Overview and Cloud Cover Parameterization

Bob Plant

With thanks to: C. Morcrette, A. Tompkins, E. Machulskaya and D. Mironov

NWP Physics Lecture 1

Nanjing Summer School

July 2014

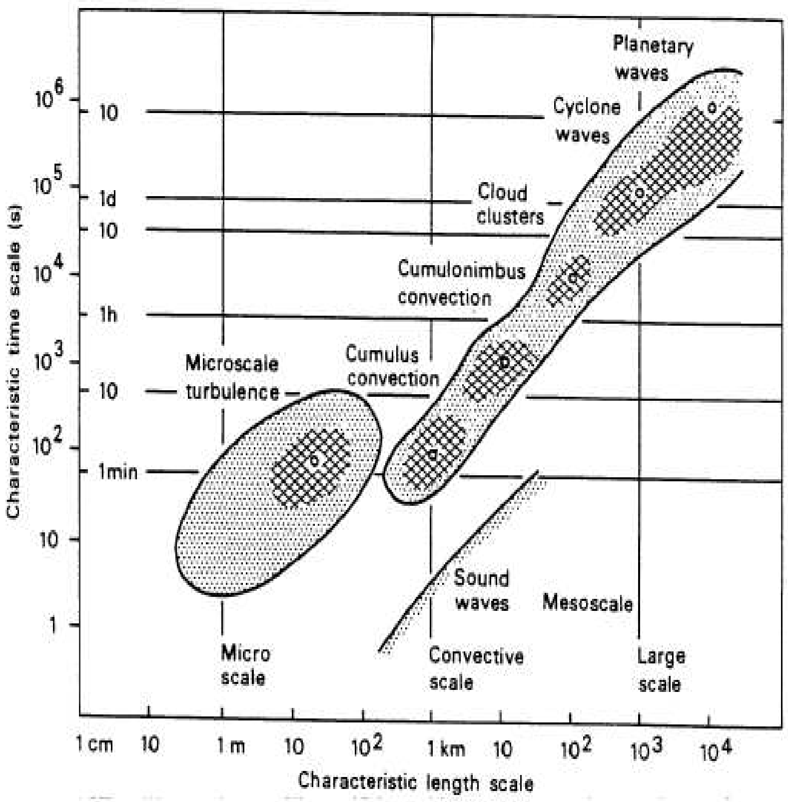
The University of Reading

Outline

- Introduction and context
- Cloud cover parameterization problem
- Relative humidity methods
- PDF based methods
- Joint PDFs and consistency with turbulence

Motivation and context

Atmospheric scales



Typical grid box size ranges from 1km (short-range NWP) to 100km (GCMs)

Things to parameterize

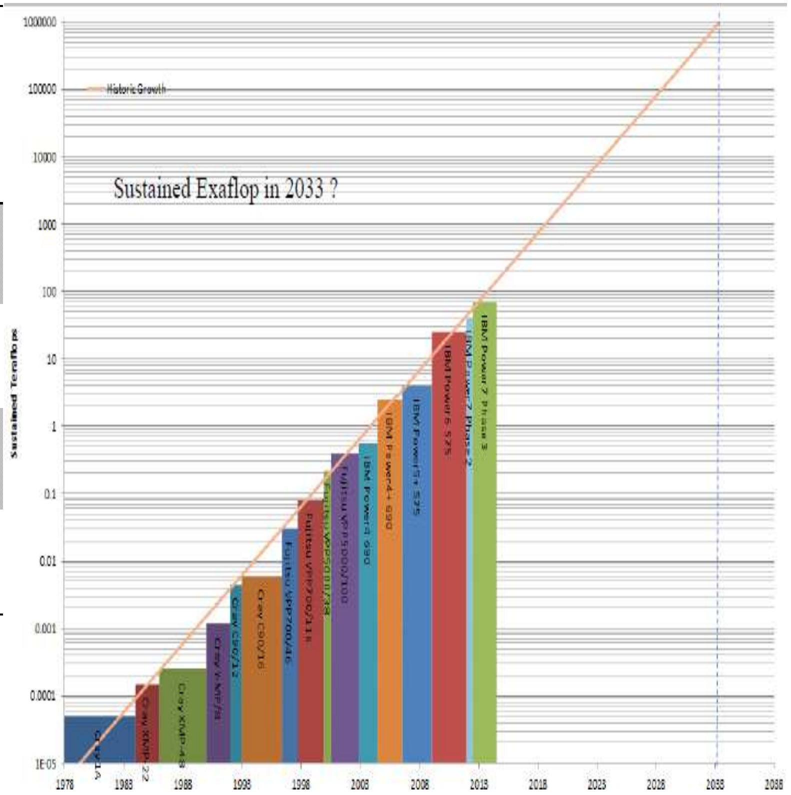
- Radiation
- Interactions with the surface
- Boundary layer turbulence
- Stratiform cloud
- Microphysics
- Convective cloud
- Gravity wave drag
- Chemistry
- Aeorsol species
- Microbiology
- Hydrology....

Advance of computing power

Plans at ECMWF:

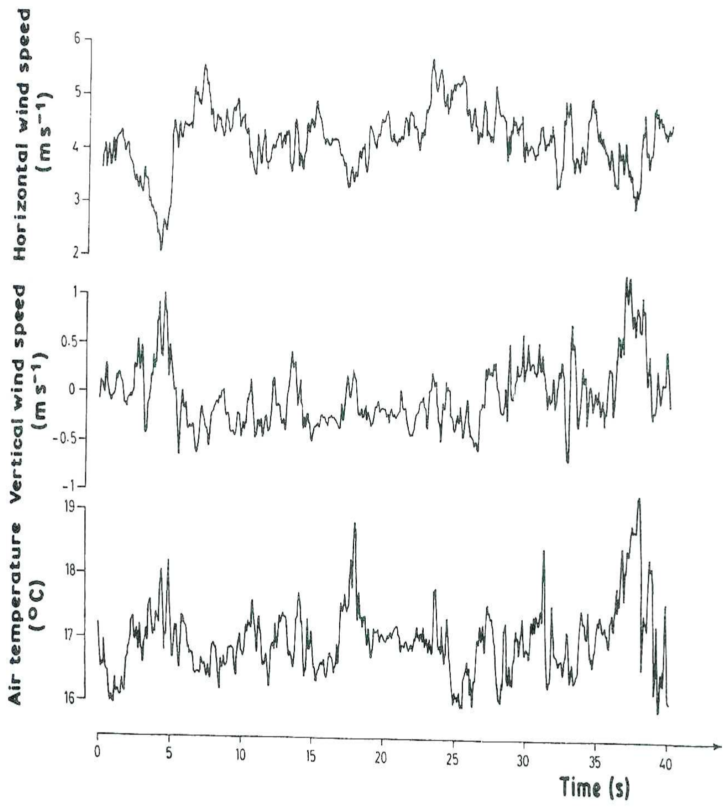
IFS model resolution	Envisaged Operational Implementation	Grid point spacing (km)	Time-step (seconds)	Estimated number of cores[1]
T1279 H[2]	2013 (L137)	16	600	2K
T2047 H	2014-2015	10	450	6K
T3999 NH[3]	2023-2024	5	240	80K
T7999 NH	2031-2032	2.5	30-120	1-4M

1 – a gross estimate for the number of 'IBM Power7' equivalent cores needed to achieve a 10 day model forecast in under 1 hour (~240 FD/D), system size would normally be ~10 times this number.
2 – Hydrostatic Dynamics
3 – Non-Hydrostatic Dynamics



50 member ensemble at T3999 ≈ single run at T7999

Small scale motions



- Variability at many different scales
- Structure and self-correlation
- $-$ve correlation of u and w $\implies$ turbulent transport of momentum

Reynolds decomposition

- We split the full variable as $u = \overline{u} + u'$
- In ensemble averaging we have many realizations of the process

$$\overline{u}(x,y,z,t) = \lim_{N\to\infty} \frac{1}{N} \sum_i u_i(x,y,z,t)$$

- Obeys Reynolds rules:

$$\overline{\overline{a}} = \overline{a} \qquad ; \qquad \overline{a'} = 0$$

$$\overline{a+b} = \overline{a} + \overline{b} \qquad ; \qquad \overline{\frac{\partial a}{\partial t}} = \frac{\partial \overline{a}}{\partial t}$$

Time and Space averaging

- More practical is time and/or space averaging

$$\overline{u}(x,y,z,t) = \int dx'dy'dz'dt'G(x',y',z',t')u(x',y',z',t')$$

  with filter G centered on (x,y,z,t)

- eg, top hat filter for averaging over grid box $\Delta x \Delta y \Delta z$ and timestep Δt
- Reynolds rules don't necessarily apply: eg, $\overline{\overline{a}} \neq \overline{a}$ for a running average
- Such effects can be take into account
- But: here, we won't specify G and we neglect any non-Reynolds contributions

Model equations

- Our numerical model predicts $\overline{u}$
- Filter the basic equations

$$\overline{\frac{Du}{Dt}} - f\overline{v} + \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x} = 0$$

which includes

$$\overline{w\frac{\partial u}{\partial z}} = \overline{\overline{w}\frac{\partial \overline{u}}{\partial z}} + \overline{\overline{w}\frac{\partial u'}{\partial z}} + \overline{w'\frac{\partial \overline{u}}{\partial z}} + \overline{w'\frac{\partial u'}{\partial z}}$$

Model equations

Using our averaging rules

$$\overline{w\frac{\partial u}{\partial z}} = \overline{w}\frac{\partial \overline{u}}{\partial z} + \overline{w'\frac{\partial u'}{\partial z}} = \overline{w}\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w'u'}}{\partial z} - \overline{u'\frac{\partial w'}{\partial z}}$$

Putting everything together we have

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial y} + \overline{w}\frac{\partial \overline{u}}{\partial z} - f\overline{v} + \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x} = -\frac{\partial \overline{u'u'}}{\partial x} - \frac{\partial \overline{v'u'}}{\partial y} - \frac{\partial \overline{w'u'}}{\partial z}$$

Similar to original u equation but terms on RHS describe sub-grid effects

Equations for the unresolved fluxes

- We want to know fluxes such as $\overline{u'w'}$

$$\frac{\partial \overline{u'w'}}{\partial t} = \overline{w'\frac{\partial u'}{\partial t} + u'\frac{\partial w'}{\partial t}}$$

- Get equation for $\partial u'/\partial t$ from $(\partial u/\partial t) - (\partial \overline{u}/\partial t)$
- Multiply it by w'
- Apply the averaging
- Eventually...

Closure problem

$$\frac{\partial \overline{u'w'}}{\partial t} = \{\text{terms that depend on mean flow and the turbulent fluxes}\}$$

$$-\frac{\partial \overline{u'w'w'}}{\partial z}$$

- We can indeed make an exact equation to predict $\overline{u'w'}$
- But now we need equation for $\overline{u'w'w'}$!
- Which contains terms like $\overline{u'u'w'w'}$ etc etc

Cloud cover parameterization problem

All or nothing schemes

- Consider the total moisture content, $q_t = q + q_l + q_i + q_g$
- If $q_t > q_{\text{sat}}(T)$ then the grid box is cloudy
- Otherwise it is clear
- Only reasonable for very small grid boxes, where the cloud is well resolved

On larger scales

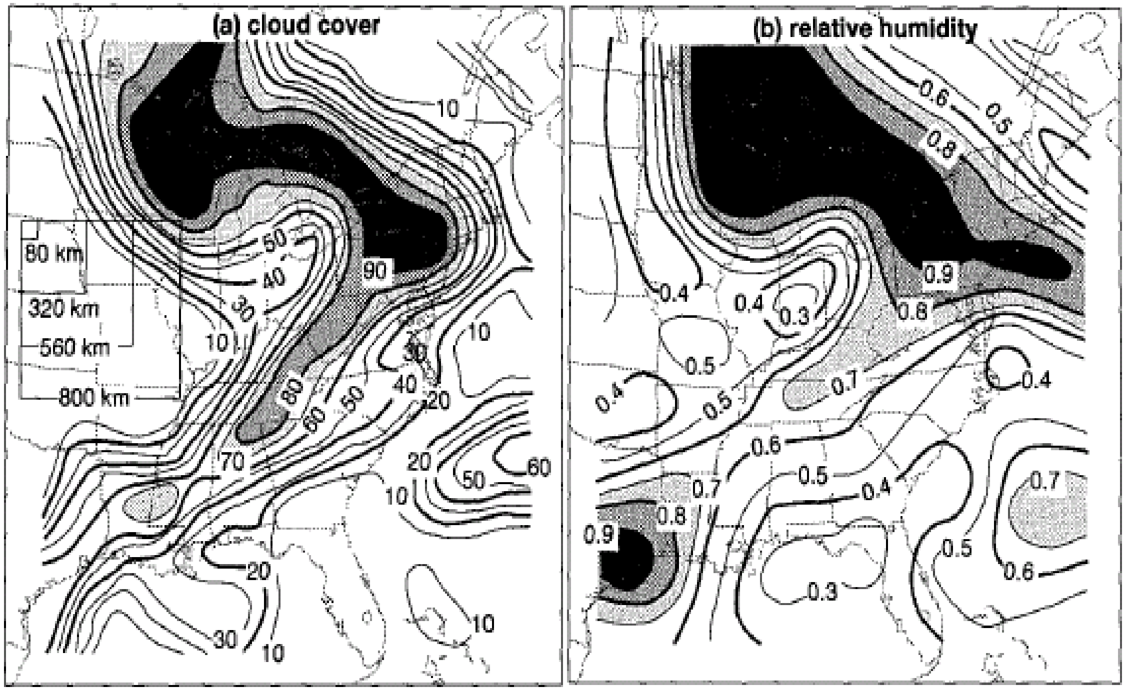
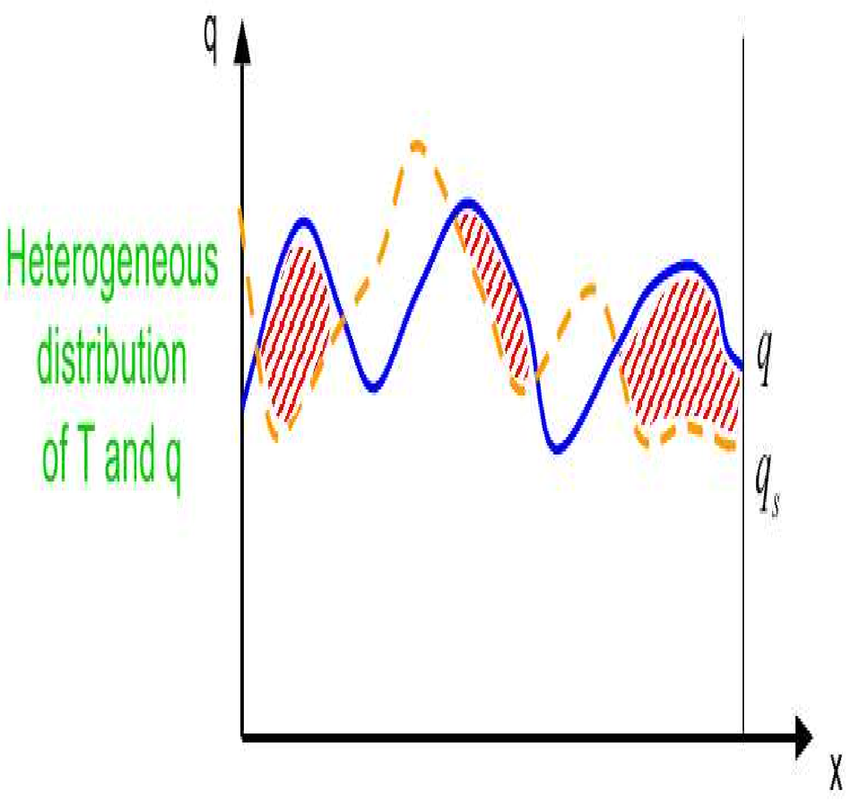


FIG. 2. (a) Cloud cover and (b) relative humidity averaged over (320 km)^2 areas in the layer 800–730 mb at 1800 UTC 23 April 1981. Cloud cover extracted from the U.S. Air Force 3DNEPH compilation of surface reports, aircraft observations, and satellite-derived data. Inset boxes show averaging scales used in this study. Relative humidity interpolated from radiosonde observations in time and space using a hydrostatic mesoscale meteorology model.

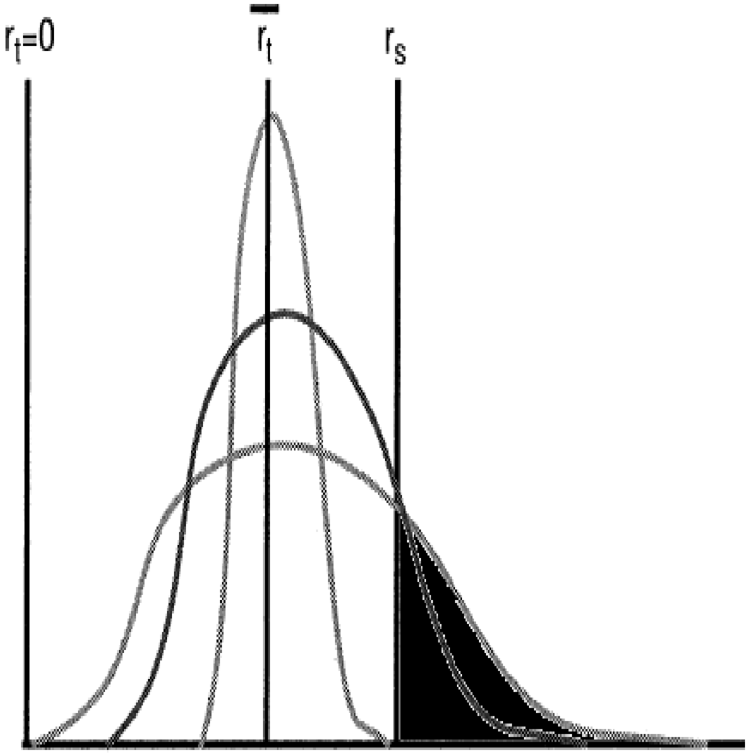
Cloud cover, $C > 0$ where $RH < 100\%$

Variability of T and q



- Imagine an aircraft flying across a grid box
- It encounters local fluctuations in q_t and T
- Where $q_t > q_{\text{sat}}(T)$ there is cloud
- This may happen in only some parts of the track

Cloud cover



- Plot all values of q_t as a histogram (PDF)
- Cloud amount is the integral over the saturated portion of the pdf of total mixing ratio
- Saturation value can also vary because T fluctuates also

Relative importance of T' and q'

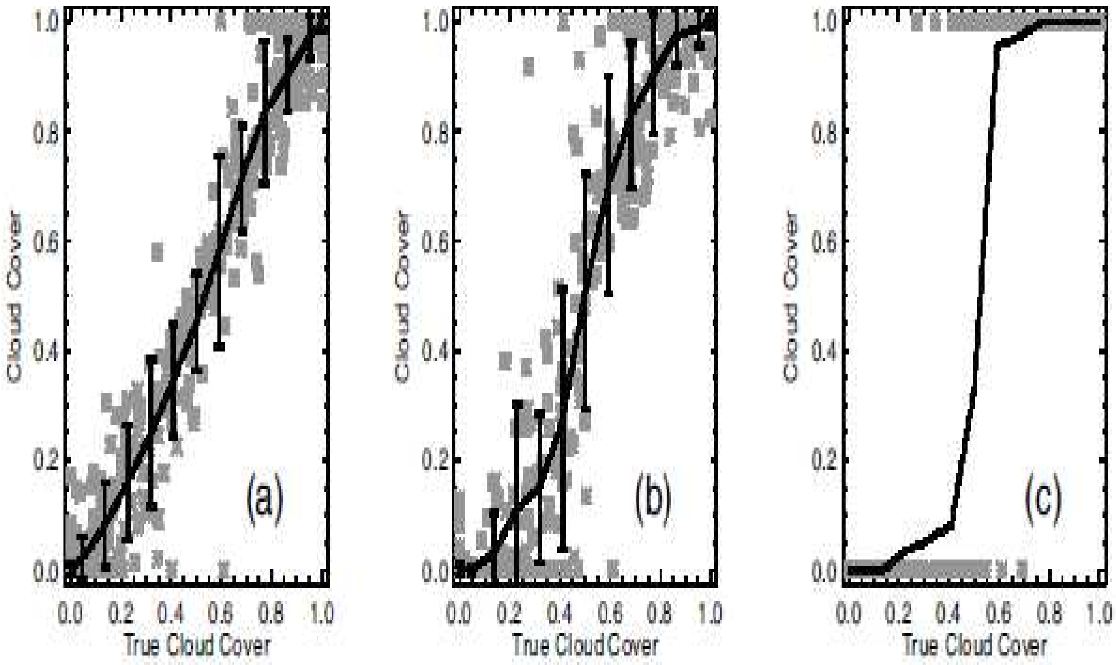
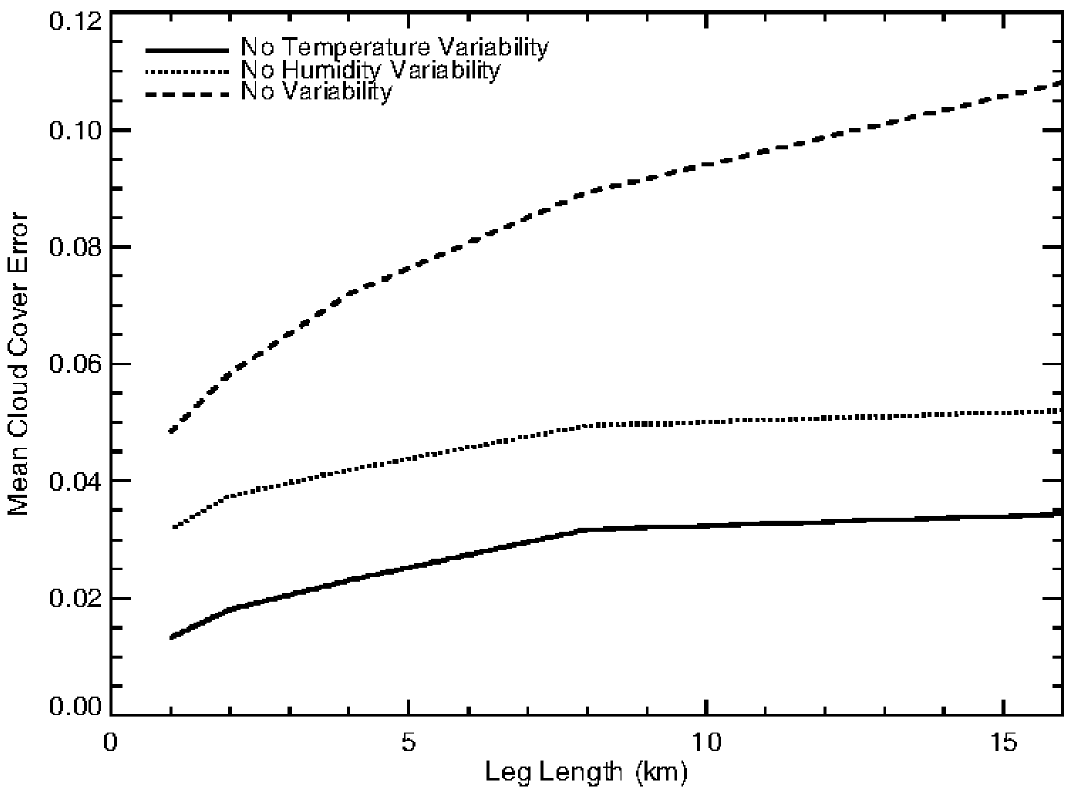


Figure 4. Scatter plots of apparent cloud cover versus true cloud cover when (a) temperature, (b) humidity and (c) all variability is neglected. The line gives the mean of the binned data, with the vertical bars indicating plus/minus one standard deviation for each bin. Calculation is shown for leg length $\mathcal{L} = 4$ km.

4km flight tracks, neglecting (a) T' (b) q' (c) T' and q'

Relative importance of T' and q'



Variability more important as length scale increas

Relative humidity methods

“Critical” relative humidity

- Define a critical RH as the minimum needed for non-zero cloud cover
- For intermediate RH interpolate using

$$C = 1 - \sqrt{\frac{1 - RH}{1 - RH_{\mathrm{crit}}}}$$

- Why this formula?

Cloud cover "derivation"

- A fraction C of the box is at saturation and a fraction(1-C) is at RH_{clear}

$$RH = C + (1 - C)RH_{\mathrm{clear}}$$

- Now assume that the clear RH is given by a reference value plus a linear correction depending on cloud cover

$$RH_{\mathrm{clear}} = RH_{\mathrm{ref}} + C(RH_{\mathrm{clear}} - RH_{\mathrm{ref}})$$

- Eliminate RH_{clear} and rearrange for C,

$$C = 1 - \sqrt{\frac{1 - RH}{1 - RH_{\mathrm{crit}}}}$$

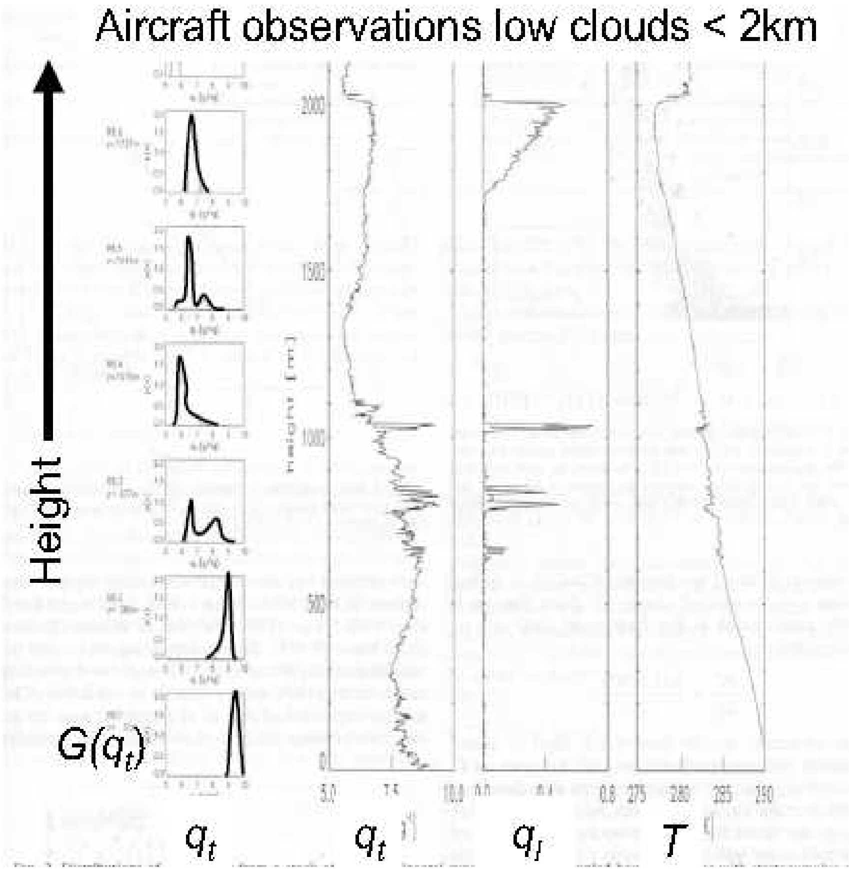
- where $RH_{\mathrm{ref}} = RH_{\mathrm{crit}}$

RH schemes

- Very simple to implement
- In practice RH_{crit} decreases with height
- And is reset (increased) when resolution improves
- The idea of a unique relationship between C and RH is overly simplistic
  - e.g., Roeckner et al 1996 in ECHAM increased C in the vicinity of a temperature inversion to resolve issues with Sc
  - Slingo 1987, modified C at mid-levels with factor proportional to ω_{500} (and set $C = 0$ for $\omega_{500} > 0$)

PDF based methods

Actual PDFs



Aircraft observations of low clouds by Wood and Field (2000)

Linearized saturation deficit

$$s = \frac{1}{a}(q_t - \overline{q_{\mathrm{sat}}}) \quad ; \quad a = 1 + \frac{L}{c_p}\frac{\partial \overline{q_{\mathrm{sat}}}}{\partial T}$$

- Note that some schemes operate with $P(s)$
- s comes from a linearization of the saturation curve, such that if local condensation occurs then $q_l \approx sa$
- $s > 0$ for locally cloudy air and $s < 0$ if clear
- Using $P(s)$ rather than $P(T, q_t)$ means we do not account for the separate fluctuations of T and q_t but rather consider a net effect implicitly assuming T and q_t correlations that apply for air close to saturation

Assumed PDF approach

If we have a PDF for s then we can determine

- cloud cover, $C = \int_0^\infty P(s)ds$
- liquid water content, $\overline{q_l} = \int_0^\infty sP(s)ds$

Assumed pdf approach does not try to represent full P(s) but instead takes a functional form for P with a few parameters to be determined

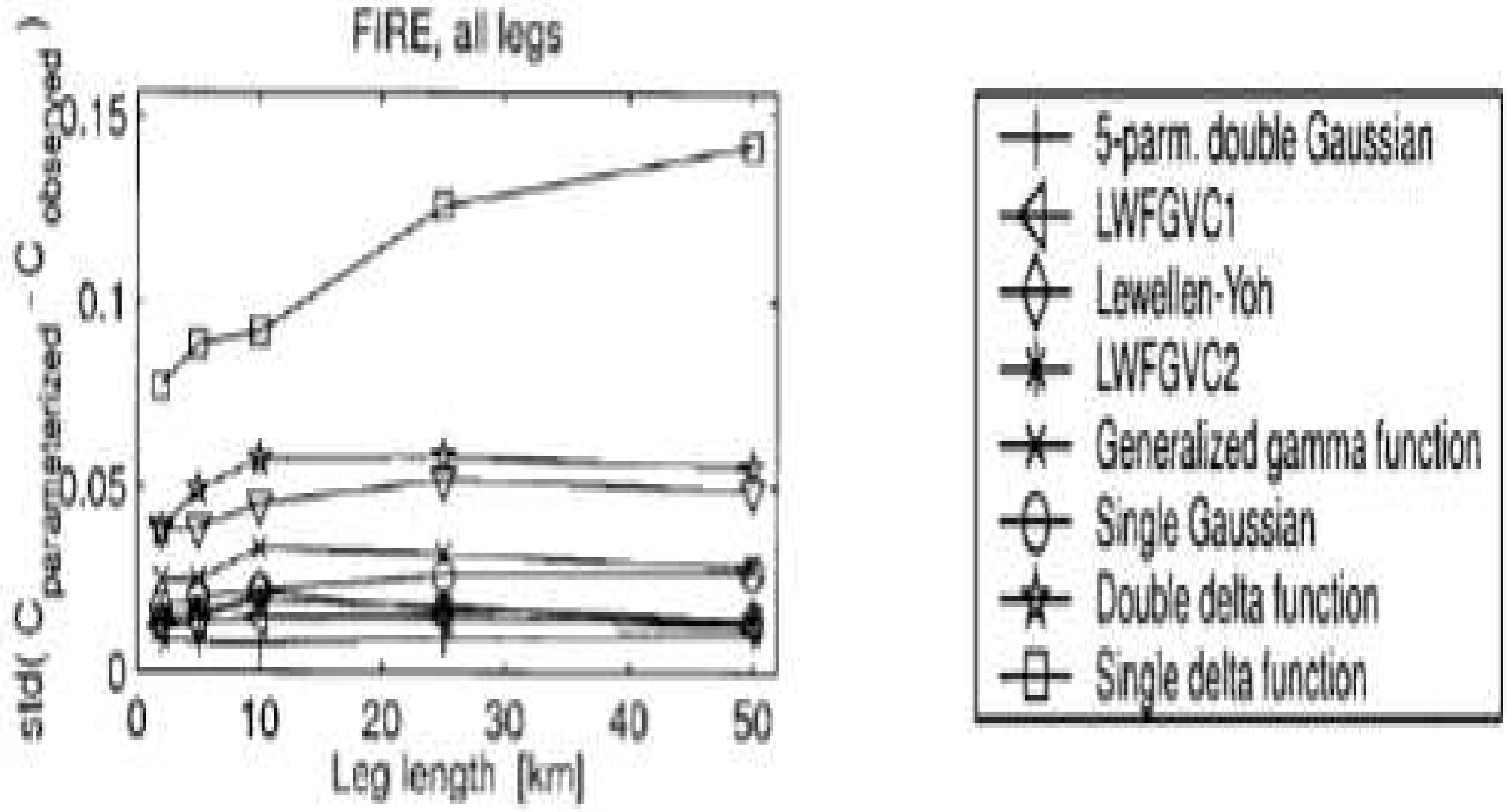
Many forms of PDF proposed

- no subgrid variability
- uniform (eg, LeTreut and Li, 1991)
- double delta function (eg, Fowler et al 1996)
- triangular (eg, Smith 1990)
- Gaussian (eg, Sommeria and Deardorff 1977)
- Gamma (eg, Tompkins 2002)
- double Gaussian (eg, Golaz et al 2002)
  may have 3 or 5 free parameters
- and more (polynomial, beta, log-normal, exponential...)

Possible forms of PDF

- Some of these are unbounded
  - $\implies C > 0$ never $= 0$
  - $\implies -$ve q values within the grid box, unless special steps are taken
- Quality of fit to observed C and $\overline{q_l}$ improves for more complex shapes
- But: more PDF parameters to determine somehow

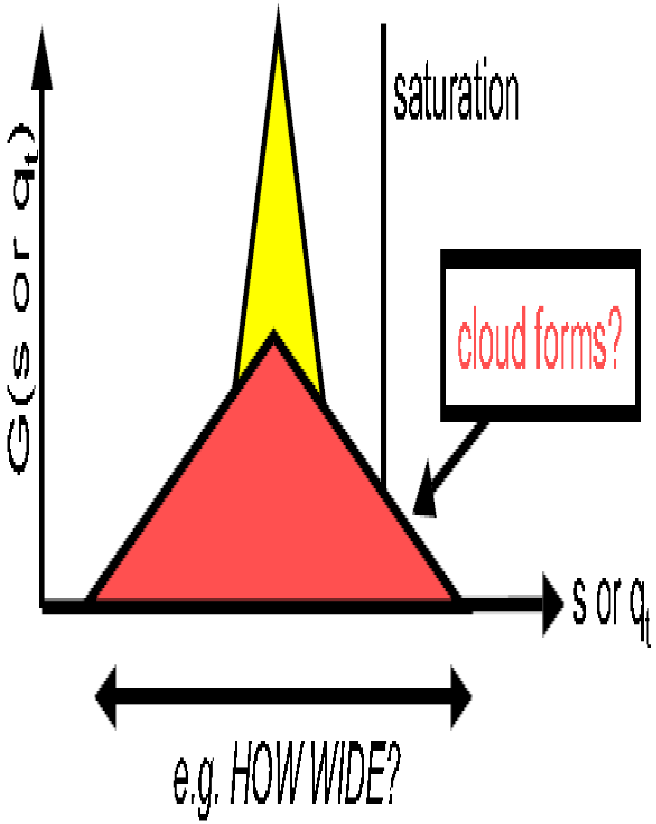
PDF testing


FIRE, all legs
std(C_parameterized − C_observed)
0.15
0.1
0.05
0
0
10
20
30
40
50
Leg length [km]
5-parm. double Gaussian
LWFGVC1
Lewellen-Yoh
LWFGVC2
Generalized gamma function
Single Gaussian
Double delta function
Single delta function

PDF testing

- Barker et al (1996) suggest that for high C the distribution is relatively simple and likely uni-modal
- Bi-modal or even multi-modal structures more common for low C
  $\Longrightarrow$ For Cu/Sc type clouds, a two parameter PDF is insufficient
- Tail of distribution more important and need something more complex
- Open Q: Consistent treatment of stratiform and Cu, or treat them separately?

Parameters of the PDF



- One parameter from q_t
- Another from variance of q_t^2 which we could estimate from turbulence scheme
- Others from other turbulent moments, or empirical

$$\frac{\partial \sigma_{q_t}^2}{\partial t} = -2\overline{w'q_t'}\frac{\partial q_t}{\partial z} - \frac{\sigma_{q_t}^2}{\tau} + \ldots$$

Diagnostic treatment if $\Delta t >> \tau$

A very simple PDF

- Consider a top-hat PDF that is uniform between two possibles values of q_t
- Let the width of the distribution be $2q_{\mathrm{sat}}(1 - RH_{\mathrm{crit}})$
- Algebra....

A very simple PDF

- Consider a top-hat PDF that is uniform between two possibles values of q_t
- Let the width of the distribution be $2q_{\mathrm{sat}}(1 - RH_{\mathrm{crit}})$

$$C = 1 - \sqrt{\frac{1 - RH}{1 - RH_{\mathrm{crit}}}}$$

- i.e., RH and PDF schemes are closely linked
- If a PDF is defined with fixed parameters it can be reduced to an RH scheme
- But an RH scheme does not necessarily have a realizable associated PDF

Prognostic Schemes

Recall

$$\frac{\partial \sigma_{q_t}^2}{\partial t} = -2\overline{w' q_t'}\frac{\partial q_t}{\partial z} - \frac{\sigma_{q_t}^2}{\tau} + \ldots$$

- For long lived cloud, with evolution over several hours we may want to carry an explicit memory
- e.g. could save σ_{q_t} across timesteps and retain LHS above

Tiedtke 1993

- First mainstream attempt and still popular
- Deal with C explicitly with sources/sinks due to various processes
- e.g. increase in cloud fraction due to cooling is determined in terms of how the cooling reduces q_{sat}

$$\left.\frac{dC}{dt}\right|_{\text{cond}} = -\left(\frac{1-C}{q_{\text{sat}}-q}\right)\frac{dq_{\text{sat}}}{dt}$$

  This Tiedtke derives by assuming a top hat pdf for moisture centered on the grid box mean value
- ie, an assumed pdf is still being used!

Tiedtke 1993

- Homogeneous forcing assumption used for various processes (eg, turbulent mixing)
  distribution of s is shifted left or right but shape is not changed
- Separate plausible assumptions made for effects on C and q_l
- A possible problem is inconsistency such that no PDF exists
  eg, if one of C and q_l is zero and the other not (in which case clear sky is imposed)

Tompkins scheme, 2002, 2003

- Neglects T'
- Uses 4 parameter gamma distribution of q_t with prognostic equations for the sources/sinks of 3 parameters of the assumed distribution
- Formulating sources and sinks of such parameters from eg, microphysical processes is difficult and somewhat ad hoc
- A fourth parameter is assumed as diagnosed from the other 3

Met Office UM, Wilson et al 2008

- Previously used an RH_{crit} scheme equivalent to a symmetric triangular PDF (Smith 1990)
- Now using a prognostic scheme for C and q_l

$$\frac{\partial C}{\partial t} = \left.\frac{\partial C}{\partial t}\right|_{\text{advection}} + \left.\frac{\partial C}{\partial t}\right|_{\text{rad}} + \left.\frac{\partial C}{\partial t}\right|_{\text{conv}} + \left.\frac{\partial C}{\partial t}\right|_{\text{micro}} + \left.\frac{\partial C}{\partial t}\right|_{\text{blayer}}$$

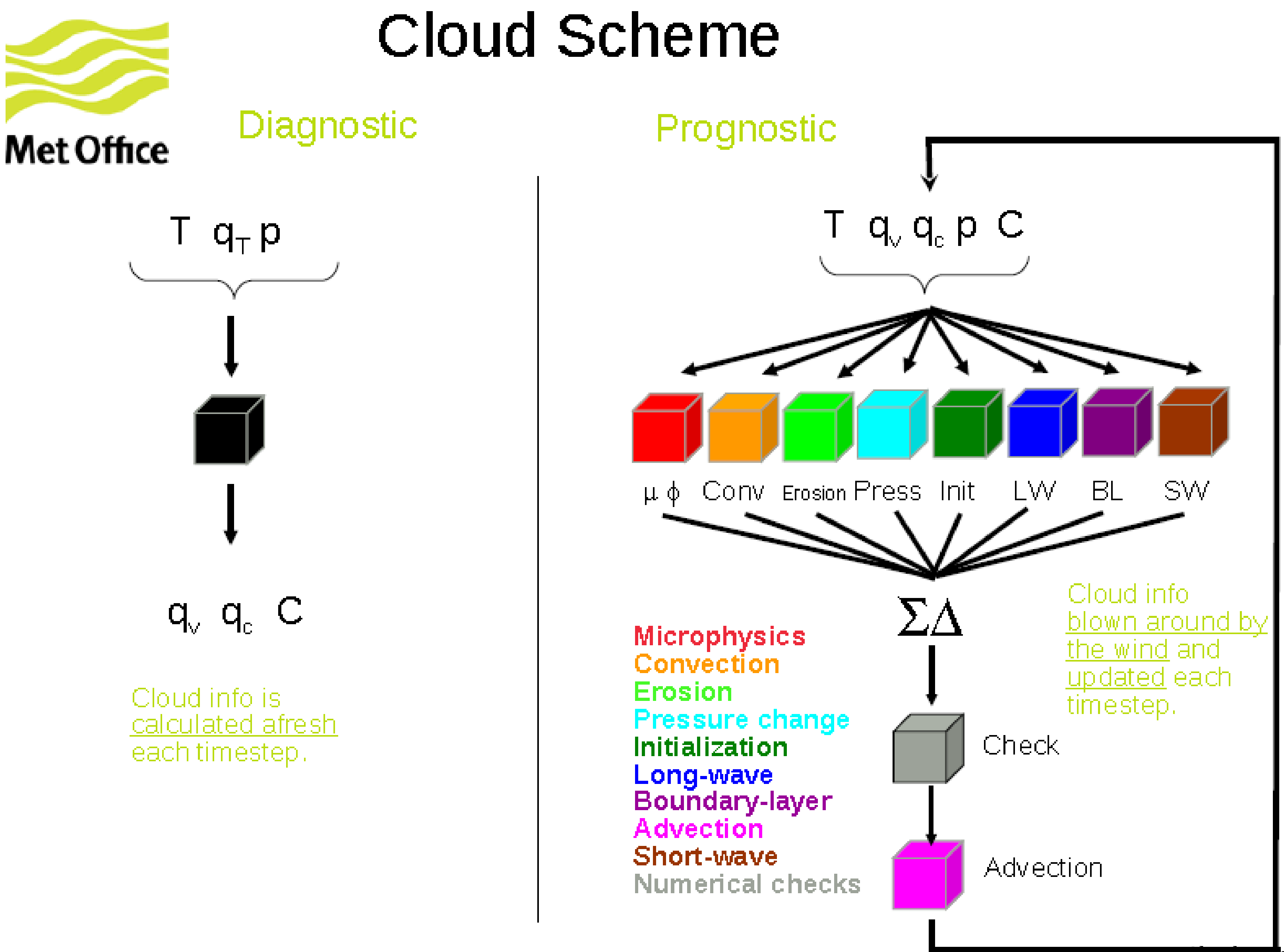
$$+ \left.\frac{\partial C}{\partial t}\right|_{\text{erosion}} + \left.\frac{\partial C}{\partial t}\right|_{\text{expansion}}$$

- Originally climate, global NWP, now at mesoscales
- Radiation, turbulence and expansion only alter q_t, not C, q_l

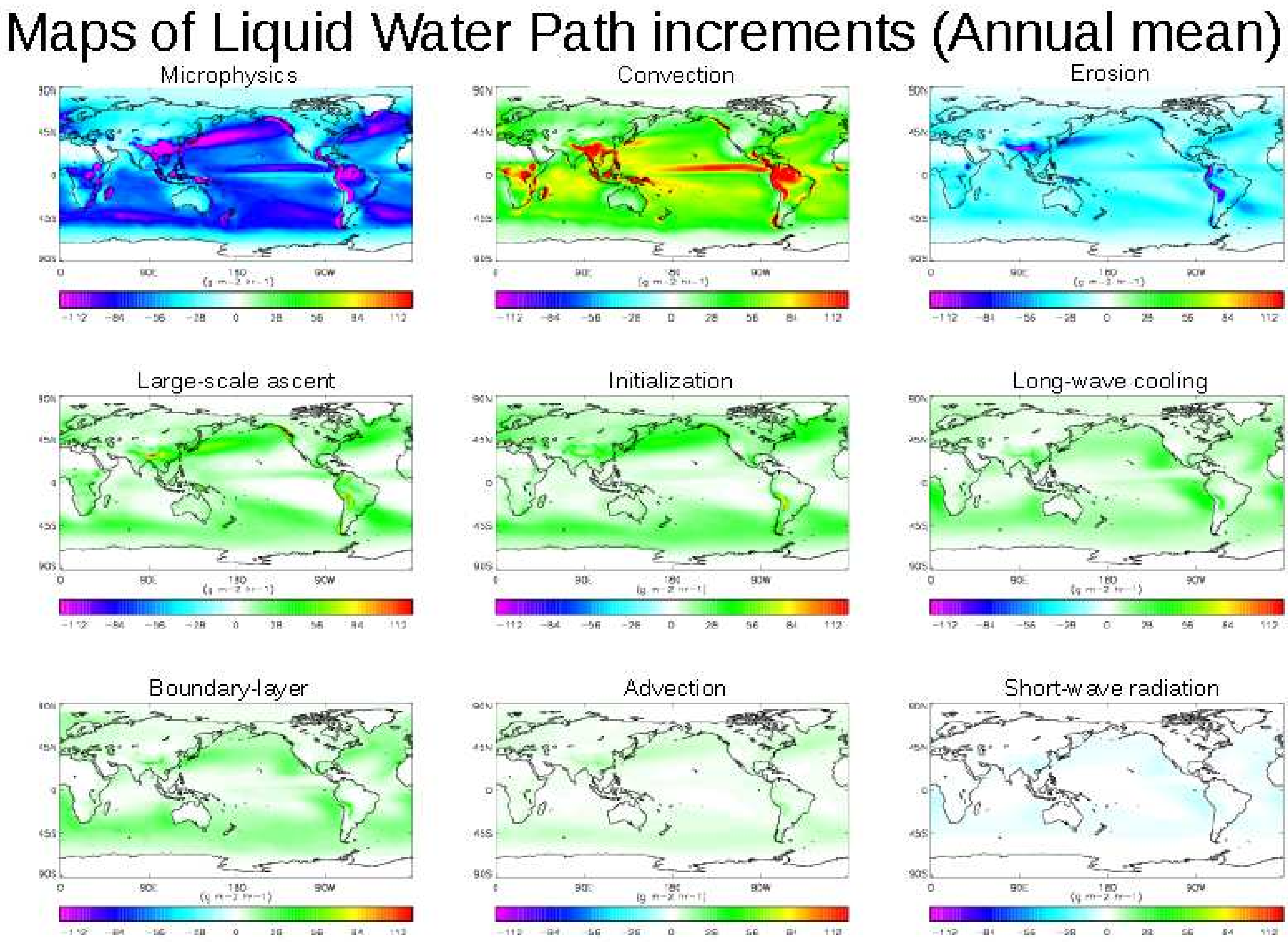
Met Office UM, Wilson et al 2008

- Need to be able to initiate cloud from clear skies
- Prognostic equations not always appropriate for doing so, as rationale based on assuming change sto pre-existing cloud
- Use the RH_{crit} scheme for initialization
- The scheme does not assume any PDF; it only computes moments

PC2 overview



PC2 decomposition



Joint PDFs: consistency with turbulence

Connection to turbulence

- Consider a joint PDF of w, a moisture variable and a thermal variable, $P(w, q_t, T)$
- Directly from the PDF we can perform various integrals to obtain $\overline{w'T'}$, $\overline{w'q_t'}$, $\overline{w'^7 T'^2 q_t'}$ as well as the cloud cover C, all in a fully self-consistent way
- For example

$$\langle w'q_t' \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} w'q_t' P(w', q_t', T') dw' dq_t' dT'$$

Connection to turbulence

- Especially important is the buoyancy flux $\overline{w'\theta_v'}$ in a partially cloudy area
- eg, for boundary layers including Sc or shallow Cu
- Key argument: it matters which values of w correspond to those locations where condensation occurs

Schemes with triple PDFs

- Lappen and Randall (2001), $P(w, \theta_l, q_t)$ as sum of two delta functions
- Golaz et al (2002), $P(w, \theta_l, q_t)$ as sum of two Gaussians
- Even a very simple assumed triple PDF has many free parameters
- These (and variations) are interesting research methods but currently too complex and expensive for NWP or GCMs

Fully consistent sub-grid approach

- Consider a PDF for all subgrid variables
- An evolution equation for this PDF can be rigorously derived theoretically (the Liouville equation) that respects the full dynamic and thermodynamic equation set of atmosphere
- A powerful approach in principle and useful for classifying all existing schemes in terms of different assumptions made to simplify it (Machulskaya 2014)
- An explicit Liouville equation has been carried in a few non-atmospheric LES problems but is incredibly expensive (cf DNS)

Conclusions

- Grid boxes of NWP size may be partially covered by cloud
- Simplest approach is to make C a function of RH
- Better (more flexible) is to assume a PDF shape and attempt to diagnose its parameters
- Better still is to prognose the parameters, but more difficult to develop and control such methods
- A joint PDF would be best, but not practical at present