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Understanding Basic Concepts of Numerical Weather Prediction Using Single Level Atmospheric Model

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ABSTRACT: *Weather impacts all daily lives from a very hot summer day to a cold winter storm. Predicting these events and other weather phenomena has lead scientist to develop the most accurate way to forecast weather, numerical weather prediction. This system developed over the last 100 years has created more accurate and longer forecast periods, as well as, created a highly complex system of calculations designed to simulate atmospheric motions. This simulation requires the use of large computing systems for the computation but through the use of a simplified computer program one can gain a full understanding of the process of numerical weather prediction and the complexity of its parts. The aim of this research is to use a single level atmospheric model to understand some basic concepts of numerical weather prediction. Reference geopotential height of 5500 meters which represent the height of 500 mb pressure level was used as a single level. The model results showed that initial geopotential has two distinct centres of low and high geopotentials and the high centre is situated close to reference point. The results also indicated that the change in the time step interval of the integration does not affect the solution of shallow water equations and increasing the forecast length would result in the deformation in the geopotential patterns. Adding a mean zonal flow to the system resulted in a wavy pattern of the geopotential height but the behaviour of the mid-point geopotential and wind filed were similar to those cases of no mean zonal flow.*

Keywords: *Shallow, Weather, Prediction, Model.*

I. INTRODUCTION

Numerical weather prediction is the most widely used and accurate prediction system today. Its complexity and enormous calculations require the use of large computing systems for computation. Through the use of a simplified computer program one can analyze wind patterns and how they change over time.

Simplified numerical atmospheric model based on the shallow water equations provides a guide for understanding the basic concepts behind numerical weather prediction. Such concepts include: finite differences, time stepping scheme, and Rossby waves. These important concepts are basic and found in many larger and more complex atmospheric models. Through studying these ideas and analyzing the results one can gain a full understanding of the process of numerical weather prediction and the complexity of its parts.

In meteorology the shallow water equations, which is also called the primitive barotropic equations, has been used to test new numerical models before implementing them in the 3-D atmospheric models. The pioneer researches on this matter include works by Grammelvedt [1], Gustafsson [2], Cullen [3], Elvius and Sundstrom [4], and Fairweatter and Navon [5]. Lynch has developed a simplified model to solve the one-dimension barotropic primitive equation using shallow water equations [6]. Neta, el al., (1997) [7] have solved 2-D shallow water equations in spherical coordinates using Turkel-Zwas scheme. Navo, el al., (2004) [8] proposed linearized shallow water equations models using perfectly matched layer approach. Lee and Sulliva (2007) [9] suggested a fast simplified scheme for solving shallow water equations by simplifying Navier Stokes equations. They assumed that the fluid compressibility is weak to avoid solving Poisson equations. Cheng (2008) [10] studied the effect of stability on the circulation of non-linear shallow water equations. Ferguson (2008) [11] developed a simplified climatological to understand the mechanism of energy transfer between tropical and mid-latitude regions. Verkley (2009) [12] derived the barotropic vorticity equation for the 1-D spherical shallow water equations. Burkardt (2010) [13] developed an algorithm to solve the shallow water. Al-Maksosy (2011) [14] developed and applied three numerical models are quasi-geostrophic model, the large scale tropical circulations, and the barotropic model to investigate of some characteristics of atmospheric flow. Roomi (2013) [15] used the non-divergent barotropic, shallow water equations, and Weather Research and Forecasting (WRF) models to evaluated the numerical weather prediction over middle east. Zaiter [16] (2016) studied the thermal wind characteristics over Iraq and surrounding regions by calculated the thermal wind as a function of latitude for the northern hemisphere to investigate its variations over longitudinal cross-sections.

II. MATERIALS AND METHODS

2.1 SINGLE LEVEL ATMOSPHERIC MODEL

2.1.1 MODEL FORMULATION

The shallow water equations may be rewritten as [17]:

$$\frac{du}{dt} - fv + g\frac{dz}{dt} = 0 \quad (1)$$

$$\frac{dv}{dt} + fu + g\frac{dz}{dt} = 0 \quad (2)$$

$$\frac{dw}{dt} + z\left(\frac{du}{dx} + \frac{dv}{dy}\right) = 0 \quad (3)$$

where u is the zonal velocity component, v is the meridional velocity component, and z is the geopotential height.

In order to solve the model equations, a single level atmosphere is assumed with a fixed initial geopotential height. Initial zonal and meridional velocity components are assumed to be geostrophic.

2.1.2 MODEL IMPLEMENTATION

The model was implemented using the followings steps:

- Initial Conditions: setting initial geopotential height

$$Z_o = Z_{ref} + \bar{Z} + Z_{wave} \quad (4)$$

where Z_{ref} is the reference height, $\bar{Z}$is height of mean zonal flow, and Z_{wave} is the height of perturbations.

- Initial winds (u_0, v_0) are geostrophic.
- Boundary Conditions: Periodic in x Walls at North and South (v = 0, dz/dx = 0).
- Four to one aspect ratio was used for defining the domain ($L_x = 32 \times 10^6$m, $L_y = 8 \times 10^6$ m, $N_x = 41, N_y = 11$).
- Define initial conditions

$$Z_{ref} = 5500m \quad (5)$$

$$\bar{Z} = -(\bar{u}/g)[f_o(y - y_o) + 0.5\beta(y - y_o)^2] \quad (6)$$

$$Z_{wave} = Z_{amp}\left[sin(2\pi m_x x/L_x)cos(\pi m_y(y - y_o)/L_y)\right] \quad (7)$$

where $\bar{u}$ is the mean flow, g is the acceleration of gravity, f_o is the mean value of Coriolis parameter ($f_o = 2\Omega sin\phi$), $y_o = L_y/2$, $\beta = 2\Omega cos\phi/a$where Ω is the rotation of Earth [$\Omega = 2\pi/(24 \times 60 \times 60)$], and *a* is the radius of Earth. m_x and m_y are the wavenumber in and x and y directions respectively.

Figures 1 to 3 show an example of the model output for 2 days forecast, Figure 1 shows the initial geopotential which illustrate two distinct centers of low and high geopotential, the high center is situated close to reference point. Geopotential height approximates the actual height of a pressure surface above mean sea-level. Therefore, a geopotential height observation represents the height of the pressure surface on which the observation was taken. Since cold air is denser than warm air, it causes pressure surfaces to be lower in colder air masses, while less dense, warmer air allows the pressure surfaces to be higher. Thus, heights are lower in cold air masses, and higher in warm air masses. In this example it was assumed that reference geopotential height was 5500 meters which represent the height of 500 mb pressure level. The center of high geopotential is located at (x=7500 km, y=4000 km) and the center of low geopotential is located at (x=25000 km, 4000 km).

Figure 2 gives the forecast steps at 12 hours' interval, it is seen that the system is moving westwards and high and low centers to x=2500 and 225000 km. The motion of the system becomes slower with time step progress. It is also seen that the initial circular shapes of low and high centers start to deform in the direction of motion.

Figure 3 shows the variations of mid-point (x/2, y/2) for geopotential and wind components u and v with time step. It is seen that the geopotential height at the mid-point decreases with time step reaching below 5100 m at ending time step of 96 (2 days×3600 sec/1800 sec = 96). The mid-point u and v behaves similarly and generally increasing with time steps. u and v are both negative indicating westward movement. It is also noticeable that the rate of change of both u and v becomes slower as time progresses.

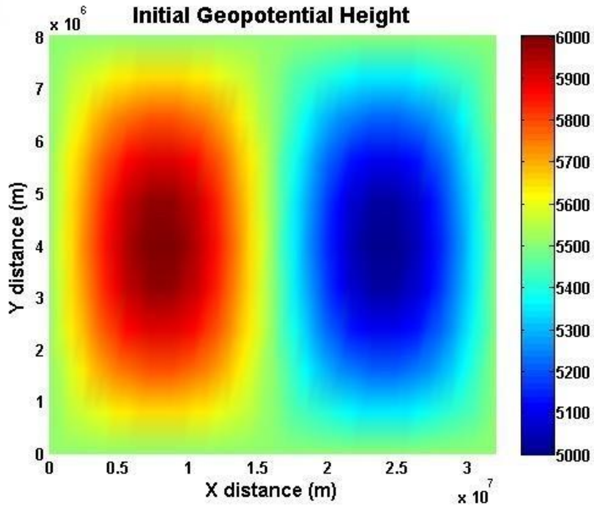

Figure 1. Initial geopotential height and for a reference height of 5500 meters.

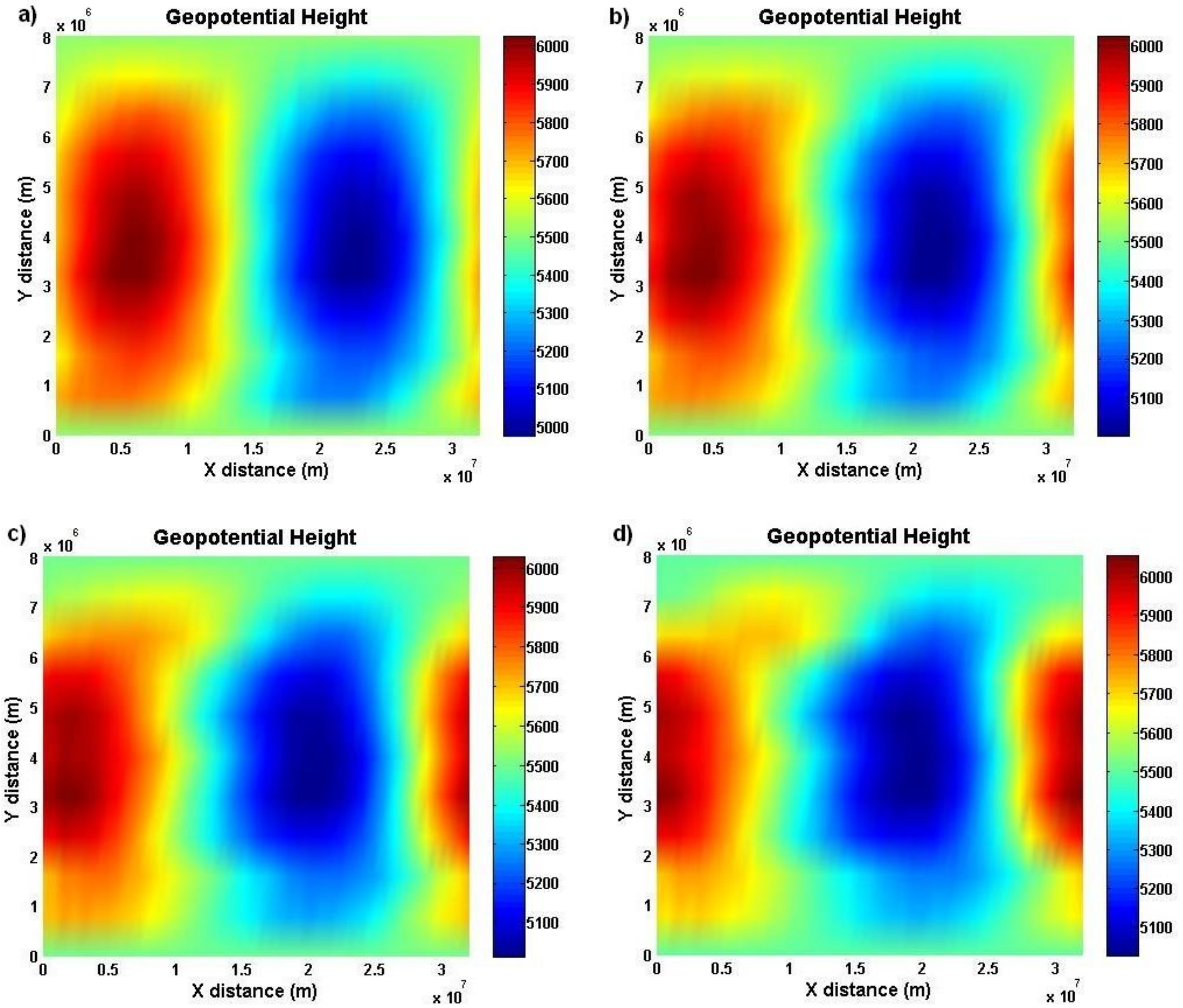

Figure 2. Geopotential heights after a) 12 hrs., b) 24 hrs., c) 36 hrs. and d) 48 hrs. for reference height of 5500 meters.

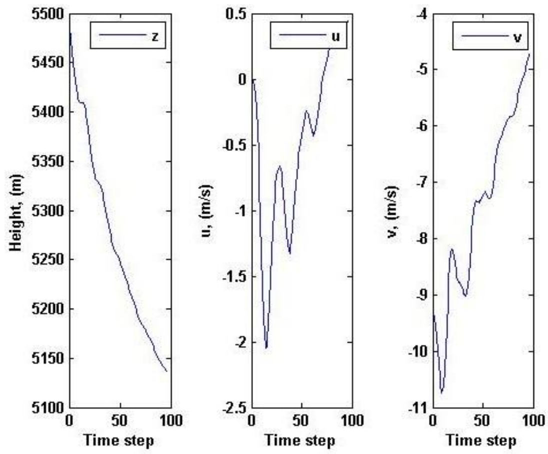

Figure 3. Geopotential heights and wind fields at mid-point of for reference height of 5500 meters.

III. RESULT AND DISCUSSION

The single atmospheric model was used to investigate the effects of time step interval, pressure level, length of forecast, and mean zonal flow on the geopotential height behavior. Figure 4 illustrates the behavior for 5500 m geopotential height for 600 seconds time step interval for 2days forecast, i.e 288 time steps, it is seen that the results are identical to those for 1800 seconds time step interval. This suggests that changing the time step interval does not affect the solution of shallow water equations.

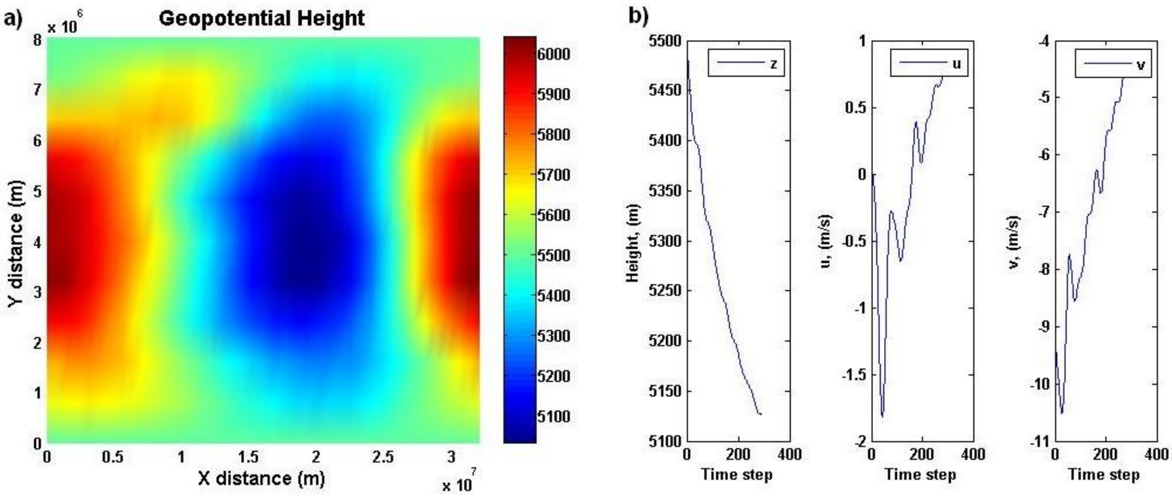

Figure 4. Final geopotential heights (a) and mid-point geopotential and wind filed (b) of 5500 meters reference height for time step interval of 600 sec.

Figure 5 shows the effect on increasing the forecast length from two days to four days. It is apparent that more deformation in the geopotential patterns is occurring. For the mid-point the geopotential height starts to increase at 150-time step (about 72 hours or 3 days) and u component of the wind starts to decrease while the v components is much less affected.

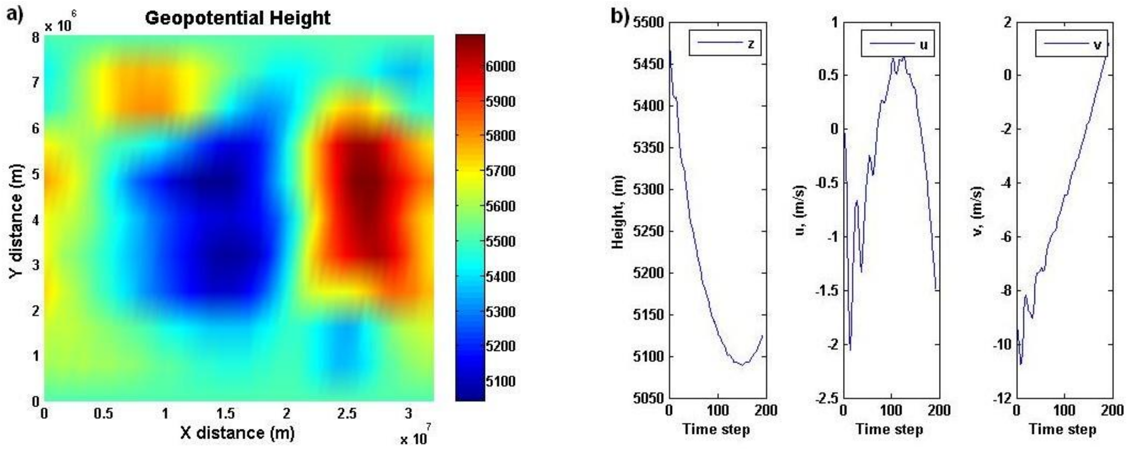

Figure 5. Final geopotential heights (a) and mid-point geopotential and wind filed (b) of 5500 meters reference height for four days forecast length.

Figure 6 gives the results for adding a mean zonal flow of 10 m/s to the system. It is evident that adding mean zonal flow would result in a wavy pattern of the geopotential height but the behavior of the mid-point geopotential and wind filed is similar to those obtained in previous cases. Needleless to mention that the main zonal flow was added to the zonal components of the wind. The geopotential height pattern in this assumed a shape similar to the real world patterns of the geopotential height such as the example depicted by Figure7.

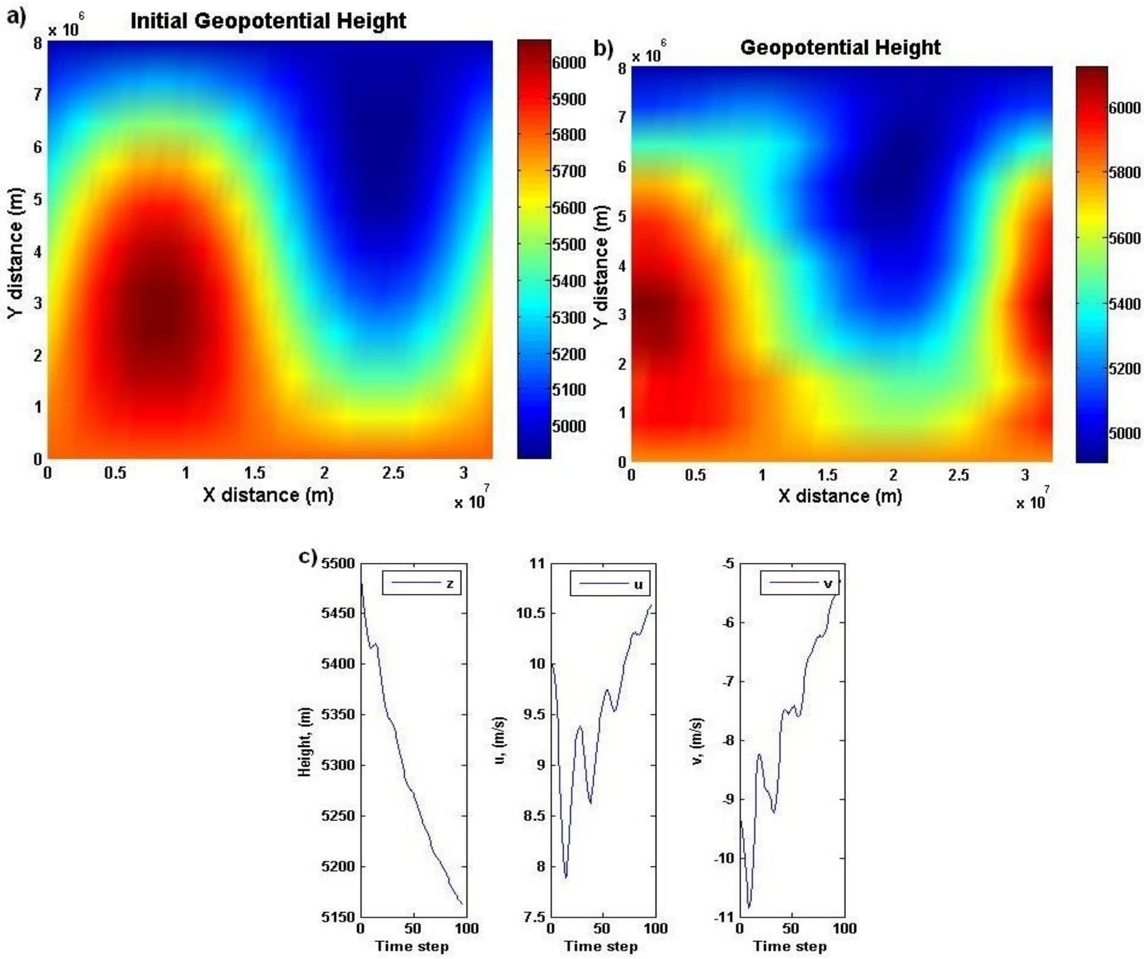

Figure 6. Initial geopotential height (a), final geopotential heights (b) and mid-point geopotential and wind filed (c) of 5500 meters reference height for mean zonal flow of 10 m/s.

IV. CONCLUSION

In this research a simple single level atmospheric model which is based on the shallow water equations was used to illustrate some basic concepts of numerical weather prediction. Results indicated the solution of shallow water equations is not affected by the change of the time step interval but duplicating the forecast length would result in the deformation in the geopotential patterns because the zonal component of the wind is much affected by the forecast length than the meridional component. The results also illustrated that adding a mean zonal flow to the system would result in a wavy pattern of the geopotential height and no effects on the wind filed.

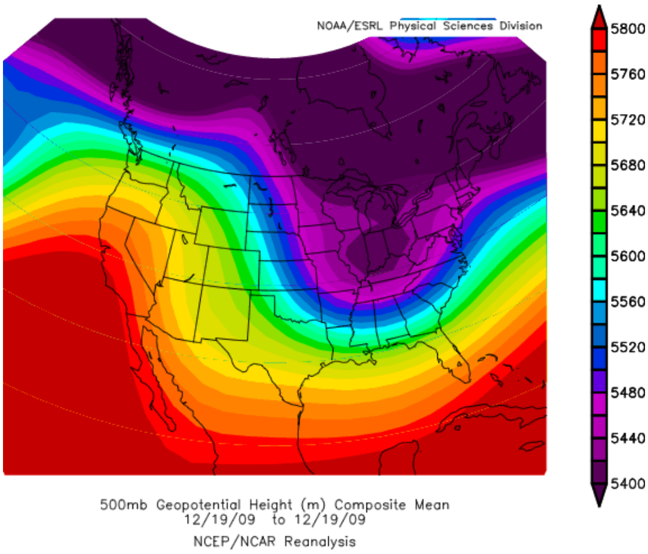

Figure 7. An example of real geopotential height map for 19th December, 2009 over North America.

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