AAPG2024	PaleoTempesto		PRC
Coordinated by:	Camille Risi	48 months	485 000 euros
CE01 – 1.1 Terre fluide et solide			

PaleoTempesto : Is the isotopic composition of tropical rain a paleo-tempestology proxy ?

Summary table of persons involved in the project:

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month) throughout the project's total duration
LMD	*Risi*	*Camille*	*CR CNRS*	*Coordinator, lead WP2, WP1, WP2, WP3, co-advise PhD student and post-doc 2, scientific leader LMD*	*28.8 p.month*
LMD	*Rochetin*	*Nicolas*	*MdC ENS*	*WP2, co-advice PhD student*	*2.4*
LAERO	*Barthe*	*Christelle*	*CR CNRS*	*WP1b, co-advice post-doc 1*	*4.8*
LSCE	*Fromang*	*Sébastien*	*CR CNRS*	*WP2b, scientific leader LSCE*	*4.8*
LSCE	*Vimeux*	*Françoise*	*DR IRD*	*WP1a,b, co-advise post-doc 1*	*14.4*
CEREGE	*Leduc*	*Guillaume*	*CR CNRS*	*WP3, scientific leader CEREGE*	*14.4*
CEREGE	*Sylvestre*	*Florence*	*DR CNRS*	*WP3*	*2.4*
CEREGE	*Alexandre*	*Anne*	*CR CNRS*	*WP3*	*2.4*
CEREGE	*Cartapanis*	*Olivier*	*post-doc*	*WP3, co-advise post-doc1*	*4.8*
LSCE	-	-	*Postdoctoral contract*	*WP1, write papers P1a, P1b*	*24*
LMD	-	-	*PhD contract*	*WP2, write papers P2ab, P2c*	*36*
CEREGE	-	-	*Postdoctoral contract*	*WP3, write papers P3ab, P3c*	*24*

Any changes that have been made in the full proposal compared to the pre-proposal / compared to the registration

The salaries of the post-docs and students have been updated with the current salary grid of each organism, and other expenses have been reduced (internal workshops, international conference, one M2 internship removed) to keep the budget within 7% of that of the pre-proposal.

I. Proposal's context, positioning and objective(s)

a. Objectives and research hypothesis

Motivation: Reconstructing past rainfall from water stable isotopic archives in the Tropics

Rainfall has important impacts on populations and ecosystems. Predicting how rainfall will change in the coming decades is essential to assess human vulnerability and future adaptation pathways. Tropical regions are where the populations are most vulnerable to climate change, yet where the rainfall changes are subject to the largest uncertainties in sign and magnitude (IPCC 2021).

Past climate offers storylines to inspire and test hypotheses on the response of rainfall changes to forcing, and constraints for climate models (Braconnot et al 2012, Tierney et al 2020). The last glacial maximum (LGM) and the mid-holocene (MH) periods are the most frequently used periods: they show large climate and hydrology changes, they are routinely simulated in climate model inter-comparison projects and numerous proxies are available for model evaluation.

To reconstruct past rainfall changes, two kinds of proxies are notoriously used:

1. Isotopic proxies based on the water isotope composition of rainfall ($\delta^{18}O_p$, δD_p) recorded in e.g. speleothems (Atsawawaranunt et al 2018) or leaf waxes (Sachse et al 2012),
2. Non-isotopic proxies of the water cycle, e.g. terrigenous fraction of sediments (Haug et al 2001) or pollen assemblages (Bartlein et al 2001, Mollier-Vogel et al 2013).

The interpretation of isotopic records in terms of past rainfall is based on the present-day observation that the tropical rain is more depleted when the local rain rate is larger (Dansgaard 1964). Actually, it is now well established that in most regions, the isotopic composition of rainfall does not only reflect the local rainfall, but also the rainfall integrated over the previous days along trajectories (Vimeux et al 2005, Risi et al 2008, Gao et al 2013, He et al 2014). Isotopic records in the tropics are thus widely used as proxies for regional precipitation (Wang et al 2001, 2005, Midhun et al 2022). However, even at the regional scale, rainfall reconstructions based on isotopic and non-isotopic proxies often diverge, e.g. in Western Africa, the Middle East and Southern Asia during the Holocene (Leduc 2013, Thompson 2021), South America during the LGM (Sylvestre et al 2009, Reis et al 2022), central America (Luciani et al., in prep). The goal of this project is to address this long-standing enigma.

Hypothesis: the type of storm affects the interpretation of paleoclimate archives

Several hypotheses have been proposed to explain the discrepancy, such as changes in moisture origin (Hu et al 2019) or continental recycling (Lee et al 2012). However, these processes are not always sufficient to interpret isotopic variations.

Our recent work using in-situ observations (Vimeux et al 2024), satellite observations [Risi et al in prep1, Risi et al in prep3) and storm resolving simulations (SRMs, Risi et al. 2023) suggests that the **type of storms (i.e. their duration, size, internal dynamics)** that produce rainfall is the first-order controlling factor on the rain isotopic composition on daily to inter-annual timescales. Specifically, in the present-day, the observed rain is more depleted in organized convective systems such as squall lines (Risi et al 2008) or tropical cyclones (Lawrence et al 2004) than in isolated cumulonimbi. Using observations in water vapor for larger sampling, we recently showed that this property holds on even when considering the same rain rate (Vimeux et al. 2024, Risi et al in prep). This is illustrated in Fig 1: for a given rain rate of e.g. 5 mm/day, water vapor, and presumably subsequent precipitation, is more depleted when the rain comes from long-lived convective systems (Fig 1a) and even more depleted when it comes from squall lines and tropical cyclones (Fig 1b).

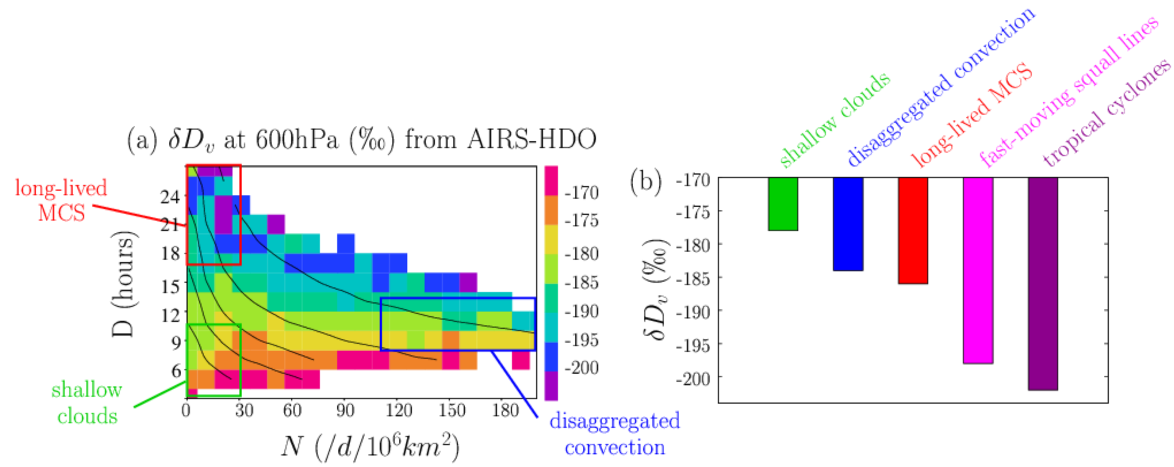

Fig 1: Impact of storm organization on the water isotopic composition (Risi et al in prep). (a) Water vapor δD observed by satellite over tropical oceans as a function of the number of convective systems N and the mean duration of convective systems D, for a rain rate in the range of 4.5-6 mm/d, for 5x5° daily scenes over tropical oceans. This shows that even for a given rain rate, the life duration of convective systems strongly impacts the isotopic composition of the water vapor, and thus of the subsequent rainwater. (b) Mean water vapor δD observed by satellite around different kinds of convective systems for the same rain rates as in a. This shows that squall lines and tropical cyclones are associated with more depleted water vapor than other convective systems for the same rain rate.

The goal of this project is to investigate the hypothesis that the type of storm, also called storm organization, plays a critical role in driving the isotopic variations at the paleoclimate scale and could explain the discrepancies between isotopic and non-isotopic proxies.

If this is the case, then **the interpretation of isotopic records as rainfall proxies should be revised. The isotopic composition of climate archives should then be thought in terms of storm type instead of regional rain rate**. Besides, this would support recent **interpretations of isotopic records as paleo-tempestology proxies**, in terms of tropical cyclones (Lawrence et al 2003, Frappier et al 2007, Baldini et al 2016) or squall lines (Maupin et al 2021) frequencies.

Approach

To test the hypothesis of the key role of the type of storm and assess the extent to which this could help resolve the long-standing inconsistencies between isotopic and non-isotopic precipitation proxies, our approach will be threefold (Fig 2):

First we will investigate the physical processes by which the type of storm affects the isotopic composition of rain. Our recent work with idealized storm resolving simulations (SRM) (Risi et al 2023) and general circulation models (Vimeux et al 2024 Risi et al in prep) showed that both storm-scale and large-scale processes play a role. To resolve processes at both scales, we will use **SRM simulations on realistic case studies of squall lines and tropical cyclones**, evaluated against in-situ and satellite observations (WP1).

Then, a major challenge is to **bridge the time scale gap from storms** of a few hours/days in the present climate **to past climates** with isotopic records at the annual/multi-annual scale. Our **consortium gathering expertise in storm processes and paleoclimate reconstructions** is a unique opportunity to bridge this gap (WP2). To do so, we will use the isotope-enabled general circulation model (GCM) LMDZ with a state-of-the-art resolution (100-200 km), in which we will implement a representation of the type of storm and its impact on the isotopic composition. Ideally, high resolution (<50km) is necessary to properly capture tropical cyclones (Camargo et al 2013, Bourdin et al 2024) and even higher (<10km) for squall lines (de Vries et al 2021). However, SRMs are too costly in terms of carbon footprint to be routinely run at the global and climatic time scales (Balaji 2021, Balaji et al 2022). State-of-the art GCMs represent storms in a statistical way in coarse grid boxes and are thus blind to storm organization. Representing storm organization in GCMs has been a long-standing issue (Rio et al 2019), but the LMDZ GCM (Hourdin et al 2020) offers a unique opportunity to overcome this challenge: a detailed physical representation of cold pools (Grandpeix and Lafore 2010) which are known to be key for storm organization (Rotunno et al 1988, Abramian et al 2021). The process study from WP1 will provide the physical basis for this parameterization, and the realistic case studies from WP1 will provide a benchmark for GCM evaluation.

Finally, **paleoclimate simulations** with isotopes will be run with the LMDZ version developed in WP2, compared with isotopic and non-isotopic proxies, and used to quantify the role of the storm type on isotopic variations at the paleoclimatic scale (WP3).

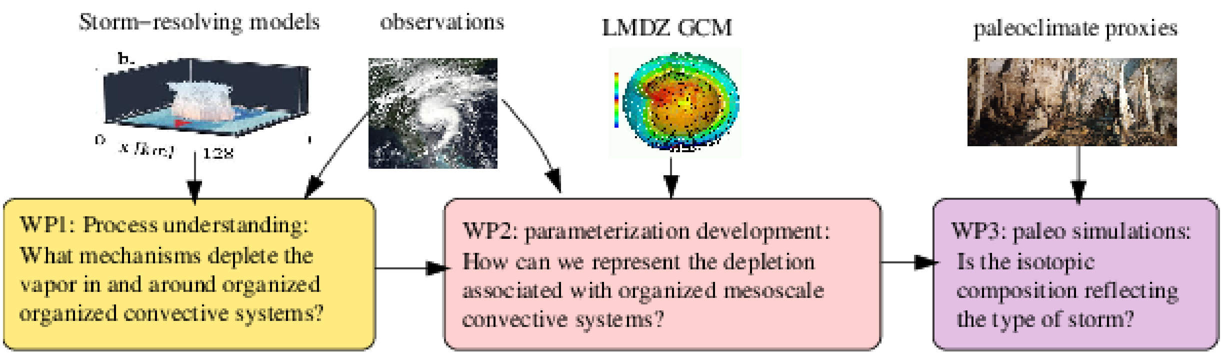

Fig 2: Overview of the work packages and their interactions

b. Position of the project as it relates to the state of the art

There is already a large corpus of research on the interpretation of water isotopic archives in tropical regions, to which the consortium has significantly contributed, using both present-day observations (Vimeux et al 2005, 2011, 2024) and general circulation modeling (Lee et al 2012, Gao et al 2013, He et al 2015, Botsyun et al 2019). **The originality of this project relative to the state-of-the-art is the exploration of an additional factor: the type of storm**. Although the type of storm has been suggested for two decades to impact the isotopic composition of tropical archives (Lawrence et al 2003, Frappier 2007, Maupin et al 2021), this factor has never been quantified so far through GCM modeling. Here with a GCM, which comprehensively simulates the different intricate local and large-scale factors, we propose to quantify the impact of storm type on paleoclimate isotopic variations.

Studies on the impact of storm type on water isotopes in observations have long been hampered by varying rain rate as a confounding factor (e.g. Lawrence et al 2004, Maupin et al 2021). Large, long-lived, organized convective systems such as squall lines and cyclones are typically associated with larger rain rates, which is aso expected to deplete the rain in heavy isotopes. The approach to study storm type for a given rain rate, pioneered by Tobin et al (2012), has only **been applied to water isotopes very recently by the consortium**, thanks to the unprecedented length of in-situ water vapor observations at Reunion Island (Vimeux et al 2024) or to satellite observations (Galewsky et al 2023, Risi et al in prep 2).

The approach of using SRM to understand processes and to guide GCM parameterization development has long been successful outside of the isotopic community (Randall et al 2003). It is more seldomly used for isotopic applications (Blossey et al 2010, Moore et al 2014). This project is part of a **steady effort by the consortium to use SRMs to understand how storms impact the isotopic composition of rain and water vapor** (Risi et al 2020, 2021, 2023).

Representing storm organization in GCMs has been a long-standing issue (Rio et al 2019). Several efforts have been made in other GCMs in the past decade (Mapes and Neale 2012, Park 2014, Ahn et al 2019, Rooney et al 2021). In these attempts, a variable that represents storm organization (e.g. named “Org” in Mapes and Neale 2012) is diagnosed from the convective parameterization and/or cold pool parameterization, and some convective parameters are adjusted to represent the variations of the effect of storms depending on their organization. We will build on these approaches. **Our originality relative to these attempts will be to account for the isotopic effect of storm organization**.

c. Methodology and risk management

WP0: Coordination, management and dissemination

➤ C. Risi (WP leader), all

Tasks in this WP are to ensure the smooth running of the project. From an administrative point of view, support will be provided by administrative staff at LMD, LSCE and CEREGE. From a scientific point of view, 2 internal in-person meetings between participants will be organized in the middle of year 1 and 3, to ensure the coherence of the project. In addition, more frequent, operational meetings will be organized by video within each WPs and between the PI and WP leaders. From a human resource point of view, the PI and WP leaders will deal with the recruitment process of the 2 post-docs and PhD and M2 students. They will elaborate a data management plan (section “Open Science Practices). The PI will organize the international conference on precipitation changes (section “Impacts”) and will coordinate the dissemination and communication activities (section “Impacts”).

WP1 : What mechanisms deplete the rain in organized storms?

➤ F. Vimeux (WP leader), C. Risi, C. Barthe, 2-year post-doc (co-advised by C. Barthe, F. Vimeux and C. Risi), M2 student (co-advised by C. Risi, F. Vimeux and post-doc)

We aim at understanding the mechanisms through which organized storms deplete the water vapor and subsequent rain more than isolated storms for a given rain rate. Preliminary studies show that both storm-scale and large-scale processes interact to deplete the rainfall in and around organized storms (Risi et in prep 3, Vimeux et al 2024). Therefore, instead of using idealized SRMs as in Risi et al (2023), we will use **isotope-enabled SRMs in realistic configurations for real case studies**, both for squall lines (WP1a) and cyclones (WP1b).

WP1a: In squall lines

We will focus on Western Africa. The choice of the region is motivated by the **unprecedented long-term in-situ isotopic observations acquired by the consortium at Niamey** (Tremoy et al 2012, 2014, 6-year long dataset for water vapor and 15-year long dataset for rain), and the availability of an isotopic **SRM simulation by COSMO-iso** (De Vries et al 2021). Observations in rain (Risi et al 2008) and water vapor (Tremy et al 2014) show larger depletion in squall lines relative to isolated systems. What are the mechanisms? Possible hypotheses are the higher relative humidity in which the rain partially evaporates, the higher altitude from which the condensate comes from, or the more depleted vapor in the cold pool under the squall line in which the rain evaporates (Risi et al 2023). To test these hypotheses, the C. Risi and the M2 student will:

- Acquire the COSMO simulation from A. de Vries, which lasts from 1 June to 30 July 2016. The horizontal resolution is 7-km, enough to simulate squall line systems, the main updrafts and downdrafts and the vapor isotopic composition (de Vries et al 2021).
- Evaluate the simulated isotopic variations at the intra-event scale against in-situ observations (Tremoy et a 2014), and at the inter-event scale using in situ and satellite observations.
- Identify a few cases studies and check their representativeness (in time and space at the scale of the entire tropics) using satellite observations of water vapor isotopes (Worden et al 2019, Diekmann et al 2021) which we have already processed and co-located with storms (tracked by the TOOCAN algorithm, Fiolleau and Roca 2014) (Risi et al in prep).
- Analyze the additional depletion in squall lines with respect to isolated storms using water and isotopic budgets and analytical equations expressing rain-vapor interactions.

WP1b: In cyclones

We will focus on Réunion Island on the Southeastern Indian Ocean. The choice of the region is motivated by the **unprecedented long-term in-situ isotopic observation acquired by the consortium** at Réunion Island since 2014 [Vimeux et al 2024] and by the expertise of the consortium to run simulations in this region using **MesoNH** (Lac et al 2018)**, in which isotopes have recently been implemented by the consortium**. They were evaluated in a 2D squall line case (fig 3). A manuscript is in preparation for *Geophys. Model. Dev.*, and should be submitted during the summer 2024. In autumn 2024, before the start of the project, water isotopes will be added to the trunk of MesoNH by C. Barthe.

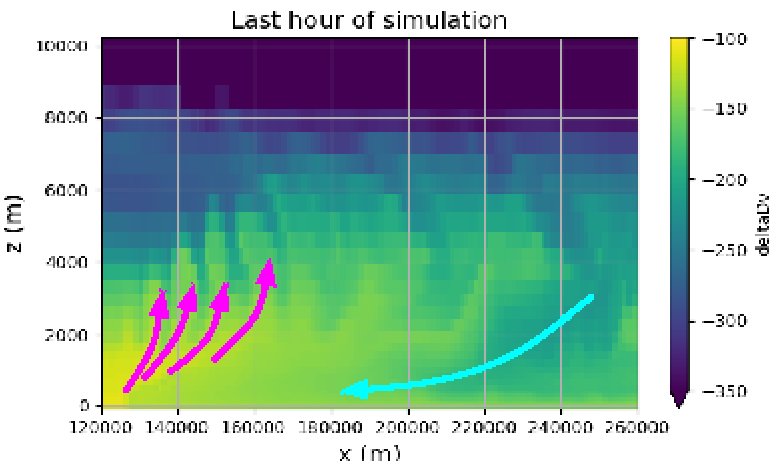

Fig 3: isotopic field simulated by MesoNH in the idealized 2D squall line case. It shows the enriched values in convective updrafts (pink arrows), and the depleted values in the rear-to-front flow associated with meso-scale descent and rain evaporation (cyan arrow).

Observations in rain and water vapor at Réunion Island (Guilpart et al., 2017, Vimeux et al 2024) and at the scale of the entire tropics (Risi et al in prep) show larger depletion in tropical cyclones relative to isolated systems for the same rain rates. To investigate the mechanisms at play in this depletion, the post-doc will:

- Identify cases studies based on observations (Vimeux et al 2024, complemented by recent sampled cyclones from 2021 to 2024), and check their representativeness (in time and over different oceanic basins) using satellite observations (as for WP1a)
- Run MESO-NH simulations with isotopes for a few cyclone and isolated storms case studies, forced by reanalyses for meteorological variables and LMDZ nudged by reanalyses for isotopic variables. Simulations will run on TGCC where Meso-NH is being installed (F. Brient, pers. comm.) and where we have yearly computing allocation.
- Analyze the additional depletion in cyclones using the same methodology as for squall lines.

Deliverables

- Two publications: one on the isotopic depletion associated with squall lines, and the other on that associated with cyclones
- An updated database of in-situ observations of cyclones in Reunion Island from 2021 (the 2014-2020 dataset is available on Zenodo)
- A database of Meso-NH simulations of cyclones

Risks

- There are technical risks associated with MesoNH at TGCC, especially its isotopic version. They will be mitigated by the expertise of C. Barthe and local technical support..
- A scientific risk is that COSMO-iso or MesoNH-iso do not capture the depletion associated with squall lines and cyclones. This risk is low because COSMO-iso was already evaluated in de Vries et al (2021), though not for land surface precipitation, and even some GCMs were able to capture the depletion associated with cyclones at La Réunion (Vimeux et al 2024). Even if this happens, investigating the causes (e.g. relative role of the forcing and internal physics) would be interesting in itself.
- Another scientific risk is that depletion in squall lines and tropical cyclones is regionally-dependent and our two regions of interest are not representative. This risk is low based on preliminary analysis of satellite observations (Risi et al in prep).

WP2 : Representing the isotopic depletion associated with organized convective systems in a GCM

➢ C. Risi (WP leader), N. Rochetin, S. Fromang, 3-year PhD student (co-advised by N. Rochetin and C. Risi)

The process study from WP1 will provide the physical basis for the development of a GCM parameterization accounting for the effect of cyclones and squall lines on water isotopes. We will use the isotope-enabled GCM LMDZ (Risi et al 2010) because the consortium has a thorough expertise on this model and its parameterizations. Currently, LMDZ is completely blind to squall lines: it represents the rain in grid boxes where squall lines are expected, but without knowing whether it is due to squall lines or isolated storms. LMDZ already explicitly simulates tropical cyclones, but realistic intensity requires high resolution (>50km, Bourdin et al 2024, in press). Therefore, first we will represent the isotopic depletion associated with squall lines (WP2a) and tropical cyclones (WP2b) assuming we know where there are (based on observations), and then we will implement a variable that diagnoses the presence or not of squall lines and cyclones (WP2c). Note that this work will benefit from the work of the PhD student A. Lhotte (2022-2025) currently advised by C. Risi on the representation of the impact of convective organization on tropospheric humidity.

WP2a: Represent depletion by squall lines

Here we use LMDZ in a nudged mode, i.e. the winds are relaxed towards those of the reanalyses. This ensures that the simulated meteorological situations are consistent with the observations at all times and locations. We can diagnose the location of squall lines from the storm-tracking algorithm TOOCAN (Fiolleau and Roca 2014). All mesoscale convective systems since 2012 have been tracked. To represent the additional depletion by squall lines relative to isolated storms, the PhD student will:

- Create a variable called “Org” (as in Mapes and Neale 2011) that represents the occurrence or fraction of rain by squall lines in each grid cell.
- Based on WP1, identify what parameters in the convective parameterization (e.g. precipitation efficiency in updrafts controlling where the condensate comes from, entrainment into unsaturated downdrafts controlling the humidity in downdrafts) should depend on “Org”, or whether some equations in the convective parameterization should be added depending on “Org” (e.g. adding a near-cloud environment that is moister). Implement these changes.
- Run nudged simulations over the TOOCAN period (beyond 2012) and including the COSMO-iso period. Test different versions of the parameterization if needed.
- Evaluate the new parameterization using in-situ and satellite observations and COSMO-iso simulation from WP1a.

WP2a: Represent depletion by cyclones

To represent the additional depletion by tropical cyclones relative to isolated storms, the PhD student will proceed exactly as in WP1a, except that the location of cyclones will be diagnosed from the iBTrACS database (Knapp et al 2010), and we will evaluate the simulation using in-situ and satellite observations and Meso-NH simulations from WP1b.

Several studies suggest that rain bands around tropical cyclones are analog to squall lines (Robe and Emanuel 2001, Yu et al 2018). We will investigate to what extent the isotopic depletion in squall lines and tropical cyclones can be thought of in a common framework, or whether processes in these two types of storm really deserve a different parameterization.

WP2c: Diagnose the occurrence of squall lines and cyclones

Squall lines arise from the interaction between cold pools under storms and the ambient vertical shear of the wind (Rotunno et al 1988, Robe and Emanuel 2001, Abramian et al 2021). We will thus exploit the cold pool model already implemented in LMDZ (Grandpeix et al 2010). Based on the work by recent interns advised by C. Risi and N. Rochetin, we will formalize equations that define the “Org” variable as a function of wind shear and cold-pool properties. Alternatively, recent developments on the population dynamics of cold pools (L. Thiam’s thesis in which N. Rochetin is involved) open the possibility to make the cold-pool-population dynamics depend on wind shear and directly use the number of cold pools per convective cell as the “Org” variable. From the cold pool strength and wind profile, the propagation velocity of squall lines can also be diagnosed (preliminary works by interns) and can be used to propagate the cold pools and associated “Org” variable from one grid cell to the next. For tropical cyclones, we will diagnose their occurrence by implementing an on-line diagnostic in LMDZ that can readily be applied to large-scale fields available in a GCM (Tory et al 2013). The PhD student will:

- Develop the equations and implement them in LMDZ
- Run nudged simulations and evaluate on a daily basis the occurrence of squall lines and cyclones against TOOCAN and iBTRACS.
- Run free simulations and evaluate on a climatological basis the occurrence of squall lines and cyclones against TOOCAN and iBTRACS.

Deliverables

- Two publications: one on the representation of the isotopic depletion associated with cyclones and squall lines in nudged LMDZ simulations, and one on the diagnostic of convective organization in LMDZ
- Nudged LMDZ simulations with and without the new parameterizations
- New parameterizations that will be proposed for inclusion in the trunk of LMDZ.

Risks

- Because of the development of new parameterizations, WP2 is very ambitious. If the PhD student is short on time, he/she can deliver a simple, back-up version of the new version of LMDZ without WP2c.

- The propagation of cold pools from the grid box to the next is a numerical challenge, since currently there are no ways for the atmospheric columns to interact with each other in the physical parameterization part of LMDZ. The parallelisation strategy of the code is built on this assumption. We will inspire from what is done for river routing and discuss with LMDZ engineers. In the worst case, the rest of the project can continue even without the propagation of squall lines.

WP3 : Reconciling isotopic and non-isotopic records

➢ O. Cartapanis (WP leader), G. Leduc, C. Risi, A. Alexandre, F. Sylvestre, F. Vimeux, 2-year post-doc (co-advised by C. Risi and O. Cartapanis)

LMDZ with isotopes and with the parameterization developed in WP2 will be used to quantify the relative role of changes in the rainfall and the type of storms in past isotopic variations. We will run LMDZ simulations for the Last Glacial Maximum (LGM, 21ka) and Mid-Holocene (MH, 6ka) periods, for which rainfall changes are large in response to external forcings (Braconnot et al 2012) and data compilations are already available (Atsawawaranunt et al 2018). Because we are interested in the **long-term frequency of different types of storms, multi-annual-resolution records are enough**.

WP3a: Identify hotspots of divergence between isotopic and non-isotopic proxies

We will identify regions and periods that display robust divergence between isotopic and non isotopic proxies of the hydrological cycle. We will look especially in regions where isotopic and non-isotopic records diverge the most, because this is where the storm type may impact rain isotopes the most.

According to previous studies, this includes Western Africa, Southern and Central America, but we will systematically identify these regions. To do so, we will:

- Gather data compilations and individual records from LGM to present day, encompassing MH and PI. Isotopic data indicators such as the isotopic compositions of speleothems, tropical (i.e. andean) ice cores and leaf wax will be compiled from existing compilation (SISAL: Atsawawaranunt et al 2018, SISAL V3: Kaushal et al 2023; Hancock et al 2023; and the literature, e.g. Yacoub et al 2023). Non isotopic datasets including pollen based records, lake levels, and terrigenous fluxes will also be gathered from preexisting databases and the literature (Herzschuh et al 2023; Hancock et al 2023; Shanahan et al 2015, de Cort et al 2021). Additional datasets will also be mined from online data repositories (Pangaea; NOAA; NEOTOMA). A particular attention will be paid to **quality control and uncertainties quantification**.
- Investigate the most relevant spatial scale at which we should look at the precipitation, to include regional precipitation upstream archives.
- Systematically compare the sign and amplitude of variations of rainfall proxies and isotopic composition. For the first time, such a literature review effort will provide key constraints on where and when the interpretation of the isotopic composition of rainfall of paleo-records in terms of precipitation rates, vastly used in the literature, should be revised.

WP3b: Compare observations to LMDZ simulations

Where discrepancy between variations of rainfall proxies and isotopic composition was identified, is it caused by changes in storm type, or by more traditional effects such as moisture origin or continental recycling? To test these hypotheses, we will:

- Run LMDZ for the pre-industrial period (PI), MH and LGM without storm type parameterization. Boundary conditions will be provided by coupled-model simulations from CMIP6 (Coupled Model Intercomparison Project Phase 6, Eyring et al 2016, e.g. as in Risi et al 2010a).
- Can LMDZ with constant organization explain the discrepancy? If so, we will use water and isotopic budgets simulated by LMDZ to re-examine the roles of regional rainfall patterns, moisture source and recycling on the isotopic proxy.
- Re-run the simulations with lower and higher prescribed occurrences for squall lines and cyclones (WP2a-b), and with interactive occurrences (WP2c): does it improve the comparison in the regions where the discrepancy could not be explained?

WP3c: Can we use isotopic archives as paleo-tempestollogy proxies?

For regions and periods where WP2b concluded for a role of storm type on isotopic variations, we will propose a method to deconvolve the storm type signal from the combination of isotopic and non-isotopic precipitation proxies. The validity of this method will be tested in a “perfect model” context of the LMDZ simulations with interactive occurrences of storms.

Delivrables

- Two publications: one on the divergence between isotopic and non-isotopic proxies in archives and in LMDZ, and one on the use of paired isotopic and non-isotopic proxies for paleo-tempestology.
- LMDZ simulations

Risks for WP3:

- One risk is that LMDZ does not capture well climate changes (especially precipitation) in the regions of interest. If the case, we will further restrict our regions of interest where LMDZ works well.
- It is also possible that even when considering different scenarios of changes in storm types, LMDZ is still unable to capture isotopic changes. If the case, we will focus on regions where LMDZ works. Besides, understanding the LMDZ biases will be Interesting in itself.
- A usual concern is the **stability through time of the relationship between storm type and isotopes**. This is mitigated in our approach because we will not attempt to use observed relationships at present for past climates. Rather, we will use GCM modeling with a parameterization of the physical processes through which storm type impacts isotopes (WP2). Although the final relationship between storm type and isotopes is expected to depend on the time period and the region, the elementary physical processes are not.

Gantt chart

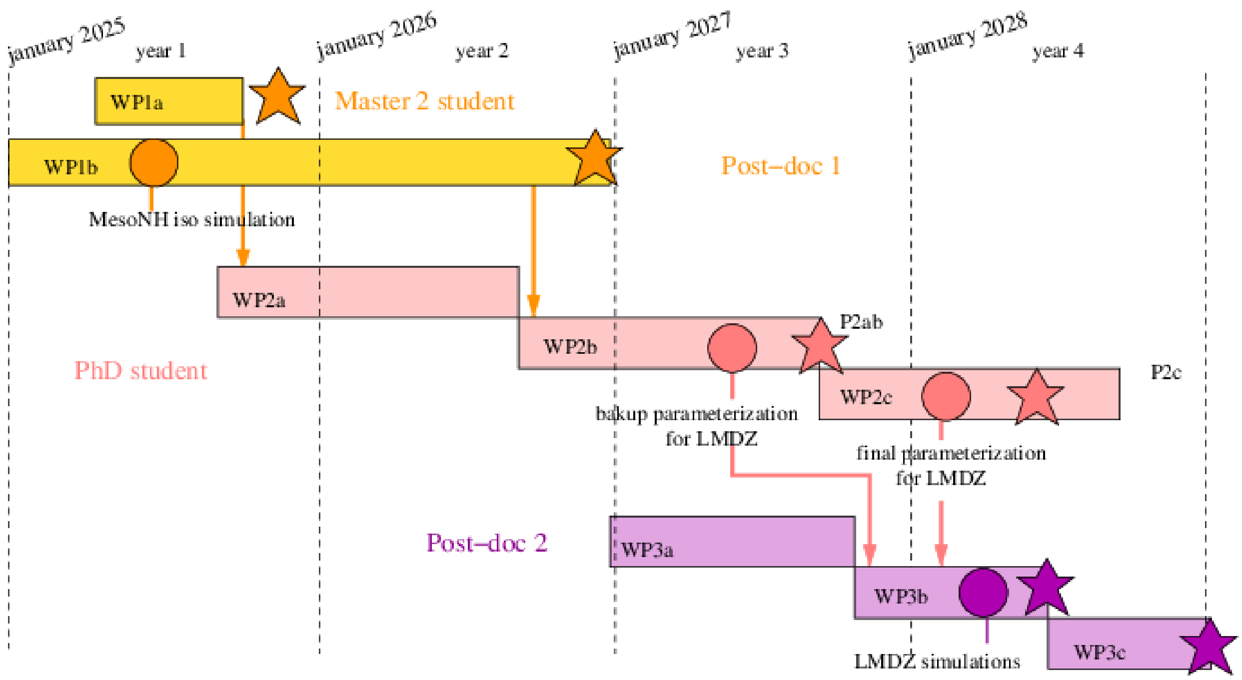

Fig 4: Gantt chart showing the different work packages and associated tasks, how they rely on each other (arrows), and the main deliverables as publications (stars) or simulations (circles).

Open Science practices

We will mainly use existing datasets:

- existing and on-going observations for rain and water vapor isotopes in Niamey and Reunion Island.
- existing and ongoing data compilations for paleoclimate archives (e.g. version 2 and 3 for the SISAL compilation, which now includes non-isotopic proxies from speleothems; version 1.0 of Legacy Climate database for pollen based climate reconstruction;); and datasets mined from online data repositories (Pangaea; NOAA; NEOTOMA). All datasets used in the study and the associated publications will be duly referenced over the course of the project. All datasets produced will comply with the **FAIR principles** (Findable-Accessible-Interoperable-Reusable, Wilkinson et al 2016).
- existing simulation for the Sahel (de Vries et al 2021)

We will make new products available on a repository and complying with FAIR principles:

- MesoNH is already freely available and isotopes will be included in the standard version
- Simulation of cyclones on Réunion Island with the isotopic version of MesoNH
- LMZ paleoclimate simulations with isotopes
- New isotopic observations at Réunion Island on both rain and water vapor.

Organisation and implementation of the project

a. Scientific coordinator and its consortium / its team

The coordinator

The project will be coordinated by C. Risi (LMD, 60%, i.e. 70% of her 80% work time), CR CNRS. She has a unique combination of expertise necessary for this project: water isotopes (Risi et al 2008), convection (Abramian et al 2022) and past climates (Lee et al 2012), modeling with SRMs (Risi et al 2020, 2021, 2023) and LMDZ (Risi et al 2010). She has coordinated the LEFE project SAMiso (2020-2022) that served as a springboard to this proposal.

The consortium

- **LMD** (convection, LMDZ, parameterization development): C **Risi** (60%), N **Rochetin** (5%) to co-advise a PhD student on WP2.

- **LSCE** (water isotopes observations and modeling): F **Vimeux** (30%, long experience in in-situ isotopic observations and background in paleoclimate reconstructions) to co-advise post-doc on WP1; **S Fromang** (10%, cyclone simulations and tracking in LMDZ); S. Nguyen (LMDZ-iso support)

- **CEREGE** (paleoclimate): **G Leduc** (30%), **O Cartapanis** (10%), A **Alexandre** (5%) and F **Sylvestre** (5%).

- **LAERO** (administratively associated with LMD): C **Barthe** (LAERO, 10%, MesoNH-iso).

Local, national and International collaborations: J-Y Grandpeix, S Bony, B Fildier (LMD, convection), S Bourdin (LSCE, cyclones), R. Roca and T. Fiolleau (LEGOS, storm-tracking dataset TOOCAN), C. Rio (CNRM, convective parameterization), C Muller (IST Vienna, convection), P Blossey (U. Washington, SRMs), A de Vries (ETH Zurich, COSMO simulation).

Implication of the scientific coordinator and partner's scientific leader in on-going project(s)

Name of the researcher	Person.month	Call, funding agency, grant allocated	Project's title	Name of the scientific coordinator	Start - End
Guillaume Leduc	9.6	ANR	WomenSoFar: Individual life histories and WOMEN Status at the Onset of FARming. Bioarchaeological perspectives in the French and Mediterranean Prehistoric context	Gwenaëlle Goude	2022-2026
Guillaume Leduc	19.2	ANR	ITCH: An Integrated Test of Climate Hypotheses: Paleoclimate Cycles and Plankton Evolution in the Pleistocene equatorial Indian Ocean	Clara Bolton	2023-2027

b. Implemented and requested resources to reach the objectives

General:

- We assume 3000 euros per article. The cost is based on the recent publication fees we experienced in AGU journals, appropriate for the scientific subject (e.g. Vimeux et al., 2024)
- We assume 3000 euros per conference participation. The cost is based on an AGU-like conference with air plane tickets (1000 euros), perdiem during one week according to economie.gouv.fr: 320 *5 euros, meeting registration: 400 euros).

Partner 1: LMD

Staff expenses (in French: *"Frais de personnels"*)

- PhD student 125 000 euros

  He/she will work on WP2, co-advised by C. Risi and N. Rochetin. A candidate with background in atmospheric physics and good programming skills will be recruited.

Outsourcing / subcontracting

- 2 publications, one for WP2a-b and another one for WP2c 6000 euros
- 2 conferences for the PhD student during his/her second and third year 6 000 euros
- Workshops between participants 5000 euros

  We expect 2 internal meetings between participants in the middle of year 1 and 3, with C. Barthe coming from Toulouse and GU Leduc, O. Cartapanis, A. Alexandre and F. Sylvestre coming from Aix-en-Provence. → 2x 5x 500 euros

- Organization of an international workshop for 3 days and 50 people 10 000

  The detailed costs are: 5000 euros for renting the room at Sorbonne University, 5 000 euros for the meals, according to expenditures from a previously organized workshop of a similar format.

Total budget for LMD **152 000 euros**

Overheads costs

with additional 14.5% tax **174 040 euros**

Partner 2: LSCE

Staff expenses

- Post-doc, 2 years (2-7 years' experience, CNRS salary) 167 539 euros

  The post-doc will work on WP1b and will co-advise M2 student on WP1a. He/she will be co advised by C. Barthe, F. Vimeux and C. Risi.

- Internship Master 2 (CNRS salary) to work on WP1a 4370 euros

Instruments and material costs

- Maintenance of instruments (picarro and pluviometer) on Réunion Island over the first 2 years of the proposal for additional cyclones sampling 6000 euros

Outsourcing / subcontracting

- 2 publications, one for WP1a and one for WP1b 6 000 euros
- 2 conferences for the WP1 post-doc: 6000 euros

Total budget for LSCE **189 909 euros**

Overheads costs

with additional 14.5% tax **217 445,81 euros**

Partner 3: CEREGE

Staff expenses

- Post-doc, 2 years (2-7 years' experience, CNRS salary) **164 238 euros**

  The post-doc will work on WP3. He/she will be co advised by G. Leduc and O. Cartapanis and collaborate with F. Vimeux and C. Risi. He/she will have experience in paleoclimate, data mining and model-data comparison..

Outsourcing / subcontracting

- 2 publications, one for WP3a-b and one for WP3c 6 000 euros
- 2 conferences for the post-doc during his/her 1st and 2nd year 6 000 euros

Overheads costs

Total budget for CEREGE **176 238 euros**

Overheads costs

with additional 14.5% tax **201 792,51 euros**

Requested means by item of expenditure and by partner*

	Partner *LMD*	**Partner** *LSCE*	**Partner** *CEREGE*
Staff expenses, including costs of a partial release from teaching obligations in a JCJC project	125 000	171 909	164 238
Instruments and material costs		6 000	
Building and ground costs			
Outsourcing / subcontracting	27 000	12 000	12 000
Overheads costs			
Administrative management & structure costs**	22 040,00	27 536,81	25 554,51

Sub-total	**174 040,00**	**217 445,81**	**201 792,51**
Requested funding	**593 278,32 euros**		

II. Impact and benefits of the project

Impacts on Science:

- **Resolve the long-standing enigma** of the divergence between isotopic and non-isotopic proxies of past rainfall; possibly revise the paleoclimatic interpretation of isotopic records in tropical area.
- Assess the validity of the interpretation of isotopic records as paleo-tempestology proxies, paving the way to a better constraint on **future projections of extreme rainfall** (Emanuel 2003).
- Inspire novel approaches to **parameterize in GCMs the organization of storms**, identified as a major modeling challenge for several decades [Rio et al 2019].
- The paramaterization of organization in LMDZ opens **many perspectives for future work related to the long-standing issues of interactions between convection and large-scale circulation**: representing the impact of future organization changes on tropospheric humidity and cloud cover, quantifying the impact on climate sensitivity of organization feedbacks, investigating the impact of organization on the large-scale circulation and precipitation changes...

Impacts on the way we make science:

The project will foster **interactions between the convection and paleo communities**, which are seldom but promising (Sherwood et al 2020, IPCC 2021); with this aim, we plan to organize an **international conference** on rainfall changes to gather both communities.

Impacts on society:
The consortium has a long experience in science outreach, including participation to science festivals, designing novel outreach activities (e.g. clay workshop on hail), writing books or booklets for children ("Le changement climatique", Fleurus Eds., "Petit guide de la chasse à l'orage" on the IPSL web site). These activities will continue and interact with the project. In addition, we will make a website for the project mentioning the major scientific advances.

III. References related to the project (consortium members in bold)

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