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PROJECT REPORT

Simulation of zonal flow on Jupiter

Niklas Johansson, Patrick Brem

Project in Computational Science: Report

Supervisors: Jonas Nycander, Heiner Körnich
(Meteorologiska institutionen Stockholm Universitet)

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Abstract: In this project we have used a simplified 3D model used for simulations of Earth's atmosphere and modified it to do simulations of Jupiter. The goal was to test a theory that moist convection is a vital part to why the pattern of alternating zonal jets seen on Jupiter and the other outer planets of our solar system are created. We tried both with and without bottom friction but were unable to reproduce the observed pattern in our simulations using our modified model. In some cases we saw zonal flow, but the direction of the flow was wrong and could not reproduce the superrotation at the equator. The zonal flows was also confined to a narrow band near the equator with usually only 3 jets, two east flowing jets, one on each side of the middle west flowing jet. Without moist convection, no zonal flows were seen, so the theory may still be valid only that there could be more factors that needs to considered in the model to fully be able to reproduce the pattern seen on Jupiter.

Contents

1 Introduction

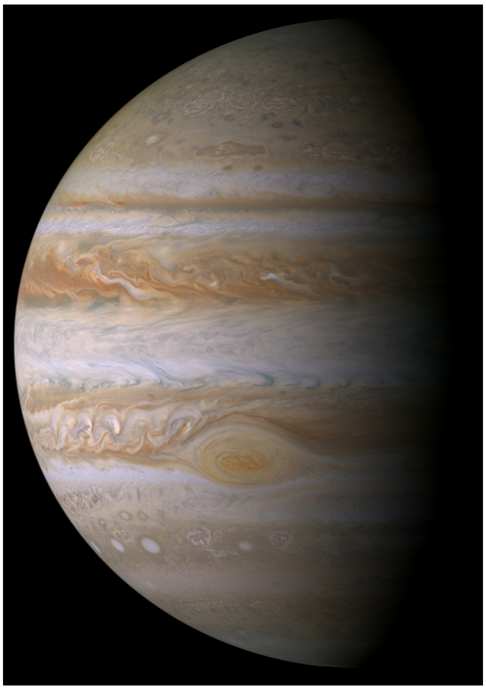

Figure 1: Jupiter

Jupiter is the largest planet in our solar system. The radius is about 11 times larger than Earth's. Together with the other gas giants Uranus, Neptune and Saturn it has the property that the atmosphere mostly consist of zonal jets and that the direction of these jets alternates with latitude. The reason for the appearance of zonal flows is not yet fully understood by the scientific community as some details remain unknown even though Jupiter has been studied for 300 years. One new hypothesis is that moist convection plays an important role in the formation of these alternating jets. In Figure 2 we see that the zonal flow is a persistent phenomena and that the wind speeds and structure of the atmosphere hardly changed at all between the measurements made in 1979 and 2000 by Voyager and Cassini, however the visible stripes do change colours and disappear occasionally. Figure 3 shows a recent photo of May 8 2010 of Jupiter where the typical south equatorial belt is missing.

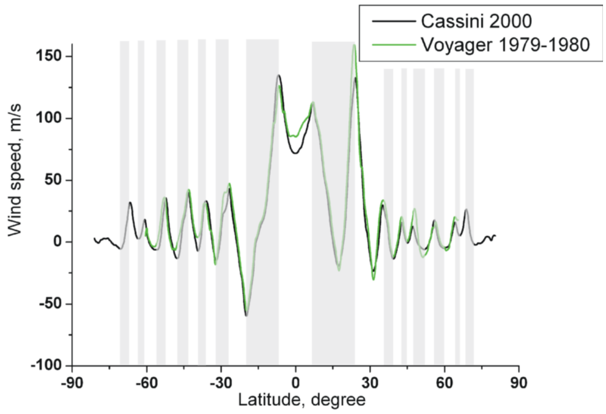

Figure 2: Observational data

Figure 3: Recent picture of Jupiter

2 Background

2.1 Why zonal flows?

On Earth, the radiation from the Sun is causing a great temperature difference between the equator and the north and south pole because the equator receives more heat. On Jupiter on the other hand, this effect is almost non existing because of the planets high heat generation in the interior that evens out most temperature differences in the atmosphere, which means that each imaginary shell in Jupiter's atmosphere has almost the same temperature. Because of this there doesn't have to be any heat transport between equator and poles, i.e. almost no meridional winds. The very high rotation speed and planet radius result in a very strong Coriolis effect and is therefore also a reason why meridional winds are almost nonexistent except in the many storms.

2.2 Atmospheric structure and composition

The clouds in Jupiter's atmosphere are either bright or brown. The brighter areas are called zones and have a higher concentration of ammonia and are very dense. These clouds appear on high altitudes and hide the darker brown clouds below them called belts. The reasons for the brown colour is not yet known but they are believed to consist of sulfur and phosphorus.

2.3 Deep vs. Shallow model

The two main competing theories of how the zonal flow is formed are the shallow and deep models. In the shallow model, the idea is that the zonal jets are confined to only a shallow layer of the atmosphere above a stable interior. There are two different approaches within the Shallow model: One uses an initial condition with small-scale perturbations and lets the flow evolve freely. The other one includes a random forcing term at runtime. The simulation is then run until it arrives at a steady state. This model has a significant problem since simulations with it usually produce a subrotation jet at the equator, which goes in the wrong direction compared to observations on Jupiter where we have superrotation, i.e. the jet goes in the same direction as the planet rotates.

In the deep model, the observable zonal flow is the result of a deeper motion driven by interior convection. If the atmosphere can be considered to be barotropic, i.e. the pressure depends only on density, then by the Taylor-Proudman theorem from fluid mechanics, the atmosphere will consist of a number of cylinders parallel to the planet's rotation axis. Where these cylinders intersect with the surface, the flow will be observed as zonal jets.

Measurements done by the Galileo probe showed no signs of decreasing wind speeds at lower altitudes, which seems to support the idea of a deep model, but both models have their pros and cons.

2.4 Previous work

Many simulations and experiments have been made. In most of them, jets were observed only near the equator and nothing closer to the poles, or could not reproduce the superrotating equatorial jet.

- Gareth P. Williams (1978) [5] found similarities between circulations on terrestrial and jovian planets, and applied terrestrial circulation theories also in jovian settings to try to explain the processes in Jupiter's atmosphere.

- M. Heimpel et al. (2005) [1], got a very broad superrotating equatorial jet and many jets far away from the equator using a deep convection model simulation.

- In an earlier thesis project by Pontus Forsberg at Uppsala University (2006) [2], he used a modified version of COAMPS(Coupled Ocean/Atmospheric Mesoscale Prediction System) to try the moist convection theory. The results of those simulations were only a few jets near the equator and he was unable to get the correct directions of the zonal jets.

- Schneider and Liu (2008) [3] managed to somewhat more accurately reproduce the superrotating equatorial jet as well as several jets away from the equator by using a model with magnetohydrodynamic drag everywhere in the bottom layer of the atmosphere except near the equator. Their result is very good considering that both superrotation and many jets usually don't show up in the same simulation. This is also as far as we know the numerical simulation which is closest to observations than any other attempt to reproduce the zonal flow pattern seen on Jupiter.

Not only computer simulations have been made, but also some experiments with rotating cylinders in a laboratory have been done, for example by P. L. Read et al. (2004) [4], but they could not reproduce the zonal jets seen on Jupiter.

2.5 Theory

2.5.1 Dry Adiabatic Lapse Rate (DALR)

The adiabatic lapse rate (ALR) describes the temperature decrease with height in the atmosphere. If the atmosphere is in hydrostatic equilibrium (gravitational forces downwards on an air parcel equal bouyancy forces), i.e.

$$\frac{\partial P}{\partial z} + \rho g = 0 \tag{1}$$

with P being the pressure, z the vertical coordinate, ρ the density and g the gravitational constant, the dry adiabatic lapse rate Γ is given by [6]

$$\Gamma_d = -\frac{\partial T}{\partial z} = \frac{g}{c_p}. \tag{2}$$

c_p is the specific heat capacity of the atmospheric gas mixture. This means that rising air cools at this given rate.

2.5.2 Moist Adiabatic Lapse Rate (MALR)

In reality, the atmosphere contains water vapor which condensates eventually upon cooling. This condensation releases latent heat, which means that the rising air cools less than without water vapor (See Figure 4). This effect leads to a smaller Lapse Rate than the DALR described above, and it provides an extra "passive" source of energy. Also, this effect could be the reason for the strong zonal winds on Jupiter, and it is this new hypothesis that we we wanted to test with this project.

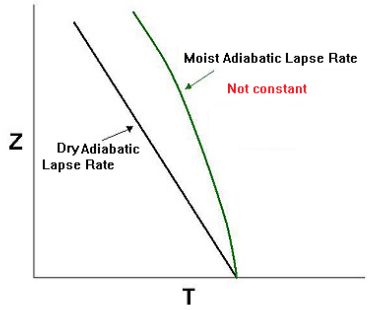

Figure 4: Dry and moist adiabatic lapse rates. Y-axis: Height. X-axis: Temperature.

3 The Model

3.1 PUMA

PUMA (Portable University Model of the Atmosphere, developed at the University of Hamburg [7]) is a rather simple software package used to simulate the seasonal evolution of the Earth's atmosphere. Typical simulation results are shown in Figure 5 and 6 (visualized with GrADS [8]). In this project we want to modify the model so that the parameters match the conditions on Jupiter. In particular, we changed the model variables as shown in Table 1.

Table 1: Modification of the model parameters

Variable name in the code	Meaning	Value on Earth	Value on Jupiter
GA	Gravitational Constant [m/s^2]	9.81	24.79
GASCON	Specific Gas Constant [J/(kg K)]	287	3770
PLARAD	Planet Radius [m]	6 370 000	70 000 000
PSURF	Surface Pressure [Pa]	101 000	200 000
WW	Rotation Speed ($2\pi/T$) [1/s]	0.00007292	0.00017585
dtep	Temperature Difference Poles $\leftrightarrow$ Equator [K]	60	0
dtrop	Tropopause Height [m]	12 000	40 000
rotspd	Rotation Speed (In Earth units)	1	2.4
tgr	Ground Temperature [K]	288	165

Among these values we can only be sure about GA, PLARAD, WW, dtep and rotspd. The other parameters are not well defined on Jupiter, since it is a gas giant.

- dtrop: It is difficult to define an atmosphere if there is no solid ground. According to [9], the Scale height is 27 km. On Earth the scale height is 8.5 km and the model uses 12 km. An educated guess of a reasonable value should be dtrop = 40 km for Jupiter.
- tgr: We define the ground to be at a pressure of PSURF = 2 bar. At this level, according to [10] and [11] the temperature should be about 165 K.
- PSURF: This is the pressure at the artificial surface that we need to define in order to get a working model. The visible clouds are located in a pressure range between 0.7 - 1 bar [12]. We would like to have them in our atmosphere so we choose 2 bar as the surface pressure, in agreement with [9].
- GASCON: This value has been calculated using the mean composition of the atmosphere, which is mainly 90% Helium and 10% Hydrogen [9]. This amounts for an average molar mass of 2.2 g/mol giving GASCON = 3770 J/(kg K).

With these changes, typical simulation results look as shown in Figure 7 and Figure 8.

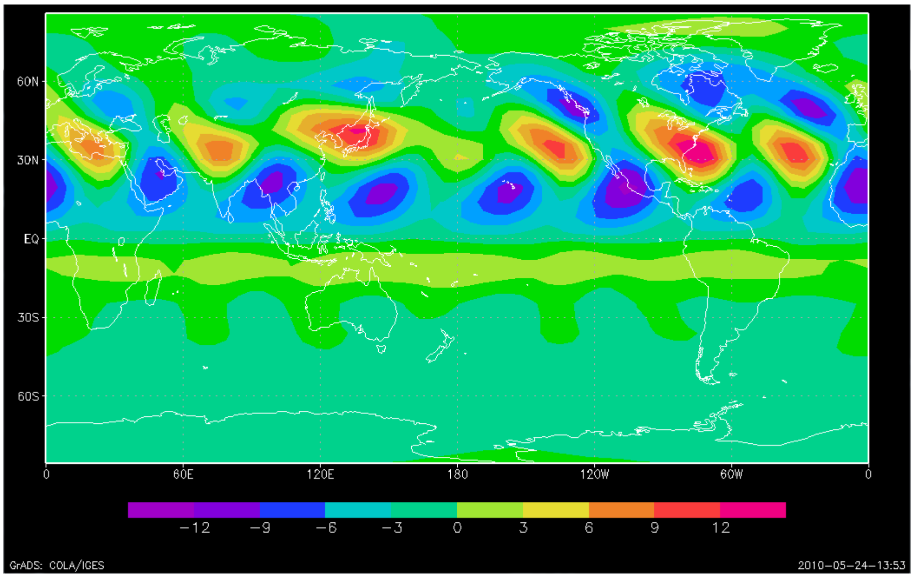

Figure 5: Zonal wind (m/s) in a typical Earth simulation at ground level

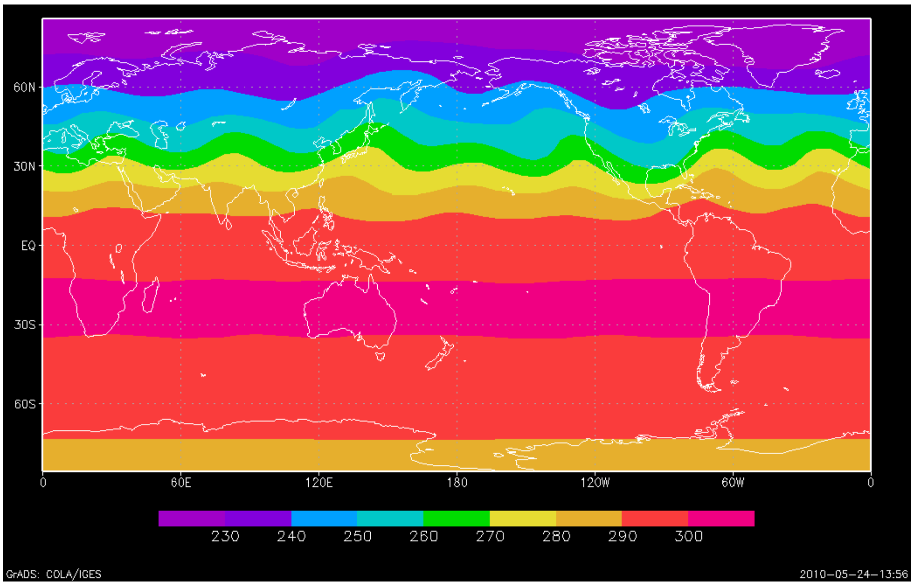

Figure 6: Temperature (K) in a typical Earth simulation at ground level

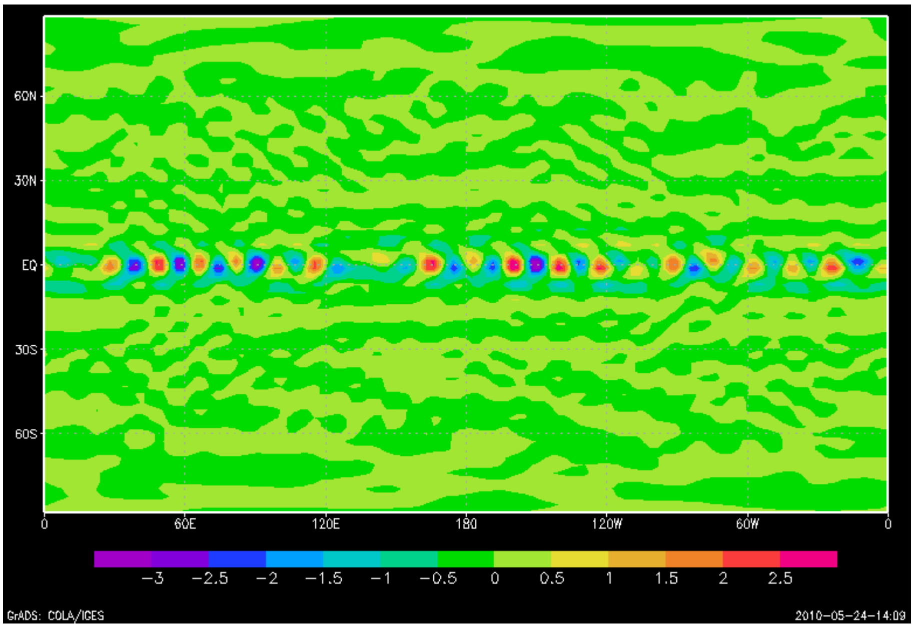

Figure 7: Zonal wind (m/s) in a typical Jupiter simulation at ground level

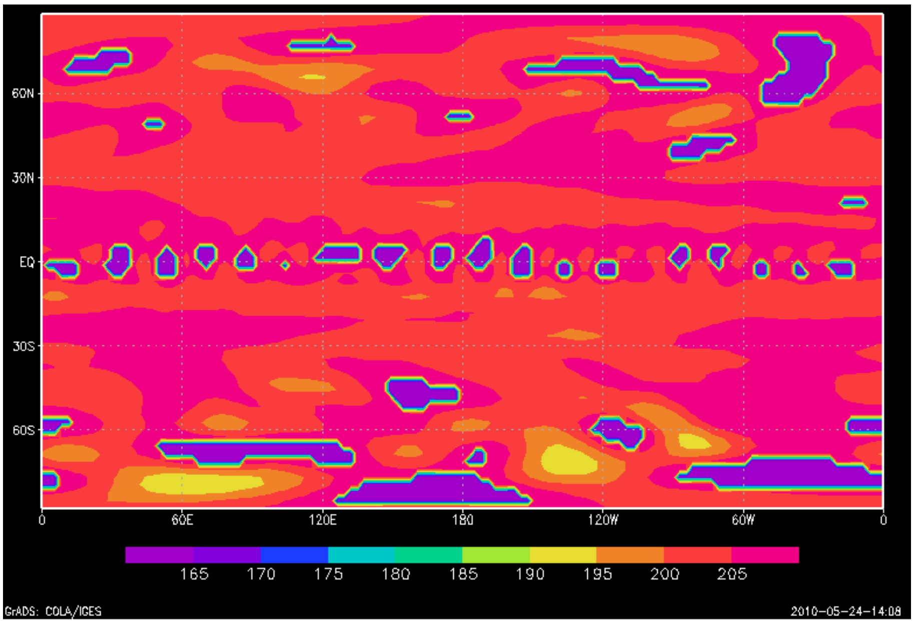

Figure 8: Temperature distribution (K) in a typical Jupiter simulation at ground level

3.2 Changes to the model

3.2.1 Changes in the code

Additionally we changed the following features of the software code:

- Restoration time scale: The model comes with a background temperature field. This is used to relax the temperature perturbations to certain (height-dependent) values with certain (height-dependent) relaxation timescales. We "fixed" the temperature at the bottom and top layers (Restoration time = 2 days) and let the atmosphere evolve rather freely in all the other regions (Restoration time = 50 days). The fixture at the top of the atmosphere should prevent the model from heating up too much after we introduced the convective heating parametrization later on.

- Bottom friction: We did simulations with and without bottom friction. The difference was that with bottom friction, zonal winds are suppressed. Because there are no real shear forces in gaseous substances we decided to turn off the bottom friction (which is relevant on Earth). This was a decision based both on practical reasons (we want zonal winds) and physical justification.

- Added variables to the namelist: PUMA reads some variables from a namelist file in the beginning. To have better control and be able to restart a simulation with different parameters without recompiling the code, we added the variables ALR (Adiabatic Lapse Rate, explained below) and ALPHA (Moisture coefficient introduced by us) to the namelist.

- Moisture term in the temperature equations: This is the most important change to achieve the goal of seeing zonal flows on Jupiter. A detailed description of the incorporation of this additional heating is given below (See 3.3.2).

3.2.2 Changes to the Graphical User Interface MoSt

We also made some minor changes to the GUI that comes with PUMA. We added a checkbox "Jupiter" to select if we want to work with the Jupiter parameter set instead of the Earth's. Another textbox "Months" was added in order to be able to run shorter simulations for quick tests. We also added the two parameters "ALR" and "ALPHA" to be able to change them easily since we had to do that a lot. Editions are shown in Figure 9.

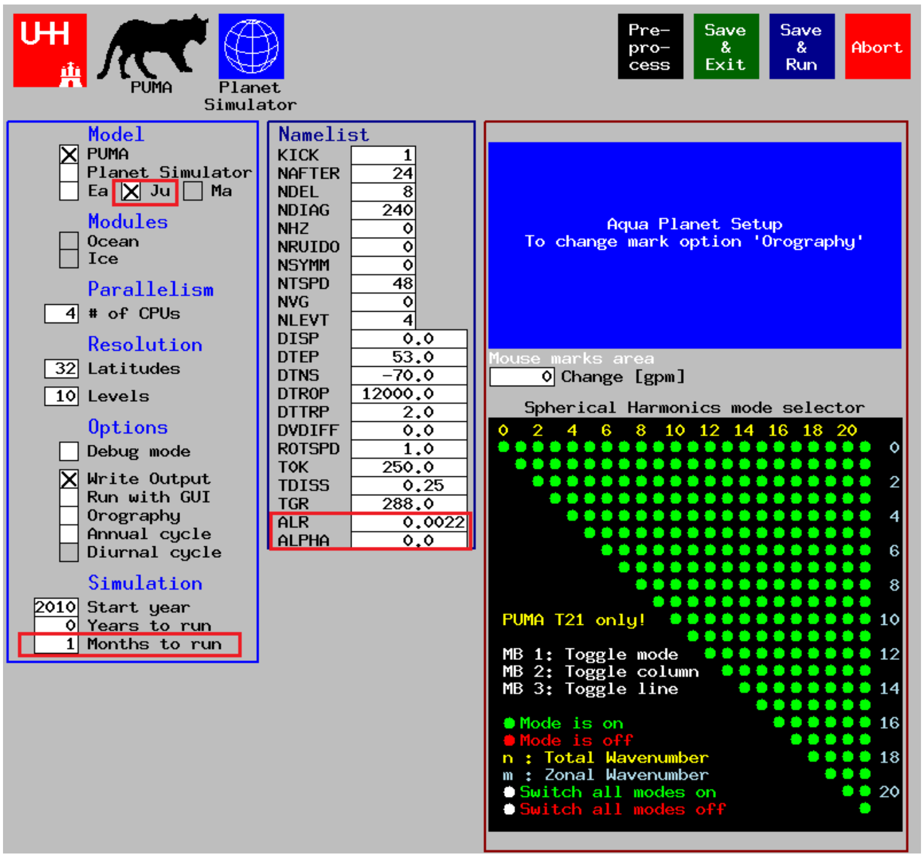

Figure 9: Changes to the GUI "MoSt"

3.3 The restoration temperature field

Now that the model is working with Jupiter conditions, we need to adjust the vertical temperature profile to get reasonable results. If the temperature decreases too slowly with height, the situation becomes stable. If the temperature decreases too rapidly, the atmosphere becomes unstable and turbulent, causing huge wind speeds up to a breakdown of the model. The key to control the vertical temperature profile in PUMA is the parameter "Adiabatic Lapse Rate" (ALR). It simply defines the decrease of temperature with height. On Earth this value has been set to ALR = 0.0065. We have no reason to believe that it shouldn't be completely different on Jupiter.

3.3.1 Stability Analysis

The equation governing the evolution of the temperature in the atmosphere is

$$\frac{\partial T}{\partial t} = -\dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{\kappa \omega T}{p}. \tag{3}$$

Here we have omitted all the terms that deal with horizontal effects and other heating sources. The temperature profile is marginally stable if $\frac{\partial T}{\partial t} = 0$. Knowing that $\omega = \frac{dp}{dt}$ and $\sigma = \frac{p}{p_s}$, we get the ODE

$$\frac{\partial T}{\partial \sigma} = \kappa \frac{T}{\sigma}. \tag{4}$$

with the solution

$$T(\sigma) = T_s \ (\frac{\sigma}{\sigma_s})^{\kappa}. \tag{5}$$

The index s denotes the value at the surface. κ is the adiabatic coefficient given in the source code of the model, $\kappa = 0.286$. One can now find the ALR which comes closest to the temperature profile given by the theoretical marginally stable condition. Using $T_s = 165\ K$, the temperature at the top level $\sigma = 0.1$ according to the formula is $T = 85\ K$. This temperature is obtained in the restoration temperature profile using an ALR of 0.0021.

On the other hand, several simulations with different ALR were run to find the value at which motion sets in. Figure 10 shows the maximum zonal wind after a period of one month with different ALR.

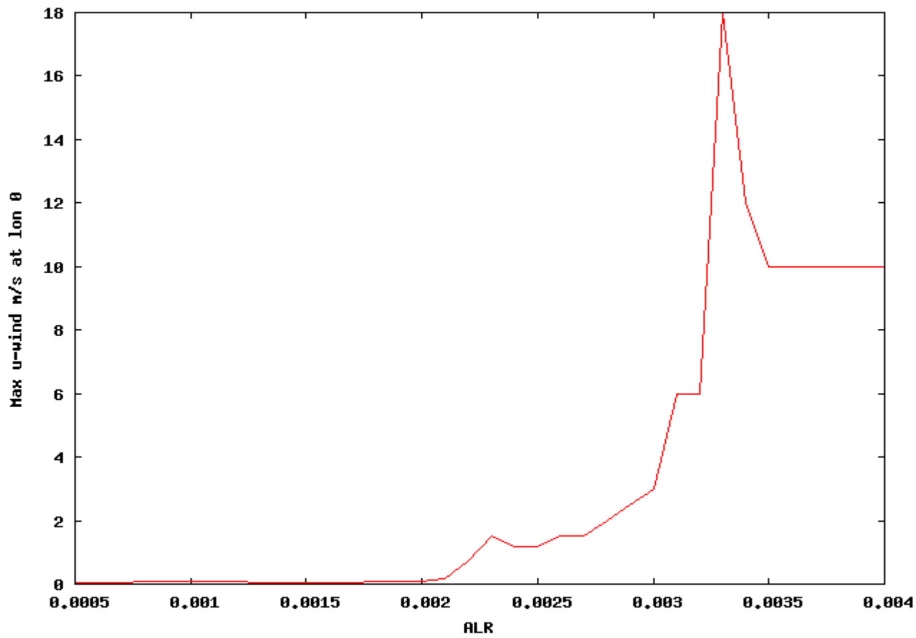

Figure 10: Maximum zonal wind [m/s] at the ground level for different ALR after one month simulated time

As can be seen, motion sets in at about 0.0021, which matches the theoretical expectation very well. This should be the value we want to use for the simulations. However, after introducing the additional heating later on, we need to consider picking a different value in order to get desirable results, since more heating changes the temperature profile, too.

3.3.2 How to introduce the MALR in a numerical model

If you want to work with the full effects of water vapor, you would have to introduce a new grid variable containing information about the water content of every single cell in the simulation. This would require a lot of changes in the model and is not practical for this project. Our approach is as follows:

- We assume that every parcel contains enough water vapor to experience the effect of latent heat release when rising.
- The reverse process, vaporization of descending water, is neglected.
- The additional heat is translated into a temperature increase for rising air, proportional to the vertical velocity.

Mathematically, it is expressed as

$$\Delta T = \Theta(-\omega) \cdot (-\omega) \cdot \alpha \tag{6}$$

$\Theta()$ is the Heaviside-function and ω the vertical velocity in pressure units, hence being negative for rising air. α controls the magnitude of the heating.

In the source code, we added the following line to the calculation of the temperature change:

$$T(:, jlev) = T(:, jlev) - \Theta(-\omega'(:, jlev)) \cdot (\omega'(:, jlev)) \cdot \alpha \quad (7)$$

Here, α denotes the newly introduced parameter controlling the strength of the heating. $T(:, jlev)$ is the temperature at all the grid points (Fortran notation). Θ is the Heaviside-function and ω' is the scaled vertical velocity in the model (in pressure units, thus negative for rising air). Suitable values range from 0 (no heating) to about 0.03, highly depending on the relaxation temperature profile, the spatial resolution and the number of time steps per day. One of the main things to do was to find appropriate values for ALR and α which lead to the desired zonal flow pattern we see in observations of Jupiter.

3.4 Test runs to find suitable parameters

A significant time was spent on tuning the model parameters. Usually this was done by modifying the source code, compiling it, running a few months of a simulation on the lowest latitudinal resolution (32 grid points in latitudinal direction) and looking at the results. The parameters we modified were mostly ALR and α, but also ntspd (number of timesteps per day):

- ALR: As mentioned in 3.3, the Adiabatic Lapse Rate controls the vertical restoration temperature profile. Because of the stability analysis and the test runs with different ALR, we chose values around 0.0020 to 0.0022. The higher the ALR, the more turbulent the dynamics and vice versa. The problem was to find a value which is not too large, causing a crash of the model, but large enough to give wind speeds as high as possible.

- α: This value is highly dependent on the latitudinal resolution. With the low resolution of 32 latitudes, values as high as 0.03 would still not cause a crash. Going up to 128 latitudes, however, a value of 0.008 caused too much turbulence, leading to a crash after a few weeks in simulated time. But if you choose a value that is too low, the effect of simulated moisture was not recognizable or too weak. Thus the problem was the same as with ALR: Find a value that is large enough to change the results significantly, compared to the simulations without the moisture term, but not too large as to cause crashes.

- ntspd: When a simulation crashed, most of the time because of a slightly too big α, another method to make it stable again was to increase the number of timesteps per day. This prevented the model from crashing to some extent, but also increased the needed CPU time.

We used a resolution of 32 to get an idea of the values we can use and if our moisture parametrization seemed to produce any reasonable results. The ultimate goal was to increase the resolution then up to 128 or even 256 to do more accurate and thus physically more meaningful simulations.

4 Results

In this section we decribe the best numerical simulation illustrates the global, high speed zonal flows. It was a simulation with a resolution of 64, $ALR = 0.0021$ and $\alpha = 0.013$. It was run for 2 years and crashed on April 13th in the second year.

All wind speeds given below are in m/s and all temperatures in Kelvin.

4.1 Evolution of the wind pattern

First we look at the development of the winds in time. On Jupiter, the winds are extremely stable over time (see Figure 2). Figure 11 shows the zonal wind at different latitudes over time at the lowest level of the atmosphere. You can clearly see that, after a period of about 4 months in the beginning, the bands are persistent until the model crashes. They spread from approximately 40 degrees south to 40 degrees north. Especially in the last months you can observe that the winds are getting stronger and stronger and eventually lead to a crash. This is due to the high sensitivity regarding α as mentioned above. We have to run simulations at the limit to see high speed zonal flows.

Another important feature is that it takes a long time to see winds of considerable speed. This made it also very difficult to try to find suitable values in high resolution simulations, where a simulated time of a year corresponds to many hours or a few days in real time.

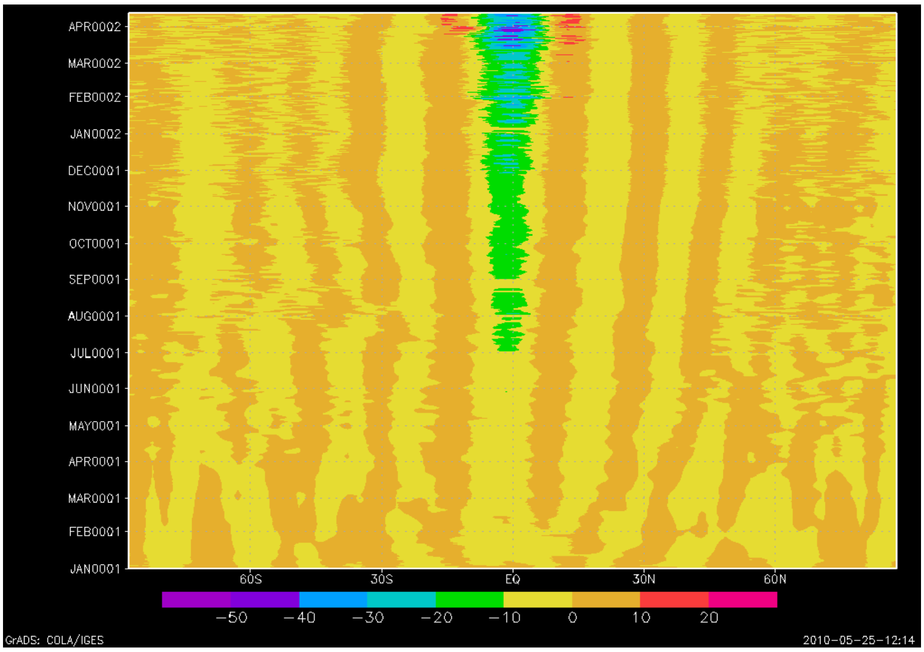

Figure 11: Zonal wind [m/s] evolution over time at the ground level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

You can also see the alternation between positive (eastwards) and negative (westwards) zonal winds in the different bands.

Figure 12 shows the meridional wind in the same plot. As expected there are no steady patterns and the magnitude, even in the end, stays mostly close to zero, because of the high rotation speed.

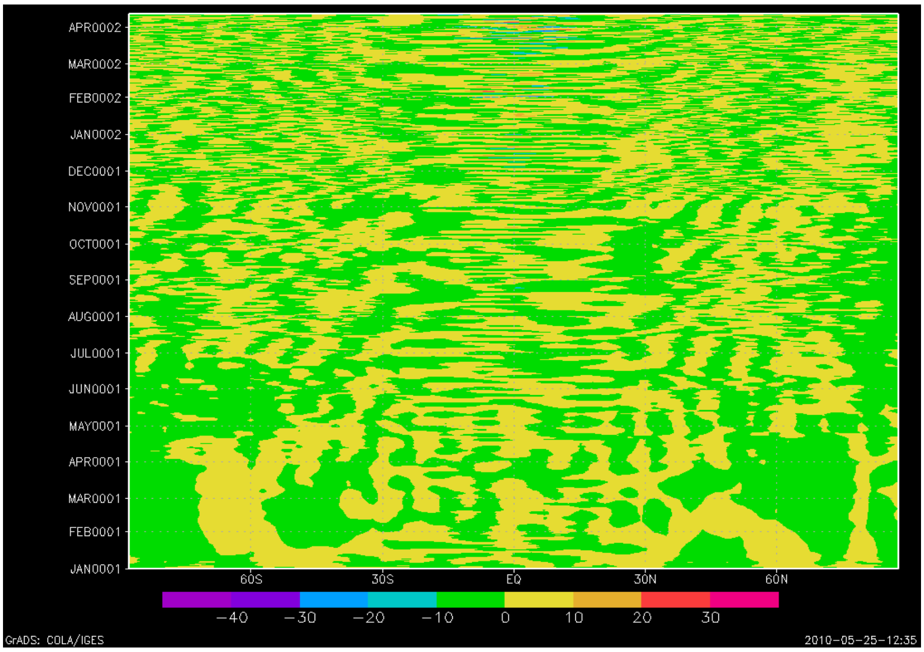

Figure 12: Meridional wind evolution over time at the ground level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

4.2 The zonal wind pattern

Now we consider snapshots close to the end of the simulation, because the wind speeds are the largest then. Figure 13 shows the zonal wind on the map one month before the crash. The zonal bands are stable over all longitudes. There are 8 bands reaching from 40 degrees north to 35 degrees south. To take a closer look at the actual magnitudes, Figure 14 shows the zonal wind at longitude 0 in white and the zonal average in green. You can see that the two graphs are almost the same, which means that the magnitude is practically stable over all longitudes. The magnitude decreases rapidly as we go towards the poles and the zonal flows completely disappear at about 40 degrees on each side. Again you can count the 8 bands one already saw on the map plot in Figure 13. One important feature of the pattern is that the equatorial jet is directed westwards, i.e. against the direction of rotation, which is not what we observe on Jupiter. This will be discussed in more detail below (See 4.5).

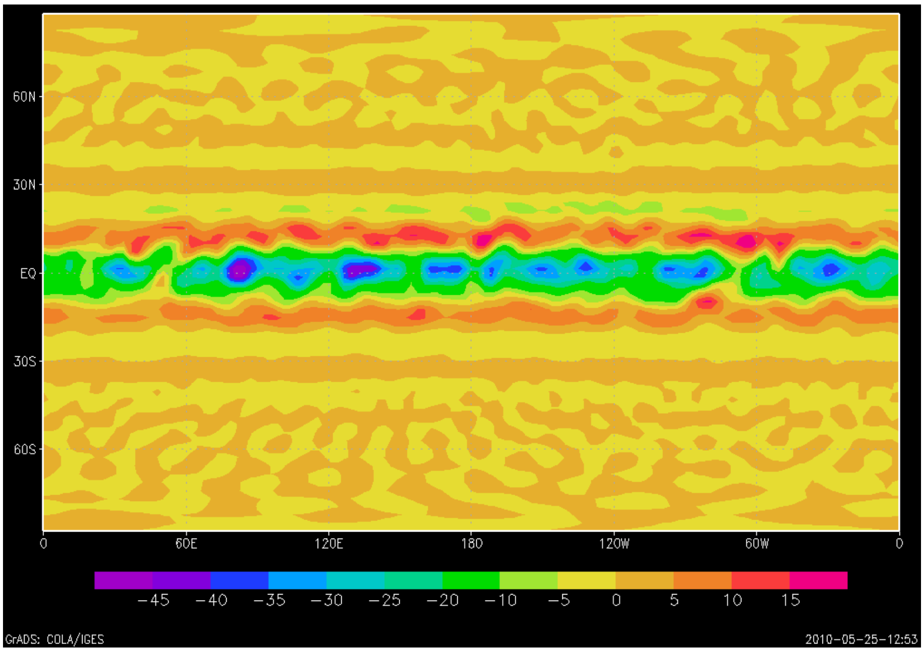

Figure 13: Zonal wind plotted on the map after 15 months at ground level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

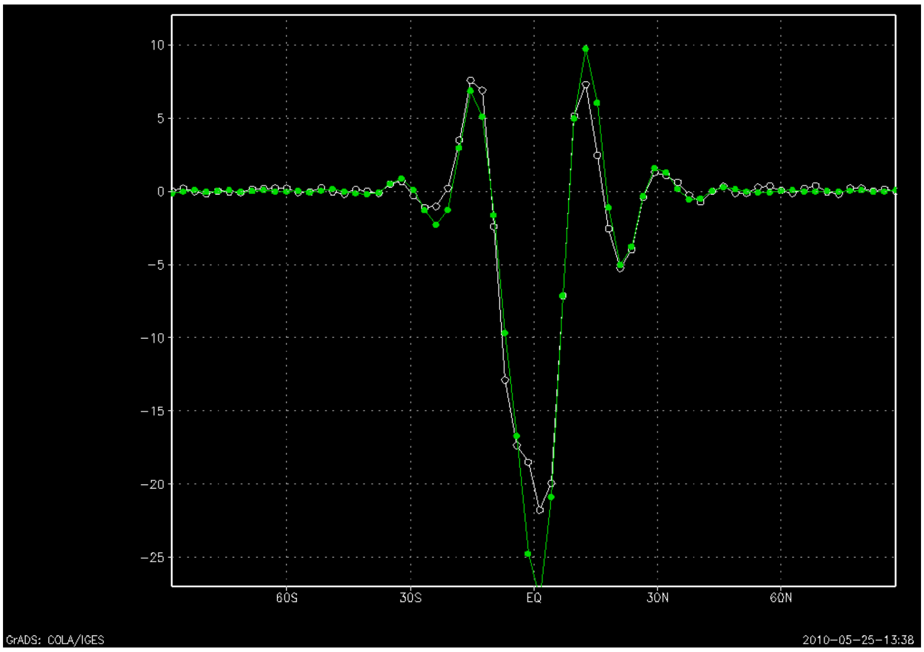

Figure 14: Zonal wind at longitude 0 in white, zonal average in green. Ground level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$.

4.3 The vertical zonal wind profile

Figure 15 shows the zonal average of the zonal wind in m/s. The y-axis is the height in terms of pressure (mbar) and the x-axis the latitude. You can see that the zonal winds are not only stable over longitudes but also stable with height. An exception is the top level, because we artificially fix the temperature there and thus perturb the dynamics.

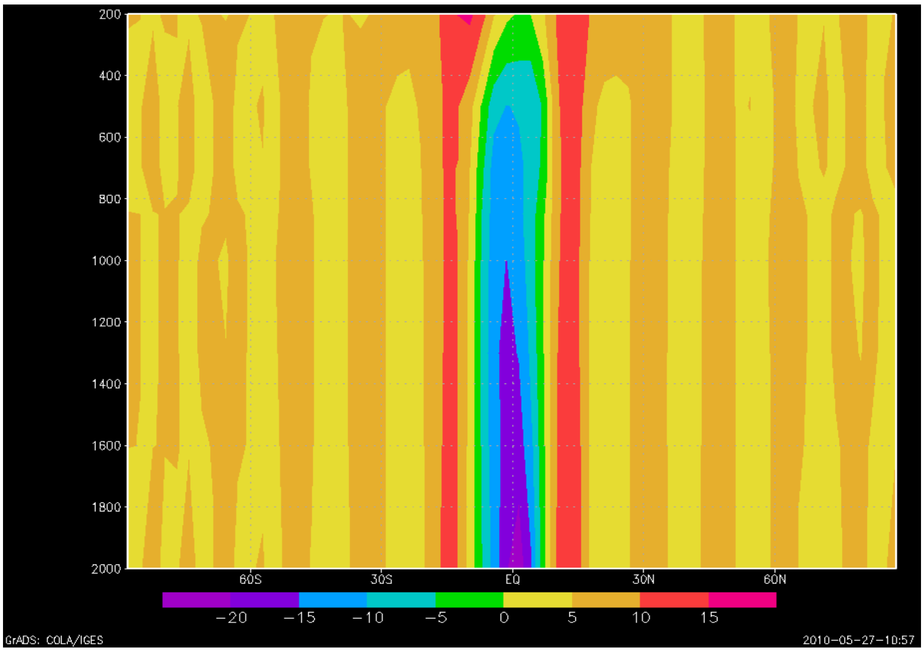

Figure 15: Vertical profile of the zonal average of the zonal wind with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

4.4 The temperature profile

Figure 16 shows the temperature profile after 15 months at the ground level. As mentioned above, we force the temperature at the ground level quickly towards a fixed value of 165 K. This causes a strange pattern, where the temperature is lowest in regions of highest wind speeds (equator) and higher and constant at the poles. If we look at a medium level as shown in Figure 17 (p = 1000 mbar), where we let the atmosphere evolve freely, the pattern is quite different and higher temperatures are seen at the equator. You also can spot some bands, following the wind pattern. This can be seen more clearly in Figure 18. One can observe that the highest wind speeds occur where the highest temperature gradients are present. You can also see the change of the coriolis coefficient crossing the equator, because in the south the winds have the same sign as the temperature gradient and in the north it is the opposite way.

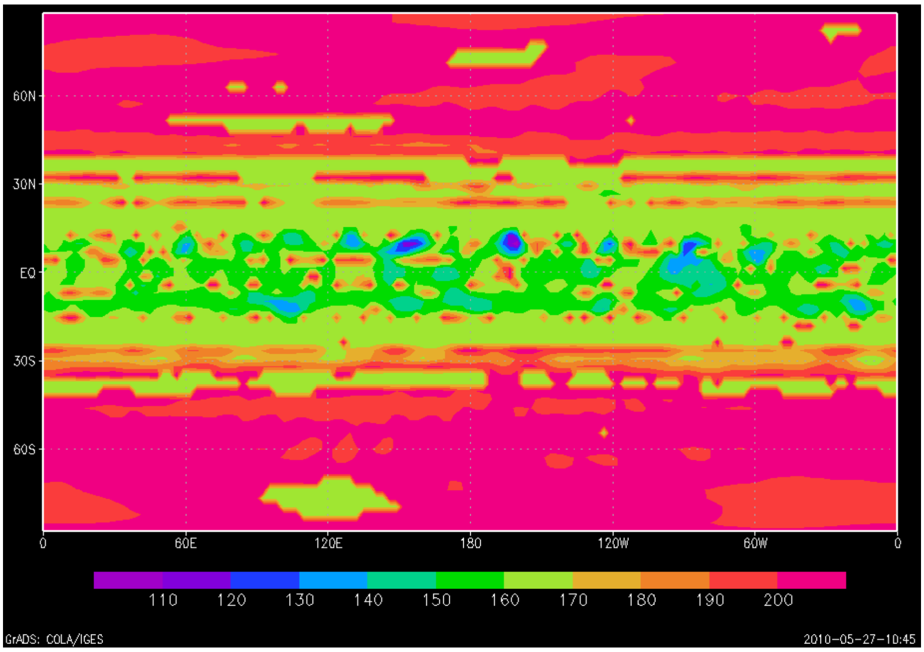

Figure 16: Temperature [K] map at the ground level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

We can also look at the vertical temperature profile and compare it to the vertical profile of the vertical velocity $-\omega$ in units of mbar per second. Figure 19 shows the temperature and Figure 20 the vertical velocity. You can see that the upward motion is also somewhat arranged in bands and the temperature is higher where strong upward winds (positive values) occur, which is to be expected after introducing the moist parametrization.

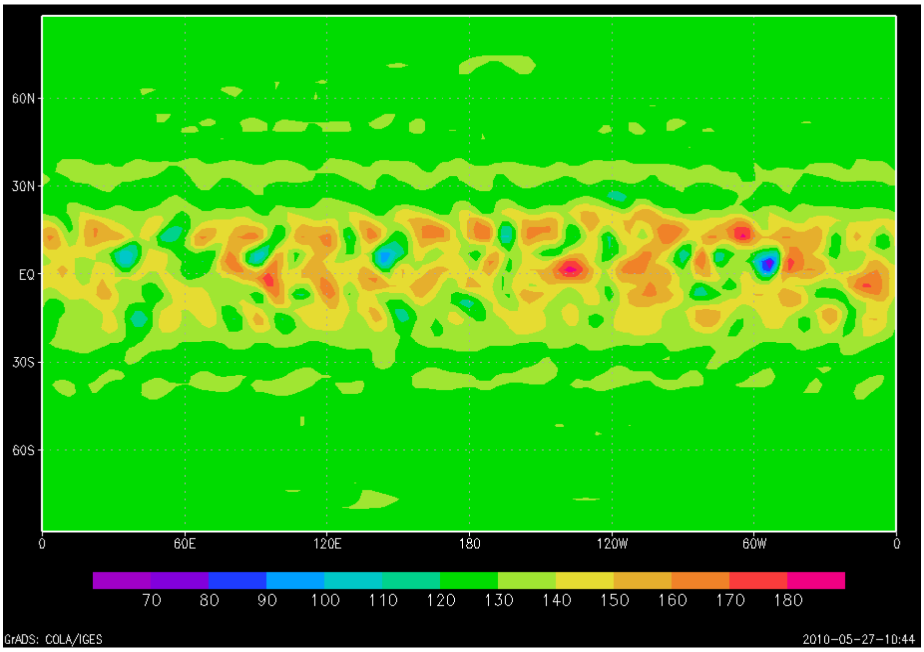

Figure 17: Temperature [K] map at the p = 1000 mbar level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

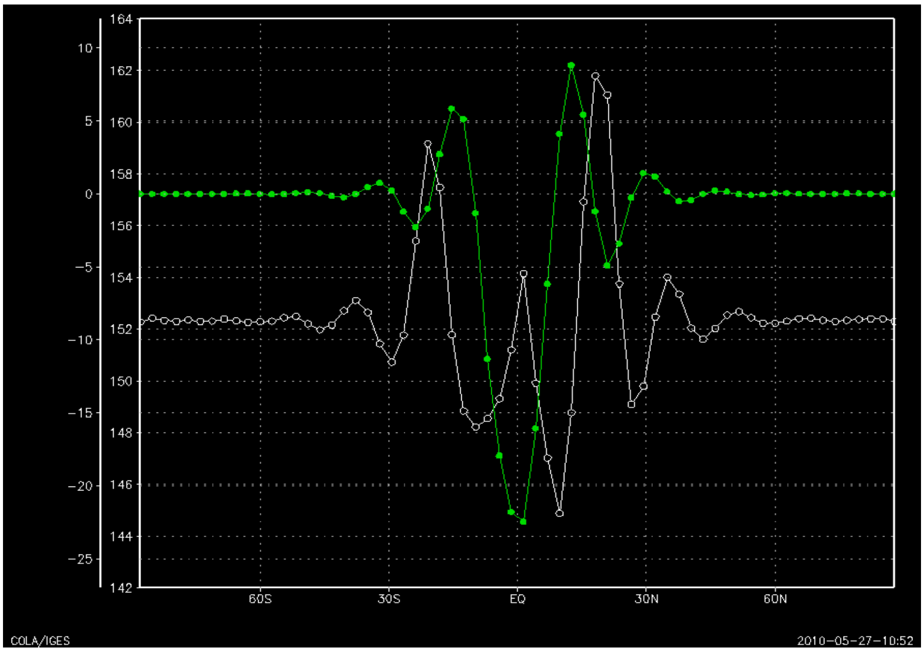

Figure 18: Temperature (white) and zonal wind (green) at the p = 1500 mbar level with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

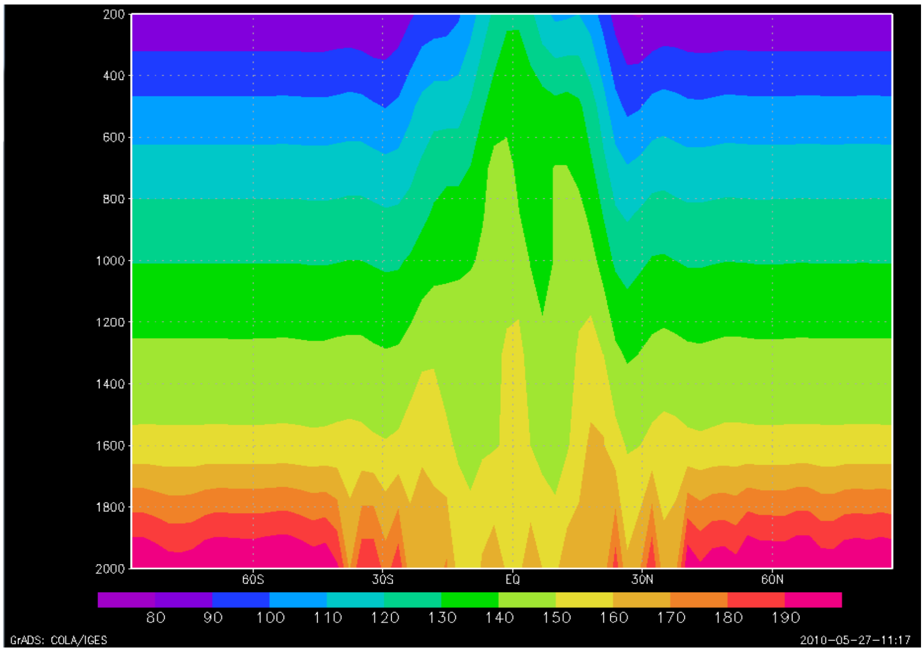

Figure 19: Vertical temperature [K] profile, zonal average, with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

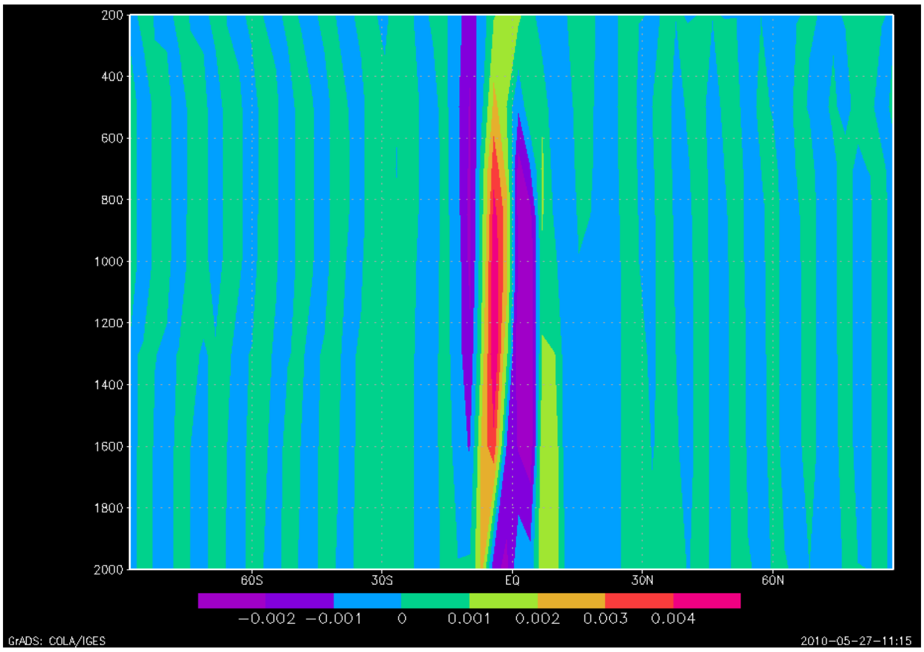

Figure 20: Vertical $-\omega$ [mbar/s] profile, zonal average, with 64 latitudes and 128 longitudes, $ALR = 0.0021$ and $\alpha = 0.013$

4.5 Equatorial Jet

One major problem with the simulation results is that the strongest band, the equatorial jet, goes in the "wrong" direction, i.e. westwards instead of eastwards, what you observe on Jupiter. However, previous attempts on simulating zonal flows on Jupiter showed mostly the same behavior. This suggests that there is something missing in the model, for example magnetohydrodynamic drag in the bottom layer. One should not expect to get this superrotation correctly using a simple model as PUMA.

However, in one simulation, using 64 latitudes, an ALR of 0.0024 and $\alpha = 0.001$, we got a very weak equatorial flow into to correct (eastwards) direction after one year of simulated time (See Figure 21).

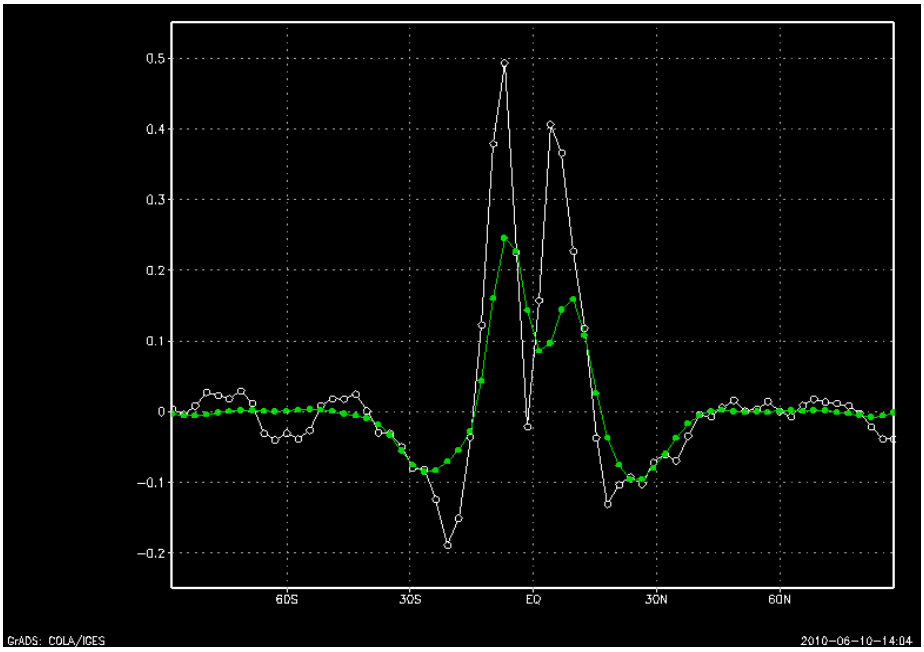

Figure 21: Zonal wind at the p = 700 mbar level. Average in green, values at longitude 0 in white, with 64 latitudes and 128 longitudes, $ALR = 0.0024$ and $\alpha = 0.001$

4.6 Absolute values of the wind speeds

So far we only considered the change of the sign of the zonal wind with latitude to see that we have alternating bands of east- and westwards directed winds. The real value in meters per second, however, is a lot smaller than observed on Jupiter (see Figure 2). On the other hand, a crucial parameter for the magnitude of the wind speeds is the spatial resolution of the model. This should not influence the physics, of course. Thus a reasonable comment on the actual wind speeds cannot be made. The only thing which can be analyzed is the ratio of neighboring bands. Here we see that the magnitude drops very fast if we go to higher latitudes. This is also not observed on Jupiter, but might be a consequence of resolution as well. In the 128 latitudes simulation, the zonal bands were not seen as clearly as for the 64 latitudes simulation, but the decrease in magnitude is lower (Figure 23).

4.7 The 128 latitudes simulation

If we go to higher spatial resolution, the model gets a lot more sensitive with regard to α. The following simulation was run with $ALR = 0.0021$ and $\alpha = 0.007$ for one year. Figure 22 shows the zonal wind on the map at the ground level. You can see that the general pattern is the same as for 64 but the band structure is less developed. Also you see fewer bands and the magnitude of the winds is a lot lower. Figure 23 shows the zonal wind at longitude 0 in green and the zonal average in white. You see that they overlap but not as clearly as for the 64 simulation. You also see that the maximum wind speeds are about 3 m/s compared to 25 m/s in the previous simulation. This is due to the fact that α is probably a little too low. However, all our attempts to increase it a little bit led to crashes before clear, strong zonal flows could develop.

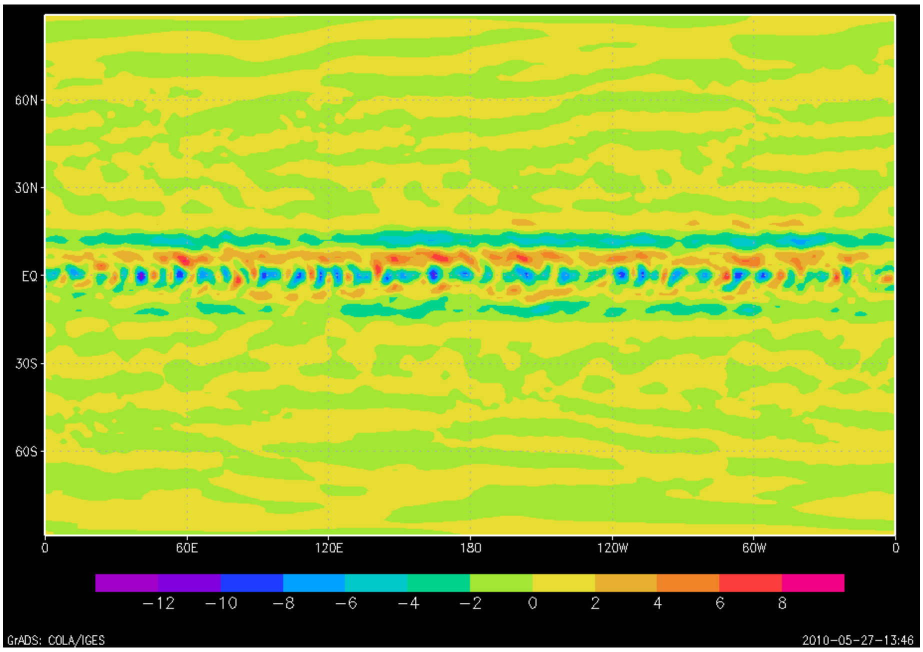

Figure 22: Zonal wind map at ground level, with 128 latitudes and 256 longitudes, $ALR = 0.0021$ and $\alpha = 0.007$

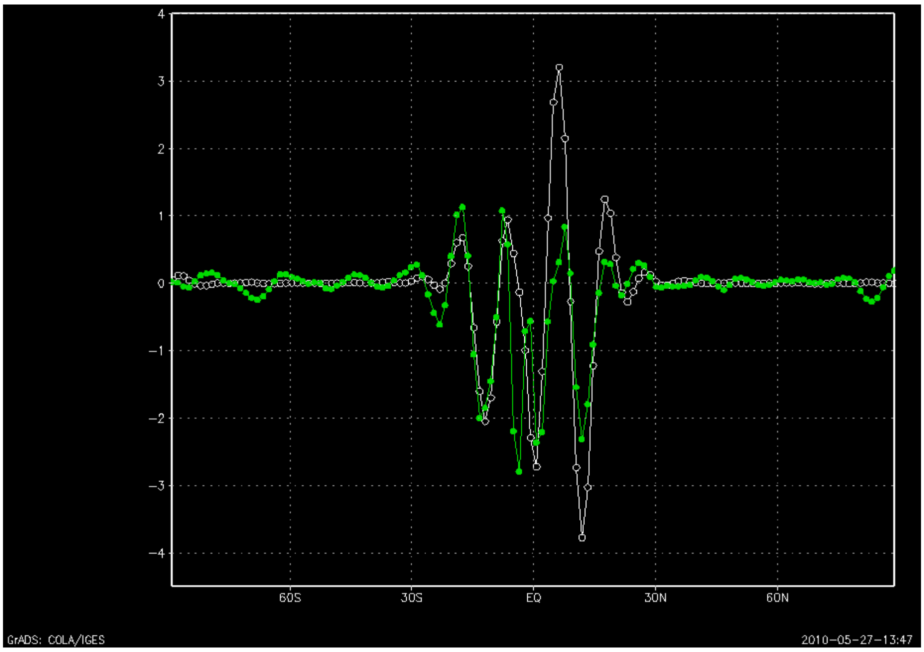

Figure 23: Zonal wind at longitude 0 in green and zonal average in white. At ground level with 128 latitudes and 256 longitudes, $ALR = 0.0021$ and $\alpha = 0.007$

5 Conclusion

Our experiments have shown that PUMA most likely isn't the best starting point for doing Jupiter simulations. Not only do wind speeds increase when resolution is increased but there are also some inconsistencies between what happens in the northern and southern hemisphere which leads us to believe that there are some errors in the initial model. One difficulty was that the model crashed more easily with higher numerical resolution, and when a stronger forcing by moisture was applied.

The numerical simulations, presented here,turn out not to be sufficient to confirm or reject the hypothesis that zonal flows are casused by moist convection. Zonal flows are not present if the model does not include moist convection. When included in the model, zonal flows do accur. However (1) their direction is opposite to the observed on Jupiter and (2) the pattern usually only appears close to the equator, which could imply that we are on the right track but that there are some other key factors that we haven't considered in our model that are necessary for accurate modeling of Jupiter's atmosphere.

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