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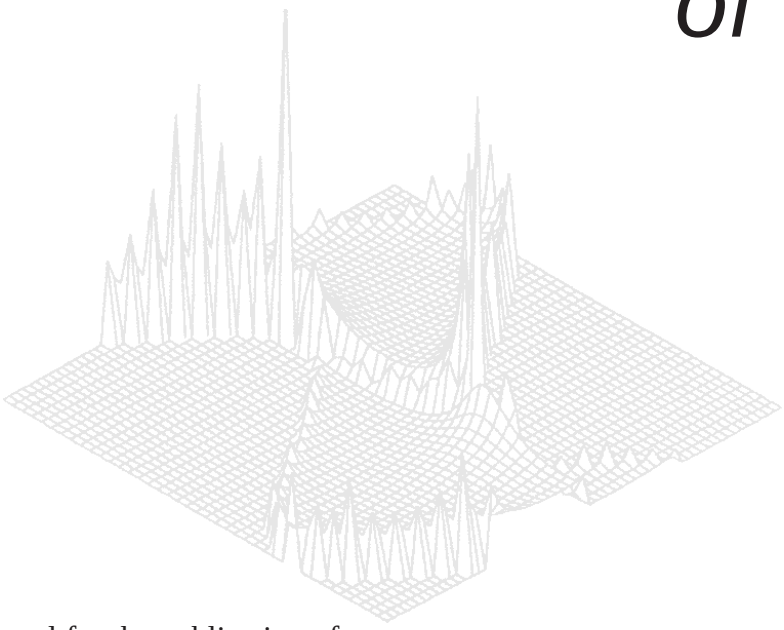

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Planetary-scale Coherent Structures of Tropical Moist Convection

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Abstract

Two competing pictures for planetary-scale moist convective coherency in the tropical atmosphere exist. The nonlinear turbulent picture emphasises the scaling nature of the system, whereas the traditional picture emphasises the characteristic scales associated with the variability. Some idealised simulations were performed as an initial attempt to reconcile these two competing pictures.

1. Introduction

A global picture of clouds from a geostationary satellite (e.g. Fig. 1 of Yano and Takeuchi 1987) shows that convective clouds form planetary-scale coherency, or large-scale organisation over the tropical oceans. This paper presents the author's attempt to look at such tropical convective coherency in analogy with two-dimensional turbulence. Such an approach is a tempting one, considering the substantial success in understanding the mid-latitude atmospheric system as a two-dimensional turbulence (cf. Rhines 1979). Since the flows are almost two-dimensional in the large scale of the atmosphere, even in the tropics, the extension of this analogy to the tropics appears to be natural, but it is to be applied under a coupling with convective moist thermodynamics. Note that atmospheric convection is normally accompanied by a phase change of water and ice, and the latent heating as its consequence. Such convective heating is crucial in simulating the tropical atmospheric system.

This nonlinear turbulent picture of the tropical atmosphere is best supported by the fractality of the horizontal structures of tropical clouds. The most intuitive way to demonstrate this point is to pick up two arbitrary segments (idealistically one belongs to a part of the other) and enlarge them by a different rate (see Fig. 2 of Yano and Takeuchi 1987): the difficulty of distinguishing the difference in the enlargement rates demonstrates that the characteristic of a horizontal pattern of the clouds is very similar over a wide range of the scales. Such a characteristic is called 'self-similar' and a geometrical pattern that satisfies this characteristic is called 'fractal'. This is usually considered as a signature of strong nonlinearity of the system such as fully-developed turbulence.

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A similar characteristic is found in the temporal direction as well. A slightly different way to demonstrate the point is to examine the frequency power spectra of, say, outgoing longwave radiation (OLR), which measures the infrared radiation from the atmosphere by satellite and reflects the height of the cloud top level. It is found that the OLR spectra closely follow a power law (Yano and Nishi 1989), which indicates 'self-affinity' (i.e. the corresponding concept for self-similarity in the temporal direction) of the tropical atmosphere. This again is a common signature of fully-developed turbulence.

As a whole, the two analyses indicate that there is no characteristic scale both in space and time in the large-scale tropical convective system. They are rather self-similar and self-affine in space and time, respectively, even though it does not deny an obvious fact that there is an upper bound to the scale of the motion due to the finite extent of the tropical atmosphere (and henceforth the finite size of the globe).

Such a nonlinear turbulent picture is strongly contrasted with the traditional picture that the tropical atmosphere consists of various phenomena with characteristic scales. The most notable among them are the so-called Madden–Julian waves (*or* equivalently, Madden–Julian oscillations, 40–50 day oscillations, 30–60 day oscillations), which were originally discovered by Madden and Julian (1971, 1972) and much delineated by more recent observational analyses (cf. Madden and Julian 1994). The Madden–Julian wave is normally interpreted to be initiated at the Indian Ocean as a convective anomaly accompanied by a low-level convergence, an upper-level divergence and a pressure anomaly. The whole structure, which scales over 5000–10000 km, starts to propagate eastwards as it enhances. Its activity reaches a peak over the Western Pacific, and the convective component almost dissipates out as it crosses the Dateline, although the dry dynamical component is observed to circulate around the globe. This single cycle is observed to take 40–50 days (or 30–60 days, depending on how the significant width of the spectrum peak is defined).*

The propagation of Madden–Julian waves is best graphically depicted by a time-longitude cross section of, say, OLR: it is seen that a puffy conglomerate of cloud convection moves eastwards with time. Although the clarity of such an eastward-propagating signature rather depends on a subjective judgement, it is clear that a Madden–Julian wave is accompanied by a substantial shorter time-scale component. Nakazawa (1988) examined such fine structure and pointed out that a hierarchical structure exists within Madden–Julian waves. In his standard picture, a Madden–Julian wave contains a few eastward-propagating cloud structures (super clusters) of 3000 km scale within. These structures tend to propagate at twice the speed of the Madden-Julian waves. A super cluster further consists of several cloud clusters of the 100 km scale, which tend to propagate westwards. Each such cloud cluster is known to consist of a few cumulus convective elements. Hence, Nakazawa proposed a picture of the tropical convective system consisting of a hierarchy of the convective organisations, each of which is characterised by the distinguished space and time scales. This picture

* It may be worthwhile to emphasise that, although this spectrum peak is determined to be statistically significant against a red noise background, it is not as much so against the power-law spectrum.

further leads to an attempt to describe these disturbances as a hierarchy of the linear waves.

Such a picture is in contradiction with the nonlinear turbulent picture presented above. Therefore, the main question to be asked is: how can these competitive views of the tropical atmosphere be reconciled? Some preliminary investigations intending to eventually answer this question are presented here. A picture proposed here is an analogy of the tropical atmosphere with the fully-developed two-dimensional turbulence, which is known to generate coherent vortices by nonlinear interactions from a random initial condition. Similarly, we speculate that the two-dimensional turbulent-like tropical atmosphere can generate a hierarchical coherency by its own nonlinear interactions from a random initial condition.

2. Idealised Experiments (1): Equatorial β-plane Case

A highly idealised atmospheric model is used for the present study (see Yano *et al.* 1995 for the details of the formulation: YM^2E hereafter). In order to achieve horizontal resolution as high as possible, the vertical resolution is sacrificed in maximum into only one vertical layer in the dynamical description, which reduces to a shallow water analogue. In order to describe vertical exchange of the thermodynamic quantities by moist convection, the evolution of moist entropy is described by two discretised layers: surface-boundary and the free atmospheric layers. The moist convective process, which plays a central role in this system, is represented by the so-called bulk mass-flux formulation. In our particular formulation, we divide the sub-grid scale vertical motion into three components: cumulus updraft, downdraft (both convective and one accompanied by shallow clouds) and environmental subsidence as a compensative circulation to the cumulus updraft (cf. Fig. 1 of YM^2E). The adiabatic cooling by cumulus updraft is assumed to be completely balanced by the accompanying latent heating by water condensation. Hence, the evolution of the dry entropy (temperature), which further defines the pressure field by hydrostatic balance, is solely controlled by the adiabatic heating by the environmental subsidence, as well as the horizontal advection and the radiative cooling. The last process is described by a sum of constant cooling and Newtonian relaxation. Both the downdraft and environmental subsidence contribute to dry the surface boundary layer by vertical advection of the upper dry, cold air. The surface boundary layer is stabilised as a consequence. It is recovered by the surface flux from the ocean surface, which is assumed to be proportional to both the surface wind speed and the dryness of the boundary layer. The moistening of the boundary layer as well as the radiative cooling at the free atmospheric layer eventually destabilise the atmosphere to trigger moist convection.

Several options are available to predict the sub-grid scale vertical motions. The problem is called the cumulus parametrisation problem in the meteorological community. Here I choose a scheme called the convective life cycle (CLC: Yano *et al.* 1998, which was originally called the grid column: cf. Yano *et al.* 1995, 1996), which appears to be largely consistent with the turbulent view of the tropical atmosphere presented in the Introduction. In this scheme, the cumulus updraft is accelerated by a model defined buoyancy whenever the latter remains positive. When the model buoyancy turns negative, the cumulus updraft is totally replaced by downdrafts of the same magnitude, and the latter decay exponentially

in time with a characteristic time-scale of 1·8 hours. The idea of this scheme is to mimic a typical life cycle of the convective system at a horizontal grid point.

The computation domain is taken to be a half globe size, extending from the south pole to the north pole in latitude, and the half length of the great circle (i.e. 180°) in longitude along the equator. The domain is periodic in longitude and side walls are imposed to the latitudinal ends. A plane geometry is assumed with a local linear approximation of the Coriolis factor around the equator (the so-called the equatorial β-approximation): 128 × 128 grids were used over the domain. The computation is started from a random temperature distribution with no motion.

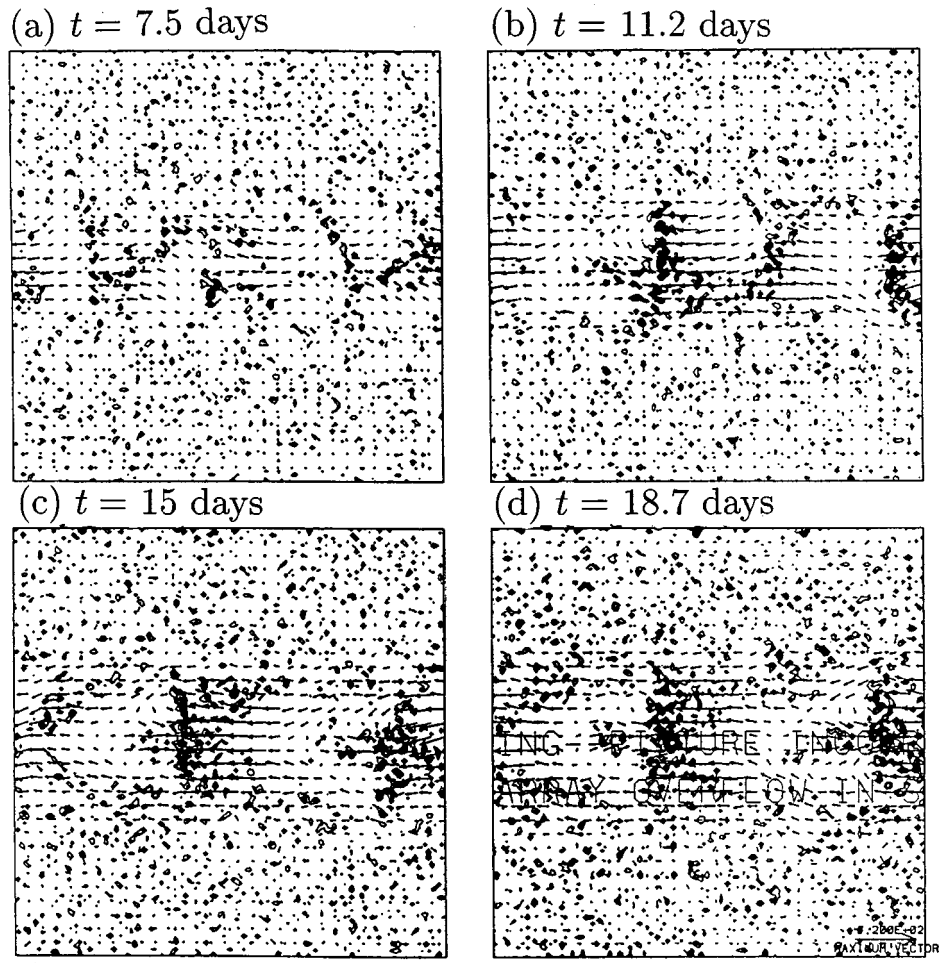

Fig. 1. Temporal evolution of the cloud field from a random initial condition (standard case on the equatorial β-plane): (*a*) $t = 7{\cdot}5$ days, (*b*) $t = 11{\cdot}2$ days, (*c*) $t = 15$ days and (*d*) $t = 18{\cdot}7$ days. Also shown are the wind vectors with a unit of 20 m/s shown at the bottom right.

The evolution of the system is shown in Fig. 1 in about a 3·7 day interval starting from day 7·5. Coherent cloud structure is gradually generated from the random initial state. By day 7·5 (Fig. 1*a*), four cloud clusters are organised

along the equator. After a merger of two and the growth of two others, three super clusters are recognised on day 11·2 (Fig. 1*b*). Two super clusters merge together to create a single one by day 15 (Fig. 1*c*). The two super clusters remain stable for the remainder of the time integration (Fig. 1*d*). The structure of the simulated super clusters is reasonably close to the observed structure. Furthermore, smaller-scale organisations of clouds are seen to be radiated westwards from the core of super clusters (cf. Figs 3 and 4 of YM^{2}E). The latter can be identified as cloud-clusters. Hence, this idealised model simulates the hierarchy of the large-scale convective coherency in the tropical atmosphere.

The overall evolution of the cloud field with time is quite akin to the process of generation of coherent vortices by inverse cascade in two-dimensional turbulence (cf. McWilliams 1984). Evolution of the kinetic energy spectrum shows a gradual accumulation of energy to the largest scales with time (cf. Fig. 11*b* of YM^{2}E), which further supports this inverse-cascade picture. In order to test this hypothesis, an identical run was repeated with all the nonlinear advection terms

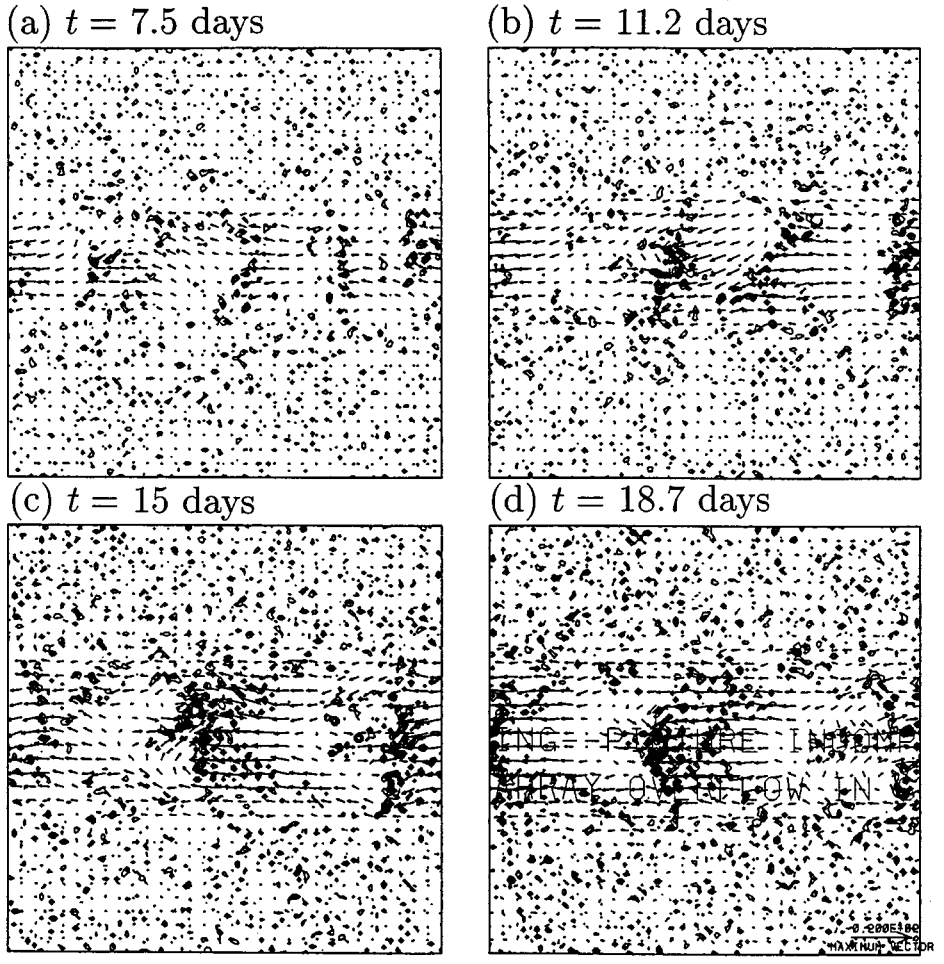

Fig. 2. The same as Fig. 1, but for the run without nonlinear advection terms.

removed from the system. The result shown in Fig. 2 is strikingly similar to the fully nonlinear case. The temporal evolution of the kinetic energy was also found to be very similar (cf. Fig. 12*b* of YM^{2}E). Hence, we conclude that the nonlinear advection terms, which play the central role in the inverse cascade in two-dimensional turbulence, do not play any crucial role in the emergence of the large-scale convective coherency simulated here.

In order to further assess the mechanism, in the last experiment, all the nonlinearity in the system is removed aside from the switch in the CLC scheme. This run was started from an initial condition that represents the zonal average of the equilibrated fully nonlinear system, which was obtained by using a 32×32 resolution run for 122 days. The system was linearised around this zonal mean state. Although this results in an exponential growth of the disturbance with

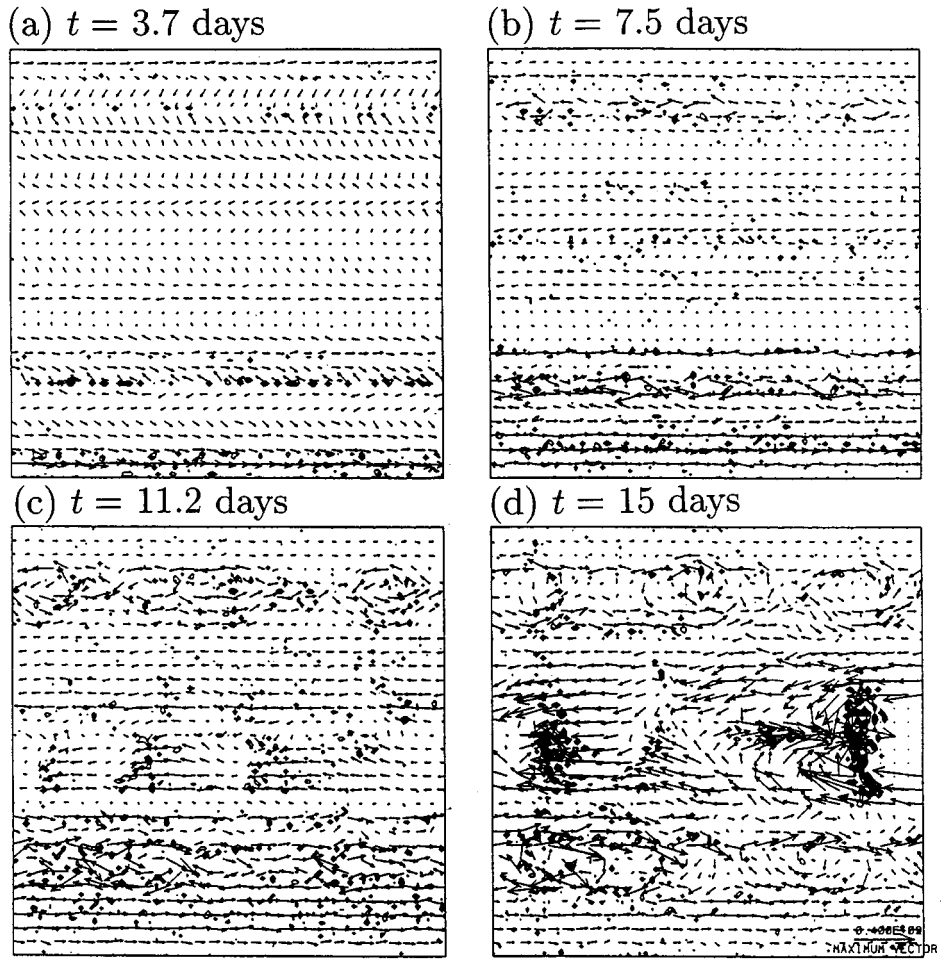

Fig. 3. The same as Fig. 1, but all the nonlinearity aside from the switch in the cloud representation is removed. The unit wind vector length is changed to 40 m/s. Also the frame starts from an earlier time: (*a*) $t = 3{\cdot}7$ days, (*b*) $t = 7{\cdot}5$ days, (*c*) $t = 11{\cdot}2$ days and (*d*) $t = 15$ days.

time, the overall feature of the evolution still indicates a tendency of mergers with time (Fig. 3). The evolution of the kinetic energy spectrum (Fig. 13*b* of YM^2E) is still remarkably similar to the fully nonlinear case, except that it is flatter at the largest scales. Consequently, we conclude that the merger process of cloud clusters to generate planetary-scale convective coherency is controlled by an implicit nonlinearity due to the switch in the cumulus parametrisation.

3. Idealised Experiments (2): Non-rotating Case

In the previous section, it has been shown that our idealised model can reproduce the observed planetary-scale convective coherency in the tropical atmosphere with a hierarchical structure. In this section, we further idealise the system by turning off the planetary rotation effect (Yano *et al.* 1996). The domain size is kept the same as the previous section, but the boundaries are changed to be doubly

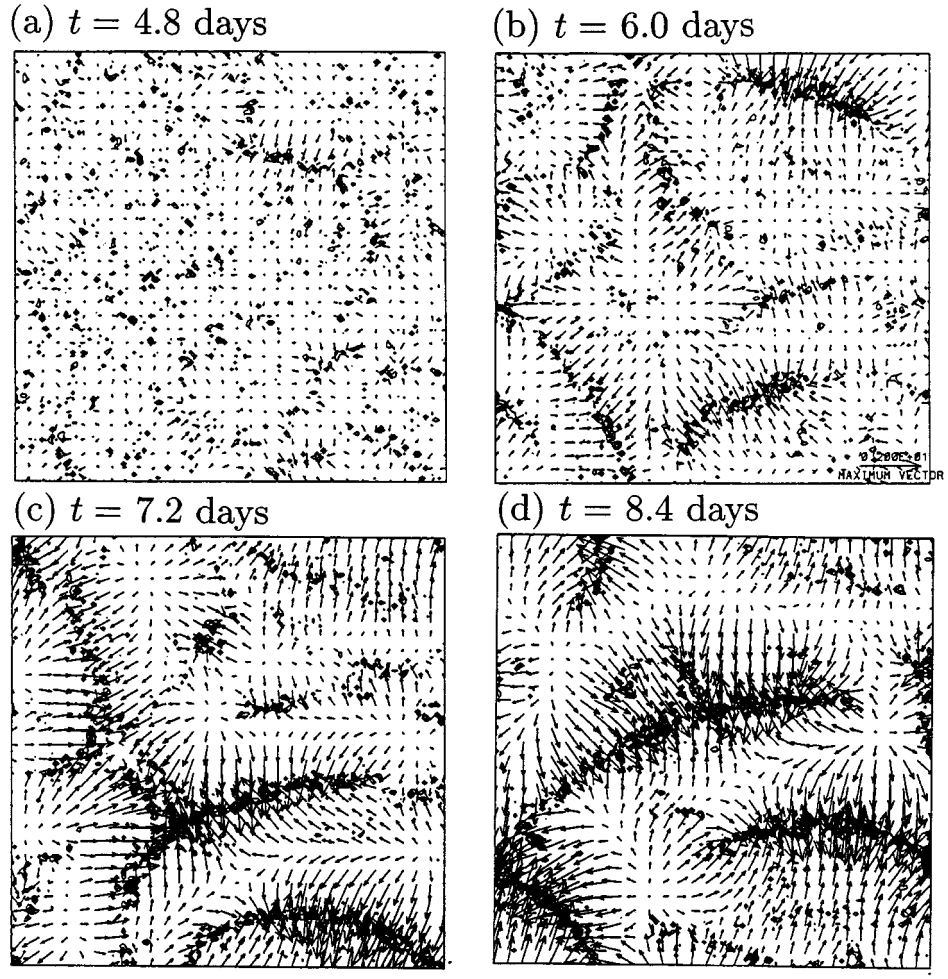

Fig. 4. Temporal evolution of the cloud field from a random initial condition (the case without planetary rotation): (*a*) $t = 4{\cdot}8$ days, (*b*) $t = 6{\cdot}0$ days, (*c*) $t = 7{\cdot}2$ days and (*d*) $t = 8{\cdot}4$ days.

periodic. Also, in order to see more detail of the cloud structure, the resolution is increased to 512 × 512 grid points.

The time integration was initiated with the same random initial condition for the temperature with no motion. The evolution of the cloud field with time shown in Fig. 4 is basically similar to the standard case (Fig. 1): a randomly distributed cloud activity gradually coalesces together to form larger cloud coherency (cloud clusters). A major difference is that due to the removal of planetary rotation, conspicuous easterly winds at the middle latitude (i.e. equator) no longer exist, and as a result, cloud activity is no longer confined to that region. The wind field is self-enhanced with time presumably due to a positive feedback with the cloud field (WISHE or wind-induced heat exchange instability: Yano and Emanuel 1991)*. The planetary-scale convective coherency generated at the final stage may be interpreted as a strong analogue of the squall-line type convective system (cf. Moncrieff 1995) accompanied by a strong wind perpendicular to the convection line.

Since the cloud distribution in this simulation is more homogeneous over the domain than the standard equatorial β-plane case, it is easier to test fractality of the cloud pattern generated. The change of the total perimeter length of the cloud areas with a change of the averaging scale was examined (Yano *et al.* 1996). It was shown that the curve obtained roughly follows the scaling law for the dimension $D \simeq 1{\cdot}8$. The dimension obtained is higher than the observed value $D = 1{\cdot}3$–$1{\cdot}5$ (Lovejoy 1982; Yano and Takeuchi 1987), and the degree of self-similarity is weaker than the observed case. Nevertheless, this is noted as a realism achieved by this idealised, but physically based simulation.

4. Summary and Discussion

The dynamics of the planetary-scale moist convective coherency in the tropical atmosphere were investigated by shallow-water analogue dynamics with a two-layer description of the thermodynamics. A representation (parametrisation) of sub-grid scale moist convective processes (cumulus clouds) is added as a crucial part of the tropical dynamics. As the most idealised case, we took a half globe size plane domain and ran the model without the Coriolis effect. Planetary-scale convective coherency is spontaneously generated by an initial random cloud field by a series of mergers of cloud clusters. Although the process is akin to the inverse cascade in two-dimensional turbulence, parametrised moist cloud convection plays a more important role than the nonlinear advections in this system. The final cloud distribution was shown to be fractal.

The inclusion of the Coriolis parameter (linearly approximated around the equator) introduces the planetary wave dynamics (cf. Pedlosky 1987), which tend to confine the atmospheric motions to the equatorial region. An equatorially trapped easterly zonal mean wind and high cloud activity along the equator are generated as a result. In the final stage, a two-level hierarchy of convective coherency was established: eastward-propagating coherency in the larger scale, and the smaller-scale westward-propagating features embedded in the former. Those are interpreted as an idealised reproduction of the observed super-clusters and cloud clusters, respectively.

* This view is confirmed in Yano *et al.* (1995) by removing the wind dependence in the surface flux.

The present study has been further extended to the case of the inhomogeneous distribution of the sea surface temperature (SST: Yano and McBride 1998). Our particular interest was the role of a high SST anomaly climatologically placed at the Western Pacific. This SST anomaly is known to drift in latitude with a seasonal cycle and we hypothesised that the seasonal transition from the normal state to the monsoon state of this region (i.e. West Pacific–Australia region) is controlled by such a seasonal cycle of the SST forcing. A major test of this hypothesis is whether a gradual seasonal evolution of SST can induce the observed sudden transition from the normal state to the monsoon state. We placed an idealised SST anomaly to the model with varying amplitudes and latitudinal positions. The response of the atmosphere to such an idealised SST anomaly was investigated with both time-independent and seasonally varying anomalies. A sudden transition from the normal to the monsoon state was simulated by a seasonal evolution of the idealised SST field. This simulation was reasonably close to the observed features of the Australian monsoon: the close association of high cloud activity with westerly-wind bursts, and active periods dominated by a cyclonic circulation.

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