A modelling case-study of a tropical tropopause layer cirrus: roles of dynamics and microphysics and cirrus impacts

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Introduction

Cirrus formation:

*in situ formation (uplift in altitude)* or convection
Introduction

In situ cirrus:

- sensitive to different types of atmospheric waves (e.g. Kelvin waves, inertio-gravity waves) *Immler et al. 2008*

- can be very large-scale clouds

- can show very small scale features (a few meters, at least!)

We will focus on the large-meso scale

*From Jensen et al., 2013*
Presentation of the case study

Backscatter along CALIOP track

Timing and location of cirrus formation

Large-scale, apparently long-lasting cirrus in the tropical Eastern Pacific in late January 2009

Described from satellite observations by Taylor et al., 2011

From Taylor et al., 2011
Problematic

Is the mesoscale WRF model in a "default configuration" able to reproduce a realistic cirrus event? How does it compare to CALIPSO observations?

Why does the cloud form?

To what choices in the parametrizations/initial conditions is the simulated cirrus sensitive?

What are the impacts of this cirrus event on the TTL?
Outline

• Model setup and model evaluation
• Cloud formation
• Sensitivity of cloud modelling
• Cloud impact
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Presentation of the case study

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Associated with a cold temperature anomaly, and a mid-latitude Potential Vorticity intrusion below the cirrus (200 hPa)

Potential vorticity at 200 hPa, NCEP

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WRF domain
Modelling set-up

- Mesoscale modeling with the NCAR Weather Research and Forecast model v3, in January 27-29, 2009

- Thompson scheme (2 moments for ice), (and different sensitivities)

- 10 km horizontal resolution (tests with 4 km), about 250-300 m vertical resolution

- Initial and boundary conditions taken from ECMWF operational analyses (including water vapor)
Presentation of the simulation

Black contours = cirrus
Comparison of the simulation to CALIPSO Lidar observations:

Use of a "Lidar simulator" COSP to compare the simulated and observed cloud induced backscatter at 532 nm

Comparison with a "night profile" on January 28th
Comparison to CALIOP Lidar observations:

1) Interpolation along the satellite track
Comparison to CALIOP Lidar observations:

1) Interpolation along the satellite track

2) Use of a "Lidar simulator" to compare the simulated and observed clouds
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Model Evaluation

Points to be compared:

• Amplitude of the returned signal ("optical depth") ; can be misleading for those thin clouds (because of instrumental noise, etc.)
• Spatial characteristics : location (altitude), extension, thickness, optical thickness
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• **Cloud formation**

• Sensitivity of cloud modelling

• Cloud impact
Dynamics of cloud formation

Correlation of the cirrus with low temperature
The temperature decrease causes a relative humidity increase along air parcel trajectory, which in turn causes the cloud to form.
In a Lagrangian perspective, the decrease in temperature is due to adiabatic cooling forced by a large-scale vertical uplift. *Cause of the uplift?*
Dynamical structures in the simulation

Antisymmetric temperature and symmetric Potential Vorticity in quadrature phase relationship
Temperature signature of a Yanai (Mixed Rossby-gravity) wave during the simulation explains the overall geometry of the cirrus in WRF.
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Sensitivity of the simulated cirrus (36 hours)

ECMWF op. an.

Thompson microphysics

Morrison microphysics

Sensitivity:

-microphysics scheme (2 moments Morrison vs. 2 moments Thompson)
Sensitivity of the simulated cirrus (36 hours)

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- Microphysics scheme (2 moments Morrison vs. 2 moments Thompson)
- Initial and boundary conditions (ECMWF op. an. vs. ERA interim)

No cloud radiative heating
Sensitivity of the simulated cirrus (36 hours)

- Microphysics scheme (2 moments Morrison vs. 2 moments Thompson)
- Initial and boundary conditions (ECMWF op. an. vs. ERA interim)
- Cloud induced radiative heating (with vs. without cirrus radiative heating included)
Sensitivity of the simulated cirrus (36 hours)

Sensitivity:

- microphysics scheme (2 moments Morrison vs. 2 moments Thompson)
- initial and boundary conditions (ECMWF op. an. vs. ERA interim)
- cloud induced radiative heating (with vs. without cirrus radiative heating included)
### Summary of sensitivities at 36 hours

<table>
<thead>
<tr>
<th></th>
<th>Amplitude (IWC)</th>
<th>Horizontal position</th>
<th>Vertical position</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>++</td>
<td>no</td>
<td>+</td>
<td>no</td>
</tr>
<tr>
<td>Initial and boundary conditions</td>
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<td>++</td>
</tr>
<tr>
<td>Radiation</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Differences in the large-scale dynamics and water vapor (as can be found in different analysis systems) are as important as the microphysics. They play more role to determine the geographic structure and evolution of the cloud field, when the microphysics and the initial water vapor essentially act on the amplitude.
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Cirrus impact: radiative heating

Cirrus radiative impact estimate from simulations with and without cloud radiative heating included (RRTMG scheme):

- Mean heating in the domain of the order of 0.1 K/day by the cirrus
- Cloud radiative effect absent in the ERA interim: bias
Cirrus impact: water redistribution

Water vertical transport (through sedimentation):

- Thompson: reference
- Max Dehy:
  \[ q_v = \min(q_v, q_{v\text{SAT}}) \]
- No Sedim: sedimentation suppressed (for temperature below 210 K)

Rough estimate of cloud effect, but illustrates the role of the cloud in dehydrating AND rehydrating different layers.
Conclusions

• Default WRF able to reproduce the main cirrus characteristics

• Cirrus formation due to large-scale dynamics: equatorial wave response excited by interaction with the midlatitudes (PV intrusion)

• Strong sensitivity of the modelled cloud to the initial dynamics (U, T). Initial and boundary conditions in dynamics and in water vapor, and choices for the microphysics parametrization affect different characteristics of the cloud field.

• Cirrus impact: 0.1 K/day in radiative heating, water vertical redistribution with de and re-hydration (- 0.5 ppm / + 0.5 ppm) (emphasized with a single column model by Ueyama et al., 2014 or idealized simulations by Dinh et al. 2014)
Thank you for your attention