

## Model of a Thermally Driven Pump to Assist in Driving the Meridional Circulation from Summer to Winter Pole Via the Mesosphere

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October 8, 2009

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### Abstract:

The possibility that the meridional pole to pole circulation is at least partially thermally driven has been reexamined. The model results in a contribution of meridional flow velocity of 5 m/s and enhances the conveyance of water vapor into the mesosphere.

### Introduction

Kellog and Schilling [1951] first proposed a pole to pole circulation in the upper stratosphere. This model was analyzed in detail by Murgatroyd and Singleton [1961] who suggested that the heating occurred in the stratosphere over the summer pole so that the air would rise vertically to the mesopause, flow with a velocity of about 1 m/s horizontally to the winter pole where it would descend. Leovy [1964] carried this model further. In the intervening years the concept thermally driven flow has been replaced with a pole to pole flow driven entirely by gravity waves (see Holton 1983 and Plumb 2002). Currently none of the models agree with measured meridional flow rates (see Yuan et al. 2008).

However, neither the originally proposed thermally driven models nor the newer gravity wave driven models produce a large enough flow rate needed to explain the observed meridional wind velocities in the mesopause measured by Lidars are over 10 m/s while velocities from radar and optical measurements of noctilucent clouds at high latitudes are as high as 50 m/s.

In this paper it is suggested that the contribution of the vertical portions to the circulation of the flow provide a pump to drive the flow.

The proposed concept is as follows:

- 1] The air in the region of the upper stratosphere is heated by the constant solar radiation at the summer pole.
- 2] The heated air expands causing a vertical column to form which has excess pressure at the level of the mesopause.
- 3] The excess pressure provides the force which starts the air moving away from the summer pole towards the winter pole.
- 4] More air from the stratosphere at the bottom of the column moves in to complete the cycle.

In the steady state the air leaving near the top of the column will be very cold as a result of the adiabatic expansion which takes place as the column rises. At the winter pole the descending air is adiabatically heated in a complementary manner. The entire system is

somewhat analogous to the “Einstein refrigerator” [Einstein and Szilard, 1930]. In this system a heat source, normally a propane flame, drives an ammonia water mixture acting as a refrigerant around a circular path to produce a refrigerator without a pump or any moving parts. While the Einstein refrigerator needs a refrigerant, that changes state as the mixture circulates, gravity provides sufficient change in pressure for a refrigerator to work in the atmosphere without a change in state. A basic requirement for its operation is that the air column over which the circulation operates be a significant fraction of the scale height of the gas. Therefore in order to demonstrate this “gravity based” refrigerator we need to resort to a mathematical model implemented in computer code as building a circular path which pipes extending vertically many kilometers is not practical.

### Model details

The model is based on a vertical column of air  $1\text{m}^2$  in cross-section extending made of discrete parcels on equal mass,  $m$ , where

$$m = M_{\rho} A_w N f \quad (1)$$

$$M_{\rho} = \text{atomic mass} = 1.6726 \times 10^{-27} \text{ kg}$$

$$A_w = \text{atomic weight of air} = 28.8$$

$$N = \text{number of molecules in “mole”} = 6.02 \times 10^{23}$$

$$f = \text{fraction of a “mole” in each packet}$$

In hydrostatic equilibrium the pressure the  $k^{\text{th}}$  parcel is just equal to

$$p_K = n_K g m \quad (2)$$

where  $g = \text{acceleration of gravity} = 9.8 \text{ m/s}^2$

$$n_K = \text{number of parcels above the } k^{\text{th}} \text{ packet}$$

and the vertical extent of each parcel is given by the gas law

$$v_K = N f K T_K / p_K \quad (3)$$

where  $K = \text{Boltzmann’s constant} = 1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ k}^{-1}$

$T_K = \text{temperature of parcel and the height of each parcel above the base of the column is}$

$$z_K = \sum_0^{n_K} v_K \quad (4)$$

when the solar heat is applied the temperature of a parcel increases at a rate of

$$\Delta T / dt = P v_K / (C_p m) \quad (5)$$

where  $P = \text{solar flux absorbed by 1 m of the column}$

$$C_p = \text{the specific heat of air under constant pressure}$$

$$= 1.005 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

When the parcels expand they move upwards and at a height, H, they can exit from the column horizontally to be replaced by another equal mass parcel which enters at the base of the column. This “one for one” parcel exchange ensures continuity of mass. When a parcel moves up the pressure drops by the weight of one parcel which results in adiabatic cooling of  $\Delta T = -\nu_K g / C_p$

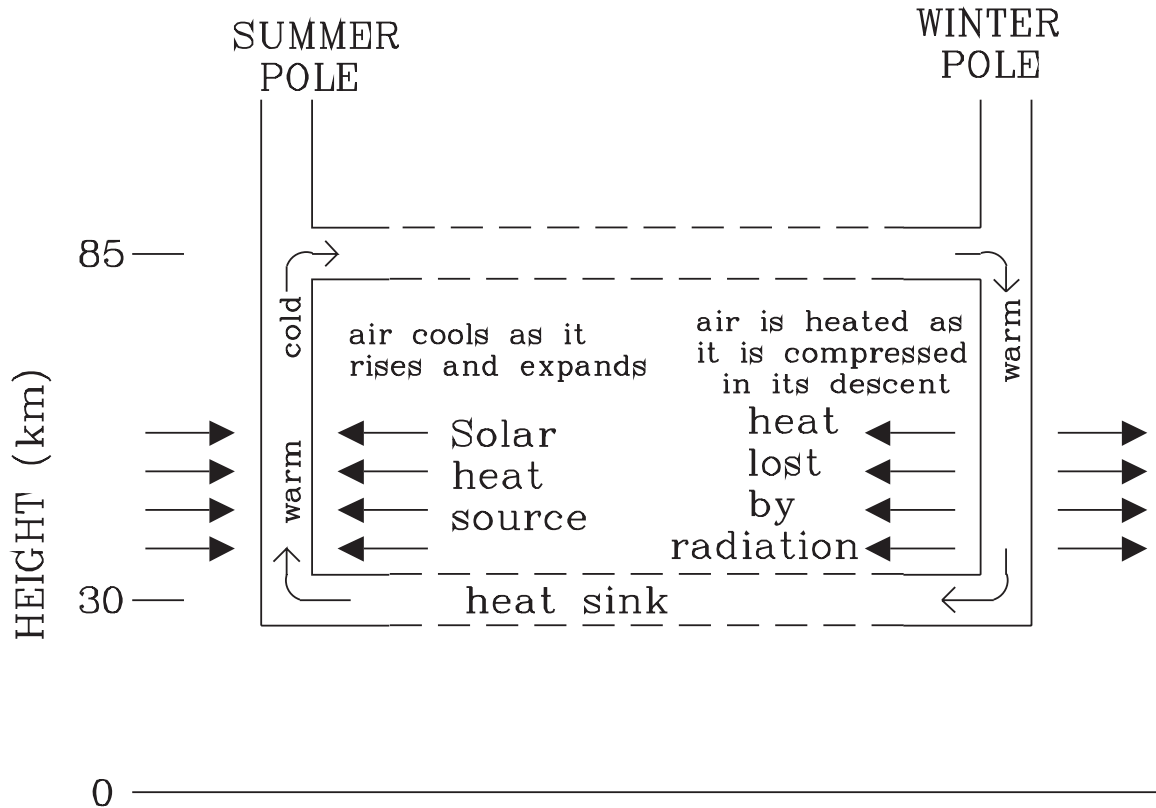


Figure 1. Diagram of proposed pole to pole circulation driven by “gravity” refrigerator  
 Figure 1 illustrates the geometry of the model. The model does not address the nature of the horizontal meridional flow to the winter pole and assumes that the momentum transfer needed to allow this flow to follow the Earth’s rotation is provided by the mixing which results from gravity waves breaking in the mesosphere. The model, at this point, only considers the driving heat engine of the flow. For the computer modeling the following additional parameters were assumed:

Height of exit above column base	85 km
Height of the column base	30 km
Pressure at the base of the column	$10^3$ Pa
Temperature at the base of the column	220 K
Solar heating rate	10 K/day (see Fomichev, 2009)
Altitude range of heating	30 to 70 km

## **Results of model simulation**

The model started with a column of air with a uniform temperature of 220 K and reached steady state in about 10 days. At this point the solution reached a minimum temperature of 110 K at 85 km, the top of the column, a maximum temperature of 320 K at 40 km and a corresponding flow rate of 4 m/s. As expected the rate of change of potential energy in the column mass flow resulting in a 4 m/s at 85 km minus the rate of loss of internal energy equals the solar power absorbed in the column. The model simulation is reversible. If the solar heating is replaced with radiative cooling the column descends and the air in the mesosphere is heated.

## **Pole to pole circulation**

While the model only demonstrates the possibility that a significant driving force for the pole to pole circulation is thermal the modeling of the overall circulation is extremely complex and has to involve momentum transfer. If the flow is primarily driven by the heat pump engine at the summer pole the circulation will peak at the solstices and reverse flow at each equinox. If the layer of the flow has a constant height thickness the flow rate will be a minimum at the equator and increase at high latitudes. In addition, there will be a phase lag at of about 10 days.

## **Comments on the model**

The model produces a flow rate of 4 m/s which is larger than the 1 m/s of earlier thermally driven models but not large enough to account for velocities ten times larger seen in the observations of the noctilucent clouds which are thought to be conveyed by the meridional circulation. Holton (1983) estimates a meridional flow due to a hemispheric asymmetry in the gravity wave drag of about 10 m/s at the equator at solstice. The Holton model predicts declining velocity at higher latitudes dropping to about 3 m/s at 75 degrees. If the proposed thermal drive is added to the gravity wave drive the flow velocity might be more uniform or even increase with latitude and also exceed 10 m/s. Adding the proposed “gravity refrigerator” increases the upwelling and lowers the temperature in the mesosphere above the summer pole. In addition, the thermal drive should increase the transport of water vapor from lower altitude thereby enhancing the formation of ice crystals in the mesosphere needed to form the noctilucent clouds. In the combined thermal and gravity wave model the velocities could be further increased by increasing the solar heating, which may be underestimated.

It is emphasized that this proposed model to “boost” to the meridional circulation is extremely tentative and is only put forward to encourage more work on the circulation in the mesosphere. This work was motivated by the strong semidiurnal signature in concentration of the mesospheric ozone, seen in the 11 GHz ozone line which might be explained by the pole to pole circulation of water vapor.

## **References**

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