quantity can be used as a gross indicator of moisture advection, with negative values indicating the addition of moisture and positive values indicating moisture loss. The mean divergence of the moist wind at 850 hPa (in ($kg\,m\,s^{-1}$)) for the period between 00z 21 May and 00z 3 Jun 2008 was calculated from the following equation $\frac{\partial(\vec{V}\cdot q)}{\partial x} + \frac{\partial(\vec{V}\cdot q)}{\partial y}$, where $\vec{V}$ is the average wind velocity (in $m\,s^{-1}$) and q is the average specific humidity (in $kg\,kg^{-1}$). This field was superimposed on the 850 hPa mean wind (in streamlines), over the same period, to produce Figure 4.

Vertically integrated divergence of the moist wind, which is the sum of the quantities of moisture concentrated into a vertical column of air, was calculated between the surface and 300 hPa and areally summed over the region, MW. This calculation was made, as a five-day running mean, using the equation $(1/g)\int_{p_0}^{p} \nabla\cdot(\vec{V}\cdot q)dp$ where g is the acceleration due to gravity at the surface ($9.81\,m\,s^{-1}$), p_0 is the surface pressure (in Pa), p is the pressure at the top of the column (in Pa), $\vec{V}$ is the wind velocity (in $m\,s^{-1}$), and q is the specific humidity (in $kg\,kg^{-1}$).

3.3 Water Vapor Tracer

The water vapor back-tracing scheme, which was intended to be used to determine the evaporative sources for the Midwest flood, followed the quasi-isentropic back-trajectory technique developed by Dirmeyer and Brubaker (1999); used by Turato et al. (2004), Reale et al. (2001), and Dirmeyer and Brubaker (2007); and based on the fully implicit algorithm of Merril et al.

(1986.) The back-trajectory calculations are performed by launching a specified number of parcels from each grid cell, where precipitation has occurred, for a given time step. The number of parcels launched is proportional to the local precipitation rate. The vertical level at which the parcels are launched is randomly determined; however the parcels are weighted by the quantity of precipitable water $(p_s/g)\int_\sigma^1 q d\sigma$ (where p_s is the surface pressure, q the specific humidity and σ is the vertical coordinate) in the column to ensure that most parcels will be launched from lower levels. At each time step n the horizontal position of the parcel x^{n-1}, y^{n-1} is calculated by

$$x^{n-1} = x^n + \frac{\tau}{2}[u^n + u^{n-1*}]$$

$$y^{n-1} = y^n + \frac{\tau}{2}[v^n + v^{n-1*}]$$

where τ is the time interval and u and v are the components of the wind. The trajectories are first calculated backward (from x^n,y^n to x^{n-1*}, y^{n-1*} using the wind components u and v at x^n,y^n) and then forward (from x^{n-1*},y^{n-1*} using the wind components u and v at x^{n-1*},y^{n-1*}); these two trajectories are then averaged to get a final trajectory. At each time step, the ratio of the surface evaporation to the quantity of precipitable water in the vertical column is calculated. A fraction of total precipitation, equivalent to this ratio, is added to the grid cell as an evaporative contribution. These contributions are summed over all the time steps until either 90% of the precipitation is accounted for or the parcel has been traced back for longer than 20 days, whichever comes first (full details in Dirmeyer and Brubaker (1999).

4 Results

4.1 Synoptic discussion

An analysis is a gridded representation of the state of the atmosphere at a specific moment in time. A synoptic discussion involves the review of a series of analyses over a specified time interval to understand how the state of the atmosphere changes over time and the progression of atmospheric disturbances. Synoptic discussions are often conducted after major weather events to understand how and why they happened; a synoptic discussion of the 2008 Midwest flood event follows.

The most important synoptic feature is the presence of an anomalous high located in the Atlantic between 00Z 21 May and 00Z 05 Jun (Figures 1-3.) This high blocked the progression of midlatitude systems across the U.S. forcing a series lows which developed over the southern Rocky Mountains, during this period (Figures 1-2), to track to the northeast through the Midwest. Of greater importance is the fact that this high directed the atmospheric flow into the Midwest from the Gulf of Mexico and tropical Atlantic in a non-precipitating (subsiding) environment for such an extended period of time. The high temperature of these bodies of water allowed for very high rates of evaporation (Wallace and Hobbs, 1977). The implication, as is evidenced from Figure 3, is that large quantities of moisture were being transported with the flow. This moisture was then able to be used by the series of weather systems passing across the Midwest to produce the prolonged

and intense precipitation event that occurred.

4.2 Gross Moisture Calculations

The mean divergence of the moist wind over the eastern half of the U.S. between May 21 and June 3, 2008 (Figure 4) was negative for much of the Midwest indicating that there was a prolonged period of moisture accumulation in this area. This figure also shows the time averaged 850 hPa flow over the same time period. It is clear, from this figure, that the flow into the Midwest came from the Gulf of Mexico and the tropical Atlantic for a prolonged period of time prior to the floods. This implies that the source of moisture for the floods was the Gulf of Mexico and tropical Atlantic.

The five-day running mean of the vertically integrated divergence of the moist wind over the region MW between 00Z 10 May and 00Z 19 Jun 2008 (Figure 5) showed an unusual pattern of divergence. Normally, over a large region like MW, the plot would fluctuate around $0\,kg\,day^{-1}$ as convergence in one region is balanced by divergence in another; however, in this instance values depart significantly from $0\,kg\,day^{-1}$ for much of the period. Starting around May 21 the values become negative and stay negative through June 5. This indicates an unusually prolonged and strong period of moisture convergence over this region. This implies that during this period there were significant amounts of moisture being transported, with the wind, and concentrated into this region at all levels (from the surface to 300 hPa).

4.3 Water Vapor Tracer

The water vapor tracer was to be used to quantify the sources of moisture for the flood. The complex algorithm had to be altered from its original state, as a climatological model, to be used for a particular rainfall event. It also had to be adjusted to use the Tropical Rainfall Measuring Mission's (TRMM) 3-hourly 3B42 (TRMM-Adjusted Merged-Infrared Precipitation) precipitation data set and the GEOS-5 DAS two and three dimensional analysis fields. Difficulties arose in these alterations and as a result, in the short duration of this project, we were unable to successfully run the tracer for this event. It is our hope that in the future we will be able run the tracer for this flood event to prove our hypothesis that the sources of moisture for the event were from the Gulf of Mexico and tropical Atlantic.

5 Summary and Conclusion

Over the course of this internship we attempted to discern the sources of moisture for a series of catastrophic floods which affected the Midwestern United States in June 2008. To accomplish this we first analyzed the synoptic situation in the Midwest prior to the start of the flood to better understand the state of the atmosphere at that time. A plot of 850 hPa specific humidity and streamlines between May 22 - 31 showed that an anomalous high located over the Atlantic which forced the flow into the Midwest to come from the Gulf of Mexico and tropical Atlantic. This plot also indicated that there was a significant amount of moisture present over the Midwest during this period. Sea level pressure and 500 hPa geopotential height plots showed a series of low pressure systems forming over the Rocky Mountains and passing over the the Midwest from June 3 - 12. These systems were able to use the moisture present in the Midwest to cause a series of significant rainfall events even though the systems themselves were fairly weak.

Two gross moisture balances were then calculated to determine the significance of moisture advection into the domain area of the study: mean divergence of the moist wind over the period from May 21 - June 3 and the five day running mean of the vertically integrated divergence of the moist wind from May 10 - June 19. The mean divergence of the moist wind was negative, on average, during this period over the Midwest indicating a flux of moisture into the region. The vertically integrated divergence of the moist

wind was negative from May 21 - June 5 indicating a prolonged period of moisture advection into the domain at all levels from the surface to 300 hPa.

These calculations were only able to give a general idea of the importance of moisture advection into the domain during this event. The water vapor tracer would have been able to quantify the sources of moisture for the floods and the period during which the advection took place. This would be an important finding as it would allow us to better understand why the flood was as severe as it was and also confirm our hypothesis that the moisture sources were in the Gulf of Mexico and the tropical Atlantic. We hope to continue this line of research in the future and run the water vapor tracer on this flood at some point to complete this study.

REFERENCES

Bosilovich, M. G., S. D. Schubert, M. Rienecker, R. Todling, M. Suarez, J. Bacmeister, R. Gelaro, G.-K. Kim, I. Stajner, and J. Chen, 2006: NASA's modern era retrospective-analysis for research and applications. *U. S. CLIVAR Variations*, **4,** 5-8.

Dirmeyer, P. A. and K. L. Brubaker, 1999: Contrasting evaporative sources during the drought of 1988 and the flood of 1993. *J. Geophys. Res.*, **104,** 19,383-19,397.

Dirmeyer, P. A. and K. L. Brubaker, 2007: Characterization of the global hydrologic cycle from a back-trajectory analysis of atmospheric water vapor. *J. Hydrometeorol.*, **8,** 20-37.

Horvath, S., 2008: Two 500-year floods within 15 years?. *USGS Core-Cast,* **Ep. 50.** *Available at* `http://www.usgs.gov/corecast/details.asp?ID=81`.

Lin S.-J., 2004: A "vertically Lagrangian" finite-volume dynamical core for global models. *Mon. Weather. Rev.*, bf 132 2293-2307.

Merrill, J. T., R. Bleck, and D. Boudra, 1986: Techniques of Lagrangian trajectory analysis in isentropic coordinates. *Mon. Wea. Rev.*, **114,** 571-581.

National Weather Service (NWS), 2008a: AHPS precipitation analysis *Available at* `http://water.weather.gov`.

National Weather Service (NWS), 2008b: National climate *Available at* `http://www.weather.gov/climate`.

O'Connor, J. E. and J. E. Costa, 2003: Large floods in the United States: where they happen and why. *USGS Circular*, **1245,** 1-19.

Perry, C. A., 2000: Significant floods in the United States during the 20th century - USGS measures a century of floods. *USGS Fact Sheet*, **024-00**.

Reale, O., L. Feudale, and B Turato, 2001: Evaporative moisture sources during a sequence of floods in the Mediterranean region. *Geophys. Res. Lett.*, **28,** 2085-2088.

Turato, B., O. Reale, and F. Siccardi, 2004: Water vapor sources of the October 2000 Piedmont flood. *J. Hydrometeorol.*, **5,** 693-712.

United States Geological Survey (USGS), 2008a: High flow statistics *Available at* `http://ia.water.usgs.gov/flood/table_2.htm`.

United States Geological Survey (USGS), 2008b: USGS surface-water data for the nation *Available at (*`http://waterdata.usgs.gov/nwis/sw`.

Wallace, J. M. and P. V. Hobbs, 1977: *Atmospheric Science: An Introductory Survey*, Academic Press, 93-96.

Wu, W.-S., R. J. Purser, and D. F. Parrish, 2002: Three-dimensional variational analysis with spatially inhomogeneous covariances. *Mon. Weather Rev.*, **130,** 2905-2916.

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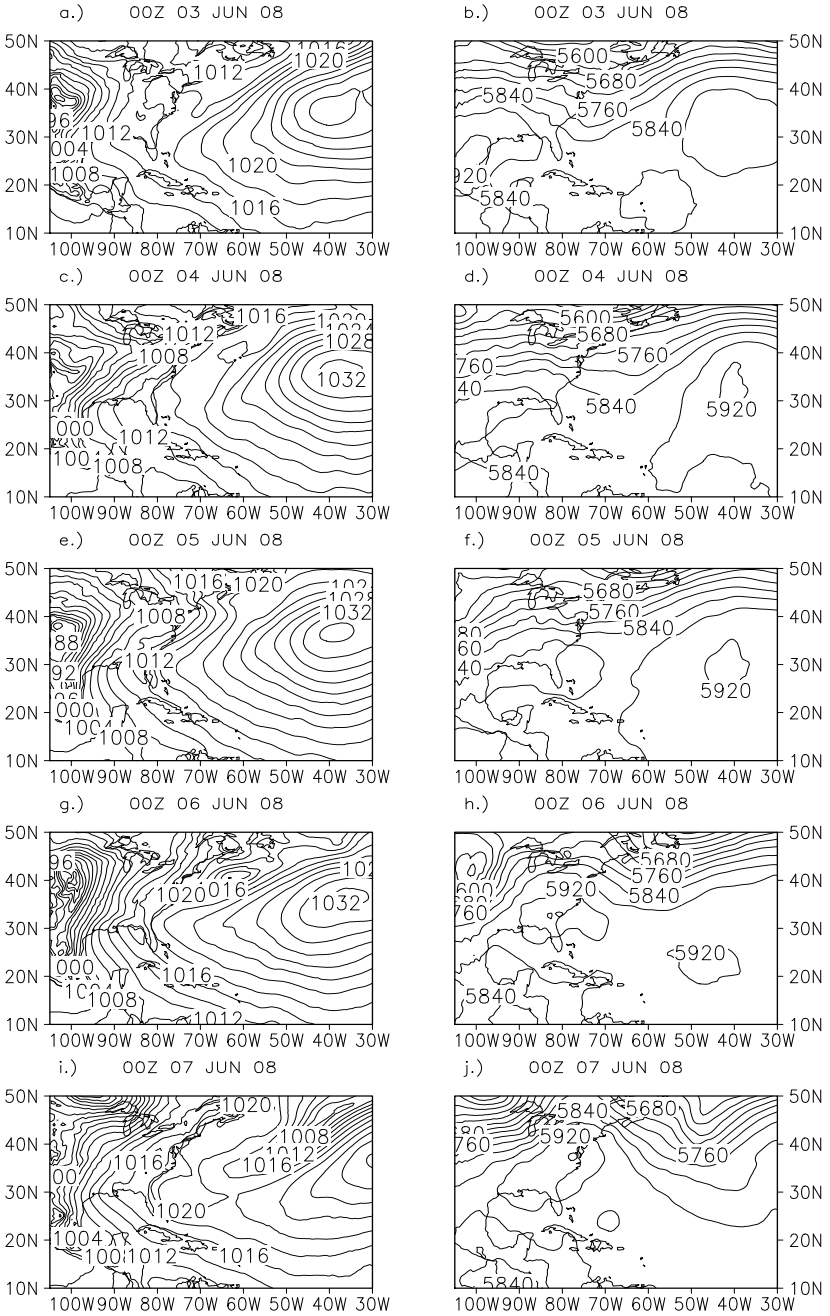


Figure 1: Sea level pressure (hPa) (right) and geopotential height (m) at 500 hPa (left) from 00Z 03 Jun to 00Z 07 Jun 2008 (going down each column)

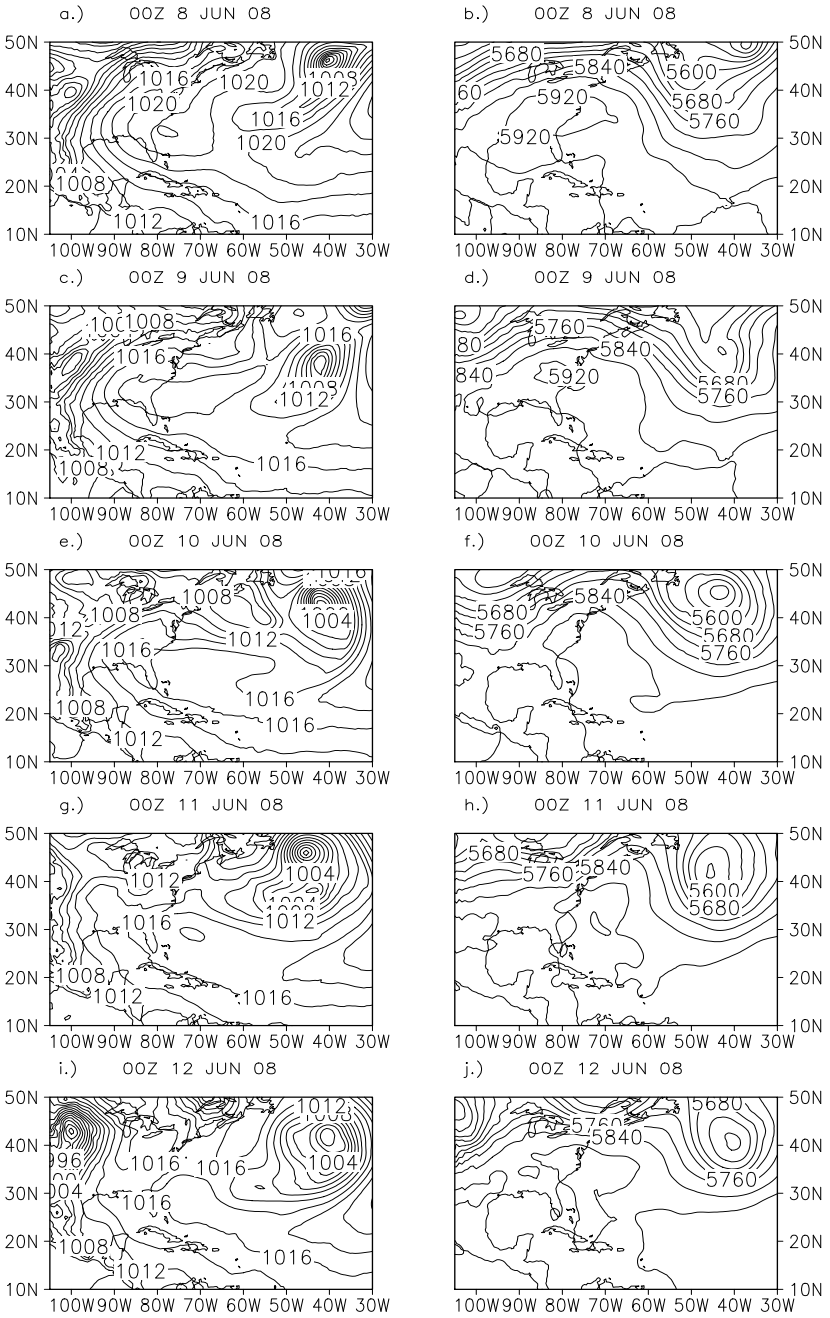


Figure 2: Same as Figure 2 only from 00Z 08 Jun to 00Z 12 Jun 2008

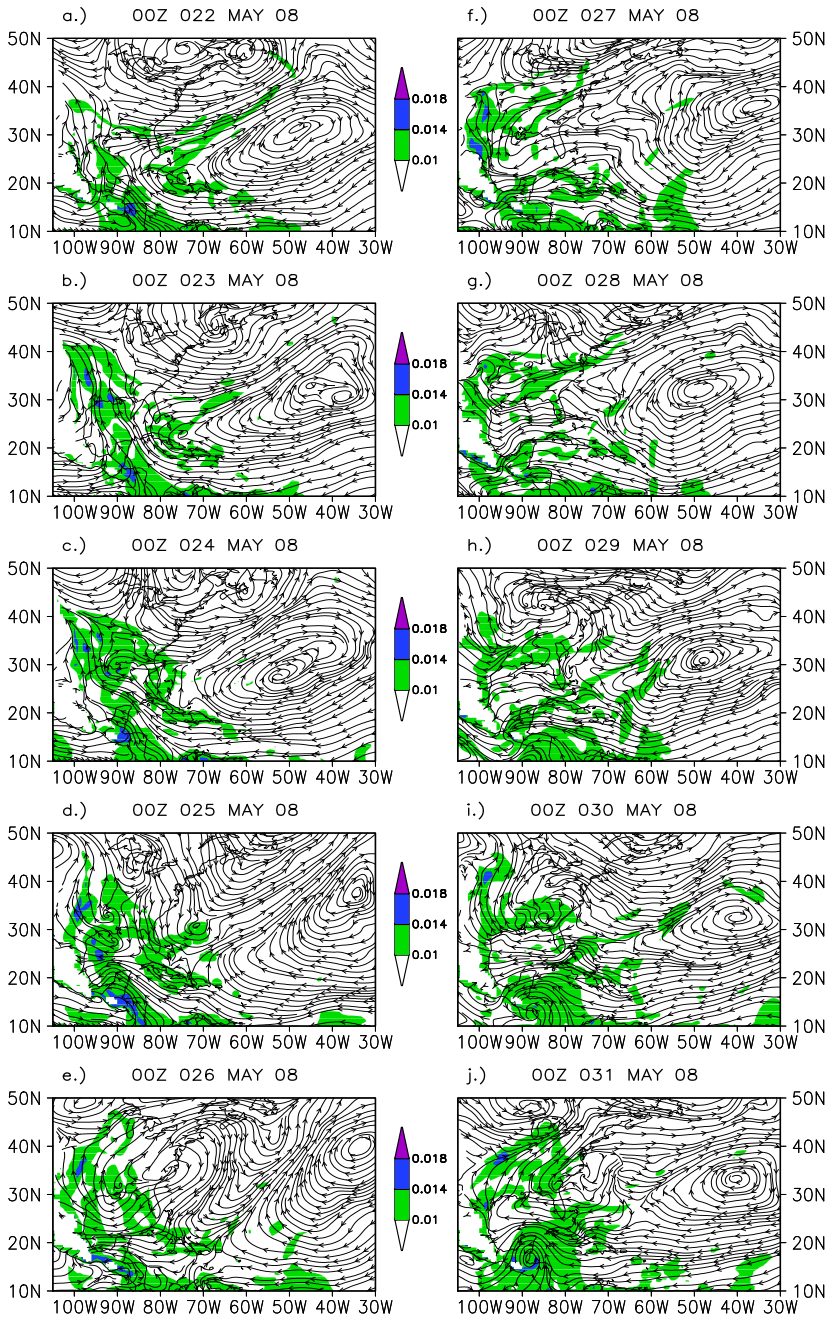


Figure 3: Streamlines and specific humidity ($kg\,kg^{-1}$) at 850 hPa with values greater than 0.01 $kg\,kg^{-1}$ shaded

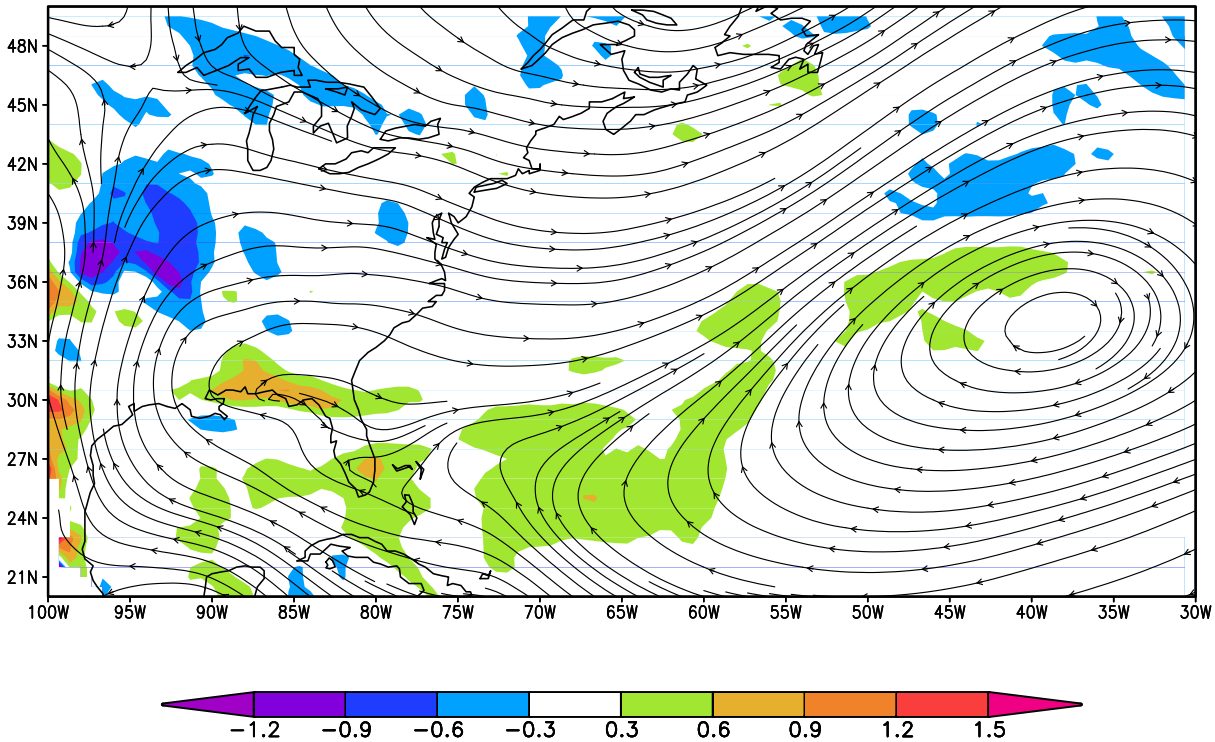
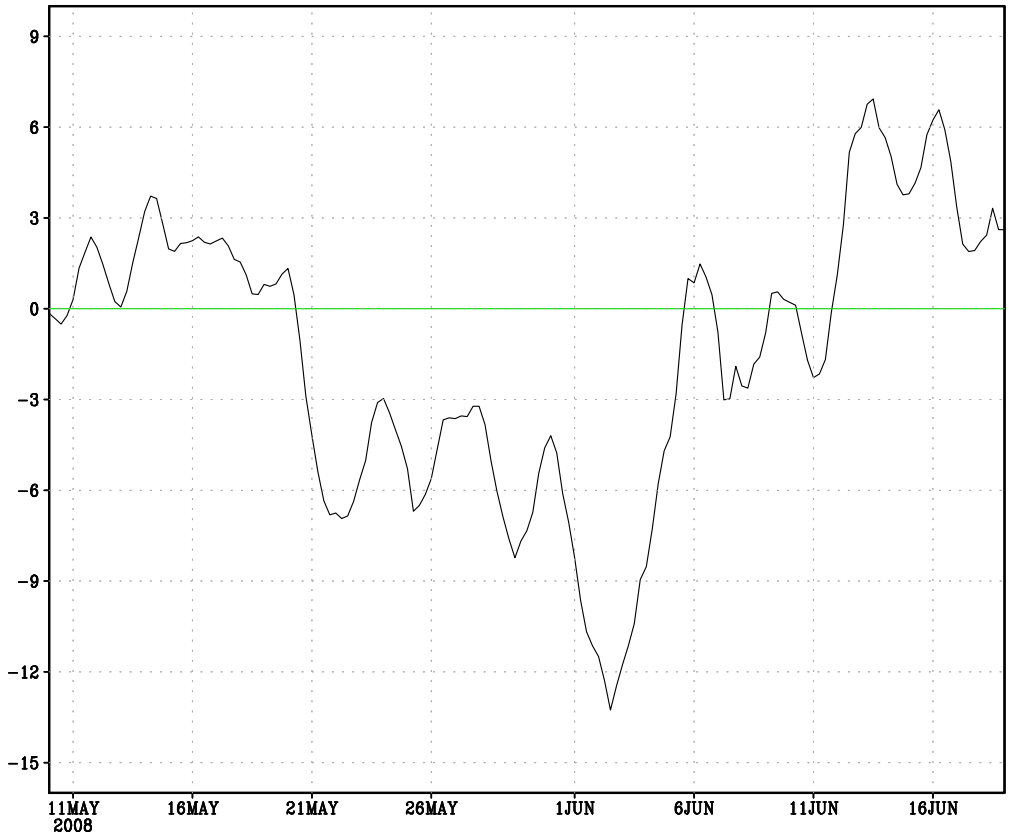


Figure 4: Mean convergence of the moist wind (in ($kg\,m\,s^{-1}$)) and winds (in $m\,s^{-1}$)) at 850 hPa (streamlines) computed as an average between 00z 21 May and 00z 3 Jun 2008 (with values above $0.3\,kg\,m\,s^{-1}$ and below $-0.3\,kg\,m\,s^{-1}$ shaded)



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