Titan Wind Analysis using Lagrangian Coherent Structures

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California Institute of Technology, October 16, 2008

Abstract: For all the intrigue about liquid water being on the surface of Mars at one time or locked in its polar caps, perhaps an even more fascinating is Titan, the largest moon of Saturn, which is the only stellar object known to have stable bodies of liquid, namely hydrocarbons, on its surface. Titan has a nitrogen atmosphere, with clouds of methane and ethane, and the presence of water ice "rocks" in abundance. This moon, because of the presence of liquid, exhibits very similar weather and geological patterns to earth, with equatorial sand dunes and high latitude seas. It is believed that methane on Titan takes the place of water on earth in that it is involved in a hydrological cycle of evaporation and precipitation. Because of tilt on its axis, it also shares seasonal characteristics with earth. This lends to wind patterns on Titan that generally includes a meridional flow of broad Hadley cells, single during the solstice and double during the equinox, and a zonal flow of superrotating westerlies above the tropopause and easterlies nearer the surface, increasing in speed nearing the equator.

In July of 2004, the Cassini mission, intended to explore the Saturnian system, released the Huygens probe, which landed on Titan and was able to take some clear pictures of the surface. Because of the promise of this moon, NASA has decided to return for further study. But the details of this mission have yet to be finalized. It is estimated that the launch will be sometime around 2016, arriving at Titan at 2026. There are initial plans to include a hot air (Montgolfiere) balloon for this trip so that exploration of multiple locations of interest will be possible. In order to effectively use a balloon, we must be able to predict the drift patterns of our balloon in the unique atmosphere of Titan. Using a model for the wind patterns on Titan called TitanWRF, outputs for the possible wind conditions expected on the moon, for a specific time of Titan year and day and taking into account of the Saturn-influenced tidal effects, was produced. These outputs were generated around the year 2026 corresponding to approximately spring solstice (L_s~180). Previous analysis of wind conditions were mostly done in a Eulerian reference frame, which interprets the wind patterns by taking the time-average of the wind speed relative to a position on the surface of Titan. This leaves a general view of the wind, noting locations of stronger or weaker flow. But, to understand the trajectories of the wind flow, we must consider the wind as a giant mass of air particles instead, taking a view of the wind from a lagrangian frame, interpreting the wind field essentially from the reference frame of not a location but a particle.

The balloon can simply be considered as a piece of driftwood caught in the currents. To properly map out trajectories that a balloon can expect to follow on Titan, an analysis of the LCS (Lagrangian Coherent Structures) of the wind field was carried out using the Newman code. LCS are the seperatrices of a time-dependent system, such as the wind field on Titan, which

distinguish dynamically distinct areas in the flow. A plot of the FTLE (Finite-Time Layaponov Exponent), a scalar value that describes the amount of stretching about a trajectory point, of the flow can be used to find the LCS. Ridges of especially high FTLE values indicate that particles around that location will be sensitive to high variability in trajectory. Using LCS as reference points of dynamic movement of air particles, possible trajectories of the balloon were mapped. With this knowledge, a proper landing location and planned course of movement was outlined for a balloon to navigate the moon of Titan and explore key areas that generate the most interest.

I. Introduction

a. Titan

Titan, the largest moon of Saturn, shares many similar characteristics with Earth, making a very unique specimen in our solar system, and one worth a closer inspection. Titan's large size (~2576 km radius), larger than even Mercury, is what gives it its planet-like characteristics. This moon is composed of rocky material and also water ice. It is believed that Titan has a rocky silicate core surrounded by layers of ice and a liquid layer of water and ammonia. It is in synchronous orbit with Saturn, with an orbital period of 15.945 earth days. Titan orbits the sun along with Saturn in ~29.5 terrestrial years. Similar to earth, Titan is tilted on its side, with an orbital eccentricity of 0.0288, corresponding to an inclination of 0.348 degrees relative to the Saturnian equator. This gives Titan its seasons which manifests itself in seasonal wind patterns observed in its meteorology

The key characteristic that separates this body from others in the Solar System is the presence of an atmosphere. Titan remains to be the only moon known to have a fully developed atmosphere; this moon's atmosphere is very thick and hazy, composed primarily of nitrogen (98.4%) and methane (1.6%) and trace amounts of many other hydrocarbons (fig 1). The atmospheric methane should have been degraded by the sun's energy throughout Titan's life cycle suggesting that there is a replenishing source of methane on Titan. This led to the discovery that Titan possesses its own hydrological cycle similar to earth's, with methane taking the place of liquid water. Sure enough, lakes of methane have been discovered on Titan's surface near its poles.

Figure 1: Real color image of the haze in Titan's atmosphere.

These amazing attributes of Titan make it a deserving candidate for exploration. The meteorological processes taking place on Titan is complex, fascinating, and unlike any other stellar body. Like Earth, Titan has an atmosphere, a replenishing hydrological cycle, and seasons. Its abundance of hydrocarbons suggests the possibility of complex organic processes that may provide a prebiotic environment similar to an early earth, albeit at a much lower surface temperature (93.7 K).

b. Exploring Titan's Surface Features

With so many similar meteorological processes, Titan shares many congruous surface features with earth. In 2004, the Cassini spacecraft was able to map out many of Titan's surface features after a series of close fly-bys. Titan is known to be a geographically young body, and its surface exhibited a very diverse geology yet contained very little height variation. Coupled with its dense atmosphere, low surface temperature, and high surface pressure (146.7 kPa), Titan is an ideal candidate to be explored via Montgolfiere balloon.

There are initial plans to send a spacecraft to Titan with a launch date of 2018. That would put the arrival date between 2026-2028. Since the Titan surface is littered with interesting sites, scattered across the globe, exploring every site through the air is very appealing. Right now, a lighter-than-air vehicle is being seriously considered as a means of exploration. To two models include a Montgolfiere balloon with no external controls (riding wind currents only) afloat by heating the ambient air or an aerobot which will use a lighter than ambient air medium (hydrogen, helium) with external propellers. Both airships will be greatly affected by the wind conditions on Titan and utilizing the winds to explore the planet is a necessity. These ships would presumably cruise below 10 km altitude to avoid icing problems and be able to image the surface at 1m resolution and perform over half a dozen soft-landings at different sites over a year.

c. Titan's Key Features

i. Equator

1. Drainage Channels (10.3 S, 192.3 W)

Near the Huygens probe landing site, it appears that there are deeply cut channels in the ground, perhaps caused by flowing rivers of methane. These channels like to the grand canyon on earth. (fig 2)

2. Sand Dunes (7 S, 250 W)

Because of the winds on Titan, there are large sand dunes that are sculpted similarly to the Nimibian sand dunes on earth. Instead of sand, it is possible that the dunes consist of eroded particles of water ice. (fig 3)

ii. **Mid Latitudes**

1. **"The Smile" (20 S, 80 W)**

   This is the brightest and most visible spot on Titan's surface, measuring over 560 km wide. It is not clear what this feature is composed of, or what caused it, but it is speculated that a recent event such as a landslide or cryovolcanism could be the cause. (fig 4)

2. **Xanadu (20S, 130 W)**

   This flat, highly reflective plateau is a large area of Titan's surface that exhibits great tectonic activity. This surface is paved with water ice. (fig 5)

3. **Titan's Sierras**

   These massive mountain ranges stretch across Titan running 150 km long and 30 km wide. These mountain represents the most variation in the height of surface features on Titan, measuring 1.5km at its highest peaks. (fig 6)

4. **Cryovolcano (32 N, 133 W)**

   This massive volcano possibly spews hydrocarbon ice from the planet's subterranean layers. This process may explain the origin of the methane abundance in Titan's atmosphere. (fig 7)

5. **Impact Crater (30 N, 70 W)**

   Due to its thick atmosphere, there are only a few lasting impact craters that appear on Titan's surface. (fig 8)

iii. **Poles**

1. **Hydrocarbon Lakes**

   There are numerous radar dark patches near Titan's poles that resemble lakes, probably containing pools of liquid methane taking part in the moon's hydrological cycle. (fig 9)

iv. **Reaching these Locations**

Figure 10 is the complete collection of the points of interest on Titan and this provides valuable insight into the approach to have when planning a course for the balloon. It is clear that most of the points of interest are located around the equator, with a few scattered in the mid-latitudes and finally, one important feature at the poles. That means that, given a choice, circulating the equator would be most rewarding in covering the most number of points with least meridional movement. But since there is so much importance place on the lakes, moving to the poles is also a top priority. That is what makes this mission so challenging in its push to explore as many crucial areas as possible. Finding a trajectory that includes all these points translates to finding a way to explore the entire globe of Titan.

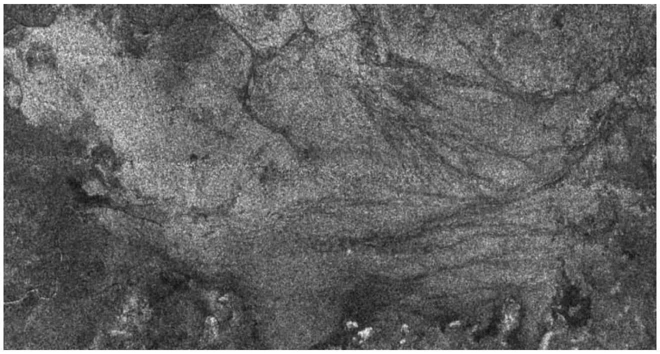

Figure 2: Drainage Channels

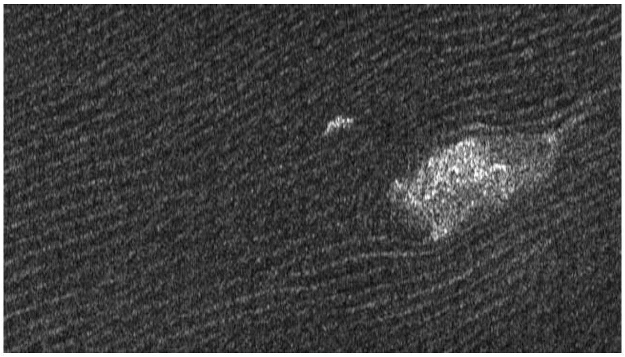

Figure 3: Sand Dunes

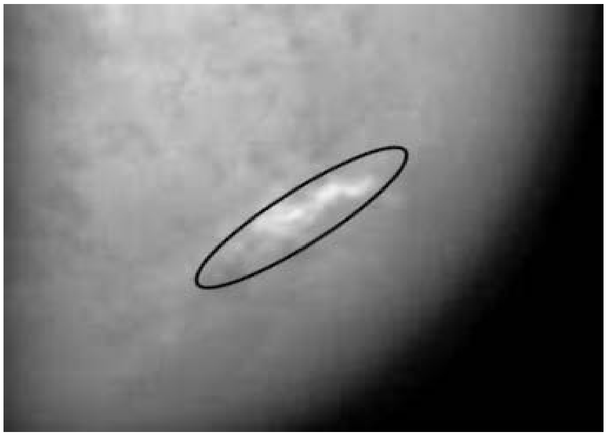

Figure 4: The Smile

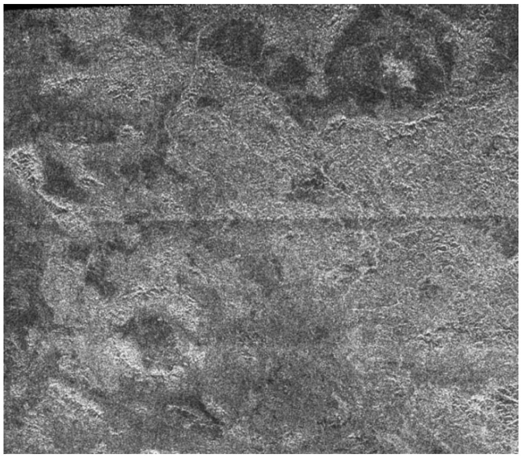

Figure 5: Xanadu

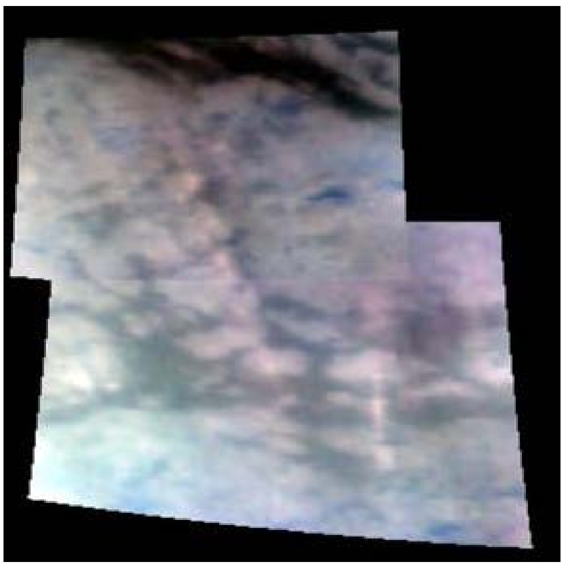

Figure 6: Titan's Sierras

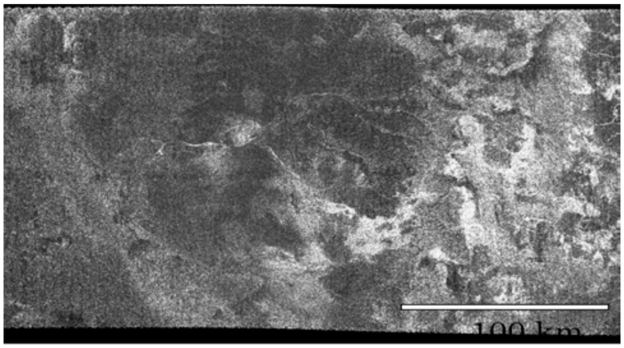

Figure 7: Cryovolcano

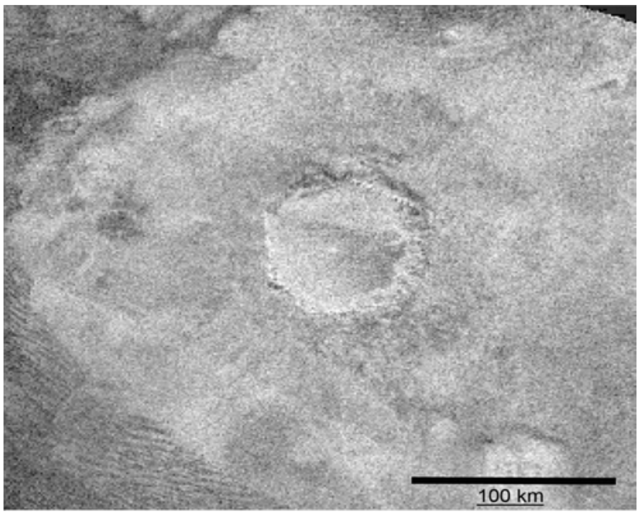

Figure 9: Impact Crater

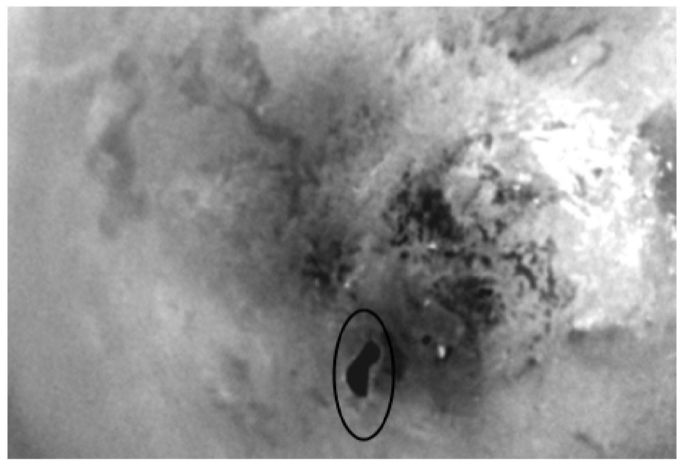

Figure 8: Polar Lakes

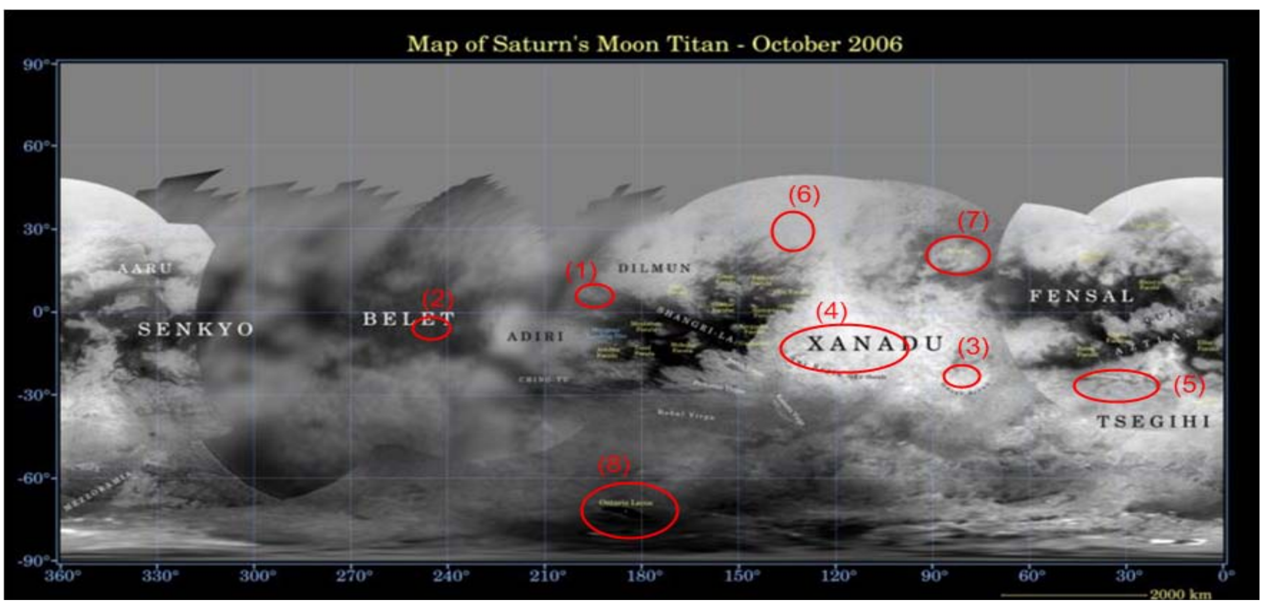

Figure 10: Points of Interest on Titan

II. Methods

a. Wind Patterns

i. Technical Background

1. Atmospheric Wind Characteristics

Previous studies done on the wind flow on Titan has been a product of GCM (global circulation models). Since there is so little empirical data on Titan's actual wind conditions, only models are used for studying Titan wind flows. In Hourdin et al. 1995[1], their study was done using a grid point model developed at the Laboratoire de Meteorologie Dynamique, which accounted for "radiative heating and cooling by molecular gases and haze as well as parametrization of the vertical turbulent mixing of momentum and potential temperature". They concluded "strong superrotation with prograde equatorial winds increasing from the surface." This somewhat agrees with the few measurements done of the Titan wind from the Huygens probe and also Viking I, at least in general wind direction if not the exact severity of the gusts.

In Tokano et al. 2002[3], the tidal forcing is predicted to cause a "time-dependent radial and librational tide whose potential circles eastward." The combination of the tides with the general wind patterns on Titan results in "equatorward flow and high-latitude whirls." The tidal wind also "manifests itself as eastward traveling planetary-scale wave of wavenumber 2."

The large scale flow of atmospheres such as Titan's is very similar to that observed on earth. Because Titan has an atmosphere and a methane replenishing cycle with clouds and precipitation, the winds on Titan are dominated by large scale circulation of its atmosphere. Just like earth, the two major factors that affect air movement is the heating from the sun and the tidal pull from a nearby mass, in this case Saturn.

Characteristic of the large scale structure of atmospheric flows, Titan experiences flow that varies "most rapidly in the vertical direction and least rapidly in the zonal direction." Thus, in general, the meridional flow is more closely analyzed while the zonal flow can be more or less averaged across the planet.

The types of meridional flow on Titan is similar to earth in that it is thermally driven. In 1735, George Hadley proposed a theory for the circulation of rising motion in the tropics and descent in the winter hemisphere to explain the presence of trade winds blowing towards the equator on earth. This type of circulation, now known as Hadley cells, is believed to be the dominant meridional characteristic of Titan's atmosphere (fig 11).

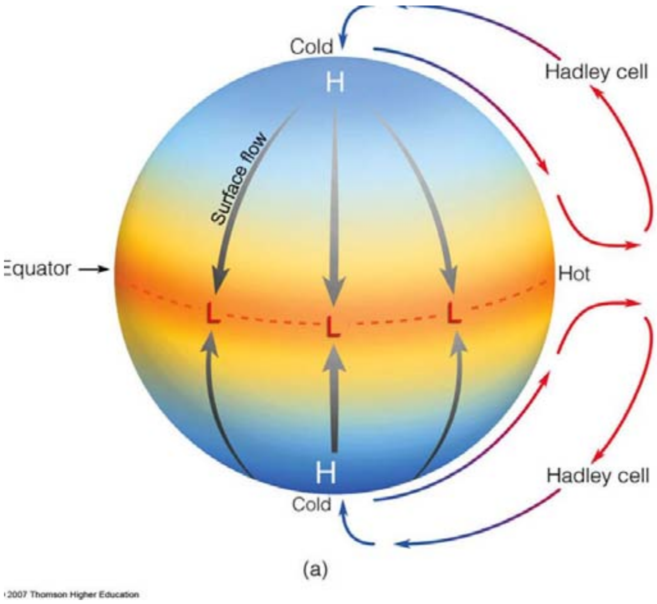

Figure 11: Hadley Circulation (Equinox)

2. Titan's seasonal characteristics

The basis of the Hadley circulation is rising air in the warmer portions of the atmosphere caused by solar heating flowing towards colder parts. This causes air flow in the troposphere from warm to cold and to satisfy the conservation of mass, there is a return flow near the surface from the cold to warm portions. This large overturning circulation is exhibited by Titan, changing with its seasons as Saturn and in turn Titan orbits the Sun and is heated by solar radiation.

In figure 12**,** Titan's path around the Sun is shown with its solstice and equinox points marked; Titan moves eccentrically around the sun and it turns out that its northern summer solstice (northern hemisphere is closer to the sun because of its axial tilt) occurs at a point where it is closer to the sun than the southern summer solstice. That makes the northern summer slightly more intense in its weather patterns than its southern summer counterpart. The equinoxes on the other hand are more or less the same with very similar distances from the sun. The Ls corresponds to solar latitude, which marks the position of Titan relative to the sun. The Titan mission will arrive presumably between 2026-2028 if it launches in 2018 as scheduled now. That corresponds to a

Titan season of northern autumn (Ls=180) which will be the season that is mainly analyzed in this paper.

Characteristic of Hadley circulation, the summer and winter solstices correspond to heating in the summer hemisphere, with air primarily rising around mid to high latitudes (~75^{o}) and falling in the winter hemisphere around the same latitude. The summer and winter contains one giant Hadley cell moving from summer to winter. The equinoxes are different because it marks the point where the equator is the closest to the sun. That means that each hemisphere receives very equal heating so the air rises in the equator and moves outwards towards the poles. The air falls again in the mid latitudes of each hemisphere (~40-50^{o}) with return flow moving towards the equator closer to the surface.

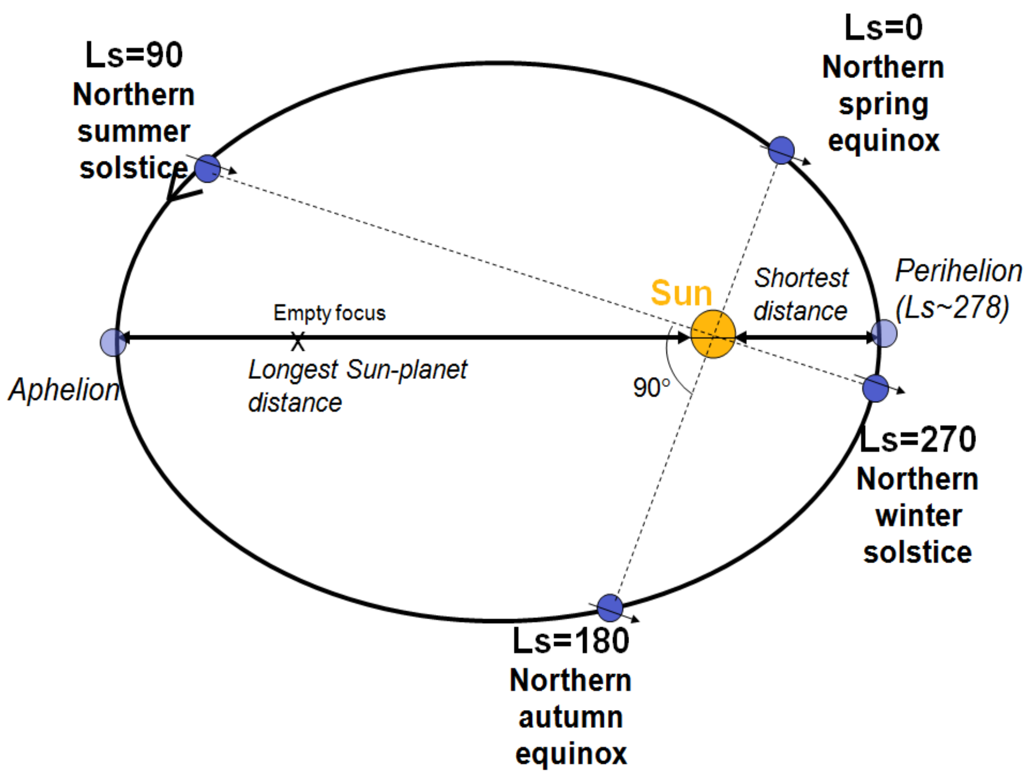

Figure 12: Path of Titan and Saturn around the Sun

3. Coriolis Effect

As Titan rotates on its axis, there is a coriolis effect that defines its zonal wind movement. Observed throughout Titan's atmosphere by the Huygens probe and also by the quickly circulating clouds visible in its atmosphere, Titan has a superrotating atmosphere of westerlies. Given that Titan has a constant rate of rotation, the speed of rotation of a point on the surface of the moon depends on its radius of rotation. Thus, nearer the poles, the speed of rotation of the surface is less and moving towards the equator, the speed of rotation increases. At the poles, there are strong westerlies because the speed of rotation is slow. But moving toward the equator, the fast rotation of the surface relative to the westerlies makes the wind speed from the perspective of the surface slow down. This explains the presence of weak easterlies at the equator due to the high speed of rotation and strong westerlies at the poles.

4. Titan WRF

The meteorological characteristics on Titan , as of now, are very speculative because they are based on only a handful of information obtained very early first by Viking, and then later from Cassini and the accompanying Huygens probe. Because of the thick atmospheric haze surrounding the entire moon, it is very difficult to view any characteristics within its atmosphere. The Huygens probe did provide a real measurement of wind conditions on Titan but it remains to be the only set of real wind data and can only reveal on vertical slice of wind components in one specific area of the moon. To plan for this upcoming mission to Titan, a predictive model of the winds expected on Titan must be used. This model is called TitanWRF which is a branch of the WRF (weather research and forecasting model) of weather on earth. This model is described as a "next-generation mesoscale numerical weather prediction system designed so serve both operational forecasting and atmospheric research needs".

The model which is used in this report was operated by my mentor Claire Newman in the Geological and Planetary Science Department at the California Institute of Technology. It is a moderated version of the earth based model accounting for the characteristics of Titan instead of earth, such as orbit eccentricity, atmospheric composition, surface temperature, planetary size, etc. This model represents the latest development in predictive conditions for the moon of Titan and the model is able to explain and match up with a majority of the observations made about Titan's conditions. This paper will not go into the details of the calculations behind the model, merely go over the final results produced by it.

ii. Visualizing Wind Data

Outputs from the TitanWRF model produce three dimensional vector fields over the entire moon, over a set period of time usually one Titan rotation around Saturn. Interpolated across all latitude, longitude, and altitude, there are x, y, and z wind components which are produced for each point. Visualizing such a large set of data effectively is difficult, especially just viewing the wind from a Eulerian frame. The vectors fields can be plotted using Matlab scripts.

A most simplistic interpretation of the wind vectors starts with a time-averaged approach. For viewing the meridional circulation, it is better to average the winds zonally, over all longitudes. Plotting the winds using a contour graph of altitude versus latitude, the meridional movement of the wind is clear. It is useful to relation between altitude and latitude wind flow since the meridional flow is dominated by Hadley cells which are large overturning structures. To view the zonal flow, and its flow relative to meridional circulation, slices of graphs of longitude versus latitude at different heights are revealing. This demonstrates the dependence of the wind conditions on height.

To get a more insightful interpretation, movies can be made with the wind vectors and instead of averaging over all time, a frame can be taken of a wind vector graph at each time and strung together. Time averaging eliminates periodic wind movement. By taking movies of wind vectors, other features of the wind can be observed such as eddies and periodic waves that travel across Titan.

b. LCS

i. Technical Background

By time-averaging the wind field, this eulerian view only shows the large scale structures in the wind flow. To try to determine a trajectory that a balloon caught in the current of the wind flow can take, a lagrangian view is much more applicable.

A lagrangian frame is one that follows trajectories in a flow by following the path of a particle in the flow as opposed to simply viewing the flow as a whole. The lagrangian view is a time-dependent interpretation that creates a more complicating but useful perspective. By analyzing the movement of particles in the flow based on starting location as a function of time can reveal how to effectively use the balloon to explore Titan completely.

Since it is so convoluting to simply observe all the trajectories in the wind field, a method of analysis can be used that involves finding the LCS (Lagrangian Coherent Structures) in a flow to more accurately interpret the dominant movement of particle trajectories.

The wind field on Titan is a time-dependent dynamical system. To understand any dynamical system, finding its stable and unstable manifolds reveals its behavior but for time-dependent systems, this becomes very difficult. In figure 13, the line represents a manifold or separatrice, which is a division in the flow which separates areas of dynamic movement. Since points on either side of the line behave very differently, and diverge suddenly in space going forward in time, this is an object of interest in defining the behavior of the system. To understand the wind flow on Titan, it will be crucial to find the "regions of qualitatively different dynamics."

In time-dependent flows, these seperatrices are referred to as LCS since the idea of stable and unstable manifolds are not completely applicable in time-dependent flows. To find these pseudo-seperatrices, the use of FTLE (finite time lyapanov exponents) is employed. Simply put, the FTLE is a scalar value that "characterizes the amount of stretching about the trajectory point." By finding the FTLE value at each point in the flow, ridges of high FTLE values correspond to LCS; ridges of highest FTLE value are, by definition, the separation between two areas of dynamic behavior since points around that ridge exhibit the most stretching of its trajectory as the system progresses forward in time.

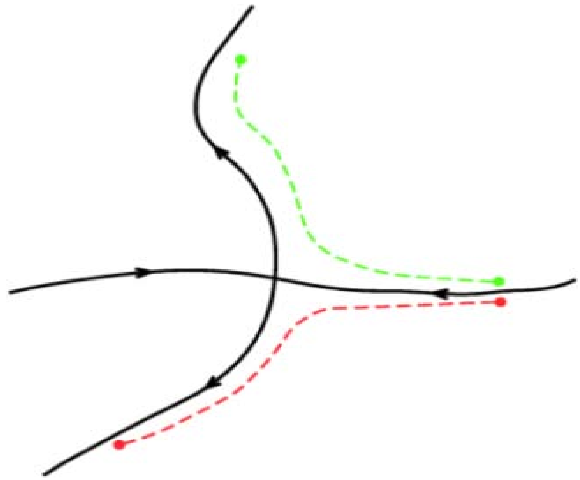

Figure 13: Seperatrice in a dynamic flow.

ii. Newman Code- Computing LCS

Without going into the details about the calculation of FTLE values, the method used to calculate and graph FTLE values to find LCS was carried out using a program called the Newman code. This is a Linux based program written by my mentor Philip du Toit which takes in inputs of a text formatted file of a vector field and then outputs velocity plots, particle trajectories, and FTLE plots. The plots that resulted required Tecplot to be interpreted and were lengthy in time to run. The average time for one run of the FLTE plots were around three hours.

III. Results

a. Wind Fields

The specifics of the montgolfiere balloon's arrival to Titan is at Northern Autumn Equinox (Ls=180). Taking outputs from the TitanWRF model for that season, the data was narrowed down to the height of interest, from the surface to 25km. Specifically, even regions above 12-15km do not need to be analyzed since icing becomes a problem at those heights but to be on the safe side, the initial data set started from 25km and below.

The first plots were done to visualize the meridional flow and to confirm the presence of Hadley cells during the solstice and equinox seasons. For this initial set of data, both Ls=270 and Ls=180 were used and contour graphs of height versus latitude were produced. In figure 14 and 15, the two different Hadley cell structures can be clearly observed

Figure 14 has two structures symmetric about the equator that indicates that it is an equinox because the wind flow goes outwards from the equator at higher altitudes (1x10^4m) and nearer the equator at (5x10^3m). Conversely, figure 15 clearly has one large structure flowing from warm to cold hemisphere at higher altitudes and a return flow near the surface from cold to warm hemisphere. The plots are time averaged over close to 8 titan days and it is a plot of latitude versus altitude so it is also averaged over all longitudes. Since the general behavior of the wind zonally should be westerlies mostly circulating the globe.

To confirm the zonal wind flow, vector graphs were produced of latitude versus longitude for one height, which are time averaged over 8 titan days again. From figure 16 and 17, the difference in wind flow varying with altitude becomes clear.

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In both figures, the zonal flow dominates the wind movement. The coriolis effect is observed moving from the poles to the equator, as the magnitude of the zonal wind flow decreases. Closer to the surface, at 5 km, figure 16 shows the return flow going towards the equator creating the swirls around the equator. This data is time averaged so the actual trajectories of the wind is not clear and that is what makes the Lagrangian analysis necessary. Higher up at 25km, there is almost no meridional component to the wind because the altitude is high enough so that the return flow is not present but it is not high enough in the atmosphere for the original Hadley cell wind movement from hot to cold parts of the hemisphere to be observed.

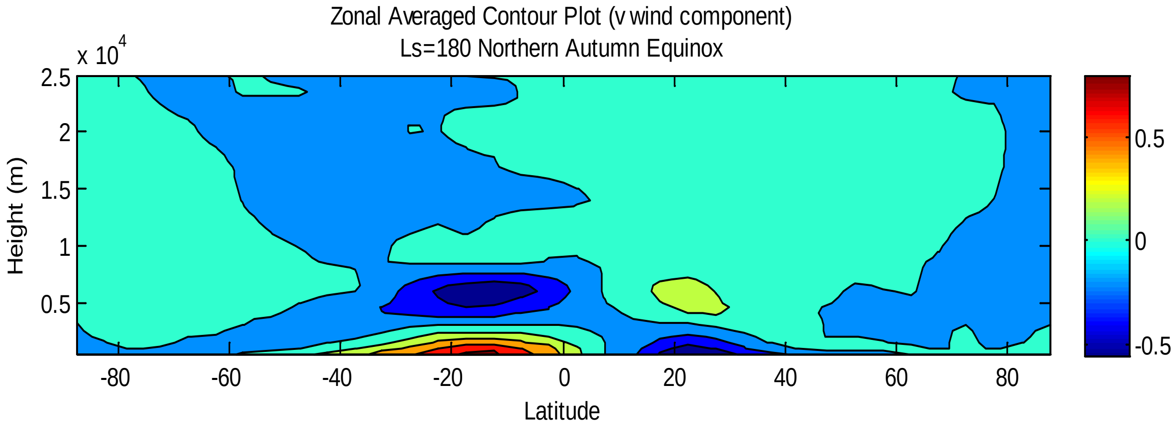


Figure 14

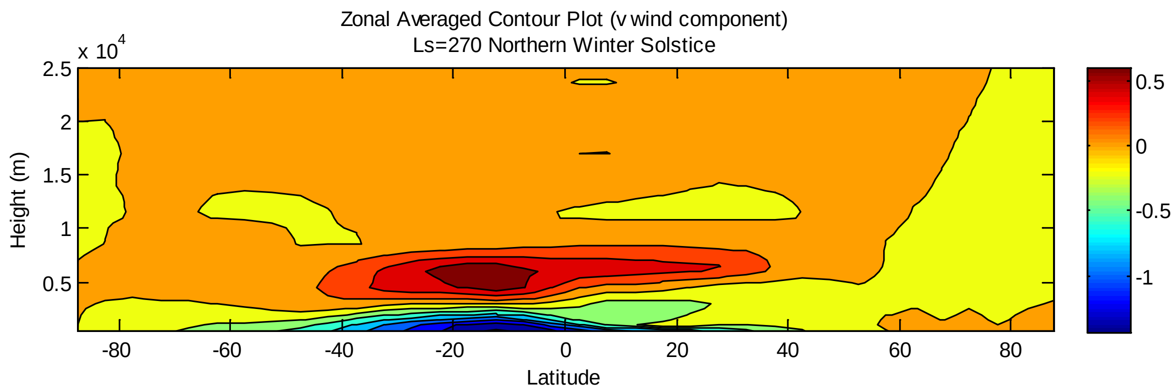


Figure 15

Figure 16

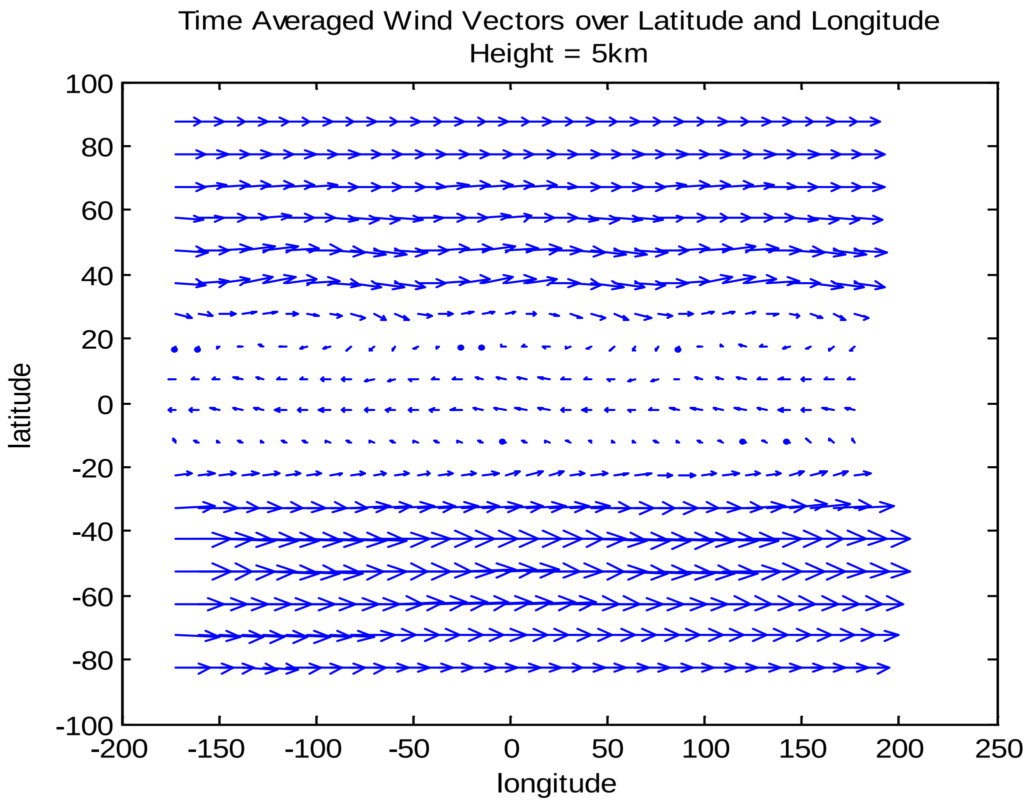
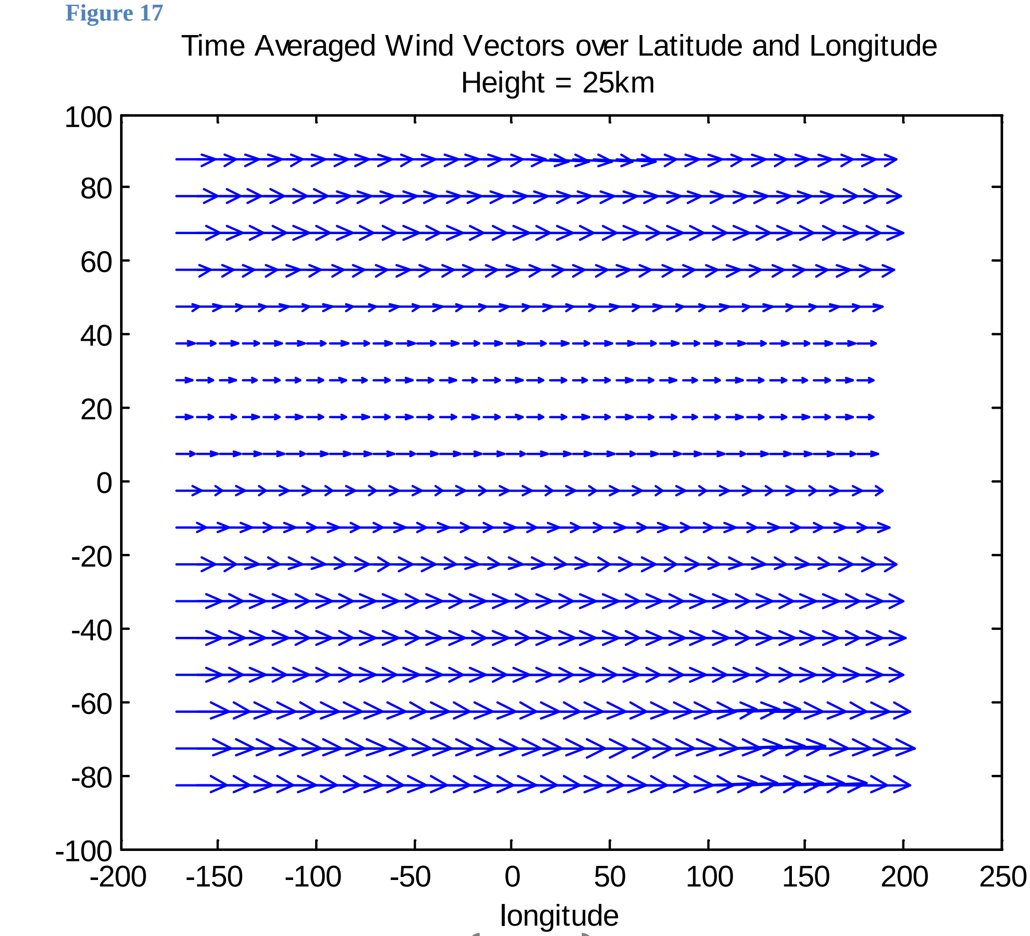


Figure 17



b. Wind Trajectories

To view the wind vectors in a Lagrangian perspective, the vector wind fields from the Titan WRF output was put into the Newman code for processing. Capable of producing drifter plots as well as FTLE plots that reveal the LCS for a particular wind field, this data revealed the behavior of a particle within the wind field given a starting location.

The drifter plot function in the Newman code allows drifters to be simulated over a mesh of latitude, longitude, and altitude. The first trials of the drifter plots resulted in too many drifter leaving the domain after moving forward in time over the data set. With drifters floating out of the domain mainly through the top of the bottom of the domain, the excess of vertical movement was likely the cause. Because this study is for a Montgolfiere balloon, vertical movement from winds is not a factor since there is vertical control. Therefore, the z components of the winds were changed to zero and the program rerun, eliminating the escape of drifter particles. This also resulted in more accurate FTLE plots because quickly escaping drifters would produce large FTLE values due to the high degree of separation between drifters as they leave. Vertical separation is not important for this study of the passive drift of a balloon to explore points of interest on Titan when vertical control is possible for Montgolfiere balloons.

These drifter plots used data from Ls=0 which is not the season that the balloon will be arriving but should be analogous because it is spring equinox as opposed to autumn equinox. This data set was used instead because that was the only available Titan WRF output with enough data sets in time. Figure 18 shows the initial placement of the drifters in the wind field, put against a background of a color map of Titan. They are evenly spaced across latitude and longitude and placed in a region around 1km in height.

Drifter Plots: 1km Altitude, Ls=0

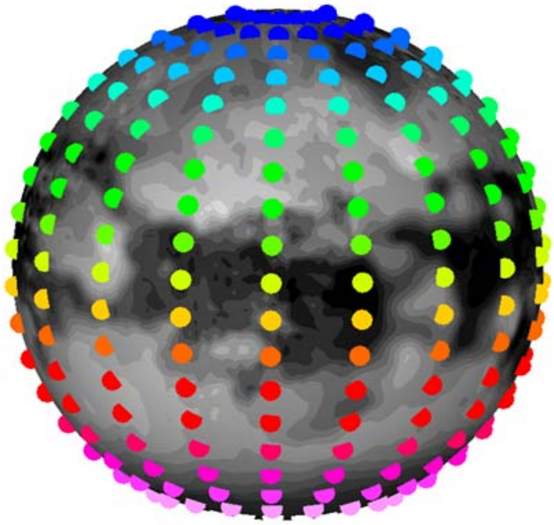


Figure 16: Frame 1, t=0

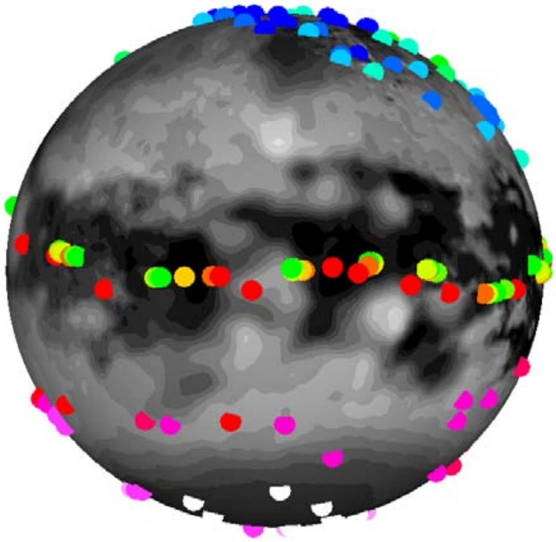


Figure 17: Frame 100, t=8 titan days, 128 earth days

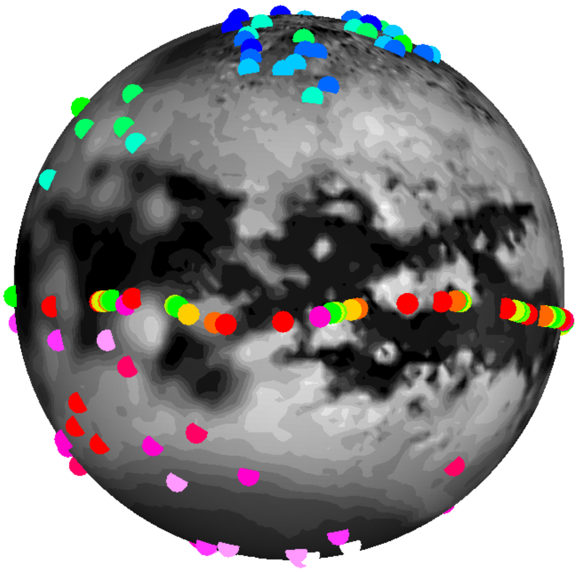


Figure 18: Frame 200, t=16 titan days, 256 earth days

Figure 19 shows frame 100 which is the drifter locations after 100 titan days, and figure 20 shows the drifter locations after 200 titan days, the entire data set. The drifters are colored by latitude to key their meridional movement. The key observation is to test the ability of drifters to move significantly across many latitudes while moving zonally across Titan.

The FTLE graphs were also produced for this data set for the same time intervals. These graphs should match the drifter plots, defining dynamic areas of the flow. In figure 21, the FTLE graphs show the divisions in the flow where particles behave very differently. Figure 22 reveals the time dependent nature of LCS structures. The large red ridges of high FTLE values, defining the LCS of the flow, are clear in figure 21. It is obvious that the drifter movement in the higher latitudes is very dependent of starting location since there are large time-varying FTLE ridges moving across the atmosphere. But as time goes on, these dynamic structures fade slowly and the behavior of drifters become much more uniform and steady.

FTLE Plots: 1km Altitude, Ls=0

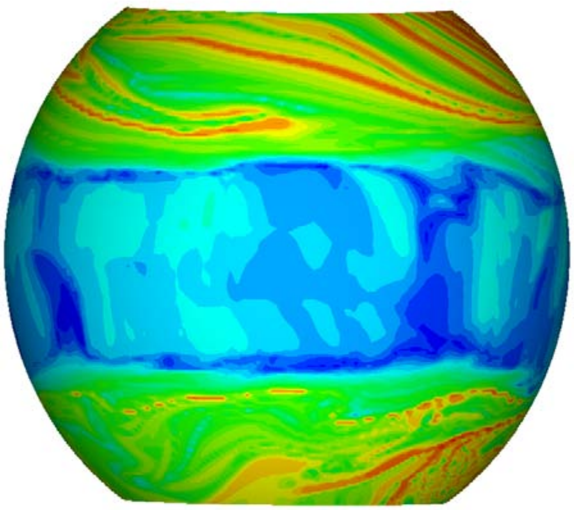


Figure 21: Frame 1, t=0

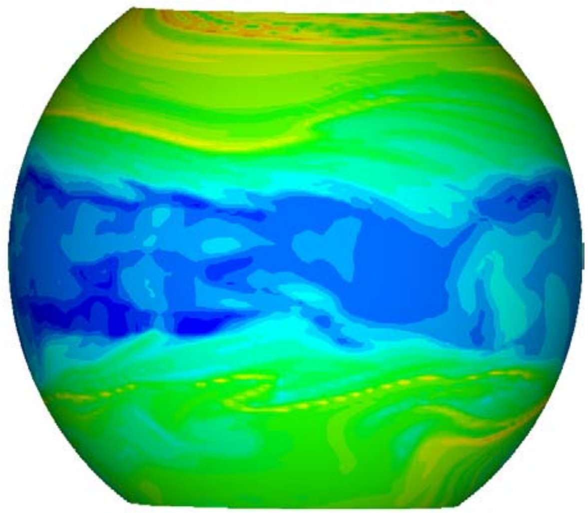


Figure 22: Frame 100, t=8 titan days, 128 earth days

IV. Discussion

a. Mission Plan

To explore the entire moon, the wind flow needs to be able to take a passive balloon across many latitudes while the strong superrotational zonal winds move the balloon across all longitudes. Viewing just the wind vectors, the bulk behavior of the wind fields is zonal flow predominance above 10 km and noticeable meridional flow only close to the surface. But the meridional flow produces winds that move towards the equator for low latitudes, near the surface. That means, an effective initial plan for balloon exploration includes landing hear the poles and allow the near surface flow to take the balloon towards the equator while being superrotated around Titan. Theoretically, this should work but this would imply that, at best, half the moon will be explored because there are symmetric wind flows going towards the equator so there should be no possible way to cross the equator.

The drifter plots are more telling to the specific behavior of the Titan wind because they are not time averaged. The drifter plots show that there is a separation in the flow where drifters starting around 30 degrees latitude move in very different ways. There is bunching of drifters around the equator and the poles evident in figure 19 and 20. As time moves forward, the drifter at latitudes greater than 30 degrees seem to move towards the poles and congregate there while any drifters less than 30 degrees move towards the equator. This is pretty consistent with the bulk wind flow shown in figure 17. There seems to be a significant increase of meridional movement below 30 degrees latitude. And in fact, the drifters do not pass across the equator but are instead trapped there. The intense zonal superrotation in the latitudes greater than 30 result in slight movement towards the poles so these drifters aggregate around the poles.

This behavior is consistent with the FTLE plots too. In figure 21 and 22, there is an obvious separation at around 30 degrees latitude evidenced from the change from green to blue color abruptly. The blue and green color demonstrates the separation of different dynamical areas of behavior. There are also red ridges of extremely high FTLE values which represent some planetary waves that travel around Titan. These ridges of highest FTLE are in red so that means that there is a great amount of separation on either side of those ridges, but from the drifter plots, we know that that separation is mostly zonal separation. But in the areas defined by the separation at 30 degrees latitude, there is less dynamic, but more large scale meridional separation, which is what we are interested in.

All three plots agree in the definition of the Titan wind flow but it is clear that the drifter and the FTLE plots provide a new perspective that adds insight into the wind flow. The vector graphs provided a useful summary of the bulk wind movement but from the FLTE plots, different areas of dynamic behavior are clear. The drifter plots are even more discerning in the specificity of the effects of starting location on drifter movement. Comparing the first drifter slide with the last one, only a handful of drifters were able to move from any latitude above 30 degrees to the equator. The drifter plots in combination with the FLTE plots were able to give a more clear view of movement in the wind field; revealing dynamic structures in the flow, these plots refuted the predictions of the bulk wind flow that a return flow near the surface and superrotation above the surface was sufficient to define wind movement below 20 km.

b. Balloon Trajectory and starting location

With the current understanding of the wind trajectories, it is clear that exploration of the entire surface of Titan by a passive balloon is very difficult, if not impossible. The starting location is very relevant in the movement of the balloon. Purely viewing bulk flow, riding the return flow near the surface to move from pole to equator and then using the superrotation in the zonal direction should allow the moon to be explored somewhat completely with two passive balloons placed at the poles. Viewing the FTLE graphs, it is clear that the flow is not that simple near the surface. At 1km, the wind flow is separated into two regimes, with the region near the equator pushing all drifters equatorward and the region near the poles pushing drifters poleward. This separation excludes the possibility to simply move down towards the surface to guarantee equatorward flow from the poles. Even more specifically, viewing the drifters, there are only a few high latitude points that were able to make its way across the barrier to the equator. If there were a way to correctly place a balloon in those locations, more of Titan could be explored but these rare cases will be difficult to locate since this is only a model of Titan wind; any small discrepancy between actual conditions and the model would make the behavior depending on starting location incorrect and the predictions void.

The superrotation in the higher altitudes remains to be the constant in the wind model. All graphs agree that drifters in the higher altitudes would remain to move eastward around Titan much faster than its rotation. There would also be a planetary scale wave moving across the moon. Besides being able to move zonally at will, there is presently no secure mechanism to take a passive balloon meridionally from pole to pole. The feasibility of using a passive balloon to explore the moon, to arrive at all points of interest, while relying only on a wind model remains to be a challenge.

V. Conclusion

a. Result

The work in this project has led to a greater understanding of the wind conditions on Titan but has produced more questions than answers. With a passive balloon, there is no way reliably conclude a method of exploration when the planning is relying on models that has such little empirical data to support. Since these issues are so sensitive, as well as the time of arrival, the use of a passive balloon seems to be ineffective if the goal is to actually arrive at specific locations on Titan, especially if they are littered in different areas of the surface.

b. Future Work

This technique of flow analysis is very effective when trajectories are in trajectories are sought after. The dynamic areas of Titan's wind, as well as the actual drifter trajectories were found and that gave great insight into a proper method of exploring Titan. But what remains is to continue to use this method to view different parts of Titan's wind field. Visualizing the Newman code outputs is very difficult because the FLTE graphs only reveal areas of dynamic movement and not the actual trajectories. The drifter plots are extremely hard to view because even put into Tecplot, and color coded, tracking the movement of the drifters is impossible with the naked eye, especially when different altitudes are outputted. With the radius of titan so much larger than the increments of altitude of the drifters, keeping track of the movements of separate altitudes, as well as the change from one altitude level to another is indiscernible. That means that each altitude must be viewed separately and run in the Newman code separately. Since even a passive balloon has altitude control, a good method of moving around Titan would inevitably require the ability to move to the effective altitude level to utilize certain wind fields. Finding a trajectory involving the movement between altitude levels would require a long series of trial and error and testing of many different altitudes.

Of course, the final area of improvement would be in the TitanWRF model so that it will match the actual wind fields on Titan when the mission arrives between 2026-2028. By having a very accurate model as well as mapping out trajectories for all altitudes within the effective range of a passive balloon, perhaps a plan can be constructed for the exploration of Titan’s areas of great interest.

VI. Acknowledgements

This project has been very fascinating and a great learning experience for me in terms of doing research. It would not have been possible without the great help and support from my mentor Jerry Marsden and my co-mentors Claire Newman, the expert on Titan and master of the Titan WRF model, and Philip DuToit, the expert on LCS and the master of Tecplot. I know that they’re happy I have been able to complete my project and I would not have gotten anywhere if not for them putting up with me bugging them constantly. This SURF project also would not have been possible without the support of Fred and Jean Felberg and countless others whose donations make it possible for this program to continue. I would also like to thank Dan and Anuj as well as the entire Titan SURF team for getting together to try to contribute to the mission to explore Titan. Also, thanks to Bill Richardson, Jonathan Cameron, Alberto Elfes, and others at JPL for hosting us for that aerobot test. I have learned so much from this SURF program and it is great to know that I am contributing as a member of the science and research community.

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