Subsidence Required to Replace Heat Loss by Radiation with Work of Compression

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ABSTRACT

The temperature of the troposphere is constant over the long run because energy lost by radiation is compensated for by subsidence warming. Compensating for radiative cooling requires that the troposphere subside at a velocity of approximately 500 m d^{-1}, corresponding to subsidence mass fluxes of 5 kPa d^{-1} near the bottom and 1 kPa d^{-1} near the top of the troposphere. The mass flux decreasing in the upward direction results from surface air rising to a range of levels.

The warming occurs where the air subsides and not where the latent heat of water vapour is released. The subsidence tends to occur where the atmosphere is coldest and easiest to compress. The warming produced by intense updrafts is not limited to the local area and can be distributed over the whole globe. The warming can occurs in areas remote from the updraft such as the rainless sub-tropical regions and the polar regions.

The subsidence velocity is limited by warming because subsidence velocities greater than 500 m d^{-1} increase local temperature causing the subsidence to take place elsewhere. A subsidence velocity of 500 m d^{-1} (0.006 m s^{-1}) is much lower than the typical updrafts velocity of 1 m s^{-1}. Mass balance limits the fractional area of the updrafts to about 1% thereby restricting possible flow regimes. There can be no classic Hadley direct or and Ferrel indirect circulation cells with upflow and downflow of approximately equal areas. A general circulation scheme consisting of fast penetrative drafts and slowly subsiding layers is proposed.

The paper analyses how energy is transferred from the updrafts to the subsiding layers. The convection process transfers energy for rising air to descending air, from wherever the energy is received to wherever it radiated to space. Heat of compression is shown to be effective at transferring energy both upward and poleward.

1. Introduction

Infrared radiation to space cools the troposphere, but over the long run the temperature of the troposphere remains constant. Compensating for radiative cooling requires that the upper troposphere subside at a definite rate. Updrafts and downdrafts move to their level of zero buoyancy where their temperature is essentially the same as the temperature of the environment. Updrafts do not increase the temperature of the environment at the level of detrainment, they increase the temperature of the compressed underlying subsiding air. Latent heat of condensation contributes to keeping the updrafts buoyant, but does not increase the temperature at the level of detrainment.

McBride (1981) pointed out that much research has been performed on how cumulus clouds warm the atmosphere and noted: that the updraft continues to rise until it loses its buoyancy and temperature excess; that the updraft mixes with the environment at a temperature little different from the environment and therefore does not directly warm the environment; and that there is typically no local warming in the vicinity of updrafts, instead there is often a local cooling.

The subsidence model will be compared to the convective models of Satoh and Hayashi (1992, SH hereafter), the static energy conservation model of Bhat (1998), and to the cloud resolving model of Grabowski et al. (1996). The type of circulation required to produce uniform subsidence is examined and shown to be consistent with the GATE observation and with cloud resolving models.

There can be no classic direct Hadley or indirect Ferrel circulation cells with updraft and downdraft areas of approximately equal area. The downward velocity of the subsiding layers has to be much lower than the upward velocity of the updrafts, and the area of the updrafts has to be much smaller than the area of the subsiding environment. The subsidence must have a fairly uniform horizontal distribution, but the updrafts can be concentrated in small areas.

Michaud (2000, M4 hereafter) used continuous cycles to explain how heat is transferred both upward and poleward by the expansion-compression process. This paper expands the technique developed in M4 to investigate how energy is transferred from the updraft to the subsiding layers and to calculate the mass flux required to transport heat upward and poleward.

The concept that radiative cooling is compensated for by heat of compression and the type of circulation required to do so are not well understood. A paper by Iwasa *et al.* (2002) reached conclusions regarding atmospheric circulation which support the concepts presented in the present paper. The paper shows that the consequences of the Iwasa *et al.* (2002) results as far as understanding Atmospheric circulation go much further than described in their excellent article.

Section 2 uses a single column model to calculate the subsidence required to compensate for the heat loss through radiative cooling. Section 3 examines how updrafts can be redistributed to produce the subsidence required to compensate for radiative cooling. The Fractional Area Cover (FAC) of updrafts is estimated. The implications of subsidence warming on the general circulation are examined. The classical symmetrical circulation cells are replaced with a system of quickly rising updrafts and slowly subsiding layers. The self-regulation of the subsidence process is briefly discussed. Section 4 introduces the use of static energy to calculate the heat transferred to subsidence areas.

2. Subsidence requirement

The atmospheric upward heat convection process is shown in Fig. 1. The layers lose heat by radiation, and compensating for radiative cooling requires that the layers subside and be compressed. The bottom layer is heated by solar radiation (Q_i) while layers at intermediate levels in the troposphere are cooled by infrared radiation to space (Q_o). As the updrafts of heated air rise; the layers at intermediate level subside to replace the rising air. Compressing the subsiding air increases its temperature. Over the long run, radiation to space from the subsiding layer keeps the temperature of at a given level constant.

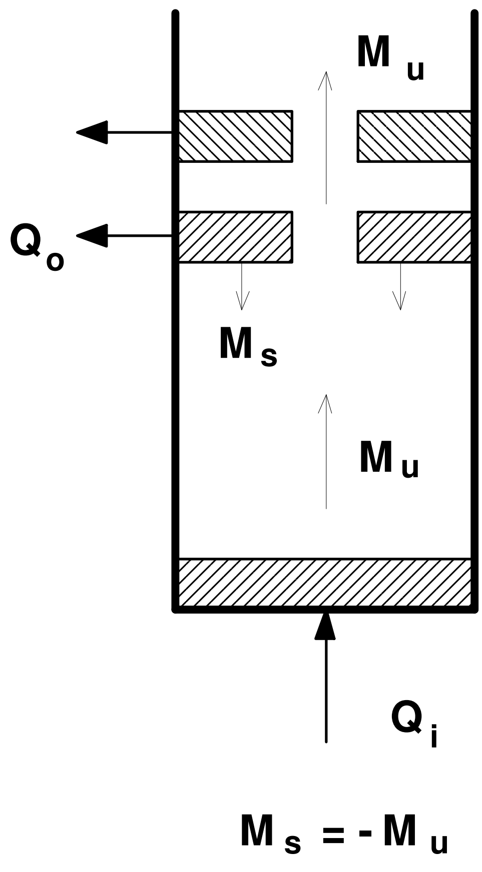


Fig. 1 Atmospheric upward heat flow process

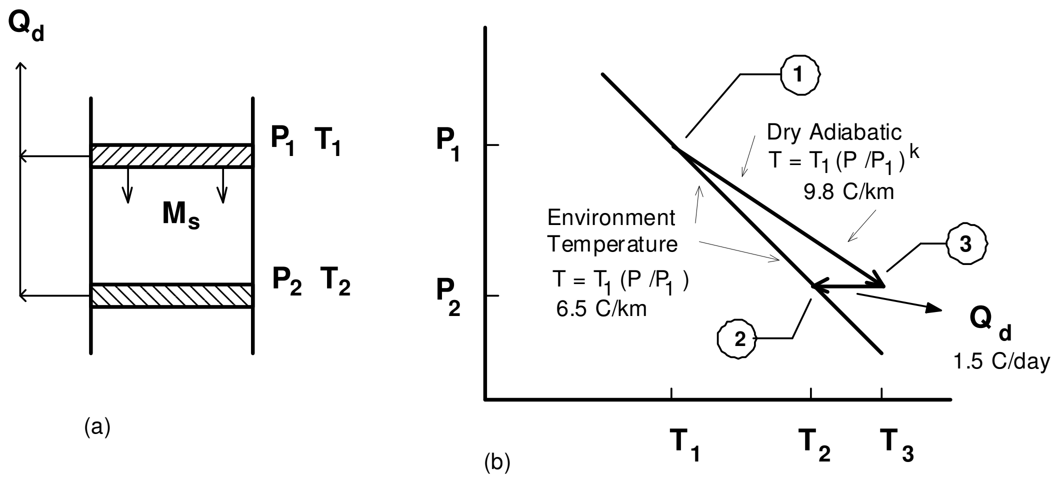


Fig. 2 Without cooling the temperature of the subsiding layer would exceed the temperature of the environment.

Fig. 2 shows that keeping the temperature of a layer constant while it is being cooled by radiation requires that the layers subside. The daily subsidence ($z_1 - z_2$) of the layer originally at elevation z_1 must be such that its temperature (T_3) after adiabatic descent to elevation z_2 exceeds the initial temperature (T_2) at elevation z_2 by the daily radiative cooling rate Q_d.

$$Q_d = T_3 - T_2 = \left(T_1 - a_d \frac{dz}{dt}\right) - \left(T_1 - a \frac{dz}{dt}\right) = w\,(a_d - a) \qquad (1)$$

where w is the subsidence velocity in m d^{-1} where Q_d is the daily radiative cooling rate is in K d^{-1}, where a is the environmental lapse rate in K m^{-1}, and where a_d is the dry-adiabatic lapse rate equal to g/C_{pa}; where g is the acceleration of gravity and C_{pa} is the specific heat at constant pressure of air. The subsidence velocity is directly proportional to the cooling rate and inversely proportional to the difference between the dry adiabatic lapse rate and the actual lapse rate.

For a cooling rate of 1.5 K d^{-1}, the subsidence velocity of the standard atmosphere, which has a lapse rate of 6.5 K km^{-1}, is 461 m d^{-1} (0.0053 m s^{-1}). Compensating for radiative cooling in the Standard Troposphere which has an average lapse rate of approximately 6.5 K km^{-1} therefore requires a subsidence velocity of approximately 500 m d^{-1}. The subsidence velocity in the Standard Winter atmosphere which has a lapse rate of zero, and a cooling rate of around 1 K d^{-1} would be approximately 100 m d^{-1}.

Lowering an air mass 1000 m isentropically increased its temperature by 9.75 K. If the air mass is initially at ambient temperature and the lapse rate is 6.75 K km^{-1}, its temperature at the lower level is 3 K higher than ambient. Preventing the temperature of the air mass from rising above ambient requires that the air be lowered slowly to allow time for heat loss by radiation. If the cooling rate is 1.5 K d^{-1}, the subsidence velocity must average approximately 500 m d^{-1}. Without subsidence the temperature at any given pressure level would decrease by 1.5 K d^{-1}.

Small masses of dry air become buoyant if they subside at significantly more than 500 m d^{-1}. The subsidence rate of large air masses does not need to be uniform, a rapid descent of 1000 m every two days has the same warming effect as a uniform descent of 500 m d^{-1}. The time required for a layer to subside from the top to the bottom of the tropical troposphere, approximately 16000 m, is approximately 32 days. Bhat (1998) used static energy balance to show that the subsidence time is around 32 days.

The subsidence velocity does not change much with elevation, but the subsidence mass flux decreases with increasing elevation. The required subsidence mass flux per unit area is the subsidence velocity multiplied by density. The following equations give the subsidence mass flux.

$$\omega = \frac{g}{R_a} \frac{P}{T} \frac{Q_d}{(a_d - a)} = g \rho \frac{Q_d}{(a_d - a)} \qquad (2)$$

$$M_s = \frac{1}{R_a} \frac{P}{T} \frac{1}{N} \frac{Q_d}{(a_d - a)} = \frac{\rho}{N} \frac{Q_d}{(a_d - a)} \qquad (3)$$

(2) and (3) permit direct calculation of the subsidence mass flux. M_s is the subsidence in kilogram per meter square per second, ω is the subsidence in Pascal per day. *N* is the number of seconds per day. All equations are based on SI units; numerical results are expressed in the nearest convenient engineering multiple. Numerical values for ω and M_s are therefore kilopascal per day and gram per meter square meter per second respectively. Grams per second per meter square are useful in energy calculations; kilopascals per day are easier to visualize, 1 kPa d^{-1} equals 1.18 g m^{-2} s^{-1} (10^6/N*g*).

A subsidence velocity of 460 m d^{-1} corresponds to a subsidence mass flux of 6.4 g m^2 s^{-1} (5.4 kPa d^{-1}) near the bottom of the troposphere, and 2 g s^{-1} m^{-2} (1.7 kPa d^{-1}) near the 25 kPa level. Fig. 3a illustrates the fact that the troposphere is heated from the bottom by the earth's surface and cooled by infrared radiation to space at higher level. Compensating for the uniform radiative cooling rate shown in Fig. 3a requires a subsidence mass flux which decreases with height. A height dependent mass flux can be produced by steady state updrafts from the base of the sounding terminating at various heights as shown in Fig. 3b. A uniform subsidence velocity requires that air be inserted between the layers as they subside either by updrafts terminating at intermediate levels or by horizontal inflow from adjacent areas.

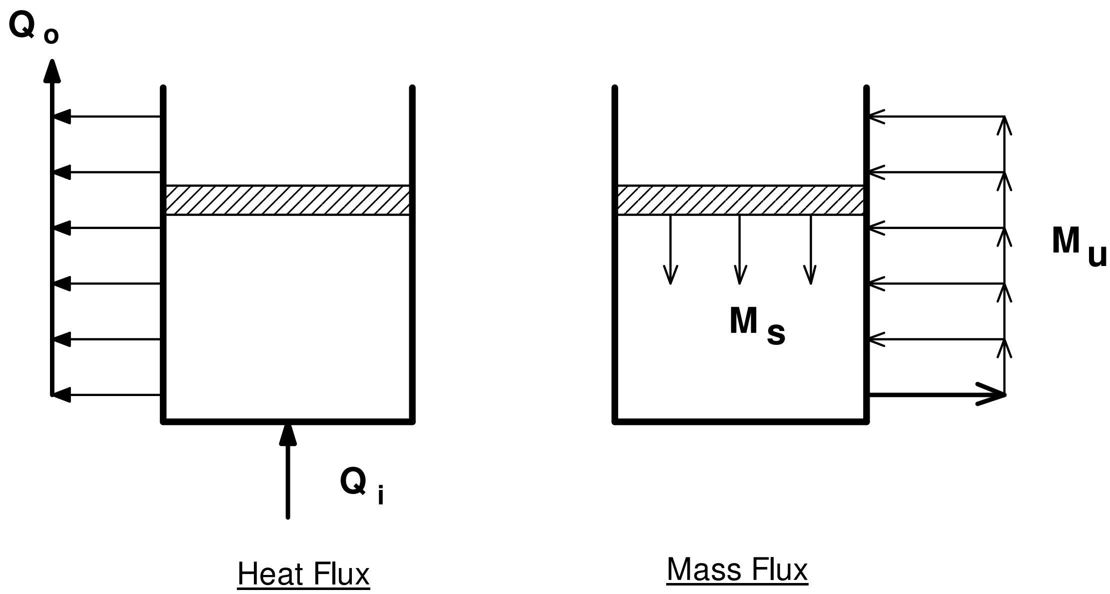


Fig. 3 Heat and mass flux diagrams for a system heated from the bottom and cooled at higher elevations

SH calculated the mass flux required to compensate for radiative cooling. SH initially tried to balance radiative cooling with a mass flux independent of height, but they realized that the roughly uniform cooling profile of the troposphere requires a subsidence mass flux which decreases with height. They then used a time-dependent model where air masses rise to their level of neutral buoyancy. SH did not consider the possibility of using a steady-state mass flux rising to various heights as shown in Fig. 3b to produce a height dependent mass flux, but the above steady state-mass flux is in excellent agreement with the time-dependent mass flux shown in their Fig. 9. The long term mass flux required to compensate for radiative cooling is independent of whether the updraft is a steady-state or varies with time. SH pointed out that deep penetration warms the upper atmosphere and that shallow convection then prevails until the upper atmosphere is again cooled by radiation. Bister and Mapes (2004) showed that increasing the temperature in the upper half of the troposphere decreases the level to which updrafts rise. Deep convection warms up the upper troposphere more than the lower troposphere. Bhat (1998) showed that, for his no divergence case, the daily subsidence is 3% of the mass of the troposphere; 3% of 90 kPa is 2.7 kPa.

Randall and Wang (1992, RW hereafter) showed that raising a 2.5 kPa layer from the bottom to the top of the troposphere increases the temperature of the troposphere by an average of 1.3 K. The temperature increase is higher at the top (3.5 K) than at the bottom (0.4 K) of the sounding because the temperature increase depends on the pressure ratio, and the effect of a given pressure increase on pressure ratio is greater at low pressure than at high pressure. Note that the temperature increase occurs throughout the troposphere rather than in the raised layer within which the latent heat of condensation was released.

Raymond (1995) showed that, where the primary balance is between vertical advection and radiative cooling, the subsistence velocity is given by

$$w = \frac{Q_d}{\Gamma} \qquad (4)$$

where Γ=dθ/dz is the lapse rate of potential temperature. When applied to the base of the standard atmosphere (8) gives the same subsidence rate as (3), namely 461 m/s. Renno and Ingersoll (1996) calculated the subsidence velocity required to compensate for the heat loss of a slab of air radiating like a grey body. Their equation gives a subsidence velocity of 519 m/d for the standard atmosphere.

The concept, that compensating for radiative cooling requires that layers subside, is fundamental. The subsistence of the layers is difficult to measure because subsidence velocity is much lower than the velocity of the drafts. The drafts mix with the layers into which they become incorporated; the layers cannot be distinguished from the drafts. RW realized that raising a layer more than 2.5 kPa thick would reduce the Available Potential Energy to zero. SH realized that a uniform upward mass flux of more than 3.4 g s^{-1} m^{-2} would warm the upper troposphere. Without heat of compression, the temperature of a layer taking 25 days to subside from the top to the bottom of the troposphere while being cooled at 1.5 K d^{-1} by radiation would decrease by some 40 K. With heat of compression and no radiative cooling, the temperature of the subsiding air would increase by 100 K. With heat of compression and radiative cooling, the temperature of the subsiding air increases by some 60 K. Over the long run, the temperature at any given level remains constant because heat of compression compensates for radiative cooling.

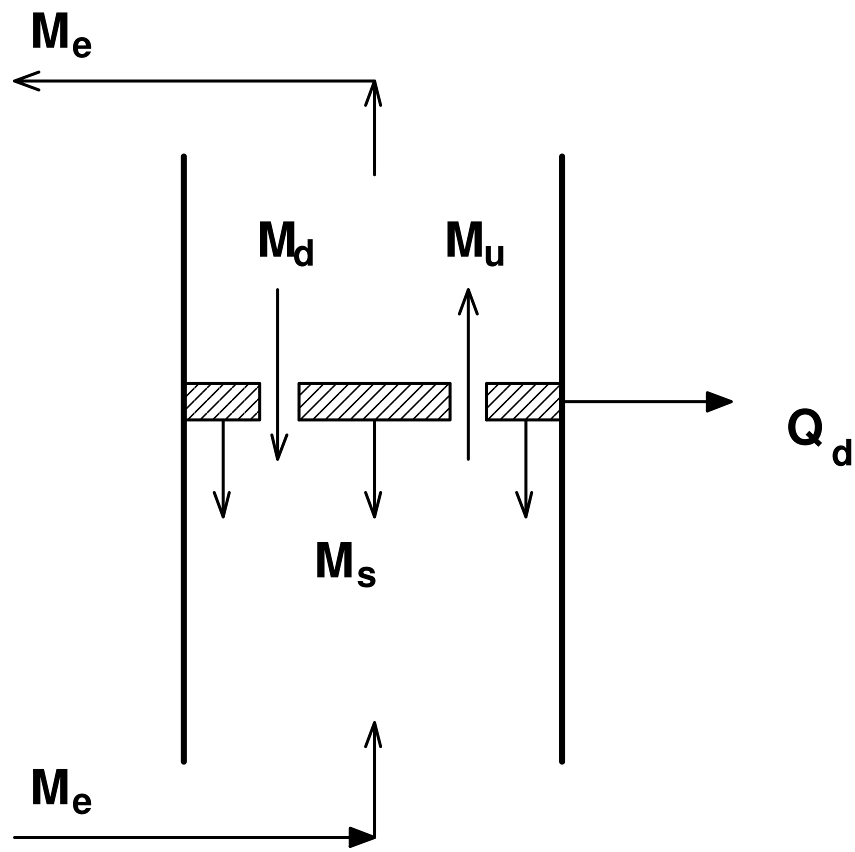
3. Atmospheric circulation

The actual atmosphere is not a single uniform column. The troposphere can be considered to consist of layers penetrated by positively buoyant updrafts and negatively buoyant downdrafts as shown in Fig. 4. The subsidence does not necessarily occur in the same area as the updrafts. Compensating for radiative cooling requires that the layers subside at a specific rate irrespective of where the drafts occur. In the long run, the subsidence of the layer (M_s) must compensate for radiative cooling irrespective of where the drafts occur.

Mass balance requires that the sum of the subsidence of the layer (M_s), the penetrative updraft (M_u), the penetrative downdraft (M_d), and the external flow to other areas (M_e) add to zero. The subsidence of the layer is therefore

$$M_s = -(M_u + M_d) + M_e = -(M_n + M_e) \qquad (5)$$

where the net upflow in the drafts $M_n = M_u + M_d$, all flows are positive upward. The penetrating updrafts and the penetrating downdrafts are assumed not to mix and not to exchange heat with the layer.



$$M_s = -(M_u + M_d + M_e)$$

Fig. 4 Net subsidence of the layer depends on updrafts, downdrafts, and flow to other areas.

Compensating for radiative cooling requires that there be subsidence not only in active convection areas but also in areas with little active convection. Fig. 5 shows how updrafts in the convection area can produce subsidence in both the relatively small active convection area and in the much larger subsidence area.

Zipser and LeMone (1980, ZL hereafter) calculated updraft and downdraft mass flux form velocity measurements. Updraft velocities in active convection are typically 0.5 to 5 m s^{-1}. The velocity of the updrafts is slightly stronger than the velocity of the downdraft. The mass flux in the downdrafts is approximately half of the mass flux in the updraft. Downdrafts only occur in active convection area because they are caused by evaporative cooling and condensed water loading, and because updrafts are required to produce the condensed water. There is little vertical mixing in the subsidence area because of the stability associated with sub-adiabatic lapse rate.

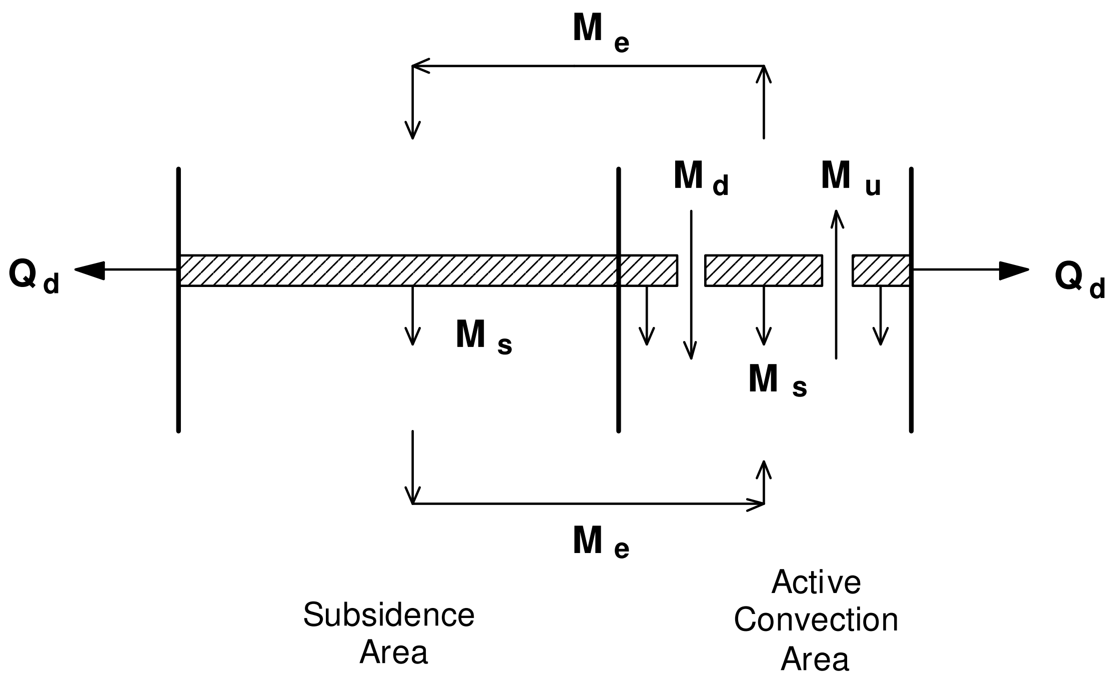


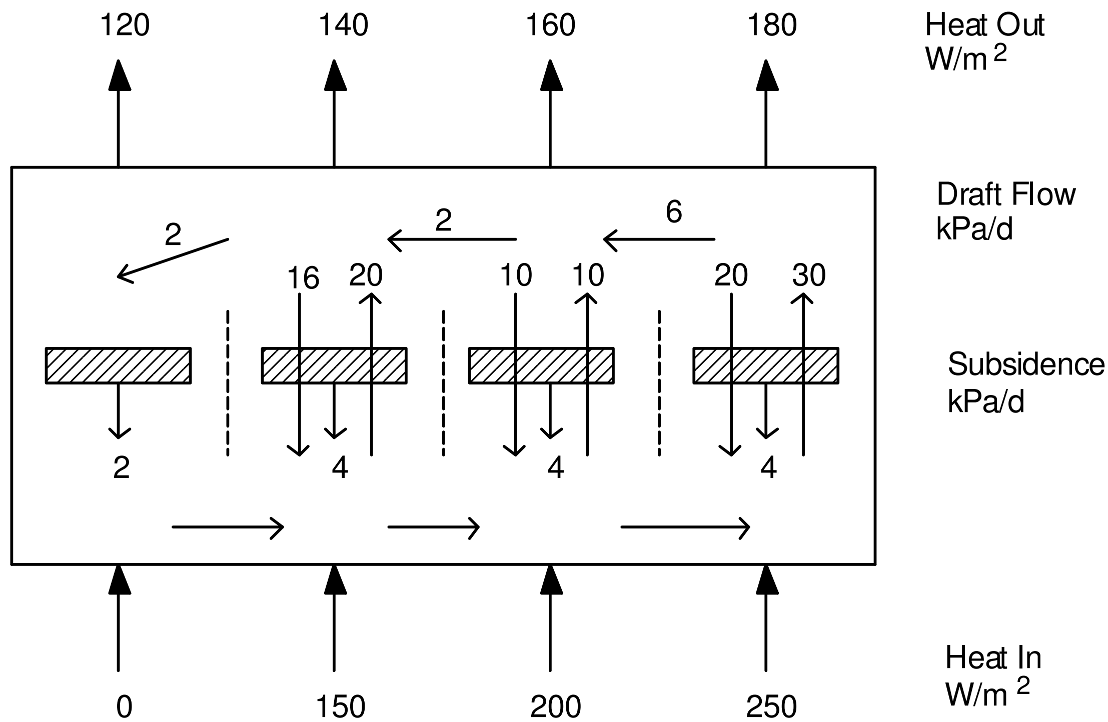
Fig. 5 Subsidence of the layeroccurs in areas of active convection and in larger subsidence area.

The velocity of the drafts is much smaller than the subsidence velocity of 0.005 m s^{-1}, but the net upward mass flux in the drafts must equal the subsidence mass flux. The fractional area of drafts is related to velocity by

$$v = - v_u A_u + v_d A_d \qquad (6)$$

where v_u and v_d are the velocity and A_u and A_d are the fractional areas of the updrafts and downdraft respectively. Taking the average velocity of updrafts and downdraft as 1 m s^{-1} the fractional area of the downdrafts as half the fractional area of the updrafts, the fractional areas of the updraft and downdrafts are 1% and 0.5% respectively.

Zipser and LeMone (1980) noted that areal coverage of updrafts cores in the GATE area is only 4%. ZL found that approximately 20% of the active convection area is covered by updrafts and 25% of the area is covered by downdrafts. An active convection area of 5% of the earth's surface would be more than adequate to accommodate the penetrating updrafts and downdrafts. The fraction area of the earth with deep convection and the fractional area of the earth with medium to heavy precipitation at a given time are both in the order of 1%.



Latitude	Polar	Middle	Trade	ITCZ
M_s (kPa/d)	2	4	4	4
M_u	0	20	10	30
M_d	0	16	10	20
M_n	0	4	0	10
M_e	2	0	4	-6

Fig. 6 Updraft are redistributed to produce subsidence required to compensate for radiative cooling.

Fig. 5 illustrates the kind of circulation required to produce a subsidence (M_s) of 4 kPa/d in most of the troposphere and 2 kPa d^{-1} in the polar regions. A single layer is shown for simplicity, but in the real atmosphere there are several layers and the poleward air movement occurs at many levels. The subsidence, shown in Fig. 5, is representative of the mid-troposphere; the subsidence mass flux would be higher at the bottom of the troposphere and lower near the top of the troposphere. The meridional flows are based on the four regions having equal areas.

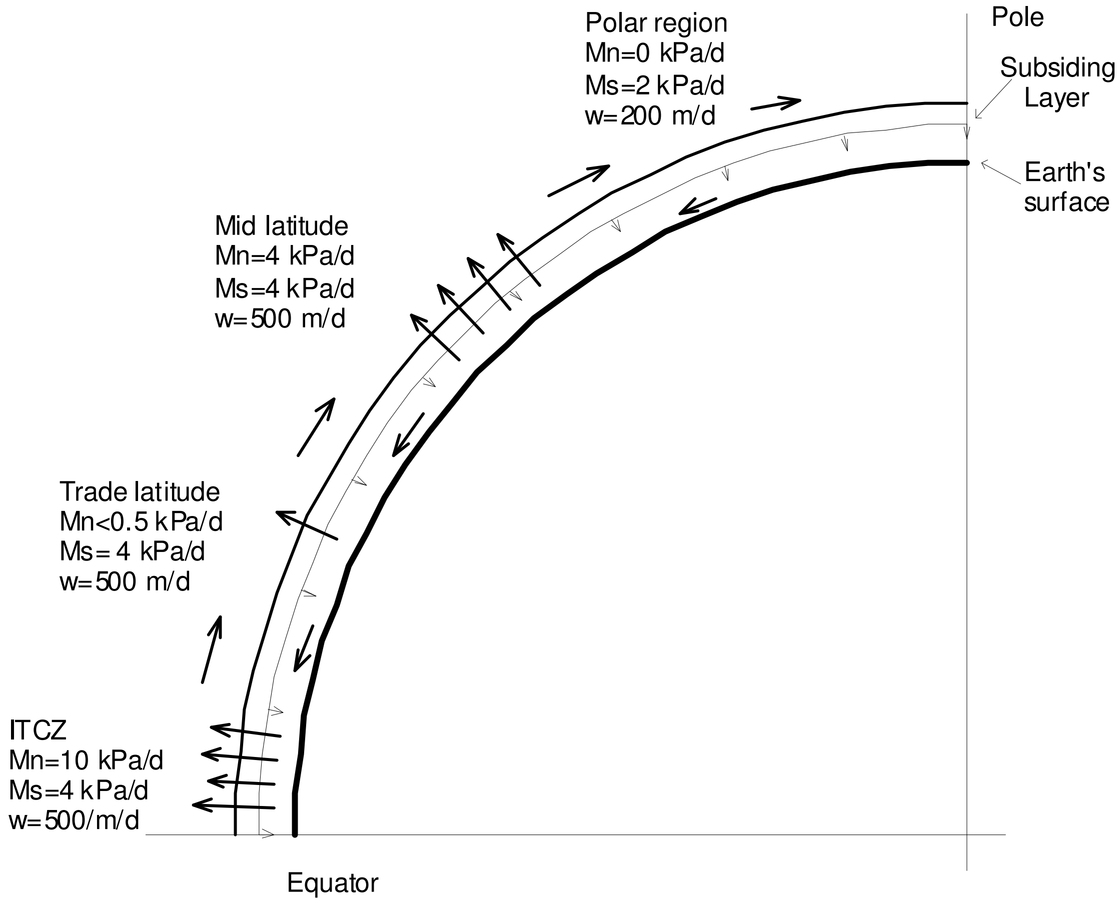


Fig. 7 Subsiding Layer General Circulation Model.
The drafts are redistributed by meridional flow as required to compensate for radiative cooling. The layers which are penetrated by drafts subside at roughly unform velocity. The mass fluxes apply to layers at mid troposphere level.

Heating from below and cooling from above produces instability which eventually leads to updrafts. The location of the updrafts has a major effect on weather but little importance for the energy balance because the subsidence can take place a long distance from the updrafts and tends to take place where the air is coldest and easiest to compress. Subsidence warming is independent of the location of the updrafts.

Fig. 7 is another representation of the kind of atmospheric circulation required to provide a uniform subsidence rate. The traditional circulation loops, Lorenz (1967), are replaced with a subsiding layer penetrated by updrafts. The limitation on the subsidence velocity puts severe restrictions on the circulations regimes that are possible. There can be no classic Hadley direct or Ferrel reverse circulation cell with updraft and downdraft areas of approximately equal size and vertical velocity.

Penetrative updrafts in the ITCZ can result in subsidence in the ITCZ itself, in the trade zones, and in the polar regions. The temperature profile in the ITCZ is determined by the moist-adiabatic lapse rate of the air at the base of the sounding. ITCZ upper sounding temperatures are usually a few degrees below the moist-adiabatic expansion temperature of the air at the base of the sounding. Stone and Carlson (1979) found that in low latitude the lapse rate is essentially determined by the moist-adiabatic lapse rate. In the ITCZ, the lapse rate is typically 0.1 to 0.2 K km^{-1} higher than the moist-adiabatic lapse rate so that a parcel rising from the surface is 1 to 2 K warmer than the environment at the 10 km level.

The ITCZ troposphere act as a reservoir of high energy air and provides other areas with additional upper level air as required to produce enough subsidence to compensate for heat loss by radiation. In the summer, when local updrafts produce enough subsidence to compensate for radiative cooling, there is no need for inflow from the ITCZ. In the winter, when the local updrafts are insufficient, high level inflow from the ITCZ is responsible for subsidence in high latitudes. The inflow of upper level air from the ITCZ to higher latitude is a self regulating process. Subsidence occurs once the air in the high latitude regions has been cooled sufficiently by radiation. The polar regions lose more energy by radiation than they receive, but over the long run their temperatures remain constant because the energy which they lose by radiation is replaced with energy transferred from low latitudes. In Fig. 5, the ITCZ updrafts flow (M_u) is estimated at 30 kPa d^{-1} and the downdrafts flow (M_d) is 20 kPa d^{-1} for a net draft flow (M_n) of 10 kPa d^{-1}. When the layers subside at 4 kPa d^{-1}, a net penetrative updraft of 10 kPa d^{-1} produces an export (M_e) of 6 kPa d^{-1} (7.2g s^{-1} m^{-2}).

The subsidence velocity of 500 m/s is an average over a period of several days. In a given location there can be several days with little or no subsidence followed with days with higher than average subsidence. When the subsidence is high the temperature of the troposphere increases, when the subsidence is low the temperature of the troposphere decreases. The day to day variation in temperature at a given pressure level in the mid atmosphere is probably more due to variation in subsidence velocity than in variation in outgoing radiation. Subsidence controls the temperature of the troposphere and takes care of keeping the temperature of the troposphere close to seasonal average irrespective of local outgoing radiation. Winter cold outbreaks may be caused by the troposphere not subsiding fast enough to compensate for radiative cooling rather than by outbreaks of polar air. Coriolis acceleration contributes to preventing poleward air movement. Satoh (1994) showed that reducing the earth's rotation rate increases temperature in high latitudes; the poleward air movement is delayed until the zonal velocity is reduced by friction.

4. Static Energy

M4 showed that the energy, heat (q) plus work (w), given up by an air mass undergoing any process is equal to the reduction in its static energy (μ), where static energy is the sum of enthalpy (h) and potential energy (gz).

$$w - q = -\Delta h - \Delta gz = -\Delta \mu \qquad (7)$$

which reduces to q = Δμ, for processes without external work. The static energy of an air mass undergoing radiative cooling at a rate of 1.5 K d^{-1} decreases by 1.5 C_p per day, by 1500 J d^{-1}.

Static energy is a good tool for analyzing energy transfer as shown by the following examples. The static energy of the air entering the top of the polar troposphere is around 30000 J kg^{-1} and the static energy of the air leaving the bottom of the polar troposphere is around -30000 J kg^{-1}. Adding a kilogram of air at the top of the polar troposphere while removing a kilogram of air at the bottom of the polar transfers 60000 J/kg to the polar region. Removing 60000 J kg^{-1} at a cooling rate of 1 K d^{-1} would take 60 d, which is roughly equal to the polar subsidence time. Subsidence is far more effective at transporting heat poleward than purely horizontal mass exchange. Replacing air at the bottom of the polar troposphere with 5 K warmer air at the same pressure would only transports 5000 J kg^{-1}. Subsidence is 12 times more effective at transporting heat poleward than horizontal exchange. Work of compression is the only process capable of transferring the vast quantity of energy transferred to the polar regions. The polar regions receive energy by importing air with high static energy at high level and exporting air with low static energy at low level.

The polar regions lose more energy by radiation than they receive, but over the long run their temperatures remain constant because the energy which they lose by radiation is replaced with energy transferred from low latitudes. The energy transferred to a region into which the net mass flow is zero is equal to the difference between the static energy of the air imported into the region and the static energy of the air exported from the region.

$$e = \mu_i - \mu_o \qquad (8)$$

where e is the energy transferred to the region per unit mass of air moved in the region, where μ_i is the static energy of the air entering the region and where μ_o is the static energy of the air leaving the region.

The static energy of the air at the bottom and at the top of the ITCZ troposphere are both roughly 75000 J kg^{-1}; there is negligible external energy transfer during the fast updraft process. The static energy of air moving from the top of ITCZ troposphere to the top of the polar troposphere decreases from 75000 J kg^{-1} to 30000 J kg^{-1}. Losing 45000 J kg^{-1} at a cooling rate of 1.5 K d^{-1} would take 30 d which is roughly the time required for the air to travel the distance. The dry air above the mixing layer in the trade wind zone has a static energy of around 25000 J kg^{-1}. The static energy of air moving down from the top of ITCZ troposphere to this location decreases from 75000 J kg^{-1} to 25000 J kg^{-1}. At a cooling rate of 1.5 K d^{-1}, the descent time would be about 33 d. Heat received once the air is near the surface returns the static energy to its initial high level.

The subsidence mass flux required to compensate for subsidence heating is roughly independent of whether the upflow takes place in reversible a constant entropy (constant equivalent temperature process) or in an irreversible constant moist static energy process. The temperature of the updraft is slightly higher in the irreversible process because the work that would be produced in a reversible process reverts to heat. Consequently the updrafts rise slightly higher in the irreversible upflow process.

5. Conclusion

Fig. 6 seems to be in accord with the results of the numerical model of Satoh (1994). The streamlines in Satoh fig. 1 shows a Hadley cell with upward flow in the ITCZ, but gives no indication that the layers in the ITCZ are subsiding. The fact that there are updrafts, that the updrafts are primarily in low latitudes, and that there must be subsidence can be inferred from Satoh's Fig. 3 which shows the distribution of precipitation.

TA calculated mean upward velocity in the GATE area from horizontal velocity measurements. TA figure 6 shows the mean vertical velocity in the lower troposphere to be 8 kPa/d, (3.3 mb/hr). The net upward velocity corresponds to the export to other regions (M_e). The work of compression exported to other regions is proportional to export (M_e). TA table 4, shows that a quarter of the latent heat of condensation released in the ITCZ is used to compensate for radiative heat loss in the ITCZ and that the remainder is exported to other regions.

Pierrehumbert (1995) used a two-box model which recognized the need for subsidence. Webster and Houze (1991) state that the process responsible for transferring latent heat released in the tropics to higher latitudes is not satisfactorily understood and postulate a fast teleconnection to explain the heat transfer. Updrafts in the tropic can cause warming in the polar regions almost immediately by displacing the air in the upper troposphere towards the poles. The latent heat of condensation reappears where the compression occurs rather than where the vapor condenses.

Emanuel and Raymond (1992) state that the validity of the widely used apparent heat source approach is questionable. The static energy approach eliminates the need for apparent heat sources, and the need for explicitly including latent heat. The validity of the enthalpy approach has been demonstrated in the process industries where it is used extensively. The whole mixture is put through the process, the mixture is not separated in components or phases. The enthalpy of the substance is not allocated to the condensable component and the non-condensable component. Separating the energy content of air into dry and moist static energy leads to unnecessary computational difficulties. The attention given to where the latent heat is released is unwarranted because the energy is transferred to where the compression occurs.

Mapes (2004) pointed out that computer models can not simulate the whole atmosphere. Low-resolution models need some representation of convective clouds, and high-resolution models need some representation of the rest of the atmosphere. Fig. 5 brings out the interdependence of the active convection area and the surrounding subsidence areas. The subsidence area could be broken up into columns. At first subsidence tends to take place in the coolest columns. At some point subsidence warming inhibits further subsidence in that column and the subsidence moves to the next coolest column. A model approach based on subsidence required to compensate for heat loss by radiation might eliminate the need to need to use separate low and high resolution models.

The downward velocity is much smaller than in traditional circulation cells, and the meridional wind is negligible compared to the actual wind. There must be penetrating updrafts which cover only a small part of the total area. The updrafts can be local or can be large scale disturbances. The warming effect of raising a mass of air is the same whether it is raised in a local or a large scale disturbance. There are physical locations where updrafts form preferentially, but the location of the updraft is not important to the warming process. Subsidence eventually takes place where the air is colder and easier to compress. Latent heat of condensation does not increase the temperature at the final level of the updraft; the temperature increase occurs wherever the corresponding subsidence occurs.

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