An Iterative Mathematical Climate Model of the Atmosphere of Titan

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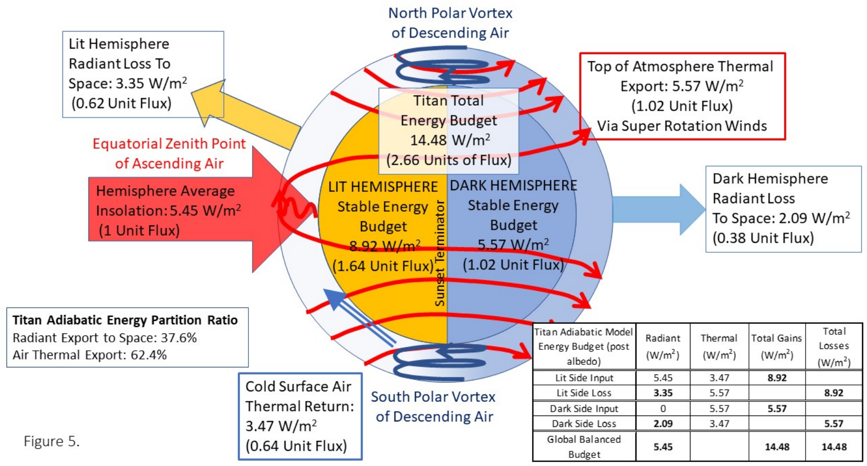
Abstract

Titan, the giant moon of the planet Saturn, is recognized to have meteorological processes involving liquid methane that are analogous to the water generated atmospheric dynamics of planet Earth. We propose here that the climatic features of Titan by contrast are more akin to those of the planet Venus, and that this structural similarity is a direct result of the slow daily rotation rate of these two terrestrial bodies. We present here a simple mathematical climate model based on meteorological principles, and intended to be a replacement for the standard radiation balance equation used in current studies of planetary climate. The Dynamic-Atmosphere Energy-Transport climate model (DAET) is designed to be applied to terrestrial bodies that have sufficient mass and surface gravity to be able to retain a dense atmosphere under a given solar radiation loading. All solar orbiting bodies have both an illuminated hemisphere of net energy collection and a dark hemisphere of net energy loss. The DAET model acknowledges the existence of these dual day and nighttime radiation environments and uses a fully transparent non-condensing atmosphere as the primary mechanism of energy storage and transport in a metrological process that links the two hemispheres. The DAET model has the following distinct advantages as a founding model of climate: It can be applied to all terrestrial planets, including those that are tidally locked. It is an atmospheric mass motion and energy circulation process, and so is fully representative of a Hadley cell; the observed fundamental meteorological process of a terrestrial planet's climate. The diabatic form of the DAET model fully replicates the traditional vacuum planet equation, and as it applies to a totally transparent atmosphere it therefore demonstrates that thermal radiant opacity, due to the presence of polyatomic molecular gases, is not a fundamental requirement for atmospheric energy retention. For the adiabatic form of the DAET model, where the turbulent asymmetric daytime process of forced radiant convection applies, the intercepted solar energy is preferentially retained by the ascending air. The adiabatic DAET climate model shows that the atmospheric greenhouse effect of surface thermal enhancement is a mass motion process, and that it is completely independent of an atmosphere's thermal radiant opacity.



Titan Adiabatic Model Energy Budget (post albedo)	Radiant (W/m^2)	Thermal (W/m^2)	Total Gains (W/m^2)	Total Losses (W/m^2)
Lit Side Input	5.45	3.47	**8.92**	
Lit Side Loss	**3.35**	5.57		**8.92**
Dark Side Input	0	5.57	**5.57**	
Dark Side Loss	**2.09**	3.47		**5.57**
Global Balanced Budget	**5.45**		**14.48**	**14.48**

Figure 5: Stable Adiabatic Model of Titan: Showing Energy Vectors and Total Energy Distributions.

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Keywords: Climate Model, Titan Atmosphere, Atmospheric Dynamics, Terrestrial Planets

1. Introduction

Titan is the largest moon of the giant planet Saturn, and the second largest moon in the solar system [1]. Titan is a unique moon in that it possesses a thick atmosphere of nitrogen gas with a surface pressure of 1.43 Bar [2}. There are convective meteorological processes occurring in the atmosphere of Titan that generate liquid methane rain [3]. These low temperature processes can be compared with the standard convective rainfall on planet Earth that involves the evaporation and condensation of water. In addition to the direct weather analogy that can be made between the terrestrial bodies of Titan and Earth there is another analogy that can be considered, but this time between the climates of Titan and the planet Venus. These two terrestrial bodies have the following features in common.

1. Titan and Venus are slow rotators and therefore both bodies possess a single atmospheric system of hemispheric encompassing Hadley cells [4].
2. Titan and Venus are both veiled worlds that have an optically translucent upper atmosphere [5]. In the case of Titan, this is caused by the presence of tholins [6].

Tholins are complex hydrocarbons generated by the UV ionisation of methane to create methyl radicles, which then polymerise and condense to form the particles of the upper atmospheric veil.

3. Titan, like the planet Venus, has a solar zenith generated, bow-shockwave structured, super-rotational wind in the upper atmosphere [7].
4. Like Venus, Titan also has uniform day and night time temperatures, with no significant surface diurnal effect seen in the data points corresponding to the dayside and those of the nightside of this slowly rotating moon [2].

The objective of this study is to generate a dynamic atmospheric model that accounts for the climatic features of Titan, specifically the observed uniform diurnal surface temperatures and the presence of a hemispheric encompassing Hadley cell.

Under the influence of intercepted solar radiation, the atmosphere of a rotating terrestrial body self-organises into a series of latitudinally defined closed loops, or cells, that transport mass and energy across the surface of a globe. Climate is the presence and action at the surface of a terrestrial planet (or moon) of this series of solar energy driven mechanically coupled atmospheric cells. The atmosphere of a terrestrial body under solar radiation loading can be considered to act as a dynamic mobile-fluid mass-transport and energy delivery system.

A terrestrial body's mobile-fluid mass transport system collects high-frequency energy from a region of incoming surplus around the solar zenith, and delivers it to a region of energy deficit towards the poles of rotation. At the location of energy deficit, the energy imported by the atmospheric system is then lost to space by low-frequency thermal radiation from the planet. As with any mass transport system it must form a closed loop, otherwise all of the heat necessary for the dynamic flow will be dissipated and the system will run down. Indeed, if too much energy is lost from the cell at the region of energy deficit, then the transport mechanism will cease, as the mobile fluid carrying the heat freezes solid, and the planetary body will no longer possess a gaseous atmosphere.

Consequently, it is a fundamental requirement that sufficient energy is retained by the mobile fluid for it to return to the original location of energy surplus. On its return to this origin, the mobile fluid is then able to collect additional energy, and the mass transport system becomes recharged. This interception of additional solar energy by the globe's surface reheats the mobile-fluid, and so the cycle is able to continue and repeat indefinitely, and be maintained as a sustainable system.

Modern climate science starts with the vacuum planet equation, a conceptual model devised by astronomy, and used to determine the average thermal emission temperature of a rapidly rotating solar illuminated planetary body. The basic form of this equation is used by [8] to calculate the equilibrium temperature T_e of an airless, rapidly rotating planet (*or moon*).

Equation 1 (corrected from the published error *pers comm*): -

$$T_e \equiv [S\, \pi\, R^2 (1-A)/4\, \pi\, R^2\, \varepsilon\, \sigma]^{1/4}$$

where σ is the Stefan-Boltzmann Constant, ε the effective surface emissivity, A the wavelength-integrated Bond albedo, R the planet's (*or moon's*) radius (*in metres)*, and S the solar constant (*in Watts/m^2*) at the planet's (*or moon's)* average distance from the sun."

Using Equation 1 for Titan: - T_e = 83.2 K, however the observed uniform surface temperature for this moon is T_s = 94 K, therefore the difference Δ T between T_e and T_s = 10.8 K, and this value is the atmospheric thermal enhancement effect for Titan. (Table 1).

Table 1. *The Expected Surface Temperature for an Airless Titan compared with its actual Surface Atmospheric Temperature [8].*

Parameter	Symbol	Titan	Units	Dimensions
Solar Constant at distance a	S	14.82	W/m^2	MT^{-3}
Radius of Body	R	2,576,000	m	L
Bond Albedo	A	0.265	Constant	Constant A
Stefan-Boltzmann Constant	σ	5.67E-08	$W/m^2/K^4$	$MT^{-3}K^{-4}$
Effective surface emissivity	ε	1	Constant	Constant ε
Expected T_e	T_e	83.2	Kelvin	K
Greenhouse Effect	GE	10.8	Kelvin	K
Expected T_s	T_s	94	Kelvin	K
Distance from the Sun	a	1.4270E+12	m	L

All models are abstractions based on assumptions, in order to understand modern climate science, the elements of the model and the fundamental assumptions need to be recognised and understood. The primary assumption that directly arises from the use of the vacuum planet equation is this: -

It is the daily rotation of the globe that distributes the intercepted solar energy from the lit to the unlit hemisphere of the terrestrial body.

We can demonstrate that this assumption is paramount because it is correctly deduced that if the vacuum planet was tidally locked in its orbit around the sun, then only one hemisphere the sun-facing side would ever receive solar energy. Consequently, the unlit far side would have a never-ending night, and experience vacuum surface temperatures of only a few degrees above absolute zero.

Data show that the surface day and night time temperatures on slowly rotating Titan are almost identical [2]. It appears therefore that it is not rotation that distributes the solar energy between the lit and unlit hemispheres of this terrestrial body, instead it is the presence of the thick and mobile non-condensing atmosphere of Titan that performs this function.

For the purposes of this study, we define climate as the presence and action of a solar energy driven atmospheric cell over the surface of a terrestrial body. Modelling studies of planetary atmospheric dynamics have shown that the latitudinal reach of a Hadley cell for a given terrestrial body, is determined by its daily rotation rate [4]. Because all planets and moons are rotating globes (even tidally locked ones) it follows that the latitudinal reach of the primary atmospheric cell determines the number of climate zones on a given terrestrial body. Slowly rotating Titan has a Hadley cell that extends from the moon's equator to its pole of rotation, and therefore it has a single climatic zone with a uniform surface temperature.

The process of forward modelling creates a numerical prediction, that must be matched and verified against external data for the model to be both valid and useful. In order to study the climate of a terrestrial body with a thick atmosphere, we need to formulate a model that can be applied in all possible scenarios. The vacuum planet equation [8] by its very definition cannot be applied to a planet with an atmosphere, nor can it be applied to a planet that is tidally locked.

To address both of these restrictions a new planetary climate model, the Dynamic-Atmosphere Energy-Transport (DAET) Climate Model, was devised using a tidally locked planet as the fundamental element. We call this model planet "Noonworld" and populate it with a transparent atmosphere of pure nitrogen gas, so that all the processes of energy conversion can only take place at the basal surface boundary of the model.

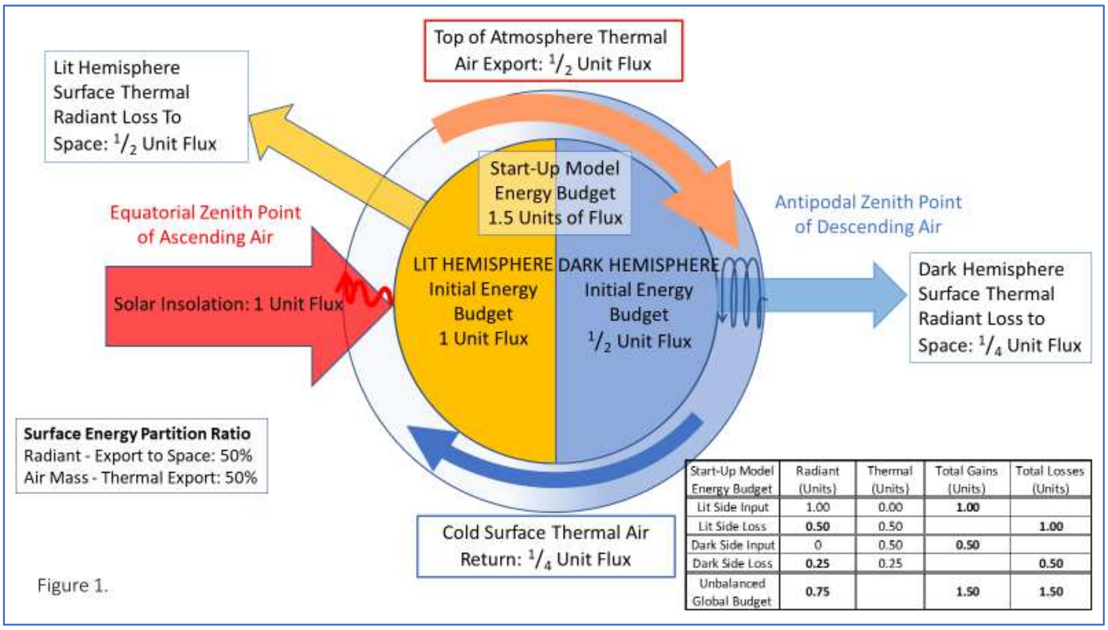
2. Methods

With forward modelling studies of a terrestrial body's energy budget, the first and overarching assumption is that the only way that it can lose energy is by thermal radiation to space. This assumption is not in dispute, and it correctly leads to the adoption of the Stefan-Boltzmann (S-B) equation of thermal radiation, which is used to establish the direct relationship between energy flux in Watts per square metre (W/m^2) and the absolute thermal temperature of the emission surface in Kelvin (K).

The second critical assumption made in the analysis of a planet's energy budget, is that it receives incoming thermal energy in the form of solar radiation or insolation from a central star or sun, and so is only ever lit on one side. Solar system bodies orbit around our Sun, and consequently they all have both a lit (day) and an unlit (night) hemisphere, and are never illuminated on both sides simultaneously.

2.1. Building the Dynamic-Atmosphere Energy-Transport (DAET) Climate Forward Model

The Dynamic-Atmosphere Energy-Transport Model of planetary climate presented here is a 2-dimensional atmospheric model, that preserves the globular dual hemisphere component of solar illumination (Figure 1). This forward model represents a globe with two environmentally distinct halves. A dayside lit by a continuous incoming stream of solar energy which creates an energy surplus, and a nightside that is dark and has an ongoing energy deficit, due to the continuous exit to space of thermal radiant energy. Consequently, a mobile fluid atmosphere that transports energy from the day to the night side is the fundamental requirement of our atmospheric model.



Start-Up Model Energy Budget	Radiant (Units)	Thermal (Units)	Total Gains (Units)	Total Losses (Units)
Lit Side Input	1.00	0.00	**1.00**	
Lit Side Loss	**0.50**	0.50		**1.00**
Dark Side Input	0	0.50	**0.50**	
Dark Side Loss	**0.25**	0.25		**0.50**
Unbalanced Global Budget	**0.75**		**1.50**	**1.50**

Figure 1. *Basic Thick Atmosphere Globe with Initial Static Model: Showing Energy Vectors and Start-Up Energy Partitions.*

On all rotating terrestrial planets and moons, the solid ground cools by thermal radiation to space all of the time (both day and night), but the surface only gains radiant heat during the hours of sunlight throughout the day. The current accepted climate paradigm assumes that it is the effect of daily rotation, and seasonal axial tilt that distributes the energy intercepted from the Sun across the full surface area of the globe. In order to remove the complications associated with axial rotation, and the impact that rapid daily rotation has on global atmospheric cell circulation patterns; we will assume that the model world presented here is tidally locked in its orbit around the Sun, and so the Coriolis Effect on air motion [9] is minimised.

2.2. Starting the Dynamic-Atmosphere Energy-Transport Engine from Cold

On all illuminated planets and moons the atmospheric process of energy transmission begins on the sunlit side (Figure 1). Here the solid surface is illuminated and warms as it receives radiant energy from the sun, and as it warms it also warms the air above it by conduction. This buoyant warmed air then rises by convection, and because in our model example the atmosphere is fully transparent, and also because the air is no longer in contact with the ground, it retains all of its energy internally.

However, the lit ground surface below our model's transparent atmosphere does not retain all of its energy. It cools in two separate ways; it both loses energy to the air above it, and also transmits low frequency radiant energy directly out into space. In the forward modelling process, we assign an initial partition ratio of 50% to conduction and 50% to radiation to study this dual process of energy loss. This assignment was chosen to permit a first assessment to be made of the impact that the partition process has on the energy budget of the atmospheric model.

On the dark side of the planet, the ground surface is also continuously emitting thermal radiation directly out to space. As this solid surface cools, it also cools the air above it, creating a surface pool of cold dense air. It is a critical feature of the DAET model that as the air cools it retains its mobility, and does not freeze on to the solid surface below. Consequently, the gaseous atmosphere is able to advect back to the sunlit side, where it can again be warmed and replenished.

As the cold air moves away across the surface of the ground towards the lit hemisphere, more warm air from above descends on to the dark cold surface. This descent of air delivers heat to the ground, which is also then lost to space by direct thermal radiation. As with the lit surface, we assign an energy partition ratio of 50% to be retained by the advecting air, and 50% to the ground. This partition allows us to study the dual cooling process of energy transfer to, and subsequent radiant loss of energy from the dark surface to space, and the associated role of horizontal cold air advection in the transport of atmospheric energy.

The process of energy collection on the lit side; energy delivery to the dark side; energy loss by the unlit surface, and then cold dense air return to the source of heat on the lit side, forms a closed loop of energy transport that can then begin to endlessly cycle (Table 2).

Table 2. Starting the Dynamic-Atmosphere Energy-Transport Engine from Vacuum Empty.

Step	Process	Energy Flow
1	Interception of solar energy by the lit surface	1 unit.
2	No flow of frozen air from the dark side	0 Unit
3	Total energy available to drive the system	**1 unit.**
4	50:50 partition of the intercepted energy between the ground and the air leading to: -	
5	Direct radiant loss to space from the warm surface	½ unit
6	Retention of energy by the lit air, followed by transport and delivery of this warm air to the dark side	½ unit
7	50:50 partition of the delivered energy between the ground and the air leading to: -	
8	Radiant loss to space from the ground on the dark side	¼ unit
9	Return flow of cold surface air from the dark side to the lit side	¼ unit

The cycling of air driven by thermal imbalance is a characteristic feature of a Hadley cell. Because for the cycle to be maintained it must retain energy internally, the Hadley cell therefore has the capacity to form an energy amplifier, capturing and retaining solar energy within the reservoir of the atmospheric system.

2.3. Warming up the Dynamic-Atmosphere Energy-Transport Engine

Because the priming stage of the process retains energy within the atmosphere, the next overturning cycle starts with 1 unit of insolation plus ¼ unit of thermal atmospheric energy left over from the first cycle. Clearly the retention of energy within the atmospheric system by this first cycle overturn means that the global radiant energy loss to space does not balance at this point. However, the endless mass movement recycling by the air and the progressive energy retention by the developing Hadley cell does not grow indefinitely. We have here two separate geometric series that both tend to different finite limits, one for the lit and one for the dark surface.

The geometric series limit for the lit side energy loss to space is: -

Equation 2: $^1/_2 + ^1/_8 + ^1/_{32} + ^1/_{128} \cdots + 2^{-n\,(odd)} = 2/3$

While the geometric series limit for the dark side energy loss to space is: -

Equation 3: $^1/_4 + ^1/_{16} + ^1/_{64} + ^1/_{256} \cdots + 2^{-n\,(even)} = 1/3$

Note that the aggregate sum for the limits of both series is: -

$$2/3 + 1/3 = 1$$

and so, the total energy recycling system is now in radiative balance (Table 3).

Table 3. *Developing the Dynamic-Atmosphere Energy-Transport Forward Model.*

Building the Dynamic-Atmosphere Energy-Transport Model							
Cycle Number	**Space Incoming Captured Radiation (Units)**	**Heating the Lit Hemisphere (Units)**	**Lit Hemisphere Thermal Radiation Loss to Space (50% Lost)**	**Thermal Cell Export to Dark Side (50% Retained)**	**Dark Hemisphere Thermal Radiation Loss to Space (50% of 50% lost)**	**Surface Return Loop from Dark to Lit Hemisphere (50% of 50% Returned)**	**Radiant Energy Exiting to Space (Units)**
0	1					0	
1	1	1	0.5	0.5	0.25	0.25	0.75
2	1	1.25	0.625	0.625	0.3125	0.3125	0.9375
3	1	1.3125	0.65625	0.65625	0.328125	0.328125	0.984375
4	1	1.328125	0.6640625	0.6640625	0.33203125	0.33203125	0.99609375
5	1	1.33203125	0.666015625	0.666015625	0.333007813	0.333007813	0.999023438
6	1	1.333007813	0.666503906	0.666503906	0.333251953	0.333251953	0.999755859
7	1	1.333251953	0.666625977	0.666625977	0.333312988	0.333312988	0.999938965
8	1	1.333312988	0.666656494	0.666656494	0.333328247	0.333328247	0.999984741
9	1	1.333328247	0.666664124	0.666664124	0.333332062	0.333332062	0.999996185
Infinite Series Limit	1	1.333333333	Energy Surplus Thermal Cell Lit Hemisphere Budget		Energy Deficit Thermal Cell Dark Hemisphere Budget		
			0.666666667	0.666666667	0.333333333	0.333333333	1
Process	Insolation	Insolation plus Thermal Recycled Air	Final Lit Side Thermal Radiant Energy Lost to Space	Atmospheric Energy Transported to the Dark Side	Final Dark Side Thermal Radiant Energy Lost to Space	Atmospheric Energy Returned to the Lit Side	Space Outgoing Radiation Balance
Hemisphere Energy Budget			1.3333		0.6667		Units
Total Global Energy Budget				2.0000			

We can consider that the consequence of this process of infinite recycling by the Hadley cell is the formation and maintenance of a dynamic machine made of air (Figure 2).

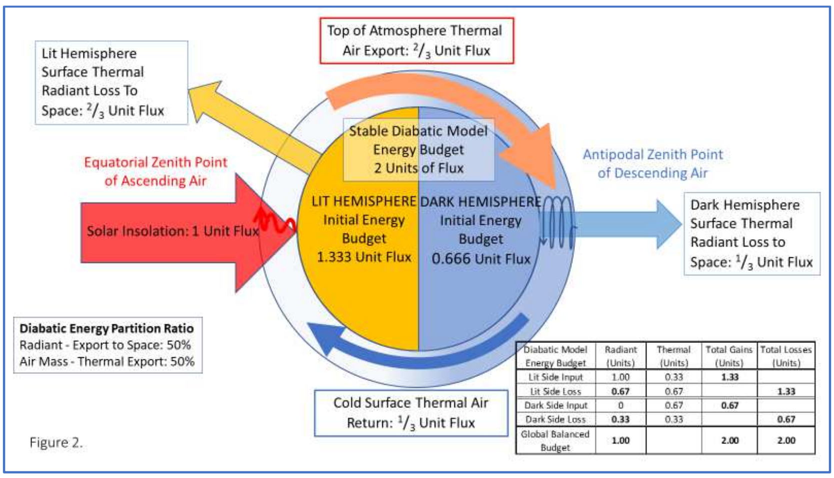


Figure 2. *Basic Globe with a Stable Diabatic Advection Forward Model: Showing Energy Vectors and Unitary Energy Distributions.*

If we couple the planet's thermal Hadley cell of energy surplus and link it to a thermal Polar cell of energy deficit, we create a global atmospheric mass motion entity. This entity is the global climate system that transports energy from a region of surface energy surplus and delivers it to a region of surface energy deficit, and then returns to repeat the cycle endlessly (Table 4).

Table 4. *Running the Dynamic-Atmosphere Energy-Transport Engine "Warmed Up".*

Step	Process	Energy Flow
1	Interception of solar energy by the lit surface	1 unit.
2	Return flow of cold air from the dark side	1/3 unit
3	Total energy available to drive the system	4/3 unit
4	50_S:50_A partition of the intercepted energy between the ground and the air leading to: -	
5	Direct radiant loss to space from the warm surface	2/3 unit
6	Retention of energy by the lit air, followed by transport and delivery of this warm air to the dark side	2/3 unit
7	50_S:50_A partition of the delivered energy between the ground and the air leading to: -	
8	Radiant loss to space from the ground on the dark side	1/3 unit
9	Return flow of cold surface air from the dark side to the lit side	1/3 unit

2.4. Modelling Slowly Rotating Titan

In order to study the process of energy transmission within a globular modelled atmospheric system, we will first apply our diabatic model to Titan, the slowly rotating Saturnian satellite, using standard published metrics for this moon (Table 5).

Table 5. *The Metrics of Titan (Various Sources).*

Parameter	Value	Units	Source
Diameter of Titan	5150	Km	[10]
Radius of Titan	2576	Km	[11]
Average Surface Atmospheric Pressure	146.7	Kpa	[11]
Average Surface Temperature	94	Kelvin	[11]
Average Surface Temperature	-179	Celsius	[11]
Expected T_e	83.2	Kelvin	[8]
Greenhouse Effect	10.8	Kelvin	[8]
Eclipse duration	Minimal	% time in eclipse	[12]
Surface gravity	1.352	m/s^2	[10]
Tropopause height	45.3	km	[2]
Tropospheric lapse rate	0.533	K/km	[2]
Average Solar insolation per solar orbit	14.82	W/m^2	[13]
Bond Albedo	0.265	A (Constant)	[14]
Average Surface Solar Insolation	5.45	W/m^2	[13] [14]
Average Orbital Distance (Saturn)	1,427,000,000	Km	[13]

If for the purpose of analysis, we remove the presence of the giant planet Saturn (Titan's parent body), from the solar system and replace it with a hypothetical solar orbiting tidally-locked minor planet Titan. Then for a vacuum Titan with no atmosphere, the solar lit hemisphere of the now minor planet will receive 5.45 W/m^2, for a surface Bond albedo of 0.265 at the average orbital distance of Saturn. The Stefan-Boltzmann (S-B) equation gives us a temperature of 99.0K for the lit surface of a vacuum Titan (Table 6). The unlit dark side of solar tidally locked vacuum Titan therefore receives no radiant heat, and so will be at a nominal temperature of zero Kelvin, therefore the tidally locked vacuum Titan's surface average temperature will be 49.5K (Table 6).

Table 6. *The Impact on Global Surface Temperature of Adding an Atmosphere to a Vacuum Titan.*

Hypothetical Circulation Type	**Incoming Solar Radiant Energy (W/m^2)**	**Lit Hemisphere Outgoing Thermal Radiant Energy (W/m^2)**	**Lit Hemisphere Surface Temperature (Kelvin)**	**Dark Hemisphere Outgoing Thermal Radiant Energy (W/m^2)**	**Dark Hemisphere Surface Temperature (Kelvin)**	**Global Average Surface Temperatur e (Kelvin)**	**Hemisphere Average Outgoing Thermal Radiant Energy (W/m^2)**
No Atmosphere, No Solar Day, Vacuum Titan	5.446	5.446	99.0	0.000	0	49.5	N/A
No Circulation Static Atmosphere Titan	5.446	2.723	83.2	2.723	83.2	83.2	2.723

If we now add a fully optically transparent atmosphere of Nitrogen gas to vacuum Titan, and let this atmosphere distribute the heat from the Lit to the Dark Hemisphere, then on achieving thermal equilibrium (and assuming no ongoing cycling of mass and energy) the energy on the lit side will be halved to 2.72 W/m^2, and the remaining half (also 2.72 W/m^2) will be distributed to the dark hemisphere, and raise its temperature from zero Kelvin to 83.2 Kelvin (Table 6).

This temperature is identical to the Expected T_e value of 83.2K previously established for Titan (Table 1) using Equation 1 of [8], and this demonstrates that daily rotation is not an *a priori* requirement to distribute captured solar energy across the surface of a globe. Fluid atmospheric circulation that links the two separate hemispheres achieves exactly the same thermal effect.

2.5. How the Presence of an Atmosphere Distributes the Captured Solar Energy Across a Planet

We now need to test how our DAET model behaves when we apply standard Titan insolation parameters to the diabatic form of our model. The annual average solar irradiance for Titan is 14.82 W/m^2, and its Bond Albedo is 0.265 [14], which means that the Annual Average Planetary Energy flow that the lit hemisphere of Titan receives is 5.446 W/m^2. This insolation flux equates to 2.723 W/m^2 per hemisphere after internal atmospheric redistribution (Table 7).

Table 7. *The Titan energy budget and atmospheric system energy deficit.*

Metric	Thermal Radiation (W/m^2)	S-B Sigma	Kelvin	Celsius
Titan Average Annual Solar Insolation (Expected T_e)	2.723	5.67E-08	83.2	-189.8
Target Global Average Annual Air Temperature (Actual Ts)	4.427	5.67E-08	94.0	-179.0
Titan Thermal Energy Deficit	1.704			10.8

The total global atmospheric energy budget that the diabatic equipartition model achieves for Titan is 10.89 W/m^2 (Figure 3). This value results from applying the solar interception flux for the sunlit hemisphere of 5.45 W/m ^{2} (Table 5), to the equipartition diabatic advection model (Table 3).

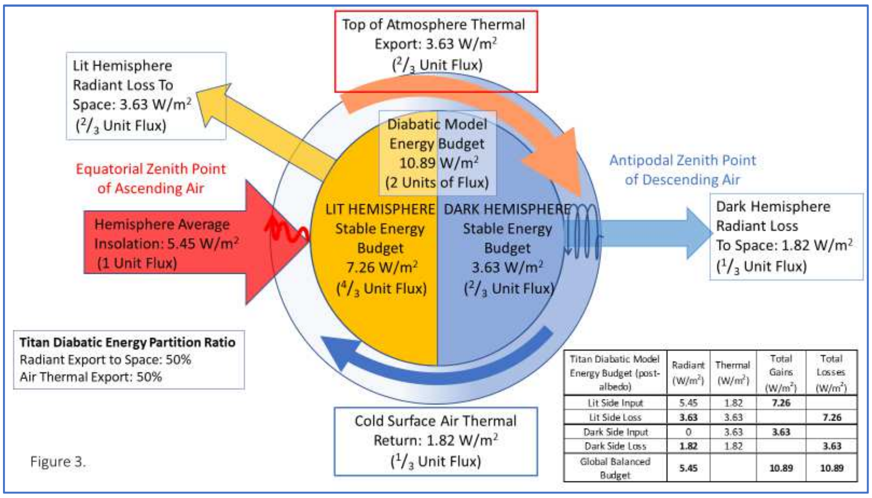


Figure 3. *Stable Diabatic Advection Model of Titan: Showing Energy Vectors and Total Energy Distributions.*

This equipartition energy ratio, when applied to the modelled atmosphere of Titan, creates an air temperature of 82.3 K (-190.7°C), which is slightly below the T_e = 83.2 K of the standard vacuum planet equation for the moon (Table 1). This lower temperature value for Titan (Table 8) is as result of the larger surface radiant energy loss from the lit surface to space (Figure 3), because of the higher insolation applied to our diabatic model under the divide by 2 rule of lit hemisphere radiation loading.

Table 8. *Diabatic Model of Titan showing Internal Energy Recycling with Equipartition of Energy for Both Hemispheres.*

Diabatic Model Partition Test 50_S:50_A Titan Insolation Parameters							
Cycle Number	**Space Incoming Captured Radiation (W/m^2)**	**Lit Ground Received Energy (W/m^2)**	**Lit Hemisphere 50% Thermal Radiation Loss to Space (W/m^2)**	**Lit Hemisphere 50% Export to Dark Side (W/m^2)**	**Dark Hemisphere 50% Thermal Radiation Loss to Space (W/m^2)**	**Dark Hemisphere 50% Surface Return Loop to Lit Side (W/m^2)**	**Space Outgoing Radiation Balance (W/m^2)**
Diabatic Equipartition Ratio			50.0000%	50.0000%	50.0000%	50.0000%	
0	5.4464						
1	5.4464	5.4464	2.7232	2.7232	1.3616	1.3616	4.085
2	5.4464	6.8079	3.4040	3.4040	1.7020	1.7020	5.106
3	5.4464	7.1483	3.5742	3.5742	1.7871	1.7871	5.361
4	5.4464	7.2334	3.6167	3.6167	1.8084	1.8084	5.425
10	5.4464	7.2618	3.6309	3.6309	1.8154	1.8154	5.446
11	5.4464	7.2618	3.6309	3.6309	1.8154	1.8154	5.446

Diabatic Model Partition Test $50_S:50_A$ Titan Insolation Parameters							
Cycle Number	Space Incoming Captured Radiation (W/m^2)	Lit Ground Received Energy (W/m^2)	Lit Hemisphere 50% Thermal Radiation Loss to Space (W/m^2)	Lit Hemisphere 50% Export to Dark Side (W/m^2)	Dark Hemisphere 50% Thermal Radiation Loss to Space (W/m^2)	Dark Hemisphere 50% Surface Return Loop to Lit Side (W/m^2)	Space Outgoing Radiation Balance (W/m^2)
12	5.4464	7.2618	3.6309	3.6309	1.8154	1.8154	5.446
13	5.4464	7.2618	3.6309	3.6309	1.8154	1.8154	5.446
14	5.45	7.26	3.63	3.63	1.82	1.82	5.45
S-B	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08
Kelvin	99.0	106.4	89.5	89.5	75.2	75.2	99.0
Celsius	-174.0	-166.6	-183.5	-183.5	-197.8	-197.8	-174.0
	Statistic	Mean Exit Temp	Mean Air Temp	Lit-side	Dark-side	Global	
	Kelvin	82.3	82.3	W/m^2	W/m^2	W/m^2	
	Celsius	-190.7	-190.7	7.26	3.63	10.89	
	Thermal	Atmospheric Response		Lapse rate	Top of Atmosphere (TOA)		
	Enhancement			K/Km	Delta K	Km	
	(Celsius)	Lit Hemipshere		0.533	16.9	31.8	
	0.0	Dark Hemisphere		0.533	14.2	26.7	

The most critical feature of the diabatic climate model of Titan is that it fully and accurately replicates the computation of the vacuum planet equation of astronomy (Figure 4).

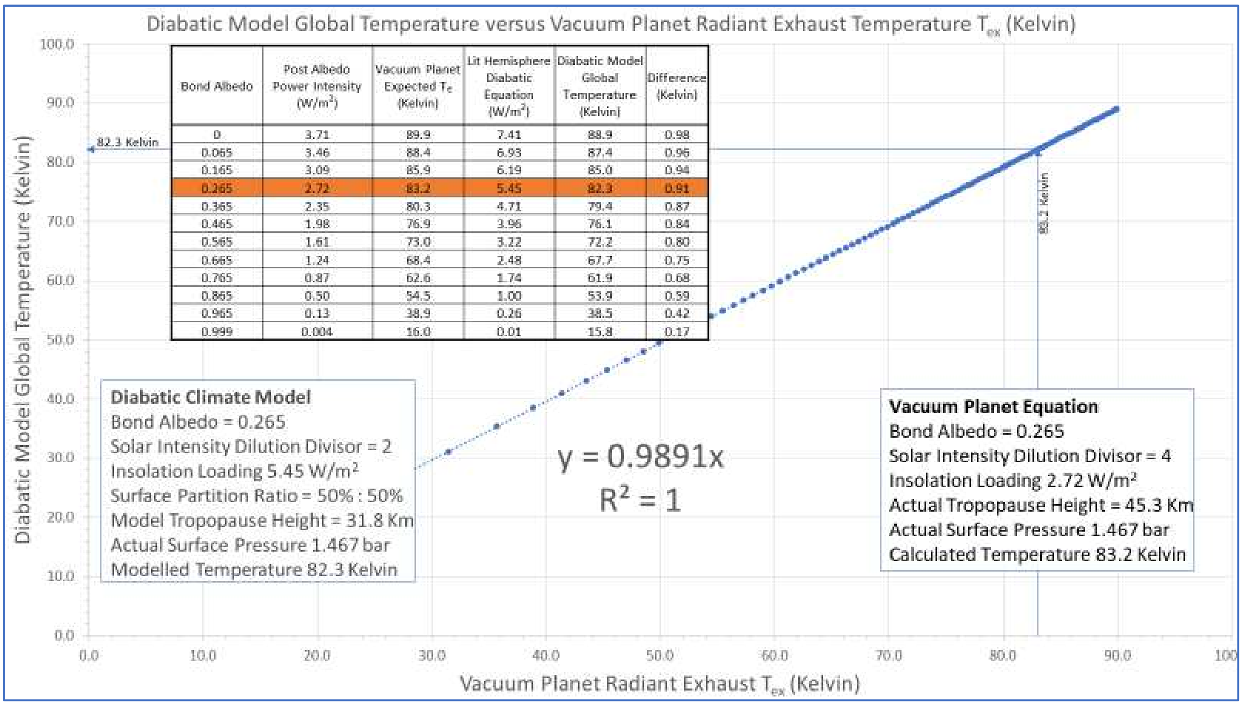


Figure 4. The Direct Equivalence of the Vacuum Planet Equation Top of Atmosphere Radiant Exhaust Temperature (Astronomy) with the Diabatic Climate Model Surface Atmospheric Temperature (Meteorology).

2.6. Establishing the Global Energy Partition Ratio for Titan by Inverse Modelling

The process of establishing the average surface temperature that Titan experiences as a consequence of the adiabatic meteorological actions of turbulent air motion, energy partition and internal atmospheric pressure induced energy retention, is achieved by applying the mathematical technique of inverse modelling to our standard diabatic forward model.

The following steps describe the logic flow of our inverse modelling analysis: -

Step 1: That the repetitive air recycling process of a Hadley cell retains energy within the atmosphere, and that the quantity of energy retained by the air stabilises when the amount of outgoing radiant energy has the same value as the incoming solar flux (Figure 3). This is the diabatic forward model.

Step 2: That on applying Titan insolation parameters to the diabatic forward model we have achieved an average global air temperature of 82.3 K. This temperature is a small underestimation of the Expected T_e for a vacuum Titan of 83.2 K that the standard radiative balance equation computes. The difference arises because in our model we apply a divide by 2 rule to the distribution of incoming solar energy, rather than the divide by 4 rule of the standard vacuum equation model. (Table 8).

Step 3: That by applying the standard geoscience technique of inverse modelling to our basic diabatic atmospheric model of Titan, we can create an adiabatic model that has the flexibility to allow exploration of the surface energy partition ratios that determines the thermal enhancement observed in the atmosphere of this slowly rotating moon. (Table 9).

Table 9. *Adiabatic Energy Partition Test for Titan (~37.6% Thermal Radiant Loss to Space: ~62.4% Atmospheric Energy Retention).*

Adiabatic Partition Test of Slowly Rotating Titan							
Cycle Number	**Space Incoming Captured Radiation (Units)**	**Lit Ground Received Energy (Units)**	**Lit Ground Energy Partition is ~37.6% Lost to Space (Units)**	**Sun Lit Air Energy Partition is ~62.4% Retained and Exported (Units)**	**Dark Ground Energy Partition is ~37.6% Lost to Space (Units)**	**Dark Air Energy Partition is ~62.4% Retained and Exported (Units)**	**Radiant Energy Exiting to Space (Units)**
	Partition Ratio Target Temperature 94 Kelvin (-179°C)		37.6017%	62.3983%	37.6017%	62.3983%	
0	1					0	
1	1	1	0.376017256	0.623982744	0.234628279	0.389354465	0.610645535
2	1	1.389354465	0.522421253	0.866933212	0.325981847	0.540951365	0.8484031
3	1	1.540951365	0.579424303	0.961527062	0.361550767	0.599976295	0.94097507
20	1	1.637611244	0.615770086	1.021841158	0.384229908	0.63761125	0.999999994
21	1	1.63761125	0.615770088	1.021841162	0.384229909	0.637611253	0.999999998
22	1	1.637611253	0.615770089	1.021841164	0.38422991	0.637611254	0.999999999
23	1	1.637611254	0.615770089	1.021841164	0.38422991	0.637611254	1.000000000
24	1	1.637611254	0.615770089	1.021841165	0.38422991	0.637611254	1.000000000
Infinite Series Limit	1	1.64	Energy Surplus Thermal Cell Lit Hemisphere Budget		Energy Deficit Thermal Cell Dark Hemisphere Budget		
			0.62	1.02	0.38	0.64	1.00
Process	Insolation	Insolation plus Thermal Recycled Air	Final Lit Side Thermal Radiant Energy Lost to Space	Atmospheric Energy Transported to the Dark Side	Final Dark Side Thermal Radiant Energy Lost to Space	Atmospheric Energy Returned to the Lit Side	Space Outgoing Radiation Balance
Hemisphere Energy Budget			1.64		1.02		Units
Total Global Energy Budget				2.66			

Step 4: That on applying Titan insolation parameters to the adiabatic model, using the energy partition ratio identified by inverse modelling, we achieve the known average global air temperature of 94 K (-179°C) for this slowly rotating moon (Table 10).

Table 10. *Adiabatic Model of Titan showing Internal Energy Recycling for Both Hemispheres*

Titan Adiabatic Model							
Cycle Number	**Space Incoming Captured Radiation (W/m^2)**	**Lit Ground Received Energy (W/m^2)**	**Lit Ground Partition is ~37.6% (W/m^2)**	**Sun Lit Air Partition is ~62.4% (W/m^2)**	**Dark Ground Partition is ~37.6% (W/m^2)**	**Dark Air Partition is ~62.4% (W/m^2)**	**Space Outgoing Radiation Balance (W/m^2)**
	Partition Ratio Target Temperature 94 Kelvin (-179°C)		37.6017%	62.3983%	37.6017%	62.3983%	
0	5.446						
1	5.446	5.446350000	2.047921580	3.398428420	1.277867728	2.120560692	3.325789308
2	5.446	7.566910692	2.845288992	4.721621700	1.775411234	2.946210467	4.620700226

Titan Adiabatic Model							
Cycle Number	**Space Incoming Captured Radiation (W/m²)**	**Lit Ground Received Energy (W/m²)**	**Lit Ground Partition is ~37.6% (W/m²)**	**Sun Lit Air Partition is ~62.4% (W/m²)**	**Dark Ground Partition is ~37.6% (W/m²)**	**Dark Air Partition is ~62.4% (W/m²)**	**Space Outgoing Radiation Balance (W/m²)**
3	5.446	8.392560467	3.155747554	5.236812912	1.969132019	3.267680893	5.124879574
20	5.446	8.919003998	3.353699406	5.565304592	2.092650559	3.472654033	5.446349965
21	5.446	8.919004033	3.353699419	5.565304614	2.092650567	3.472654046	5.446349986
22	5.446	8.919004046	3.353699424	5.565304622	2.092650571	3.472654052	5.446349995
23	5.446	8.919004052	3.353699426	5.565304625	2.092650572	3.472654054	5.446349998
24	5.446	8.919004054	3.353699427	5.565304627	2.092650572	3.472654054	5.446349999
25	5.45	8.92	3.35	5.57	2.09	3.47	5.45
S-B	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08
Kelvin	99.0	112.0	87.7	99.5	77.9	88.5	99.0
Celsius	-174.0	-161.0	-185.3	-173.5	-195.1	-184.5	-174.0
	Statistic	Mean Exit Temp	Mean Air Temp	Lit-side	Dark-side	Global	
	Kelvin	82.82	94.00	W/m²	W/m²	W/m²	
	Celsius	-190.18	-179.0	8.92	5.57	14.48	
	Thermal Enhancement (Celsius)	Atmospheric Response		Lapse rate	Top of Atmosphere (TOA)		
				K/Km	Delta K	Km	
		Lit Hemisphere		0.533	24.3	45.6	
	11.2	Dark Hemisphere		0.533	21.6	40.5	

The final adiabatic global energy budget for Titan is 14.48 W/m² (Figure 5). This value results from applying the solar interception flux for the sunlit hemisphere of 5.45 W/m² (Table 5), to the Titan adiabatic convection model (Table 9) with a surface partition of 62.4% of the intercepted solar energy being retained by the air. By this means of solar energy capture and retention, as a result of atmospheric adiabatic convection on the lit hemisphere, the stable average air temperature of 94 K (-179°C) is thereby achieved for Titan (Table 10).

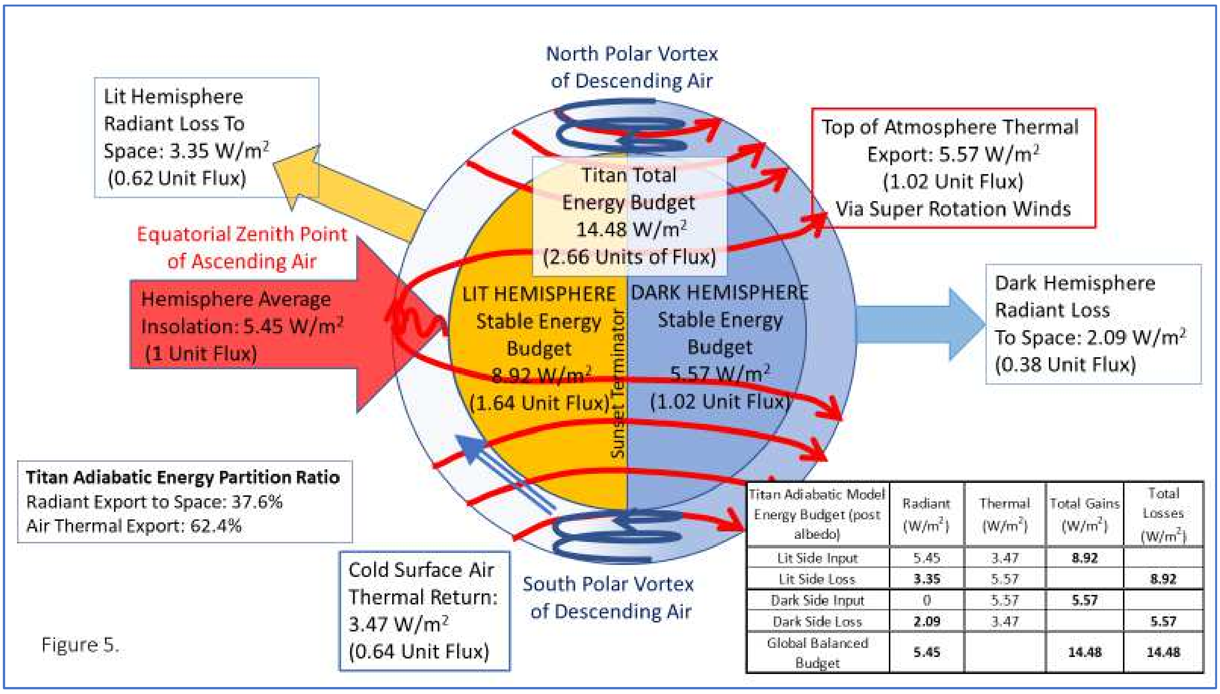


Figure 5. *Stable Adiabatic Model of Titan: Showing Energy Vectors and Total Energy Distributions.*

3. Results of Applying the Adiabatic Modelling Process to Titan

We have now established three important facts about a planetary atmosphere on terrestrial globes:

1. That the presence of even a fully transparent mobile-fluid atmosphere raises the global average surface temperature above that of a non-rotating vacuum world.
2. That this atmosphere both retains and recycles solar energy, and achieves a stable energy flow across the globe's surface.
3. The stable limit of the energy flow within the system is set by the partition ratio of energy between the radiant

loss to space of the emitting surface of both hemispheres, and the quantity of energy retained and recycled by the air.

The process of inverse modelling was applied to the DAET forward model of atmosphere, by constructing a cascade algorithm that allowed the initial unknown energy partition ratio of the lit hemisphere to be determined. This value was established by means of the Excel Inverse Modelling Tool called “Goal Seek”. Initial forward modelling tests where undertaken to establish the number of iterative cycles that are required by Goal Seek to create a stable thermal outcome.

It was established that 25 cycles of atmospheric overturn would produce a stable adiabatic outcome for the atmosphere of Titan. The global average air temperature of this giant moon was achieved using the DAET model with a global atmospheric reservoir energy budget of 2.66 times surface solar energy input (Table 9).

The results of applying the inverse modelling run to Titan are shown in Table 10. The surface energy partition ratio that achieved this result is 37.6% of the moon’s surface energy being directly lost to space, and 62.4% of its surface energy being retained by the atmosphere (Figure 5).

The adiabatic model of Titan computes a dark side thermal separation between the surface and the air of 21.6°C (Table 10). In our model of Titan, the hemisphere of energy deficit is a proxy for the moon’s thermal polar cell. Using the troposphere 45 km gross thermal lapse rate of 0.533 K/km for Titan (Figure 6), this temperature difference equates to a physical separation of 40.5 km (Table 10). This value is our modelled estimate of the tropopause height for the polar regions of Titan.

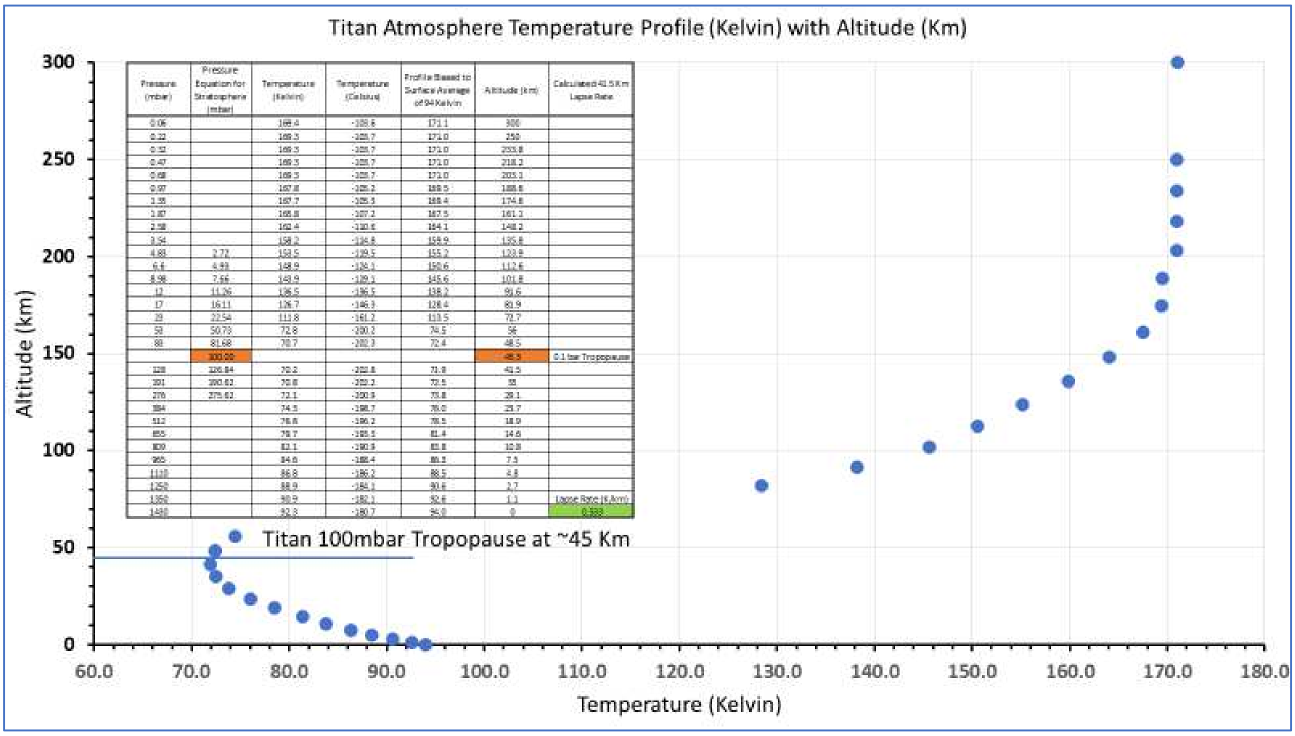


Figure 6. *Titan Atmosphere Temperature Profile [2].*

4. Discussion

Our numerical atmospheric model is based on the fundamental astronomical principle that all globes are sun lit on one side only. This fact applies to all solar system planetary bodies and moons of whatever form and type. For a climate model to be valid, it must be capable of being applied to all bodies, and include all possible types of planetary rotation, including those bodies that are tidally locked.

To address the problem that the standard vacuum planet equation of astronomy cannot be applied to a tidally locked planet, we created a geometric climate model based on meteorological principles. The fundamental distinction of our model is that it honours the reality of a single illuminated hemisphere, and therefore uses the divide by 2 rule as the power intensity divisor for the intercepted surface illumination flux.

The purpose of the diabatic meteorological model is to replicate the form of the standard radiation balance equation of astronomy. The standard model uses the divide by 4 rule of surface radiant energy distribution (Equation 1), and we apply this concept of flux intensity dilution to a globe that is only lit on one side. For such a model, the sunlit energy is distributed over the surface of a single hemisphere, and so a divide by 2 rule of surface radiant energy distribution is applied. For our meteorological model the transmission of energy from the lit hemisphere of energy surplus to the unlit side of energy deficit, is mediated by the atmospheric process of advection.

A comparison of the approach to climate analysis used by the two different scientific disciplines of astronomy, which uses the vacuum planet equation as its founding concept, and our meteorological approach, using a model of the Hadley cell as the fundamental element, is given in Table 11.

Table 11. *A comparison of the approach to climate analysis used by the two different scientific disciplines of astronomy and meteorology.*

Source Discipline	Astronomy	Meteorology
Analytics	Vacuum Planet Equation	Dynamic-Atmosphere Energy-Transport
Illumination Intensity Divisor	4	2
Power Intensity Distribution Mode	Rapid Planetary Rotation	Atmospheric Mass Motion
Surface Environment	Uniform whole globe	Two distinct hemispheres
Analytical Approach	Descriptive Physical Equation	Explanatory Mathematical Model
Initial Conditions	Starts by assuming that there is no atmosphere	Starts by assuming that the planet does not rotate
Physical Process	Low frequency Radiant Flux recycling	Air Motion Thermal recycling
Application	Treats the atmosphere as an opaque system	Treats the atmosphere as a compressible mobile fluid
Appropriate Use	Measures the external low frequency radiant flux exhaust temperature of a planet	Studies the internal process of solar energy capture and atmospheric distribution
Critical Distinction	Applies the concept of energy balance to the top of the atmosphere	Applies the concept of energy balance to the base of the atmosphere

In order to replicate as closely as possible, the form of the standard equilibrium temperature equation of astronomy, the energy partition ratio between the surface and the air in our DAET model is maintained at a diabatic 50%:50% ratio for both the lit and unlit hemispheres. Our model therefore performs, by means of an analogous numerical series with a finite limit (Equations 2 and 3), the same function as, and it sums to the same result as that observed for the standard radiation balance equation of astronomy (Equation 1).

Because an equipartition of energy between a radiatively heated (or cooled) solid surface and an overlying mobile fluid is characteristic of laminar flow, it is clear that this equipartition ratio cannot be used to describe the transmission of energy into (or from) a fluid that is undergoing turbulent motion at the boundary interface. Turbulent fluid motion under daytime solar illumination is characteristic of forced radiative heating and adiabatic convection, consequently a partition ratio weighted in favour of the air is the required metric.

Because the DAET atmosphere model has two distinct surfaces, both representative of the separate environments of energy surplus and energy deficit, we have the opportunity to explore the effects on energy flow within the atmospheric model by applying the process of inverse modelling. Using the known atmosphere parameters, we can explore how two distinct energy partition ratios, one for day and a separate one for the night, impact on internal energy retention within the modelling system. Inspection of the day time temperature profile for Titan (Figure 6) suggests that the energy partition ratio should be weighted in favour of the air for the convective environment on this slowly rotating moon.

An important feature of our DAET model is its predictive capability, specifically the ability of the adiabatic model of slowly-rotating Titan to predict the tropospheric altitude of the Hadley cell of energy surplus, the Polar cell of energy deficit, and also the parameters and dynamics of the Titan atmosphere.

Our adiabatic model incorporates the numerical process of energy partition in favour of the turbulent air for the sunlit surface boundary. Because we know *a priori* the required average surface air temperature for Titan, we can apply the numerical technique of inverse modelling to establish the energy partition ratio that creates the required thermal enhancement for an atmosphere of any opacity. Because our model creates a thermal contrast between the surface and the air, we can also use this temperature difference as a measure of the tropospheric height by applying the appropriate environmental lapse rate for Titan from measured data.

The key insight gained from this analysis is that it is energy partition in favour of the air, at the lit surface boundary that achieves this thermal energy boost within a dynamic atmosphere; and that the energy retention is a direct result of the standard meteorological process of convection. Put simply energy retention by surface conduction and buoyancy driven convection wins over energy loss by radiation, and that the retention of energy by the air is a critical feature of planetary atmospheric thermal cell dynamics.

5. Conclusions

We have designed our mathematical model to retain the critical dual surface element of a lit globe, namely night and day. Figure 4 shows that our simple process diabatic model, when applied to a fully transparent pure Nitrogen atmosphere, matches the results of the standard atmosphere equation which is traditionally applied to an airless world [8].

The following key points arise from the application of our model to Titan:

1. By applying a diabatic forward model to the atmosphere of Titan we have demonstrated that the expected temperature of an airless planet can be replicated on a moon that has a thick (but fully transparent) atmosphere, which can transport air from a lit region of net energy surplus to a dark region of net energy deficit.
2. A slowly rotating moon, such as Titan, does not have a counter rotating mechanical Ferrel cell, therefore there is no dynamic restriction on the latitudinal reach of the Hadley cell on Titan [4], and consequently this slowly rotating moon experiences a single climatic surface environment with a common energy partition ratio for both hemispheres.

3. By applying the inverse atmosphere modelling process to the atmosphere of Titan, and accounting for the fact that there is no surface thermal contrast between day and night on the slowly rotating moon; we can determine the global energy partition ratio on Titan that accounts for its thermally enhanced atmospheric energy retention, and explain the presence of super-rotational winds.
4. By using the appropriate planetary lapse rate for Titan, our inverse modelling process predicts the global atmospheric thickness for this Saturnian moon.
5. Our modelling study of Titan confirms that the opacity of an atmosphere fundamentally controls the height of the radiant emission zone that vents energy to space [15].
6. Consequently, the computational dynamics of the adiabatic model demonstrate that the presence of a troposphere that is opaque to thermal radiation is not an *a priori* requirement for the retention of energy within an atmospheric system.

Our adiabatic model can be tuned to replicate the known conditions of surface atmospheric temperature and pressure of Titan. The issue of atmospheric opacity, due to the presence of polyatomic molecular gases, then becomes a passive atmospheric process, and the concept of thermal radiative feedback as an explanation for the greenhouse effect can be abandoned. This assessment agrees with the recent analysis using balloon profile data that the Greenhouse Gas hypothesis as an explanation for the thermal structure of the Earth's tropopause is flawed [16].

Glossary

Adiabatic: The process of air movement in which there is no energy exchange with the surroundings.

Advection: The process of horizontal transport of air by the mass motion of the atmosphere.

Albedo: An environmental property of a lit surface that acts as a radiant energy bypass filter. Defined as the ratio of reflected radiant energy to incident radiant energy.

A priori: Proceeding from a known value to deduce the consequential result.

Convection: The process of vertical transport of air by means of differential atmospheric heating and air density contrast.

Diabatic: The process of energy exchange by conduction between two adjacent bodies.

Forward Modelling: The technique of computing the result for an unknown parameter from a set of known measurements using a mathematical model.

Insolation: The amount of direct sunlight energy received by the surface of a planet or moon.

Inverse Modelling: The mathematical process of determining the variable input parameter that creates a known measured result.

Lapse Rate: The change of atmospheric temperature with height in a given gravity field. The lapse rate is defined as positive when the temperature decreases with increasing elevation.

Laminar: An atmospheric layer in which air flow is smooth. This layer is usually associated with stable air mass formation and radiative surface boundary cooling.

Opacity: The capacity of a substance to impede the transmission of radiant energy.

Partition Ratio: The ratio of energy distribution at the boundary between two environments.

Terrestrial Planet: A solar system planetary body (or moon) that has a solid surface and is Earth-like in its basic composition and form.

Tropopause: The upper limit of the troposphere marked by a transition to a zero or negative lapse rate in the atmospheric layer above.

Troposphere: The lowest layer of a terrestrial planet's atmosphere dominated by surface heating and cooling, and turbulent air motion.

Turbulence: The process of random mixing of air undergoing forced radiant thermal heating at the surface boundary.

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