Universiteit Utrecht

Relation of meridional circulation of mass and the Northern Annular Mode

Master's Thesis

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March 2018

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Abstract

The Northern Annular Mode is an oscillation with a period of weeks to months in the sea level pressure difference between the subtropics and the arctic in the Northern Hemisphere. The amplitude of the Northern Annular Mode, which is measured in terms of the NAMindex, is related with many atmospheric phenomena and determines the climate and the weather in the middle latitudes. For example it can determine whether a winter is colder or hotter than normal, or whether a summer is drier or wetter than normal. As a result many studies attempt to interpret this NAM index. Some of them try to give an explanation using statistical tools such as the empirical orthogonal function and some other to just show how this index influence some other metereological variables, such as the sea surface temperature. The main goal of our research is to try to answer a difficult question, what is the physical mechanism behind the Northern Annular Mode? What factors are behind this index? A significant variable that will help us to interpret this index is the meridional mass flux in isentropic coordinates and the cross isentropic mass flux. The initial stimulation of this research is that NAM index is related with the meridional isentropic mass flux, which, in turn, may be related to the zonal mean location of cross isentropic mass flux. Our analysis leads us to observe a correlation of the meridional mass flux with the NAM index. The eddy meridional mass flux was found to be responsible for this correlation. Finally we observe that the eddy Potential Vorticity Substance (PVS) flux determines the behavior of the mean meridional mass flux and as a result the relation of the total meridional mass flux with the NAM index.

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Common Abbreviations

- NAM-Northern Annular Mode
- NAO-Northern Atlantic Oscillation
- MMF-meridional mass flux
- PVS-Potential Vorticity Substance
- PVS flux-Potential Vorticity Substance flux
- TMMF-Total Meridional Mass Flux
- CIMF-Cross isentropic mass flux
- PCA-Principal component analysis

[1]

Chapter 1

Introduction

The Northern Annular Mode is an oscillation with a period of weeks to months in the sea level pressure difference between the subtropics and the arctic in the Northern Hemisphere. It owes its existence to atmospheric processes. The amplitude of the Northern Annular Mode, which is measured in terms of the NAM index, is related with many atmospheric phenomena and determines the climate and the weather in the middle latitudes. NAM index is related with the strength of the zonal wind. For example a positive NAM index leads to a strongly westerly winds the midlatitudes. These winds tranfer warm air mass from the ocean to the continents. As a result the temperature above the continents is increased. This is a case that is observed in the Europe during the winter. Generally it determines whether a winter is colder or hotter than normal, or whethera summer is drier or wetter than normal. Consequently there is a lot of research that tries to approach NAM index.

To begin with, a fraction of the aforementioned research focuses on the behavior of the NAM index.The researchers study the temporal variability of NAM index with the use of statistical tools such as the Empirical Orthogonal Function (EOF). They conduct observations and try to figure if there is any correlation between the pressure anomalies at high latitudes and the pressure anomalies of opposite sign in lower latitudes. What is more, the areas that exhibit the above behaviour is also an additional goal of the ongoing research. Furthermore this temporal variability of the NAM index is correlated with large scale weather and climate irregularities in the Northern hemisphere during winter. Moreover, McHugh and Rogers [2001] have proposed that the Northern Annular Oscillation influences eastern African rainfall. Moulin et al [1997] have showed that the Northern Atlntic Oscillation (NAO) counteracts dust transportation from Sahara desert.

Many studies have tried to interpret the NAM index by making use of different variables. One of the most notable is sea surface temperature.It has been noted that the NAM index variablity is related with sea surface temperature (SST). Thus the latter is a justifiable variable in order to try and describe the behaviour of the NAM index.

Moreover, many studies have been developed trying to explain the physical mechanism behind the variability of NAM index. A common characteristic of these studies is the use of the quasi geostrophic theory. This is because the annular mode fluctuation demands the wave momentum transport. As a result the quasi-geostrophic zonal mean of zonal wind equation is suitable for this case. For instance, the distribution of the NAM index from the zonal symmetry reverberate the zonally fluctuating amplitude of the subtropical and eddy-driven jets (David W.J Thompson et al. 2002).

Our hypothesis is that the NAM index is related to the meridional isentropic mass flux,which,in turn,may be related to the zonal mean location of cross isentropic upwelling.This research project is concerned with studying the relation among the distribution of the isentropic meridional mass fluxes,cross isentropic meridional mass fluxes and the NAM index.The winter phase of the NAM index is presumably related to anomalously weak equatorward mass fluxes in the lower troposphere.Where and why these anomalies occur?

Chapter 2

Theory - Data - Methods

2.1 Theory

2.1.1 NAM INDEX

In the Northern hemisphere the mean sea level pressure is generally below the usual values in a latitude ring between 55N and 70N.It is observed that the majority of the mid-latitude cyclones show a peak in iintensity and finish their life-cycles in this so called "annular belt of action".Additionaly a second "annular belt of action", which is indicated by high mean sea level pressures,is located in the area of sub-tropics (20N-40N). This area is characterized by both strong creation and decay of anticyclone activity.The zonal mean sea level pressure is characterised by intense anomalous shifts of mass in one hemisphere,mainly travelling from the one "belt of action" to the other(from high latitudes to low latitides and vice versa). The mean annual path of sea level presure in these two areas in the Northern hemisphere appear to follow three phases.In the first phase (August -December) the atmosphere in the NH it becomes colder while in the SH it becomes warmer.As a result we have a movement of mass from south to north and this process leads to an increase of the mean sea level pressure in the Northern hemisphere. In the second phase (December-April) the increase of sea level pressure at high latitudes continues, while the same variable at lower latitudes decreases. In the final phase (May-August) the sea level pressure decreases in both annular belts of actions. In this study we will mainly focus on the second phase of the aforementioned procedure.

The path of the mean sea level pressure in the two "annualar belt of actions" can be described by irregular fluctuations of the pressure at sea level from the long-term mean seasonal cycle,which are named "anomalies" and they appear mainly in phase 2. From figure 2.1 we can see that the mean sea level pressure "anommalies" in these two areas are anticorrelated. This anticorrelation reveals that the pressure difference is probably the result of the movement of mass between these two "annular belt of actions" and this is the case that we are interested to investigate.

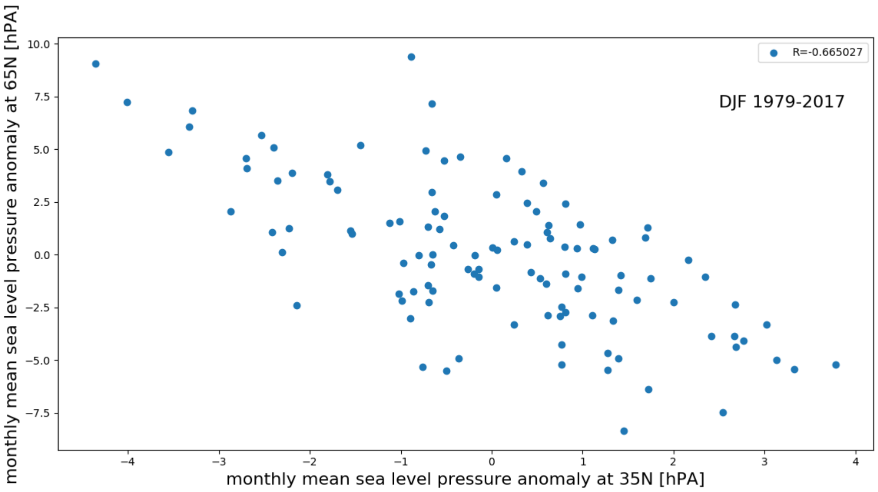


Figure 2.1: Zonal mean and monthly mean sea level pressure anomalies at 35N and 65N in December,January and February for the years 1979-20017,showing the anticorrelation in mean sea level pressure anomalies in the "belt of acion".

CarL Gustav Rossby showed that the highest anticorrelation is observed for 35N and 65N. Li and Wang examined this anticorrelation for different latitude combinations.According to their analysis the zonal mean sea level pressure anomalies in these two centers of action show the highest anticorrelation at 35N and 65N.Furthermore using this result we may define Zonal index as the "normalized difference" of the zonal mean sea level pressure anomaly,between 35N and 65N.In addition irregular deviation in the "Zonal index" represents the already mentioned oscillation called "Northern Annular Mode". NAM sometimes is refered as "Nothern Annular Oscillation" . However the reader should not get confused with the NAO index, which is a specific application of the NAM index to North Atlantic Ocean.The NAM index plays an importan role to the fluctuation of local climate and weather and also influences the general atmospheric circulation.

Northern Atlantic Oscillation

Sometimes the Northern Annular Mode (NAM) is referred as Northern Atlantic Oscillation (NAO) and vice versa. However, the NAO is referred only to the atlantic section. The NAO is also identified as the difference of mean sea level pressure anomalies of two belts of action. These two belts of action are estimated by the empirical orthogonal function (EOF) but are located in different places compared to NAM index, between subtropical (Azores) and subpolar areas. The positive and negative phases of NAO are related to changes of the jet stream and in turn to changes of heat and moisture transport. As a result it affects temperature and precipitation from eastern North America to western and central Europe.

2.1.2 Meridional mass flux

As mentioned before, the march of zonal mean pressure anomalies by shift of mass and this motivated us to look further into mass fluxes. The difference between the pressure anomalies of the two centers of action is defined as the difference between latitudes 35N and 65N. This difference means that in one place there is abundance of mass while in the other place there is lack of mass. As a result, this situation indiacates that there is a mass flux between the two centers. Since the mass movement takes place in a N-S direction we will focus on the meridional mass flux in the Northern Hemisphere (20N-70N).

$$.Massflux = v * \sigma(\frac{Kg}{m^2 * K * s}) \tag{2.1}$$

$$\sigma = -\frac{1}{g} * \frac{\partial P}{\partial \theta}(\frac{Kg}{m^3 * K}) \tag{2.2}$$

The meridional mass flux is estimated by equation 2.1, while equation 2.2 represents the isentropic density. The v component represents the meridional velocity, P is the the pressure while θ is the potential temperature of the air parcel and g is the gravity acceleration. It is important to mention that we seperate the total meridional mass flux in two parts, the mean meridional mass flux and the eddy meridional mass flux,the method that we estimated these values will be explained in the next chapters.Furthermore the eddy mass flux is seperated in two parts the transient and stationary eddy mass fluxes.Actually the behavior of the eddy mass flux (stationary or transient eddy) represents what kind of wave activity is developed.

Eddy Meridional mass flux

Stationary and transient eddies represent the two kinds of eddy activity. Stationary eddies are the eddies that do not vary in time and are found in a specific geographic location.One example are the stationary planetary waves that are generated by large scale mountains, such as the Himalayas and Rocky mountains and by heat difference between land and ocean.On the other hand, transient eddies vary in time and are expressed through the cyclones and anticyclones in the area of the mid latitudes.They play an important role as they transport heat,momentum and moisture in meridional direction.

2.1.3 Storm track areas

Stationary and transient eddies play important role in certain aspects of atmopsheric circulation.One of those is the storm track areas . In the northern hemisphere we observe two main storm track areas,one in the Atlantic and one in the Pacific showing similar behavior. In the storm track areas we have a region of generation of cyclones where they appear to have a strong eddy activity. Consequently they follow one path of collapse close to the main axis of the geopotential height deviation.The cyclones start to decline and propogate mainly towards the eastern side of the ocean where the cyclones reach their minimum intensity. As a result we call "storm track" areas the connection between the depression tracks and intensive eddy variances. The eddy activity is related to the baroclinic instability in this area.The baroclinic instability is characterised by the conversion of Potential energy into Kinetic energy. Moreover the baroclinic instability is revealed by with the existence of transient eddies in the area. The transient eddies are characterized by vorticity flux (Hoskins, 1983) and transfer of mass. For this reason we will try to investigate the behavior of the eddy meridional mass flux in these areas with respect to NAM index.

2.1.4 Cross isentropic mass flux

An air parcel that travels from the midlatitudes to higher latitudes accomplishes a circulation where we a observe an upwelling in the midlatitudes, a meridional transport towards the higher latitudes, a downwelling in the area of the polar cap and a return back to the lower latiude. This indicates that apart from the meridional mass flux, we have to consider the cross isentropic mass flux. The mechanism that drives the cross isentropic mass flux is different from one that drives the meridional mass flux which we are interested in. The radiation in the midlattides and especially the latent heat release contributes to the upwelling in these latitudes.Also clouds in high levels of potential temperature release heat in the atmosphere and as a result influence the direction of cross isentropic mass flux.

2.1.5 Potential Vorticity

The Potential vorticity substance (PVS) or the absolute vorticy is defined as the sum of the relative vorticity (ζ_a) and Coriolis parameter f, for each latitude(equation 2.3). Equation 2.4 represents the adiabatic vorticity equation (the equation 2.4 is valid only if $\frac{d\theta}{dt} = 0$). J represents the vorticity flux vector(4.2), while u and v are the zonal and meridional velocity components respectively. PVS flux does not contain a vertical component since isentropic surfaces are impermeable with regard to PVS.

$$PVS = \zeta_a + f \tag{2.3}$$

$$\frac{\partial \zeta_a}{\partial t} = -(\frac{\partial u * \zeta_a}{\partial x})_\theta - (\frac{\partial v * \zeta_a}{\partial y})_\theta = -\nabla J \tag{2.4}$$

$$J = (u * \zeta_a, v * \zeta_a, 0) \tag{2.5}$$

The equation 2.4 shows the relation of PVS (absolute vorticity) with the PVS flux.Furthermore the evolution of PVS over time is estimated by integration of equation of 2.4. In equation 2.6 we see the result of this integration. Equation 2.7 describes the meridional flux of zonal mean PVS which is one of the variable we are interested into.The equation 2.8 shows the circulation of the air over a closed line.In equation 2.9 the circulation is equal to the vorcity bounded by an area of surface S. As a result an averaged vorticity over a surface,S, equals to the circulation divided by the enclosed surface.Using the equation 2.9 we observe that the zonal mean of PVS determines the zonal mean of the zonal wind at this latitude.If we use equation 2.7 we can see that the meridional PVS flux can act as a zonal force and leads to an acceleration or deacceleration of the zonal wind.The same results we can be observed for a diabatic process.The eddy PVS flux mainly influences the intensity of the zonal mean zonal velocity at a specific latitude.

$$\Delta F = \int_0^t J\, dt. \tag{2.6}$$

$$\Delta F = \int_0^t [v * \zeta_a]\, dt. \tag{2.7}$$

$$\Gamma = \int [\vec{v}]\, d\vec{l}. \tag{2.8}$$

$$\Gamma = \iint \vec{\omega}\, dS. \tag{2.9}$$

2.1.6 Thermal wind

We consider that the atmosphere under examination is nearly under geostrophic and hydrostatic equillibrium. This indicates that we can describe the zonal wind with the eqution 2.10 (u_g is the geostrophic velocity and and ρ is the denisty of the air parcel). The relation 2.11 represents the Exner function, where C_p is the specific heat capacity at constant pressure and P_{ref} is a constant pressure reference. The equation 2.12 represents the hydrostatic equillibrium. We can combine these two equations and conclude in the vertical change of the zonal geostrophic wind.The result is described by equation 2.13. The second term on the right hand of equation 2.13 is much bigger than the first term. This means that the variation of geostrophic wind with the height is proportional to the meridional gradient of potential temperature.As a result we can express the thermal wind with the following relation.

$$u_g = -\frac{1}{f * \rho} * \frac{\partial P}{\partial y} = -\frac{\theta}{f} * \frac{\partial \Pi}{\partial y} \tag{2.10}$$

$$\Pi = C_p * (\frac{P}{P_{ref}})^k \tag{2.11}$$

$$\frac{\partial \Pi}{\partial z} = -\frac{g}{\theta} \tag{2.12}$$

$$\frac{\partial u_g}{\partial z} = \frac{u_g}{\theta} - \frac{g}{f * \theta} * \frac{\partial \theta}{\partial y} \tag{2.13}$$

2.1.7 K-theory

K-theory or eddy viscosity theory is applied mainly in order to describe the turbulence flux of eddies. The equation 2.14 represents the K-theory. K has units of $m^2 * s^{-1}$ and for positive values the equation implies that the vortcity flux flows down the local gradient of vorticity. This approximation is also named small eddy closure technique because it fails for larger eddies. The general concept it can be used also in the large scales. To be more specific the PVS flux slows down the local gradient of vorticity.

Large scales of eddies are related with the mean flow, such as fronts,low and high pressure. This is ususlly called synoptic scale.There is smaller scale that is called “Turbulent scale”. The peak value is caused by production of turbulent kinetic energy by buoyancy production and shear production. These eddies have the time scales of minutes.

$$\overline{v\zeta} = -K\frac{\partial \bar{\zeta}}{\partial y} \tag{2.14}$$

2.2 Data

The data used,were derived from the The European Centre for Medium-Range Weather Forecasts (ECMWF).To be more specific we use the reanalysis data from ERA-INTERIM which is the result of a global climate reanalysis from 1979 until today. First of all for the meridional mass flux, we used temperature at 2 meters from the surface data, meridional velocity at 10 meters from the surface and the Pressure surface data. Moreover we used the Pressure and the meridional velocity in levels of potential temperature(between 265K and 430K).We used the mean sea level Pressure in order to estimate the NAM index.For the cross isentropic mass flux we needed the meridional, zonal velocity and the pressure in levels of potential temperature.As we know PVS is the sum of the relative vorticity and parameter "f",so we used the relative vorticity in levels of potential temperature(between 265K and 430K).The common characteristic of all these analyses is that they are for the months December(1979-2016), January and February (1980-2017),the analyses are for every 6 hours (4 times daily measurements).Also the area that we are interested in is from -180W to 180E and 75N to -15S and the analysis of the grind points is 2.5x2.5 degrees.

2.3 Analysis-Method

As we mentioned above the values that are analyzed are on levels of potential temperature.This is important because our analysis is in isentropic coordinates compared to other studies that they are working mainly in pressure coordiantes.As a result the meridional velocity,the zonal velocity,isentropic density,mass flux,cross isentropic mass flux,and absolute vorticity are in isentropic coordinates except from the mean sea level pressure measurements that we need to estimate the NAM index.Usually we need the zonal mean of our variables so the variables depend only the latitude,time and level or layer of potential temperature.Subsequently it is important to mention the process that we followed in the analysis of our measurements and the different methods that we developed.

2.3.1 Meridional Mass flux

As we mentioned above the meridional mass flux is the zonal mean of monthly mean of the product of the meridional velocity and isentropic density.We observe that the isentropic density depends on the difference of the Pressure between two levels of Potential temperature.This leads us to estimate the meridional mass flux not in levels of Potential temperature but in a layer of Potential temperature.We define the layer as the average of two levels of Potential temperature.Furthermore we know that the lower levels of Potential temperature in the low latitudes intersect into the surface.This boundary condition plays an important role as we have to consider the mass flux zero at this point.

Eddy mass flux

As we have mentioned above the total eddy meridional mass flux is divided in two parts, the stationary and transient eddy meridional mass flux.In equation 2.15 the meridional mass flux is divided in two parts the mean meridional mass flux and the eddy meridional mass flux.The second term represents the stationary eddies and the third term is the transient eddies.The [v],[σ] represent the zonal mean of meridional velocity and of isentropic density.The $\bar{\sigma}$,$\bar{v}$ show the time mean of these two values.σ',v' represent the perturbation from time mean while the $\sigma*$ and v* represent the deviation of these two quantities from the zonal average.As a result we can estimate for each layer of potential temperature and each latitude the two kind of eddies.It is important to mention that we have be careful with the time average.The time ensemble that we use (monthly average) is convenient to distinguish the stationary and transient eddies.For time ensemble less than month,eg:daily average,is difficult to separate the eddy mass flux in two parts.Sometimes we can observe what kind of eddy activity we have only qualitively and not quantatively in this case.

$$[\overline{v\sigma}] = [\bar{v}][\bar{\sigma}] + [\bar{v}*][\bar{\sigma}*] + [\overline{v'\sigma'}] \tag{2.15}$$

CIMF

The cross-isentropic mass flux between isentropic surfaces is determined by evaluating the mass budget of a control volume. The change or tendency, T, over a time interval, Δt, of the mass of air in this control volume is determined by the change of the pressure difference, Δp, between the upper and lower boundary isentropic surfaces.The mass flux in this volume of air depends on firstly to the mass flux perpendicular to a circle of latitude, averaged over a longitude area($F\bar{X}$) secondly to the mass flux perpendicular to a circle averaged a longitude ($F\bar{Y}$). The upwelling cross isentropic mass fluxes,averaged over the area S,at the bottom and at the top of the control volume are respectively, $F\bar{\Theta}_1$, $F\bar{\Theta}_2$.. The mass conservation equation for the volume of air is given by the equation 2.16. The cross-isentropic mass flux at each isentropic level we integrate this upward flux from the earth's surface, where the upwelling mass flux is zero. The lower boundary of the lowest control volume corresponds to the earth's surface (equation 5.3).

$$T = (F\bar{X}_1 - F\bar{X}_2) + (F\bar{Y}_1 - F\bar{Y}_2) + (F\bar{\Theta}_1 - F\bar{\Theta}_2) \tag{2.16}$$

$$F\bar{\Theta}_2 = (F\bar{X}_1 - F\bar{X}_2) + (F\bar{Y}_1 - F\bar{Y}_2) + F\bar{\Theta}_1 - T \tag{2.17}$$

By dividing $F\bar{\Theta}_2$ by S, we obtain the cross-isentropic mass flux at $\theta = \theta_2$ in units of $kg/(s*m^2)$. So we have evaluated the quantity CIMF (equation 2.18).The σ represents the isentropic density as we mentioned above and $\frac{d\theta}{dt}$ is named diabatic heating.

$$CIMF = \sigma * \frac{d\theta}{dt} \tag{2.18}$$

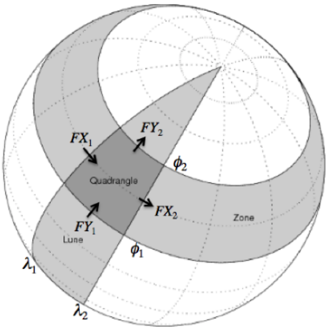


Figure 2.2: A quadrangle between latitudes, ϕ_1 and ϕ_2 and the longitudes, λ_1 and λ_2. The mass budget of a control volume between the quandragles at two adjacent isentropes is evaluated by evaluating the mass fluxes, F_X and F_Y, perpendicular to the edges of the quadrangle.

PVS

The Potential vorticity substance is estimated by the equation 2.3.The parameter f is estimated by the equation 2.19, the ϕ represents the latitude.We see that the parameter f is independent of the longitude and the time.The relative vorticity is in level of potential temperature and we estimate the zonal mean,monthly mean of the relative vorticity.As a result we can estimate for each latitude and for each level of potential temperature the PVS.

$$f = 2 * omega * sin(\phi) \tag{2.19}$$

local gradient of PVS

As it is mentioned above the K-theory includes the estimation of the local gradient of PVS. We used the central differential scheme. The equation 2.20 represents the method that we estimated the local gradient of PVS. The gradient of PVS is estimated for the meridioanl direction of the zonal mean of PVS. Moreover it is important to mention that we estimated the local gradient of PVS only between 87.5S-87.5N. The local gradient of PVS at 90S and 90N is not possible with the process of central differential scheme.

$$\frac{\partial\bar{\zeta}}{\partial y} = \frac{(\overline{\zeta(y+1)} + \overline{\zeta(y-1)})}{2y} \tag{2.20}$$

2.3.2 Method-Statistical tools

This research tries to research the various variables seperately and among them. Subsequently we used some methods-statitistical tools that helped us to investigate the behavior of our variables.

Correlation Coefficient

Correlation coefficient (R) is a statistical tool that help us to estimate the relationship between two variables(equation 2.21).The correlation coefficient has values between -1 and 1. When the coefficient is close to the 1 this means that when the one value increases also the other value increases.On the other hand when the coefficient is close to -1 this mean that when the one value increases the other value decreases.Finally when the coefficient is closed to 0 the two values have no relation.

$$R = \frac{cov(X,Y)}{\sigma_X * \sigma_Y} \tag{2.21}$$

Principal Component Analysis

The correlation coefficient is a useful statistical tool when observing the relationship between two variables.If we want to investigate the correlation among more than two variables the Principal Component Analysis is a more appropriate statistical tool and at the same time is convinient for the analysis of multiple datasets. Principal component analysis (PCA) is a mathematical procedure that transforms a number of (possibly) correlated variables into a (smaller) number of uncorrelated variables called principal components. Furthermore the first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible.

Chapter 3

NAM index-Meridional Mass flux

Our hypothesis,as it is mentioned above, is that the NAM index may be related with the isentropic meridional mass flux and, in turn, with the zonal mean of isentropic meridional mass flux. As a result, the first part of our research aims mainly to examine the relation between the NAM index and meridional mass flux and the mechanism behind this relation.

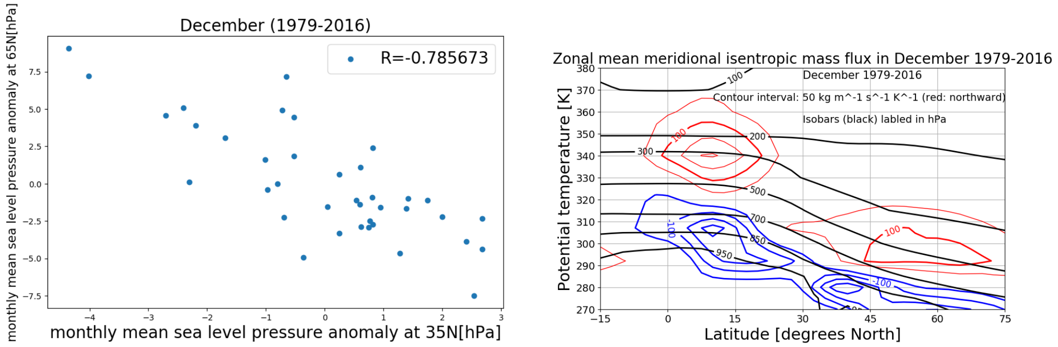
3.1 NAM index-Meridional mass flux

Firstly, this paper is focused on the winter phase of NAM index and particularly the months of December,January and February, when the oscillation of NAM index is intensive. Each month is examined separately.

3.1.1 The Insentive for relating of NAM index and meridional mass flux

As it was mentioned in the previous chapter,the difference of pressure in the two belts of action indicates that there is a mass flux from one center of action to the other center (and vice-versa).The figures 3.1a, 3.2a and 3.3a indicate the highest anticorrelation values between the two belts of action, December(R=-0.78) ,January(R=-0.65) and February(R=-0.52). For the months of December and January, the anticorrelation is high but for the month of February is low.The high anticorrelation value between the two centers is the first indication that there should be a shift of mass from the low latitudes to the higher latitudes and vice versa. Furthermore, figures 3.1b, 3.2b, 3.3b display the behavior of the meridional mass flux for different layers of Potential temperature and different latitudes. All 3 months share common meridional mass flux behavioral patterns.

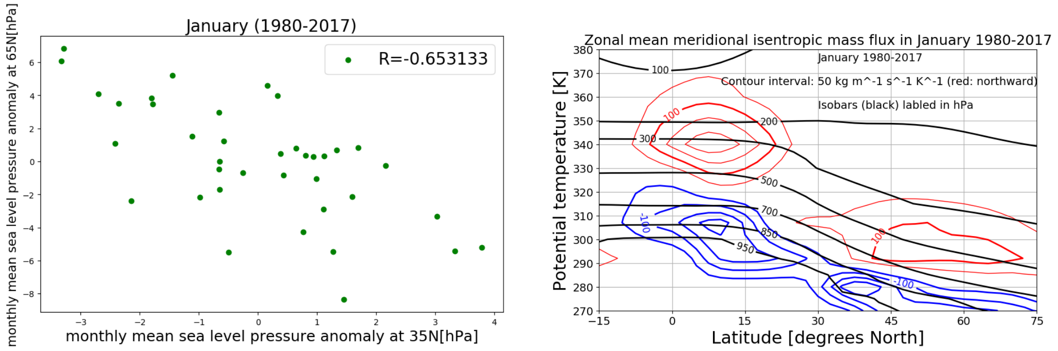
To be more specific, we observe two branches of mass flux in the middle latitudes and in the lower latitudes (Hadley cell), one poleward and one equatorward. We are interested in the two branches of mass flux in the middle latitudes. The center of the poleward meridional mass flux originates between 30N and 60N approximately and it is found between 292K and 322K, while the equatorward mass flux is located in the lower layers of potential temperetature (270K and 292K) but in the same region approximately. Also, the 292K consists of a boundary of the poleward and equatorward mass flux. These two branches of mass flux are the second indication that the meridional mass flux in this region (30N -60N) has to be correlated with the NAM index. As a result, our first hypothesis/goal is to investigate the correlation between the NAM index and the meridional mass flux.



(a) Zonal mean monthly mean sea level pressure anomalies at 35N and 65N in December for the years 1979-2016,showing the negative correlation in mslp anomalies in the two belts of action ($R = -0.78$).

(b) Zonal mean, time mean meridional mass flux for December, illustrating the mass flux in different latitudes and different layers of Potential temperature. The red line represents the northward mass flux, while the blue line represents the equatorward mass flux.

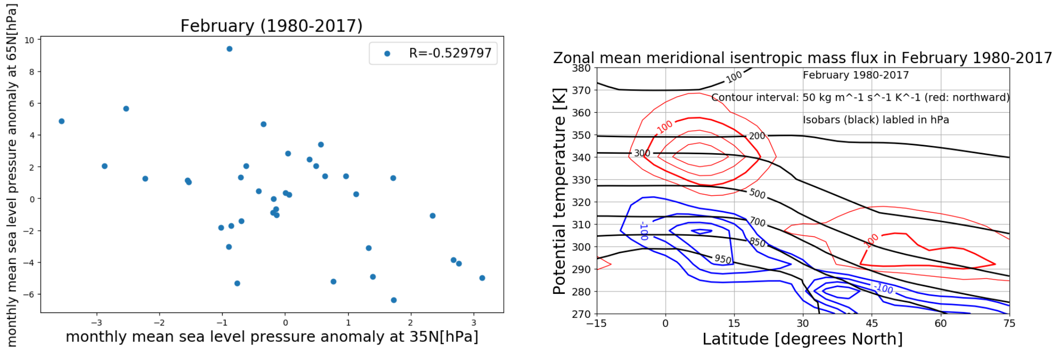
Figure 3.1: mslp anomalies and meridional mass flux for December.



(a) Zonal mean monthly mean sea level pressure anomalies at 35N and 65N in January for the years 1980-2017,showing the negative correlation in mslp anomalies in the two belts of action ($R = -0.52$).

(b) Zonal mean,time mean meridional mass flux for January,illustrating the mass flux in different latitudes and different layers of Potential temperature. The red line represents the northward mass flux, while the blue line represents the equatorward mass flux.

Figure 3.2: mslp anomalies and meridional mass flux for January.



(a) Zonal mean monthly mean sea level pressure anomalies at 35N and 65N in February for the years 1980-2017,showing the negative correlation in mslp anomalies in the two belts of action.

(b) Zonal mean,time mean meridional mass flux for January, illustrating the mass flux in different latitudes and different layers of Potential temperature.

Figure 3.3: mslp anomalies and meridional mass flux for February.

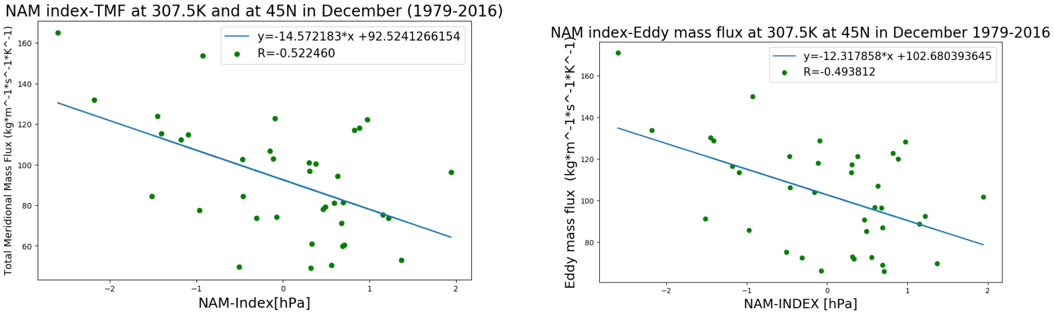
3.1.2 The Relation of NAM index to total and eddy meridional mass flux

The goal of this paper is to examine the relation between the NAM index and the meridional mass flux and also, to investigate whether the eddy meridional mass flux is the main contributor of the total meridional mass flux. The same examination pattern is used , as above, as each month is analyzed separately.

December-January-February

In figure 3.4a and in figure 3.4b we observe the relation between total and eddy meridional mass flux and NAM index for the month of December. Both these quantities show low correlation with the NAM index, $R = -0.52$ and $R = -0.49$ respectively. As a result, it is not possible to extract a specific result from this analysis for the month of December. For month of February, the results do not provide us with noteworthy information as the correlation of the NAM index and total meridional mass flux is quite good (R=-0.61) and the relation of NAM index and eddy meridional mass flux is very low(only R=-0.33). Finally, the month we choose, because of its higher anticorrelation compared to the other two months, and enables us to put together notable conclusions is the month of January. We can observe that the total meridional mass flux and NAM index have a correlation almost -0.8 while the eddy mass flux shows a correlation with the NAM index of -0.73. This means that when the meridional mass flux increases, the NAM index decreases and vice versa. Furhermore, we observe that the eddy mass flux shows strong correlation with the NAM index. This indicates that eddy meridional mass flux is the main mechanism that drives the meridional mass flux. Also it is worth mentioning that all three months show the highest correlation of total meridional mass flux and NAM index in a layer of potential temperature 307.5K but in different regions, 45N for the month of December, 50N for the month of January and 55N for the month of February.

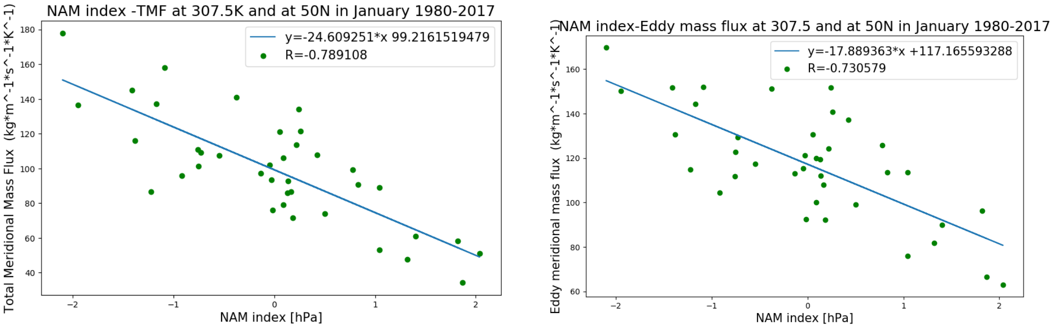
The as above mentioned layer (layer of potential temperature $307.5K$) that had the highest correlation amongst the different variables, exhibits a poleward mass flux. A positive NAM index is correlated with a weak poleward meridional mass flux whereas a negative NAM index is related to strong NAM index .Moreover, it is observed that,for the month of January, the latitude which has the highest anticorrelation is 50N. This area is in the middle of the two belts of action and this indicates that it is the center of the meridional mass flux or of the NAM index. Finally due to the positive nature of the results in the month of January, in relation to the goals of this study, we will focus mainly on said month.



(**a**) Correlation NAM index and zonal mean,time mean of total meridional mass flux at 45N and at 307.5K for December 1979-2016 ($R = -0.52$).

(**b**) Correlation NAM index and zonal mean,time mean of eddy meridional mass fluxat 45N and at 307.5K for Decemeber 1979-2016 ($R = -0.49$).

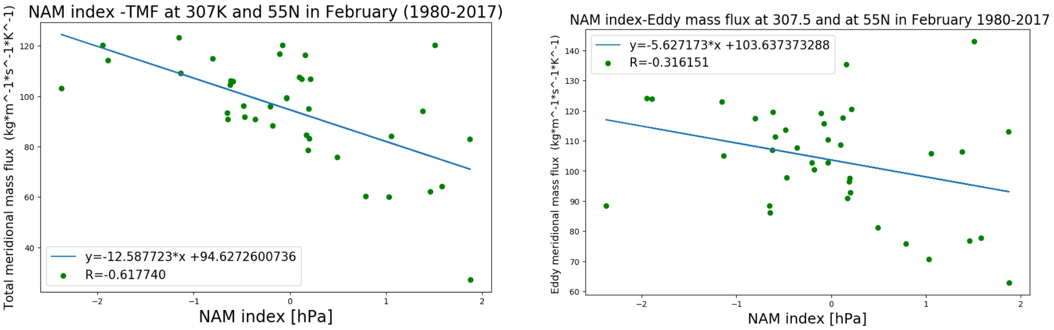
Figure 3.4: NAM index and total and eddy meridional mass flux for December 1979-2016.



(**a**) Correlation NAM index and zonal mean,time mean of total meridional mass flux at 50N and at 307.5K for January 1980-2017 (R=-0.78).

(**b**) Correlation NAM index and zonal mean,time mean of eddy meridional mass fluxat 50N and at 307.5K for January 1980-2017 (R=-0.73).

Figure 3.5: NAM index and total and eddy meridional mass flux for January 1980-2017.



(**a**) Correlation NAM index and zonal mean,time mean of total meridional mass flux at 45N and at 307.5K for February 1980-2017 (R=-0.61).

(**b**) Correlation NAM index and zonal mean,time mean of eddy meridional mass fluxat 45N and at 307.5K for Decemeber 1979-2016 (R=-0.31).

Figure 3.6: NAM index and total and eddy meridional mass flux for February 1980-2017.

3.1.3 Storm track areas

In our first assumption, the aim was to investigate the relation of NAM index and total meridional mass flux and especially in relation to the eddy meridional mass flux. So our next step, was to explore the reasons why the eddy meridional mass flux was the main mechanism in mass flux and as a result of the NAM index. The initial assumption that was made, was that the storm track areas were the main mechanism of the eddy mass fluxes. Consequently, we had to further examine the behavior of the total meridional mass flux and eddy meridional mass flux with the NAM index in the area of Atlantic and Pacific ocean.

As was observed, the latitudes that have the highest anticorrelation for the two belts of action in the Atlantic and the Pacific Ocean is different from the NAM index. Firstly, we attempted to reproduce a figure for the NAM index in order to verify the correlation of the two belts of action for the month of January. In figure 3.7, we observe that the correlation amongst different latitudes is displayed for the zonal mean montly mean sea level pressure anomaly.The extracted results that form this figure are significant. It is important to note that the highest value of the anticorrelation amongst the latitudes is R=-0.78 and is located between 25N and 62.5N.These results differ from the analysis of Li and Wang. The analysis of Li and Wang concentrates on the annual monthly mean sea level pressure, whereas our analysis focuses only on the monthly mean sea level pressure of the month of January. As a result, we have reached different conclusions.

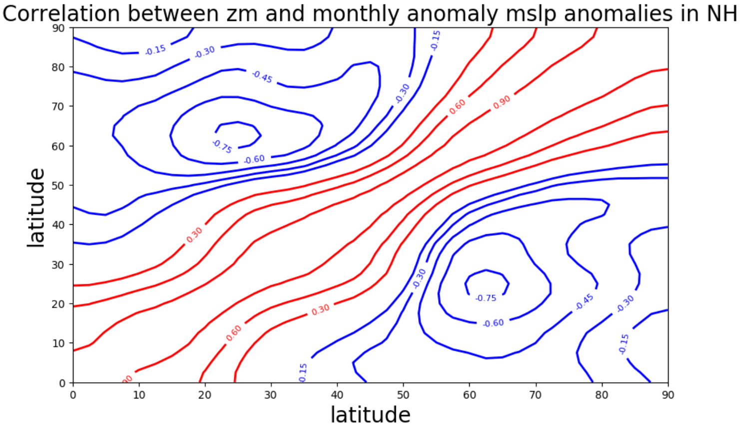
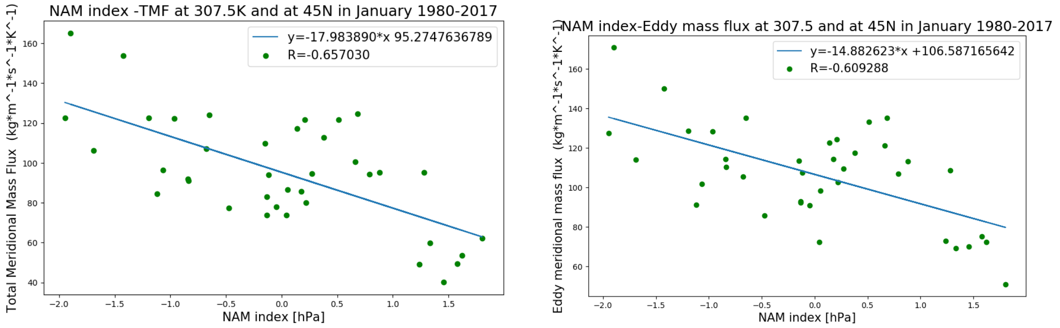


Figure 3.7: Correlation between zonal-mean and monthly mean sea level pressure anomalies in the Northern Hemisphere for January (1980-2017).The contour interval is 0.3 for positive values and 0.15 for negative values.

The results of the initial analysis that was undertaken in the course of this paper, rendered a supplementary analysis of the total and eddy meridional mass flux with the NAM index before continuing with the second assumption. Such an analysis was informed by the same process as described above. Its is observed that the results differ from figure 3.5. In figure 3.8, we notice that the correlation of total and eddy meridional mass flux with the NAM index is decreased, R=-0.65 and R=-0.61 respectively. The layer with the highest anticorrelation remains the 307.5K but in this case, the latitude appears to shift, 45N. The change of the center of the meridional mass flux compared to NAM index is reasonable, as the latitudes of the NAM index appear to have shifted. One possible explanation behind the fact that the correlation amongst the values has declined is that in the lower boundary of the NAM index there is a circulation due to the Hadley circulation which probably influences the mass flux in the region that we are interested in. The area that is of interest to this study is not isolated and as a result, it may interact with other areas such as the Hadley cell in the lower boundary of the NAM index.



(a) Correlation NAM index and zonal mean,time mean of total meridional mass flux at 45N and at 307.5K for January 1980-2017 ($R = -0.65$).

(b) Correlation NAM index and zonal mean,time mean of eddy meridional mass fluxat 45N and at 307.5K for January 1980-2017 ($R = -0.61$).

Figure 3.8: NAM index and total and eddy meridional mass flux for January 1980-2017.

Furthermore, we can proceed with our assumption that the storm track areas is the main mechanism of the eddy activity .As it was mentioned above, it is necessary to estimate the latitudes of the highest correlation of the mean sea level pressure anomalies for the Atlantic and Pacific ocean.

Atlantic Ocean

This study defines the area of the Atlantic ocean to be between 60W-10W. In figure 3.9, we observe that the highest anticorrelation is R=-0.81 and it is found between the latitudes 62.5N and 27.5N. In figure 3.10a, one notices that the total meridional mass flux at the layer of the potential temperature, that this study is interested in, and at the centre between the two belts of action the correlation coefficient is very weak (R=-013).The same is true for the transient eddies (R=-0.18). We can then conclude, that the NAM index does not present any correlation with the total and transient eddy meridional mass in the area of the Atlantic ocean.

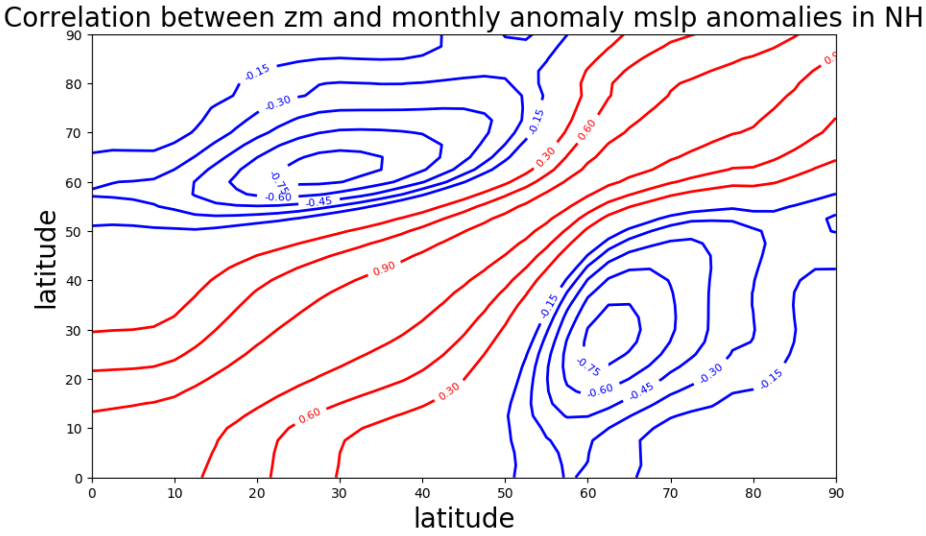
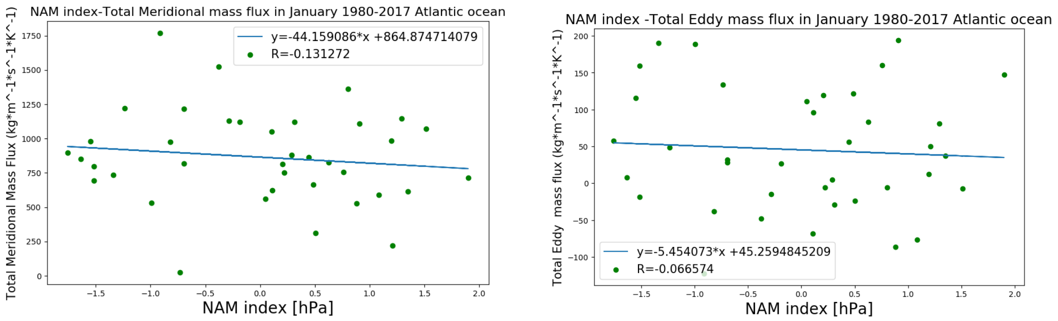
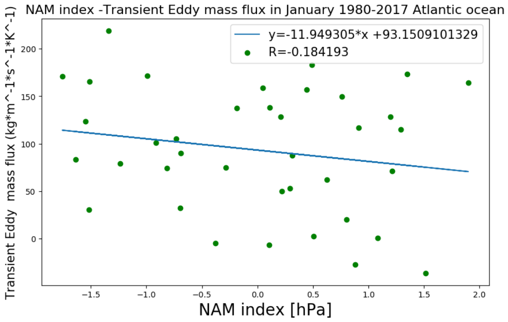


Figure 3.9: Correlation between zonal-mean and monthly mean sea level pressure anomalies in the Northern Hemisphere for Atlantic Ocean [60W-10W] for January (1980-2017).The contour interval is 0.3 for positive values and 0.15 for negative values.



(a) Correlation NAM index and zonal mean,time mean of total meridional mass flux at 45N and at 307.5K for Atlantic Ocean for January 1980-2017 ($R = -0.13$).

(b) Correlation NAM index and zonal mean,time mean of total eddy meridional mass fluxat 45N and at 307.5K for Atlantic Ocean for January 1980-2017 ($R = -0.06$).



(c) Correlation NAM index and zonal mean,time mean of transient eddy meridional mass fluxat 45N and at 307.5K for Atlantic Ocean for January 1980-2017 ($R = -0.18$).

Figure 3.10: NAM index and total,total eddy and transient meridional mass flux for Atlantic Ocean for January 1980-2017

Pacific Ocean

The same process as the one used in the analysis of the Atlantic ocean is, then, applied to the area of the Pacific Ocean (125W-150E). The highest correlation is observed for 67.5N and 22.5N and i R=-0.41. It is noticeable that the correlation in the Pacific ocean is weak (only -0.41). Figures 3.12a and 3.12c display the correlation of the NAM index in the Pacific ocean with the total and transient eddy meridional mass flux. It is observed that at 37.5 degrees North and at 307.5K, the correlation of NAM index with the total meridional mass flux is a little higher (R=-0.52) compared to the Atlantic ocean. On the other hand, the transient eddy shows insignificant relation to NAM index (only R=0.006)

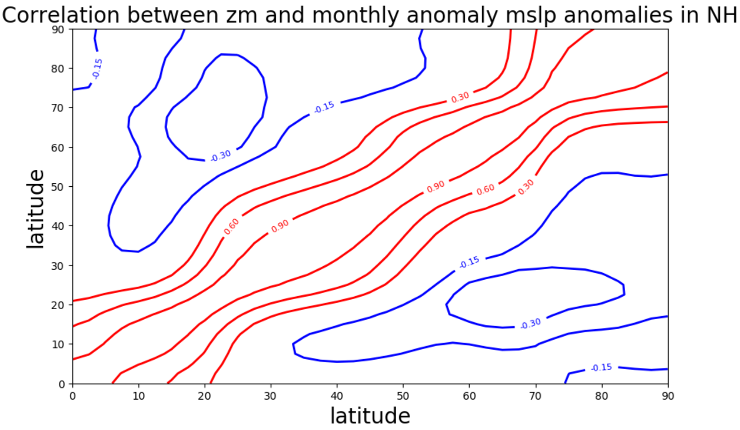
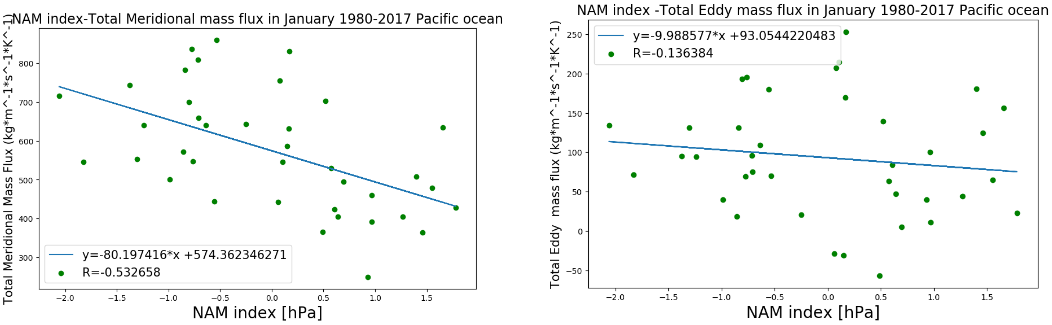
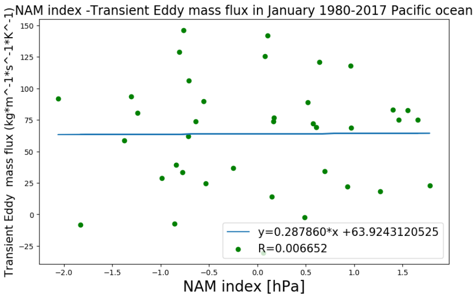


Figure 3.11: Correlation between zonal-mean and monthly mean sea level pressure anomalies in the Northern Hemisphere for Pacific Ocean[125W-150E] for January (1980-2017).The contour interval is 0.3 for positive values and 0.15 for negative values.



(a) Correlation NAM index and zonal mean,time mean of total meridional mass flux at 37.5N and at 307.5K for Pacific Ocean for January 1980-2017 ($R = -53$).

(b) Correlation NAM index and zonal mean,time mean of total eddy meridional mass fluxat 37.5N and at 307.5K for Pacific Ocean for January 1980-2017 ($R = -0.13$).



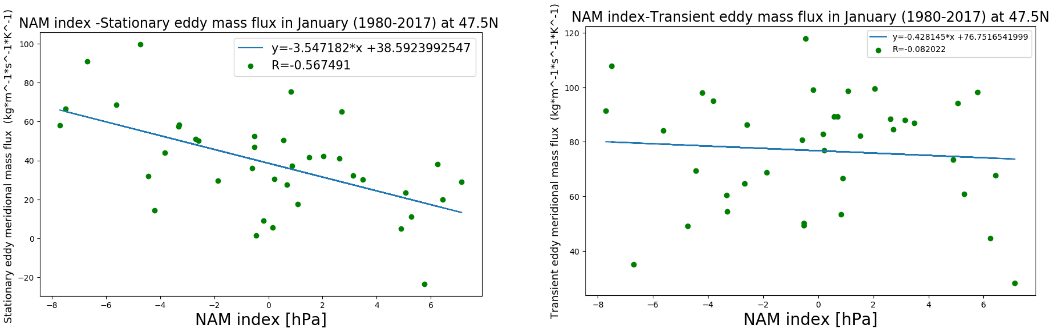
(c) Correlation NAM index and zonal mean,time mean of transient eddy meridional mass fluxat 37.5N and at 307.5K for Pacific Ocean for January 1980-2017 ($R = -0.006$).

Figure 3.12: NAM index and total,total eddy and transient meridional mass flux for Pacific Ocean for January 1980-2017.

Our assumption that the storm track areas, as areas of generation of transient eddies, are the mechanism behind the force of eddy meridional mass flux and consequently drive the total meridional mass flux, was not proven correct. The only result worth noting from this assumption is that the NAM index coincides with the NAM index in Atlantic whereas the NAM index in the Pacific Ocean is weak. This result is reasonable since during the winter the NAM in Atlantic Ocean (Northern Atlantic Oscillation) is strong (R=-0.81) and the NAO index is used instead of the NAM index.

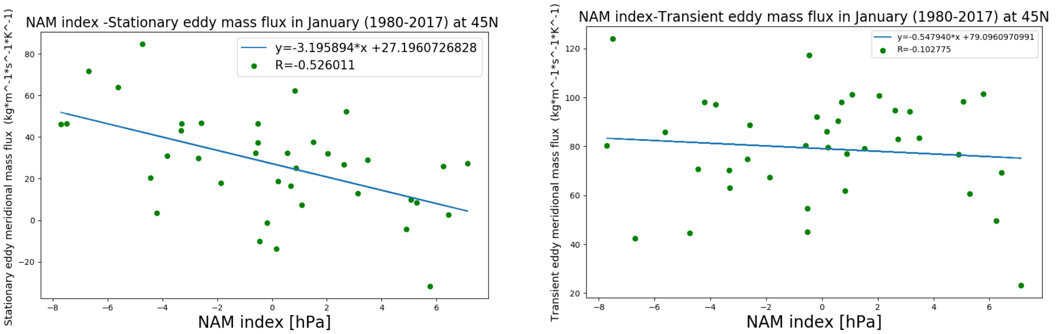
3.1.4 Eddy activity

The results of this study exhibit that the storm track areas, as areas of generation of transient eddies, are not responsible for the behavior of eddy meridional mass flux related to the NAM index. Thus, our main question, which is which mechanisms influence the eddies remains unanswered. It is considered until now that the transient eddies in storm track areas dominate and drive the mass flux. However, it is crucial to mention that the eddies are divided in two parts, the transient and stationary eddies. As such, it is imperative to observe whether the transient or stationery eddies are prevalent when compared to the NAM index. We correlated the NAM index with the stationary and transient eddies. As it is seen in figure 3.13a and figure 3.13b, the stationary eddies dominate compared to the transient eddies at 42.5N. When it comes to the latitude that we are interested in (45N), the correlation of NAM index and the stationary mass flux is weaker (R=-0.52). We should mention that the total eddy meridional mass flux has a correlation with the NAM index R=-0.61. From this type of analysis, we can conclude that the stationary eddies show bigger correlation with NAM index compared to transient eddies and the NAM index. The correlation of stationary eddy mass flux and NAM index is low and this conclusion does not enables us to fully understand what kind of eddy activity is actually prevalent. Consequently, the research is focused mainly on the extreme years of NAM index, namely the years of low and high NAM index.



(a) Correlation NAM index and zonal mean, time mean of stationary meridional mass flux at 47.5N and at 307.5K for January 1980-2017 ($R = -0.56$).

(b) Correlation NAM index and zonal mean, time mean of transient eddy meridional mass fluxat 47.5N and at 307.5K for January 1980-2017 ($R = -0.08$).



(c) Correlation NAM index and zonal mean, time mean of stationary eddy meridional mass fluxat 45N and at 307.5K for January 1980-2017 ($R = -0.52$).

(d) Correlation NAM index and zonal mean, time mean of transient eddy meridional mass fluxat 45N and at 307.5K for January 1980-2017 ($R = -0.10$).

Figure 3.13: NAM index and stationary and transient eddy meridional mass flux for January 1980-2017 for 2 different latitudes.

High and Low NAM Index

Figure 3.14 showcases that the years 1989, 1990, 1992, 1993, 2002, 2007 are extreme years of high NAM index while the years 1980, 1996, 1998, 2004, 2010, 2011 are extreme years of low NAM index. These years of high and low NAM index generate interest due to their yearly distribution and also because they are accompanied by extreme values of the total meridional mass flux. The years of high NAM index are correlated with weak values of total meridional mass flux, whereas the years of low NAM index are related with strong total meridional mass flux.The eddy meridional mass fluxes play an important role to the contribution of total meridional mass flux.

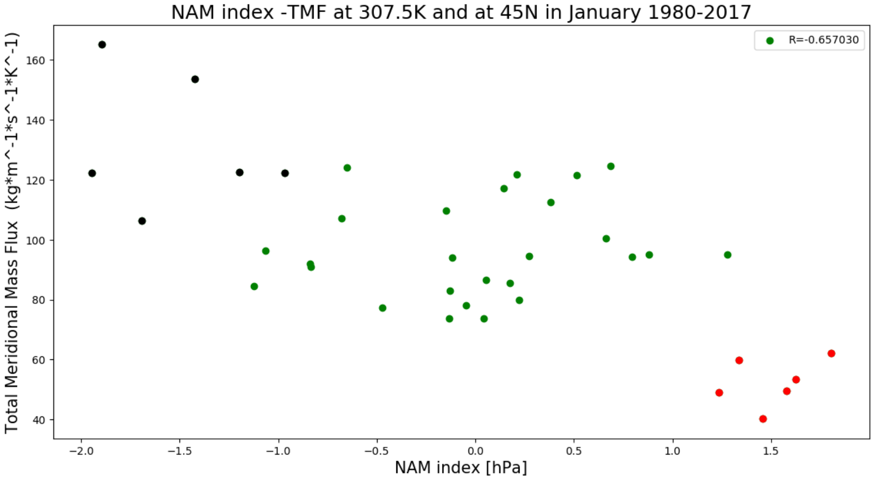
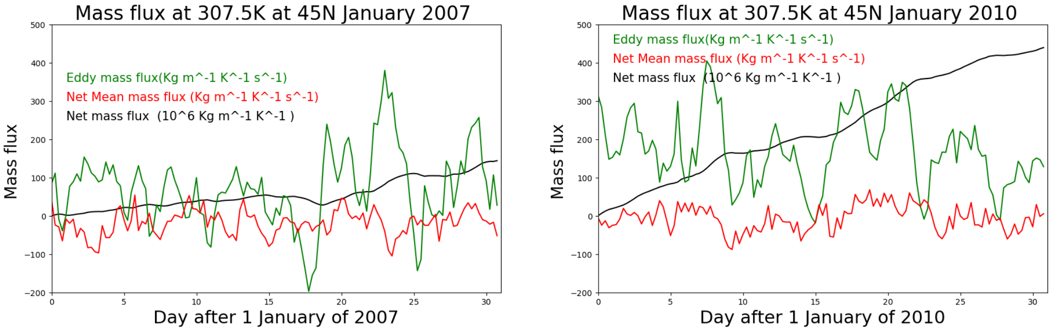


Figure 3.14: Correlation of NAM index and total meridional mass flux at 45N and 307.5N,indicating the years of low and high NAM index

Furthermore, the net meridional mass flux for two representative years of low and high NAM index (2010 and 2007 respectively) is displayed in figure 3.15. In 2010 the net meridional mass flux reaches aproximately $500 * 10^6 Kg * K^{-1} * s^{-1}$ whereas in 2007 it hardly reaches one fifth of the afforementioned 2010 numbers. In the same plots, one observes that in both years the eddy meridional mass flux is poleward but in 2010 is stronger when compared to 2007. In year 2010 the eddy meridional mass fluctuates between $200 Kg * m^{-1} * K^{-1} * s^{-1}$ and higher values, whereas in 2007 the eddy meridional mass flux deviates between 100 and lower values. Subsequently, These results turn our attention towards these extreme years of low and high NAM index.

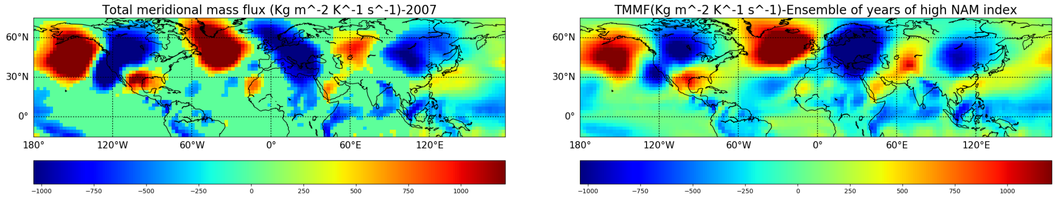


(a) Evolution of net,mean and eddy meridioanal mass flux for January of 2007 at 307.5K and 45N. The black line represents the net mass flux, while the green and red line represent the eddy and mean meridional mass flux, respectively.

(b) Evolution of net,mean and eddy meridional mass flux for January of 2010 at 45N and at 307.5K. The black line represents the net mass flux, while the green and red line represent the eddy and mean meridional mass flux, respectively.

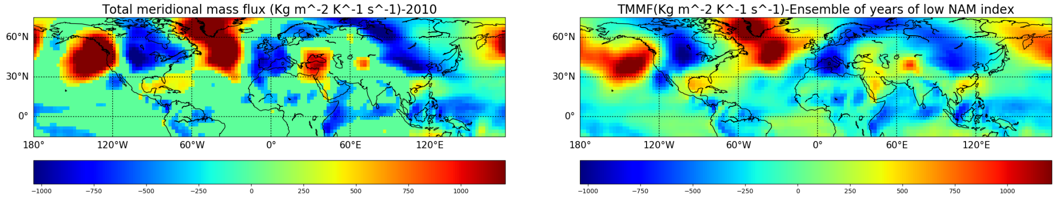
Figure 3.15: Net, mean and eddy meridional mass flux for January of 2007 and 2010.

As a result, this study concentrates on researching the behavior of the eddies only in those years . So we make a plot of the total meridional mass flux in the global map for the region and the layer ofpotential temperature that we are interested in.



(a) Total meridioanal mass flux for January of 2007 at 307.5K

(b) Total meridional mass flux of time ensemble of years of high NAM index at 307.5K



(c) Total meridional mass flux for January of 2010 at 307.5K

(d) Total meridional mass flux of time ensemble of years of low NAM index at 307.5K

Figure 3.16: Net, mean and eddy meridional mass flux for January of 2007 and 2010.

High NAM index

Figures 3.16a and 3.16d display the total meridional mass flux plotted in global map for the year of 2007 and for the time ensemble of the years of high NAM index. A common characteristic between those two figures is that the two main ridges exist in the west part of the oceans, namely North Atlantic (mainly closer to the west coastline of Europe) and the Pacific Ocean. These two peaks are usually followed by two troughs above North America and Europe (mainly in the borders of Europw and Asia). Also, it is clear, mainly for the year 2007, that the total meridional mass flux exhibits ridges and troughs from the poles to the equator with decreasing magnitude(from the east North Atlantic until the east part of Asia). Finally, from all the above it can be deducted that a stationary eddy mass flux with 3 modes exists.

Low NAM index

When it comes to the years of low NAM index the case is different. Figures 3.16b and 3.16d represent the total meridional mass flux for the year 2010 and time ensemble for the years of low NAM index as they portray different patterns than the years of high NAM index. To be more specific, ridges are nearer to the east side of the Atlantic ocean and troughs are closer to the east side of Europe. In addition to that, a trough of small magnitude exists in the east side of the Mediterranean Sea. The total meridional mass flux is constrained in specific bounds of latitude (mainly between 30 and 60 degrees of latitude). Finally, in years of low NAM index it is noticed that stationary eddies with two modes occur.

Chapter 4

Potential Vorticity Substance Flux

In the previous chapter, the behavior of the eddy meridional mass flux is identified. However, the generation mechanism of the eddy meridional mass flux has to be examined more. In that way, we can understand which physical phenomena influence the intensity of the total meridional mass flux and finally determine the sign of the NAM index.

4.1 Atmospheric balance

The Figure 4.1 represents the relation of zonal mean of zonal wind ,for different latitudes, with the zonal mean of geostrophic zonal wind at 307.5K, for the month of January 2007. The correlation coefficient is almost 1 and the slope of the linear fit is almost 1 and as a result the zonal mean of zonal geostrophic velocity equals approximately with the zonal mean of zonal velocity. This means that the atmosphere is nearly under geostrophic and hydrostatic balance.This statement is significant because the atmosphere tries every moment to remain in balance.

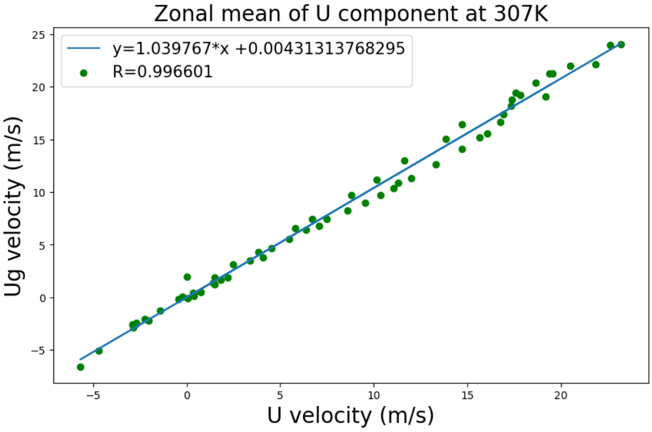


Figure 4.1: Relation of zonal mean of zonal wind and zonal mean of geostrophic zonal wind at 307.5K for month of January 2007.

In order to examine if the value of the zonal wind changes during the time,the zonal mean of zonal wind, the integrated PVS flux, the eddy and mean PVS flux, during the month of January 2007, at 307.5K and at 45N are illustrated in figure 4.2. First of all, it is observed that the zonal wind does not remain constant but it fluctuates during this period. Secondly, the integrated PVS flux is almost parallel to the zonal wind at this layer of potential temperature and this latitude and they have a correlation of $R = 0.97$. The correlation coefficient departs from 1, because we estimated the PVS flux taking into account only the adiabatic and not the diabatic terms. Thus, the integrated PVS flux determines the behavior of the zonal wind at this latitude and the PVS flux can be expressed as zonal force of the zonal wind.

Furthermore, it is noticed that the eddy PVS flux follows approximately the same pattern as the zonal wind. This implies that the eddies accelerate or decelerate the zonal mean zonal wind at this latitude,driving the atmosphere out of the zonal mean of thermal wind balance.

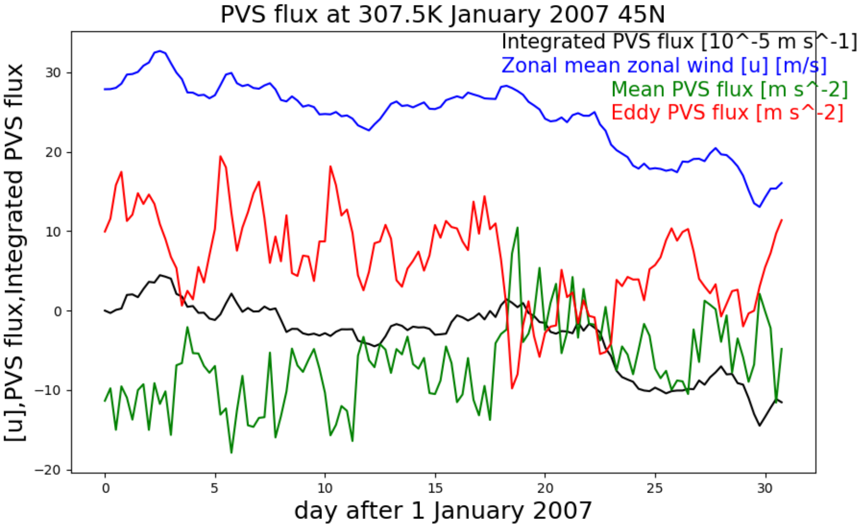
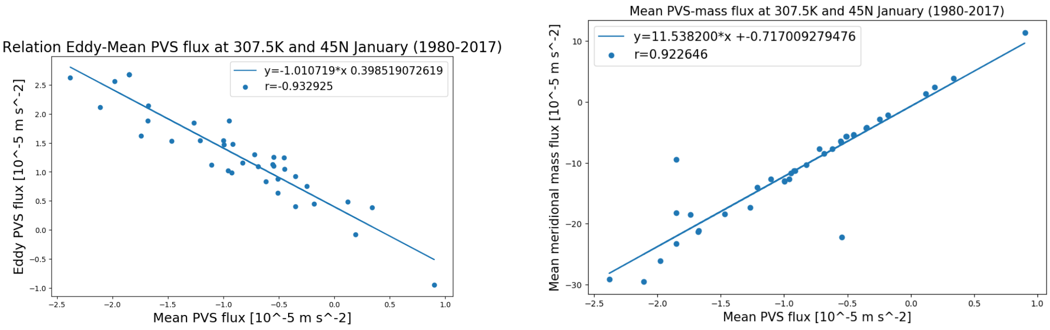


Figure 4.2: Evolution of the zonal mean of zonal wind, Integrated PVS flux, the eddy and mean meridional PVS flux at 307.5K and at 45N during the January 2007

4.2 Eddy PVS flux-Mean meridional mass flux

In the previous section, it is explained how the eddy meridional PVS flux drives the atmosphere out of zonal mean of thermal wind balance. On the other hand, the atmosphere "tries" to remain close to thermal wind balance. Consequently, it responds to the eddy PVS flux with a zonal meridional circulation (Ferrel circulation), which counteracts the action of the eddies. The meridional circulation is interpreted by the development of mean meridional PVS flux. The aforementioned behavior can be observed in figure 4.3a. It is noticed that the anticorrelation between eddy and mean meridional PVS flux is strong ($R = -0.92$) and this indicates that the mean PVS flux tries to counteract the activity of the eddy PVS flux. Moreover, the figure 4.3b displays the relation of mean PVS with the mean mass flux at 307.5K and at 45N. In this case the correlation is also strong ($R = 0.92$). The zonal mean meridional circulation also transports mass along the isentropes and toward the equator. Consequently, the mean PVS flux and mean meridional mass flux, as features of the zonal mean meridional circulation, show strong correlation.



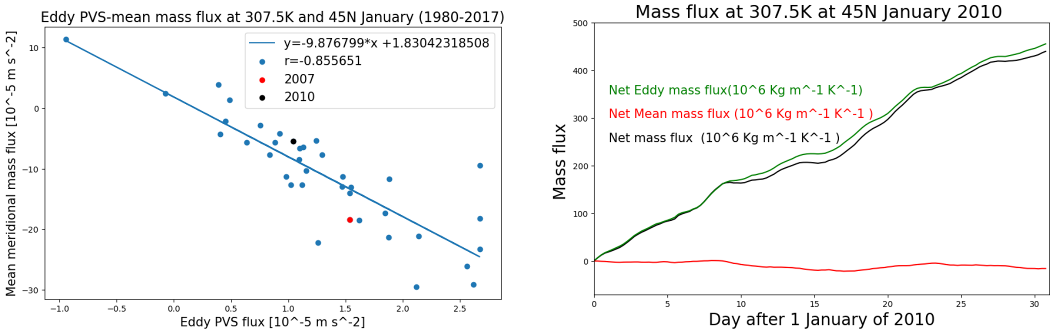
(a) Relation of zonal mean, time mean of eddy and mean meridional PVS flux, at 307.5 K and at 45N for month of January 1980-2017($R = -0.92$).

(b) Realation of zonal mean, time mean of mean meridional PVS and mass flux, at 307.5K and at 45N for month of January 1980-2017 ($R = 0.92$).

Figure 4.3: Relation of eddy PVS flux with mean PVS flux and in turn with the mean mass flux, at 307.5K and at 45N for January 1980-2017

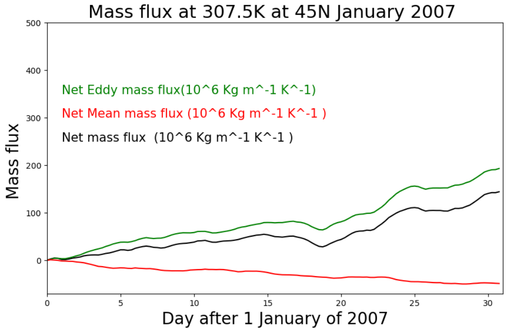
In addition, a reasonable consequence of all these processes is that the eddy meridional PVS flux drives the mean meridional mass flux. Figure 4.4a, confirms this statement and displays the anticorrelation of eddy PVS flux and mean mass flux. Moreover, it is observed that the eddy meridional flux of PVS and as a result the isentropic flux of mass due to the zonal mean meridional circulation, are weak in months, which are characterized by a negative NAM-index (e.g :2010).

Moreover, another significant result can be extracted by figure 4.4. The equatorward isentropic flux of mass due to the zonal mean meridional circulation, usually counteracts the poleward meridional eddy isentropic flux of mass. In the case of negative NAM index, the mean meridional mass flux is weak while the eddy meridional mass flux is strong. This leads the net total, isentropic, meridional, poleward mass flux to be more intense during negative NAM-index months (figure 4.4b) than during positive NAM-index months (figure 4.4c).



(a) Relation of zonal mean, time mean of eddy PVS and mean mass flux, at 307.5 K and at 45N for Jnauary 1980-2017 ($R = -0.85$).

(b) Net total, eddy mean mass flux ($10^6 Kg * m^{-1} * K^{-1}$), at 307.5K and 45N for month ofJanuary 2010.



(c) Net total, eddy mean mass flux ($10^6 Kg * m^{-1} * K^{-1}$), at 307.5K and 45N for month of January 2007.

Figure 4.4: Relation of eddy PVS flux and mean mass flux. Net mass flux for months of low and high NAM index. The black line represents the net of total mass flux, while the green and red line represent the net eddy and mean mass flux, respectively.

4.3 Mechanism of evolution of eddy PVS flux

It is proved that the eddy PVS flux determines the magnitude of the mean meridonal mass flux and as a result the magnitude of the total meridional mass flux. A reasonable question that comes up is what mechanism is behind the development and the magnitude of eddy PVS flux. K-theory was used in order to explain the behavior of eddy PVS flux, but mainly for small size eddies. However, in our case, we study large size eddies. Thus, K-theory might not be completely valid, but we expect the general concept to be. That is, the PVS flux flows down the local gradient of the PVS.

In figure 4.5 is represented the relation of eddy PVS flux and zonal mean of meridional gradient of PVS ($R = 0.64$), for 45N-55N. The positive correlation coefficient is an unexpected result as we would expect an anticorrelation between these variables. This means that the PVS flux increases the local gradient of PVS. This behavior should be due to a rare physical phenomenon that is called negative viscosity phenomena. According to this theory, the eddy activity drives the circulation which is confirmed in the circulation that we examined.

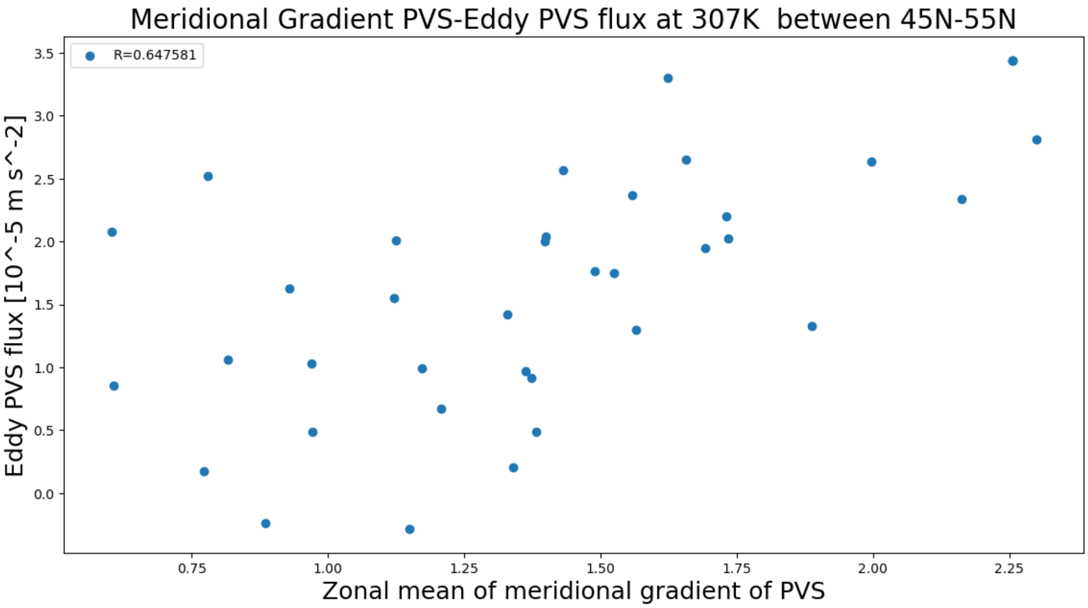


Figure 4.5: Relation of eddy PVS flux and zonal mean of meridional gradient of PVS, at 307.5 at 45N-55N.

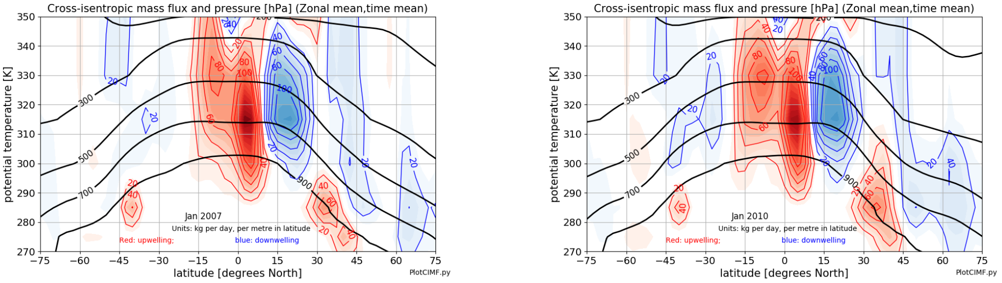
Chapter 5

Cross Isentropic mass flux

In introduction it is mentioned that we are interested in investigating the relation between the NAM index and the distribution of meridional mass flux and in turn the cross isentropic mass flux.

5.1 Distribution of CIMF

Figure 5.3 represents the zonal mean, time mean of the cross isentropic mass flux over different latitudes and different levels of potential temperature, for a representative year of high NAM index and low NAM index respectively. In the area that is under interest (between 30 and 70 degrees North) the CIMF indicates two branches. The first branch of CIMF is upwelling and is extended between 30N and 45N approximately, while the second one is downwelling and is extended between 45N and 70N approximately. Moreover, the CIMF shows some differences between these two years. In 2010, the upwelling and downwelling branch of CIMF covers bigger area than in 2007, especially in the level 285K and 300K of potential temperature. Also, the amplitude OF CIMF in 2010 is stronger compared to 2007.



(a) Zonal mean, time mean of cross isentropic mass flux over different latitudes and different levels of potential temperature for January of 2007

(b) Zonal mean, time mean of cross isentropic mass flux over different latitudes and different levels of potential temperature for January of 2010

Figure 5.1: Distribution of zonal mean,time mean of cross isentropic mass flux for January of 2007 and 2010

Furthermore, it is important to research the behavior of the distribution of cross isentropic mass flux, specificaly in the level of potential temperature at 300K. Figure 5.2 enable us to understand the disribution of CIMF, and also the mechanisms that lead to upwelling and downwelling mass flux. It is observed that the distribution of CIMF over the world is complicated. Two main results can be extracted from this figure. Firstly, above the ocean (eg: Pacific and Atlantic ocean) there is upwelling mass flux, while above the continents (eg: North America, Europe) there is downwelling mass flux. This behavior is due to the different heat capacity of the oceans and continents. The heat capacity of the oceans is larger than that of the continents. The surface temperature at ocean is higher than the continent surface temperature. The temperature of the air over ocean increases, while the temperature of the air above the continents decreases. As a result, the mass flux above the oceans becomes warmer and propagates upward, whereas the mass flux above the continents becomes colder and propagates downward. In addition, in the area of the Rocky mountains (North America) and the mountains of Scadinavia, there are two distinct branches of cross isentropic mass fluxes. One upwelling mass flux above the oceans and one downwelling mass flux above the continents. The mechanism behind this process, is the upslope mass flux on the west side of the mountains lead to cloud formation, trying to overpass the mountains, and it releases latent heat to the atmosphere. Subsequently it becomes colder and heavier and starts to propagate downward above the continents.

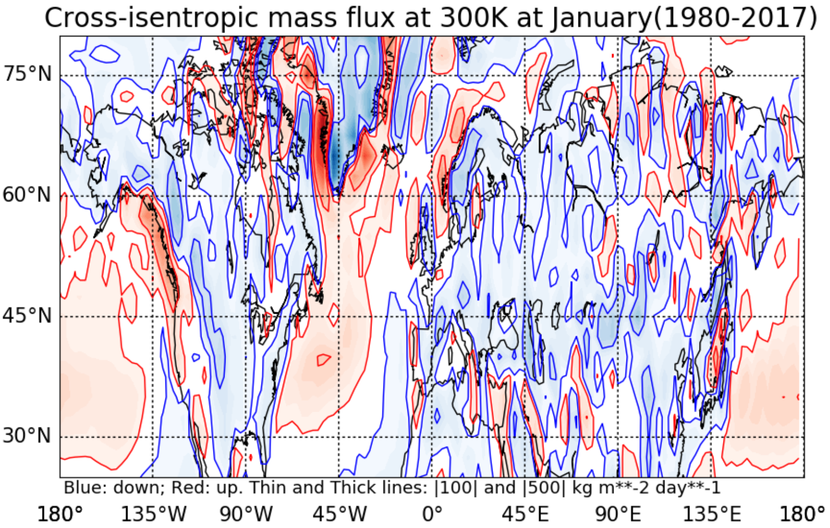
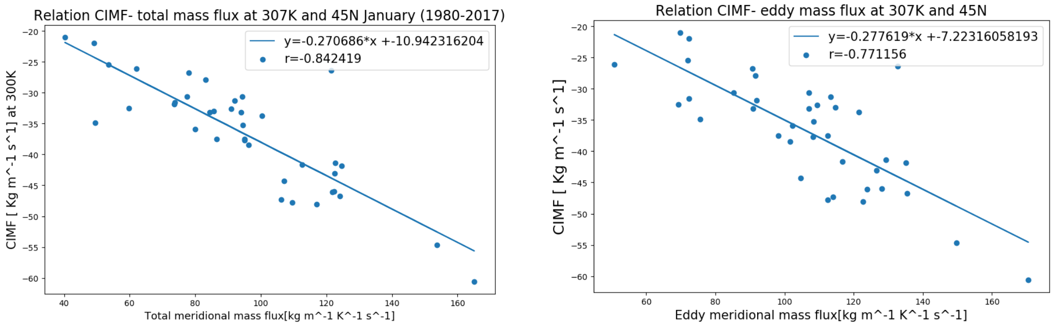


Figure 5.2: Distribution of the time mean of cross isentropic mass flux over a map at 300K for January (1980-2017).

5.2 Relation of CIMF with NAM index and meridional mass flux

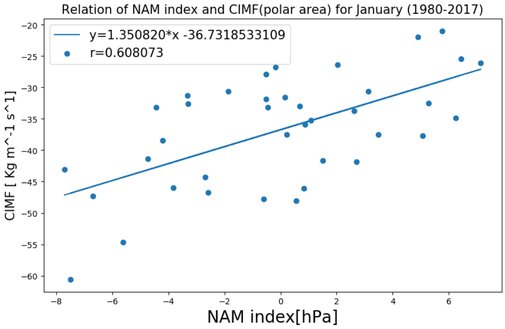
The behavior of cross isentropic mass flux seperately can not give significant informations for the relation of NAM index and meridional mass flux or generally the meridional criculation. Figure 5.3a displays the relation between the weighted cross isentropic mass flux over the polar area (50N-90N) and the meridional mass fluxand at 45N , at 307.5N . The anticorrelation between the two variables is strong ($R = -0.84$). Moreover, it is observed that in the polar area, the cross mass flux propagates downward while the meridional mass flux at 307.5K propagates towards the pole. Secondly, in the years of high NAM index the meridional mass flux and the cross isentropic mass flux are both weak. On the other hand, in the years of low NAM index, the meridional mass flux and the cross isentropic mass flux are strong. This is important because we can conclude that both meridional mass flux and cross isentropic mass flux are influenced by the same mechanism.

In Figure 5.3b, the correlation of cross isentropic mass flux with (total) eddy meridional mass flux ($R = -0.72$), is illustrated. This anticorrelation between these two variables is reasonable, as the cross isentropic mass flux is anticorrelated with total meridional mass flux. A significant consequence of it,is that the mechanism behind the generation of the eddy meridional mass flux is also responsible for the behavior of the cross isentropic mass flux.



(a) Relation of zonal mean and monthly mean of cross isentropic mass flux (polar area) at 300K with zonal mean and monthly mean of total meridional mass flux at 307.5K and 45N ($R = -0.84$).

(b) Relation of zonal mean and monthly mean of cross isentropic mass flux (polar area) at 300K with zonal mean and monthly mean of eddy meridional mass flux at 307.5K and 45N ($R = -0.77$).



(c) Relation of zonal mean and monthly mean of cross isentropic mass flux (polar area) at 300k with NAM index ($R = 0.6$).

Figure 5.3: Relation of cross isentropic mass flux over the polar area with total and meridional mass flux and NAM index.

Chapter 6

Connection of all variables

It is now important to observe how all the variables are connected. This proccess can help us to understand if there is a main mechanism that drives the circulation and the relation of the meridional mass flux with the NAM index. iN this chapter the principal component analysis is used in order to examine how all variables are connected.

6.1 Principal Component Analysis

The principal component analysis (PCA) is used so as to study the relation of mean PVS flux, eddy PVS flux, mean mass flux, eddy mass flux estimated for the layer of potential temperature 307.5K and 45N, NAM index and cross isentropic mass flux (CIMF) estimated for the level of potential temperature of 300K and weighted over the polar area (50N-90N). The process of PCA includes the correlation matrix of all the variables, the eigevalues and the eigenvectors of this matrix. Also, the amplitude of the principal components is estimated.

	Mean PVS FLUX	Eddy PVS flux	Mean mass flux	Eddy mass flux	NAM index	CIMF
Mean PVS flux	1	-0.93	0.92	0.19	-0.35	-0.46
Eddy PVS flux	-0.93	1	-0.85	-0.16	0.29	0.33
Mean mass flux	0.92	-0.85	1	0.16	-0.34	-0.44
Eddy mass flux	-0.19	-0.16	0.16	1	-0.6	-0.77
NAM index	-0.35	0.29	-0.34	-0.6	1	0.6
CIMF	-0.46	0.33	-0.44	-0.77	0.6	1

Table 6.1: Analysis of PCA. Corellation of all the variables. The mean, eddy PVS flux, the mean and eddy meridional mass flux are estimated for the layer of potential temperature 307.5K and 45N. The cross isentropic mass flux is estimated for the level of potential temperature 300K and weighted over the polar area (50N-90N).

The table 6.1 displays the correlation among the variables that we are interested in. We can distinguish two groups of variables that represent high correlation among them and as a result the behavior of the one variable is connected with the variable of the other. The first group of variables that shows high corrrelation is the mean PVS flux, eddy PVS flux and mean mass flux. The high correlation among these variables is according to the previous analysis. The second group of variables that displays high correlation among them is the eddy mass flux,cimf and NAM index. Also this high correlation was expected, according to the previous results. Finally, an outcome of this table is that the eddy PVS flux can explain a part of the circulation (mean meridional mass flux) but can not determine the intensity of the whole circulation and consequently the behavior of NAM index.

Furthermore, we can extract the eigenvalues and the eigenvectors of the covariance matrix. The eigenvalues show the contribution of each principal component to the total variance of our components. In table 6.2 the eigenvalues of the principal components are represented. It is observed that the first two principal components (λ_1 and λ_2) contribute more than 0.8 to the total variance. This result indicates that these two eigenvalues can explain very well the relation of among the six variables.

	λ_6	λ_5	λ_4	λ_3	λ_2	λ_1
Eigenvalue	0.039	0.093	0.24	0.44	1.64	3.54
Normalized eigenvalue	0.006	0.01	0.04	0.07	0.27	0.59

Table 6.2: Eigenvalues of the principal components

Next, we estimated the eigenvectors of the covariance matrix. The eigenvectors represent the direction of each variable for each principal component. The table 6.3 shows the eigenvectors of each variable for each principal component. We are mainly interested in the first two eigenvectors (E_1,E_2). E_1 and E_2 show the direction and the amplitude for each variable for the first two eigenvalues. The results from the first eigenvector show that when the mean PVS flux is negative, the mean mass flux is also negative, but the eddy PVS flux is positive. Moreover, when eddy mass flux is negative,the NAM index and CIMF are positive. The behavior of the first eigenvector is in agreement with the results in the previous chapters.

However, the results from the second eigenvector are quite different. Now, the first three variables have opposite direction compared to the first eigenvector and thus the relation with the last three vriables is not the expected. As a result, we can conclude that there is also another mechanism influencing the circulation, but less significant compared to the mechanism of the first eigenvector.

	E_6	E_5	E_4	E_3	E_2	E_1
Mean PVS flux	0.78	-0.2	0.02	0.04	0.32	-0.47
Eddy PVS flux	0.53	0.36	-0.49	0.002	-0.37	0.44
Mean mass flux	-0.19	0.72	-0.33	0.017	0.32	-0.45
Eddy mass flux	0.12	0.36	0.56	0.33	-0.57	-0.29
NAM index	0.004	0.04	0.05	0.84	0.39	0.34
CIMF	0.19	0.39	0.55	-0.41	0.39	0.4

Table 6.3: Eigenvectors of the principal components.

Figure 6.1 represents the amplitude of the first two principal components, otherwise the contribution of each principal component to the total variance of our variables. The first and the second principal components show the highest variance compared to the others. Actually, the amplitude of the other principal components is so low that can be considered insignificant to our analysis. This result strengths the previous opinion that the first and the second principal components can explain very well the relation of our variables. Furthermore, the sign of the first and second principal component for the years of low NAM index (1980,1996,1998,2004,2010,2011) is the same (negative). This behavior is an indication that probably in the years of low NAM index, the mechanism behind these two components acts similarly.

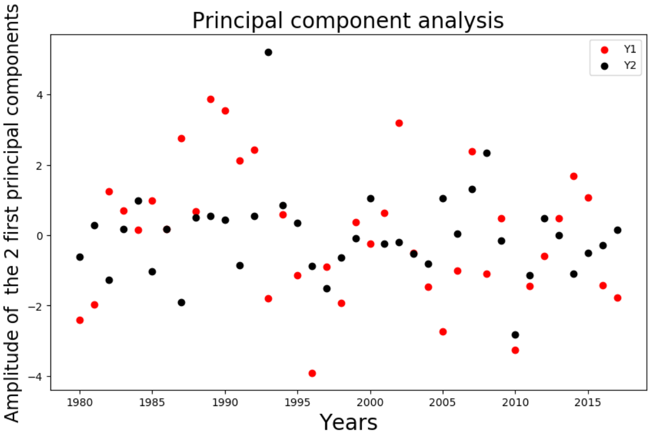


Figure 6.1: Variance of the first two principal components.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

The eddy meridional mass flux drives the total meridional mass flux. To be more specific, stationary eddies mass fluxes dominate in the circulation that we have examined and are related with the NAM index. In addition, the extreme years of low and high NAM index represent different features of stationary mass flux. For these years, the centers of poleward and equatorward mass fluxes are located in different places and different modes of stationary eddies appear.

The atmosphere is close to geostrophic and hydrostatic balance but the eddy PVS flux leads to acceleration or deceleration of the zonal mean of zonal wind. The atmosphere tries to remain constantly in thermal wind balance. This process leads the eddy PVS flux to determine the behavior of mean meridional mass flux and subsequently the total meridional mass flux.

Another variable that determines the circulation of mass is the cross isentropic mass flux (CIMF). The total meridional mass flux is anticorrelated with CIMF. A poleward mass flux leads to downwelling mass flux in the polar area (50N-90N). Moreover, a strong total mass flux is related with strong CIMF (low NAM index), while a weak total mass flux is related with weak CIMF (high NAM index). The eddy mass flux is also related to CIMF. This means that the mechanism that influences the behavior of eddy mass flux determines the behavior of CIMF.

Finally, the principal component analysis shows that there are two groups of variables that indicate strong correlation amongst them. The first and the second principal components can describe efficiently the behavior of all variables that we are interested in. In addition, the eddy PVS flux can describe one part of the circulation of the mass flux. Subsequently, it can determine the behavior of the mean mass flux but it can not influnce the behavior of eddy meridional mass flux and cross isentropic mass flux.

7.2 Future Work

The research of this project is still ongoing. A lot of aspects can be improved and further investigated. The time resolution of our variables plays an important role in order to understand the physical phenomena that dominate and influence the behavior of mass flux. NAM index represents an oscillation of weeks or months. Consequently, a daily resolution of the variables can help us to look further into the examined situation. A significant example of this process is the daily resolution of the total meridional mass flux. The daily evolution of the mass flux over different longitude for the years of low and high NAM index is different. As a result, a question that shows up is why the total meridional mass flux reacts different in these extreme years of NAM index.

A significant aspect that is interesting to investigate further is the sensitivity in the results. To be more specific, in case we follow the same process for the pricipal component analysis for 50N instead of 45N, the results are improved. In our case a minor difference in latittude (from 45N to 50N), leads to unexpected changes in the output.

Furthermore, it is observed that the eddy PVS flux speeds up the zonal mean of the meridional gradient of PVS. This is an indication of negative viscosity phenomena. This process can be analyzed as a different chapter because it includes information that is difficult to explain only in few paragraphs. The further investigation of the mechanism and the physical phenomena behind this relation can help us to understand which factors influence the eddy pvs flux and consequently the whole circulation and the NAM index.

Moreover, the NAM index represents an oscillation with a period of weeks or months. The years of low and high NAM index are characterised by strong negative or positive shifts of NAM index. The relation between these strong shifts and eddy PVS flux behavior in a period of days could be a good opportunity for further analysis of the phenomena. The daily resolution of the eddy PVS flux, for the case of the extreme years of NAM index, could help us to gain more detailed results in comparison with the monthly analysis of the eddy PVS flux.

Finally, an additional subject of research could be the behavior of the equatorward branch of mass flux (in the middle latitudes). The equatorward mass flux consist of a part of the total circulation. As a result should be interested in to investigate its behavior related to the poleward mass flux and the cross isentropic mass flux. In addition, we could examine the behavior of the equatorward mass flux in the extreme years of NAM index.

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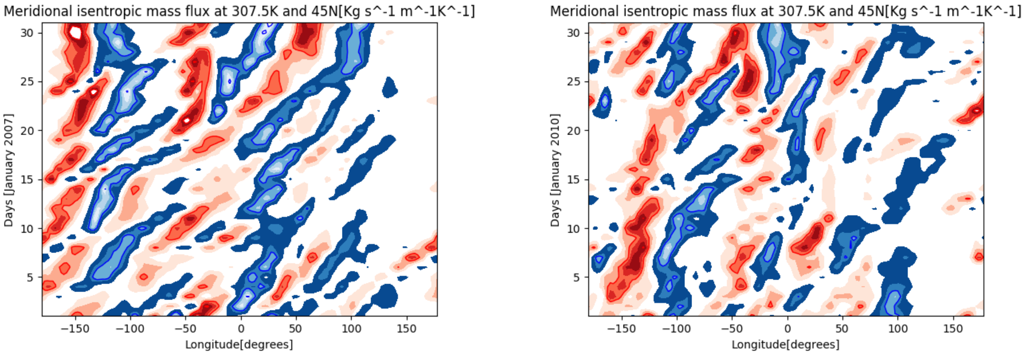
Appendix

A Daily resolution of meridional mass flux

In hapter of Future work it is mentioned that would be interested in to research the daily behavior of total meridional mass flux for the years of high and low NAM index. Figure A.1 represent the daily evolution of meridional isentropic mass flux at 307.5K and at 45N for different longitudes, for years of 2007 and 2010. It is observed that the behavior of meridional mass flux is different in 2007 compared 2010. We observe qualititavely in year of 2007 the existence of transient eddy mass fluxes until 20/1 when the waves become stationary , whereas in year of 2010 the existence of stationary eddy mass fluxes. However, it is difficult to distinguish the eddy mass fluxes in transient and stationary eddy mass fluxes when we take the daily resolution of mass flux. As a result, we can examine only qualitively the merididional mass flux in a daily resolution.



(a) Meridional isentropic mass flux at 307.5 and 45N for the month of January 2007

(b) Meridional isentropic mass flux at 307.5 and 45N for the month of January 2010

Figure A.1: Meridional isentropic mass flux at 307.5 and 45N for the month of January 2007 and 2010