Patterns of energy input to the atmosphere and receipt at the surface control Earth’s broad climatic regimes. Write an account of the geographical dimensions and characteristics of the energy fluxes involved

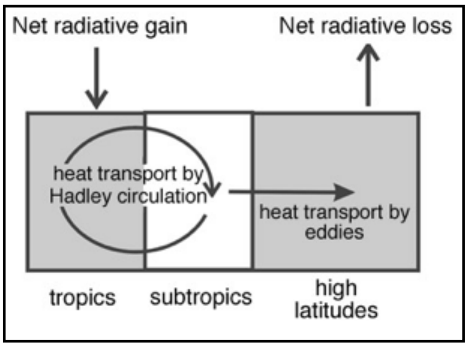
Energy input comes predominantly from the sun. The receipt of energy at the Earth surface is however not uniform, varying by in large due to the sphericity of the Earth and the differing, latitudinal distributions of albedo. As such, the low latitude equatorial and subtropical regions receive a surplus of solar energy over earth radiation loss. Conversely, the high latitudes have greater loss of energy by earth radiation to space than the gain from solar radiation. If this unequal distribution were not rectified by the ocean-atmosphere system, there would be a massive accumulation of heat within the tropics and a corresponding deficiency at the poles. Thus, the unequal receipt of energy at the Earth surface drives a poleward energy transfer system. As Henderson postulates: “all aspects of the climate system of the Earth are the result of [these] energy transfers and transformations within the ocean-atmosphere system.” Primarily, this essay serves to contextualise the energy input and receipt scenario before suggesting the causes and consequences of latitudinal differences. One will then explore the mechanisms through which the ocean-atmosphere system transports energy polewards, with particular reference to the latent heat transfers within the Hadley cell and the advection currents within the Atlantic meridional overturning circulation. Finally, one will explore the feedbacks within the ocean-atmosphere system that serve to increase the Earth’s responsive capacity to radiative perturbations, such as anthropogenic climate change.

The predominant source of energy into the Earth-atmosphere system comes from the Sun in the form of radiation. The sun continually sheds part of its mass by radiating waves of electromagnetic energy and high-energy particles into space. About half of these waves received by the earth are in the visible short-wave part of the electromagnetic spectrum with the other half consisting of near-infrareds and ultraviolets. The energy received at the top of the atmosphere on a surface perpendicular to the solar beam for mean solar distance is termed the solar constant. This stands at 1366 Wm-2 with small periodic variations of just over 1Wm related to sunspot activity. Due to the earth’s sphericity however, the average radiation received per unit of surface area is only one quarter as strong at 342 Wm-2. This incoming radiation can be absorbed (in the atmosphere and at the surface), scattered (in the atmosphere) or reflected (by clouds and at the surface).

Energy arrives at the top of the atmosphere predominantly as visible radiation, with 70% passing through the earth’s atmosphere, feeding into the climate system, and the other 30% sent directly back into space as a result of reflection by clouds, dust and highly reflective regions of the earth surface. This 30% of reflected radiation accounts for the planetary albedo. Of the 70% of radiation which is not reflected but absorbed, the processes which account for its distribution involve the interactions between radiative sunlight and tropospheric gas. As a beam of sunlight enters the atmosphere it first passes through the thermosphere and mesosphere with little change. However, on descent into the denser troposphere the beam begins reacting with atmospheric molecules. Many shorter waves of the spectrum are scattered at this point, a process by which the wave changes its direction with no change in its form after its collision with a molecule. Scattering gives rise to the blue sky and the diffuse radiation which accounts for the radiative warmth experienced during cloudy conditions when no direct sunlight is actually present. The incoming radiation that is not scattered is absorbed by the surface and certain atmospheric gases, cloud and dust[1]. Absorption converts short wave radiation into long wave, emitting heat and energy in the process. This system adjusts towards a state of dynamic equilibrium whereby the surface, rather than overheating, will eventually return its absorbed radiative heat to the atmosphere in its new form. Earth and its atmosphere as such emit radiation in abidance with the Stephan-Boltzmann law by which 'the amount of radiation emitted from a body increases exponentially with a linear rise in temperature.' [2]. The re-released radiation is not returned to space with immediacy however, most being repeatedly absorbed and emitted before it is able to leave the system. This greenhouse effect modifies energy flows and promotes energy storage to sustain the temperatures of the Earth and atmosphere at high, habitable levels.

The distribution of radiation at the top of the atmosphere is constantly changing. Diurnal variations occurs as earth rotates on its axis, exposing different portions of the atmosphere to the incoming solar radiation. As the sun rises in the sky, surface area decreases which gives rise to a subsequent increase in intensity. Eventually, a surface at right angles to the solar beam will receive the maximum intensity of radiation, a phenomenon evidenced in the high-sun, high-radiation levels of the equator and subtropics. Furthermore, the duration of daylight affects the amount of radiation received - the longer, the greater. The annually changing distance of the earth from the sun produces seasonal variations in solar energy received by the earth. Owing to the eccentricity of the earth's orbit around the sun, the receipt of solar energy on a surface normal to the beam is 7% more on 3rd January at the perihelion than on 4th July at the aphelion.The receipt of energy at the Earth surface is not uniform. Several factors alone, the large spheroidal body, 23.5% axial tilt and elliptical orbit have considerable influence on the distribution of radiation. The low latitude equatorial and subtropical regions receive a surplus of solar energy over earth radiation loss. Conversely, the high latitudes have greater loss of energy by earth radiation to space than the gain from solar radiation. In specific terms the surplus of energy is often exhibited between 38ºN and 38ºS, and the deficit in the polar regions; with the equator receiving on average 2.5 times as much annual solar energy as the poles.[3]

The primary cause of this imbalance is that the higher latitudes receive solar radiation at a less direct angle than the tropics which have an overhead, intense sun for much of the year. Furthermore, the intensity of radiation at the polar latitudes is less because of the increased scattering and absorption associated with a longer temporal path through the atmosphere. A secondary cause for the high latitude deficit, and one which strongly exacerbates the primary cause, is the high surface albedo of polar snow and ice which reflect much more incoming radiation than the tropics[4].



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[1] Approximately 23% of the shortwave radiation is absorbed by these stratospheric gases, clouds and particulates. Clouds, having immediately denied the receipt of insolation at the surface, later serve to reproduce this very surface receipt. The high-albedo water droplets and ice crystals on the lower edges of clouds are effective reflectors of rebounding surface insolation, thus serving to promote energy storage within the earth system.

[2] Any object whose temperature is above absolute zero (-273°C or 0K) emits radiant energy. Reiterating Stephan-Boltzmann, as temperature rises, the emission of radiant energy increases in intensity. This, however, coincides a decrease in the size of the wavelength.

[3] Localised variations exist such as those between the ocean and land in the tropics. The ocean, being able to mix and convect heat between its layers, absorbs radiant energy in excess of 160Mw whereas the absorbs 80-105Mw. The Asian summer monsoon is closely linked to these imbalances of receipt. Net radiation is also lower in arid continental areas than humid because in spite of the increased insolation receipt under clear skies there is at the same time greater net loss of terrestrial radiation

[4] Four factors influence the surface albedo of a region: the condition of the surface (its colour and smoothness) ; the zenith angle of the sun; the amount of cloud cover and the slope angle in relation to the sun. The albedo of the cryosphere averages around 90%.

If this unequal distribution were not rectified by the ocean-atmosphere system, there would be a massive accumulation of heat within the tropics and a corresponding deficiency at the poles. As Ruddiman postulates, in 'the absolute absence of this meridional interchange of heat, a radiation balance at each latitude would only be achieved if the equator were 14ºC warmer and the North pole 25ºC colder than at present. In order to rectify this imbalance and reach a steady state equilibrium of 15ºC, the transport of energy and heat is achieved by the fluid components of the system - the atmosphere and oceans; their net poleward transfers essentially feeding the higher latitudes and draining the lowers. Originally, it was postulated that within each region of the world there was an equalisation such that the amount of incoming short wave radiation was simply matched by outgoing longwave radiation. However, observations later falsified this hypothesis, because, whereas incoming radiation varies appreciably with changes in latitude, being highest at the equator and declining to a minimum at the poles, outgoing radiation has a more even latitudinal distribution due to the rather small variations in its main determinant atmospheric temperature. Latitudinal equilibrium and horizontal energy flux are not the only cause and effect in the system. The ground surface, receiving more energy than it is losing and the atmosphere, losing more than it is gaining, requires a simultaneous vertical heat flux to occur. This is achieved by the sensible and latent heat transfer already intrinsic to the horizontal heat transfer process, thus both are mutually sustaining. All aspects of the climate system of the Earth are thus the result of these energy transfers and transformations; with the intensity of the poleward transfers determined largely by the meridional temperature gradient.

The mechanisms of meridional energy transport in the coupled atmosphere-ocean system vary greatly. Ocean heat transport is at a maximum close to the Equator and then falls almost monotonically polewards. The atmospheric heat transport rises more slowly from close to zero at the Equator to a maximum at about 40ºN before falling to zero again at the Poles. Poleward energy fluxes are fundamentally tied to the top of atmosphere radiation budget. Poleward energy transport peaks at about 5.5 PW at 35° latitude in either hemisphere, with the atmosphere accounting for 78% of the Northern Hemisphere peak and 92% of the Southern Hemisphere peak (Trenberth, 2001). Oceanic circulation contributes to heat transfer largely in the tropics, whereas the atmosphere dominates in the middle and higher latitudes. Further complicating the transport mechanism, the atmospheric transport of heat at low latitudes is predominantly undertaken by the overturning Hadley circulation, whilst at higher latitudes baroclinic transient eddies, such as storms tracks, dominate. There are four main forms of energy that exist in the atmosphere-ocean circulation: latent heat, sensible heat, potential energy and kinetic energy. The total energy of a unit mass of air is thus:

$$E_t = Lq + CpT + gz + V^2/2$$

Whereby Lq = latent heat (latent heat of vaporisation x specific humidity), CpT = sensible heat content (specific heat of air x temperature), gz is potential energy (gravitational force x height) and $V^2/2$ = kinetic energy

The energy surplus at the low latitudes is mostly transferred to the atmosphere as sensible and latent heat, undergoing transformations once in the atmosphere into its geopotential and kinetic forms.[5] Latent heat is the quantity of heat released or absorbed, without any change of temperature during the transformation from one state to another.[6] Where

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[5] This abides by the 1st Law of Thermodynamics which states that energy can be transformed but not destroyed.

[6] In 1958, George Simpson 'discovered' this latent heat process in which water vapor absorbed and transmitted radiation to different parts of the spectrum. He also calculated how the winds carry energy from the sun-warmed tropics to the poles, not only as the heat in the air's gases but also as heat energy locked up in water vapor. Such two-dimensional research was pioneering in his day and age.

the state of water changes to a lower energy level, such as from vapour to liquid, it will release the same quantity of energy that was originally used when it was raised to the higher energy state. Thus, latent heat is significant in the Hadley heat transfer cell whereby evaporated water extracts energy at its source, the tropics, and later releases this same energy when it condenses at the polar sink. This transference of heat energy vertically and horizontally reduces the radiation deficit of the polar regions. Sensible heat is the convectional exchange of warm air down the temperature gradient; predominating in the transfer of heat over land surfaces. Sensible heat is gained from the ground surface after the absorption of short-wave radiation, or by the release of latent heat through condensation. The significance of latent and sensible heat is often expressed equationally wherein the Net Radiation is a product of the two.

$$R_n = LE + H$$

whereby Rn = net radiation; LE = Latent heat transfer and H = Sensible heat transfer. Furthering this, the surface energy balance can be defined, if we engage with the other parameters of energy flux. In this sense, the surface energy balance formulate by the interactions between incoming solar global radiation (Rg), surface longwave radiation balance (Rl), albedo (a), latent heat flux (LE), sensible heat flux (*H*) and the heat flux to and from the soil (*G*) such that:

$$Rg(1 - a) + Rl + LE + H + G = 0$$

As early as 1963 the Russian climatologist, Mikhail Budyko studied these energy balance components in their geographical and seasonal distributions, reaching the conclusion that there existed a global radiation imbalance. Geopotential energy refers to the increase in energy as an air parcel rises; whilst kinetic energy is proportional to the square of the velocity of the wind, such that strong winds display more kinetic energy than gentler ones. There are three main methods of transfer that exist to enable the equator-to-pole movement of heat: radiation, convection and conduction. Radiation is the process by which energy is transmitted through space, mainly by electromagnetic waves. Convection involves the physical movement of substances containing heat, such as water or air, and is not possible in a solid. Conduction is the transfer of heat through a medium from molecule to molecule. These modes of energy transfer are evidenced in the physical environment as the horizontal transfer of sensible heat by warm air masses; the transfer of latent heat in the form of atmospheric moisture, and lastly; the horizontal convection of sensible heat by ocean currents. The Hadley cell follows a circulation of upwelling near the equator, poleward flow aloft, subsidence in the subtropics and equatorward return flow near the surface.

The relatively clear skies in the subtropics provide for ample absorption of solar radiation at the surface where it feeds strong evaporation, which exceeds precipitation. Such evaporation supplies the flow of latent energy into the upward branch of the Hadley cell; energy that will eventually precipitate into the polar midlatitude storm tracks. On closer study of the internal dynamics, the heat transfer process primarily begins when radiant energy from the sun is absorbed at the ocean and land surface. This absorption raises the temperature of the surface leading to the transfer of sensible and latent heat from the surface to the overlying atmosphere. The tropics, rather than uniformly supplying latent heat, exhibit localised regions of high evaporation activity. As Trenberth posits: ‘the dominant energy outflow center in the atmosphere coincides closely with the region of highest sea surface temperatures (SSTs) in the oceans’ migrating back and forth across the equator following the sun (Trenberth et al. 2000). Furthermore, on land, the abundant vegetation sourced within tropical rainforests increases evaporative activity. These centers of energy creation are evidenced stretching from Amazonia to the Zaire Basin and the waters between Indonesia and Borneo.

The evaporated, equatorial-tropical air, having risen into the atmosphere from such sources, then diverges and flows polewards, exporting its potential (due to its increased atmospheric height) energy to higher latitudes. Most of the energy, as much as 90% over the oceans, is transferred by water vapour in latent form. As the air rises pressure decreases and the air cools adiabatically at a rate of 9.8ºC/km[7]. This radiational cooling causes subsidence of the air in the sub-tropics.[8] Falling, the air dries and warms as the potential energy is converted to sensible heat, before its redistribution at the surface. Energy is partitioned in the subtropics with some transported poleward by transient eddies and the rest returned equatorward in the lower branch of the Hadley circulation to be realised once again as latent heat of condensation in the intertropical convergence zone (ITCZ) and South Pacific convergence zone. As such the large poleward transport of dry static energy[9] is compensated by equatorward transport of latent energy. These low-level equatorward flows of latent energy seem counter-intuitive, diminishing the total poleward transfer of heat. However their purpose as a feedback is in the reproduction of the energy at the tropics which resupplies the overturning Hadley circulation.

Within the midlatitude temperate and polar areas there is no general, cellular circulation of air such as the Hadley, but rather a complex patter of individual baroclinic disturbances such as rotating storms. Within these storms, warm air masses rise, releasing latent heat and gaining potential heat. At the higher latitudes, the eddies collide with descending polar air and gain sensible heat during random phases of intermixing, random because the storm is still moving and thus the position continually changes.[10] These frontal systems and their intrinsic energy fluxes serve to redistribute heat from the surplus subtropics to the deficit polar regions. The Coriolis effect, skewers the path of this energy transfer, causing the air masses to migrate towards a more westerly course. Almost hidden above these westerlies a narrow ribbon of fast flowing air, the jet stream, meanders and transports heat and water vapour from the low to high altitudes. The jet stream is reduces the Equator-Pole temperature gradient as its poleward meanders supply heat to the north, and its equatorward meanders return cold air to the warmth-rich south.

The energy surplus at the low latitudes is also transferred by the ocean, its fluid properties allowing for the creation of a thermally driven near-surface circulatory system. Oceanic energy transport in mid-latitudes is effected by both wind-driven gyres and the deep meridional overturning circulation. The surface energy budget of the ocean accounts for the parameters of latent heat transfer and sensible heat transfer but with an inclusion of the dynamic horizontal advection occurring within the current.

$$R_n = LE + H + G + \Delta A$$

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[7] The process is adiabatic because the system is thermodynamically isolated such that there is no heat transfer with the surroundings

[8] Subsiding air coincides geographically with the subtropical desert belt by disrupting the formation of convection currents, hence the cloudless sky phenomena.The lack of re-radiation from cloud cover equates to large daytime absorption, with little latent horizontal heat transfer, and almost all of terrestrial insolation being lost back into space at night, hence the wide diurnal fluctuations of temperature in arid environments. The Sahara has constantly recorded maximums above 45°C and minimums below 0°C. The desert as such holds a high thermal inertia. The inertia of a given body is a natural parameter that expresses the thermal property: $(p.c.\lambda)^{½}$ whereby p, c and λ are the density, specific heat and thermal conductivity respectively. The thermal inertia is high because the desert subsurface absorbs a greater degree of heat during the day, but conducts a great amount of longwave radiation to the radiating surface at night creating, as stated, the wide diurnal temperature variations.

[9] The energy manifests itself as dry, sensible heat because the ocean is no longer conducive to evaporation. The warming of the upper ocean is impeded by the mixing of absorbed heat to large depths. The evaporation at the surface needed for latent heat transfer is thus, by in large, rendered implausible.

[10] Having said this, in the Northern Hemisphere, zones of increased 'intermixing' exist, such as Labrador, Newfoundland and Greenland, which experience polar, southward moving flows; and Britain and Scandinavia which, in contrast, experience more warm, northward moving masses, hence their more habitable climates.

Whereby Rn = Net Radiation; LE = Latent heat transfer; H = Sensible heat transfer; A = horizontal advection of heat by currents; and G = Heat transferred into or out of storage in the water (more or less zero for annual averages).

Wind imparts a frictional force on the ocean, proportional to the square of the wind speed, which creates a film of surface waves over a more persistent, slower current. (Smithson, Addison & Atkinson, 2008). The warm equatorial waters are driven west by atmospheric trade-wind convergence before being deflected poleward - and with a trajectory in line with the mid-latitude westerlies - by the opposing continental shorelines. As such these wind-driven currents (gyres), spinning anti-cyclonically due to the coriolis, transport warm water to higher latitudes, where they release their heat.[11] The large temperature contrast between the relatively warm ocean surface and the overlying, cold atmosphere provides the temperature gradient that the sensible heat move down in being lost. As Ruddiman premises, 'such a transfer is comparable in volume to the amount of heat delivered locally by incoming solar radiation' (Ruddiman, 2001). The gyre, having been cooled by glacial melt and radiational loss[12], sinks before returning as a deep thermohaline ocean current to the equator. The energy transport by the ocean is less in the Southern Hemisphere than in the Northern; the Pacific and Indian oceans being significant in the former, the Gulf Stream and Kuro Shio currents in the latter. As such, the northwards oceanic heat flux of the Atlantic is equivalent to some 30% of the polar region's solar radiation flux.

The Atlantic meridional overturning circulation is under threat of future destabilisation from warming global temperatures (IPCC, 2008). Climate models show that increased carbon dioxide from human activity increases the temperature and water vapour content of the atmosphere. Such a change would seemingly increase meridional latent heat transfer due to increase moisture and evaporation. However, the overall ocean transport system diminishes, primarily because of a decreased surface buoyancy flux. Increased precipitation at high latitudes diminishes the deep overturning cell through supplying freshwater and thus reducing the saline-induced sinking effect. The IPCC postulates that 'at very high moisture levels this overturning circulation of the ocean switches off almost entirely', thus wholly diminishing the effect of the meridional energy transport system. Recent studies have however shown that, if the oceanic energy transport is changed, then over a range of parameters the atmosphere is able to efficiently compensate and maintain the total meridional transport fairly constant. We attribute this to the efficiency of the atmosphere in responding to changes in temperature gradients. In this sense, polewards energy transport in the ocean-atmosphere system is not fixed, and where the ocean becomes less efficient, the atmosphere responds by increasing its own, such as by increasing its latent heat transfer when moisture levels threaten to cut off the ocean from doing the same.

This system of self-regulating climate is reinforced by dynamic, feedback mechanisms. Feedbacks determine the efficiency with which the climate system comes back into equilibrium in response to a radiative perturbation. The cause of such a perturbation may be increased sunspot and volcanic activity or anthropogenic forcing such as the enhanced greenhouse gas effect. Feedbacks act to preferentially heat the tropics relative to the poles, effectively strengthening the

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[11] The polewards transport occurs above the thermocline, a zone of rapid temperature change between the warm upper layers and the cold water filling the deeper ocean basins.

[12] The density is also increased by the formation of sea ice during salt rejection, a process that stores freshwater in sea ice, leaving the salt behing. Saline water is on average 3.5% denser than freshwater.

equator-to-pole energy and temperature gradient and thus requiring the climate system to transport more heat poleward. In particular, positive water vapor and cloud feedbacks in the tropics and negative cloud feedbacks at high latitudes serve to strengthen this gradient. Water vapour feedbacks exhibit a maximum at low latitudes where outgoing longwave radiation is most sensitive to water vapor perturbations and where the greatest moistening occurs. Similarly the cloud feedback is strongly positive at low latitudes due to the rising of tropical cloud tops. These positive feedbacks increase the retention of radiative energy at the tropics. In contrast at the high latitudes, the cloud feedback is largely negative due to shifting, unstable storm tracks and the brightening of clouds due to their increased liquid water content. Brightening increases the reflection of short wave radiation, reducing penetration and thus the receipt of energy at the surface. The changing latitudinal nature of climate feedbacks thus reinforce the preexisting latitudinal gradients in net radiation. The ocean-atmosphere system thus redistributes energy and heat more efficiently than it would have, had the positive feedbacks been absent.

Patterns of energy input to the atmosphere and receipt at the surface control Earth's broad climatic regimes. The need to redistribute energy to the radiation-deficient poles drives oceanic and atmospheric patterns. That the Hadley circulation determines by in large the physically distinct desert belts of the subtropics; and the North Atlantic, the warm conditions of Europe, only serves to reiterate the importance of solar radiation in powering the Earth's climate and weather. The mechanisms of meridional energy transport in the coupled atmosphere-ocean system vary greatly. Ocean heat transport is at a maximum close to the Equator and then falls almost monotonically polewards. The atmospheric heat transport rises more slowly from close to zero at the Equator to a maximum at about 40ºN before falling to zero again at the Poles. As has been revealed the ocean-atmosphere system utilises four forms of energy: latent heat, sensible heat, potential energy and kinetic energy. It is these energy transfers, and their transformations as they travel along the Equator-Pole temperature gradient, that serve in the reproduction of the distinct climatic regimes observable today.

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