# AO INSU 2014
# Section « Océan-Atmosphère »

## *Dossier scientifique*

**Nom du porteur du projet : Benjamin Pohl (CRC-Biogéosciences) et Olivier Bousquet (LACy)**

**Titre du projet : KOUDVAN**

Le projet KOUDVAN (cyclone en créole), centré sur l'activité cyclonique sur le sud-ouest de l'océan Indien, est l'héritier des projets LEFE VOASSI (2011-2013, PI J Vialard et F Roux) et CINDY-Dynamo France (2011-2013, PI J-P Duvel), qui avaient permis de coordonner la communauté française des sciences du climat travaillant sur l'océan Indien austral. Des actions communes avaient en particulier été initiées sur la thématique des cyclones tropicaux et la désagrégation dynamique du climat. Le présent projet est resserré autour de ces points et a pour but de réunir et fédérer les actions de 9 laboratoires (CNRM-GAME, CRC-Biogéosciences, LA, LACy, LE2P, LGSR, LOCEAN, LMD, MRTE) autour de ce thème. Le financement demandé à LEFE, sur une année, concerne exclusivement l'organisation d'un workshop unique en métropole, en vue de préparer un projet coordonnant une campagne de mesures dans le secteur Mascareignes et un travail d'analyses en laboratoire (traitement statistique de données et simulations numériques). Ce projet, bénéficiant du label de LEFE, sera ensuite soumis a différents appels d'offre (européens ou nationaux type ANR, voire régionaux).

## A. Intérêt scientifique et état de l'art

## 1. Why analyze tropical cyclone activity in the Indian Ocean?

With its Overseas Territories, France is present in three of the seven cyclonic basins (North Atlantic, South Pacific and Southwest Indian Ocean, SWIO) and is thus particularly concerned by tropical cyclones (TCs). TCs are frequent over the Indian Ocean (about 18 per year): those that develop in the SWIO can strike vulnerable islands, and in particular Madagascar (22 million inhabitants, with very fragile infrastructures and agriculture-dominated livelihood for most of the population) and the Mascarene islands (mostly La Réunion: 840 000 inhabitants, and Mauritius: 1.2 million inhabitants). One of our objectives is to work on improving TC forecasts (and associated effects over land at fine scales: wind gusts and rainfall amounts) over this sector (Météo-France is responsible for TC forecasts in this region), for example by accounting better for air-sea interactions below tropical cyclones or improving initial conditions of tropical cyclones NWP systems or developing new microphysical parameterizations, among others.

There are about 14 cyclones per year developing in the Southern Indian Ocean (plus 4 cyclones in the Northern Indian Ocean). In contrast with the Pacific or Atlantic basins, for which there is ample literature, the Indian Ocean has relatively been less studied. A great deal of effort has been spent on tropical cyclone intensity forecasting in the last four years, with most of that effort focused on improving NWP models. However, the dramatic drop in track guidance forecast errors seen in the last decade has not been replicated with intensity

guidance yet. In particular, anticipating sudden intensity changes of TCs remains a major operational and scientific issue, which has been recently identified as a priority by the World Meteorological Organization, during its last two international workshops on TC (IWTC VI, 2006 and IWTC VII, 2010). TC structure and intensity changes depend on numerous factors including the atmospheric thermodynamic environment, the initial intensity of the TC, and the heat exchange with the upper ocean under the core of the system (Emanuel, *Mon. Wea. Rev.*, 2000). Some of these factors are themselves directly modulated by large-scale modes of climate variability influencing this sector, both at interannual (El Niño Southern Oscillation [ENSO], the Indian Ocean dipole [IOD : Saji et al., *Nature*, 1999]) and intraseasonal (the Madden-Julian Oscillation [MJO : e.g. Madden and Julian, *Mon. Wea. Rev.*, 1994, Zhang, *Rev. Geophysics*, 2005]) timescales. TC activity could also evolve throughout the century in the context of a changing climate and increased greenhouse gases concentrations.
Our ultimate goals are to address these issues in a future research project.

## 2. TC analysis in the Indian sector: Research proposal

Nine French laboratories (CNRM-GAME, CRC-Biogéosciences, LA, LACy, LE2P, LGSR, LOCEAN, LMD, MRTE) share a common interest for TCs in the Indian Ocean. They propose to articulate their work and investigate three scientific issues around the following axes:the fine scale processes associated with TCs, the interactions between TCs and their large-scale environment (including the effect of climate change) and the influence of ocean atmosphere coupling on TCs. We also briefly present the field campaign that we plan, as well as the instruments needed for TC monitoring.

### 2.1 Fine scale processes associated with TCs

***Representation of TC inner core processes (LACy).*** Inner-core dynamical and thermodynamical processes are one of the key factors of TCs intensification. Such processes need to be better represented and constrained in models in order to improve TCs representation and forecasts. The Laboratoire de l'Atmosphère et des Cyclones (LACy) is particularly involved in this research area through the development of a "tropical version" of the French operational AROME model. This special research version of the model has been running for about 2 years and has recently being improved through the implementation of a three-dimensional variational assimilation (3D-VAR) system and (1D) coupling with the ocean model PSY4 (Mercator Ocean). The latest version of the model, which somehow prefigures the next operational model to be deployed by Météo-France within the SWIO basin (Bousquet et al., *31st Conf. on Hurricanes and Tropical Meteorol.*, 2014, Faure et al., *World Weather Open Science Conf.*, 2014), runs at a 2.5 km resolution over a 3000x1500 km² domain encompassing La Réunion, Mauritius and Madagascar islands. The planed assimilation of high-density observations (e.g., microwave satellite radiance, radar observations) into the model will help produce both better initial conditions and more realistic inner-core structures (Du et al., *J. Geophys. Res.*, 2012, Zhang et al., *Mon. Wea. Rev.*, 2013). Similarly, the high resolution of the model will also allow investigating TCs inner core dynamics, and how they can lead to rapid TC intensification. The same tool will also be used to study the interaction between the TC and its large-scale environment (2.2) and air-sea coupling (2.3).

***Analysis of TC effects over a complex terrain: downscaling rainfall signal on La Réunion (CRC, LACy, LE2P).*** Many inhabited areas of the SWIO basin consist in island states

(Mauritius, Seychelles, Comoros and La Réunion) whose size do not exceed 70km. In these areas, the local effects resulting from orographic forcing and the consequences of insularity (land-sea contrast) form an essential component of local climates that cannot be represented realistically by current global climate models due to their coarse resolution. An efficient way to correct for those deficiencies is to use downscaling methods in order to translate large-scale weather patterns into regional or local settings (Morel et al., *Mon. Wea. Rev*., 2014). Evaluating the impact of climate change on the distribution of rainfall in those islands is an important issue for anticipating changes in water resource supply and management. This is particularly true in La Réunion island where the spatial variability of precipitation is extremely high – the annual precipitation amount generally varies from a factor 20 (10 m vs. 500mm) between wetlands, located to the east of the island, and dry lands, located less than 50 km away to the west.

Here, we propose:

1) to rank uncertainties due to the large-scale forcing and the internal variability of the forced regional climate model at fine scale (typically 500m grid spacing) through ensemble simulations performed using the non-hydrostatic WRF model. A focus will be given on TC case studies, a preliminary study (Morel et al., *Mon. Wea. Rev*., 2014) using this protocol demonstrating the reasonable skill of the model to regionalize rainfall amounts associated with TC Anso (January 6$^{th}$, 2001) over La Réunion (1200mm in the elevated regions of the island). Their work was however based on a single simulation. For future work, we plan to perform both regional ensembles, but also to use ensemble lateral forcings derived from NOAA's re-forecasting product (Hamill et al., *Bull. Am. Meteorol. Soc.*, 2013), enabling us to quantify the predictability of localized TC effects.

2) to evaluate the impact of climate change on the distribution of precipitation in La Réunion and surrounding countries through applying downscaling techniques to global climate model outputs from the CMIP5 database. Statistical approaches will be used to address the question of precipitation as a whole, while dynamical approaches (12km ALADIN model, the CNRM-CM5 coupled model with stretched coordinates over La Réunion: cf section 2.2) will be more specifically dedicated to cyclonic precipitation.

### 2.2 Interactions between TCs and their large-scale environment

***Motivation.*** Warm ocean waters (>26°C over 50m depth), large values of low-level vorticity, weak vertical wind shear, high humidity in the lower and mid troposphere, conditional instability of the atmosphere and enough Coriolis force are well-known necessary conditions for storm formation within all tropical basins over the world. It is for example the large increase of the vertical shear during the monsoon that restricts TC genesis to the pre- and post-monsoon seasons in the Northern Indian Ocean. Beyond this seasonal modulation, there is a well-known (but poorly understood) TCs modulation by the MJO and equatorial waves (e.g. Bessafi and Wheeler, *Mon. Wea. Rev*., 2006) and by El Niño over the Indian Ocean. Finally the climate change signal is bound to reflect itself on TCs occurrence and intensity.

***A climatology of categories 4 and 5 tropical cyclones in the south-west Indian Ocean for the 1980-2014 period (MRTE).*** Only a few papers have considered the tropical cyclones activity in the south Indian Ocean (Jury, *Meteorol. Atmos. Phys*., 1993; Kuleshov et al., *Geophys. Res. Lett.*, 2008; Chang-Seng and Jury, *Meteorol. Atmos. Phys.*, 2010). And these authors used best track data which are known, like the historical global tropical cyclone databases, to be questionable in terms of intensity accurate based on the maximum sustained wind (Landsea et al., *Science*, 2006). Therefore, a reanalysis of the cyclones intensity for the SWIO is needed. This kind of study has already been undertaken for the northwestern

Australian basin (Harper et al., *Australian Meteorol. Mag.*, 2008) and the northern Indian Ocean (Hoarau et al., *Int. J. Climatol.*, 2012), specifically for intense cyclones. The cyclones intensity is obtained using the Dvorak (*NOAA Technical Report*, 1984) analysis that needs the thermal infrared satellite pictures to estimate the maximum sustained wind. As there was no Meteosat geostationary satellite covering the whole Indian Ocean until May 1998, it is necessary to use the 4-km infrared imagery resolution of orbiting satellites belonging to National Oceanic and Atmospheric Administration (NOAA) and provided by the National Climate Data Center (NCDC) before that period. The available data allow establishing a climatology of categories 4 and 5 cyclones in the SWIO from summer 1979-1980 onward. In fact, the more intense cyclones are projected to increase in frequency in a warmer climate (IPCC reports). And the results could be compared to those given by the models.

***The maximum potential intensity reached by a tropical cyclone in the Mascarene islands (MRTE).*** The aim of this research would be to estimate the strongest intensity that a tropical cyclone could reach when about to hit the Mascarene islands. The winds and the atmospheric pressures measured since the beginning of the twentieth century show that category 4 cyclones have already hit these islands (La Réunion and Mauritius meteorological data). The available satellite data since 1979 indicate also that the category 4 cyclones have already reached the latitude of Mauritius (20°S) or La Réunion (21°S), but further westward or eastward. However, the thermodynamic conditions existing in the islands vicinity highlight that the maximum potential intensity could be stronger. The maximum potential intensity is defined by the energy available in a given oceanic space and the clouds temperature at the top of TCs (Emanuel, *J. Atmos. Sci.*, 1988). This concept assumes that there are no thermodynamic constraints in the atmosphere and that conditions are almost ideal. To estimate the strongest intensity that a tropical cyclone could reach would be very helpful for the cyclonic crisis actors in the Mascarene islands

***Evolution of cyclonic perturbations and tropical cyclogenesis (LA, LMD).*** Tropical cyclogenesis requires the presence of incipient disturbances, which have to pass through different stages before attaining tropical storm (TS, with sustained wind speed ≥ 18 m $s^{-1}$) or tropical cyclone (TC, with sustained wind speed ≥ 33 m $s^{-1}$) intensity. A typical pre-existing perturbation is an oceanic weather system of organized convection and wind pattern, a few hundred kilometers in diameter, maintaining its identity for 24 hours or more. Such disturbances are relatively common in the Tropics, but only a few intensify and lead to tropical cyclogenesis. The question still remains whether it is possible to identify perturbations that will develop into a TS or a TC, or are large-scale characteristics the main driving factors for such an evolution.

During the Cindy-Dynamo field campaign in October-December 2011, the convectively active phases of the three MJO events were associated to several synoptic low-pressure systems over the Indian Ocean. In relation with the westerly jet that develops during the active phase of MJO, these lows are associated with cyclonic circulation and sustained convective activity. Similar situations are also observed in relation with convectively coupled tropical and equatorial waves, such as easterly Kelvin waves and westerly Equatorial Rossby and Mixed Rossby Gravity waves. Different methods of tracking these incipient vortices in ERA-Interim reanalyses have been developed in LMD and LA, providing databases over 1979-2012 and 1998-2012 (during which geostationary satellite coverage was available overt the Indian ocean). Comparisons with the IBTrACS archive of position and intensity of tropical storms and cyclones validate these results. It is important to note that cyclonic lows are always detected in ERA-Interim before their first notice in IBTrACS, with a lead time up to more than 10 days, which allows to analyze the early phase of tropical cyclogenesis.

We will use these data and, possibly, numerical simulations of specific events with the non-hydrostatic and convection resolving Meso-NH model (see 2.1), to investigate the following questions:

1) How do the different equatorial and tropical waves modulate the kinematic and thermodynamic environment and favor or not tropical cyclogenesis in the SWIO?
2) How do the cyclonic and convective disturbances modulate the larger scale circulation?
3) What are the processes of vortex intensification (convection and/or kinetic energy transfer) and formation of a balanced circulation with a warm core aloft?
4) What are the distinguishing features between vortices that develop into tropical storms or cyclones and those who do not?

***Large scale factors influencing TC intensity over the South-West Indian Ocean (LOCEAN, NIO).*** Due to the inability of dynamical atmospheric models to properly predict cyclone intensity, alternative method shave been developed to forecast the cyclone intensity along the tracks predicted by models. The SHIPS method (Knaff et al. *Weather and Forecasting* 2005) is for example a method that predicts this intensity based on a multiple linear regression to important parameters for the cyclone development such as the large-scale vertical shear, vorticity, tropospheric humidity, vertical stability…). This model was initially developed only for the Northwest Pacific basin and based on parameters derived from the NCEP analysis. In the framework of S. Neetu (National Institute of Oceanography, India)'s PhD, we have extended the SHIPS statistical method to predict the evolution of cyclone intensity over all the oceanic basins, including the southwest Indian Ocean. The method has been improved by using ERA-I input parameters (in general more accurate than NCEP), applied over a longer (1998-2013) period, and through the use of a neural network method that provides better results than the original multiple linear regression method. We use this method in research mode, by applying it along observed past cyclone tracks. A by-product of this method is to evaluate the respective influence of various atmospheric environmental parameters on the intensity. We will apply this method specifically over the south-west Indian ocean and will compare the relative importance of various parameters with other regions.

***Simulation of tropical depressions and extratropical transitions with LMD-Z (LMD).*** An Alliance project is ongoing between LMD and the Department of Earth and Environmental Sciences of the Columbia University (J.P. Duvel and A. Sobel). This project aims to study whether either the US, Europe or both may become more frequently or severely affected by transitioning hurricanes in the future. This joint French-US project carries out and analyze a set of simulations with a state-of-the-art, high-resolution climate model, as well as analyzing a larger set of simulations done with multiple models as part of a larger international project. First AMIP type simulations were done with the LMDZ GCM zoomed over the North Atlantic (0.5°x0.5°) and forced at the boundary by ERA-I. An objective is to analyze changes in the cyclone activity and in potential extratropical transitions in a warmer climate. To this end, similar simulations forced by CMIP5 output instead of ERA-I will be performed. A similar approach could be done in the Indian Ocean, to study in particular the role of large-scale forcing (MJO, ENSO, monsoon) on the cyclone activity.

***Case studies of TC-interaction with its environment with Arome (LACy).*** Idealized simulations and case studies aiming to isolate certain features influencing TC inner-core structure change, such as aspects of the environmental wind shear (Leroux et al., *Mon. Wea. Rev.*, 2013a) or propagating Rossby waves (Leroux et al., *J. Atmos. Sci.*, 2013b) will be conducted from mesoscale models AROME and Meso-NH. Sensivity studies aiming to evaluate the impact of lateral boundary conditions on TC life cycle will also be conducted using different coupling models (Arpege, ECMWF, among others). A field experiment is also envisioned within a few years to better document the environment of TCs and investigate more accurately the ingredients favorable to trigger cyclogenis over the basin (see 2.4 and 2.5 hereafter).

***The impact of climate change on tropical cyclones in the Indian Ocean (CNRM).*** TC climatology over the SWIO has not been as studied as other regions of the earth, mainly due to lack of observations. Since resolution of the general circulation models is higher and higher, direct representation of TCs over this region is becoming possible. A 250-year atmosphere-ocean coupled simulation (1850-2100) will be performed at CNRM-GAME, covering historical period and the RCP8.5 scenario. A stretched configuration of the CNRM-CM5 model will be used for this exercise, allowing a local resolution of under 60 kms over the SWIO. Stretching technology provides a useful alternative to the Arome high resolution model to study how TC climatology in this region can be influenced by large-scale modes. Coupling allows taking the air-sea negative feedback under TCs into account, and should be implemented in long simulations in order to account for all the feedbacks (Daloz et al., *Clim. Dyn.*, 2012). A particular attention will be paid to the TC-MJO link and its possible evolution in a warmer climate. TC-rainfall, a major issue for local populations, will be an important focus of this study since it is expected to vary with global warming (Knutson et al., *Nature Geosci.*, 2010). More than an impact study, this work should provide some useful knowledge on the possible sensitivity of TC-rainfall to climate change.
Calculation of TC cyclogenesis indices (Royer et al., *Clim. Change*, 1998, Nolan et al., *Q. J. R. Meteorol. Soc.*, 2007 and Tippet et al., *J. Clim.*, 2011) will be performed from large-scale fields and comparison with explicit TC-tracked density will be done. Adequacy between the two approaches would be an important result since it may allow investigation of TC activity in low-resolution multi-model ensembles, such as CMIP5 or future CMIP6.

### 2.3 Air-sea interaction below tropical cyclones

***Motivation.*** The passing of a TC over the ocean produces important vertical upward mixing that can induce a sea surface temperature (SST) drop in the 1° - 6°C range (Price, *J. Phys. Oceanogr.*, 1981). By limiting heat and water fluxes toward the atmosphere, such cooling induces a negative feedback on the TC intensity (Shade and Emanuel, *J. Atmos. Sci.*, 1999) and can completely shut down the cyclone if it exceeds 2.5°C under the TC core (Emanuel, *Nature*, 1999). The amplitude of the cooling below Tropical Cyclones is strongly modulated by the oceanic thermal structure (Vincent et al., *J. Geophys. Res.*, 2012) A better representation of air-sea interactions below tropical cyclones is thus essential in order to properly represent the rate of intensification, peak intensity and rate of weakening of modeled TCs (Sandery et al., *Mon. Wea. Rev.*, 2010). With this regard, great efforts are currently underway to couple NWP systems with 1D or 3D ocean models.

***Influence of air-sea interactions on TCs in the SWIO (LACy, LOCEAN).*** The shallow thermocline in the SWIO is thought to enhance the effect of air-sea coupling considerably (e.g. Xie et al., *J. Clim.*, 2002), making this region a good laboratory for air-sea interactions below TCs. This seems to be confirmed by a recent global study in which we demonstrated that the SWIO is one of the regions were extreme (category 4 and more) cyclones prevalence is most affected by interannual variability of the ocean subsurface structure (Vincent et al. *J. Adv. Mod. Earth. Sys*. 2014). In order to assess the impact of air-sea coupling under TCs:

1) LOCEAN has developed a regional coupled ocean-atmosphere model for the tropical Indian Ocean (NOW, for NEMO-Oasis-WRF). This model is able to accurately simulate the main Indian Ocean climatic features at different time scales and small scale phenomenon such as TCs (Samson et al. *J. Adv. Mod. Earth. Sys.* 2014). In order to better understand the effect of coupling on TCs in the SWIO, we will use two complementary strategies. A) The tropical cyclone intensity statistical forecast model described in section 2.2 will be used to assess the intensity forecast improvement brought by including oceanic information. B) We will also analyse the existing coupled high-resolution experiments and perform sensitivity experiments in order to better understand the role of air-sea coupling on SWIO TCs intensification. Preliminary results suggest that air-sea coupling in this region reduces by ~30% the number of TCs and by ~20% their intensity (Samson et al. *in prep*).

2) LACy will perform coupled simulations of TC cases that recently developed over the SWIO (e.g., Dumilé, Giovanna, Felleng and Béjisa). The impact of ocean–atmosphere coupling on TC simulations is currently being investigated from 1-D coupled simulations performed with models Meso-NH, ALADIN- and Arome-Indien. Emphasis will then be put on coupling with a full, 3D, ocean model through the development and implementation of Arome-Réunion coupled to NEMO. Ultimately, the goal is to develop a fully coupled atmosphere (Arome-Indien, Méso-NH)–wave (WaveWatch3)–ocean (NEMO) modeling system integrating all air–sea interaction processes, as well as the effects of sea spray, which is known to also significantly influence air–sea momentum and heat fluxes.

***Detailed processes of ocean response to cyclone forcing (LOCEAN).*** Tropical cyclones generate large inertial oscillations in the mixed layer. Part of the associated kinetic energy is used to generate mixing and cool the SST (the TC “cold wake”). But part of this energy also radiates into the interior ocean under the form of internal gravity waves. It is important to understand better the controlling factor of the ratio that is used locally (and contributes to air-sea interactions) to the part that contributes to non-local abyssal mixing and to the oceanic general circulation. Previous observations from the CIRENE cruise (Vialard et al., *Bull. Am. Meteorol. Soc.*, 2009) were used to characterize the local energy transfer to near inertial internal waves and to estimate the vertical mixing and heat flux associated with internal waves following the passage of the Dora tropical storm, providing rare observations of these processes (Cuypers et al., *J. Geophys. Res.*, 2013). In our research project proposal, we plan to use numerical modelling (using the idealized TC forcing used by Vincent et al., *J. Geophys. Res.*, 2012) to provide a large-scale context that will allow to generalize our observational results, and to study the energy cycle associated to internal waves under cyclones in more details.

***Monitoring austral and cyclonic swells from seismic data analysis (LGSR).*** The laboratoire Géoscience Réunion (LGSR) develops researches in the field of environmental seismology. In addition of imaging the earth's deep structures from seismic signals, we use seismic stations to analyse the microseismic noise allowing to investigate the swell in the Indian ocean. Swell activity in the ocean generates indeed microseisms that are classically split into primary and secondary microseisms that result from different physical processes. The primary microseisms have the same periods as the ocean swells (between 8 and 20s) and are generated through interaction of swell with the sloping sea floor in coastal areas. Secondary microseisms, that dominate the seismic noise worldwide, have the double frequency of ocean waves (typically between 3 and 10 s). They have been described for a long time as generated by a depth-independent-second-order pressure fluctuation that occurs through the interference of waves of similar periods travelling in opposite directions.

Analyzing seismic records allows therefore to characterize (in amplitude, period and direction) the swell approaching the coast (for instance along the coasts of La Réunion island) but also to locate the remote storms (as for example in the austral ocean). Our recent field experiences combine terrestrial and ocean bottom observations:

1) we deployed in 2011-2014 seismic stations on La Réunion coastal areas to quantify the austral and cyclonic swells,

2) we also deployed in 2012-2013 (in the frame of the RHUM-RUM experiment www.rhum-rum.net) a large-scale network (2000x2000 km2) of ocean-bottom seismometers that provided the first opportunity to track several cyclones from the bottom of the ocean through analysing microseismic and hydroacoustic noise generated by the cyclone propagating over the seismic network at the sea surface.

### 2.4 Instrumentation

***Aeroclipper development (LMD, CNES, LA, LACy).*** Following the NABI/ARCEO proposal (J. P. Duvel, 2014), the development of the Aeroclipper for cyclone application is scheduled to start in 2015. This project concerns a new Aeroclipper instrument designed to provide in situ surface observations in the vicinity and inside tropical cyclones. The aim is to:

- Develop Aeroclipper prototypes as a cost effective instrumentation designed to be sufficiently precise for scientific measurement and usable in an eventual operational framework;
- Develop a deployement strategy and the data processing;
- Use this new instrument during a scientific campaign and demonstrate that the measurements have a positive impact on the monitoring and the forecasting of TCs.

The Aeroclipper is complementary for both Aircraft and UAV data since it gives direct in situ quasi-Lagrangian measurement in the surface layer (0-50m) along trajectories converging toward the TC eye. Also, and most importantly, the Aeroclipper is able to monitor surface atmospheric parameters in the eye continuously and in real-time during several days (Duvel et al, *Bull. Am. Meteorol. Soc.*, 2009). There is no doubt that the Aeroclipper is the only existing instrument that could give a systematic and relatively affordable mean to verify and/or recalibrate the Dvorak technique for all the cyclonic basins. Simulations of the Aeroclipper behavior in mesoscale model simulations of cyclones DINA and DORA (in cooperation with LACy, Météo-France) shows that:

- The aeroclipper indeed converge toward the eye of the cyclone from any starting position of the domain;
- The pressure measured in the eye precisely follows the minimum pressure. This confirms that the Aeroclipper is able to follow rapid evolution of the minimum pressure and thus of the cyclone intensity;
- The aeroclipper also gives a good estimate of the maximum wind during the convergence phase.

The main scientific objectives of the project are:

- To measure the surface pressure in the eye and derive near real time monitoring of the cyclone intensity, including rapid intensification or dissipation of the cyclone.
- To evaluate the improvement in the forecast of both cyclone trajectory and intensity given by the assimilation of Aeroclipper continuous time series of surface parameters.
- To derive for the first time a series of surface measurements in trajectories converging toward the eye of a cyclone. This will give unique opportunity to derive:
    - o The structure of the surface wind, in particular the ratio between the tangential and the radial wind at the surface.

o The variation of the low-level moist enthalpy of the surface air converging toward and into the cyclone eye. Air-sea fluxes of moist enthalpy is the main energy source of tropical cyclones, are not well known. The evolution of pressure, temperature and humidity measured during radial trajectory of an Aeroclipper toward the cyclone center will provide valuable information.

- To measure the low-level moist enthalpy in the eye. This low-level moist enthalpy may supplement the energy coming from the outer core of the cyclone and give “superintensity” (Persing and Montgomery, *J. Atmos. Sci.*, 2003), i.e. cyclone exceeding their Potential Intensity, as defined by Rotunno and Emanuel (*J. Atmos. Sci.*, 1987).
- To study the evolution of the surface dynamics into the eye, especially during transition phases, as was observed in DORA in 2007.
- To derive surface air circulations and turbulent heat fluxes during the cyclogenesis. In particular, combining satellite imagery and Aeroclipper in situ measurements could give information on low-level vortices generated by vorticity convergence into different convective updrafts during the cyclone genesis phase (see e.g. Montgomery et al., *J. Atmos. Sci.*, 2006).
- To evaluate numerical model simulations for the above parameters.

While this development was proposed for a first experiment in the North Atlantic Ocean, Aeroclippers could be also deployed in the Indian Ocean in the framework of an international campaign, for example in link with the international program Year of the Maritime Continent (YMC) planned in 2017-2018.

### 2.5 Organization of an international Field Experiment in the SWIO basin

Though some improvements have been made in the comprehension of physical processes at play within TC developing in the SWIO basin, the road ahead is probably more challenging. Researchers are advancing the science of inner core dynamics and other influences on intensity change, but there are still important challenges understanding all physical processes and implementing these advances into operational guidance. On the positive side, important progress is being made in tropical cyclone observation and the results of that progress is starting to reach forecasters in real-time. The ability to gather high quality observations within and in the vicinity of tropical cyclones nevertheless remain an important issue, especially over the SWIO basin where the observation network is currently extremely limited. Getting such datasets is key to better understand the physical processes at play within these systems, as well as to objectively evaluate the performance of new high-resolution systems to be soon deployed throughout all cyclonic basins. In this framework, the use of Aeroclippers will give an unprecedented opportunity to evaluate precisely the Dvorak approach above the South Indian Ocean. Other scientific issues related to the Aeroclipper are listed in the section 2.4 above.

With this regard, the French research community has started to work on the organization of a field experiment in the SWIO basin at the initiative of LACy. A first proposal has been submitted to EU through the FEDER POCT program in order to reinforce the radiosounding network over the basin and to deploy additional surface and GPS stations in Madagascar, Mautitius and Mayotte during two cyclonic seasons (2017 & 2018) in order to evaluate the benefit for numerical simulation and forecast verification. A support of WMO is also expected and contacts with the US community have also been initiated - the possible participation of US research aircrafts and scientists (to collect high resolution intensity and microphysical over a large area spanning from the Eastern Coast of Africa to Rodrigues Island), will be discussed during the upcoming International IWTC to be held in December in South Korea. An important outcome of the current project would be to create synergies between French laboratories and scientists interested in TC studies so as to support and strengthen this ongoing field experiment initiative.

## B. Plan de recherche et calendrier de réalisation

Le projet KOUDVAN est un projet resserré, sur un an, destiné à organiser un workshop de coordination unique (vraisemblablement en région parisienne ou toulousaine pour minimiser les coûts financiers) qui devrait nous permettre de dégager nos priorités scientifiques dans le but de répondre à des appels d'offre régionaux (région Réunion,) nationaux (type ANR) voire européen. Certaines thématiques sont en partie déjà initiées et ont été rendues possibles par des financements LEFE antérieurs (VOASSI et CINDY-Dynamo).

## C. Résultats attendus

Le projet de recherche envisagé devrait permettre d'améliorer la connaissance des processus influençant l'intensification des cyclones tropicaux. Certaines composantes du projet sont relativement appliquées et répondent à des attendus sociétaux forts, comme l'amélioration de la prévision de l'intensité des cyclones (LACy, LOCEAN), ou le downscaling des précipitations et du gisement solaire sur la Réunion (LACy, CRC, LE2P).

## D. Ressources nécessaires à la réalisation du projet

La totalité du budget est dédiée à l'organisation d'un workshop de coordination : notre demande porte donc exclusivement sur des frais de mission. Ceux-ci ont été calculés de manière réaliste en prenant l'hypothèse d'un workshop organisé en région parisienne auquel assistent tous les participants du projet (base de calcul : deux nuits d'hôtel à Paris pour chaque participant, 300€ (trois nuits en métropole pour les Réunionnais) ; aller-retour Réunion-Paris (avion) : 1000€ ; aller-retour Toulouse-Paris (avion) : 150€ ; aller-retour Dijon-Paris (TGV) : 100€ ; coordination + organisation du workshop : 500€). La répartition par labo est donc : CNRM et LA, 450€ chacun ; CRC-Biogéosciences, 800€ + 500€ de coordination soit 1300€ ; LACy, 9000€ dont 4500€ financés en fonds propres soit 4500€ demandés ; LE2P, 3000€ ; LGSR : 6000€ dont 3000€ financés en fonds propres soit 3000€ demandés. L'organisation du workshop ne génère pas de surcoût pour les laboratoires de la région parisienne (hors frais d'organisation / coordination). **La demande totale est donc de 12700€ sur une année.**

## E. Co-financements acquis ou soumis (hors INSU)

Une partie des actions scientifiques présentées sont financées sur différents programmes de recherche régionaux ou nationaux, ou sur les ressources propres des laboratoires. La tenue d'un workshop de coordination nécessite des moyens limités (de l'ordre de 13k€) permettant de couvrir les missions des participants et leur accueil en métropole.

**TABLEAU RECAPITULATIF DU BUDGET, A REMPLIR OBLIGATOIREMENT POUR CHACUNE DES ACTIONS CONCERNEES, EN COHERENCE AVEC LE TABLEAU DU FORMULAIRE EN LIGNE**

| | | coût total | Cofinancements (préciser la source pour chaque case concernée) | | Total demande INSU (préciser l'action concernée en cas de projet multi-actions) |
|---|---|---|---|---|---|
| | | | Acquis année 1 | Demandés Année 1 | demande INSU année 1 |
| Moyens nationaux | | | | | |
| Personnel permanent | | | | | |
| Personnel temporaire | | | | | |
| Consommables | | | | | |
| Petit équipement *(<15k€)* | | | | | |
| Missions | | 20200 | 7500 | 12700 | 12700 |
| Analyses Publications | | | | | |
| Equipement > 15 k€ | | | | | |

**<u>Récapitulatif (doivent correspondre aux cases du tableau du formulaire informatisé)</u>**

Total cofinancements acquis : 7500€
Total cofinancements demandés : 12700€
Total demande INSU : 12700€

# F. Valorisation des travaux antérieurs

**Références bibliographiques de l'équipe sur des thématiques liées au projet depuis 2012.** Les noms des participants au projet KOUDVAN apparaissent en rouge.

## ARTICLES


Callaghan, A.H., B. Ward and J. Vialard, 2014: Mixing Layer Dynamics in the Upper Indian Ocean: Influence of Surface Forcing on Near-Surface and Mixing Layer Turbulence in the Tropical Indian Ocean, *Deep See Reasearch I,* online.

Cuypers, Y., X. Le Vaillant, P. Bouruet-Aubertot, J. Vialard, M. McPhaden, 2013: Tropical storm-induced near inertial internal waves during the Cirene experiment: energy fluxes and impact on vertical mixing, J. Geophys. Res., 118, 358-380.

Daloz, A.-S., F. Chauvin et F. Roux, 2012: Impact of the configuration of stretching and ocean-atmosphere coupling on tropical cyclone activity in the variable-resolution GCM ARPEGE. Clim. Dyn., 39, 2343-2359 (doi : 10.1007/s00382-012-1561-3).

Daloz, A.-S., F. Chauvin et F. Roux, 2014 : Impact of ocean-atmosphere coupling in future changes in the north Atlantic cyclone activity as simulated by the high-resolution climate model ARPEGE. *J. Climate*, en révision (avril 2014).

Daloz, A.-S., F. Chauvin, K. Walsh, S. Lavender, D. Abbs et F. Roux, 2012 : The ability of general circulation models to simulate tropical cyclones and their precursors over the North Atlantic main development region. *Clim. Dyn.,* **39**, 1559-1576 (doi : 10.1007/s00382-012-1290-7).

Duvel, J. P., H. Bellenger, G. Bellon and M. Remaud, 2013: An event-by-event assessment of tropical intraseasonal perturbations for general circulation models, *Climate Dynamics*, 40, 857-873, doi: 10.1007/s00382-012-1303-6.

Duvel, J. P., 2014: Tropical depressions, cyclogenesis and the MJO over the Southern Indian Ocean. Submitted to *Mon. Wea. Rev.*

Jolivet, S., F. Chane Ming, D. Barbary et F. Roux, 2013 : A numerical study of orographic forcing on TC Dina (2002) in South West Indian Ocean. *Ann. Geophys.*, **31**, 107-125. (doi: 10.5194/angeo-31-107-2013).

Jourdain, N. C., M. Lengaigne, J. Vialard, G. Madec, C.E. Menkes, E.M. Vincent, G. Samson, S. Jullien et B. Barnier, 2013: Observation-based estimates of ocean mixing inhibition by heavy rainfall under tropical cyclones, J. Phys. Oceanogr., 43, 205-221.

Jourdain, N. C., N. Barnier, N. Ferry, J. Vialard, C.E. Menkes, M. Lengaigne and L. Parent, 2014: Tropical cyclones in two atmospheric (re)analyses and their response in two oceanic reanalyses, Ocean Modelling, 73, 108-122.

Hoarau, K., J. Bernard et L. Chalonge, 2012: Intense tropical cyclone activities in the northern Indian Ocean. *Int. J. Climatol.*, **32**, 1935-1945. (doi : 10.1002/joc.2406)

Leroux, M.-D., N. E. Davidson, Y. Ma, et J. D. Kepert, 2013a: Prediction and diagnosis of the motion and rapid intensification of Typhoon Sinlaku during TCS08 (Tropical Cyclone Structure Experiment, 2008), *Mon. Wea. Rev.*, 141, 1413-1436

Leroux, M.-D., M. Plu, D. Barbary, F. Roux et P. Arbogast, 2013b: Dynamic and physical processes leading to tropical cyclone intensification in relation with upper-level forcing. *J. Atmos. Sci.*, **70**, 2547–2565. (doi : 10.1175/JAS-D-12-0293.1)

Meetoo, C., et F. Roux, 2014 : Tropical cyclogenesis in the southwestern Indian Ocean : Environmental conditions and intraseasonal index. *Mon. Wea. Rev.*, en révision (mai 2014)

Morel, B., B. Pohl, Y. Richard, B. Bois et M. Bessafi (2014) Regionalizing rainfall at very high resolution over La Réunion island using a regional climate model. *Mon. Wea. Rev.*, 142, 2665-2686. (doi:10.1175/MWR-D-14-00009.1)

Neetu, S., M. Lengaigne, E.M. Vincent, J. Vialard, G. Madec, G. Samson, M.R. Ramesh Kumar and F. Durand, 2012: Influence of oceanic stratification on tropical cyclones-induced surface cooling in the Bay of Bengal, J. Geophys. Res., 117, doi:10.1029/2012JC008433.

Pohl, B., et J. Crétat, 2014: On the use of nudging techniques for regional climate modeling: Application for tropical convection. *Clim. Dyn.*, 43, 1693-1714. (doi:10.1007/s00382-013-1994-3)

Samson, G., S. Masson, M. Lengaigne, M.G. Keerthi, J. Vialard, S. Pous, G. Madec, N. Jourdain, S. Julien, C. Menkes and P. Marchesiello, 2014: The NOW regional coupled model: application to the tropical Indian Ocean climate and tropical cyclones activity, *J. Adv. Mod. Earth Sys.,* online.

Vincent, E., K. Emanuel, M. Lengaigne, J. Vialard and G. Madec, 2014: Influence of upper-ocean stratification interannual variability on Tropical Cyclones intensity, *J. Adv. Mod. Earth Sys.,* online.

Vincent, E., M., G. Madec, M. Lengaigne, J. Vialard and A. Koch-Larrouy, 2013: Influence of Tropical Cyclones on sea surface temperature seasonal cycle and ocean heat transport, Clim. Dyn., 41, 2019-2038.

Vincent, E., M., M. Lengaigne, G. Madec, J. Vialard, G. Samson, N. Jourdain, C. E. Menkes and S. Jullien, 2012: Processes setting the characteristics of sea surface cooling induced by Tropical Cyclones, J. Geophys. Res., 117, C02020, doi:10.1029/2011JC007396.

Vincent, E., M., M. Lengaigne, J. Vialard, G. Madec, N. Jourdain, and S. Masson, 2012: Assessing the oceanic control on the amplitude of sea surface cooling induced by Tropical Cyclones, J. Geophys. Res., 117, doi:10.1029/2011JC007705.

## CONFERENCES

Bousquet O. et co-auteurs, 2014: A new operational convection-permitting NWP system for tropical cyclone forecasting in the SW Indian Ocean. 31st Conference on Hurricanes and Tropical Meteorology, 30 Mar-4 Apr, San Diego, USA. (https://ams.confex.com/ams/31Hurr/webprogram/Paper244069.html)

Duvel, J. P., and R. Roca, 2014: Synoptic perturbations in MJO active phases during the Cindy-Dynamo experiment. 31st Conference on Hurricanes and Tropical Meteorology, 30 Mar-4 Apr, San Diego, USA.

Duvel, J. P., 2014: Aeroclipper surface measurements under convective systems and in tropical cyclones. Invited. Symposium on Progress of the MJO research through the field campaigns, Hokkaido University, 23 -25 Jul, Sapporo, Japan.

Duvel, J. P., and R. Roca, 2014: Tropical depressions and the MJO over the Indian Ocean. Invited. Conference of the Asia Oceania Geosciences Society. 28 Jul-01 Aug, Sapporo, Japan.

Faure G., O. Bousquet, S. Bielli, D. Barbary et P. Chambon, 2014: Météo-France next generation NWP systems for tropical overseas territories. World Weather Open Science Conference 2014, Aug. 16-21, 2014, Montréal, Canada (http://wwosc2014.org/welcome_f.shtml)

Leroux, M.-D., M Plu, et F. Roux, 2014 : On the sensitivity of TC intensification under upper-level trough forcing. *31st Conference on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc.*, San Diego (Ca., USA), 31 mars – 4 avril 2014.

Meetoo, C., et F. Roux, 2012 : Tropical cyclogenesis conditions in the South-Western Indian ocean. *10th international Conference on Southern Hemisphere Meteorology and Oceanography*, Nouméa (Nouvelle-Calédonie), 23-27 avril 2012.

Meetoo, C., and F. Roux, 2013 : Tropical Cyclogenesis Conditions in the South-Western Indian Ocean, *European Geosciences Union General Assembly 2013*, Vienne (Autriche), 07– 12 Avril 2013

Meetoo, C., et F. Roux, 2014 : Tropical Cyclogenesis Conditions over the South-Western Indian Ocean. *31st Conference on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc.*, San Diego (Ca., USA), 31 mars – 4 avril 2014.

Plu, M., D. Barbary, C. Barthe, N. Bigjee, F. Bonnardo, C. Bovalo, F. Chane-Ming, F. Chauvin, G. Faure, C. Ibrahim, M.-D. Leroux, A. Piron, H. Quetelard, A. Rechou, F. Roux, 2012 : Research activities at la Réunion regarding the intensification of tropical cyclones and their impacts. *10th international Conference on Southern Hemisphere Meteorology and Oceanography*, Nouméa (Nouvelle-Calédonie), 23-27 avril 2012.

Roux, F., 2011 : Cyclogenetic conditions in the south-west Indian ocean 2004-2010. *2011 International Workshop on Typhoon and Flood*, Taipei (Rep. de Chine, Taiwan), 23-24 Juin 2011.

Roux, F., et M. Plu, 2012 : Tropical cyclone research in France. *Indo-French Megha-Tropiques science meeting 2012 (CNES & ISRO)*, Bengaluru (Inde), 17-19 décembre 2012.

**Liste des contrats obtenus au cours des quatre dernières années (en lien direct avec le projet) :**

- ANR SPICy (2014): Système de prévision des inondations côtières et fluviales en contexte cyclonique - porteur BRGM Orléans (650 k€ total dont ~ 200 k€ pour LACy et MF Réunion)

- Programme régional "Recherche et Innovation 2012-2013", Région Réunion: Acquisition d'un radar nuage pour l'observation de la microphysique des précipitations à La Réunion (120 k€).

- Projet Franco-Indien CEFIPRA (2013-2016, 120k€): “Air-sea interactions under tropical cyclones in the Bay of Bengal”. PI: M. Lengaigne (LOCEAN, Paris).

- Le LE2P a en outre deux bourses doctorales financées par la région Réunion sur la désagrégation du climat sur le sud-ouest de l'océan Indien (une en collaboration avec le CRC, l'autre avec l'ICTP, Triste, Italie).

**Annexe : Récapitulatif des personnes contribuant au projet**

| Laboratoire | Nom | % | | Thématique scientifique |
|---|---|---|---|---|
| **CNRM-GAME** (0.3 ETP) | F Chauvin | 30 | IR Meteo-France | Impact of climate change on TCs |
| **CRC-Biogéosciences** (0.6 ETP) | B Pohl | 35 | CR1 CNRS | Downscaling rainfall and TC effects |
| | Y Richard | 25 | PR (uB) | Geostatistics |
| **LA** (0.3 ETP) | F Roux | 30 | PR (UPS) | Tropical cyclogenesis |
| **LACy** (1.6 ETP) | O Bousquet | 30 | CR1 MEDDE | Remote sensing observations & numerical modeling, field work |
| | C Barthe | 20 | CR1 CNRS | Numerical modeling |
| | MD Leroux | 30 | IR Meteo-France | TC core dynamics |
| | D Barbary | 30 | IR Meteo-France | Numerical modeling and Ocean-Atmosphere interactions |
| | D Mekies | 30 | IR Meteo-France | Numerical modeling & data assimilation |
| | S Bielli | 20 | IR2 CNRS | Numerical modeling & data assimilation |
| **LE2P** (0.6 ETP) | B Morel | 30 | MDC (UR) | Downscaling rainfall, solar radiation and TC effects |
| | M Bessafi | 30 | PR (UR) | Downscaling rainfall, solar radiation and TC effects |
| **LGSR** (0.8 ETP) | G Barruol | 20 | DR2 CNRS | Cyclonic swells |
| | F Fontaine | 20 | MdC (UR) | Cyclonic swells |
| | E Cordier | 20 | IE (UR) | Air-Sea interactions |
| | C Davy | 20 | doctorante (UR) | Observations (ocean) |
| **LOCEAN** (0.5 ETP) | J Vialard | 20 | DR2 IRD | Air-sea interactions, effect of large scale |
| | M Lengaigne | 5 | CR1 IRD | Air-sea interactions, effect of large scale |
| | Y Cuypers | 5 | MdC (Paris 6) | Oceanic mixing below TCs |
| | P Bouruet-Aubertot | 5 | Prof. (Paris 6) | Oceanic mixing below TCs |
| | S Neetu | 20 | PhD (NIO, India) | Air-sea interactions, effect of large scale |
| **LMD** (0.6 ETP) | J-P Duvel | 40 | DR2 CNRS | LMDZ simulation<br>Aeroclipper development |
| | L Guez | 20 | IR CNRS | LMDZ simulation |
| **MRTE** (0.3 ETP) | K Hoarau | 30 | MdC (UCP) | Climatology and maximum intensity of TCs |