**Abstract:**

The thermodynamical cycle and the energy transfer in troposphere is highly governed by water vapor in tropical region. Several researches has attempted to estimate the sporadic sources and sinks of water vapor in this region but suffered from observation and measurement uncertainties. The present study aimed at enhancing the temporal resolution of retrieved Relative Humidity measurements from SAPHIR sensor board on Megha-Tropiques low-inclination LEO satellite (MT) . Our goal was to create a new seamless data product using a advection by a morphing method called MIMIC. The product includes both the space-time pattern of middle troposphere water vapor (RH), and a space-time pattern of a Lagrangian tendency of water vapor or Analysis Tendency AT. The initial results water vapor product shows consistency with other observations sources. The AT fields demonstrate logically well captured trends of sources and sinks. Nevertheless they are error prone. This necessitates further studies in evaluation and characterization of these errors.

**Keywords:** advection, satellite observation, sources and sinks, troposphere, Water vapor.

Resumé:

Le cycle thermodynamique et le transfert d'énergie dans la troposphère sont fortement régis par la vapeur d'eau dans la région tropicale. Plusieurs recherches ont tenté d'estimer les sources et les puits sporadiques de vapeur d'eau dans cette région, mais ont subi des incertitudes des observations et des mesures. Cette étude vis à améliorer la résolution temporelle des mesures d'humidité relative issue du capteur SAPHIR sur le satellite Megha-Tropiques. Notre objectif était de créer un produit satellitaire en utilisant une advection par une méthode de morphing appelée MIMIC. Le produit comprend à la fois le schéma spatio-temporel de la vapeur d'eau (RH) du troposphère intermédiaire et un schéma spatio-temporel de l'advection lagrangienne de la vapeur d'eau ou de la tendance d'analyse AT. Les premiers résultats du produit vapeur d'eau, montrent une cohérence avec d'autres sources d'observations. Les champs de AT ont logiquement bien capturées des sources et des puits. Néanmoins, ils sont sujets aux erreurs. Cela propose des études d'évaluation et la caractérisation de ces erreurs en perspective de ce projet.

**Mots-clés**: advection, sources et puits, observation satellitaire, troposphère, Vapeur d'eau

**Introduction:**

Tropospheric water vapor cycle is a key controlling component of meteorology in tropical region (eg. Sherwood 1996, Salathé et al 1997) and further in word’s climate (e.g. Rind et al 1991) as for example Lindzen 1990 controversially suggested that under the climate change condition stronger subsidence, accompanying stronger tropical convection, may lead to drier air. The intensifying of synoptic export of tropical moist air masses with global warming was highlighted also by Seidel et al 2007, Allen and Mapes 2007, Knippertz et al 2013). Sporadically patterns of sources and sinks and bimodality behavior of tropical water vapor (Mapes et al. 2001, Zhang et al. 2003, Mapes et al 2018) complicates their thermodynamical budget estimation. Many studies tried to address this issue by decomposition of the local budget in its terms and explore water vapor Eulerian dynamics (e.g., Maloney 2009; Hannah and Maloney 2011; Kiranmayi and Maloney 2011; Cai et al. 2013; Hannah and Maloney 2014; Masunaga and L’Ecuyer 2014). But that budget is dominated by advective tendencies which vary from place to place, rendering it difficult to achieve a satisfying result about more spatially universal physical processes. One of these issues rises from their vertical variation and other, from lack of a lucid spatio temporal satellite observations.

Wimmers et al proposed a morphing model to establish a “seamless” set of data from blended satellite observations. Their method which called MIMIC-TPW focused on Total precipitable water vapor. Hannah et al 2016 discusses how MIMIC on column water vapor (CWV) relates to explicit calculations of advection in an atmospheric reanalysis. They also suggested a Lagrangian tendency analysis (with advection taken up in the left hand side) of column water vapor instead of traditional Eulerian equation. In a Lagrangian budget, the right hand side is the universal physical processes in above-mentioned classical budget calculation. While this approach still suffers from error ingestion from inter-satellite calibration nature of MIMIC, daily averages eliminate that error and expose the physical tendencies. Benefiting these findings Mapes et al 2018 proved the bimodal distribution of water vapor over a large part of tropical and subtropical area centering on a margin of 48mm of CWV.

The intrinsic programing manner in MIMIC as it would be explained in the method, entails treating the observed quantity (RH) as a long lived tracer, conserved following the wind. The water vapor as studied by Mapes et al 2018 with its multiday coherence and predictability of features obeys this approximation adequately over the time interval between observations, but with physical tendencies (which are of special interest) large enough to be discerned by differences between two observations (deviation from the Lagrangian conservation assumption).

Ideally we could just use multichannel microwave satellite observations which can give us a resolved vertical profile of water vapor. The Relative Humidity data provided from Radiométrie (SAPHIR) instrument on board the Megha-Tropiques satellite, grants us this opportunity. However, these data suffer from incomplete observation and time gaps. The MIMIC morphing method was used to fill these gaps by an advection approach. The RH layer chosen here is 500hpa (400-600 hPa layer mean) since it is the most accurate measurement by SAPHIR’s instruments. Its sources and sinks are far from the cooling drying and bimodality existing in the upper troposphere and evaporation and surface fluxes variability in the lower levels. Instead its sources are deep convection and its sink is vertical advection by subsidence. Some required concepts along with the idea of present project will be comprehensively explained in the following segment.

**Thermodynamic concepts and applications in present project**

The total of internal energy per mass; u and the one which is associated to the surrounding environment pressure form enthalpy:

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|  | (1) |

is specific volume . The for an ideal gas is RT. Where R depends on the molecular weight.

Enthalpy is one of the most important variables in atmospheric sciences, because we cannot control for the volume of an air parcel, but we can control for its pressure. To determine by how much the radiative heating(cooling) of an air parcel at constant pressure, rises (reduces) the temperature we use the specific heat capacity parameter:

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|  | (2) |

So in the transfer of air mass if we assume that the R is constant, by adding the gravitational potential per mass unit to parcel’s internal energy because of its new height, the enthalpy will be:

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|  | (3) |

This is also called the dry static energy .

If the air mass contains a fraction of water vapor with concentration q, the energy associated with its phase change is referred as latent heat Lq, and it will be added to the enthalpy:

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|  | (4) |

The equation 4 is an indication of the moist static energy hm.

**Radiative cooling, subsidence and convection**

The heating of the atmosphere by solar radiation is indirect, as sunlight is absorbed at the surface and transmitted by surface conduction and evaporation which begins from lower levels. Meanwhile the infrared radiation by water molecules toward space in upper layers cools it down. The heated near surface air mass becomes bauyant expands and lifts up (1-2 branch in the figure). Further it replaces and presses the upper cool air down (1-3 on the figure). The temperature of compressed mass will go up but in a long run the radiation from it, will fix the temperature. (3-1 on the figure). The lifting process is adiabatic thus the expanding air mass gets cooler gradually to the limit that its containing water vapor condenses. This process releases a latent heat to the air mass slowing down its cooling lapse rate introducing the moist adiabatic ascent in 1-2 branch of figure 1. In a point the condensate will be discharged from the mass so thereafter it undergoes a dry adiabatic operation as in 1-3 branch of figure 1. If it remains within the air mass the process referred as reversible and if some of condensate drops out it is pseudo adiabatic. This is how subsidence compensates for radiative cooling in a clear sky troposphere.

Figure 1 is the schematic of this cycle.

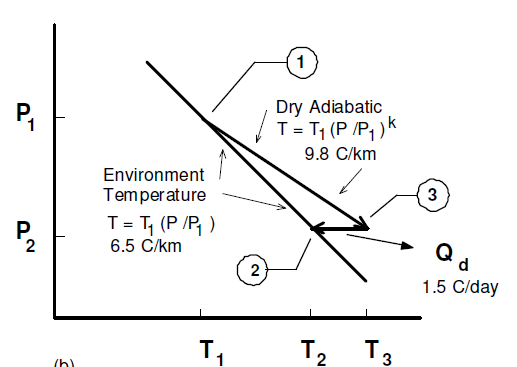


Figure1:

The 3-1 process at the end is the daily cooling and its rate Qd regarding the figure could be estimated as follow:

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| --- | --- |
|  | (5) |

Where is the subsidence velocity in where *Q*d is in , is the environmental lapse rate in , and where is the dry-adiabatic lapse rate equal to . Regarding this equation the more atmospheric lapse rate is closer to dry adibat, the subsidence velocity will rise.

Later equation(4) was the simple explication of following thermodynamic equation:

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|  | (6) |

is the heating rate is the static stability parameter. In this heat balance, The two first term of the left side correspond to the horizontal advection of the heat. The Coriolis force is noticeably low in the tropics so density gradients cannot be sustained under gravity, thus two first term are negligible above the boundary layer. Therefore what balances the cooling and heating is the vertical advection of entropy:

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|  | (7) |

Mapes et al 2001 use as an indicator of stable stability and recast the upper equation as:

(8)

The negative sign in two later equation signify an upward motion.

By the following segment the reasons of choosing the 500hPa layer will be discussed involving in the term dynamical concept part.

Figure 2 shows the vertical profile of net radiative cooling rate in troposphere in tropical region and the implied RH evolution in 5 days in the absence of sources. (Mapes 2001)

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| --- | --- |
|  | **c)** |
|  |

Figure2

Figures 2-b and 2-a indicate that the whole troposphere undergoes a cooling and drying over a time scale of days. Looking just at the 500 hpa level, the drying time scale is a couple of days.

The rapid cooling can be easily deduced from two equations 8 and 5 by their mutual concept. Regarding and equation 5, is lower in upper troposphere hence subsidence velocity will be high resulting in a drastic cooling. In terms of equation 8 the subsidence is faster due to the smaller in upper levels.

Dry and cool established condition in upper troposphere implies a heat transfer to this region by deep convection.

Regarding the figure 2-c; under the reversible and pseudo adiabatic conditions the parcel’s temperature becomes 8 degrees and 4 degrees more than the envoirnement’s, respectively in upper troposphere. Referring back to the lifting parcel theory explained in the first part, this difference is caused by the latent heat of condensate in the parcel which compensates for the internal cooling of mass air in the reversible ascent. Pseudo adiabatic ascending air mass being evacuated gradually by the instant rain is dryer and thus has more temperature difference with envoirnement. The high difference intensifies the updroughts and convective available potential energy (Mapes 2001) leading to the deep convection.

.??? No idea what you mean here

It can be concluded till here that radiative cooling is balanced by not only the subsidence but also by convection in some regions. This balance isn’t homogenously extended through whole tropics. Sporadically, one of vertical terms can prevail other in a column integral thus horizontal wind is required to fill the gaps.

The whole vertical and horizontal motion are also explainable by the enthalpy transfer. Variation in each term of the enthalpy components in equation 4 could establish a gradient between two points in troposphere and as the energy and mass continuity necessitates, a transfer forms to replenish the deficit. The moist static energy transfers the heat to tropical upper troposphere by the latent heat term of enthalpy and thereafter by losing the water content it diverges in form of dry static energy. Therefor the column integral of h is divergent horizontally in upper levels and convergent in the lower half of circulation.(figure 3) .

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| Figure 3 |

Mapes et al 2018, showed that this pattern exists centering on the margin of 48 mm column water vapor in tropical region and there is a “h” export toward subtropics (figure 4-a). The 48 mm CWV was inferred from a the distribution analysis in the same study showing 2 maximum in CWV PDF (figure 4-b) with the middle minimum on 48 mm. This motif is representative of tropical region because it is based on 3 year average of satellite data products.

|  |  |
| --- | --- |
| a) | b) |
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In accordance with the figure 4-a Hannah et al 2016 chose the 500 hpa as the cutoff point for the bottom and top of troposphere to study deep and bottom-heavy heating during the convection.

**Eulerian budget and Lagrangian tendency:**

As concluded from previous part the moist static energy gradient triggers a horizontal advection flux between two zone, which ends with convergence deficit area. The whole budget could be resolved by the use of Gauss’s integral theoreom. This is referred in thermodymanical literatures as “gross” moist stability. But the problem here is vertical velocity one of the important required variables of this integral, which is error prone.

From the Eulerian budget of water vapor in a hydrostatic pressure coordinate we have (Hannah et al 2016):

Where is specific humidity, is the horizontal wind vector. E and P are evaporation and precipitation in surface respectively. By a simple rearrangement we get:

The estimation of the right hand of this equation is challenging cause each term can cancel the other to a limit and none of them can be measured without error. The left side simply represents profile of the water vapor and horizontal wind. The latter parametrs are more or less feasible to be measured by observations. The equation can be recasted as the following

The AT gives the net moistening (3 terms on the right hand side) of a column that is advecting horizontally. By the use of AT, in the mentioned study by Mapes et al 2018 it is seen that the air mass gets moist rapidly, passing the defined margin of 48 kg/m2 (48mm of condensed water equivalent).

If we replace by Relative Humidity fields (because the saturation value is nearly constant), it will give us the tendency of net integrated static energy or enthalpy of a horizontally advecting air mass in each time step. This could be achieved by a continuous fine temporal resolution observing system. These are the final goal of this project.

SAPHIR Sensor:

Sondeur Atmosphérique du Profil d’Humidité Intertropical par Radiométrie (SAPHIR), is a passive radiometre. « Passive » in remote sensing terminology means the instrument measures the electromagnetic energy that is naturaly emitted by earth surface. Each material depending on its properties emits in a defined wavelength . This wavelength is determined based on an absorption band of electromagnetic energy for mentioned material in the laboratory with radiative transfer models. The absorption line of water vapor in infrared which we are interested here is 183.3 GHz and 6 channels around it to measure the radiation coming from six levels of atmosphere from 950 to 100 hpa in pressure term. SAPHIR sensor is on board the Megha Tropiques satellite is a cross-track radiometer that observes the earth’s atmosphere with a scan angle of 42.96 degree, a footprint size at nadir of , and a 1700-km swath made of scan lines containing130 nonoverlapping footprints. figure()

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| Figure: The footprints of SAPHIR scans(IN Green) |

The wind data are obtained from the MERRA Data Assimilation System 2-Dimensional atmospheric single-level diagnostics. That is time averaged single-level at the native resolution. It is a history file that is produced from the GCM during the corrector segment of the IAU cycle. The spatio temporal resolution for this data respectively is: 0.5 ° x 0.667 ° and 1 hour.

The same data-base gives us the specific humidity in 3 levels of pressure: 850, 500 and 250hpa. But it is reanalysis from different sensors so the purity of a single consistent observational estimate from SAPHIR may help assist interpretation.

Method:

The advection method is almost like TPW-MIMIC (Wimmers and Velden 2010) but the algorithm is manipulated to adopt to our goal. The used tracer in this study is Relative Humidity, since saturation humidity is almost constant in horizontal space and time within the tropics. In the MIMIC it is assumed that the tracer pattern evolution relies solely on advection by the wind between two consequent observation and no other thing affects it. The set of SAPHIR scans through time during one orbit of the satellite will be referred as a “swath” hereafter. Figure .. shows a simple swath of the SAPHIR . Each swath file has about 1400 (it could be 100-200 more or less) scans across the longtitude each of them containing 130 footprints.

The first step was to create two little codes in order to obtain the MERRA wind reanalysis available in netCDF format and SAPHIR data with HDF5 format relating to 500hpa layer. Then attribute them desired format especially for time dimension, rendering them compatible for our program and convert both in Matlab format.

The whole program hereafter comprises two main process:

1. Creating “synth” files. These are the backwarded and forwarded swaths established from the observations, using MERRA winds for time-to-space conversion of the position of each observed pixel under the Lagrangian conservation assumption.
2. Use the synths files as input to make composite files from many orbits of the satellite, and Analysis Tendency (AT) which is the physical source and sink that reflects deviations from the MIMI procedure’s assumption of conservation.

1-Creating “synth”files

A target or product time, a desired time step for our target product RH and AT, is set arbitrarily to be each hour. Here the development of the code started using a one day data set, then some adjustments were set to run it for a 1-week time period. A 0.5 degree and hourly product is our desired spatio-temporal resolution.

An hourly time table was created between first and last swath time plus 24 hour extrapolation. Then wind data set times were weighteed through this time table with the following equations

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|  | (9) |

is the target or product time table component, and are the closest SAPHIR observation time to the target time (valid).

The wind fields were available hourly, and further interpolated to the SAPHIR observation times with this weights. Then a structured wind data in target times are created. Average of all scan times in a swath was selected as a representative of time of that swath and it will be used for advection process. The corresponding index of this average time was searched in the above mentioned target time table to find its matching point in wind data.

Once given the both wind fields and RH data in same target times, the advection toward backward and forward could be accomplished. The longitudes and latitudes of swaths in this step were moved through the winds meridional and zonal components to new positions. By a nearest neighbor method, the established positions values were estimated in their new positions. To avoid passing the -180 and 180 edges in the later step, an expanded grid was used. The result is latitude and longitude of an graphically orbit shaped data container of RH fields. We need to change this to a grid format putting NaN where data is unavailable.

The new grided data with 241\*721\*1 dimensions respectively for latitude, longtitude and time were obtained. The 1 time dimension is the central (averaged) time that was forwarded or backwarded by one hour. Knowing that it is already the central time of the new swath, it would be used to homogenously distribute through the longtitude as for swath files. The last gridded data thus will have a 721 time step. But in the next step we will need the source observation time that has been advected. In the same way we could creat the source time and writ them in another attribute to the file. I can't understand this at all

These data being then structured to matlab files are called synths.

Figure is an interpretation of a synth.

Comparing with the ordinary orbit of SAPHIR, the distorted borders are recognized which show clearly the advection effect.

We continue the advection to a limit DT-MAX where enough synth for the next pixel processing step is reached . Some pixels are just observed once a day therefor the synths are should be made to an extent that we have a minimum of 2 advected observation near each pixel. Cause there might exist a pixel which hasn’t been scaned. (figures…). DT-MAX is found in a trivial and error process with the next step.

**2-Composite RH data and Analysis Tendency (AT)**

In this level we center on the each pixel to create target container of the following variables:

**WV** : (water vapor averaged over the nearest 2 times, forward and backward, from the pixel’s time)

**AT** : The 'analysis tendency' of the morphing operation, representing the horizintally Lagrangian tendency, or more profoundly, representing the sum of all physical source-sink terms from a RHS perspective).

**t\_early**: the time of the earlier observation that made the above products(WV and AT)

**t\_late**: the time of the later observation that made the above products (WV and AT)

To fill the above arrays, we will use the time-proximity-weighted average for WV500:

Once the composites of WV we are made in difined times in each pixel, we are able to compute AT

The simplest estimate of the time derivative using the before and after observations:

Where:

and (Stack will be described in following paragraph. )

We need to fill *time stacks* of product-shaped lat-lon arrays, then process them down by compositing.

A *time stack* is a 3D array, NLAT x NLON x (2\*DTIME+1), centered on the product time (dt=0). The DTMAX just has to be at least as big as the longest time gap between (advected) observations. Also, the time step between the layers in the stack (one hour) just has to be short enough that we aren't wasting observations by over-writing some locations with multiple observations, subject to efficiencies (1 minute would be overkill). This fact can be interpreted through figures … the case is shown just for a backward process. Since the orbit time is about 110 minutes, DTMAXE=24 and 1-hour stacks are chosen.

The program was executed with two wind adjustments; with and without the wind, in order to highlight AT contributions due purely to the neglect of advection in the no-wind case.

We devised a new code

Sifting trough a heap of synthes

This required a reversed engineering of heap of codes and nested scripts. And lack of documentation we were compeled to do a reverse encoding indeed.

The goal was to adopt the TPW-MMIC code to our data of 500mb pressure level so the first step was to create two little codes which could take the MERRA wind reanalysis and SAPHIR data relating to 500hpa layer and then attribute them desired format especially for time dimension, rendering them compatible for our program. Both

**Results:**

The model was run, and our composite product was built for one week time period data; the first week of January 2012. As in Figure.. , the product demonstrates good accordance with MERRA specific humidity data of the same pressure level with just half an hour difference.

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| Figure: Upper one for Merra q500 and the lower for RH composite product |

We could get detailed in some regions for example in the south part of Arabian Sea and interesting trends would be captured. The contours of MIMIC composite folded on the shaded view of simple RH-SAPHIR in this area are shown in figure

(figure place)

As we can observe the system’s pick are tracked westward by MIMIC while there is no change in the simple SAPHIR.

Resting in the same area by adding the new observations from a geostationary IR in water vapor channel – irwvp and folding the contours for MERRA q and SAPHIR MIMIC, we get figure 5

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|  |
| Figure: RH-MIMIC contours ,yellow and MERRA q in bleu folded on irwvp data |

It can be recognized that the RH MIMIC (yellow contours) even matches the irwvp data better than MERRA specially in tracking the picks in several times interpreted in figure... While the MERRA contours propagate loosely neglecting theses concentrated areas.

To study how the evolution observed in the satellite data differs from that predicted by a horizontal advection-only procedure we need AT. There are two interesting regions to highlight the difference between no-wind and advection. No-wind mode represents in fact our raw RH-SAPHIR data.

IN north Arabic sea there is a clear AT difference between no-wind and advection mode. When advection is neglected, the westward motion must be expressed in AT as a positive tendency to west, negative tendency to east. When the advection is used, the Lagrangian AT is then just physical tendency, such as negative (blue) tendencies around the high-RH area as the water vapor decays in that moving airmass after its recent convective source.

In the given instant the source frontiers almost meets the border of sink. The reasonable pattern is that a source can gradually appear after where sink is decayed. But they can’t be in the same size one of them must be weak or decaying. That is resolved by the use of advection in the right hand figue.

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| AT for RH SAPHIR (no advection used) and RH-MIMIC respectively the left and right | |

In western part of Africa there is source shown in red in figure that is captured by the MIMIC and it advects through western SAHEL. This pattern seems logical cause the source is on the ocean and the sink which could be rainfall happens in arriving on continent. This is while the SAPHIR simple error AT is just detecting the sink on the ocean but can’t track its migeration on the continent. It also has estimated an weak source on continent which seem wrong. The left most image is where the new observation is got available hence relating estimates from both modes.

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|  |
| Figure : |

One of other important merits of using the SAPHIR data is highlighted here. In other MIMIC products, as the data are not available on the continents, the tracking of the sink on the continent is almost impossible but with SAPHIR we have this opportunity.

**Conclusions and future works:**

The goal of this internship project was producing a synthesized product of humidity and AT from narrow swath data, which is reached successfully. The first simple graphical evaluations with other datasets prove to an extent the satisfying performance of these products.

Specially in two important regions of world, the product was able to track continuously the sources and sinks of water vapor.

A long run and more statistical evaluation is needed to justify these results.

The margin mode mentioned in Mapes et al 2018 study could be more explored in future works.

The AT demonstrates its error in two examples in results. One is indeterminacy when focusing on it in fine special resolution of about a pixel or a little more. And the other is its dipole character. These all demanding for the further studies to characterizing these uncertainties.

Regarding the first part of article in figure 2 a-b when there is subsidence drying, the prevailing process, we will have : a being an constant coefficient. This means q decays exponentially with time. As a future study if we can isolate this kind of drying subsidence or sinks regions the “a” coefficient can be estimated by regression of and q. sophistication will be added implementing the same method to source places where convection happens. The convection is a stochastic process in space and time. It is characterised by its probability density. Therefore a joint probability should be used for example with q.