Numerical Weather Prediction
Parametrization of sub-grid physical processes

Clouds (4)
Model Evaluation: Clouds

Richard Forbes
(with thanks to Maike Ahlgrimm, Adrian Tompkins, Christian Jakob)

forbes@ecmwf.int
Today’s lecture will discuss:

- Different observation types for model cloud evaluation
- Different evaluation methodologies to inform parametrization development
- Limitations of model evaluation due to uncertainties and differences in observed and modelled quantities

Two parts:
1. Methodologies for diagnosing model errors
2. Evaluation uncertainties and limitations
Cloud Validation: The issues

**APPROACH**: Validate the model generated clouds against observations, and use the information concerning apparent errors to improve the model physics, and subsequently the cloud simulation.

Cloud observations → Error → Parametrization improvements

Sounds easy?
Cloud Validation: The problems

- How much of the ‘error’ derives from observations?

Cloud observations  $\text{error} = \varepsilon_1$

Cloud simulation  $\text{error} = \varepsilon_2$

Error

Parametrization improvements
Cloud Validation: The problems

• Which Physics is responsible for the error?

Cloud observations

Cloud simulation

Error

Parametrization improvements

- radiation
- turbulence
- cloud physics
- convection
- dynamics

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The path to improved cloud parametrization...

- Cloud validation
- Forward modelling
- Case studies
- Composite studies
- Sensitivity studies
- Different observations
- Process studies
- NWP validation
- Climatological comparison
- Parametrization improvement
1. Methodologies for diagnosing errors and improving parametrizations
Cloud Validation: The problems

1. Methodology

Cloud observations

Cloud simulation

Error

Parametrization improvements

Cloud physics

Radiation

Convection

Turbulence

Dynamics
A strategy for cloud parametrization evaluation

For example, systematic errors in radiation, cloud cover, precipitation...

- Use long timeseries of observational data (satellite, ground-based profile, NWP verification)
- Statistical evaluation (mean, PDFs)
- Short-range forecasts or model climate (multi-year simulations)

Step 1: identify major problem areas
Step 2: identify major problem regimes
Step 3: identify typical case
Step 4: identify detailed problems
Step 5: improve parametrization

From C. Jakob

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Systematic errors in the model

TOA broadband SW radiation shows pattern of systematic error

Too bright, cloud too reflective

Or maybe surface albedo?

Too dark, clouds don’t reflect enough

What is causing these errors?
Total cloud cover bias - ISCCP

Traditional cloud product based on brightness temperatures – not bad, right?
Total cloud cover bias - MODIS

Total cloud cover from MODIS
Total cloud cover bias - CALIPSO

Total cloud cover from CALIPSO
Compositing of long-term data records

Global ARM and Cloudnet observation sites

devcloudnet.fmi.fi
www.arm.gov
Cloud fraction
Chilbolton Observations from 2003

Same timeseries from short-range forecasts (12-36hr) from various models
Statistical evaluation: CloudNet Example

• In addition to standard quicklooks, longer-term statistics are available.

• This example is for ECMWF cloud cover during June 2005.

• Includes pre-processing to account for radar attenuation and snow.

• See devcloudnet.fmi.fi for more details and examples!
Identifying major problem areas

• Need to evaluate the model from many different view points to identify which problems are associated with cloud.

• Evaluate the statistics of the model (mean, pdf,…) - long timeseries of data.

• Use of long forecasts (climate) and short forecasts (to avoid climate interactions and feedbacks).

• Use of data assimilation increments, initial tendencies.
A strategy for cloud parametrization evaluation: Composites

1. Step 1: identify major problem areas
2. Step 2: identify major problem regimes
3. Step 3: identify typical case
4. Step 4: identify detailed problems
5. Step 5: improve parametrization

C. Jakob
“Smart” compositing: let the bias tell you what is important

Which cloud type/regime contributes most to the radiation bias?

- CAUSES project: What contributes to the 2m temperature bias over North America?
- Is there a net radiation error when the bias grows?
- If so, what clouds are associated with that bias growth?

Size: frequency
Colour: bias magnitude
Global model outgoing shortwave radiation systematic errors

Similarities across models, across resolutions, across timescales

Annual mean top-of-atmosphere SW radiation difference from CERES-EBAF

We can use observations and short-range NWP forecasts/DA system
…to understand and reduce regime-dependent systematic errors
…to improve global models across time and space scales

Shortwave radiation bias - similar systematic errors found across models, in climate and in short-range forecasts
Top-of-atmosphere SW radiation bias focus on boundary layer cloud – marine cumulus-stratocumulus

Annual mean outgoing shortwave radiation bias (IFS minus CERES-EBAF)
Subtropical marine stratocumulus to cumulus

Annual mean top-of-atmosphere outgoing shortwave radiation error (W m⁻²)
(IFS – CERES EBAF)

Albedo too low
Albedo too high
Understanding the subtropical marine cloud/shortwave radiation bias

IFS albedo too high in trades
IFS albedo too low in stratocumulus
IFS cloud cover good in day
IFS cloud cover too low at night
IFS LWP too low vs widely used satellite microwave retrievals (Painemal et al 2016)
. . . but IFS LWP too high versus ship MWR and MODIS !
LWP – too high or too low?

All-sky LWP not that helpful a measure – strongly influenced by high-end tail of LWP distribution, which is poorly constrained.

It’s the distribution of in-cloud LWP that counts! (for SW rad)

Distribution can be shifted by changing

• Gridbox-mean condensate amount
• Cloud fraction
• Heterogeneity assumption

IFS LWP too low vs widely used satellite microwave retrievals (Painemal et al 2016)

..but IFS LWP too high versus ship MWR and MODIS !

Ahlgrimm, Forbes, Hogan, Sandu; JAMES (2018)
i) LWP bias primary cause of SW error in Trades

Experiment: force LWP to be consistent with observed values

a) Offline radiation experiments: TOA upwelling SW radiation

Reduced LWP largely eliminates SW bias.

Bias in Sc partially improved

Ahlgrimm et al. (2018, JAMES)
ii) Cloud cover and LWP both contribute to bias in stratocumulus

Experiment: force total cloud cover towards observed values (in addition to LWP)

a) Offline radiation experiments: TOA upwelling SW radiation

Trade Cu not much affected – CC was already good. Additional improvement in Sc region

Ahlgrimm et al. (2018, JAMES)
iii) Effective radius gradient along track enhances albedo in Sc

Experiment: use CDNC derived from ship-based observations in model calculation of effective radius

a) Offline radiation experiments: TOA upwelling SW radiation

Trade Cu not much affected:
• new and old $R_{\text{eff}}$ differ less
• smaller cloud fraction means less impact

Additional improvement in Sc region
iv) Subgrid variability of liquid water content enhances Scu albedo

Experiment: use in-cloud LWC variability fractional standard deviation (FSD) from satellite study

a) Offline radiation experiments: TOA upwelling SW radiation

Carefully matched observation evaluation using many different satellite and ground-based instruments can disentangle the multiple sources of cloud error and explain the observed subtropical marine shortwave radiation systematic errors in the IFS!

Helps to focus and prioritise where further developments should go to improve the model
What does the BL and shallow Cu parameterization do?

Convection removes moisture from a dry layer -> evaporation of cloud from below.

BL scheme doesn’t mix all the way to cloud base.

BL parcel rarely reaches LCL

shallow conv scheme active anyway

Sc type rare

Test parcel ascent

Moisture tendency
The shallow cloud problem has contributions from many interacting and partially compensating processes!

- Error contributions from:
  - Triggering of shallow convection/stratocumulus scheme
  - Water amount in clouds
  - Representation of cloud heterogeneity (or lack thereof)
  - Unrealistic autoconversion/accretion and evaporation rates
  - Error in effective radius
Cloud evaluation methodologies summary

- **Long term statistics:**
  - Climate systematic errors – we want to improve the basic state/climatology of the model
  - But which physics is responsible for the errors? Non-linear interactions.
  - Long term response vs. transient response.

- **Isolating regimes:**
  - Composites and focus on geographical regions.

- **Case studies**
  - Detailed studies with Single Column Models, Cloud Resolving Models, NWP models
  - Easier to explore parameter space.
  - Are they representative? Do changes translate into global skill?
2. Comparing model and obs: Uncertainty and limitations
Cloud Validation: The problems

2. Uncertainty

Cloud observations → Error → Parametrisation improvements

Cloud simulation → Error → Parametrisation improvements

Cloud physics → Convection → Dynamics

Radiation → Turbulence
What is a cloud?

- What is a cloud? It’s all (or mostly) electromagnetic radiation...
  - brightness temp
  - radar reflectivity
  - backscatter
  - sensitivity threshold

- How accurately can we measure this quantity?
  - Observation error/uncertainty
  - Conditional sampling (e.g. viewing geometry, instrument shut off)
  - Signal attenuation, noise from other stuff (insects, aerosol)

- How well does this quantity compare to variables predicted by the model?
  - Retrieval error
  - Forward model error
Verification
Uncertainty in quantities derived from observations…

Widely varying estimates of IWP from different satellite datasets!

From Waliser et al. (2009), JGR

Cloud Sat
(From Waliser et al 2009)
What is being compared?
Cloud ice vs. snow – comparing like-with like

Model Ice Water Path (IWP) (1 year climate)

IWP from prognostic cloud ice variable

IWP from cloud ice + precipitating snow

Observed Ice Water Path (IWP)
CloudSat 1 year climatology
Space-borne active remote sensing
A-Train

- CloudSat and CALIPSO have active radar and lidar to provide information on the vertical profile of clouds and precipitation. (Launched April 2006)

- Approaches to model validation:
  
  Model → Obs parameters
  Obs → Model parameters

- Spatial/temporal mismatch
Simulating Observations
CFMIP COSP radar/lidar simulator

Model Data
(T,p,q,iwc,lwc...)

Sub-grid Cloud/Precip Pre-processor

CloudSat simulator
(Haynes et al. 2007)

Physical Assumptions
(PSDs, Mie tables...)

CALIPSO simulator
(Chiriaco et al. 2006)

Radar Reflectivity

Lidar Attenuated Backscatter

http://cfmip.metoffice.com

Note: COSP now has many more satellite simulators
Example cross-section through a front
Model vs CloudSat radar reflectivity
Example section of a CloudSat orbit
26th February 2006  15 UTC

Mid-latitude cyclone

High tropical cirrus

Mid-latitude cyclone
Compare model with observed parameters: Radar reflectivity

Simulated radar reflectivity from the model for ice only (< 0°C)

Observed radar reflectivity from CloudSat (ice + rain)

26/02/2007 15Z

82° S Tropics 82° N
Compare model parameters with equivalent derived from observations: Ice Amount

Model ice water content (excluding precipitating snow).

Ice water content derived from a 1DVAR retrieval of CloudSat/CALIPSO/Aqua

(Delanöe and Hogan (2007), Reading Univ., UK)
Spatial resolution mis-match

- Need to address mismatch in spatial scales in model (50 km) and obs (1 km)
- Sub-grid variability is predicted by the IFS model in terms of a cloud fraction and assumes a vertical overlap.
- Either:
  1. Average obs to model representative spatial scale
  2. Statistically represent model sub-gridscale variability using a Monte-Carlo multi-independent column approach.
When comparing a model with observations, we need to compare like-with-like.
Model validation
Making the most of instrument synergy

- Observational instruments measure one aspect of the atmosphere.

- Often, combining information from different instruments can provide complementary information (particularly for remote sensing)

- For example, radars at different wavelengths, lidar, radiometers.

- CloudSat/CALIPSO

Radar, lidar and radiometer instruments at Chilbolton, UK (www.chilbolton.rl.ac.uk)
Example of mid-Pacific convection

CloudSat radar

Deep convection penetrated only by radar

CALIPSO lidar

Cirrus detected only by lidar

Mid-level liquid clouds

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Julien Delanoë/Robin Hogan
Combining radar and lidar... using a variational technique (Delanoë and Hogan 2010)

Cloudsat radar

CALIPSO lidar

Preliminary target classification

Global-mean cloud fraction

Radar and lidar
Radar only
Lidar only

Radar misses a significant amount of ice

Insects
Aerosol
Rain
Supercooled liquid cloud
Warm liquid cloud
Ice and supercooled liquid
Ice
Clear
No ice/rain but possibly liquid
Ground
Summary

• **Different approaches** to verification (climate statistics, case studies, composites), different techniques (model-to-obs, obs-to-model) and a **range of observations** are required to validate and improve cloud parametrizations.

• Need to **understand the limitations** of observational data. Ensure we are **comparing like with like**. Use complementary observations - **synergy**.

• The model developer **needs to understand physical processes** to improve the model. Requires, theory and modelling and novel techniques for extracting **process-oriented information** from observations.
The path to improved cloud parametrization...

Many mountains to climb!