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A GLOBAL RELATION FOR TROPICAL CYCLONE DEVELOPMENT

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1. INTRODUCTION

Fields of sea surface temperature (T) and evaporation rate (E) over the ocean are now readily available. In this paper, we consider the period (1979-2001) and use monthly sea surface temperature data from the Hadley Centre (Rayner et al., 2003) and three sets of monthly evaporation data, ERA40 (Uppala et al., 2004), NCEP (Kalnay et al., 1996) and NCEP2 (Kanamitsu et al., 2002), from which the annual average fields have been computed. Each field is then zonally averaged over the ocean - on the 2.5^0 latitude grid for the ERA40 data, and on the T62 Gaussian grid for the NCEP and NCEP2 data. From the results we plot ln E versus T for each hemisphere (Figures 1, 2 and 3), and consider in detail the subset for which T > 20 ^{0}C (Figures 4, 5 and 6). The data points correspond with the 23 years of record on each latitude grid. The aim is investigate the factors which control the evaporation regime in the subtropics and in the tropics, from which deductions can be made on tropical cyclone development.

It is apparent that there are differences in the evaporation fields obtained from the three reanalyses. In particular, the NCEP2 evaporation rates are higher than the NCEP and ERA40 evaporation rates especially in the tropics. There are also differences between the hemispheres, the southern hemisphere regressions being notably smoother (as might have been expected), although in both hemispheres the zonal variability is very well defined.

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2. THEORETICAL BACKGROUND

The classical aerodynamic bulk relationship for the evaporative mass flux is,

$$F = \rho_a K_E \mid \underline{u}_{10} \mid (q_s - q_{10}) \qquad (1)$$

in which F is the mass flux of water / unit area leaving the sea surface, ρ_a is the density of air, ρ is the density of freshwater, K_E is the drag coefficient for water vapour, q_{10} is the 10 m specific humidity, $q_s = q_s(T)$, is the saturated specific humidity at the sea surface , and $\underline{u}_{10}$ is the 10 m wind velocity (Bye 1996). On taking the logarithm of (1), we obtain the expression,

$$\ln E = \ln [\rho_a K_E / \rho] + \ln |\underline{u}_{10}| + \ln q_s + \ln (1 - r_s) \qquad (2)$$

in which $F = \rho E$ and $r_s = q_{10} / q_s$ which reduces to the relative humidity at 10 m for $T = T_{10}$ where T_{10} is the 10m air temperature.

On substituting for q_s from the relation,

$$q_s = \varepsilon e_s / p \qquad (3a)$$

in which e_s is the saturated vapour pressure, p is the atmospheric pressure and $\varepsilon = 0.622$ is the ratio of the molecular weight of water to that of dry air, and using the Clausius-Clapeyron relation,

$$\ln e_s = - [\varepsilon L / (RT)] + \text{const.} \qquad (3b)$$

in which T (K), $L = 2.5\ 10^6$ J kg^{-1} is the latent heat of evaporation and R = 287 J kg^{-1} K^{-1} is the specific gas constant for dry air (Gordon et al 1998), and differentiating (2) with respect to T, we obtain,

$$d \ln E / dT \approx \varepsilon L / (R T^2) + d \ln |\underline{u}_{10}| / dT + d \ln (1 - r_s) / dT \qquad (4)$$

where the first term on the right hand side arises from the Clausius – Clapeyron relation for the saturated vapour pressure, and the second and

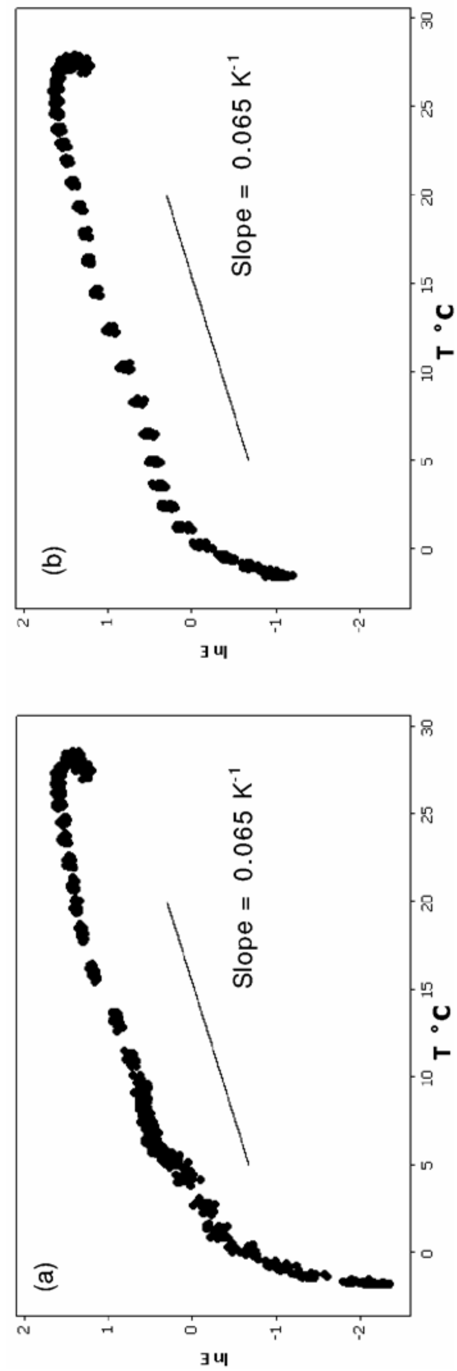

Figure 1: ln E versus T for ERA40 reanalysis. (a) NH (b) SH.

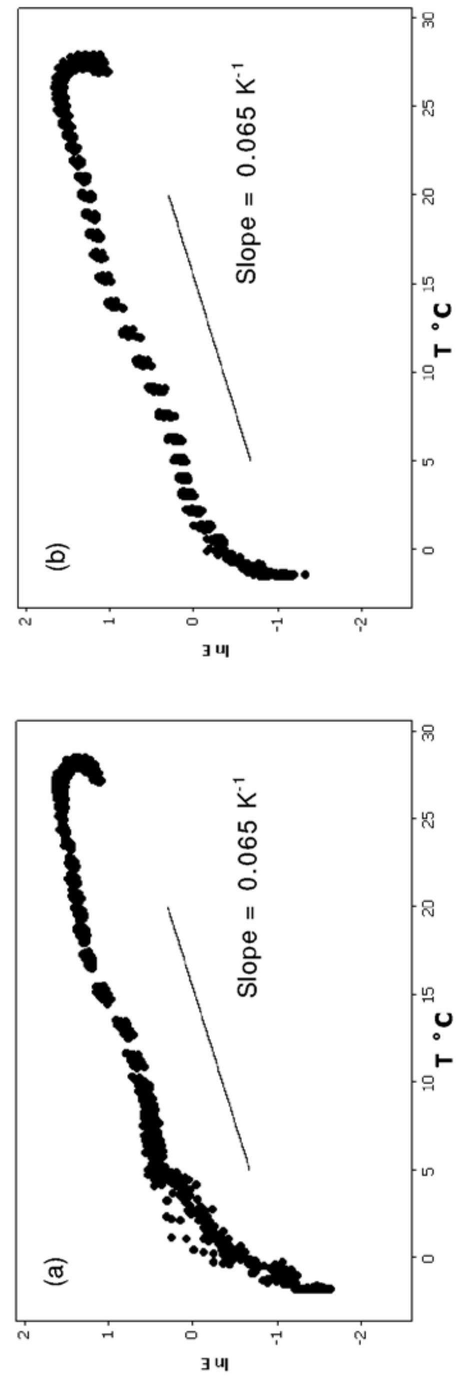

Figure 2: ln E versus T for NCEP reanalysis. (a) NH (b) SH.

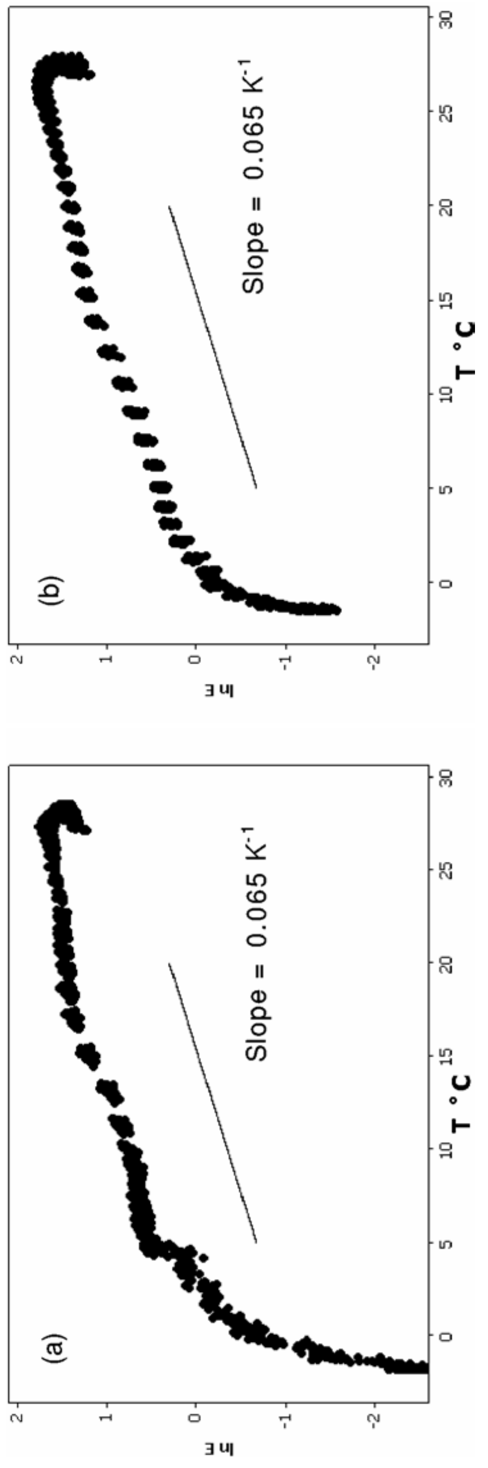

Figure 3: ln E versus T for NCEP2 reanalysis. (a) NH (b) SH.

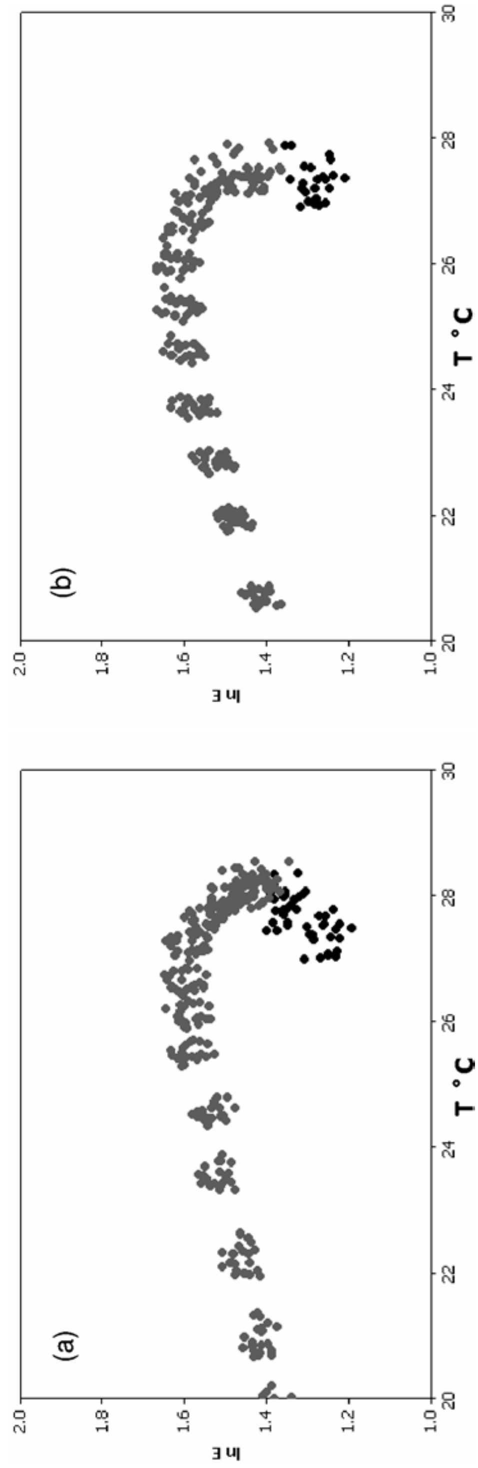

Figure 4: ln E versus T for ERA40 reanalysis (T >20˚C, φ >5˚ (grey solid circles), φ <5˚ (black solid circles). (a) NH (b) SH.

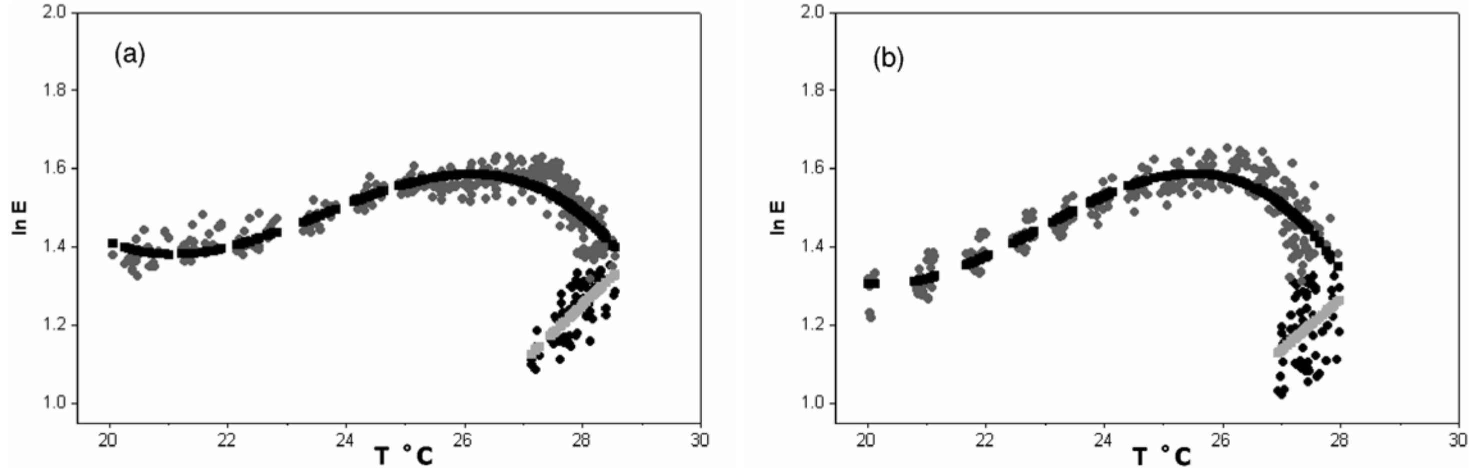

Figure 5: ln E versus T for NCEP reanalysis [T >20˚C, φ >5˚ (grey solid circles), φ <5˚ (black solid circles)], with fitted regression curves for φ >5˚ (black solid squares), φ <5˚ (grey solid squares). (a) NH (b) SH.

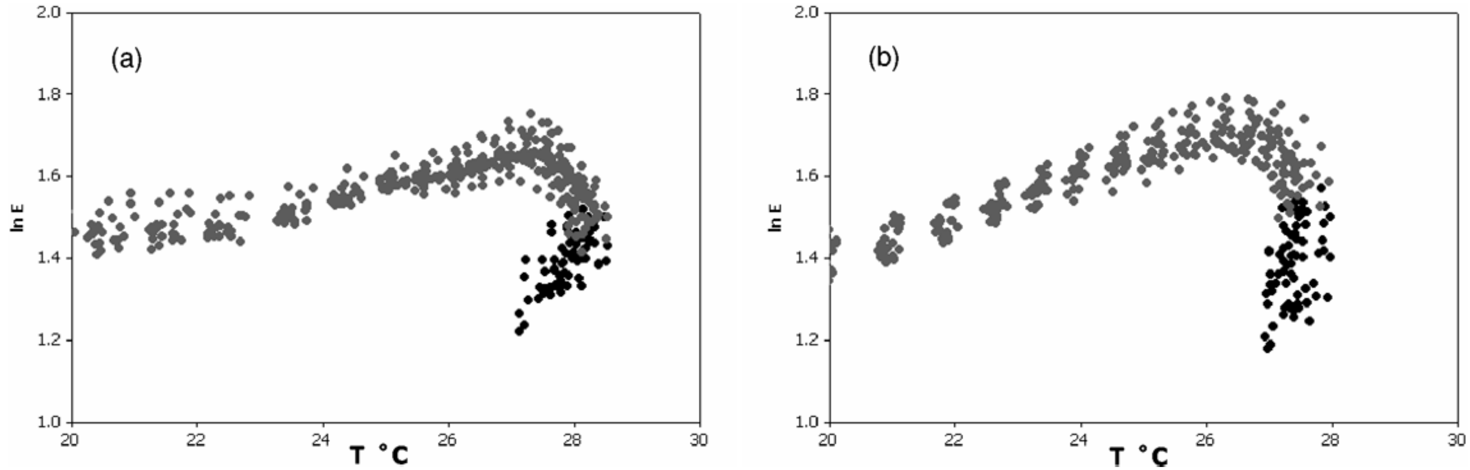

Figure 6: ln E versus T for NCEP2 reanalysis (T >20˚C, φ >5˚ (grey solid circles), φ <5˚ (black solid circles). (a) NH (b) SH.

third terms arise respectively from the wind speed and relative humidity variation with sea surface temperature, and the variation of (ρ_a K_E / ρ) with sea surface temperature has been neglected. For a sea surface temperature of 15^0 C, ε L / (RT^2) = 0.065 K^{-1} .

3. THE SUBTROPICS

Figures 1, 2 and 3 show that in the subtropics the evaporation gradient (d ln E / dT) is controlled almost completely by the Clausius-Clapeyron relation, as evidenced by the approximately linear slope of 0.065 K^{-1} between 5 and 20^0C. The combined effect of the second and third terms on the right hand side of (4) is small. This is due to the compensation which occurs between wind speed and relative humidity. In the westerlies and trades their respective values are greater than on the axis of the high pressure belt, where the winds are relatively light and the descending air is relatively dry, see for example Wells (1986).

To a first approximation therefore, in the subtropics evaporation is controlled by the thermodynamics. In the subpolar regions (which are not considered here) and in the tropics other factors become important.

4. THE TROPICS

The evaporation rate passes through a maximum (E_0) at the sea surface temperature (T_0) which both vary somewhat between the hemispheres (northern, NH and southern, SH) and the reanalysis fields. We will refer to the region, T > T_0 as the Tropics. Figures 4, 5 and 6 indicate that T_0 (^{0}C) and E_0 (mm/day) are respectively:

ERA40 NH 27, 4.9 , SH 26, 5.0 ; NCEP NH 27, 4.9 , SH 26, 4.9, NCEP2 NH 27.5, 5.2 , SH 26.5 5.5.

The temperature of the maximum evaporation rate corresponds approximately with the criterion usually adopted for the minimum sea surface temperature for tropical cyclone (TC) development, see for example Marks (2003).

In the tropics an evaluation of the third term on the right hand side of (4) indicates that the variation of relative humidity is of negligible importance, and by inspection it is clear that the first term also makes only a small contribution (which can be directly evaluated). Hence the evaporation gradient is essentially controlled by the variation of wind speed with a small correction from the Clausius-Clapeyron term.

We have added curve-fits for the NCEP reanalysis to the data (T > 20 ^{0}C) as being representative of the three fields (Figure 5). In the region, T > T_0 , the gradient , d ln E /dT reverses sign at the maximum temperature of approximately 28 ^{0} C, and for the most part, data points at latitudes ,φ > 5^0 occur in the upper quadrant (d lnE /dT > 0), whereas those nearer the equator occur in the lower quadrant (d lnE /dT < 0). From dynamical reasoning, around 5^0 is often stated as being the minimum latitude for TC formation, see for example Gray (1975). The regressions are:

NH: $\varphi > 5^0$, ln E = 42.05 -5.280T = 0.2264T^2 – 0.003198T^3 , r^2 = 77%

$\varphi < 5^0$, ln E = -2.808 + 0.1451T , r^2 = 53%

SH: $\varphi > 5^0$, lnE = 46.93 – 6.121T + 0.2709T^2 – 0.003943T^3 , r^2 = 81%

$\Phi < 5^0$, ln e = -2.359 + 0.1296T , r^2 = 15%

The higher confidence for $\varphi < 5^0$ in the NH arises from the pronounced retroflection in the data.

On expanding (εL / (RT^2)) about T = 0^0C, and evaluating , d ln E/ dT – εL/ (RT^2), we find for φ > 5^0 , that in the NH,

$$u/u_1 \approx \exp(-0.033\, t_1^2\, (1 + t_1)) \quad t_1 > 0 \quad (5a)$$

and, in the SH,

$$u/u_1 \approx \exp(0.004\, t_1^2\, (4 + t_1)) \quad t_1 > 0 \quad (5b)$$

where $t_1 = T - T_1$, in which T_1 = 24 ^{0}C, and u_1 is the wind speed at T_1 . T_1 is approximately the temperature at which the maximum trade winds occur.

The two-part regressions intersect at $T = T_2$, and for $\varphi < 5^0$ we find approximately that in the NH,

$$u/u_2 = \exp(0.069\, t_2) \qquad t_2 < 0 \qquad (6a)$$

where $t_2 = T - T_2$ and $T_2 = 29^0$ C, and u_2 is the wind speed at T_2 , and in the SH,

$$u/u_2 = \exp(0.057\, t_2) \qquad t_2 < 0 \qquad (6b)$$

where $T_2 = 28\ ^0$ C. The results for the two ranges have been combined in Table 1, which indicates that the wind speed decreases towards the equator throughout.

TABLE 1

Relative wind speed and sea surface temperature in the tropics

T	u/u_1	
^{0}C	NH	SH
24	1	1
25	0.99	0.98
26	0.96	0.91
27	0.89	0.78
28	0.76	0.60
29	0.60	-
28	0.56	0.60
29	0.52	0.57

These conclusions are (as they must be) in accord with the basic warm pool dynamics of the tropical ocean.

5. INFERENCES FOR TROPICAL CYCLONE DEVELOPMENT

The salient feature of Figures 4, 5, and 6 is that the domain in which tropical cyclones are known to develop appears on the plots of ln E versus T as a 'quadrant of instability' in which d ln E/ dT has a *negative slope..* We pose the question – is this mere coincidence?

The answer will be sought by expressing the evaporative mass flux relative to the 10m air temperature as was originally presented in Haney (1971). We obtain,

$$F = \rho_a K_E |\underline{u}_{10}|\, q_s(T_{10})\,(1 - r) + \rho_a K_E |\underline{u}_{10}|\, q_s(T_{10})\,(\varepsilon L/(RT_{10}^2))\,(T - T_{10}) \qquad (7)$$

in which the first term on the right hand side is independent of the sea surface temperature and the second term is proportional to the air-sea temperature difference ($T_{10} - T$), and $q_s(T_{10})$ and $r = q_{10} / q_s(T_{10})$ are respectively the specific humidity and the relative humidity at 10m.

In the tropics within the 'quadrant of instability', the first term in (7) dominates. Hence the evaporation rate is essentially controlled by the atmosphere, and following the arguments of Section 4, in particular by the variation of wind speed with temperature. This gives rise to the following simple system.

As one moves away from 5^0 towards the edge of the tropics at 26 ^{0}C, the evaporation rate and wind speed increase and the sea surface temperature decreases. Thus any disturbance traveling polewards enjoys an increasing energy source of latent heat, and is subject to a continually enhanced advection by the surface wind field.

We suggest that this evolution may be regarded as the overriding mechanism for tropical cyclone development. There are of course a host of other contingent factors, see for example Emmanuel (1999), however the relation between evaporation and sea surface temperature occurring in the 'quadrant of instability' in Figures 4, 5 and 6 appears to be the necessary condition.

6. ACKNOWLEDGEMENTS

The ideas discussed in this paper have evolved from results of a global stable isotope study presented in Kayaalp (2001).

7. REFERENCES

Bye, J.A.T., 1996: Coupling ocean-atmosphere models. *Earth-Science Reviews,* **40**, 149-162.

Emmanuel, K.R., 1999: Thermodynamic control of hurricane intensity. *Nature,* **401**, 665-669.

Gordon, A., Grace, W., Schwerdtfeger, P., and Byron-Scott, R., 1998: *Dynamic Meteorology: A basic course* , Arnold. London 325 p.

Gray, W.M., 1975: Tropical cyclone genesis. Dept. of Atmos. Sci. Paper 234 Colorado State Univ. Fort Collins CO. 121 p.

Haney, R.L., 1971: Surface thermal boundary condition for ocean circulation models. *J. Phys. Oceanogr.,* **1**, 241- 248.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D., 1996: The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteorol. Soc.,* **77**, 437-471.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J. J., Fiorino, M., and Potter, G. L.., 2002: NCEP-DOE AMIP-II Reanalysis (R-2), *Bull. Amer. Meteorol. Soc.,* **83**, 1631-1643.

Kayaalp, A.S., 2001: Application of rainfall chemistry and isotope data to hydro-meteorological modeling. Ph.D. thesis Flinders Univ. South Australia 273p.

Marks, F.D., 2003: *Hurricanes* 942 - 966 in Encyclopedia of Atmospheric Sciences. Holton, J.R., Curry, J.A. and J.A. Pyle (eds.). Academic P. Amsterdam, 2780 p.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., Kaplan, A., 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Res., **108**, 4407, doi: 10.1029/2002JD002670.

Uppala, S., Kallberg, P., Hernandez, A., Saarinen, S., Fiorino, M., Li, X., Onogi, K., Sokka, N., Andrae, U., and Da Costa Bechtold, V., 2004: ERA-40: ECMWF 45-year reanalysis of the global atmosphere and surface conditions 1957-2002. *ECMWF Newsletter* No. 101 - Summer/Autumn 2004, 2-21.

Wells, N., 1986: *The atmosphere and ocean:* A *physical introduction*. Taylor and Francis. London., 347 p.