The Flushing of Ligeia : Composition Variations across Titan's Seas in a Simple Hydrological Model

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Key Points

- Applies a hydrological model to disequilibrium composition of Titan's Seas
- Ligeia Mare is 'fresh' (methane-rich), analogous to the Baltic on Earth
- Kraken Mare is several times richer in involatiles (e.g. ethane) than Ligeia

Abstract

We use a simple box model to explore possible differences in the liquid composition of Titan's seas. Major variations in the abundance of involatile ethane, somewhat analogous to salinity in terrestrial waters, arise from the hydrological cycle, which introduces more "fresh" methane rainfall at the highest latitudes in summer. The observed composition of Ligeia Mare, flushed by methane rainfall and exporting its solutes to Kraken via a narrow labyrinth of channels may have a methane-rich (~80%) composition, well out of thermodynamic equilibrium with the atmosphere, whereas the basins of Kraken are relatively well-mixed and will have an ethane-dominated (~60%) composition. These variations, analogous to Earth's salinity gradient between the Black Sea and the Mediterranean, may be detectable with Cassini measurements and are important for future exploration.

Index Terms and Keywords

Planetary Sciences: Solar System Objects, Titan; Hydrology, Remote sensing

1. Introduction

Saturn's moon Titan (e.g. Lorenz and Mitton, 2010) is the only world in the solar system beyond Earth with persistent deposits of meteorologically-emplaced surface liquid - lakes and seas (e.g. Stofan et al., 2007). It is fitting, then, that the discoverer of Titan, Christiaan Huygens, considered (Huygens, 1698) that other worlds might have seas composed of fluids with properties different from water "*Every Planet therefore muft have its Waters of fuch a temper, as to be proportioned to its Heat : Jupiter's and Saturns muft be of fuch a Nature as not to be liable to Froft…."* . In the case of Titan, with a surface temperature of 90-94K, the liquids are methane and ethane, with some dissolved nitrogen, propane and other trace compounds.

Because, on seasonal timescales at least (a Titan year - Tyr - is 29.5 Earth years, Eyr for clarity), ethane and propane are essentially involatile (the saturation vapor pressure at 94K of ethane is 1000 times smaller than methane), we consider those compounds as conserved tracers in the liquid. In essence, ethane, propane and other photochemical products behave much as salt does on the Earth - a solute whose abundance can track the input and removal of the hydrological fluid (methane or water). Interestingly, it was the astronomer Edmond Halley (1714) who first considered salinity differences among bodies of water and the net accumulation of solutes in the ocean.

Now that Titan's seas have been substantially mapped (e.g. Sotin et al., 2013; Wasiak et al., 2013; Lorenz et al., 2014), we consider how these seas participate in Titan's active hydrological cycle. Since the 1980s, Titan studies have assumed surface lakes and seas in thermodynamic equilibrium (and, implicitly, of geographically-uniform composition) with the atmosphere. While a defensible starting point, this assumption is manifestly invalid for the Earth, where despite oceans of varying salinity covering >65% of the surface, the atmosphere is not saturated with moisture. Active meteorology dehumidifies the atmosphere, delivering solute-free liquid to the surface : our growing understanding of Titan now allows quantification of these processes and thus the extent to which Titan's surface liquids may be out of equilibrium. In particular, we explore with a simple box model how the composition of the seas - forced by precipitation and evaporation fluxes - may vary.

2. The Seas of Titan

The layout of Titan's northern polar lakes and seas has been presented in Lorenz et al. (2014) – see also Sotin et al. (2012). We consider here first two apparently isolated bodies of liquid. First is Punga Mare, the smallest and most poleward of the three seas. Second is Jingpo Lacus , somewhat further south (e.g. Barnes et al., 2011a). Both of these bodies have been subject of study of near-infrared sunglint observations to detectpossible wind-driven waves.

The second set of bodies are the two major seas, Ligeia Mare and Kraken Mare. Kraken sprawls across a wide latitude range and is notable for having two major basins (here designated Kraken-1 to the north, and Kraken-2) which are connected by a relatively narrow strait (17km wide by 40km long), named (Lorenz et al., 2014) the Throat of Kraken. Ligeia appears to be connected to Kraken via a labyrinth of narrow channels (hereafter, the Ligeia-Kraken Labyrinth, LKL), perhaps adding up to a collective width of ~20km across, and ~150km long.

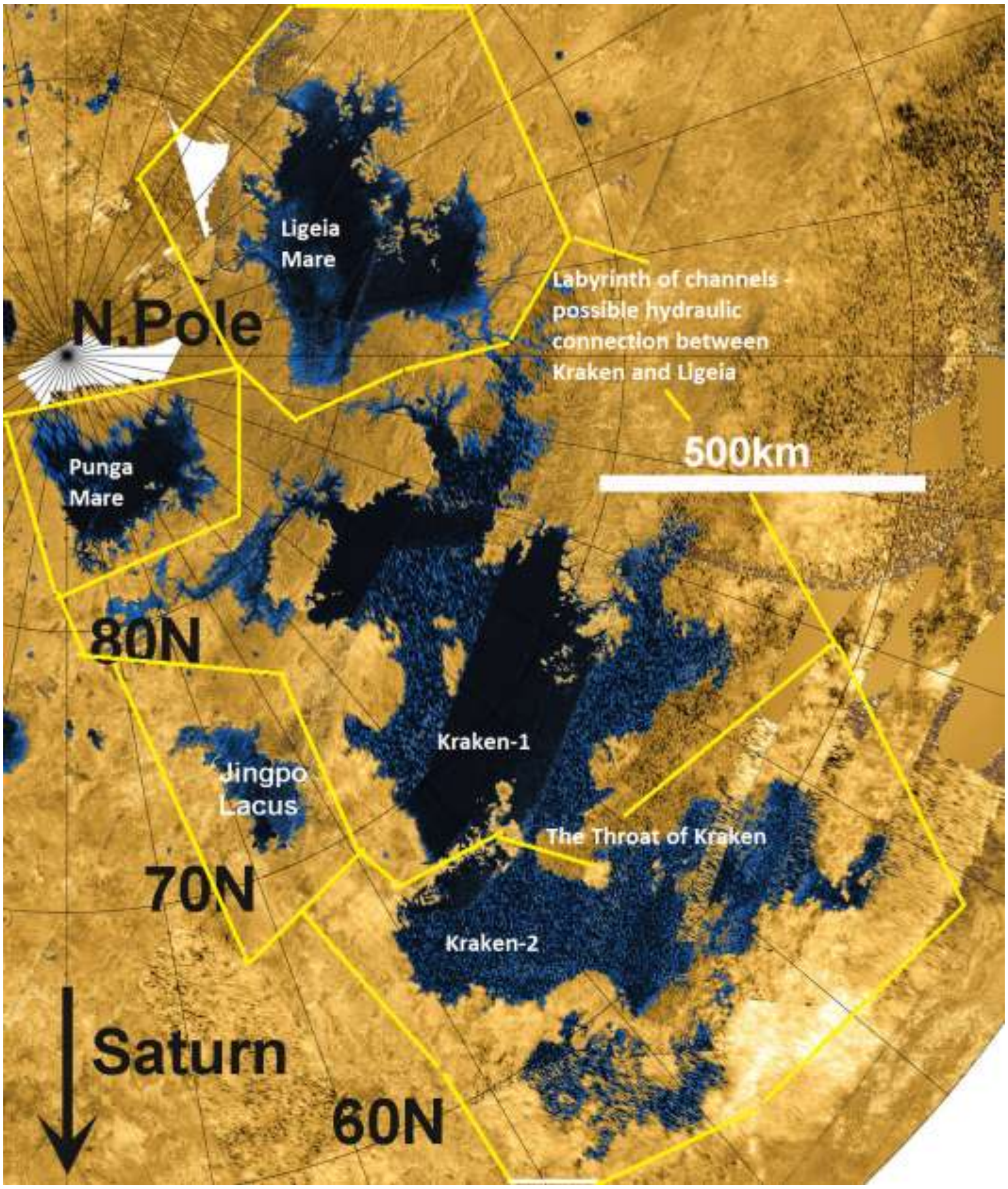

Figure 1. Radar map of Titan's seas. Lines denote the assumed catchment areas for each liquid body.

The composition of the seas has not yet been measured, but has generally been assumed (e.g. Stofan et al., 2007; Paillou et al., 2008) to be a methane-nitrogen-ethane mixture with additional solutes (e.g. Raulin, 1987; Cordier et al., 2009) determined by thermodynamic equilibrium with the atmosphere, with solute abundance estimated from photochemical models. This was the approach also used in Pre-Cassini studies studies of Titan's climate stability (McKay et al., 1993; Lorenz et al., 1999.) Thus the amount of methane in the atmosphere is given (to a first order by Raoult's law) as the saturation vapor pressure of methane at the surface temperature, multiplied by the mole fraction of methane in that liquid. These studies assumed a uniform surface temperature and composition, although did introduce activity coefficients to model deviations from Raoult's law. Here we assume a uniform methane humidity (broadly supported by Global Circulation Model (GCM) results - e.g. Tokano, 2009), but a surface temperature that is a function of latitude. Thus the surface liquid composition in thermodynamic equilibrium with the atmosphere is also a function of latitude. Crudely, the annual-average temperature (and it is reasonable to assume that the 100m-deep seas are massive enough to average out seasonal variations) is given by $T=92+2\cos(\lambda)$ where λ is the latitude. This model is in broad agreement with both GCM results (e.g. Tokano, 2005; Schneider et al., 2011) and with Cassini observations (e.g. Cottini et al., 2012) which suggest year-round equatorial and summer polar temperatures ~94K, with winter polar temperatures about 90K. It is known from microwave radiometry (Zebker et al., 2014) that the nadir brightness temperature of Ligeia Mare (78^oN) in 2013 ($L_s=42^o$) is ~90.5K ; this serves as an absolute lower limit on the physical temperature, which for plausible dielectric constants of 1.6-1.8 of methane/ethane liquid requires the physical temperature to be 91.5-92.5K.

The liquid composition in thermodynamic equilibrium with the atmosphere has been estimated using a new sophisticated model by Tan et al. (2013), assuming assuming the Huygens near-surface CH_4 abundance of 5.65% (Niemann et al., 2010). It may be noted that the Tan et al. (2013) model predicts equilibrium compositions somewhat more methane-rich than prior work (e.g. Cordier et al., 2009) with Jingpo, Punga and Ligeia plausibly at ~92K, and having compositions (mole fraction) of ~10% N_2, 50% CH_4, ~35% C_2H_6 and ~5% C_3H_8. Taking Kraken-2 at ~93K, the equilibrium composition would be depleted in the volatile N_2 and CH_4, with ~8% N_2, ~35% CH_4, 50% C_2H_6, 7% C_3H_8. Simplifying, we can bundle the volatile (N_2 + CH_4), and involatile (C_2H_6 +C_3H_8) species together, with the involatile fraction S varying from ~40% at high latitude to ~60% at lower latitude, a relatively modest variation.

However, the observation of ria coastlines on Ligeia (e.g. Wasiak et al., 2013) implying presently rising sea levels and evaporite deposits around many lake and sea basins (Barnes et al., 2011b), implying formerly higher sea levels. These may be consistent with a climate subject to astronomically-forced Croll-Milankovich cycles on ~30,000yr timescales (Aharonson et al., 2009), forcing Titan to be always off-balance. That consideration, and indeed the very existence of a hydrological cycle that has been seen to be in action today (Turtle et al., 2011) suggest that equilibrium models are an incomplete description of a dynamic world.

3. Disequilibrium Models -Hydrological Balance

The following simple model captures the essence of the Titan hydrological forcing by the atmosphere. Evaporation is assumed to occur at a rate (1-S)E_o, where S is the ‘salinity’, the mole fraction of involatile material. In principle the pure methane evaporation rate E_o should be a function of windspeed, atmospheric humidity, atmospheric stability, and possibly other factors. Since these are neither simple nor well-determined, we will assume a constant value, but retain the prefactor (1-S) to capture a principal factor of interest, namely the dependence on liquid composition. In this first order analysis I effectively assume Raoult's law, with evaporation rate proportional to the sum of nitrogen and methane mole fractions.

Mitri et al. (2007) use bulk transfer formulae to estimate an evaporation rate E_o of pure methane at 92K with winds of 1m/s at ~11m/yr, or ~300m/Tyr. Key dependencies are on temperature, roughly proportional to (T-88K), and on windspeed. More typically winds are much lower than 1m/s, so we adopt a baseline value of E of ~30m/Tyr (1m/Eyr). Mitchell (2008) determines a methane evaporation rate of 1.75m/Eyr near the equator, which seems broadly consistent with a high-latitude value of E_o ~1 m/Eyr, although Tokano (2009) found 3 m/Eyr. These large scale estimates are (likely correctly) somewhat lower than the methane evaporation rate measured at 94K in cm-scale laboratory experiments by Luspay-Kuti et al. (2012) who find ~1mm/hr, or ~11m/Eyr.

The precipitation input, assumed to be entirely methane-nitrogen (a tiny amount of ethane may act as a condensation nucleus - see e.g. Lorenz, 1993; Graves et al., 2004 - but is negligible in terms of overall flux), is a strong function of latitude. Specifically, Titan's precipitation is concentrated at the poles : the precipitation estimated in Schneider et al.'s (2012) GCM is reasonably approximated by $P_o = P_{max} \sin^{\chi}(\lambda)$, with P_{max} the peak precipitation, here P_{max}=4mm/Eday . The model shows precipitation falling off very steeply with latitude, which we capture with an exponent χ in the sine(latitude) expression : a good fit to the GCM model which has precipitation over the Titan year (Tyr) of ~8m, 4m and ~1m at 80^o, 70^o and 60^o latitude is χ=15. This strong latitude dependence accounts both for the polar seas, and the abundant sand dunes suggesting the prevalence of dry conditions at the equator.

We note in table 1 the central latitude, an area of the liquid body itself A_l, and an assumed catchment area or watershed A_{l+} A_w. The watershed area is judged by eye, guided by the radar (Lorenz et al., 2014) and near-infrared (Sotin et al., 2012)) mapping available - in all cases (see figure 1) the total catchment area appears about 3 times the liquid area, except possibly a little larger for Jingpo Lacus. On the assumption that the time for rainfall to flow through river networks into the sea is small compared with the evaporation time, the precipitation input P to a given body, is $(A_w+A_l)P_o$. The corresponding evaporative loss E is $(1\text{-}S)E_oA_l$. For now we consider pure methane, i.e. S=0.

Table 1. Methane budget for Titan's lakes and seas

Feature	Latitude λ (^{o}N)	Liquid Area A_l(km^2)	Catchment Area $A_l + A_w$(km^2)	Precipitation P (km^3/Tyr)	Evaporation* E(km^3/Tyr)	Net* P-E (km^3/Tyr)
Punga Mare	84	38,000	120,000	1100	530 (1140)	+570 (~0)
Jingpo Lacus	73	18,000	75,000	380	250 (540)	+130 (-150)
Ligeia Mare	78	98,000	340,000	2440	1370 (2940)	+1070 (-500)
Kraken-1	72	217,000	620,000	2920	3040 (6510)	-120 (-3600)
Kraken-2	65	140,000	460,000	1050	1960 (4200)	-960 (-3150)
Kraken+Ligeia						~0 (-7000)

* nominal evaporation assumes our preferred $(1\text{-}S)E_o$=14m/Tyr evaporation rate ; values in parentheses are for $(1\text{-}S)E_o$=30m/Tyr (~1m/Eyr) as suggested by prior work in the text.

It can be seen that the values in parenthesis, adopting E_o=30m/Tyr as suggested in the literature, leads to severe imbalance : all the seas would dry out (e.g. Tokano, 2009) except perhaps northernmost Punga Mare. For a 10% imbalance, i.e. $(A_w+A_l)P_o/E_oA_w$ ~0.9, then Ligeia Mare with a depth of ~160m (Mastrogiuseppe et al., 2014) would dry out in (160/3)~50 Tyrs, although in practice it would not dry out completely but would merely shrink, increasing $(A_w+A_l)/A_w$ until balance was achieved (see later). Note that 1 year of rainfall at Ligeia adds only ~16m of liquid, and thus if well-mixed, would change the composition by only 10% at most. The numerical imbalance suggests, assuming the seas are in steady-state (in fact, morphologically, flooded valleys in Ligeia indicate rising sea levels, e.g. Wasiak et al., 2013), that either the precipitation at high latitudes is underestimated, or the evaporation is overestimated. The fact that evaporation occurs, and dominates at low latitude, is amply demonstrated by the wide equatorial dunefields (Mitchell et al., 2008) and the rapid brightening (drying) of areas observed to darken due to rainfall (Turtle et al., 2011).

Evaporation could be overpredicted by bulk transfer formulae, especially over large bodies of liquid where evaporative cooling and local saturation of the air mass might occur. Thus the E_o value of 30 m/Tyr may simply be too high. An additional way to bring the system into balance is to introduce solutes such as ethane which retard evaporation by lowering the partial pressure of methane above the mixture. Suggesting S~0.5 throughout would also bring the seas into balance - as seen in the nominal values in the table ($E_o(1-S)$=15m/Tyr) where the Kraken and Ligeia fluxes sum to zero. The Punga and Jingpo are net positive in this scenario, but this is a minor detail : we might imagine that these bodies would simply accumulate more methane which has the combined effect of enlarging A_l as the lake deepens and grows, and lowering S as the ethane becomes diluted. Thus E would grow until it balances P, which is fixed for a given location.The composition in general is given by $(A_w+A_l)P_o=(1-S)E_oA_w$.

4. Exchange between the Seas

Even if we adopt a plausible reduction in evaporation to bring the ocean system in balance overall, there are severe local imbalances. Specifically, even for $E_o(1-S)$=15m/Tyr, Kraken-2 has a net loss of some 900 km^3/Tyr, which is liquid it must import from Kraken-1. Ligeia Mare, on the other hand, exports about 1100 km^3/Tyr to Kraken-1. Thus there is a substantial net flux of liquid from north to south through Kraken-1.

Now consider the equivalent of a salt balance. For Kraken-1 and Ligeia to be in ethane balance, the following relationship must hold : $S_xF_{xy}=S_yF_{yx}$, where S_x denotes the involatile mole fraction of basin x (x=L,1,2 for Ligeia, Kraken-1 and Kraken-2 respectively) and F_{yz} is the flux from basin y to basin z. Such counterflow fluxes can occur simultaneously (e.g. countercurrents at depth, such as the salty outflow from the Mediterranean which occurs below the fresh Atlantic inflow at the surface) or as a cyclic (e.g. tidal) flow. For the present exercise we can consider these terms as a net and cyclic component, $N_{xy}=F_{xy}-F_{yx}$ and $C_{xy}=(F_{xy}+F_{yx})$. On Titan, the cyclic component is dominated by tidal flow.

Unless the flow in the Throat of Kraken is restricted by shallows, Titan's tide forced by Saturn's gravity yields an exchange of about 20km^3 (Lorenz et al., 2014) to and fro between Kraken-1 and Kraken-2 each Titan day (16 Earth days - 22.8 Titan days/Eyr or 673 per Tyr). Thus the C term is ~27000 km^3/Tyr. It follows, then, with N_{12}=900km^3/Tyr that F_{12}=14000 km^3/Tyr and F_{21}=13100 km^3/Tyr. The salinity ratio then follows, S_1/S_2=0.93 : Kraken-1 and Kraken-2 are relatively well-mixed and differ in composition by only a few per cent.

In contrast, the Ligeia-Kraken labyrinth is much more constricting. The volume flux in a channel is given as F=Uwd, where U is the average flow velocity and w,d are the channel width and depth respectively. For turbulent flow in a channel (i.e. river flow), Burr et al. (2006) have calculated relevant Titan parameters and give (re-expressing their formulae slightly) $U^2 \sim (8gds/f_c$ where s is the slope (here, an elevation difference δ divided by the channel length l), g is gravity (1.35 ms^{-2}) and f_c is a friction parameter. Burr et al. (2006) give $(8/f_c) \sim$ 10 to 30, for gravel-bed and sand-bed rivers respectively – thus we adopt $f_c \sim 0.4$. The driving elevation difference for mixing is that due to tides - given the ~4m tidal range at the northern margin of Kraken (Tokano, 2010) but reducing by a factor to correct for nonrigid Titan effects, Lorenz et al., 2014) suggests an average $\delta \sim 0.3$m and thus for l=150km, $s \sim 2x10^{-6}$. Adopting d=5m, we find U~1.5cm/s, or for a total width w~10km, a volume of about 1.1km^3 in half a tidal cycle (0.5Tday=6.9x10^5s). Hence the exchange flux between Kraken and Ligeia is only of the order of C_{L1}= 1500 km^3/Tyr.

This flux does not substantially exceed the net outflow determined by the precipitation-evaporation balance. The rapid export of liquid (N_{L1}=1100km^3/Tyr) from Ligeia gives F_{L1}=2600 km^3/Tyr, F_{1L}=400 km^3/Tyr and hence S_L/S_1=0.15. This is a striking result - it requires that Kraken is 6 times more abundant in involatiles than Ligeia. Note, however, that the result is strongly sensitive to the assumed effective width and depth of the LKL : factor of two variations in these two parameters can lead to factor of ~6 variations in the tidal flux, and a range of Kraken:Ligeia salinity ratios from 1.5 to 10.

The result furthermore has the dramatic implication that Ligeia must be fairly methane-rich - since S_2 cannot exceed unity, from algebra alone S_L must be less than about 0.2. A somewhat stronger constraint (S_L<~0.12) arises by adopting as an upper limit the thermodynamic equilibrium composition of Kraken-2 of 60% involatiles (if it were higher, Kraken-2 should perhaps 'wick' more methane moisture out of the atmosphere, like a deliquescent salt).

While usefully-illustrative, the description above is not fully self-consistent. The evaporation rate depends on the local S value (even if, as we have assumed here, E_o is globally-uniform). Thus because Ligeia is more methane-rich, it has a higher evaporation per unit area than Kraken, and thus exports less liquid than if its composition were the same as Kraken. This lower flux reduces the compositional contrast required for ethane balance. A self-consistent solution can be computed, adjusting E_o such that methane and ethane are everywhere in balance (the computation was executed by trial-and-error on a spreadsheet). The resultant model of Titan's methane and solute budget is shown in figure 2, with E_o~23.6m/Tyr, mid-way between the ~30m/Tyr literature value (likely too high) and the 15m/Tyr value that leads to methane balance without the influence of solutes. We still find a rather strong compositional contrast, with Ligeia having ~80% methane composition (S~0.2) and Kraken only 40% (S~0.6).

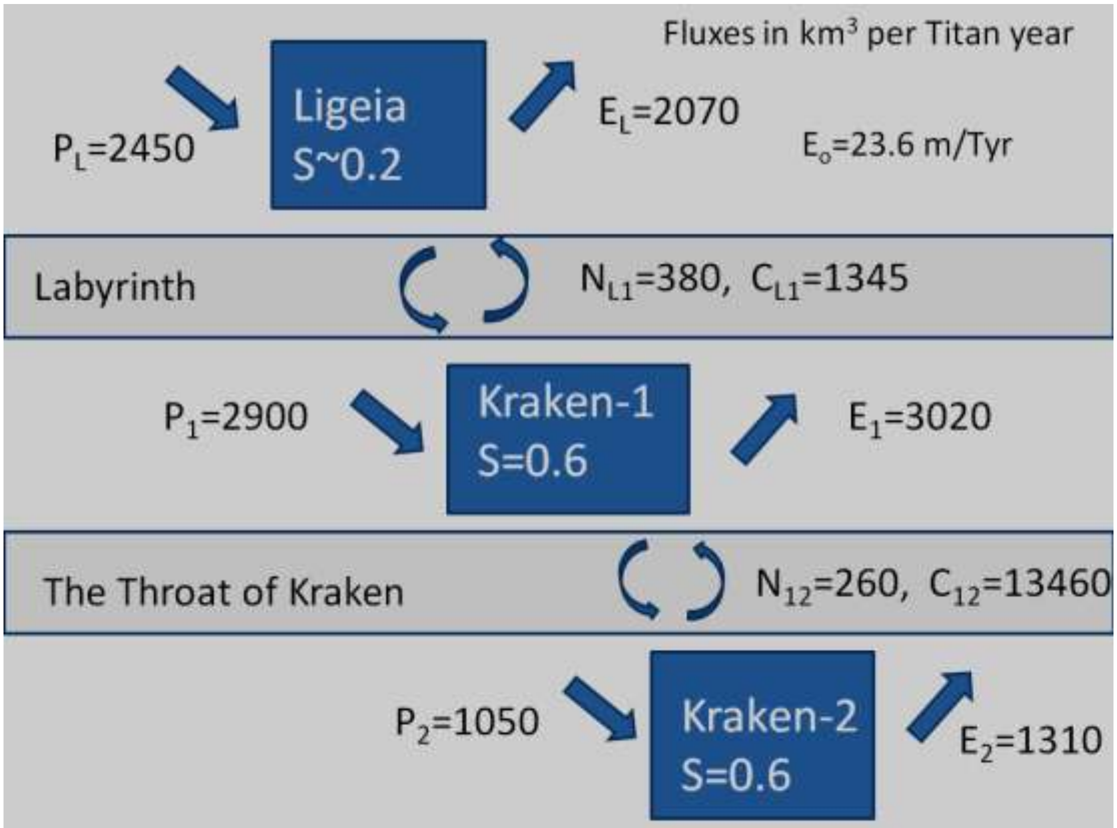

Figure 2. Fluxes and solute concentrations for an example self-consistent hydrology, subject to E_o=23.6 m/Tyr and the assumptions in the text. The N fluxes depend explicitly on the P and E values from GCMs. The C values depend on the tidal mixing through the LKL and the Throat of Kraken

It is useful to compare these fluxes and composition variations with those encountered on Earth. For example, while the open ocean has a typical salinity of ~35 psu (practical salinity units, roughly equivalent to parts per thousand by weight), the Baltic Sea has a bulk salinity of around 10-15 psu. This arises because the sea accumulates ~660km^3 of precipitation, mostly via rivers. It loses a little of this by evaporation, but most is exported to the North Sea via the Skaggerak :

in this channel about 940km^3 of near-surface water flows out (F_{BN}, using our notation above), although about F_{NB}=475km^3 of saltier water flows into the Baltic at depth (depth-salinity structure and counterflow in channels is a complication we cannot dismiss at Titan, but have little information with which to assess). Simple comparison of these two numbers suggests the Baltic should have about half the salinity of the North Sea, as observed. This flushing gradient is even more apparent in the Sea of Azov (~10 psu) fed by major rivers, draining into the Black Sea (~17 psu) and thence via the Bosphorus and Dardanelles into the Mediterranean (34 psu). Thus purely by analogy, since Titan is a hydrologically-active world, we might expect substantial composition variations in Titan's seas.

5. Conclusions

This paper has striven for simplicity and thus has not considered subsurface flows (e.g. Hayes et al., 2008), compositional layering (e.g. Tokano, 2009), nor potential effects of the seas on local meteorology (Tokano, 2009) or even Titan's shape (Choukroun and Sotin, 2012). Clearly, Titan's oceanography is a field in which much work remains - not least in considering seasonal variations and finer-scale spatial variations ignored in this steady-state box model. Nonetheless, while the precipitation and tidal fluxes will benefit from detailed numerical modeling, it is believed that the basic flow architecture and flux estimations in this paper are robust, and allow for some interesting conclusions.

First, published evaporation and precipitation rates for pure methane are not in simple balance over the full range of latitudes in which seas are observed on Titan. The presence of involatile solutes in Titan's seas helps mitigate this discrepancy, although other factors may contribute. The quantitative results of the simple model presented here depend explicitly on these rates, but are probably accurate to within a factor of about 2.

The strong precipitation gradient with latitude, a general result in all GCMs (Schneider et al., 2012; Mitchell, 2008; Tokano, 2009) implies that Ligeia Mare is flushed with methane and drives a net flow of liquid southwards. Comparing the likely net flow with mixing flows driven by tides suggests that Ligeia is probably ~80% methane and nitrogen, with only small amounts of solutes such as ethane. This composition, surprising given earlier models suggesting an ethane-rich equilibrium composition (Cordier et al., 2009) is in fact consistent with the interpretation of microwave radiometry data by Zebker et al. (2014) which suggested a dielectric constant (ε~1.7) for Ligeia, closer to a pure methane value (ε~1.6, Mitchell et al., 2014) than pure ethane (ε~1.85) - see also Thompson and Squyres (1990) and Paillou et al. (2008).

The hydrological model suggests the Kraken basins should have a solute (ethane, etc.) abundance several times higher than Ligiea, most likely S_1~S_2~60%. This solute concentration difference between Kraken and Ligeia is analogous to, and quite comparable with, those seen on Earth. The result suggests that microwave remote sensing may be able to detect a compositional variation across Titan's seas (as, indeed, dedicated satellite missions using microwave instrumentation are flown to survey ocean salinity at Earth). Near-infrared observations by Cassini (e.g. Brown et al., 2009) may also contribute to assessing composition, and observations to constrain the geometry of the LKL and any possible hydraulic connections with Punga or Jingpo would be useful.

As is well-known in the liquefied natural gas industry, basic fluid properties such as speed of sound and density depend on the methane:ethane ratio. Future missions aiming to explore Titan's seas (e.g. Stofan et al. ,2012) may need to take the variations discussed in this paper into account. It is fitting that the considerations first applied to the Earth by Halley during the age of sail are finding new application on other worlds.

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Fig. 1 is derived from a mosaic (originally due to R. Kirk of USGS) at

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