THE SIGNIFICANCE OF CONVECTION IN NWP AND CLIMATE MODELLING

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INTRODUCTION

Our understanding of atmospheric convection and its role in the general circulation has advanced substantially in the last decade or two, as has our ability to represent the relevant physical processes in numerical models. NWP and climate models have reached a stage that demands increasingly sophisticated parametrizations; likewise forecasters are increasingly under pressure to predict the location and intensity of convective storms and systems such as squall lines and convective complexes. This note will briefly review the basic role of convection and its 'climatology', the way current ideas differ from more traditional concepts of larger scale/convective scale interaction, and acknowledges the critical part played by convection and its coupling with the planetary boundary layer in the problems of tropical/extratropical interaction and low-frequency variability.

Some emphasis is placed on the importance of shallow convection throughout, and is a deliberate attempt to redress what has arguably been an imbalance in earlier discussions of the significance of convection, and reflects in part the ideas discussed in Section 4.

1. GENERAL CONSIDERATIONS

Convection is responsible for supplying the atmosphere with the majority of the solar energy absorbed at the earth's surface. In so doing, convection communicates to the atmosphere the horizontal temperature gradients upon which larger-scale motions depend. Convection influences the large-scale circulation through:

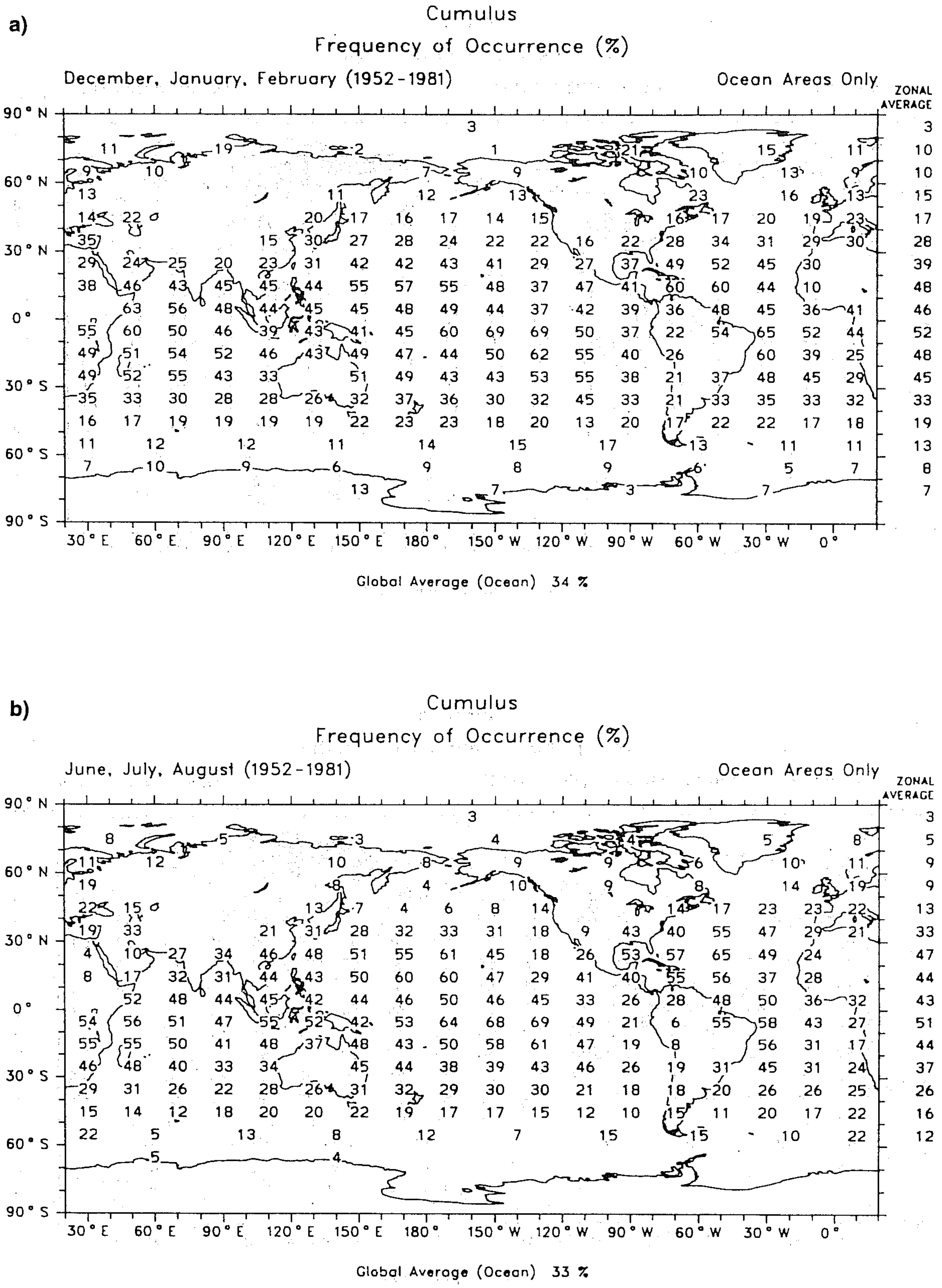
- Latent heat release
- Vertical transports of mass, heat, moisture, horizontal momentum and pollutants
- Convective cloud fields, which play a major role in the earth's radiation balance.

In the Tropics deep convection strongly couples the subcloudlayer entropy to the free atmosphere temperature and largely determines the moisture structure through the delicate balance between drying of the atmosphere by subsidence and moistening from convective fluxes and evaporation of precipitation. Estimates from models suggest that about three-quarters of the total condensate comes from convection, and more than half of this re-evaporates. Shallow convection in the Tropics occurs over the oceans virtually all the year round, and over much of the land where it modulates the diurnal cycle of surface fluxes and precipitation. For the oceanic boundary layer, shallow convection maintains the vertical structure of temperature and moisture by cooling and moistening the upper part of the PBL thus counterbalancing the warming and drying due to subsidence. This process ventilates the PBL by carrying water vapour up and mixing with the drier free atmosphere; this in turn promotes increased surface evaporation, and hence increased moisture supply for the inflow into the convergent regions of deep convection such as the ITCZ. Convection is a major process in determining the tropical climate, including the Hadley and Walker circulation, the monsoons and the superimposed high frequency transience epitomised by cloudclusters of varying scales.

Deep convection is responsible for many of the severe weather events e.g. floods, tornadoes, squalls, hail, lightning etc. Both in the tropics and higher latitudes, it sometimes becomes organised into larger scale systems such as squall lines, cloudclusters, MCCs etc. A particularly dramatic form is, of course, the hurricane/typhoon, a major challenge to the latest generation of forecast models in the tropics, and a problem for extratropical weather forecasting when they move poleward and become extratropical.

2. SOME STATISTICS

To illustrate the ubiquity of convection especially over the oceans, the reader is referred to the cloud atlases of *Warren et al* (1988), examples of which are shown in Figs 1a-c. These show that shallow (cumulus) convection is observed about half the time with a mean cloudcover of 10-15% over the oceans. An interesting further observation shown in Fig 1d is the remarkable uniformity in the observed cumulus cloudbase height which is between 500 and 600 m over much of the ocean throughout the year. There is a weak dependence on sea-surface temperature, but the statistics represent evidence for the quasi-balance and stability of the marine boundary layer which maintains a relative humidity of about 75-80% and a dewpoint depression of 4-5°K over a wide range of conditions. A more quantifiable statistic of convective


a)

Cumulus
Frequency of Occurrence (%)
December, January, February (1952-1981) Ocean Areas Only

Global Average (Ocean) 34 %

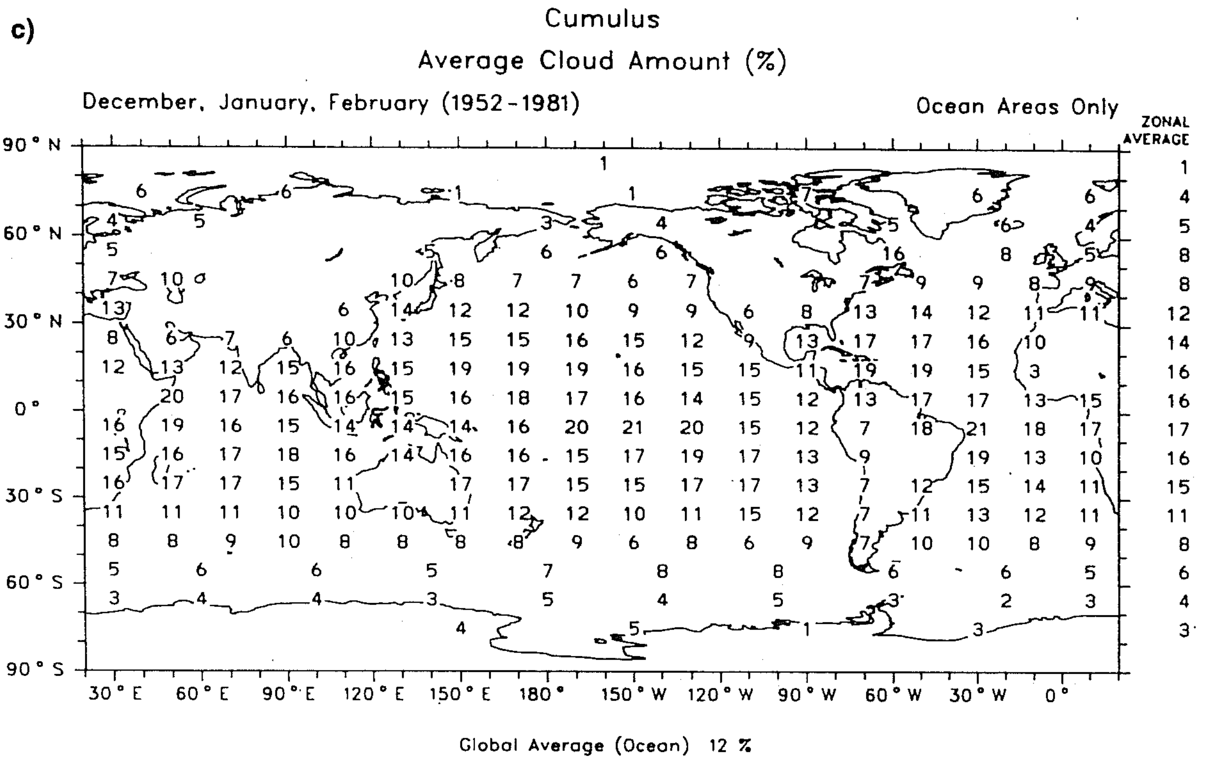
b)

Cumulus
Frequency of Occurrence (%)
June, July, August (1952-1981) Ocean Areas Only

Global Average (Ocean) 33 %

Fig 1 Climatology of cumulus clouds over the ocean (not cumulonimbus) (*Warren et al*, 1988)
a) DJF frequency of occurrence, b) JJA frequency of occurrence, c) DJF average cloud amount, d) DJF average base height.

c)



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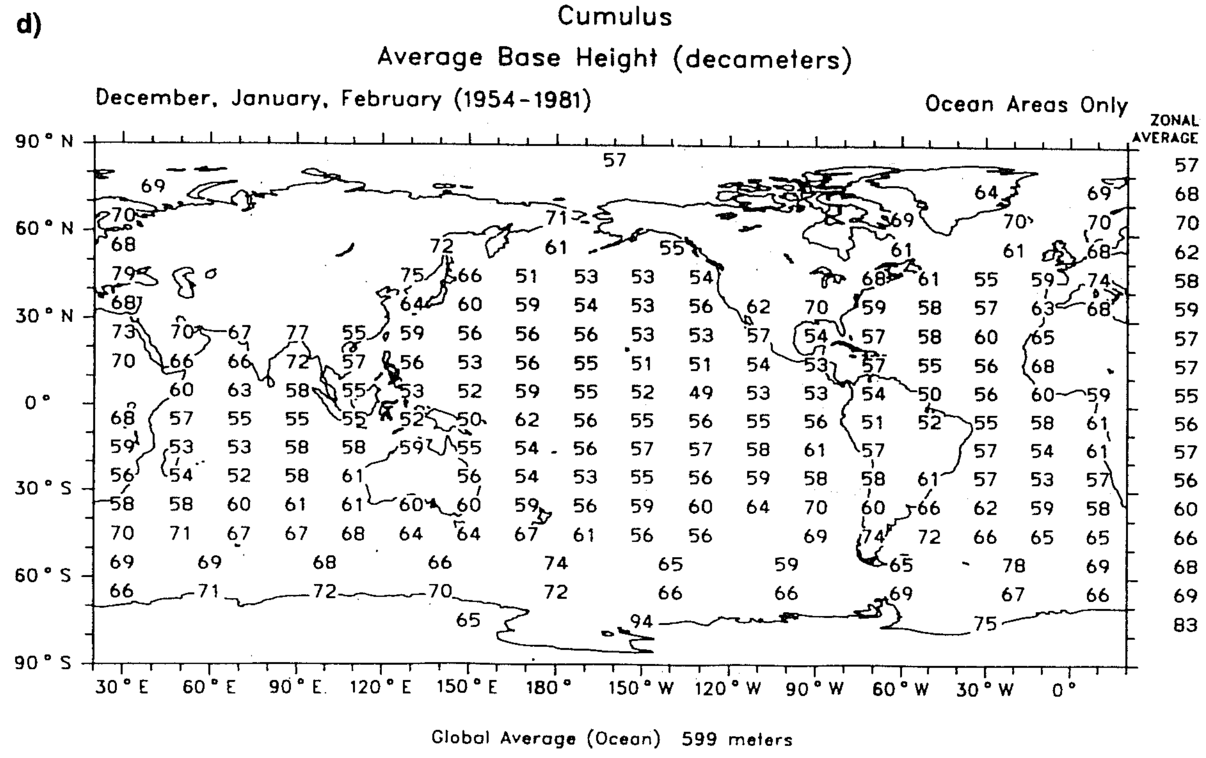


Fig 1 continued

activity can readily be made from model diagnostics. These inevitably reflect assumptions about model parametrizations, but should give reasonable insight into quantities such as cloudbase mass flux. Figs 2a,b show a 30-day mean distribution of convective mass fluxes at about 900 mb for July (see also Figs 3a,b for January diagnostics). While the fluxes for deep convection are unsurprising, with a distribution familiar from precipitation plots, those for shallow convection are perhaps less familiar, being dominated by the winter hemisphere oceans and higher latitude summer continents (as well as the subtropical oceans).

For the January example, Fig 4 shows the global mean vertical profiles of the component convective mass fluxes. The maximum in the boundary layer is marked and, although uncertainties in the model parametrizations could reduce this maxima by up to 20%, the basic distribution is clear. It is interesting to note that the mean values of shallow mass flux represent a cycling of PBL mass in about one day.

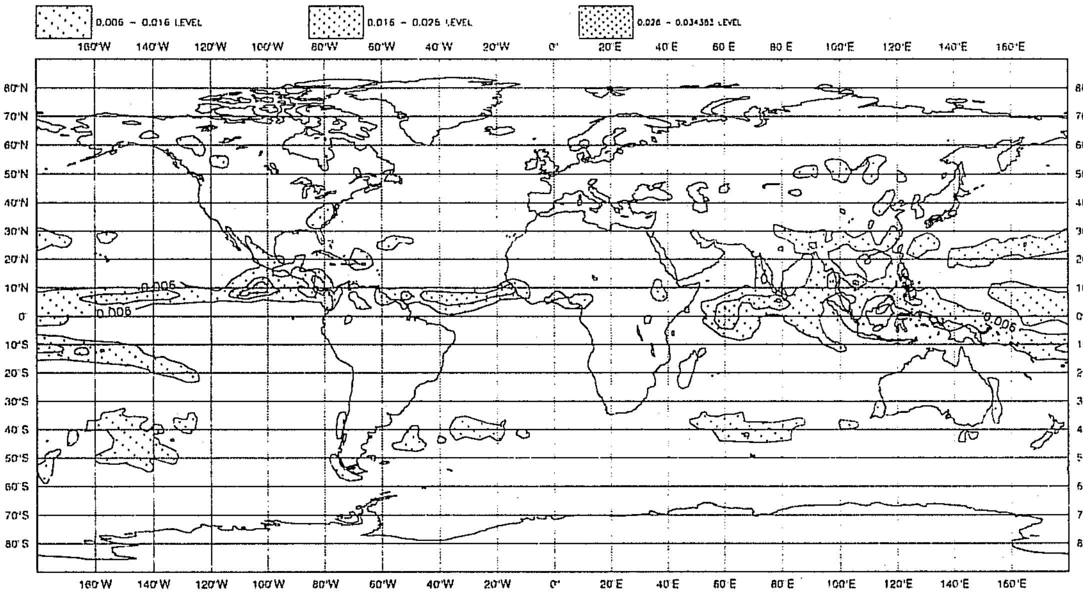
3. WINTERTIME CONVECTION OVER THE OCEANS

The marked maxima in the above massflux statistics over the wintertime oceans emphasises the major importance of convection in these areas as cold, dry continental and polar air is rapidly and extensively warmed and moistened as it advects over the relatively warm oceans. The ability to adequately represent the convection is essential to communicate the very large surface fluxes (~1 Kw/m^2) to the atmosphere and hence define the lower tropospheric baroclinity; this oceanic boundary layer air then takes part in further baroclinic developments etc. A cross-section of this convective activity as cold air moves out over the ocean is shown in Fig 5; the progressive deepening of the convective layer and transition from shallow to deeper convection is very apparent.

Forecast models often show error growth from these regions and it is likely that inaccuracies in modelling the physics in such conditions may be a significant factor. It is also interesting to note that recent studies of singular vector structures used in the ensemble prediction system often show maximum amplitudes in these regions in the lower troposphere.

a)

1/7/93
model level 27 mean deep conv mflx



b)

1/7/93
model level 27 mean shallow conv mflx

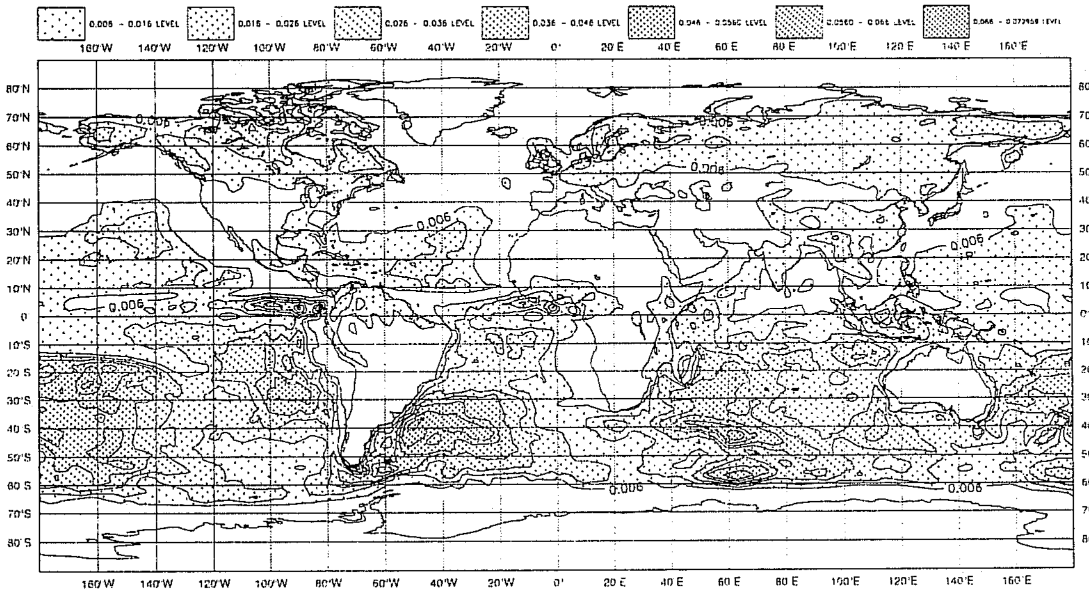
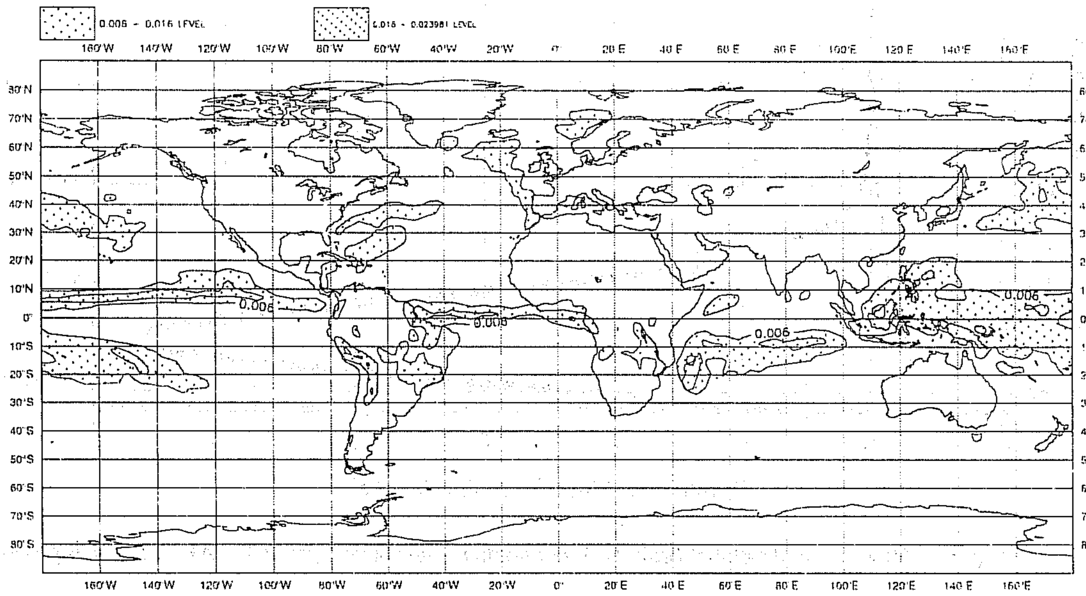


Fig 2 a) Mean deep convective massflux at about 900 mb from a 30-day T63 integration starting from 1/7/93.
b) Same as a) but for shallow convection (units: kg m^{-2} s^{-1}).

a) 1/1/94

model level 27 mean deep conv mflx



b) 1/1/94

model level 27 mean shallow conv mflx

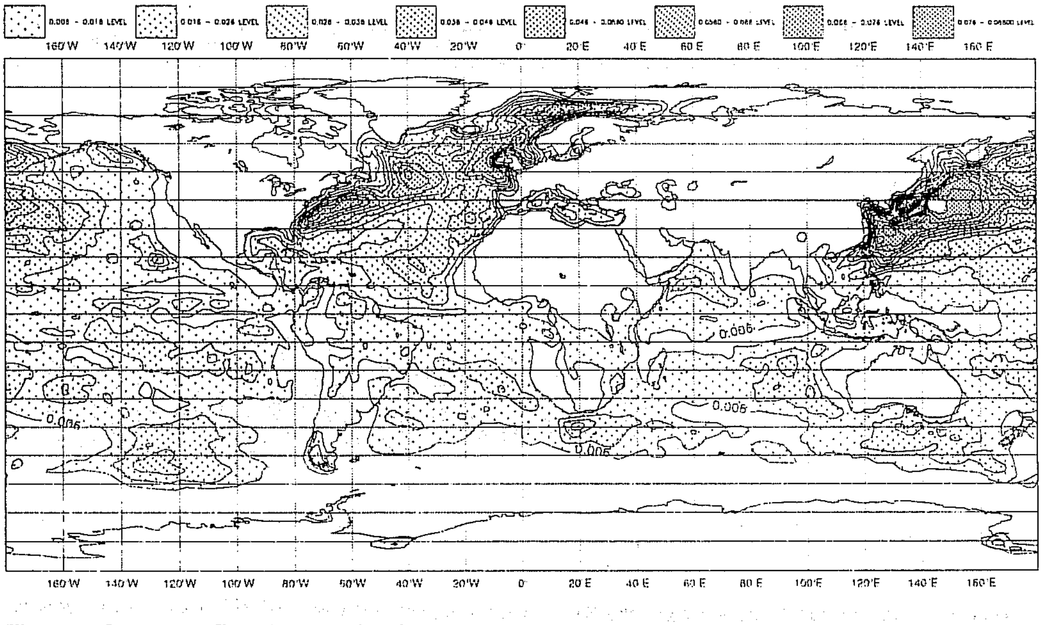


Fig 3 Same as Fig 2 but starting from 1/1/94.

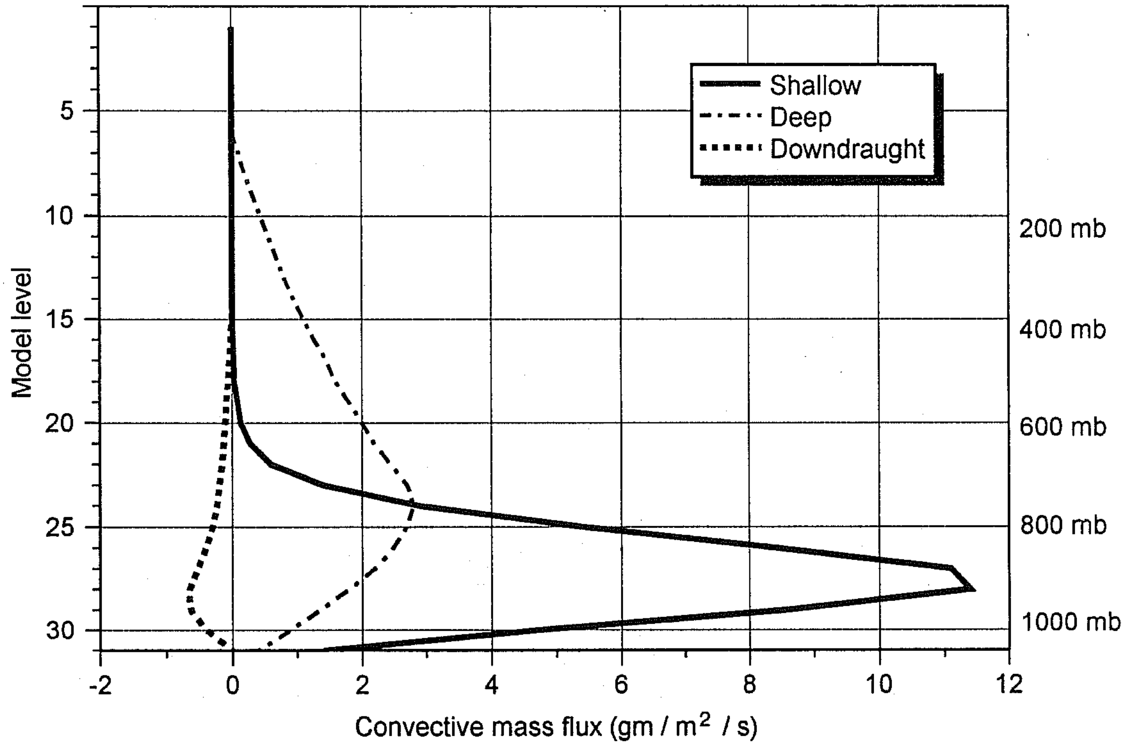


Fig 4 Global mean vertical profiles of convective massfluxes (from 1/1/94 30-day integration).

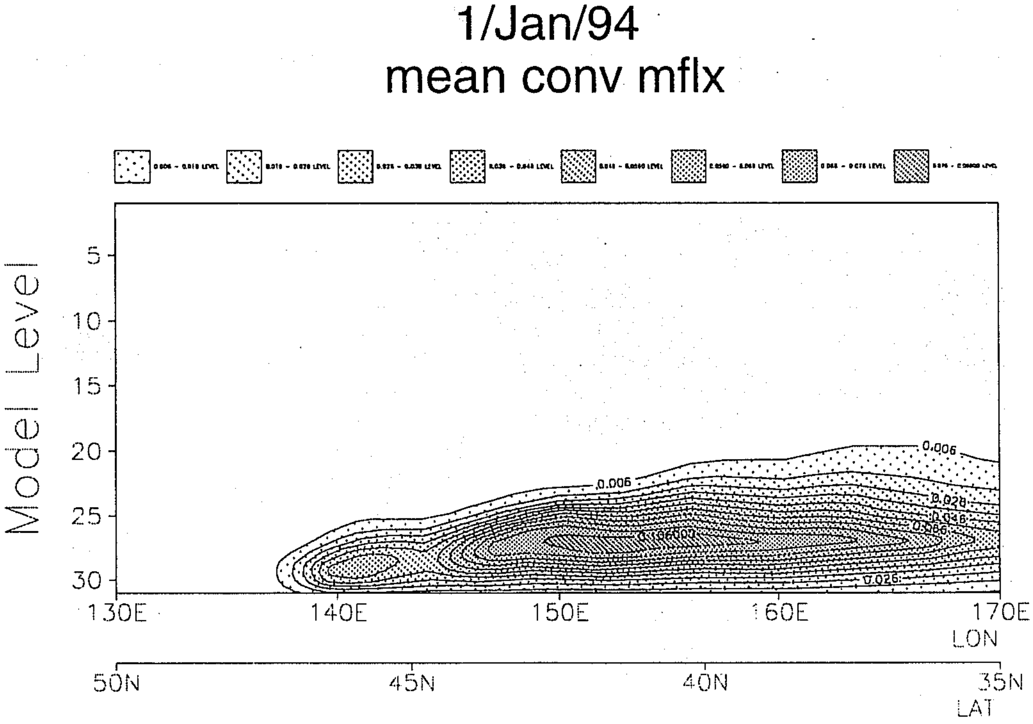


Fig 5 Vertical cross-section of mean convective massflux: approximately NW-SE near Japan (from 1/1/94 30-day integration).

4. CONVECTION AND ITS ENVIRONMENT

Although historically convection was studied mostly in the form of 'explosive' severe storms characteristic of the summer continents e.g. mid USA, the appreciation of the quasi-equilibrium that characterises atmospheres in which convection is a dominant process has been prominent in more recent studies. The ideas of *Ludlam* (1980), *Betts* (1973) for shallow convection and the parametrization approaches of *Arakawa and Schubert* (1974) and *Betts and Miller* (1986) are detailed in the book by *Emanuel* (1994), and promoted in *Emanuel et al* (1994). The reader is referred to these, but the following briefly summarises the concepts.

While accepting the relevance to forecasters of 'triggered' strong convection in situations of large Convective Available Potential Energy (CAPE), most atmospheric convection is in approximate statistical equilibrium with its environment (e.g. dry convective boundary layers, trade cumulus, stratocumulus and deep tropics). In these cases the temperature and moisture profiles are controlled by the convection, and the temperature tied directly to the subcloudlayer entropy. Thus there exists an intimate coupling between the convection and the processes which act to destabilise the atmosphere. Observations show rather small variations in CAPE compared to the generation rates of CAPE by subcloudlayer entropy changes for example. Application of the quasi-equilibrium concept and associated characteristic thermodynamic structure to the parametrization of convection has proved successful especially for global models integrated for longer than a few days. It is a more open question as to whether short-range, higher resolution forecasting (especially for the extratropics) needs a more general approach in order to capture the location, timing and intensity of showers and storms.

5. TROPICAL/EXTRATROPICAL INTERACTION

The fundamental phenomena of tropical/extratropical interaction, ENSO and related low-frequency variability depend critically on convection. For numerical models to capture the flow dynamics and variability associated with these large-scale phenomena, it is essential that the models adequately capture the temporal and spatial variations in convective activity, and its sensitivity to sea-surface temperature as the high correlation between SST and the occurrence of deep convection has been well-established. A critical process is the representation of the interaction of convection with the planetary boundary layer and the surface fluxes of heat, moisture and momentum. The coupling of these fluxes to the PBL properties and hence to the convection provides the link between sea-surface temperature and its gradients and the atmospheric flow. Likewise, the ability of convection to modulate the surface fluxes either through modifying the PBL thermodynamics or by the generation of turbulence provides feedbacks both in the atmosphere and ocean. No attempt will be made here to discuss in detail such a wide field which includes studies of:

- Direct interaction of tropical cyclones recurving into the extratropics

- Rossby wave dispersion from deep convection regions
    - 'PNA' type modes
    - Extra-tropical variability
    - Medium-range forecast skill

    (e.g. *Wallace and Guzler*, 1981; *Hoskins and Karoly*, 1981; *Palmer*, 1988)

- SST anomaly studies and seasonal forecasting possibilities (e.g. *Palmer and Anderson*, 1994)

- The impact of convection in the Indonesian/West Pacific region on model systematic errors and extratropical blocking behaviour (e.g. *Ferranti et al*, 1994).

- GCM relaxation experiments which study the sensitivity of extratropical errors to tropical ones and vice-versa.

6. REMARKS

This brief review of the significance of convection has considered rather broad issues. Two areas that have not been discussed are the related aspects of slantwise convection and convective momentum transports. While acknowledging the importance of both processes in specific circumstances, it would seem that the impact of these convective processes in NWP and climate modelling requires much more study. It may well be that a proper parametrization of these may significantly improve on current impacts, and lead to better models. On the other hand, current models do not necessarily display such large deficiencies that would indicate major shortcomings in convective processes.

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