The Physics of Jet Stream Meandering

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Abstract
Large-amplitude jet stream meanders involve diabatic processes because conservation of angular momentum leads to vortex line stretching and shrinking. This requires latent heat release during poleward flow in contrast to cooling by sublimation and radiation during equatorward flow. Moisture and its distribution, together with aerosols, play a key role. The increase of anthopogenic aerosols in the upper troposphere could be a cause for the more frequent large-amplitude jet stream meanders.
Keywords Angular momentum; Potential vorticity; Latent heat; Radiative cooling; Sublimation cooling; Rossby waves

1 Introduction

As the jet stream flows from west to east, Rossby waves can form. Large meridional excursions of the jet stream in form of meanders occur between alternating warm high-pressure ridges extending polewards and cold low-pressure troughs extending equatorwards. The balanced geostrophic flow of the jet stream is at right angle to the horizontal gradient of the pressure field, so that the resulting horizontal pressure force is balanced by the horizontal component of the Coriolis force. At the same time the angular momentum of air parcels in the flow remains constant in the absolute system, which can be expressed by the conservation of potential vorticity. Angular momentum remains constant also during horizontal convergence with vortex line expansion, visualized by a ballerina pulling her stretched arms close to her body in order to accelerate the spinning rate, or during horizontal divergence with vortex line shrinking. Potential vorticity $PV = -g(\zeta + f)\delta\theta/\delta p$ is the sum of relative vorticity ζ and planetary vorticity f (Coriolis parameter) times the difference $\delta\theta$ of potential temperature between the bottom and the top isobaric surfaces of an air parcel divided by the corresponding pressure difference δp, with standard gravity g [1].The pressure difference δp between the bottom and top of an air parcel increases during horizontal convergence with vortex line stretching, while divergence lets the pressure difference δp decrease with vortex line shrinking.

2 Conservation of Angular Momentum during Meridional Flow

In synoptic-scale geostrophic flow of meandering jet stream, relative vorticity ζ is generally much smaller than the Coriolis parameter f. As f changes with latitude, ζ of an air parcel cannot change sufficiently to conserve its angular momentum, so that a change of pressure difference δp between the bottom and top isobaric surfaces of the air parcel is needed in order to compensate the change of f.

During poleward flow of an air parcel in the jet stream, the increase of Coriolis parameter f (Northern Hemisphere) requires horizontal convergence to increase the pressure difference δp through a decrease of horizontal surface area of the air parcel (mass conservation). However the increase of the Coriolis parameter f with latitude does not directly force the required increase of δp. What occurs is the forcing of a small ageostrophic deviation ζa of relative vorticity ζ in form of negative velocity shear (anticyclonic) parallel to the flow, superimposed on the velocity profile of the jet stream, as shown in Fig.1. This causes a disturbance of the geostrophic balance in the jet stream, which is kept small by the existing pressure field. Therefore this ageostrophic disturbance by ζa remains limited to a slightly faster flow on the left side of the jet stream and slower flow on the right side (looking in flow direction).

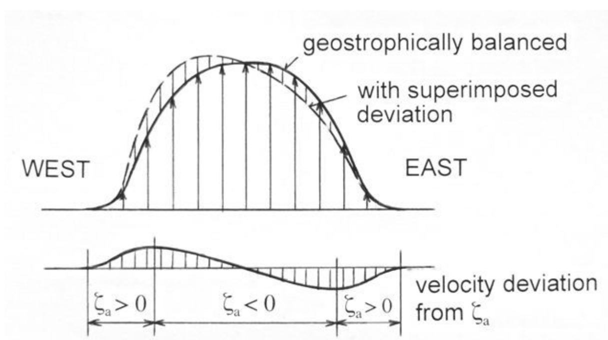

Fig.1 Velocity profile of poleward jet stream and deviation caused by ageostrophic shear vorticity ζa.

The result is a small ageostrophic imbalance between the horizontal component of the Coriolis force and the horizontal pressure gradient across the jet stream. This leads to an up-gradient flow deviation on the left side of the jet stream and an opposite down-gradient deviation on the right side. The overall result is horizontal convergence from both sides so that mass continuity of the air parcel with mass δm leads to an increase of pressure difference δp between its bottom and top surfaces. And the increase of δp assures conservation of potential vorticity and angular momentum. This increase of δp gradually changes the pressure field.

During poleward flow, the pressure difference δp of an air parcel must increase continuously in order to balance the increasing horizontal component of the Coriolis force. By producing a small amount of superimposed velocity shear, which causes lateral convergence of the jet stream, the small ageostrophic deviation ζa of relative vorticity ζ acts as a forcing agent between the continuous increase of

f and the pressure difference δp. During equatorward flow, velocity shear with opposite sign causes lateral divergence, accompanied by a decrease of δp. In Southern Hemisphere, f is negative and ζa has opposite sign.

The forcing between the change of Coriolis parameter f and the pressure difference δp is stabilized by a negative feedback, which adapts the ageostrophic deviation ζa of shear vorticity ζ and the corresponding deviation of velocity in such a way that δp changes in proportion to f. Fig.1 shows also the profile of this ageostrophic velocity deviation, whereby ζa is the derivative. The velocity deviation increases outwards from the jet stream center as long as the ageostrophic shear vorticity ζa is negative (anticyclonic). This lets the ageostrophic imbalance become larger with increasing distance from the center and therefore convergence with vortex line stretching also. As a result, starting from a certain distance from the center, the pressure difference δp becomes larger that required to compensate the increase of f. Now conservation of potential vorticity forces a positive (cyclonic) correction of ζa in the outer region of the jet stream, accompanied by a reduction of the velocity deviation until it disapperars at the outer edge of the jet stream (Fig.1).

3 Heating in Poleward Flow and Cooling in Equatorward Flow

During meridional flow of the jet stream there is a continuous increase or decrease of pressure difference δp between the bottom and top isobaric surfaces of air parcels through vertical expansion or shrinking. Because this affects an entire layer inside the jet stream, vertical expansion of the layer lifts the atmosphere above it and increases its geopotential height. This requires energy input to the upward expanding layer. In contrast, vertical shrinking of an entire layer reduces the geopotential above it and requires energy reduction.

During poleward flow of the jet stream, the increase of δp from upward expansion requires latent heat release from condensation or deposition of water vapor in order to increase internal energy of the air parcel. In contrast during equatorward flow, cooling by radiation to space and by sublimation of ice crystals is needed to decrease internal energy.

The upward expansion during poleward flow, which results from convergence and heating, increases the geopotential height of the air columns inside the jet stream as shown in Fig.2. This results is westward propagation of the eastward pressure gradient and with it of the geostrophic flow and the jet stream, as a Rossby wave. During equatorward flow, the downward shrinking caused by divergence and cooling lets the pressure gradient, which is westward now, propagate westwards also (Fig.3).

The jet stream meanders between warm high pressure ridges extending polewards and cold low pressure troughs extending equatorwards form a large-amplitude

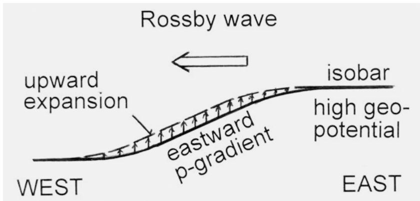

Fig.2 Vertical section of an isobar across poleward jet stream.

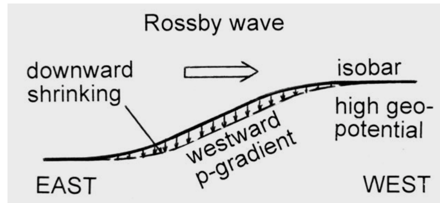

Fig.3 Vertical section of an isobar across equatorward jet stream.

Rossby wave propagating westwards relative to the air mass. Thereby air parcels enter into the jet stream from the west, are entrained by the meridional flow and slowly cross it until they exit to the east. This occurs in both poleward and equatorward jet stream. In poleward flow, the air parcels enter from the cold side with lower geopotential, are entrained by the flow and slowly traverse the jet stream towards the warm side with higher geopotential. In the equatorward jet stream, air parcels enter from the high geopotential side in the west and exit to the low geopotential side in the east.

A stationary air parcel in the low geopotential region to the west of a poleward jet stream, displacing itself slowly sideways as a westward propagating Rossby wave, is initially subjected to an increase of pressure difference δp (Fig.2). Conservation of potential vorticity at constant latitude and therefore constant f leads to an increase of relative vorticity in form of velocity shear, which accelerates the air parcel polewards. Now the Coriolis Parameter f increases also, forcing a continuous increase of δp by means of a small negative ageostrophic shear vorticity ζa (Fig. 1). This continues until the Rossby wave and the jet stream have almost propagated past the air parcel and the pressure difference stops increasing. Now δp becomes constant again as the air parcel comes to rest and reaches the high geopotential region in the east of the jet stream.

Heating during poleward flow by the release of latent heat becomes weaker with increasing height because the decrease of temperature strongly reduces the saturation water vapor concentration, a consequence of the nonlinearity of vapor pressure as a function of temperature. This lets the dry and moist adiabats almost coincide. Towards the tropopause, long wave radiation to space by ice crystals in cirrus clouds increases strongly and its cooling offsets the heating. This prevents further upward expansion of the top cloud layer.

In equatorward jet stream, ice crystals in cirrus clouds are instrumental for both radiative cooling to space and sublimation cooling. During downward shrinking, radiative cooling partly offsets compression warming with the effect that there is less sublimation and ice crystals can survive longer. As sublimation eventually lets ice crystals disappear, starting from the top cloud layer, lower clouds get directly exposed to radiative cooling.

Heating and cooling in meridional flow of the jet stream are part of a dynamic system in which moisture and its distribution play a key role. Heating and cooling however change the potential temperature, which violates conservation of potential vorticity. Angular momentum can be conserved by replacing the difference of potential temperature between bottom and top isobaric surfaces of the air parcel by its mass m, so that now it is $(\zeta + f)\delta m/\delta p$ of the air parcel that must be conserved.

4 Changes of Jet Stream Direction

Conservation of angular momentum of an air parcel requires that the ratio between absolute vorticity $(\zeta + f)$ and pressure difference δp must remain constant, δp being between the bottom and top isobaric surfaces of the air parcel with constant mass m. Changes of Coriolis parameter f or alternatively of pressure difference δp caused by convergence or divergence, lead to changes of relative vorticity ζ and subsequently to a change of the flow field. A change of ζ can be caused by either a change of f or a change of δp, depending upon the situation.

Diabatic processes play a key role in the evolution of the pressure and flow fields, including jet stream meandering. As an example, a poleward jet stream needs continuous release of latent heat to compensate the increasing f with latitude. An interruption of the moisture supply stops the convergence that increases δp. The result is that now ζ is forced to change, with opposite sign to the change of f. In Northern Hemisphere with positive f, the increase of f with latitude therefore produces a negative ζ (anticyclonic). This forces the poleward jet stream to veer to the right and eventually results in the cutting apart of the high pressure ridge to the right of the jet stream. Thereby a blocking high can form to the north of the partition. In the Southern Hemisphere with negative f, all signs are opposite, including the sign of anticyclonic ζ, but the physics is the same.

In a second example an oversupply of moisture and of latent heat release makes δp increase more than required to compensate the increase of f with latitude. The positive excess of δp causes a positive change of ζ and the formation of a cyclone to the left of the poleward jet stream.

In an equatorward jet stream, moisture at higher level is in form of ice crystals that sublimate through compression heating during downward shrinking, which is needed to compensate the decrease of f. There is also radiative cooling to space, which is added to sublimation cooling. A slowdown or interruption of downward shrinking caused by a lack of ice crystals lets the decreasing f force an increase of ζ, which makes the equatorward jet stream veer to the left and east. At this point a cyclone can form at the cold front of the cold trough. Now the warm conveyor belt of the cyclone can pick up moisture from the ocean and subsequently feed it into the jet stream, allowing it to flow polewards again in the east of the cold trough.

5 The Role of Aerosols

Aerosols form the nuclei of droplets and ice crystals by allowing condensation or deposition of water vapor. They play a key role in the formation of cirrus clouds in the upper troposphere [2,3] and in the jet stream. The size distribution and number concentration of aerosols and subsequently of ice crystals influence both the radiative properties and the evolution of cirrus clouds during upward expansion and downward shrinking in the jet stream.

When aerosols are more numerous, smaller ice crystals with higher number concentration are formed. Smaller ice crystals reduce the sedimentation rate, which influences their concentration at different levels. In addition smaller ice crystals increase the optical thickness for a given mass concentration with the effect that the top layer of the clouds which emits long wave radiation to space, becomes thinner. The higher optical thickness increases also the albedo of solar radiation by cirrus clouds, reducing the absorbed fraction and therefore solar heating of the affected top layer. The higher number density of the smaller ice crystals enhances the deposition of water vapor on ice nuclei because the average distance which a vapor molecule has to cover by diffusion decreases. The variety and subtlety of such processes can be observed in the formation and dissolving of contrails, the condensation trails of high flying airplanes. The dynamics of contrails varies strongly, depending on the properties of the air in which they form and to a smaller degree of the jet engines.

6 Potential Implications for Climate

Jet stream meandering drives the advective meridional overturn of the troposphere between mid and high latitudes and influences the formation of extratropical cyclones. During meridional flow of the jet stream, aerosols play a key role in the formation of droplets and ice crystals, which in turn controls latent heat release, radiative cooling and sublimation cooling.

Aerosols have an influence upon the size distribution and number concentration of ice crystals. In the higher troposphere small size aerosols dominate because they have a longer lifetime. Anthopogenic aerosols are generally smaller than natural aerosols. A technological reason for example are particle filters for the exhaust from coal fired power plants and Diesel engines, which are less effective for small size particles. As a consequence the increase of anthropogenic aerosols at jet stream level is relatively higher than in the lower troposphere, where short-lived larger aerosols are more aboundant. The analysis of residual particles in cirrus crystals after sublimation of the ice by Cziczo et al [3] shows that mineral dust and metallic particles are the dominant ice nuclei. At present however the anthropogenic fraction of these ice forming aerosols is still uncertain.

An increase of anthropogenic ice forming aerosols in the upper troposphere has several potential effects upon both heating and cooling during meridional flow of the jet stream:

1. The increase of the number concentration of small size aerosols leads to more numerous small ice crystals, which reduces their sedimentation speed. This increases their lifetime and in turn the mass concentration of the suspended ice crystals.

2. While this has no direct effect on latent heat release, the smaller size of ice crystals and their higher mass concentration increases the optical thickness, which concentrates the cooling by long wave radiation into a thinner top layer of cirrus clouds. This allows the decreasing amount of latent heat release with increasing height to remain effective up to a higher level and enhances the poleward flow of the jet stream.

3. Once an air parcel exits from the poleward jet stream towards the high geopotential side on the east, upward expansion and latent heat release stop, allowing radiative cooling to become dominant. And the increased albedo of solar radiation resulting from the higher optical thickness of the more numerous small ice crystals reduces solar heating, which lets cooling by long wave radiation become more effective.

4. Radiative cooling leads to subsidence, followed by compression warming, which lets ice crystals sublimate and generate additional cooling. Continuous cooling by sublimation and radiation drives the process of downward shrinking during equatorward flow. And the increase of mass concentration of the smaller ice crystals, resulting from slower sedimentation, increases sublimation cooling during downward shrinking, which enhances the equatorward flow of the jet stream.

Because of these effects, the increase of anthropogenic aerosols has the potential to enhance both the upward expansion during poleward flow and the downward shrinking during equatorward flow of the jet stream. The overall result is an increase of jet stream meandering. Evidence of the Arctic jet stream becoming wavier, starting from the mid-1990s, has been presented by Francis et al [4]. The regional effects of enhanced jet stream meandering are more frequent cold air outbreaks and the blocking of both low pressure troughs and high pressure ridges. Francis [4] presents a linkage between Arctic amplification and a wavier jet stream. The increase of anthropogenic aerosols through their role in jet stream meandering is a possible cause.

Starting from about the year 2000, a slowdown of global warming has appeared. More frequent cold air outbreaks, caused by the increase of jet stream meandering, could contribute to this in the following way. During the equatorward flow with downward shrinking of the cold air, high clouds sublimate and allow warmer low clouds and the warm ocean to radiate directly to space. This increases the heat loss by outgoing long wave radiation in a similar way as with the so called “iris effect” [5].

It is interesting to compare the slowdown of global warming during the past 15 years with a similar situation from the 40s to the 60s of the last century [6]. In both situations anthopogenic aerosols from coal burning, heavy industry and mining increased: in the first case during the Second World War and the subsequent rebuilding of industry in Europe and Japan, while in the second case during the forced economic growth in China and India.

Finally it is possible that the enhanced cooling of a thinner top layer of cirrus clouds, resulting from the higher optical thickness of more numerous small ice crystals, creates a more effective barrier between the troposphere and the lower stratosphere. This could reduce the transfer of water vapor to the stratosphere, with the effect of lowering its concentration there. Solomon et al. [7] found evidence of a 10 % decrease of water vapor in the lower stratosphere since the year 2000 and their simulations show a 25 % reduction of global warming.

7 Summary and Conclusions

Latent heat release is the main driver for convective overturn in the troposphere. The meridional advective overturn between mid and high latitudes depends also upon the presence of moisture and its distribution. We have shown that conservation of angular momentum and potential vorticity needs the release of latent heat during poleward flow and cooling by radiation and sublimation during equatorward flow of meandering jet stream. Thereby aerosols form the nuclei for droplets and ice crystals and influence their size distribution. This in turn controls the rates of precipitation and sedimentation and influences the total mass of suspended ice crystals and their optical thickness, which in turn influences cooling by radiation and sublimation.

We explain how the increase of anthropogenic aerosols can influence the meridional flow of the jet stream and suggest that this could increase both its meandering and the blocking of high pressure ridges and low pressure troughs between the meanders.

Characteristic for the physics of jet stream meandering are the multiple and complex interactions between rotational fluid mechanics, thermodynamics of moist air, aerosols and radiation. An example is the increase of stratification stability resulting from adiabatic convergence or divergence, which explains why latent heat release and cooling by radiation and sublimation are needed to reduce stability. Often the distinction between cause and effect is difficult, a challenge for numerical models. And a typical case is the evolution of the pressure field with synoptic-scale meridional flow, involving large changes of the Coriolis parameter, which lead to the formation of Rossby waves.

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