

## 2.5 Intensity change: External influences

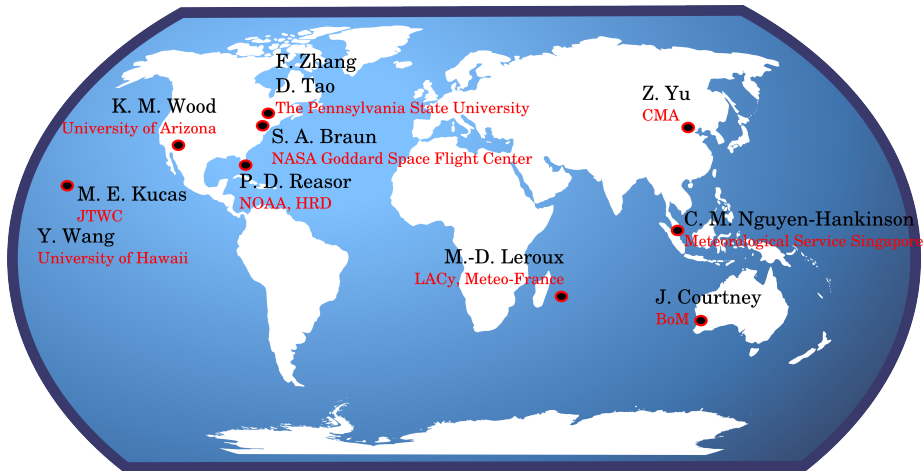
**Marie-Dominique LEROUX**

**Laboratoire de l'Atmosphère et des Cyclones (LACy)**  
(CNRS – Météo-France – Université de La Réunion)  
Saint Denis, La Réunion, France

1-10 December 2014, Jeju, Republic of Korea



# Working group



# OUTLOOK

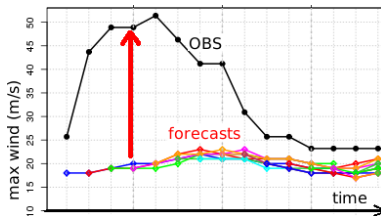
- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Motive

- Aim of the talk: report new advances and shortcomings in the matter of **TC intensity change under external forcing (forecasting and research perspectives)**. *Internal influences will be discussed in the next talk - structure changes in topic 4.1*
- Final objective: define suitable research routes to improve the prediction of TC intensity change.



# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# IWTC-VII highlights

Role of the SAL on intensity change (in the NATL basin)

Disagreement between studies

# IWTC-VII highlights

## Role of the SAL on intensity change (in the NATL basin)

Disagreement between studies

A spectrum of shear values and TC intensities that permit continued intensification (contrary to conventional wisdom)

- Empirical MPI - observational research ([Zeng et al., 2007](#)): incorporates the negative effects of storm motion and vertical shear (dynamic + thermodynamic controls)
- Ventilation index - theoretical framework ([Tang and Emanuel, 2010, 2012a](#))



# IWTC-VII highlights

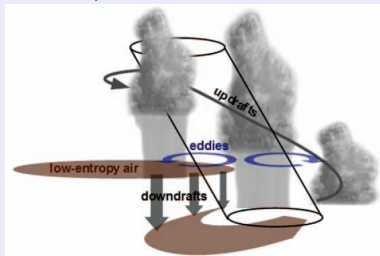
## Mechanisms for inner-core ventilation (entrainment of low-entropy air from the environment under vertical shear)

- (i) downdrafts outside the eyewall drying the inflowing BL and
- (ii) inward eddy fluxes (e.g., through VRWs) of low  $\theta_e$  air  
(Tang and Emanuel, 2010)

# IWTC-VII highlights

## Mechanisms for inner-core ventilation (entrainment of low-entropy air from the environment under vertical shear)

- (i) downdrafts outside the eyewall drying the inflowing BL and  
(ii) inward eddy fluxes (e.g., through VRWs) of low  $\theta_e$  air  
(Tang and Emanuel, 2010)
- pathway to vortex weakening (Riemer et al., 2010; Tang and Emanuel, 2012a):



relative shear flow asymmetries import low  $\theta_e$  air towards the TC core at mid levels where it excites downdrafts that flush the inflow layer with low  $\theta_e$  air, which is then taken into downstream updrafts. Such processes reduce the eyewall buoyancy and convection and thus the storm intensity.

# IWTC-VII highlights

## Rapid Intensification (RI)

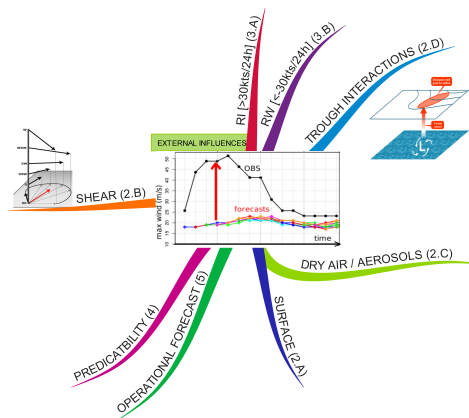
- Composite study in the NATL and WNP (Hendricks et al., 2010): few significant differences between the LS environments of intensifying and RI TCs.
- RI predominantly influenced by internal dynamics?

## IWTC-VII recommendations

- improving the understanding of the impact of various environmental parameters
  - VWS, RH, SST and OHC, outflow-layer interactions with the environment
  - water vapor advection, dust, topography, and BL fluxes
- research into predictability limits for intensity forecasting

# Outlook

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming



# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - **Surface impacts**
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Oceanic impacts

## Role of SSTs

Weakening TCs have lower SSTs than strengthening TCs in the WNP (Shu et al., 2014)

# Oceanic impacts

## Role of SSTs

Weakening TCs have lower SSTs than strengthening TCs in the WNP (Shu et al., 2014)

Changes in the SST field near the TC can be as important as the absolute value of SST

**Upper-ocean stratification** can modulate the sea surface cooling (induced by vertical mixing) by up to one order of magnitude (Vincent et al., 2014).

E.g.: In the Bay of Bengal, surface cooling is about 3 times larger during the pre-monsoon than during the post-monsoon season due to seasonal changes in oceanic stratification rather than to differences in TC wind energy input (Neetu et al., 2012).



# Oceanic impacts

## Role of SSTs

Weakening TCs have lower SSTs than strengthening TCs in the WNP (Shu et al., 2014)

Changes in the SST field near the TC can be as important as the absolute value of SST

**Upper-ocean stratification** can modulate the sea surface cooling (induced by vertical mixing) by up to one order of magnitude (Vincent et al., 2014).

E.g.: In the Bay of Bengal, surface cooling is about 3 times larger during the pre-monsoon than during the post-monsoon season due to seasonal changes in oceanic stratification rather than to differences in TC wind energy input (Neetu et al., 2012).

↪ More oceanic influences: topic 4.4

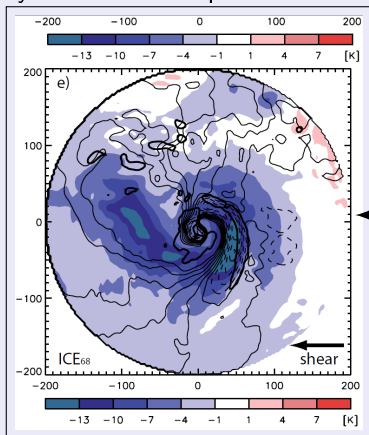
# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - **Shear impacts**
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Shear impacts

## Robustness of the low-level ventilation process (Riemer et al., 2010)

- verified for different physics/physics parameters/vortex strengths (Riemer et al., 2013) - correlation between moist entropy depression underneath the eyewall and subsequent TC weakening.



$$\Theta'_e(r, \lambda) = \Theta_e(r, \lambda) - \overline{\Theta_e}(r)$$

averaged over the lowest 1km  
and from 4-9h

# Shear impacts

## Robustness of the low-level ventilation process (Riemer et al., 2010)

- verified for different physics/physics parameters/vortex strengths (Riemer et al., 2013) - correlation between moist entropy depression underneath the eyewall and subsequent TC weakening.
- environmental air can be entrained into the inner core in the limit of strong shear and weak vortex intensity - sheared mature TCs are generally protected from environmental air intrusions (Riemer and Montgomery, 2011)

# Shear impacts

## Robustness of the low-level ventilation process (Riemer et al., 2010)

- verified for different physics/physics parameters/vortex strengths (Riemer et al., 2013) - correlation between moist entropy depression underneath the eyewall and subsequent TC weakening.
- environmental air can be entrained into the inner core in the limit of strong shear and weak vortex intensity - sheared mature TCs are generally protected from environmental air intrusions (Riemer and Montgomery, 2011)

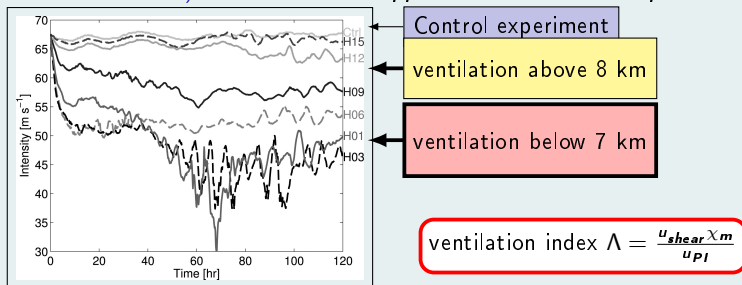
## Other path for VWS effect on TC intensity: upward flux of high-entropy air (Gu et al., 2014)

Fluxes associated with shear-induced updraft, outside the eyewall, from the boundary layer into mid levels, can weaken the radial gradient of moist entropy across the eyewall, and thus weaken the storm.

# Shear impacts

## Sensitivity to the vertical location of ventilation

- greatest impact when ventilation placed at middle to lower levels (Tang and Emanuel, 2012b) - ventilation at upper levels has little impact on intensity



- 850hPa-10m shear has more impact on TC intensification over the WNP in the 2000-2006 period (Shu et al., 2013)
- 700-1000hPa or 850-1000hPa shear averaged in a 5-9 degree annulus: highest correlation with the 24-h lagged TC intensity over the WNP in the 1981-2010 period (Wang et al., 2014)

# Shear impacts

## Sensitivity to the vertical location of ventilation

- greatest impact when ventilation placed at middle to lower levels (Tang and Emanuel, 2012b) - *ventilation at upper levels has little impact on intensity*
- 850hPa-10m shear has more impact on TC intensification over the WNP in the 2000-2006 period (Shu et al., 2013)
- 700-1000hPa or 850-1000hPa shear averaged in a 5-9 degree annulus: highest correlation with the 24-h lagged TC intensity over the WNP in the 1981-2010 period (Wang et al., 2014)

## Is the VWS effect basin-dependent?

The low-level shear is no longer important when a similar analysis is conducted over the NATL basin (Wang, pers. comm.)

→ Differences in other environmental conditions need to be investigated in future studies

# Shear impacts

## Methodology to compute the VWS

- fact: traditional two-level approach oversimplified to account for the effect of VWS on TC intensity change
- [Velden and Sears \(2014\)](#) derives the VWS from two mass-weighted layer-mean wind fields; one upper-tropospheric and one lower-tropospheric (//CIMSS)
- correlation coefficient of lagged TC intensity change with shear explains 30% the variance for NATL TCs



# Shear impacts

## Methodology to compute the VWS

- fact: traditional two-level approach oversimplified to account for the effect of VWS on TC intensity change
- Velden and Sears (2014) derives the VWS from two mass-weighted layer-mean wind fields; one upper-tropospheric and one lower-tropospheric (//CIMSS)
- correlation coefficient of lagged TC intensity change with shear explains 30% the variance for NATL TCs

## Need for a comprehensive VWS diagnostic?

take into account the total vertical profile of the ambient wind:

to include both the dynamic and thermodynamic effects of shear on TC intensity change

# Shear impacts

## Sensitivity to the direction of shear

**Easterly shear has weaker effects** than westerly shear:

- part of the easterly shear could be offset by the beta-induced northwesterly shear ([Zeng et al., 2010](#))
- westerly shear appears to promote the intrusion of dry environmental air in weakening TCs over the WNP ([Shu et al., 2014](#))
- NCEP reanalysis data from 41 NATL storms exhibited stronger westerly winds (and VWS) above weakening storms ([Braun, 2010](#))

# Shear impacts

## Sensitivity to the direction of shear

**Easterly shear has weaker effects** than westerly shear:

- part of the easterly shear could be offset by the beta-induced northwesterly shear (Zeng et al., 2010)
- westerly shear appears to promote the intrusion of dry environmental air in weakening TCs over the WNP (Shu et al., 2014)
- NCEP reanalysis data from 41 NATL storms exhibited stronger westerly winds (and VWS) above weakening storms (Braun, 2010)

## VWS affects the timing and rate of TC intensification

- influences the spatial distribution of convection and the positive feedback between diabatic heating and the TC vortex primary circulation.
- the larger the vertical wind shear, the farther and weaker the convection from the TC center, which leads to a weakening TC vortex circulation and more time for the onset of RI (Tao and Zhang, 2014a,b) - [convection-permitting ensemble simulations]

# Shear impacts

## Intensification cases under strong shear forcing

- What governs the radial distribution of convection in sheared storms remains an active area of research.
- Downshear redevelopment of a new circulation: preceded the RI of TS Gabrielle (2001) and Hurricane Irene (1999) (Molinari and Vollaro, 2010; Nguyen and Molinari, 2012). The shear and motion induced convective asymmetry focused radially inside the max winds, where heating can most effectively intensify the vortex (Nolan et al., 2007; Vigh and Schubert, 2009; Rogers et al., 2007).
- Competition between the weakening influence of ventilation through downward transport of low-entropy air into the BL by convective downdrafts (Riemer et al., 2010, 2013) and the intensifying role of enhanced heat and moisture fluxes from the ocean (Molinari et al., 2013).

# Shear impacts

## Testing the hypotheses for shear-induced intensity change

The TC in shear Experiment is part of the overarching Intensity Forecasting EXperiment IFEX (Rogers and coauthors, 2013):

[http://www.aoml.noaa.gov/hrd/HFP2014/HFP\\_2014.pdf](http://www.aoml.noaa.gov/hrd/HFP2014/HFP_2014.pdf)

Purpose: sample the TC during distinct phases of its interaction with VWS; measure kinematic and thermodynamic fields with the azimuthal and radial coverage necessary to test the hypotheses.

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - **Relative humidity/aerosols impacts**
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Dry air impacts

## Dry air intrusion into the storm core

- **A tilted TC is more vulnerable to dry air** (Tao and Zhang, 2014a,b)
- In moderate-sheared environments, dry air is able to penetrate the TC core
- In low-sheared environments, **dry air may slow intensification only when it is located very close to the vortex core at early times** (Braun et al., 2012) - [idealized simulations with no mean flow]
- When a moist envelope is present in the inner-core, the surrounding dry air has no deleterious impact on storm intensity
- (in the NH) **Dry air located to the right of the VWS direction is detrimental** to TC development because it is subsequently advected by the vortex primary circulation to the downshear side and taken into the forced updrafts (Ge et al., 2013) - [idealized experiments]

⇒ **whether dry air can be taken into the updrafts seems the most important process for the dry air intrusion mechanism**

# Dry air impacts

## SAL influence

The SAL has an inhibiting effect ([Dunion and Velden, 2004](#))

- during the pre-depression to depression stages only ([Braun](#))
- the SAL is not a primary determinant of storm intensity following formation ([Braun, 2010](#); [Braun et al., 2013](#); [Braun and coauthors, 2013](#)) - verified in three cases with different methodology. In mesoscale ensemble forecasts of TS Debby (2006), sensitivity to the dry air depended on cyclone strength and became insignificant once a TS formed ([Sippel et al., 2011](#)).



# Dust, or the indirect effects of aerosols

## Role of dust or aerosols on TC intensity and dynamics

- The modification of cloud properties via aerosols injected into idealized TCs is hypothesized to initiate interactions between cloud microphysics and storm dynamics (Carrio and Cotton, 2011; Rosenfeld et al., 2011, 2012; Cotton et al., 2012; Herbener et al., 2014)
- Aerosols introduced at the periphery of a TC with increasing concentration ranging from 100 to 2000  $\text{cm}^{-3}$  can impact both storm intensity (up to 17% increase) and size (up to 16% decrease) (Herbener et al., 2014)

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

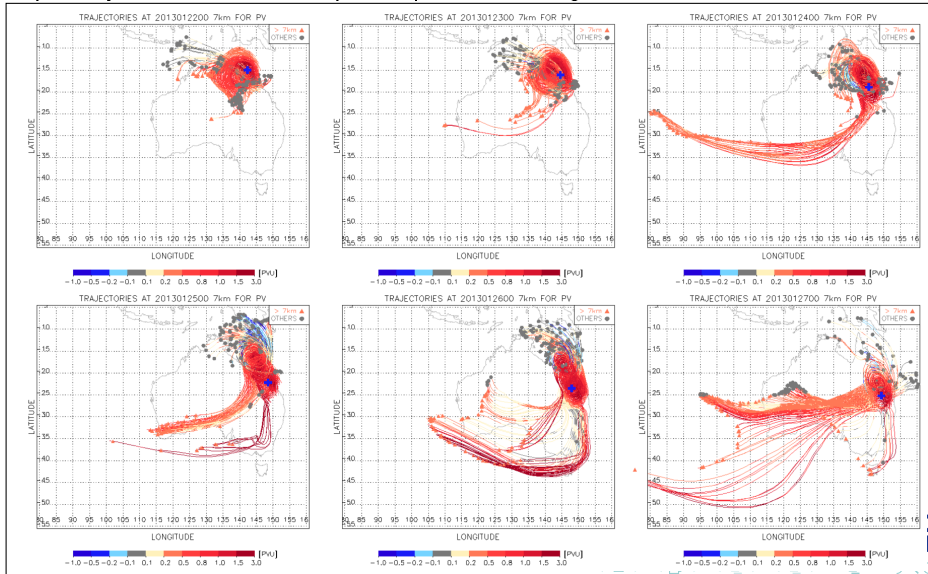
# PV / upper-level interactions

## TC-trough interactions

- primary pathway for TC-environment interaction known to be the outflow layer, region of weak inertial stability ([Rappin et al., 2011](#))
- the interaction can occur below the outflow layer: Rossby wave breaking events spawn cyclonic PV coherent structures that are advected towards TCs via the imposed asymmetric radial circulation.  
Can cause large intensity forecast errors.
- cyclonic PV injection in the mid-upper TC circulation = a potential contributor to TC intensification/structure ([Leroux et al., 2013](#); [Davidson et al., 2014](#))

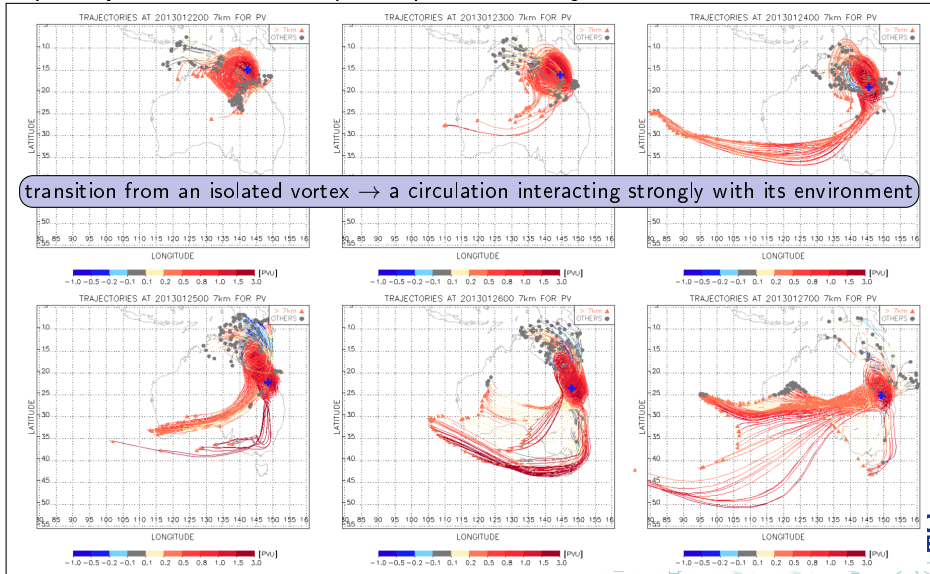
## ex-TC Oswald (2013) - PV injection

3-day back trajectories from ERA-Interim analyses, from points scattered through the mid levels of the Oswald circulation



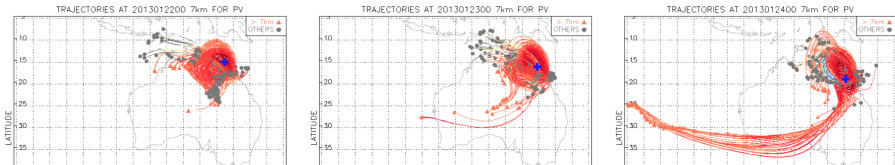
## ex-TC Oswald (2013) - PV injection

3-day back trajectories from ERA-Interim analyses, from points scattered through the mid levels of the Oswald circulation



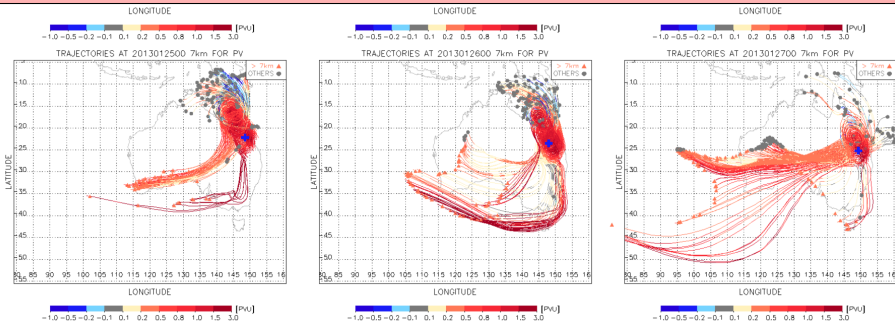
## ex-TC Oswald (2013) - PV injection

3-day back trajectories from ERA-Interim analyses, from points scattered through the mid levels of the Oswald circulation

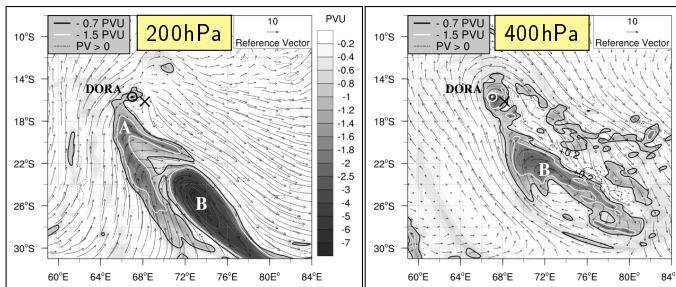


transition from an isolated vortex → a circulation interacting strongly with its environment

direct spin up of the mid-level circulation + favorable conditions for enhanced ascent, convection and rainfall within the circulation



# TC Dora (2007) - PV injection

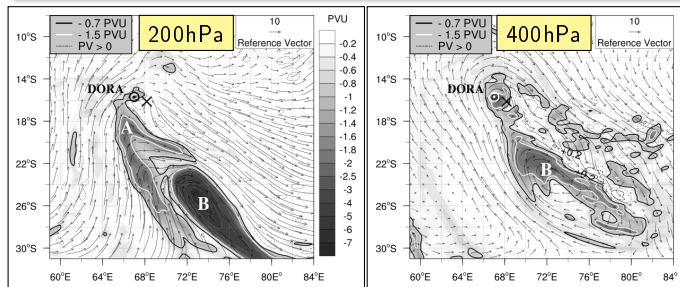


Numerical model able to reproduce the main features of the RI and ERC observed for TC Dora

# TC Dora (2007) - PV injection

## Mechanisms for vortex intensification (Leroux et al., 2013)

- 1 PV superposition (associated with  $M_a$  convergence) in a [200-500] hPa layer
- 2 SEF induced by eddy angular momentum ( $M_a$ ) convergence, eddy PV (or  $\zeta_a$ ) fluxes, and dynamically forced upward motion



Numerical model able to reproduce the main features of the RI and ERC observed for TC Dora



# TC Dora (2007) - PV injection

## Mechanisms for vortex intensification (Leroux et al., 2013)

- 1 PV superposition (associated with  $M_a$  convergence) in a [200-500] hPa layer
- 2 SEF induced by eddy angular momentum ( $M_a$ ) convergence, eddy PV (or  $\zeta_a$ ) fluxes, and dynamically forced upward motion

External forcing may excite internal processes within 200 km of the hurricane core, as speculated by [Molinari and Vollaro \(1989\)](#) and supported by [Nong and Emanuel \(2003\)](#) in an idealized framework.

# TC Dora (2007) - PV injection

## Mechanisms for vortex intensification (Leroux et al., 2013)

- 1 PV superposition (associated with  $M_a$  convergence) in a [200-500] hPa layer
- 2 SEF induced by eddy angular momentum ( $M_a$ ) convergence, eddy PV (or  $\zeta_a$ ) fluxes, and dynamically forced upward motion

## A conceptual model for TC-trough interaction?

- need for a unified theory for TC-trough interaction to help forecasters in the context of the “good trough/bad trough” issue
- clarify the dynamics and quantify the potential effects on TC intensity change
- first TC-TUTT cell interaction conceptual model in the WNP, designed for operational track guidance only (Patla et al., 2009)
- → Sensitivity experiments to modify the initial TC strength and relative TC-trough position to see if and how quickly the TC intensifies (Leroux et al., 2014)

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 **Rapid intensity changes**
  - **Rapid intensification (RI)**
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Rapid intensification (RI)

## Thermodynamics aspects for RI

- greater intensification rates associated with stronger radial gradients of RH at upper levels (300 to 400 hPa) in the front-right quadrant relative to TC motion ([Wu et al., 2012](#)).
- upper-level inertial stability increases & static stability decreases sharply 2-3 h prior to RI ([Chen and Zhang, 2013](#)) - Cloud-permitting predictions of Hurricane Wilma (2005) down to 1-km resolution
- the formation of an upper-level warm core, from the subsidence of stratospheric air associated with the detrainment of convective bursts, coincides with the onset of RI ([Chen and Zhang, 2013](#)).

# Rapid intensification (RI)

## Thermodynamics aspects for RI

- greater intensification rates associated with stronger radial gradients of RH at upper levels (300 to 400 hPa) in the front-right quadrant relative to TC motion (Wu et al., 2012).
- upper-level inertial stability increases & static stability decreases sharply 2-3 h prior to RI (Chen and Zhang, 2013) - Cloud-permitting predictions of Hurricane Wilma (2005) down to 1-km resolution
- the formation of an upper-level warm core, from the subsidence of stratospheric air associated with the detrainment of convective bursts, coincides with the onset of RI (Chen and Zhang, 2013).

## RI over the WNP (Wang et al., 2014)

- relatively higher probability for TCs drifting between  $3 \text{ ms}^{-1}$  and  $8 \text{ ms}^{-1}$ , under low shear (e.g.  $VWS_{300-850} < 11 \text{ ms}^{-1}$  and  $VWS_{700-1000} < 5 \text{ ms}^{-1}$ ): weaker negative ocean feedback.
- deep-layer shear  $\leq 7 \text{ ms}^{-1}$  or low-level shear  $\leq 3.5 \text{ ms}^{-1}$  favorable for RI.

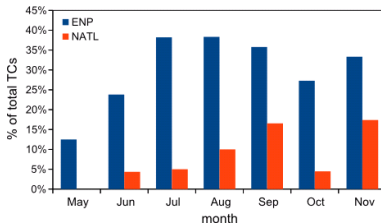
# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 **Rapid intensity changes**
  - Rapid intensification (RI)
  - **Rapid weakening (RW)**
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Rapid weakening (RW)

## Conditions conducive to RW over the ENP (1979-2012)

- RW is much more common in the ENP (33%) than in the NATL (11%) in part due to the lower areal extent of SSTs  $\geq 26^{\circ}\text{C}$  (Wood and Ritchie, 2014)
- Strongest contributor to accelerated TC decay = decreasing [400-700] hPa RH in the southern part of TCs





# OUTLOOK

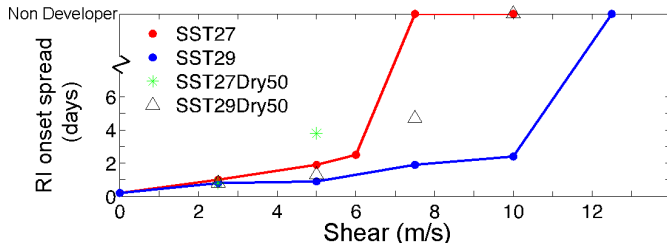
- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Predictability of RI

## Inherent predictability of TC intensity

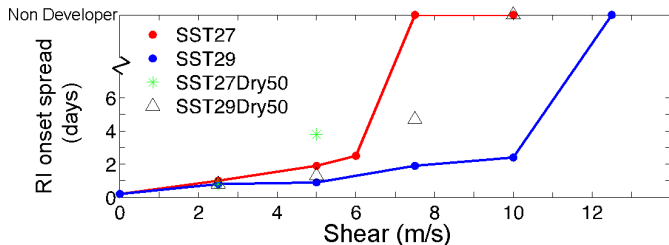
- SST and VWS have a greater impact on intensity forecast errors than other thermodynamic environmental parameters (Zhang et al., 2014) - 5-yr forecasts in the ATL basin.
- The larger the shear magnitude, the less predictable the onset time of RI (impact of high-frequency transients such as moist convection) and the larger the uncertainty in the intensity forecast (Zhang and Tao, 2013), until the shear magnitude is large enough to prevent TC formation.

(a) Uncertainty in RI onset time for sheared experiments



# Predictability of RI

(a) Uncertainty in RI onset time for sheared experiments



## Predictability $\propto$ {environment hostility + vortex vulnerability}

- Under moderate to large VWS, environmental **dry air** may have a negative impact on TC predictability (Tao and Zhang, 2014a,b).
- Higher **SSTs** also increase the predictability of RI onset (Tao and Zhang, 2014a,b; McGauley and Nolan, 2011) by shortening the onset time of RI & increasing the VWS magnitude threshold for vortex development.

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming

# Forecasting TC intensity change

## External influences contribution to the forecast (Courtney, Kucas)

- Primary driver of intensity change
  - during formation or demise: external influences
  - at tropical storm intensities (34-64 knots): intensity estimates due to external factors adjusted based on the analysis of internal dynamics.
- Short-term (to +24h or +36h): combination of persistence + subjective assessment of external influences (including SST/OHC, VWS, RH and potential dry air intrusion, low-level inflow, upper-level DIV and interaction with upper-level circulations like the TUTT)
- After +24h or +36h: combination of objective guidance and subjective interpretation of changes in dynamical model depiction of those external factors

# Forecasting TC intensity change

## Assessing external influences (Courtney, Kucas)

- Valuable standard output of environmental predictors: STIPS (Knaff et al., 2005) + SHIPS (DeMaria et al., 2005) + LGEM (DeMaria, 2009)
- Over the WNP: **consider using the low-level shear** in statistical intensity prediction schemes, since it provides a better representation of the VWS effect on TC intensity change? (Shu et al., 2013; Wang et al., 2014)

# Forecasting TC intensity change

## Intensity forecast challenges (Courtney, Kucas)

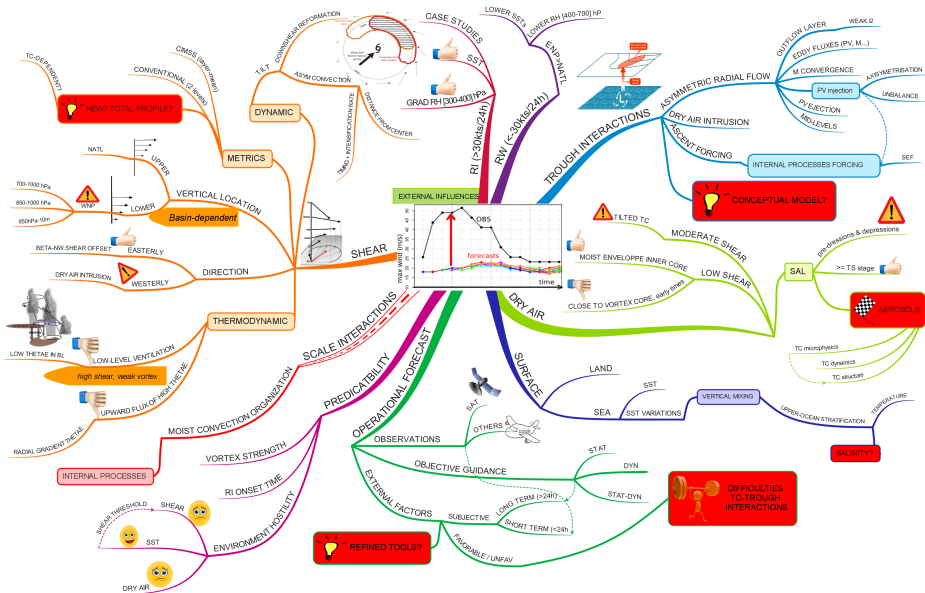
- Diagnosed dominant **external factors**  $\rightsquigarrow$  **intensity change** forecast
  - Models can have differing responses with similar representations of external factors such as the wind shear (timing of peak intensity and change to weakening).
- **Interpreting environmental VWS**: What is the effective shear on the circulation?
- Situations when some factors may favor development and others may oppose them.
  - **TC-trough interactions**: shortcomings in model forecasts cause large intensity prediction errors - e.g., Typhoon Vicente (2012) - [Shieh et al. \(2013\)](#).
  - **How quickly may a TC intensify or weaken** as it interacts with TUTTs/  
TUTT cells of various magnitudes and storm-relative positions?

# OUTLOOK

- 1 Framework
  - Motive
  - IWTC-VII highlights
- 2 Impacts of environmental parameters on TC intensity
  - Surface impacts
  - Shear impacts
  - Relative humidity/aerosols impacts
  - PV / upper-level interactions
- 3 Rapid intensity changes
  - Rapid intensification (RI)
  - Rapid weakening (RW)
- 4 Predictability of RI
- 5 Forecasting TC intensity change
- 6 Summary & Brain-storming



# Summary & Brain-storming



# Bibliography I

- Braun, S. A., 2010: Re-evaluating the role of the Saharan Air Layer in Atlantic tropical cyclogenesis and evolution. *Mon. Wea. Rev.*, **138**, 2007–2037.
- Braun, S. A. and coauthors, 2013: NASA's Genesis and Rapid Intensification Processes (GRIP) Field Experiment. *Bull. Amer. Meteor. Soc.*, **94**, 345–363.
- Braun, S. A., J. A. Sippel, and D. S. Nolan, 2012: The impact of dry mid-level air on hurricane intensity in idealized simulations with no mean flow. *J. Atmos. Sci.*, **69**, 236–257.
- Braun, S. A., J. A. Sippel, C.-L. Shie, and R. A. Boller, 2013: The evolution and role of the Saharan Air Layer during Hurricane Helene (2006). *Mon. Wea. Rev.*, **141**, 4269–4295.
- Carrio, G. G. and W. R. Cotton, 2011: Investigations of aerosol impacts on hurricanes: Virtual seeding flights. *Atmos. Chem. Phys.*, **11**, 2557–2567.
- Chen, H. and D.-L. Zhang, 2013: On the rapid intensification of Hurricane Wilma (2005). Part II: Convective bursts and the upper-level warm core. *J. Atmos. Sci.*, **70**, 146–162.
- Cotton, W. R., G. Krall, and G. G. Carrio, 2012: Potential indirect effects of aerosol on tropical cyclone intensity: Convective fluxes and cold-pool activity. *Trop. Cyclone Res. Rev.*, **1**, 293–306.
- Davidson, N. E., C. M. Nguyen-Hankinson, M. Reeder, and M.-D. Leroux, 2014: Influence of Amplifying Rossby Waves on Tropical Cyclone Intensity, Structure Change and Rainfall. *Extended abstracts, 31th Conf. on Hurricanes and Tropical Meteorology*, 31 March – 4 April, San Diego, California, Amer. Meteor. Soc., CD-ROM, 7D.3, [Available at <https://ams.confex.com/ams/31Hurr/webprogram/Paper245009.html>].
- DeMaria, M., 2009: A simplified dynamical system for tropical cyclone intensity prediction. *Mon. Wea. Rev.*, **137**, 68–82.
- DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543.

# Bibliography II

- Dunion, J. and C. Velden, 2004: The impact of the Saharan air layer on Atlantic tropical cyclone activity. *Bull. Amer. Meteor. Soc.*, **85**, 353–365.
- Ge, X., T. Li, and M. Peng, 2013: Effects of Vertical Shears and Midlevel Dry Air on Tropical Cyclone Developments. *J. Atmos. Sci.*, **70**, 3859–3875.
- Gu, J. F., Z.-M. Tan, and X. Qiu, 2014: Effects of vertical wind shear on inner-core thermodynamics of an idealized simulated tropical cyclone. *J. Atmos. Sci.*, **in press**.
- Hendricks, E. A., M. S. Peng, B. Fu, and T. Li, 2010: Quantifying environmental control on tropical cyclone intensity change. *Mon. Wea. Rev.*, **138**, 3243–3271.
- Herbener, S. R., S. C. van den Heever, G. G. Carrio, S. M. Saleeby, and W. R. Cotton, 2014: Aerosol indirect effects on idealized tropical cyclone dynamics. *J. Atmos. Sci.*, **71**, 2040–2055.
- Knaff, J. A., C. R. Sampson, and M. DeMaria, 2005: An operational Statistical Typhoon Intensity Prediction Scheme for the western North Pacific. *Wea. Forecasting*, **20**, 688–699.
- Leroux, M.-D., M. Plu, D. Barbary, F. Roux, and P. Arbogast, 2013: Dynamical and physical processes leading to tropical cyclone intensification under upper-level trough forcing. *J. Atmos. Sci.*, **70**, 2547–2565.
- Leroux, M.-D., M. Plu, and F. Roux, 2014: On the sensitivity of TC intensification under upper-level trough forcing. *Extended abstracts, 31th Conf. on Hurricanes and Tropical Meteorology*, 31 March – 4 April, San Diego, California, Amer. Meteor. Soc., CD-ROM, 7D.2, [Available at <https://ams.confex.com/ams/31Hurr/webprogram/Paper244468.html>].
- McGauley, M. G. and D. S. Nolan, 2011: Measuring environmental favorability for tropical cyclogenesis by statistical analysis of threshold parameters. *J. Climate*, **24**, 5968–5997.
- Molinari, J., J. Frank, and D. Volaro, 2013: Convective Bursts, Downdraft Cooling, and Boundary Layer Recovery in a Sheared Tropical Storm. *Mon. Wea. Rev.*, **141**, 1048–1060.

# Bibliography III

- Molinari, J. and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy momentum fluxes. *J. Atmos. Sci.*, **46**, 1093–1105.
- Molinari, J. and D. Vollaro, 2010: Rapid Intensification of a Sheared Tropical Storm. *Mon. Wea. Rev.*, **138**, 3869–3885.
- Neetu, S., M. Lengaigne, E. M. Vincent, J. Vialard, G. Madec, G. Samson, M. R. R. Kumar, and F. Durand, 2012: Influence of upper-ocean stratification on tropical cyclone-induced surface cooling in the Bay of Bengal. *J. Geophys. Res.*, **117**, C12 020.
- Nguyen, L. T. and J. Molinari, 2012: Rapid Intensification of a Sheared, Fast-Moving Hurricane over the Gulf Stream. *Mon. Wea. Rev.*, **140**, 3361–3378.
- Nolan, D. S., Y. Moon, and D. P. Stern, 2007: Tropical Cyclone Intensification from Asymmetric Convection: Energetics and Efficiency. *J. Atmos. Sci.*, **64**, 3377–3405.
- Nong, S. and K. Emanuel, 2003: A numerical study of the genesis of concentric eyewalls in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **129**, 3323–3338.
- Patla, J. E., D. Stevens, and G. M. Barnes, 2009: A Conceptual Model for the Influence of TUTT Cells on Tropical Cyclone Motion in the Northwest Pacific Ocean. *Wea. Forecasting*, **24**, 1215–1235.
- Rappin, E. D., M. C. Morgan, and G. J. Tripoli, 2011: The impact of outflow environment on tropical cyclone intensification and structure. *J. Atmos. Sci.*, **68**, 177–194.
- Riemer, M. and M. T. Montgomery, 2011: Simple kinematic models for the environmental interaction of tropical cyclones in vertical wind shear. *Atmos. Chem. Phys.*, **11**, 9395–9414.
- Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2010: A new paradigm for intensity modification of tropical cyclones: Thermodynamic impact of vertical wind shear on the inflow layer. *Atmos. Chem. Phys.*, **10**, 3163–3188.

# Bibliography IV

- Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2013: Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear. *Atmos. Chem. Phys.*, **13**, 327–346.
- Rogers, R. and coauthors, 2013: NOAA's Hurricane Intensity Forecasting Experiment (IFEX): A progress report. *Bull. Amer. Meteor. Soc.*, **94**, 859–882.
- Rogers, R., P. Reasor, and S. Lorsolo, 2007: Airborne Doppler Observations of the Inner-Core Structural Differences between Intensifying and Steady-State Tropical Cyclones. *Mon. Wea. Rev.*, **141**, 2970–2991.
- Rosenfeld, D., M. Clavner, and R. Nirel, 2011: Pollution and dust aerosols modulating tropical cyclone intensities. *J. Atmos. Res.*, **102**, 66–76.
- Rosenfeld, D., W. L. Woodley, A. Khain, W. R. Cotton, G. G. Carrio, I. Ginnis, and J. H. Golden, 2012: Aerosol effects on microstructure and intensity of tropical cyclones. *Bull. Amer. Meteor. Soc.*, **93**, 987–1001.
- Shieh, O. H., M. Fiorino, M. E. Kucas, and B. Wang, 2013: Extreme rapid intensification of Typhoon Vicente (2012) in the South China Sea. *Wea. Forecasting*, **28**, 1578–1587.
- Shu, S., Y. Wang, and L. Bai, 2013: Insight into the role of lower-layer vertical wind shear in tropical cyclone intensification over the western North Pacific. *Acta Meteor. Sinica*, **27**, 356–363.
- Shu, S., F. Zhang, J. Ming, and Y. Wang, 2014: Environmental Influences on the Intensity Changes of Tropical Cyclones over the Western North Pacific. *Atmos. Chem. Phys.*, **14**, 6329–6342.
- Sippel, J. A., S. A. Braun, and C.-L. Shie, 2011: An ensemble analysis of environmental influences on the strength of Tropical Storm Debby (2006). *J. Atmos. Sci.*, **68**, 2557–2581.
- Tang, B. and K. Emanuel, 2010: Midlevel Ventilation's Constraint on Tropical Cyclone Intensity. *J. Atmos. Sci.*, **67**, 1817–1830.

# Bibliography V

- Tang, B. and K. Emanuel, 2012a: A Ventilation Index for Tropical Cyclones. *Bull. Amer. Meteor. Soc.*, **93**, 1901–1912.
- Tang, B. and K. Emanuel, 2012b: Sensitivity of Tropical Cyclone Intensity to Ventilation in an Axisymmetric Model. *J. Atmos. Sci.*, **69**, 2394–2413.
- Tao, D. and F. Zhang, 2014a: Effect of environmental shear, sea-surface temperature and ambient moisture on the formation and predictability of tropical cyclones: An ensemble-mean perspective. *J. Adv. Model. Earth Syst.*, **6**, 384–404.
- Tao, D. and F. Zhang, 2014b: Effect of environmental shear, sea-surface temperature and ambient moisture on the formation and predictability of tropical cyclones: ensemble sensitivity and intrinsic error growth dynamics. *Quart. J. Roy. Meteor. Soc.*, **submitted**.
- Velden, C. S. and J. Sears, 2014: Computing deep-tropospheric vertical wind shear analyses for tropical cyclone applications: Does the methodology matter? *Wea. Forecasting*, **in press**.
- Vigh, J. L. and W. H. Schubert, 2009: Rapid Development of the Tropical Cyclone Warm Core. *J. Atmos. Sci.*, **66**, 3335–3350.
- Vincent, E. M., M. Lengaigne, G. Madec, J. Vialard, G. Samson, N. C. Jourdain, C. E. Menkes, and S. Jullien, 2014: Processes setting the characteristics of sea surface cooling induced by tropical cyclones. *J. Geophys. Res.*, **117**, C02 020.
- Wang, Y., Y. Rao, and Z.-M. Tan, 2014: A statistical analysis of vertical wind shear effect on tropical cyclone intensity change over the western North Pacific. *Mon. Wea. Rev.*, **submitted**.
- Wood, K. M. and E. A. Ritchie, 2014: Large-scale moisture and thermodynamic properties associated with rapid weakening in the eastern North Pacific. *Extended abstracts, 31th Conf. on Hurricanes and Tropical Meteorology*, 31 March – 4 April, San Diego, California, Amer. Meteor. Soc., CD-ROM, 13C.3, [Available at <https://ams.confex.com/ams/31Hurr/webprogram/Paper244326.html>].

# Bibliography VI

- Wu, L., et al., 2012: Relationship of environmental relative humidity with North Atlantic tropical cyclone intensity and intensification rate. *Geophys. Res. Lett.*, **39**, L20 809.
- Zeng, Z.-H., Y. Wang, and L. Chen, 2010: A statistical analysis of vertical shear effect on tropical cyclone intensity change in the North Atlantic. *Geophys. Res. Lett.*, **37**, L02802.
- Zeng, Z.-H., Y. Wang, and C.-C. Wu, 2007: Environmental dynamical control of tropical cyclone intensity-An observational study. *J. Atmos. Sci.*, **135**, 38–59.
- Zhang, F. and D. Tao, 2013: Effects of vertical wind shear on the predictability of tropical cyclones. *J. Atmos. Sci.*, **70**, 975–983.
- Zhang, Y. J., Z. Meng, and Y. W. and F. Zhang, 2014: Predictability of Tropical Cyclone Intensity Evaluated through 5-year Forecasts with a Convection-permitting Regional-scale Model in the Atlantic Basin. *Wea. Forecasting*, in press.